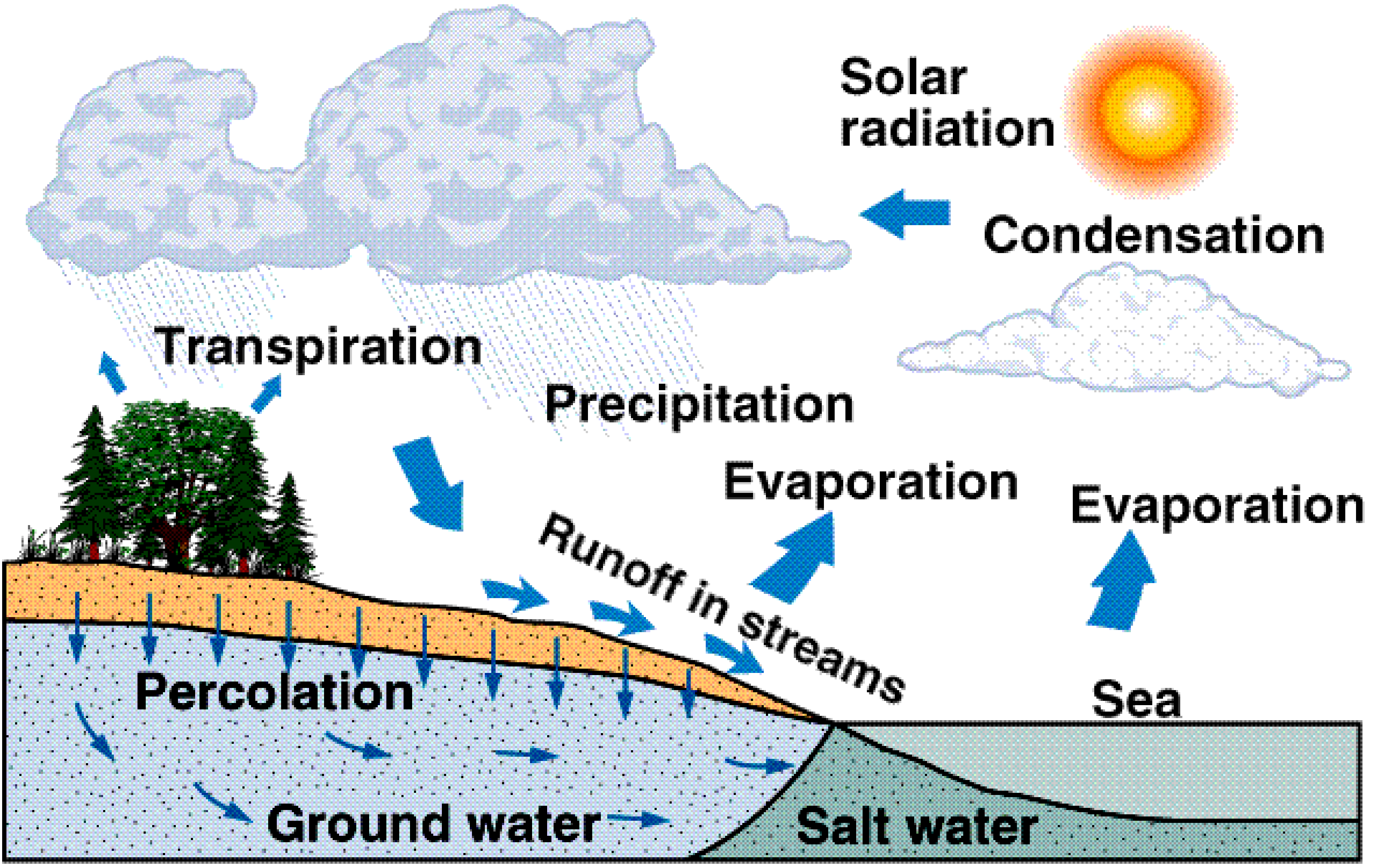
Chapter 11

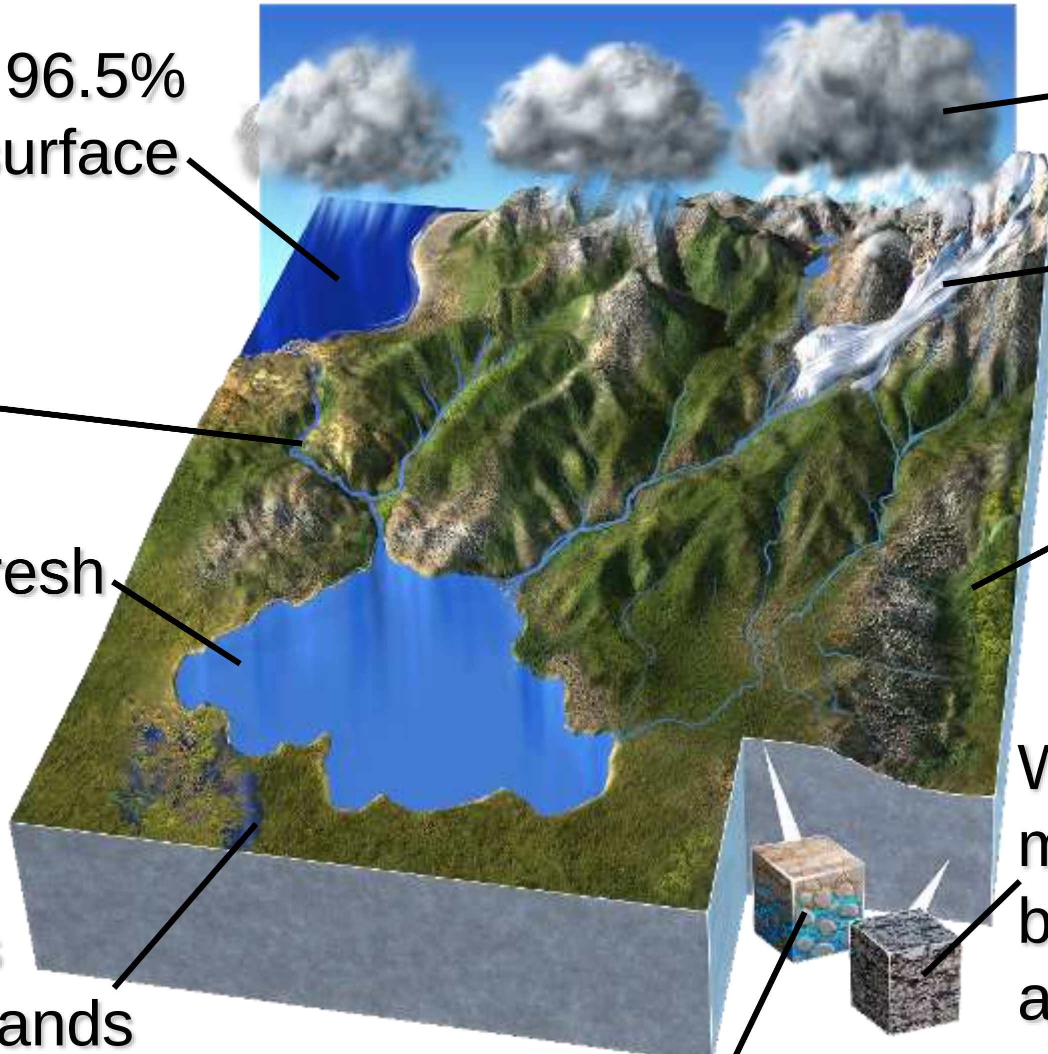
Groundwater

The Hydrologic Cycle



Settings of Earth's Water

Observe all the places where water is present



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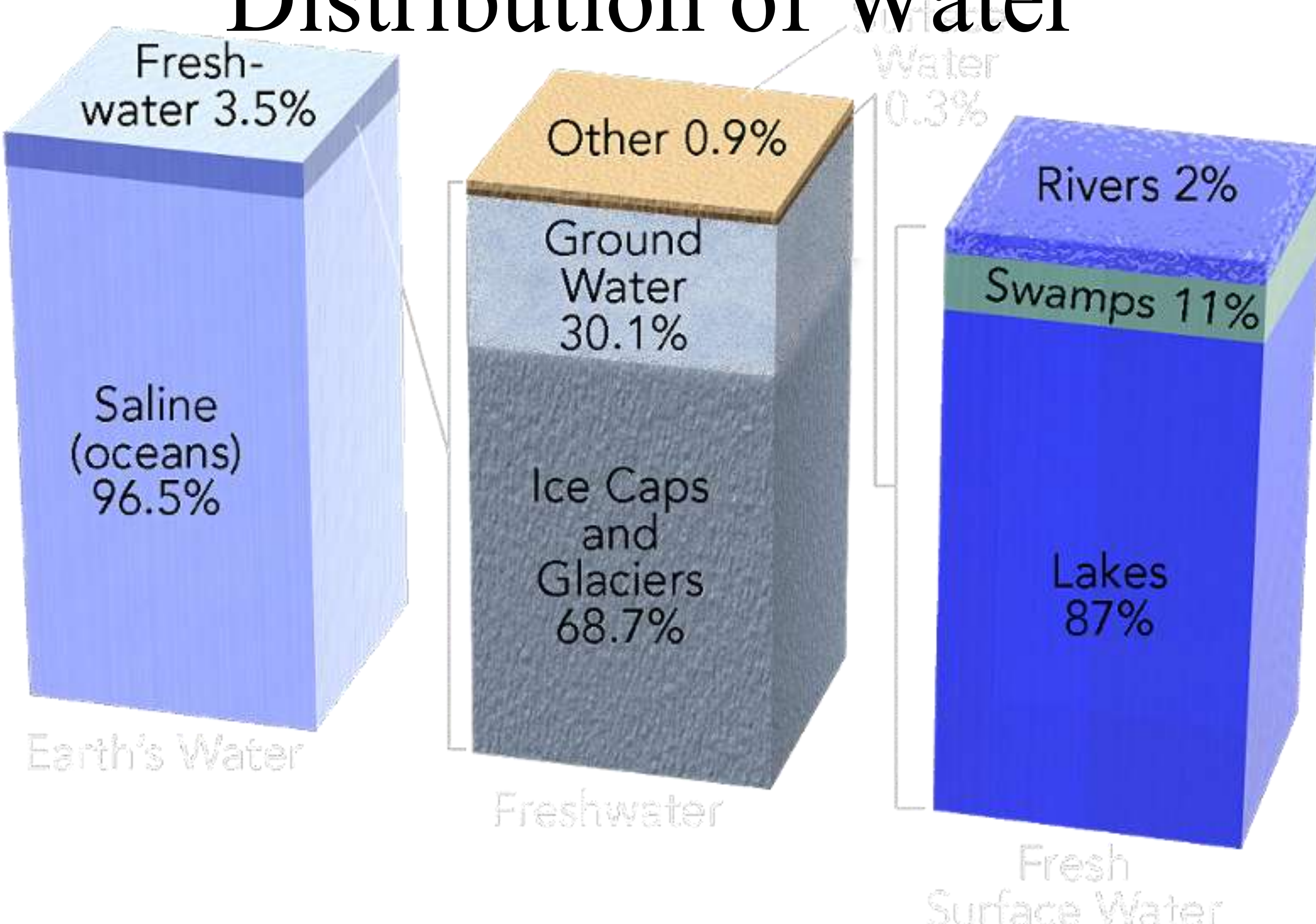
Distribution of Water



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The Water in the Hydrosphere

Reservoir	Percentage of Total Water*	Percentage of Fresh Water†	Percentage of Unfrozen Fresh Water
oceans	97.54	—	—
ice	1.81	73.9	—
ground water	0.63	25.7	98.4
lakes and streams			
salt	0.007	—	—
fresh	0.009	0.36	1.4
atmosphere	0.001	0.04	0.2

Source: Data from J. R. Mather, *Water Resources*, 1984, John Wiley & Sons, Inc., New York.

*These figures account for over 99.9% of the water. Some water is also held in organisms (the biosphere).

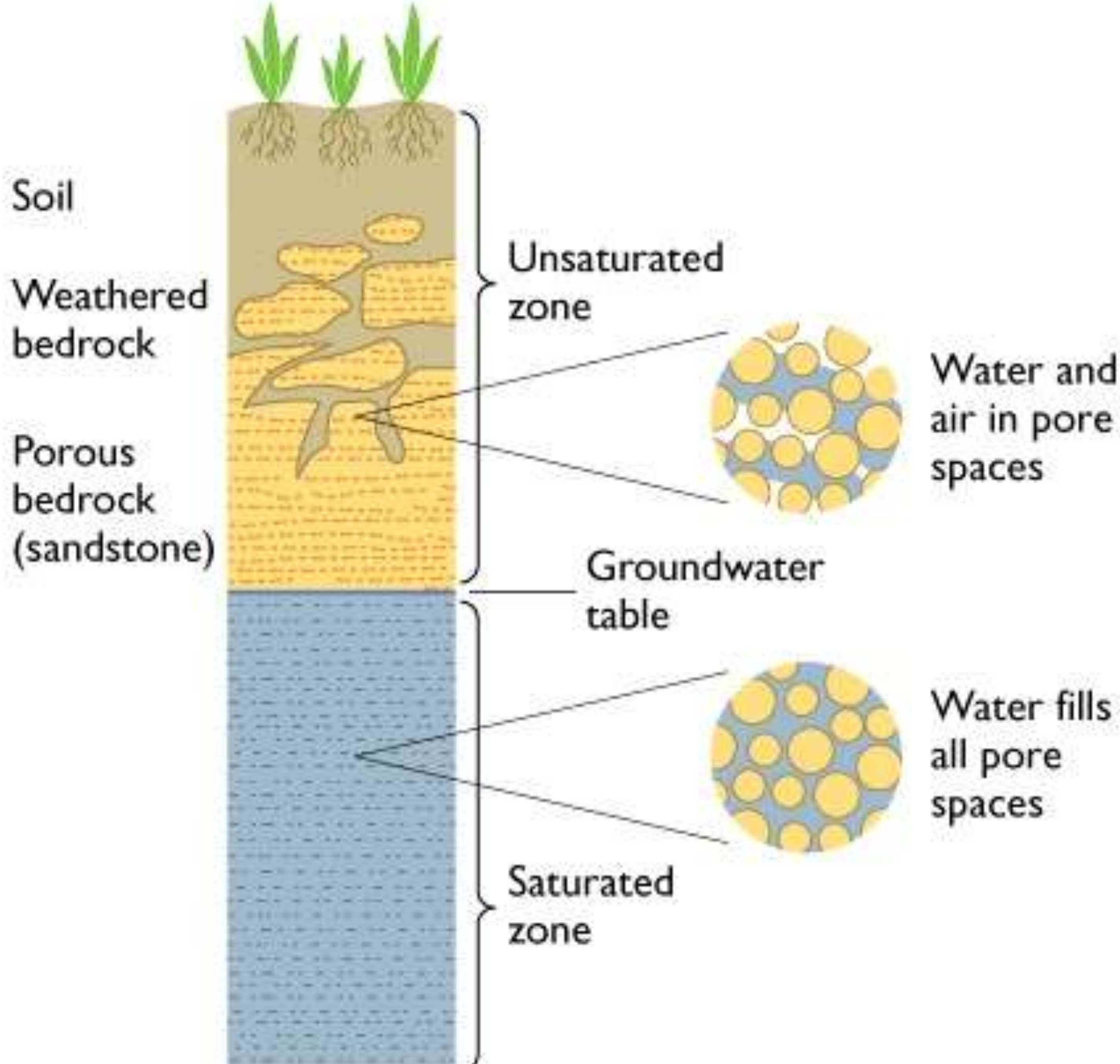
†This assumes that all ground water is more or less fresh, since it is not all readily accessible to be tested and classified.

The Global Water Budget

- Consider water as a resource because it is important for domestic use, agriculture, and industry
- Fresh water is limited on the earth
  - Mostly Polar ice and in the ground
- Water is regionally a renewable resource
  - Locally water may not be renewable
- The geologic condition affects the quality and quality of water in a region

