CE/SC 10110-20110: Planet Earth

Groundwater

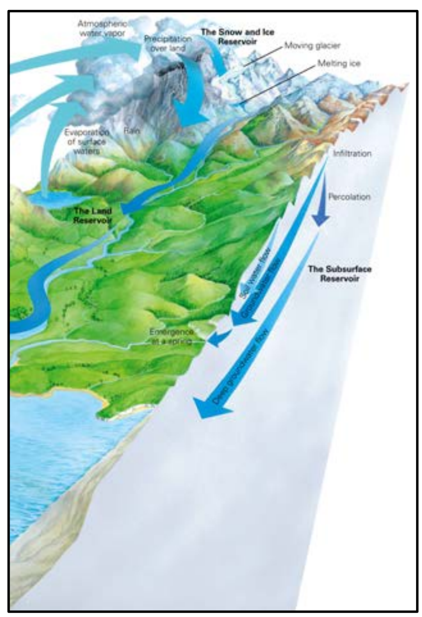
Earth

Portrait of a Planet

Fifth Edition

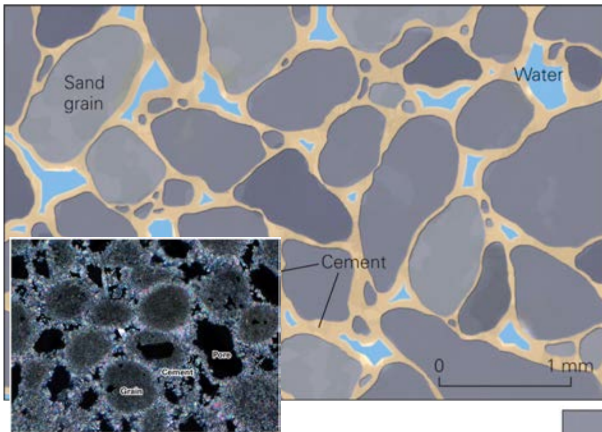
Chapter 19

The Hydrologic Cycle



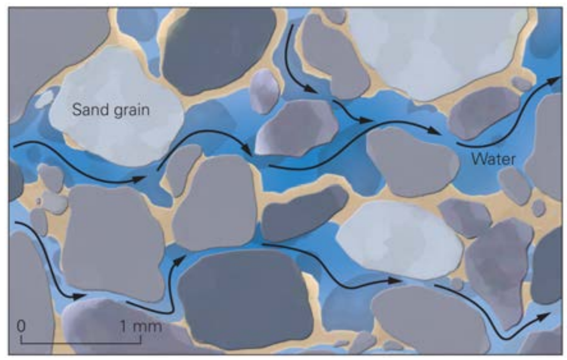
- Water moves among reservoirs (ocean, atmosphere, rivers, lakes, groundwater, living organisms, soils, and glaciers).
- Some of the water that falls on Earth's surface infiltrates and becomes soil moisture.
- Infiltrated water that percolates deeper becomes groundwater. Groundwater flows slowly underground, eventually resurfacing after months to thousands of years to rejoin the hydrologic cycle.

Porosity & Permeability



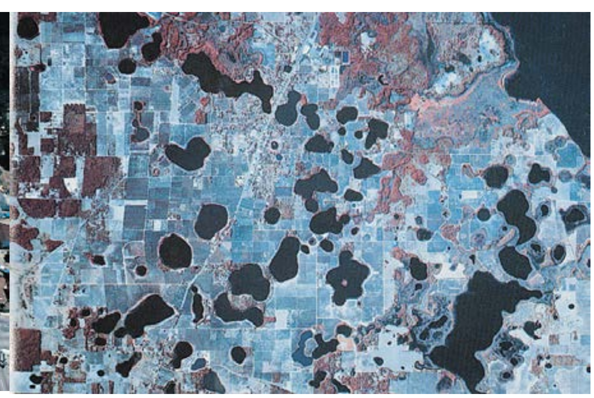
Groundwater resides in subsurface pore spaces, the open spaces. The total volume of open space is termed **Porosity**. Porosity can be filled with water or air. Pores can also become filled with mineral cement and other fluids, like oil or natural gas.

Permeability is the ease of water flow due to pore inter-connectedness.



Groundwater

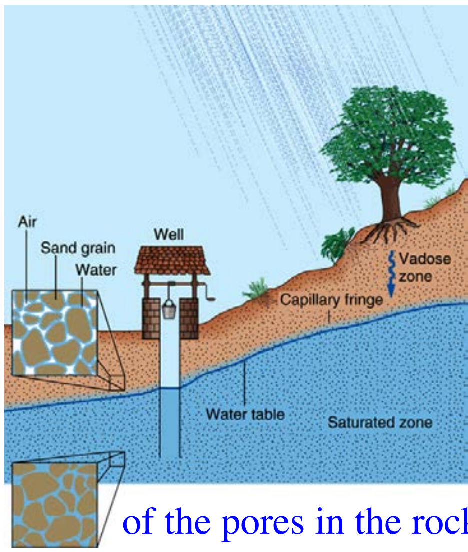
Evidence: sinkholes (predominantly in limestone terrains.



Groundwater is the water that fills pore spaces and fractures below ground level.
Groundwater flows underground and can dissolve rock, especially limestone, producing sinkholes.
Because groundwater is hidden from view, it is poorly understood by most. Groundwater is easily contaminated by human activity.

Groundwater

Groundwater forms through water infiltration into the subsurface.
Some evaporates, some is taken up by plants, some wets the surfaces of particles, and some percolates to the water table.
Groundwater accounts of two-thirds of the world's freshwater supply.

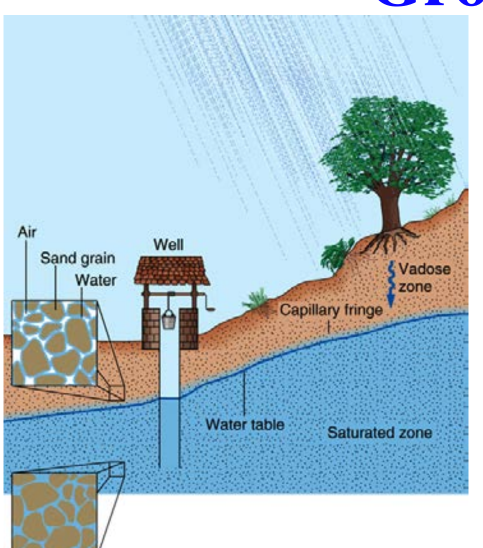


Water Table: Surface that is the contact between saturated and unsaturated zones.

Unsaturated Zone (Zone of Aeration or Vadose Zone): Water is called suspended water. Held by -
(i) molecular attraction between water and rock;
(ii) mutual attraction between water molecules.

Saturated Zone (Phreatic Zone): All of the pores in the rock or sediment are filled with water.

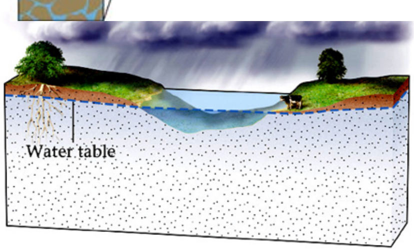
Groundwater

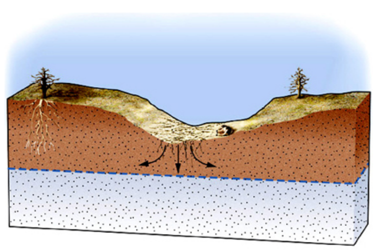


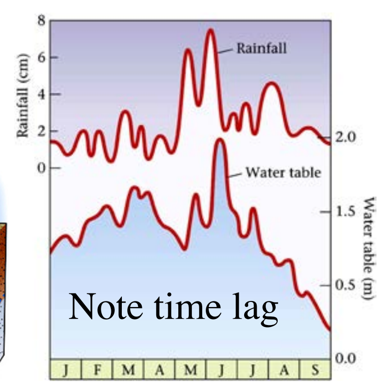
Surface tension and electrostatic attraction of water molecules to mineral surfaces causes water to seep up from the water table forming the ***capillary fringe***.

Depth to water table depends on climate and season.

Base of water table is imprecise - >15-20 km rocks are too weak for pore spaces.

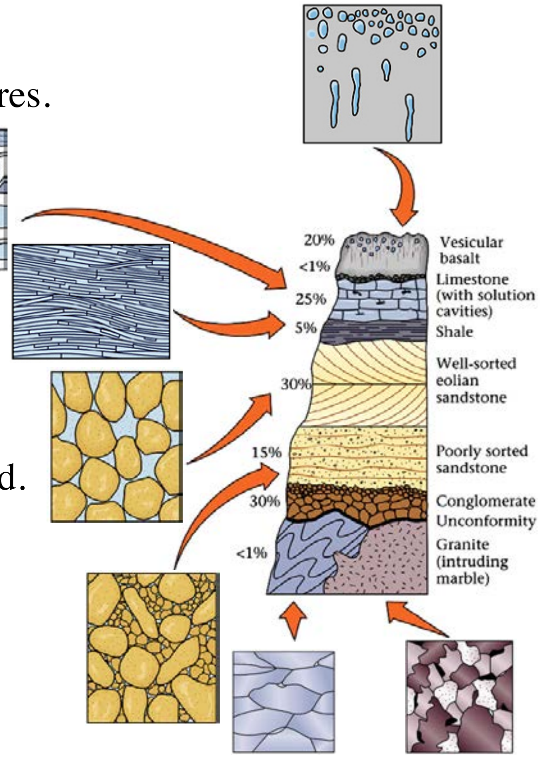






Porosity & Permeability

Porosity: amount of pores;
Permeability: interconnectivity of pores.



Primary Porosity

Space that remains between solid grains/crystals after sediment accumulates or rocks form.

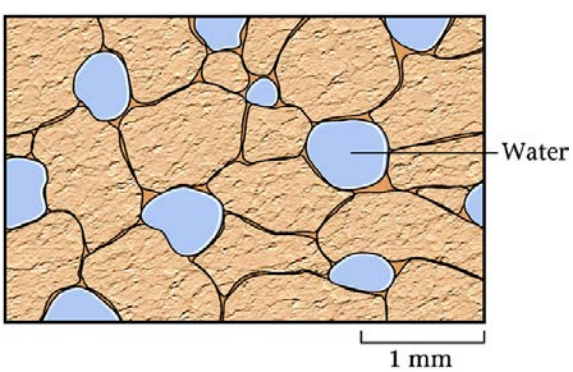
Secondary Porosity

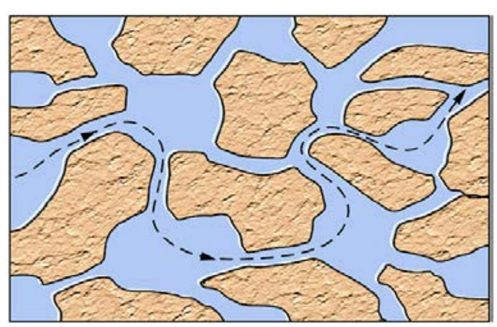
Porosity produces after the rock formed. Dissolution, faulting, jointing, etc.

Porosity & Permeability

Permeability depends on:

Number of available conduits: more conduits, greater permeability.
Size of the conduits (bigger is better!).
Straightness of the conduits: straighter allows more efficient transport.

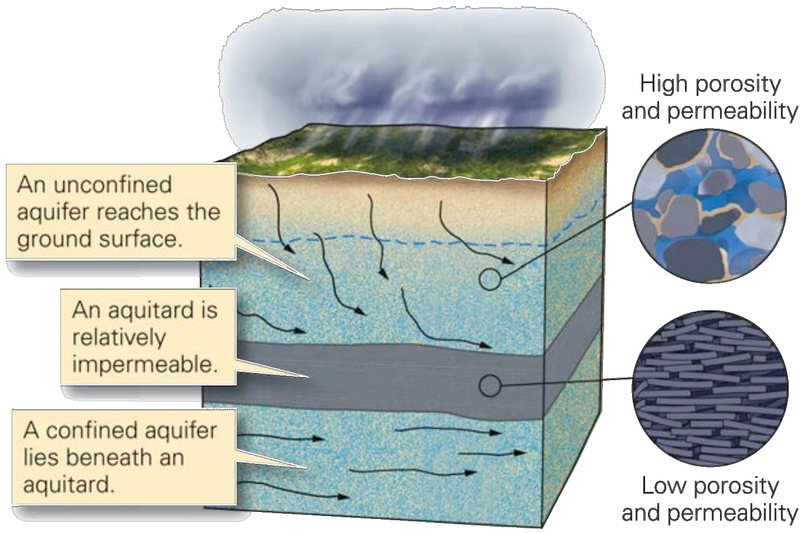




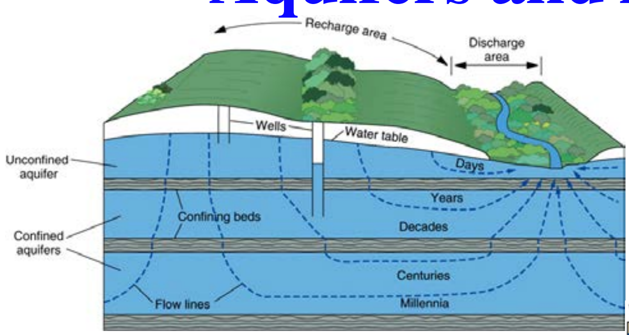
Aquifers and Aquitards

Aquifer: Permeable bed of rock or sediment that yields/contains water**.**

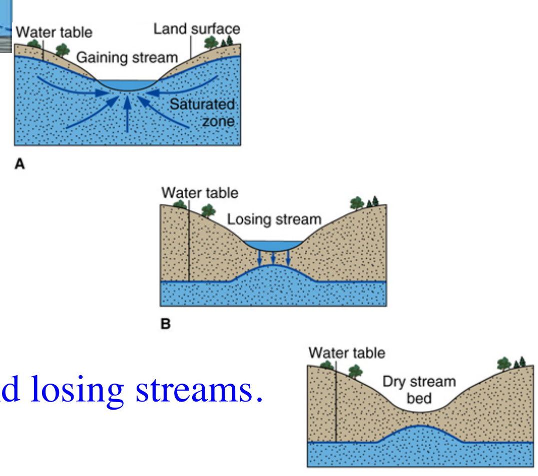
Aquitard (Aquiclude): impermeable bed (clay, shale, etc.).



Aquifers and Aquitards



Confined and unconfined aquifers.

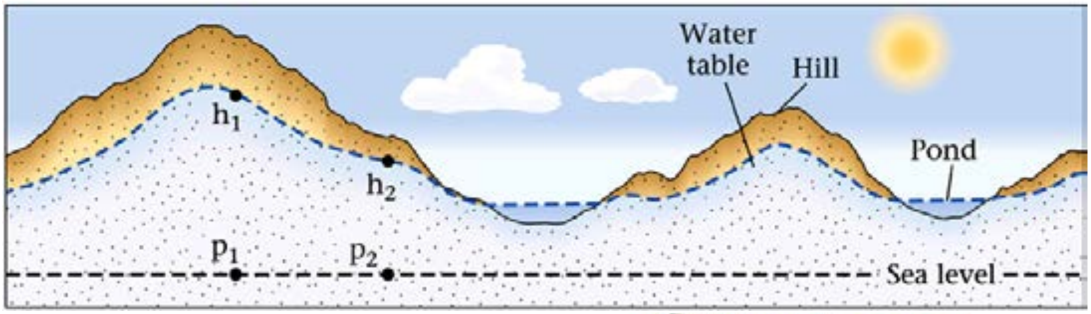


Gaining and losing streams.

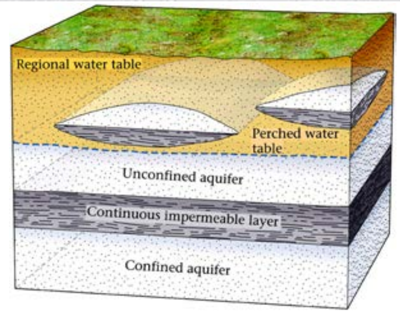
Water Table

Water table tends to parallel topography.

It is not always below ground and fluctuates annually (dependent upon rainfall and infiltration = **Recharge**).

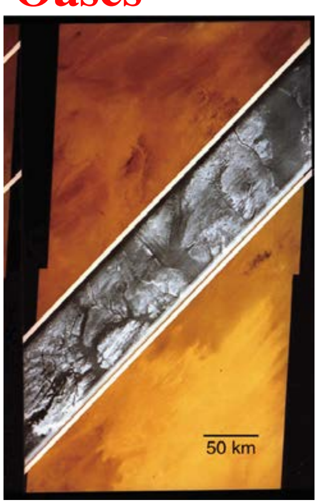


Perched water tables - discontinuous aquitards.

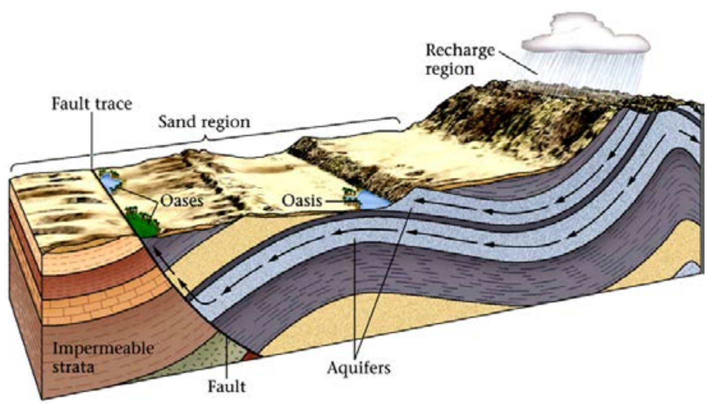


Water Table

Oases



The surface water fed aquifers that now form oases.



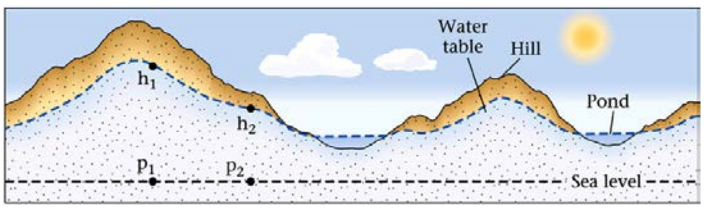
During the last glaciation, the Sahara Desert was in a temperate climate zone, with abundant flowing surface water. This was revealed through GPR.