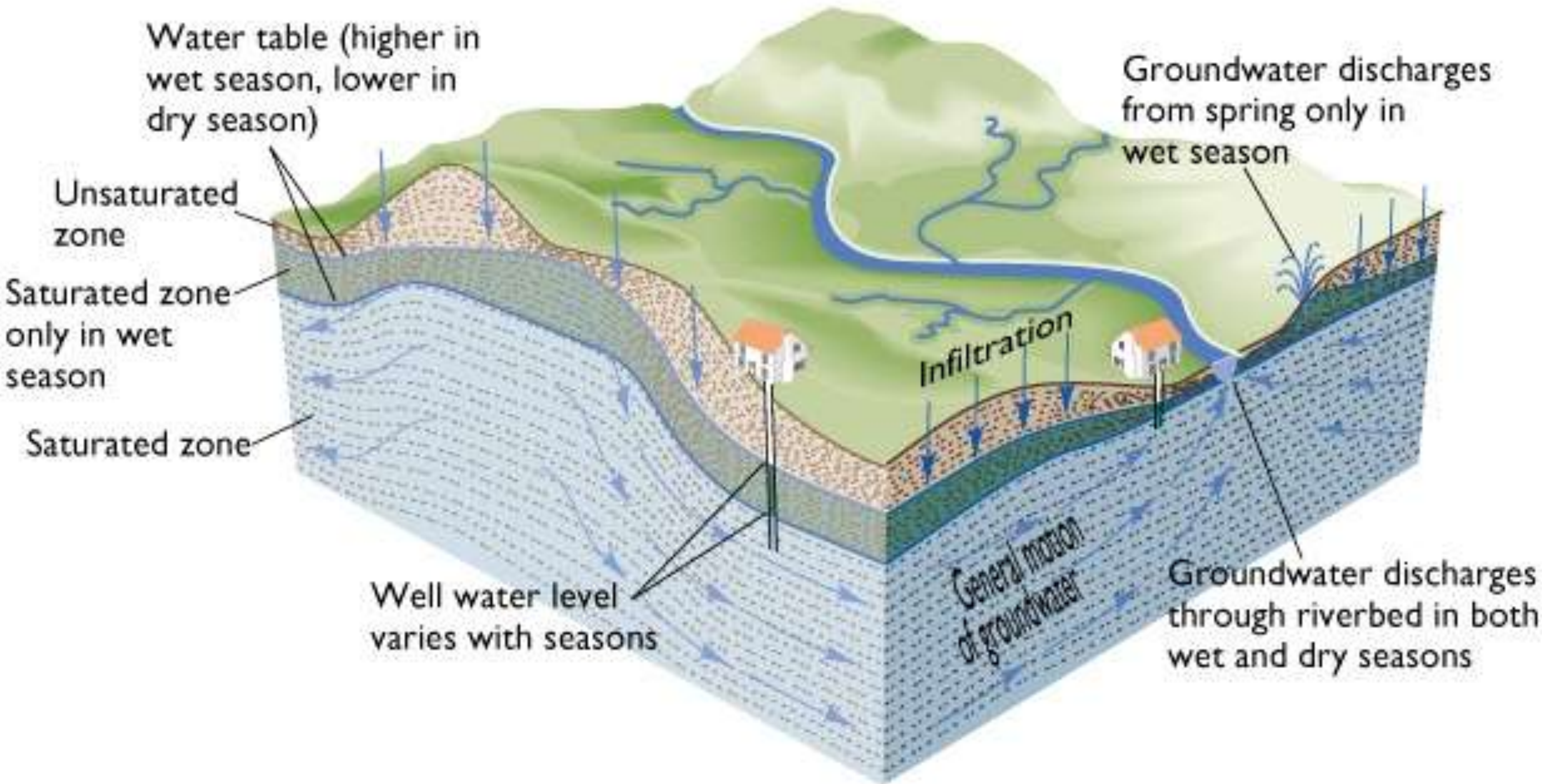
Groundwater

- Water that lies beneath the ground surface, filling pores in sediments and sedimentary rocks and fractures in other rock types is known as *groundwater*
  - Represents *0.61%* of the hydrosphere (35 times the amount of water in all lakes and rivers combined)
  - Resupplied by slow *infiltration of precipitation*
  - Generally cleaner than surface water
  - Accessed by *wells*

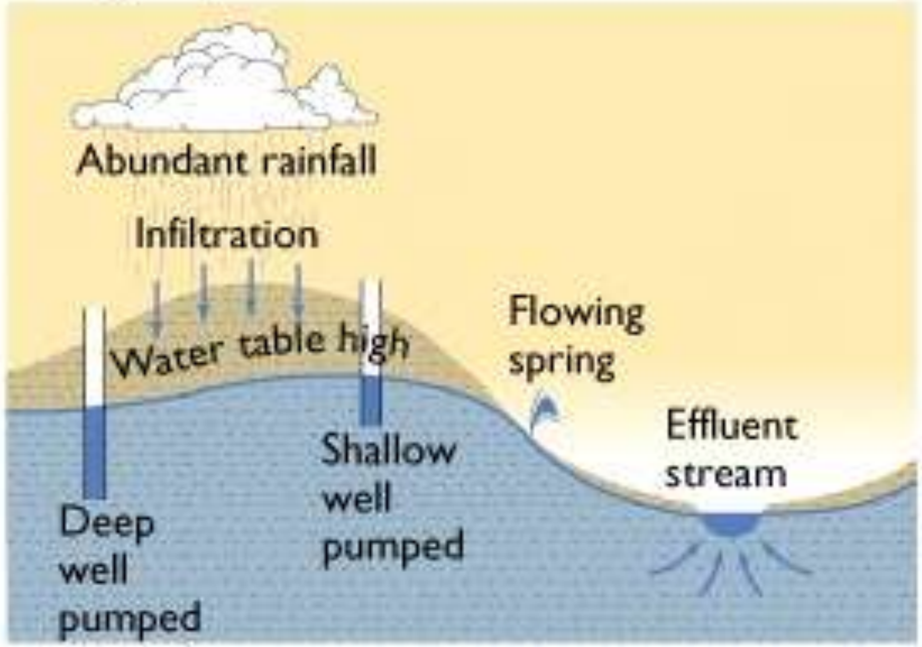


Soil
Weathered bedrock
Porous bedrock (sandstone)
Unsaturated zone
Water and air in pore spaces
Groundwater table
Water fills all pore spaces
Saturated zone

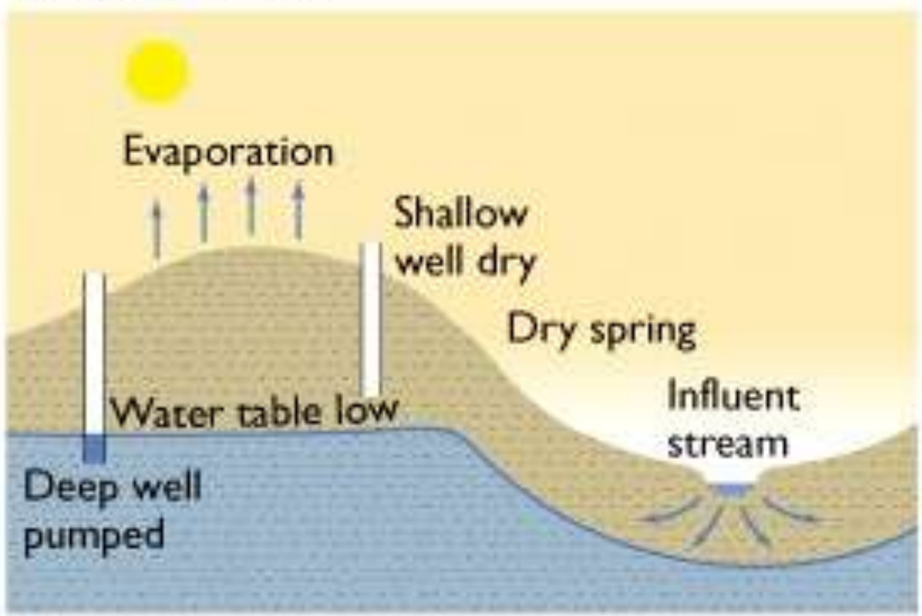
Distribution of Groundwater



During wet period



During dry period



Subsurface Waters

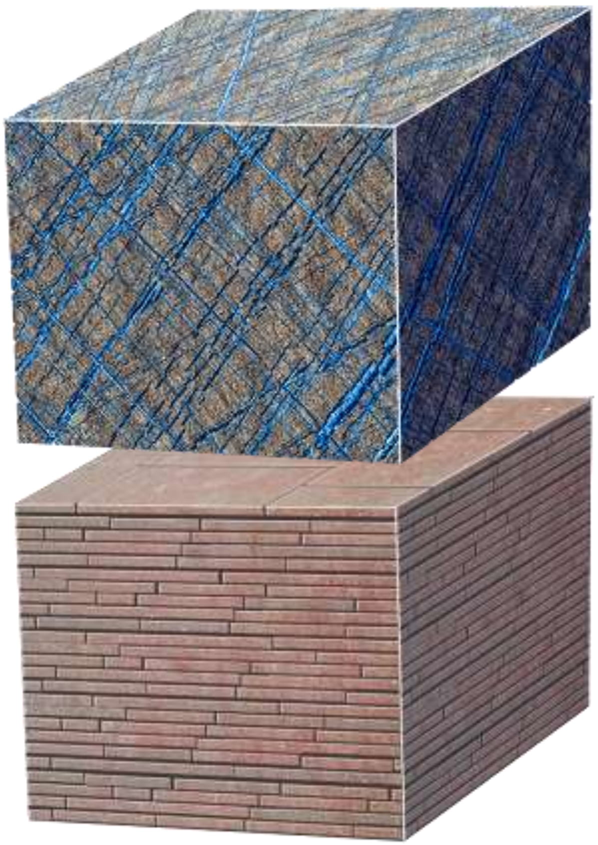
- Soils which are permeable will allow excess precipitation to infiltrate
  - Gravity will draw water down until an impermeable layer, an **aquitard**, halts it
  - Above this layer ground water will accumulate – infilling pore spaces
- The **saturated zone (or phreatic zone)** will <u>fill with water</u>
  - Ground water is stored
- The **unsaturated zone (or vadose zone)** lies above the saturated zone and some pore spaces contain water
  - **Soil moisture** is found
  - The **water table** separates the two zones; it is the top of the saturated zone
- Water stored and transmitted at rates sufficient enough to be useful is called an aquifer
  - Water moving into an aquifer to is called **recharge**

Permeability: Pores Connected So Fluids Flow

Which of the following have lower permeability and which have higher permeability?

17.03.c

High permeability



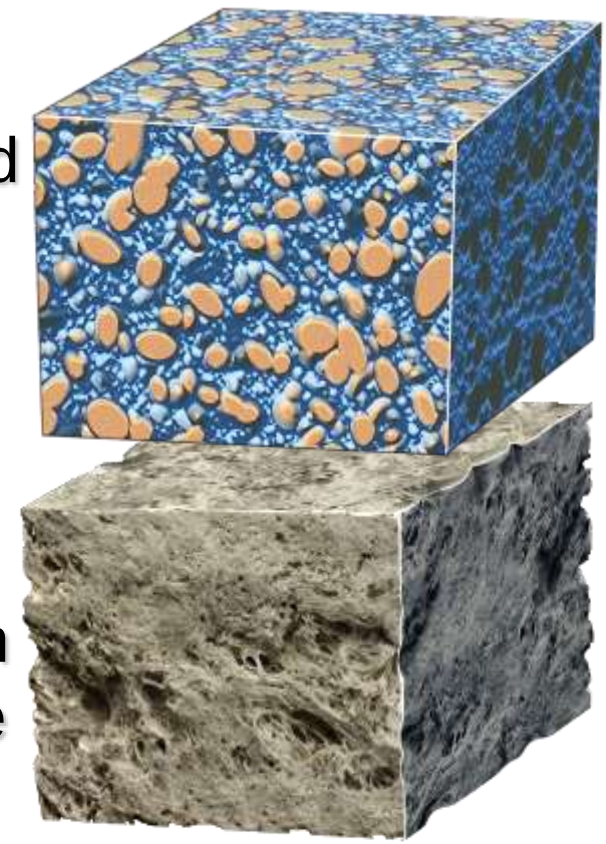
Granite with many fractures

Compact-ed clay (shale)