Groundwater Flow

Groundwater responds to gravity and differences in pressure - the latter can cause groundwater to flow uphill.

If an aquifer is horizontal and the ground surface flat, pressure on water is the same at any place.
If the aquifer/ground surface is not horizontal, a pressure differential is set up.

Pressure at point $P_1 > P_2$. Elevation and pressure provide groundwater with potential energy.

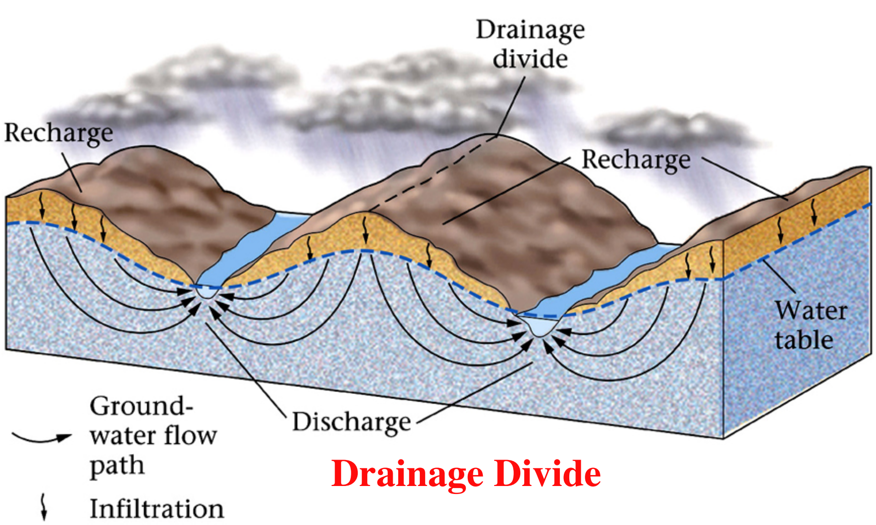


Potential energy available to drive groundwater flow = **Hydraulic Head**.

Groundwater flows from regions of high to low hydraulic head, or more simply, from regions of high to low water table.

Groundwater Flow

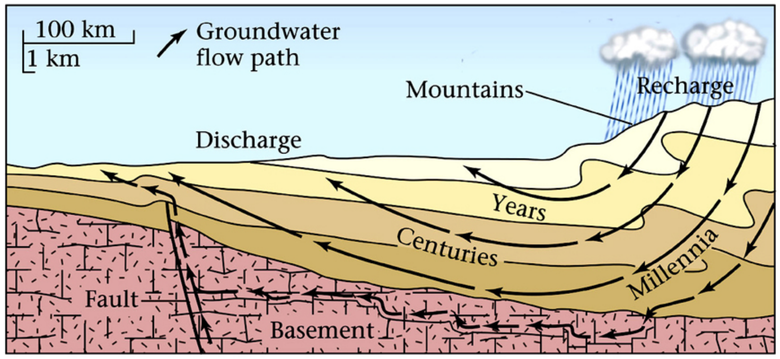
Recharge: area where water enters the aquifer system;
Discharge: area where water leaves the aquifer system.
Groundwater flows along "concave-upward" paths. This indicates that some groundwater can flow down deep into the crust (>10 km).



Drainage Divide

Groundwater Flow

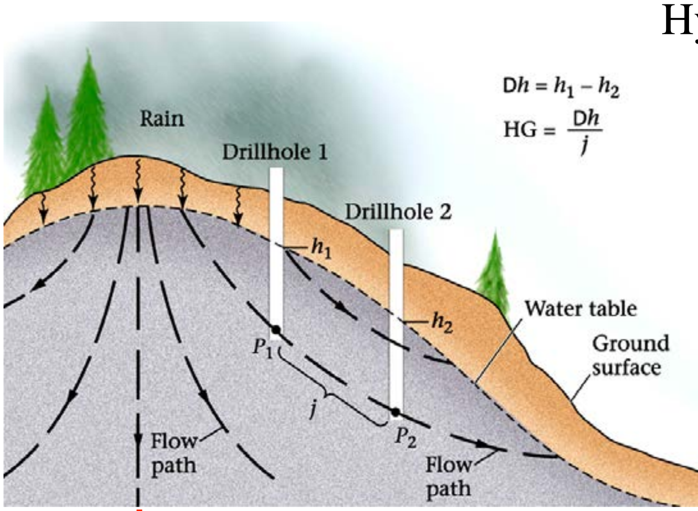
Groundwater can stay in aquifer systems for a few hours to millennia, dependent upon the pathway.



Groundwater flows much slower than surface water because of crooked pathways and friction (including electrostatic attraction between water and the conduit walls).

Rate of flow depends on the permeability and ***hydraulic gradient*** (change in hydraulic head between 2 locations as measured along the flow path).

Groundwater Flow



Hydraulic Gradient = Δh/j

Δh = difference in head, given in meters as head can be represented by elevation;

j = distance between the two points.

A hydraulic gradient exists anywhere the water table has a slope.

Darcy's Law: determines the volume of water that flows through an area of aquifer in a given time (discharge, Q).

$Q = K(\Delta h/j)A$ Δh/j = hydraulic gradient; A = area; K = hydraulic conductivity.

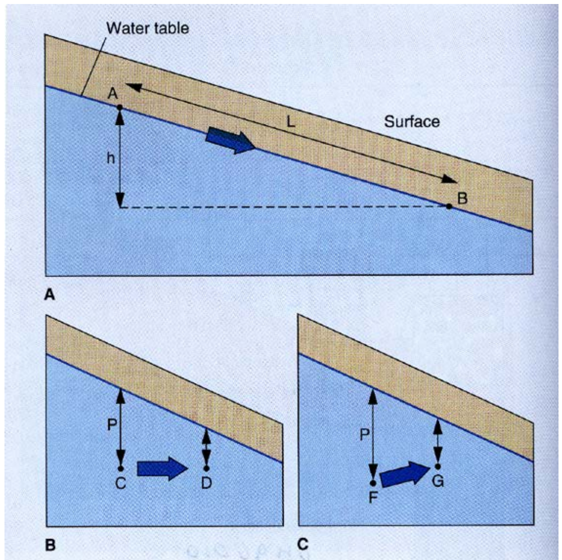
Darcy's law states that discharge volume is proportional to the hydraulic gradient times the permeability.

Groundwater Flow

Darcy's Law also shown as:

$$V = P\left(\frac{h}{l}\right)$$

V = Velocity;
P = Permeability; h = height;
l = length;
h/l = hydraulic gradient.



Box 11.1 Figure 1

Ground water moves in response to hydraulic head (elevation plus pressure). Water movement shown by dark blue arrows. (*A*) Points A and B have the same pressure, but A has a higher elevation, therefore water moves from A to B. (*B*) Point C has a higher pressure (arrow marked P) than D, therefore water moves from C to D at the same elevation. (*C*) Pressure also moves water upward from F to G.

Groundwater Flow

Hydraulic conductivity takes into account the permeability and the fluid viscosity.

Estimating Darcy's Law:

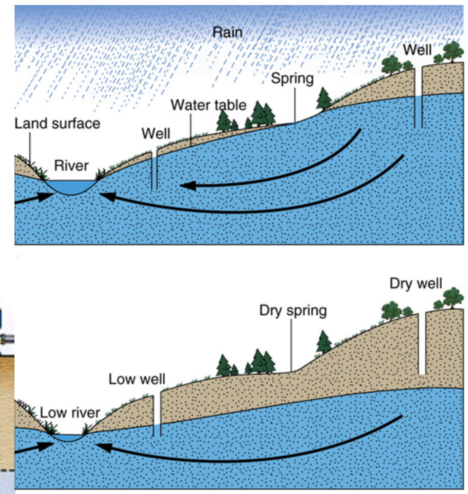
Q = [slope of the water table] X [permeability]

Permeability may change over time as the groundwater could dissolve the aquifer constituents (increasing permeability) or deposit material in the pores (decreasing permeability) or the pore spaces collapse due to over pumping.

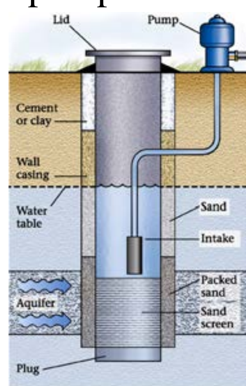
The quantity of dissolved ions in groundwater is controlled by temperature, pressure, pH.

Wells & Springs

Well: man-made holes dug to access groundwater;
Springs: natural groundwater outlets.

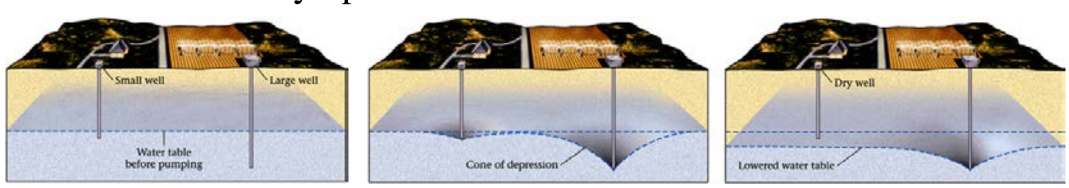


Ordinary Well: base penetrates the aquifer below the water table. Water seeps in and fills it to the level of the water table. Some may be dry part of the time.
Either drop a bucket down or pump water out.