Low permeability

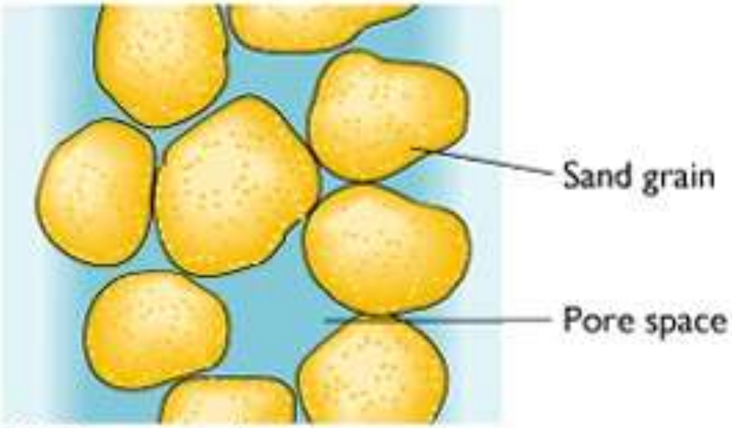
High permeability

Loosely cemented gravels

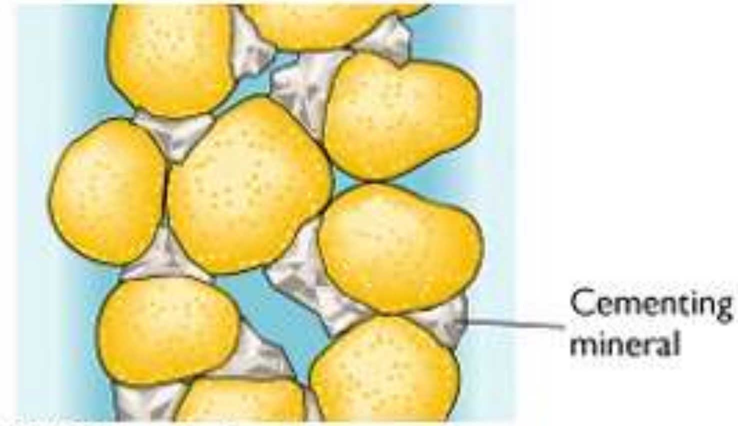


Porous volcanic rock with separate pores

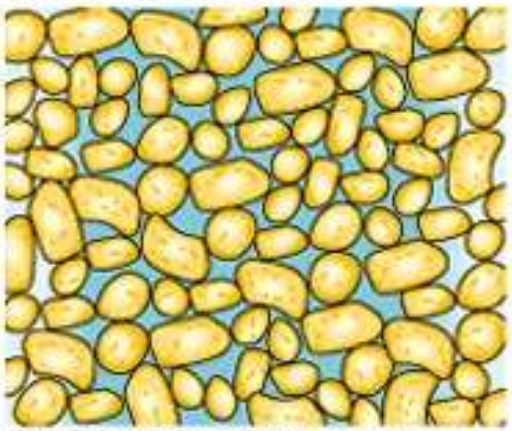
Low permeability

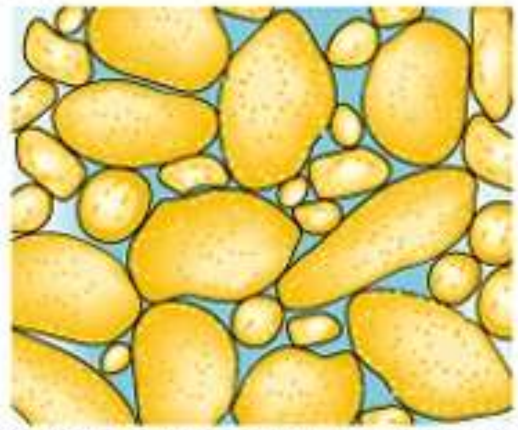


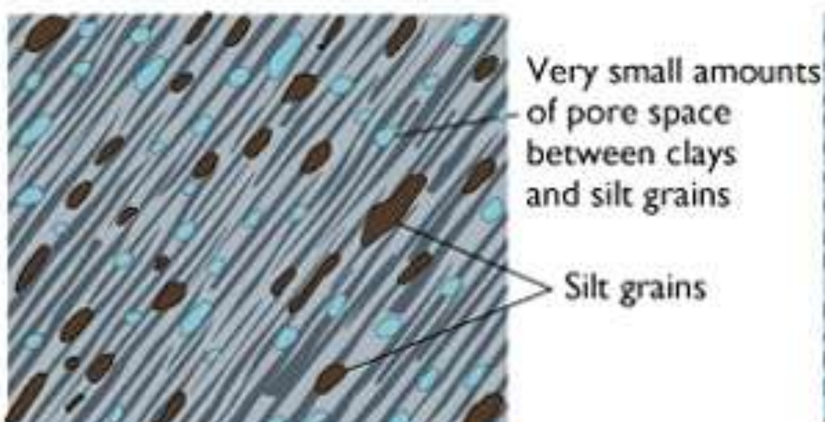
(a) Porous sandstone



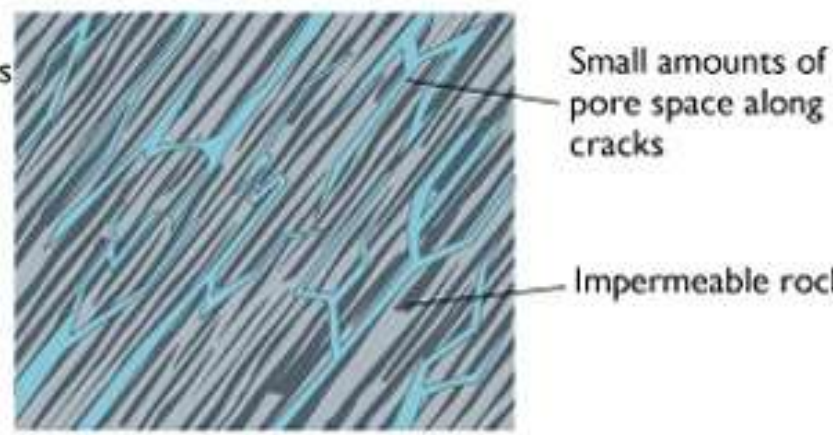
(b) Cemented sandstone


(c) Fine-grained sandstone

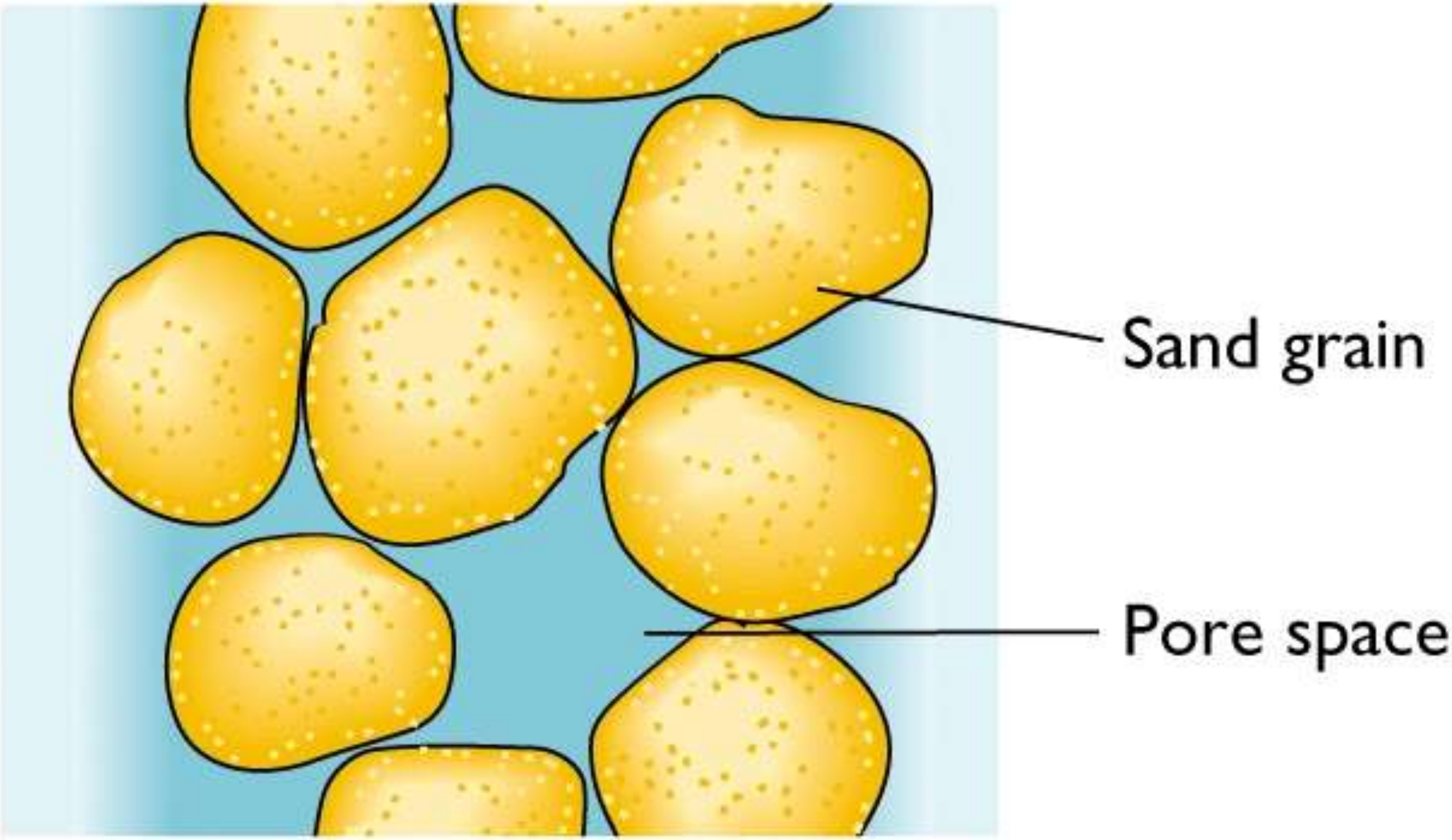

(d) Sandstone with irregular shapes



(e) Unfractured shale

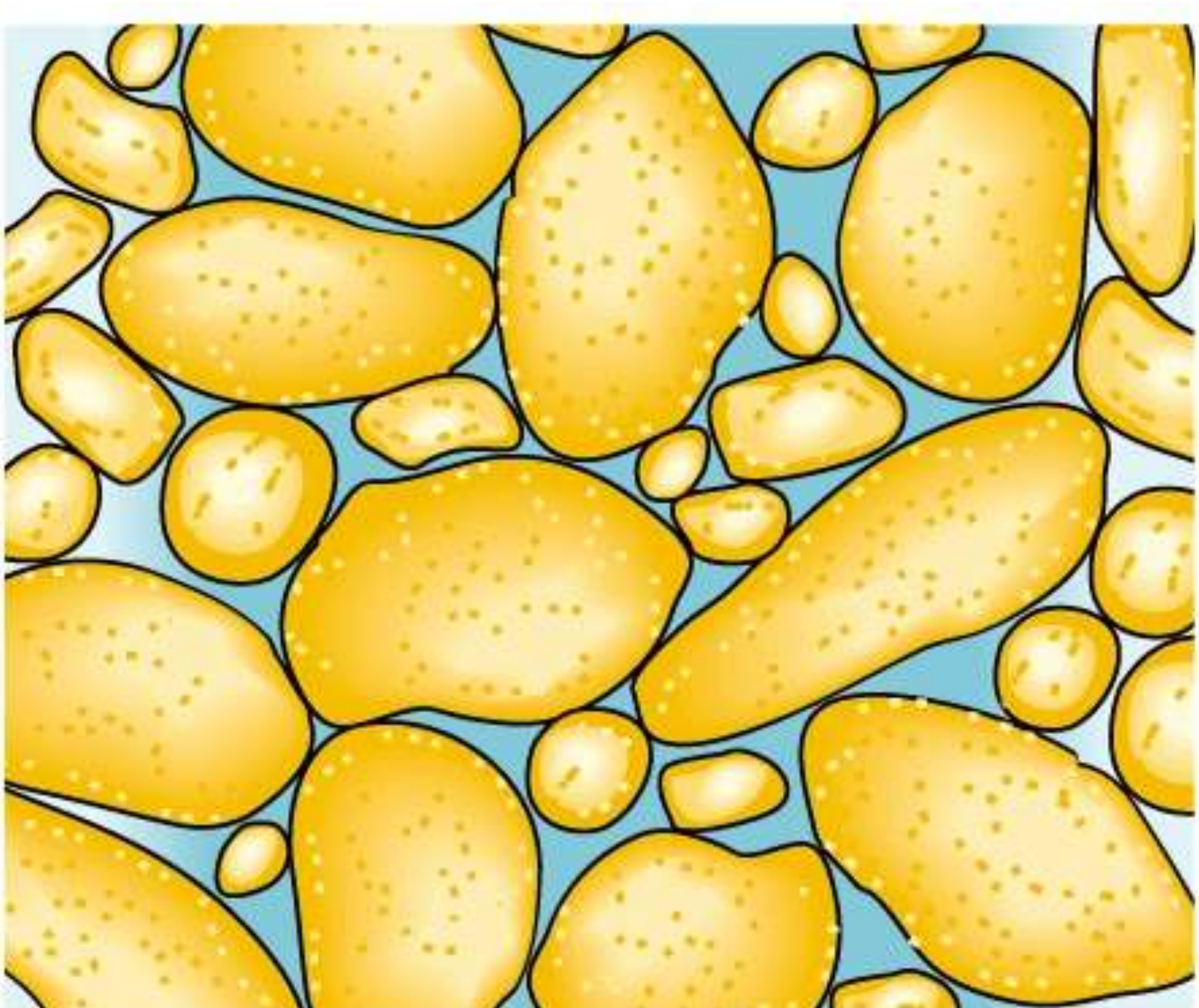


(f) Fractured shale

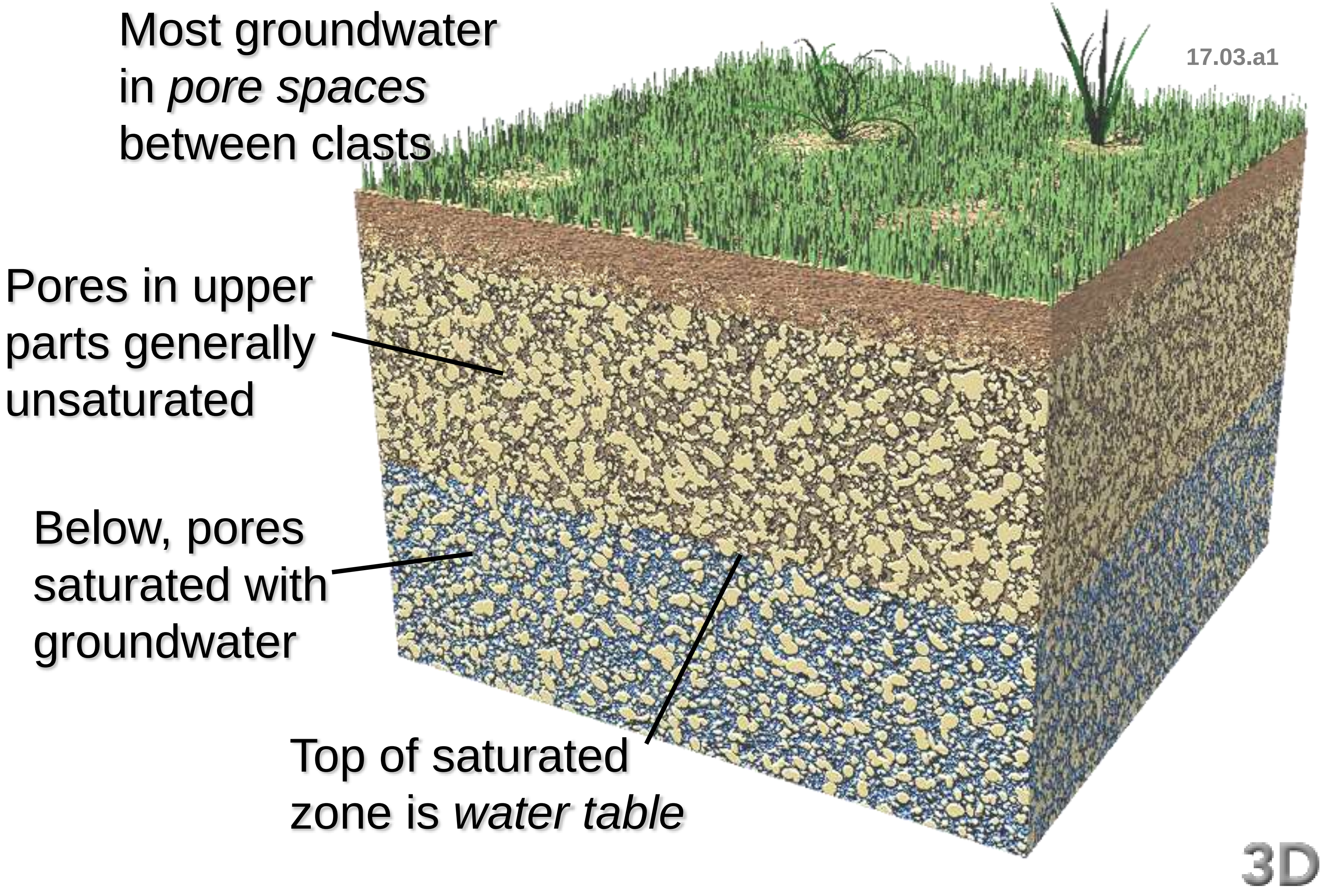


(a) Porous sandstone