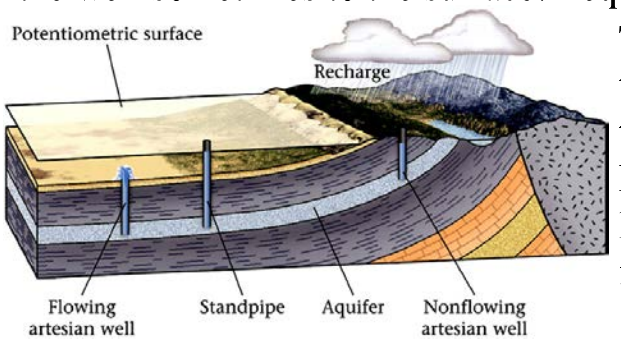


Wells & Springs

Pumping may produce a ***cone of depression***, which may lower the water table of pumping exceeds replenishment, and may also cause shallow wells to dry up.

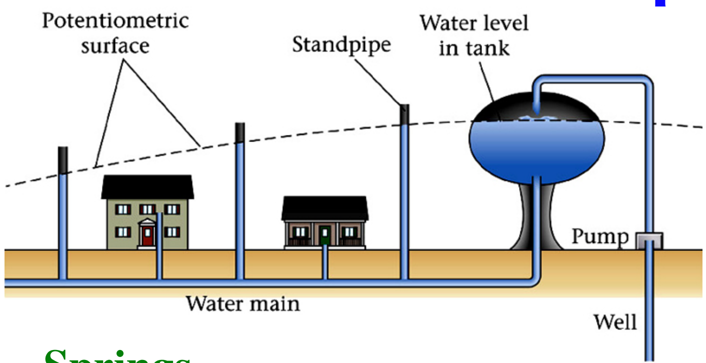


Artesian Well: groundwater is under enough pressure that it rises up the well sometimes to the surface. Requires a tilted, confined aquifer.



The ***potentiometric surface*** is the natural level of the water in the confined aquifer.
If this surface is below ground level, there will be a non-flowing artesian well.

Wells & Springs

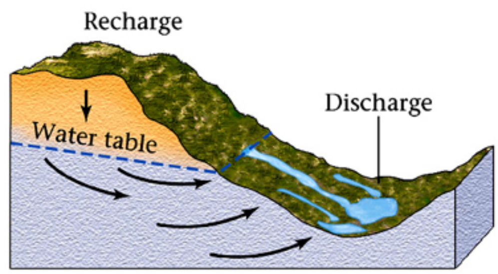


The same principle is used for domestic water tanks.

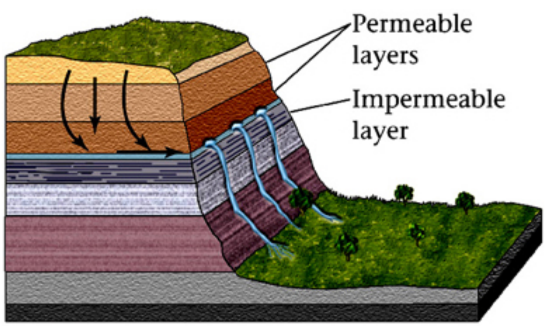
Springs

Springs form under a variety of conditions.

Where the ground surface intersects the water table (e.g., valley sides).

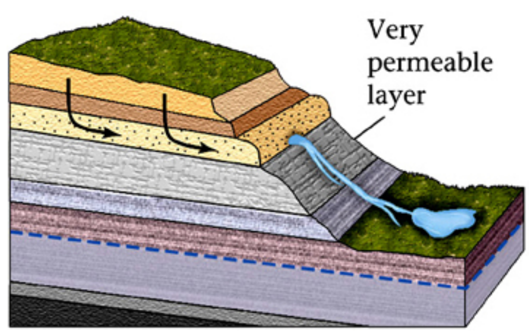


Wells & Springs



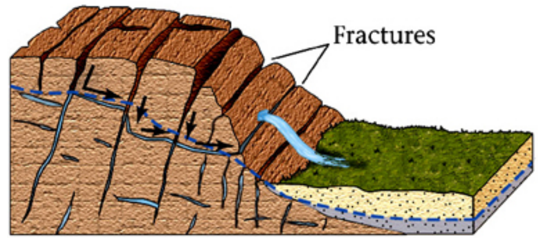
Where the water percolating downward intersects an impermeable layer and runs along the top of it until it intersects the surface.

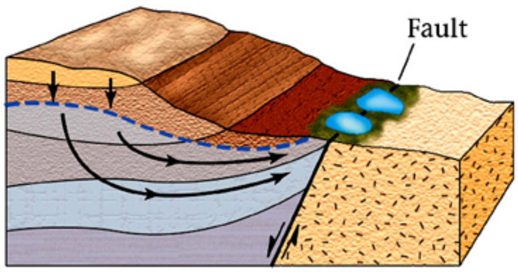
Where the aquifer intersects a hill side.



Wells & Springs

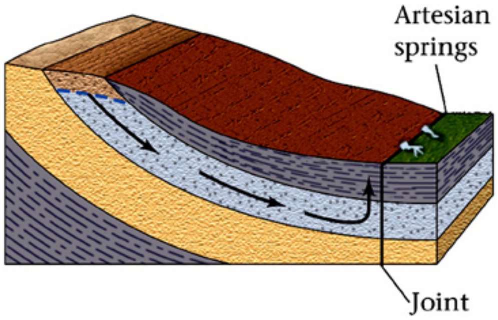
Where a network of interconnected fractures allows channeling of groundwater to the surface.





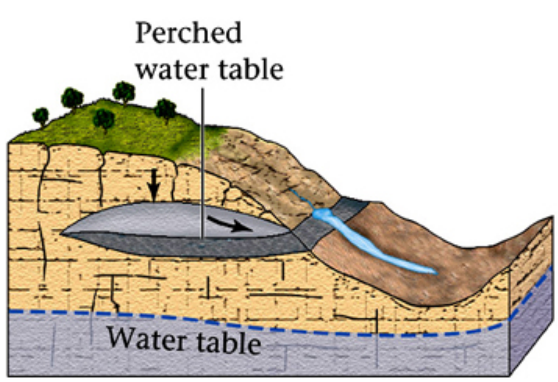
Flowing groundwater intersects a steeply dipping impermeable layer, such as can be caused by faulting.

Wells & Springs



Artesian springs form if the ground surface intersects a natural fracture that taps a confined aquifer and the pressure is sufficient to allow water to get to the surface.

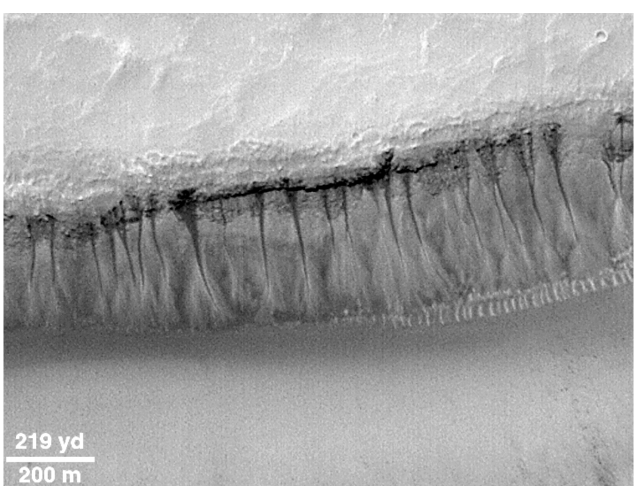
Where a perched water table intersects the side of a hill.

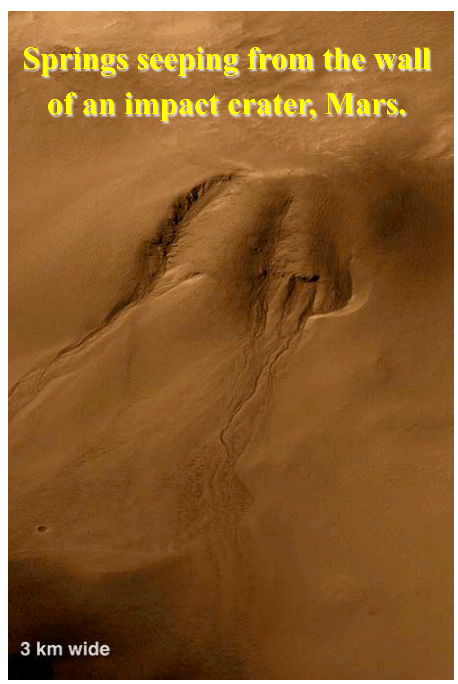


Wells & Springs

Wells & Springs

Evidence for recent water activity on Mars!

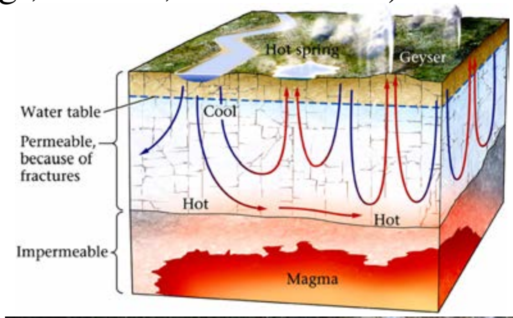




Hot Springs & Geysers

Thermal Springs: water heated to 30˚C to >100˚C by magma or hot rock beneath the surface.

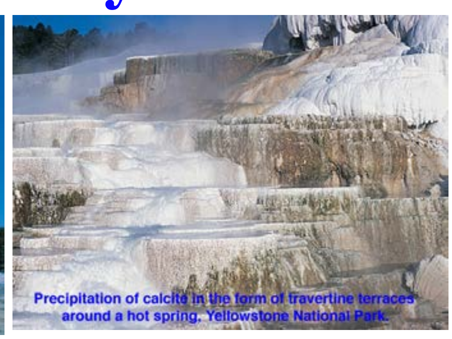
Possibility of "geothermal" energy (e.g., Iceland, New Zealand).

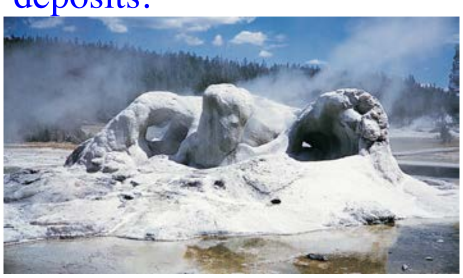


Hot pools can be multi-colored depending on the type of thermophyllic cyano-bacteria that metabolize the sulfur emitted by or contained in the hot spring.

Hot Springs & Geysers

The hot water contains a lot of dissolved materials that precipitate out when the water cools. $CaCO_3$ deposits around geyser at surface = <u>TRAVERTINE</u> deposits.





Groundwater can also percolate through buried wood and deposits silica, forming petrified wood.

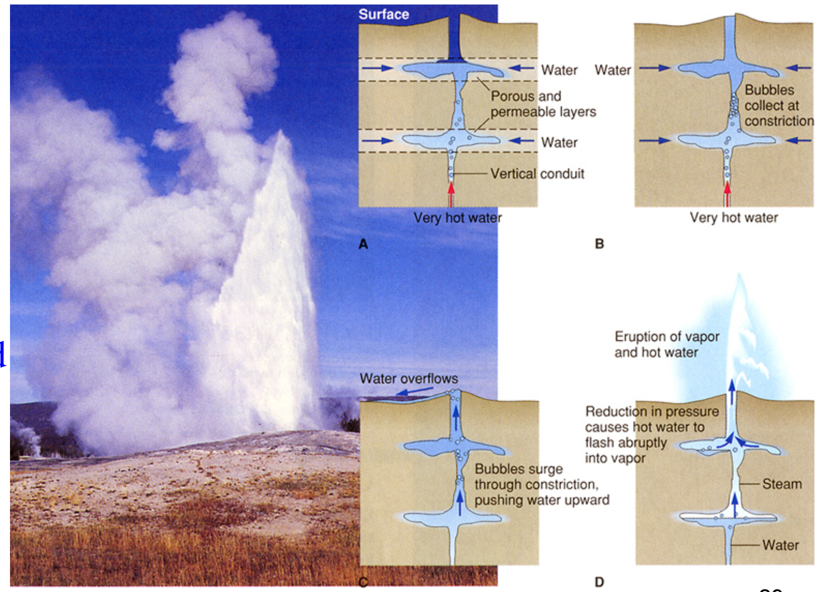
Siliceous minerals are also deposited.

Hot Springs & Geysers

Geyser: hot spring that periodically erupts hot water and steam. Water seeps into geyser chamber and slowly warms. Bubbles form as temperature increases.

The “neck” may become clogged – increase pressure = increase boiling point of water.

Pressure eventually pushes water passed the constriction – pressure drop and flash boiling + eruption (e.g., Old Faithful).

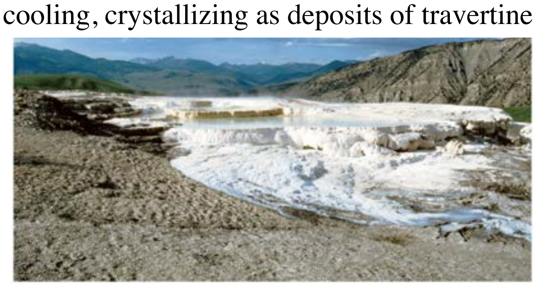


Hot Springs & Geysers


Blue Lagoon, Iceland

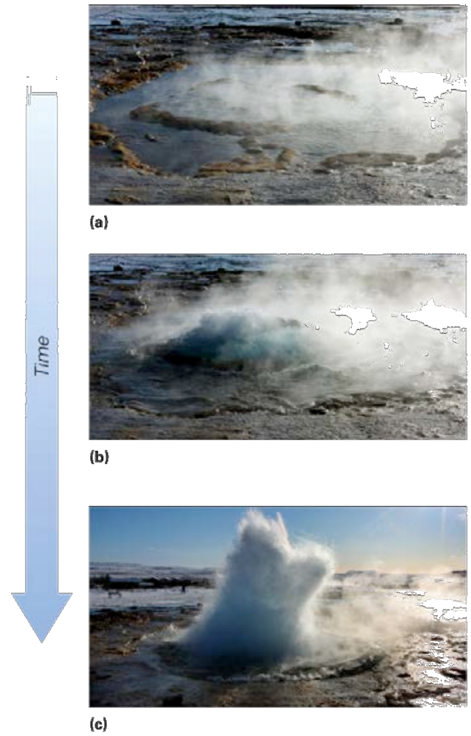

Colorful bacteria- and archea-laden pools, Yellowstone National Park, Wyoming

Hot springs lose dissolved minerals upon cooling, crystallizing as deposits of travertine.




Mudpots: where boiling water mixes with volcanic ash. The ash changes to clay and forms a hot, muddy soup.

Hot Springs & Geysers



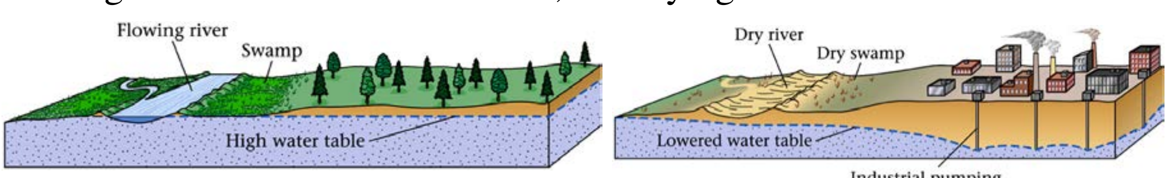
Boiling water and steam erupt cyclically from geysers. Groundwater is heated by shallow magma, but the weight of overlying water prevents boiling. Pressure drops as bubbles form, the water transforms to vapor and the water all boils at once. The cycle repeats after the emptied chamber is refilled.

Groundwater Usage Problems

Increasing population and decreasing surface water supplies has put increased pressure on groundwater supplies, especially in the development of arid regions (e.g., SW USA).

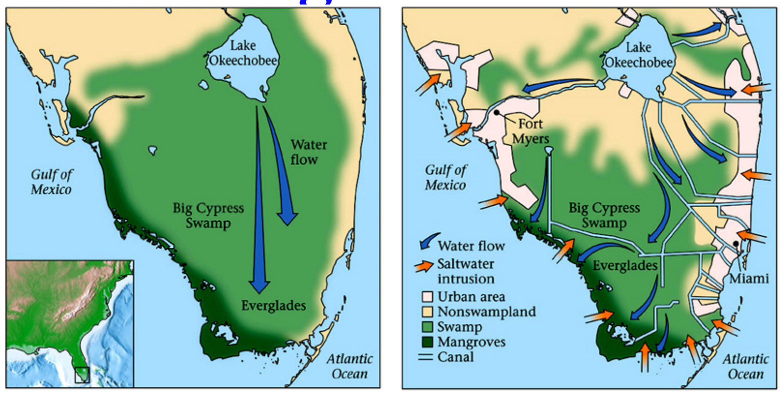
On the scale of 10,000 years, groundwater is renewable.
On the scale of 100-1,000 years, it is not.
In certain arid regions of the USA, water now being pumped is ~10,000 years old - young “deposits” have been exhausted. This causes problems.

1) **Lowering the Water Table**: as the cone of depression expands, the regional water table is lowered, destroying wetlands and rivers.