Sandstone with irregular shapes



Groundwater Between Clasts

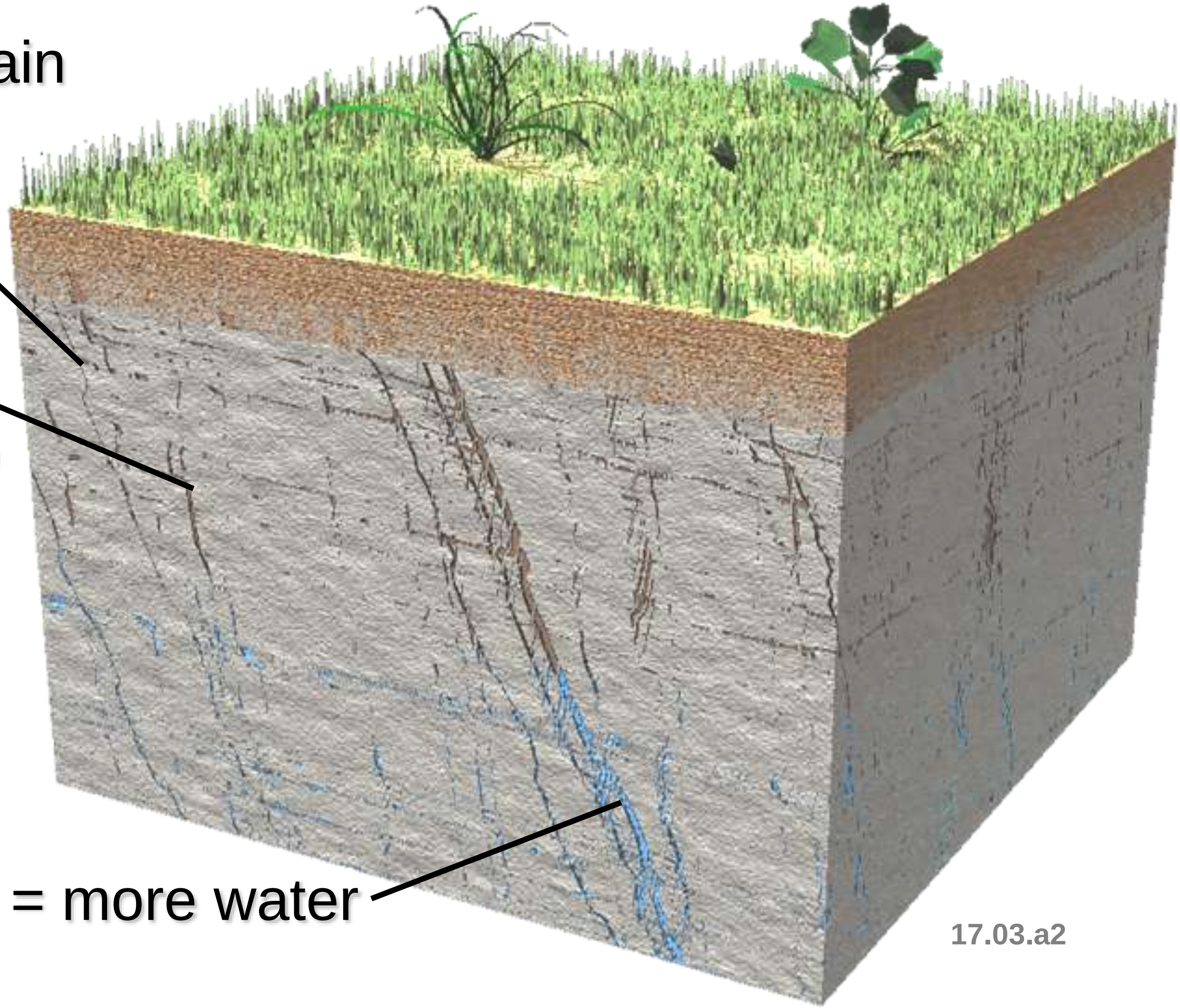


Groundwater in Fractures

Fractures can contain groundwater

May be the only pathways for water, if interconnected

More fractures = more water

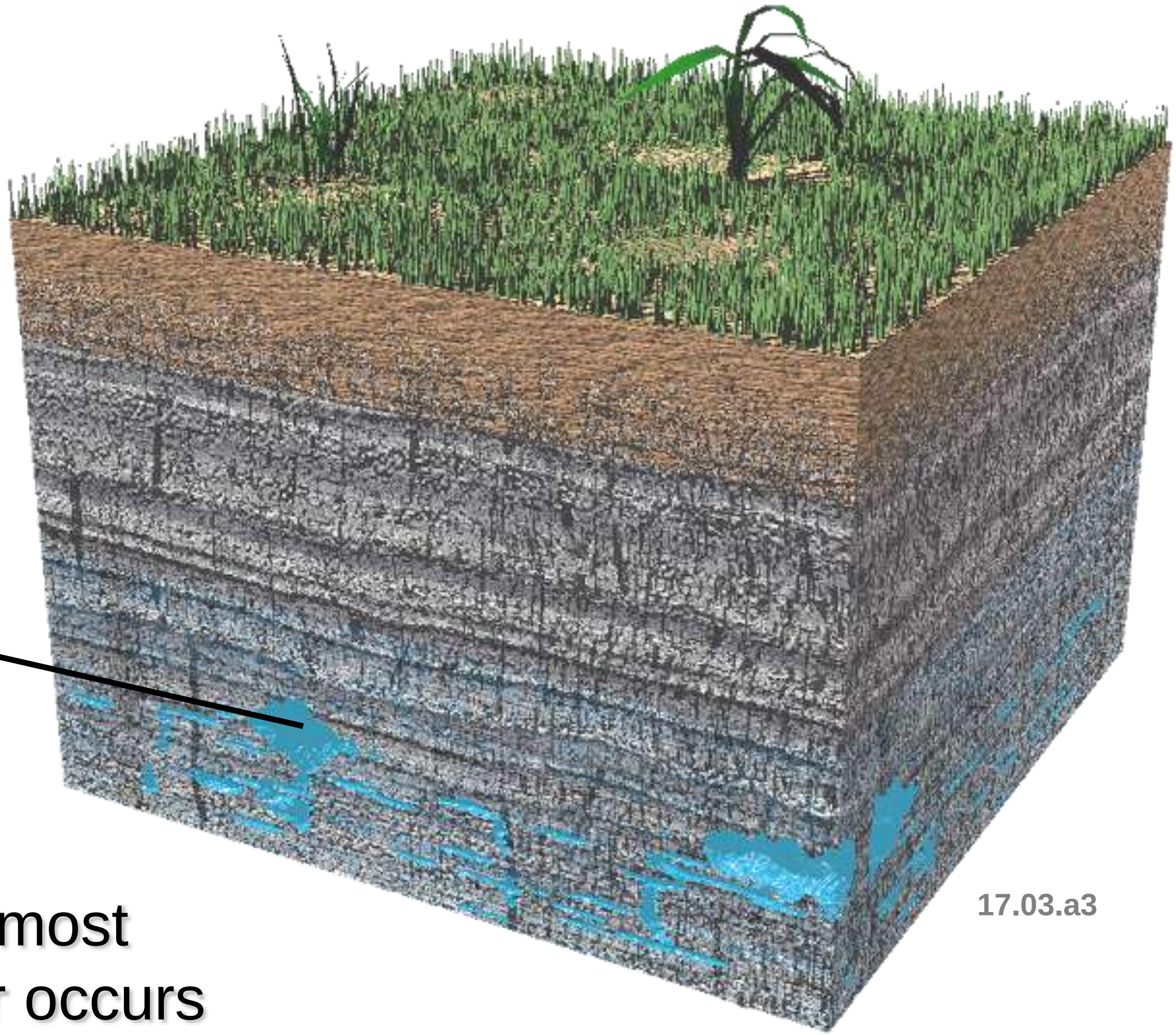


3D

Groundwater in Cavities

Some rocks, especially limestone, have *cavities*

Cavities can contain groundwater



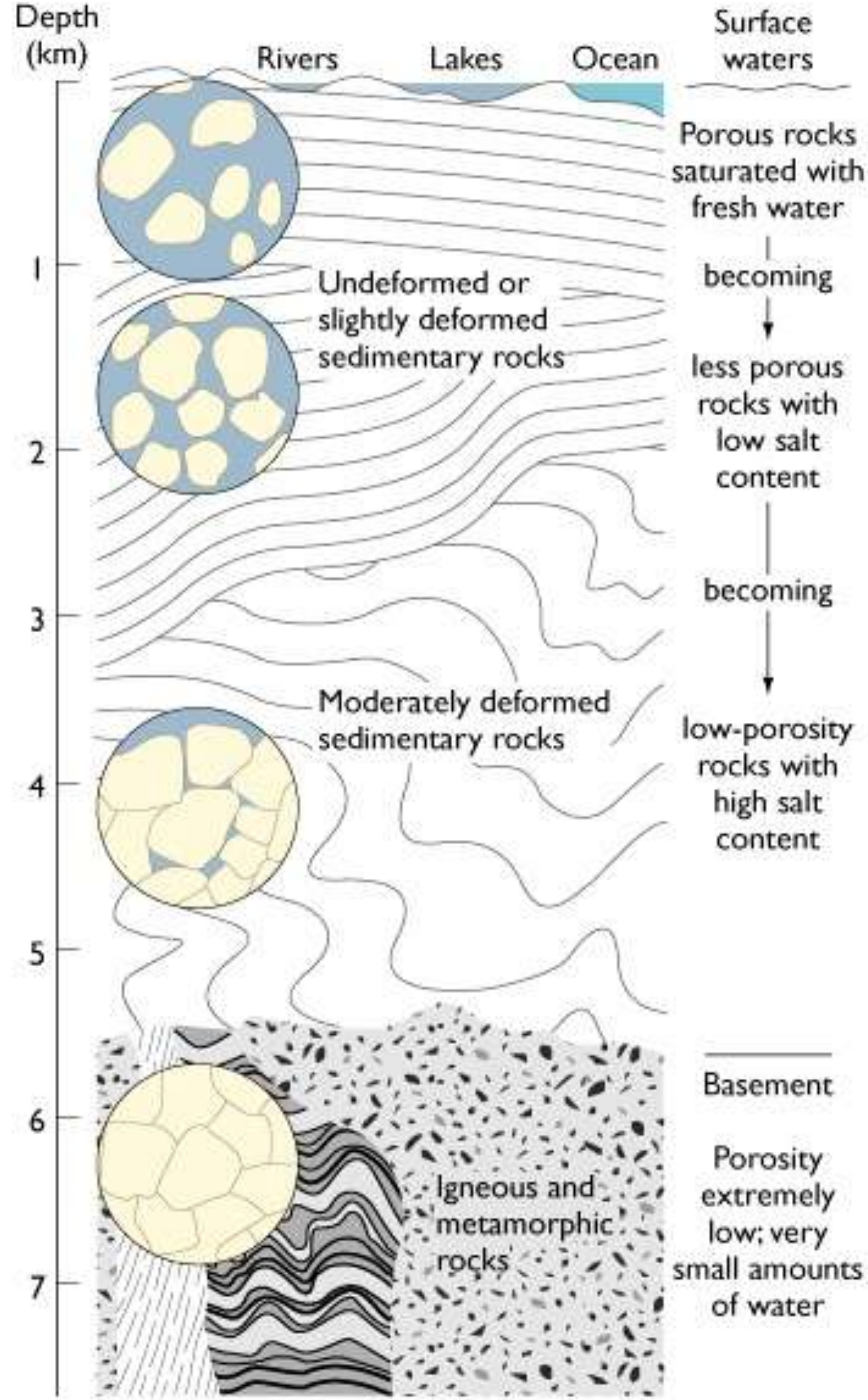
NOT where most groundwater occurs

17.03.a3

3D

Porosity and permeability

- *Porosity:* volume of pore space
- *Permeability:* a measure of the ease of flow
- *Correlated but not identical*
- Both vary with rock type, typically higher in:
  - Shallow materials