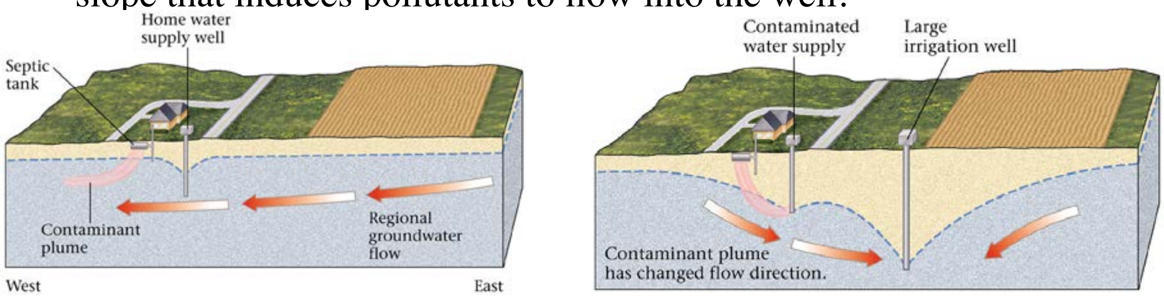


Groundwater Usage Problems

Diverting water away from recharge areas also causes the water table to drop (e.g., Florida Everglades). Part of the Everglades has dried up due to drainage canals.

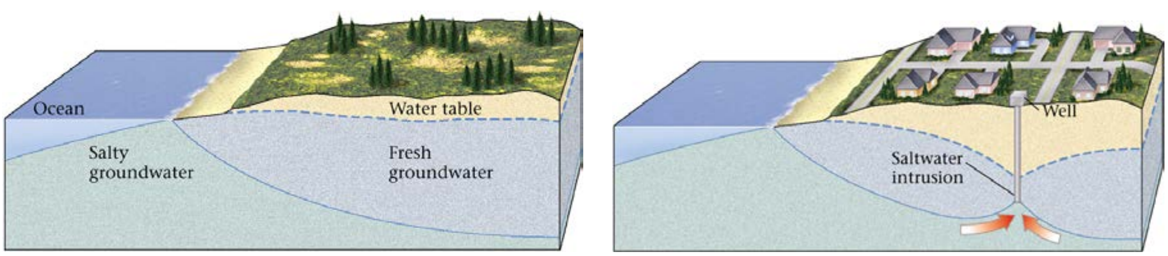


2) **Reversing Groundwater Flow**: cone of depression creates a local slope that induces pollutants to flow into the well.

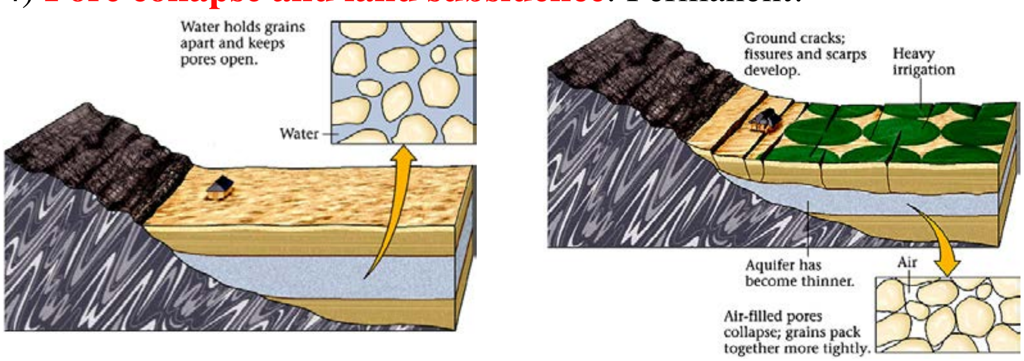


Groundwater Usage Problems

3) **Saline Intrusion**: Around the coast, salt water will replace freshwater in an aquifer. This replacement is permanent.

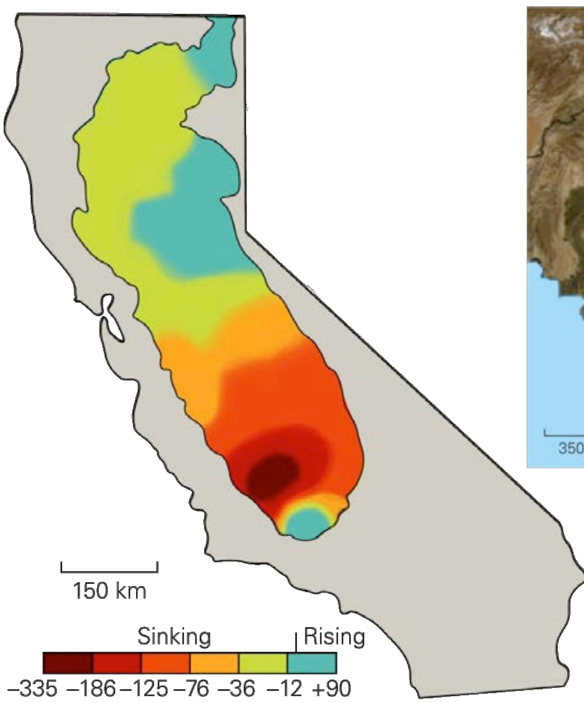


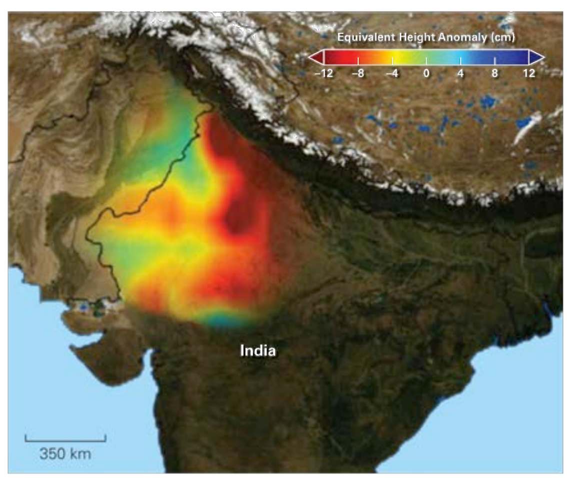
4) **Pore collapse and land subsidence**: Permanent.



Groundwater Usage Problems

Groundwater Problems: Depletion

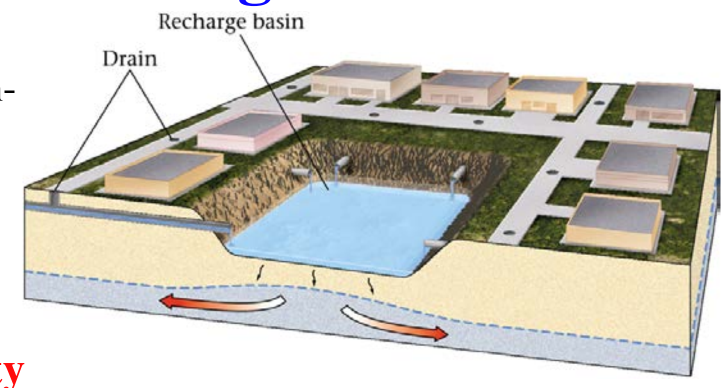




Excessive groundwater removal has created depletion problems in California and India

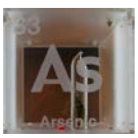
Groundwater Usage Problems

"Fixes": direct surface run-off to recharge areas or pumping surface water back into the aquifer.



Groundwater Quality

Dissolved Mg^{2+} and Ca^{2+} = hard water: scale on pipes and appliances, soap won't lather. Pipes can become clogged.
Fe^{2+} also dissolves.
H_2S = "rotten eggs".
Arsenic from Arseonpyrite (FeAsS).



Groundwater Usage Problems

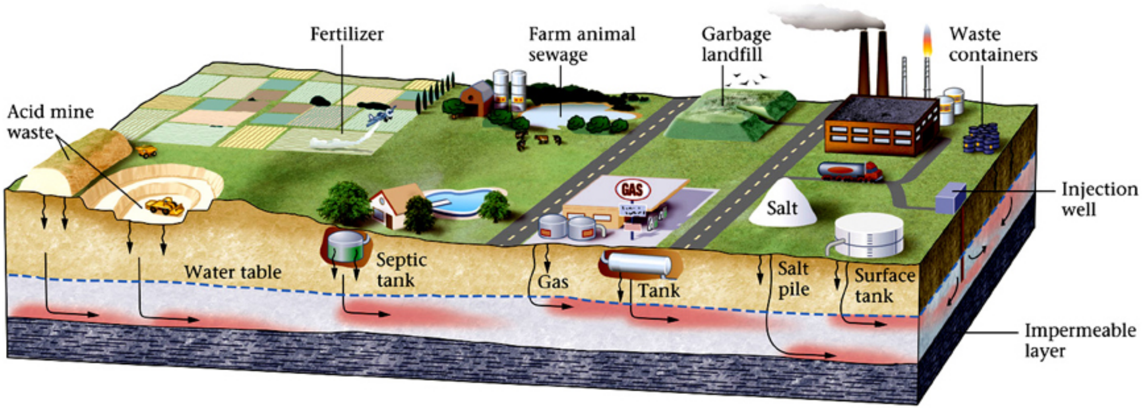
Groundwater Contamination

Rocks are good filters - suspended solids can be removed and clays can act as exchange surfaces to remove pollutants (as long as clays don't destroy the permeability of the aquifer).

However, groundwater contains dissolved materials that can be toxic (As, Hg, Pb) or non-toxic but unpleasant (lime, sulfur, salt, Fe).

Some organic materials don't mix with water (nonaqueous phase liquids - NAPL), but get pushed through the system.
Bacteria from septic systems can also go through an aquifer.

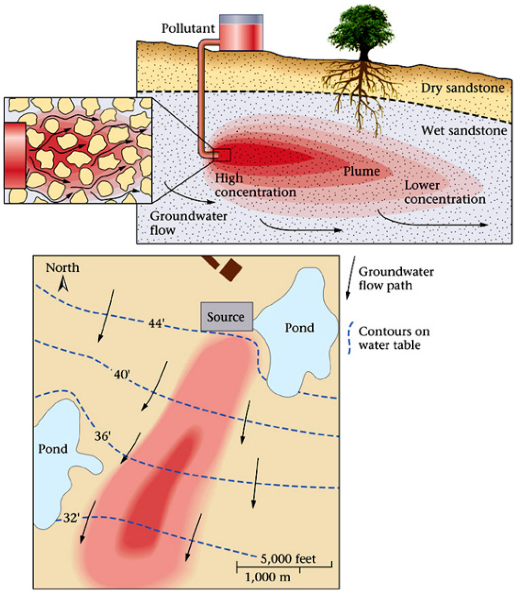
Human-Caused Contamination

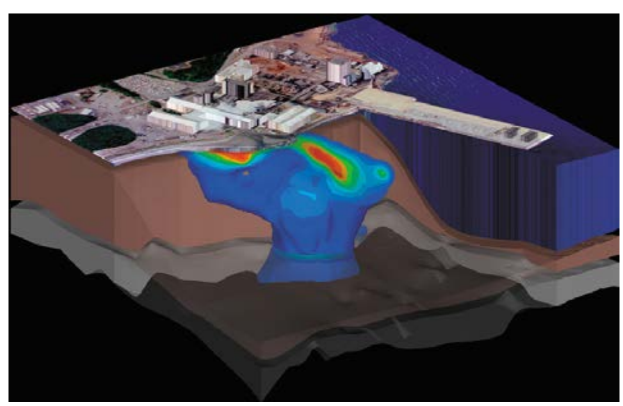


Sources of contaminants: Agriculture (pesticides, herbicides, fertilizer, animal sewage); Industry (dangerous organic and inorganic compounds); effluent from “sanitary” landfills and septic tanks; petroleum products; radioactive wastes (weapons manufacture, hospitals, spent fuel disposal); acid mine drainage.

Human-Caused Contamination

If these contaminants get into groundwater, they produce a contaminant plume as they flow away.





Human-Caused Contamination

Fertilizers

Pesticides

Human-Caused Contamination


Industrial solvents and degreasers


Paints and thinners

Human-Caused Contamination


Petroleum terminals

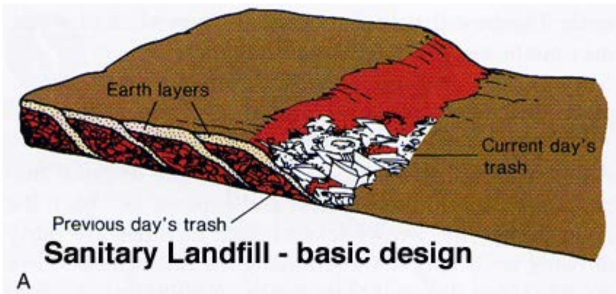

Abandoned gas stations

Human-Caused Contamination


Junkyards


Landfills

Preventing Groundwater Contamination



Sanitary Landfill

A layer of compacted trash is covered by a layer of earth at least once a day.

The soil keeps out vermin and confines the trash.

Usually sited in abandoned gravel pits or surface mines.

When full, a thick layer of earth is put on top and the area given over to other uses (parks, golf courses, car parks, etc.).

E.g., Mt. Trashmore, Evanston, IL.

Lowry Landfill in Colorado

Preventing Groundwater Contamination

Sanitary Landfill

Gas Pollutants: initially aerobic decay (trapped air) – CO_2 and SO_2. Changes to anaerobic (CH_4 & H_2S).

These gases may percolate through the soil and naturally vent, but want to keep them in – CH_4 is a greenhouse gas and both CH_4 and H_2S, if in high enough concentration, may cause asphyxiation.

If kept in, quantity of CH_4 produced could be used commercially. If not, it is burnt off.

Preventing Groundwater Contamination

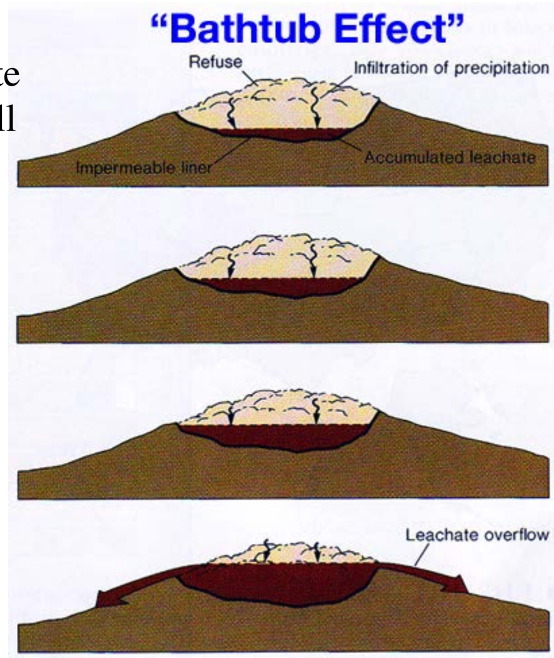
Sanitary Landfill

Infiltrating water may accumulate in the landfill and eventually spill over the liner.

Use low-permeability materials above and below landfill to minimize this.

Or pump out leachate and treat before disposal.

Plants growing on a finished landfill may uptake toxic chemicals – warning against using the site for farming.

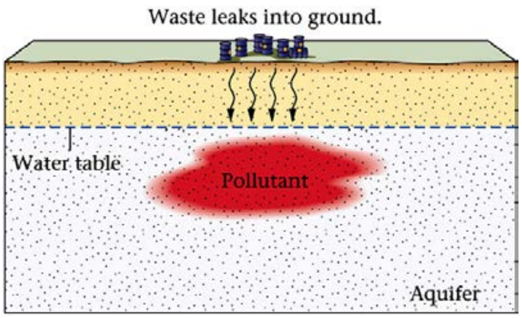


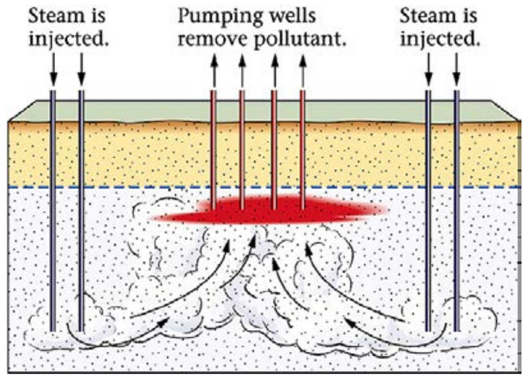
Human-Caused Contamination

Mine spoil and processing wastes

Groundwater Usage Problems

Remediating Groundwater Contamination



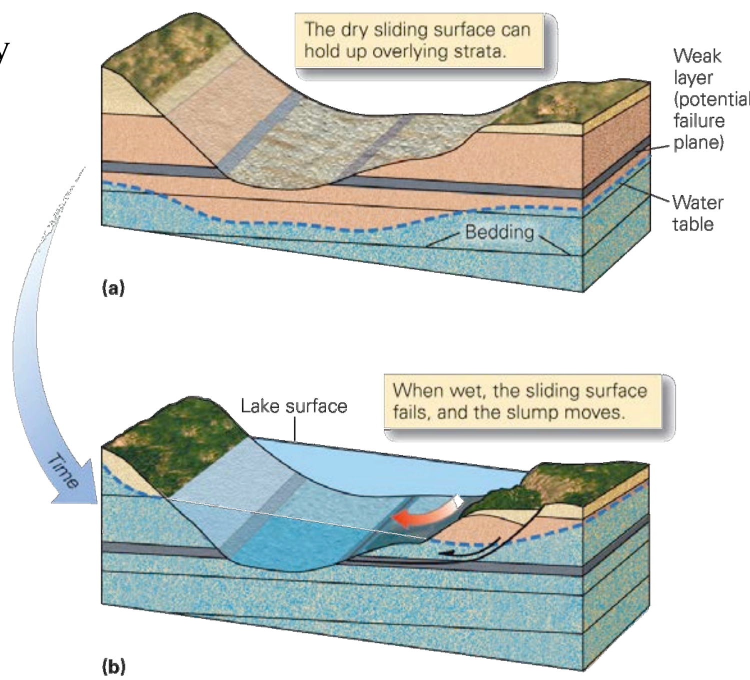


Pump and treat.
Bioremediation.
Oxygenation.

Groundwater contamination can be cleaned up by utilizing engineering principles and natural processes, but it is expensive. Most remedial strategies include removing the source. Bioremediation is a technique that utilizes bacteria to clean groundwater.

Groundwater Overabundance

Rising water tables may initiate slope failures.



Karst Topography

Karst: area of limestone underlaying the soil – lots of sinkholes defined by circular lakes.

Sinkholes occur in limestone areas that have a lot of water, which can dissolve the rock.