  - Unconsolidated materials
  - Coarser and well-sorted materials



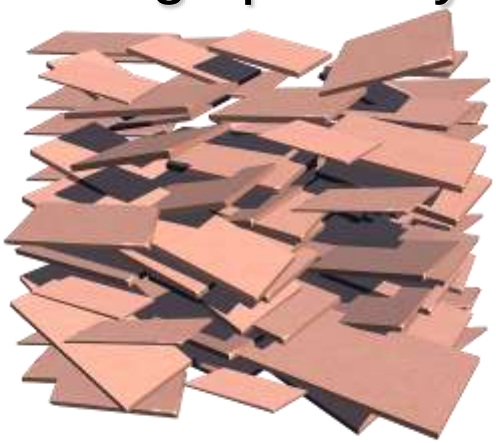
Fluid Storage and Mobility

- **Porosity** and **permeability** involve the ability of rocks/sediments/soils to contain fluid and to allow fluids to pass through them
- **Porosity** – the proportion of void space (holes and/or cracks) in material (soil or rock) where fluid can be stored
  - Usually expressed as a percent (1.5%) or a decimal (0.015) of the entire volume
  - Pore space can be occupied by fluid or gas

Porosity: Proportion of Open Space

Which of the following have lower porosity and which have higher porosity?

High porosity



Clay particles do not fit tightly

Crystals in granite fit tightly

Low porosity

Rounded, sorted clasts do not fit tightly

Poorly sorted clasts fit more tightly

17.03.c

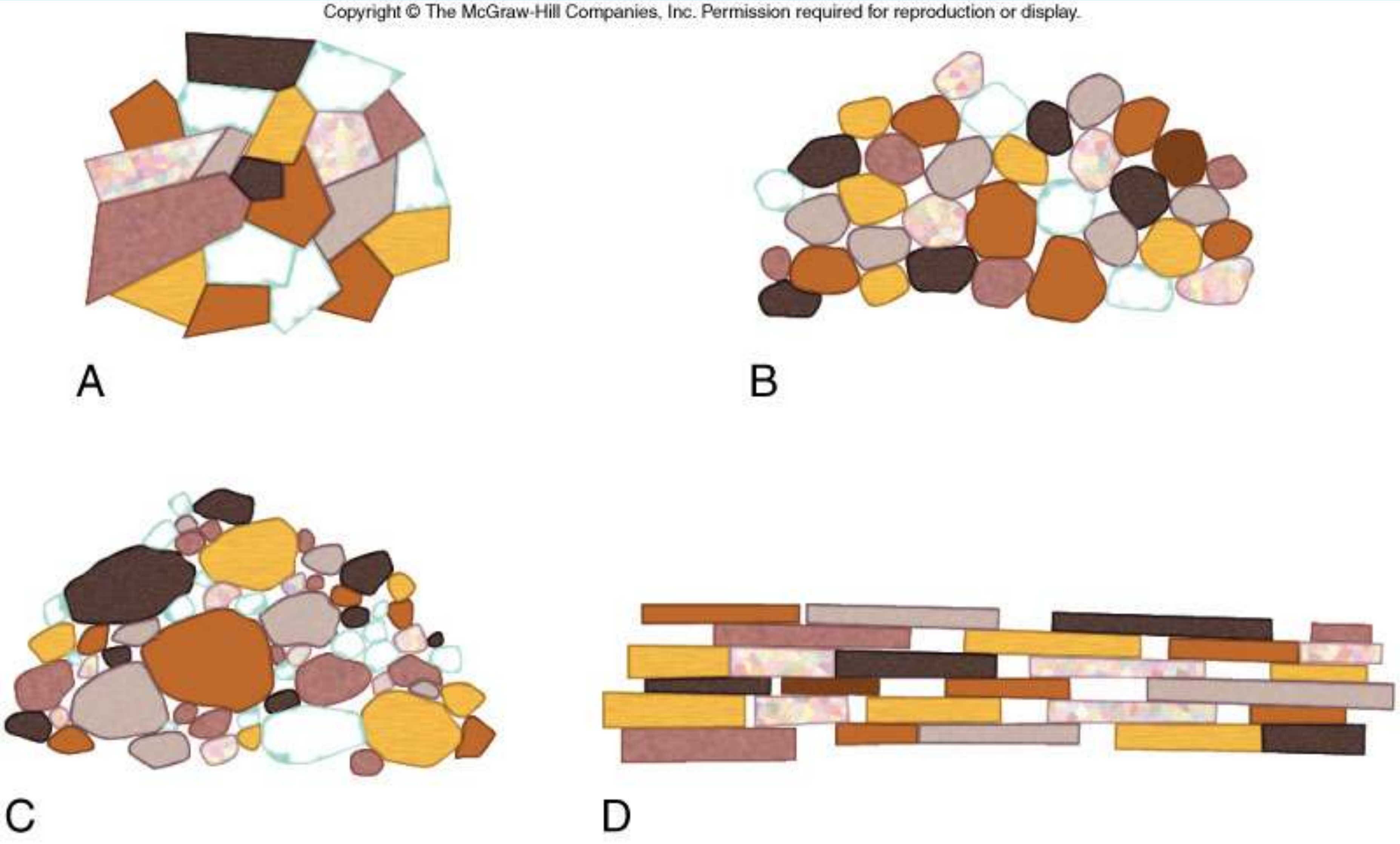
Porosity and Permeability

- *Porosity* - the percentage of rock or sediment that consists of voids or openings
  - A measurement of a rock's ability to hold water
  - Loose sand may have 30-50% porosity
  - Compacted sandstone may have only 10-20% porosity
- *Permeability* - the capacity of a rock to transmit fluid through pores and fractures
  - Interconnectedness of pore spaces
  - Most sandstones and conglomerates are porous and permeable
  - Granites, schists, unfractured limestones are *impermeable*