Surface streams uncommon and may disappear. Surface expression may not reflect the magnitude of cavern development beneath.

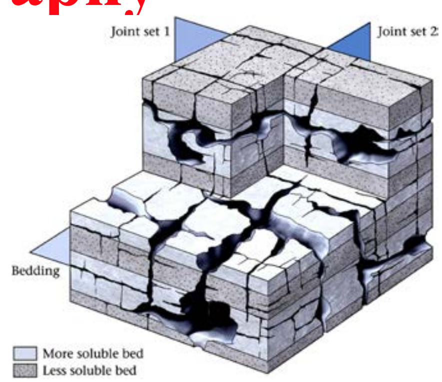
Sinkholes in limestone, New Zealand

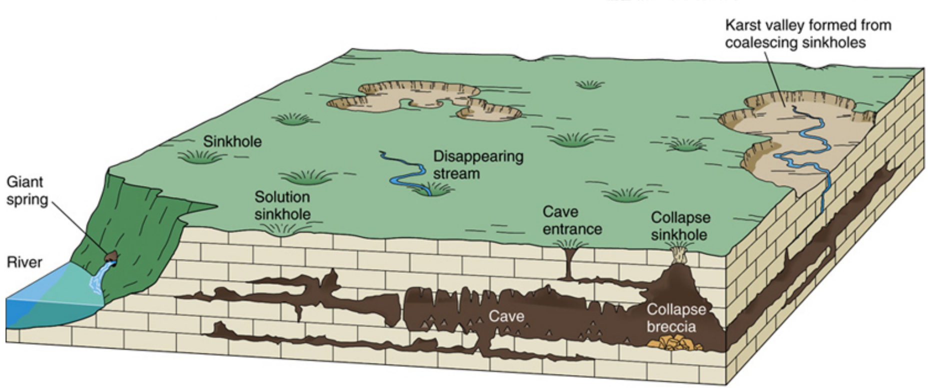
A collapse sinkhole that formed suddenly in Florida

Karst Topography

Groundwater important influence on landscape development in areas with limestone bedrock.

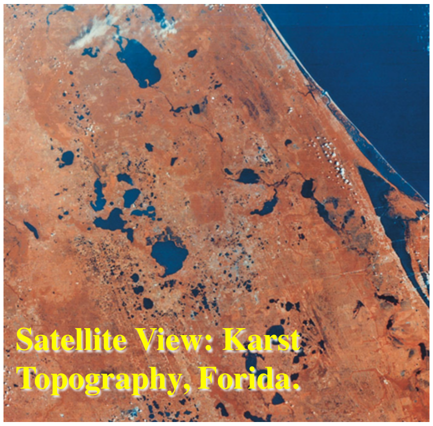
$$CO_2 + H_2O \rightarrow H_2CO_3$$
$$H_2CO_3 + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$$

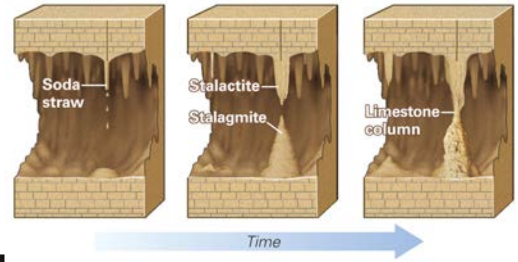


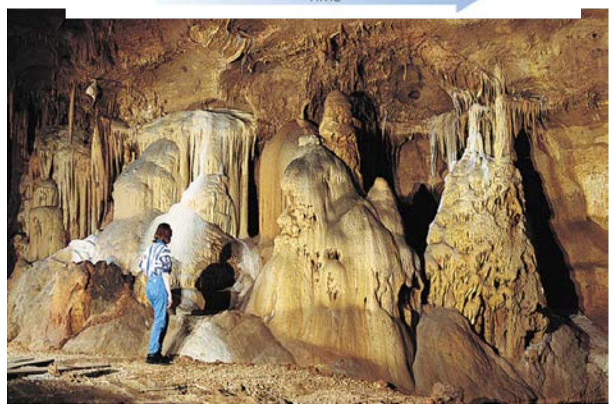


Karst Topography

Consists of **sinkholes**, **disappearing streams**, **caves**.



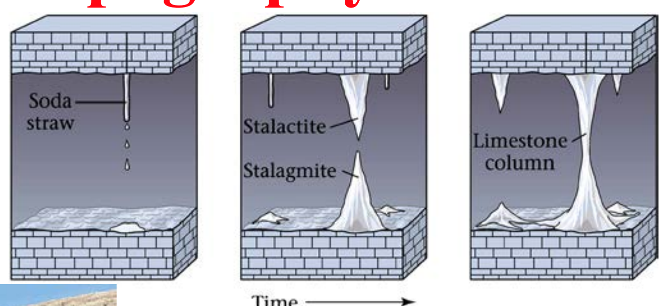




Water trickles down cave walls or drips from the ceiling, re-enters air and releases some dissolved CO_2. This precipitates $CaCO_3$ or travertine to form ***speleotherms***.

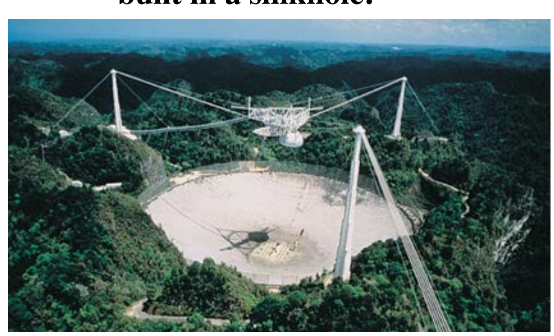
Karst Topography

Speleotherms consist of stalactites, stalagmites and limestone columns.



Karst Features.

Arecibo Radio Telescope was built in a sinkhole.



Karst Topography

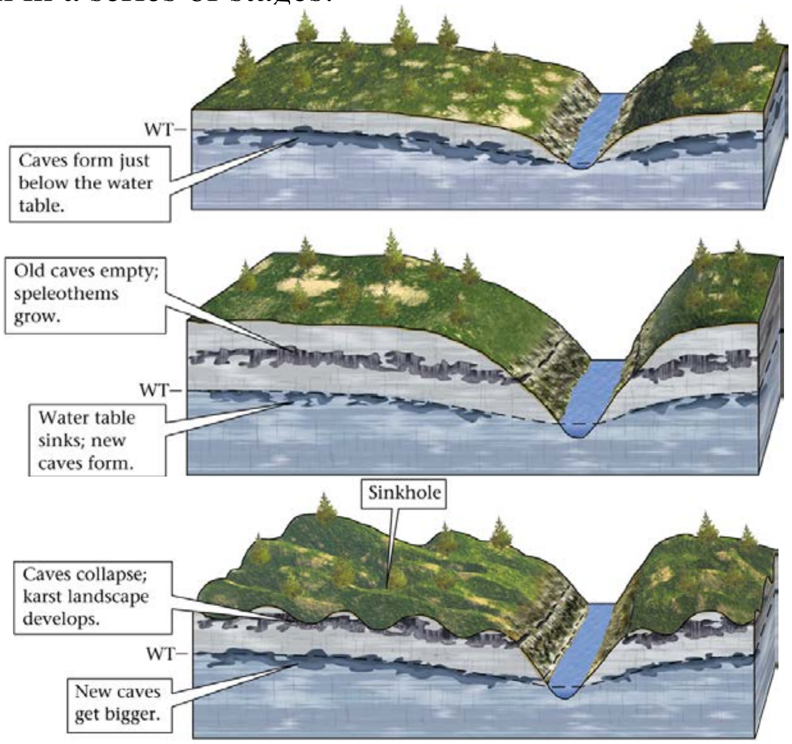
Karst landscapes form in a series of stages:

Establishment of a Water Table in Limestone.

Formation of a Cave Network: after the water table is established, dissolution begins.

A Drop in Water Table Level.

Roof Collapse.



Karst Landscapes

Limestone dissolution creates unique karst landscapes. Elements common in karst landscapes include disappearing streams, natural bridges, caves, speleothems, sinkholes, and springs.

Summary

Groundwater: Water Table; Unsaturated/Vadose Zone, Saturated/Phreatic Zone; Capillary Fringe.

Porosity & Permeability: Primary and Secondary Porosity; Interconnectivity.

Aquifers & Aquitards: Aquitards also known as Aquicludes; Confined and Unconfined Aquifers; Gaining and Losing Streams.

Water Table: Recharge; Perched Water Tables; Oases.

Groundwater Flow: Hydraulic Head; Recharge and Discharge; Flow paths; Groundwater Age; Hydraulic Gradient; Darcy' s Law.

Wells & Springs: Ordinary Well; Cone of Depression; Artesian Well; Potentiometric Surface; Different Spring formation scenarios.

Hot Springs & Geysers: Thermal Springs; Geothermal Energy; Travertine; Silica, Cyano-bacteria; Geyser Formation.

Groundwater Usage Problems: Lowering the Water Table; Reversing Flow; Saline Intrusion; Pore Collapse; Water Quality; Contamination; Sanitary Landfill; Remediation Techniques.

Karst Topography: Development; Sinkholes; Disappearing Streams; Caves; Speleotherms; Natural Bridges.