Fluid Storage and Mobility

- **Permeability** – measures how readily a fluid passes through a material
  - – Measures degree of interconnection between pores and cracks in rocks and soil
  - – Grain shape and size are factors
  - – How grains fit together influences permeability also
- **Porosity** and **permeability** play a big role in groundwater hydrology, oil and gas exploration, and nuclear waste disposal

Rock type and permeability



Fluid Storage and Mobility

- **Rock type will impact porosity and permeability**
  - **Igneous, metamorphic, and chemical sedimentary rocks have crystals that are tightly interlocked and low permeability and porosity**
  - **Weathering, dissolution, and fracturing will increase porosity and permeability in crystalline rock and carbonate rocks**
- **<u>Clastic sediments have more porosity and permeability</u>**
  - **Sandstones are generally very porous**
  - **Clay and mud rich rocks are not porous or permeable**

Table 12.2

Porosity and Permeability of Aquifer Rock Types

Rock Type	Porosity (Pore Space That May Hold Fluid)	Permeability (Ability to Allow Fluids to Pass Through)
Gravel	Very high	Very high
Coarse- to medium-grained sand	High	High
Fine-grained sand and silt	Moderate	Moderate to low
Sandstone, moderately cemented	Moderate to low	Low
Fractured shale or metamorphic rocks	Low	Very low
Unfractured shale	Very low	Very low

Representative Porosities and Permeabilities of Geological Materials

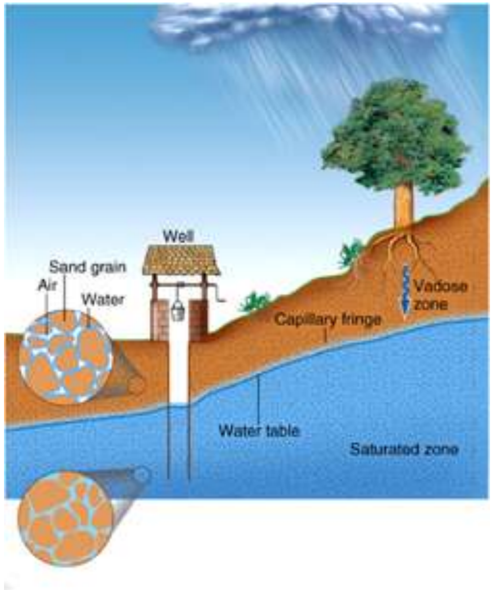
Material	Porosity (%)	Permeability (m/day)
Unconsolidated		
clay	45–55	less than 0.01
fine sand	30–52	0.01–10
gravel	25–40	1000–10,000
glacial till	25–45	0.001–10
Consolidated (rock)		
sandstone and conglomerate	5–30	0.3–3
limestone (crystalline, unfractured)	1–10	0.00003–0.1 0.0003–0.003
granite (unweathered) volcanic rock	less than 1–5 1–30; mostly less than 10	0.0003–3; depends on presence or absence of fractures or interconnected gas bubbles

Source: Data from *Water in Environmental Planning*, by T. Dunne and L. B. Leopold.

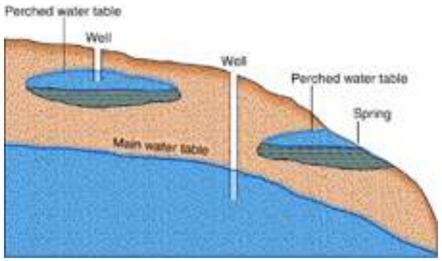
Subsurface Waters

- Soils which are permeable will allow excess precipitation to infiltrate
  - Gravity will draw water down until an impermeable layer, an **aquitard**, halts it
  - Above this layer ground water will accumulate – infilling pore spaces
- The **saturated zone (or phreatic zone)** will fill with water
  - Ground water is stored
- The **unsaturated zone (or vadose zone)** lies above the saturated zone and pore spaces are filled with water
  - **Soil moisture** is found
  - The **water table** separates the two zones; it is the top of the saturated zone
- Water stored and transmitted at rates sufficient enough to be useful is called an aquifer
  - Water moving into an aquifer to is called **recharge**

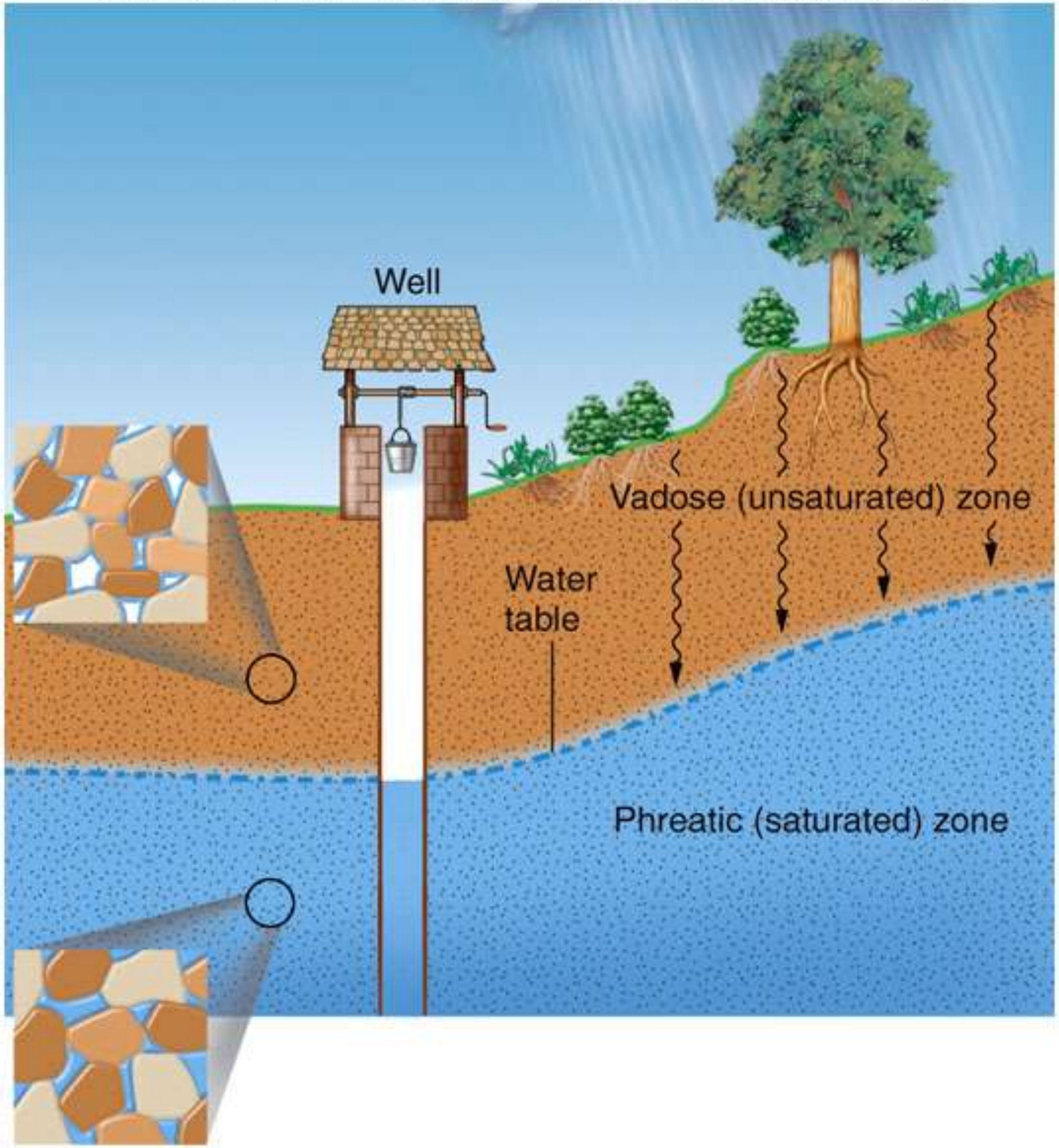
The Water Table



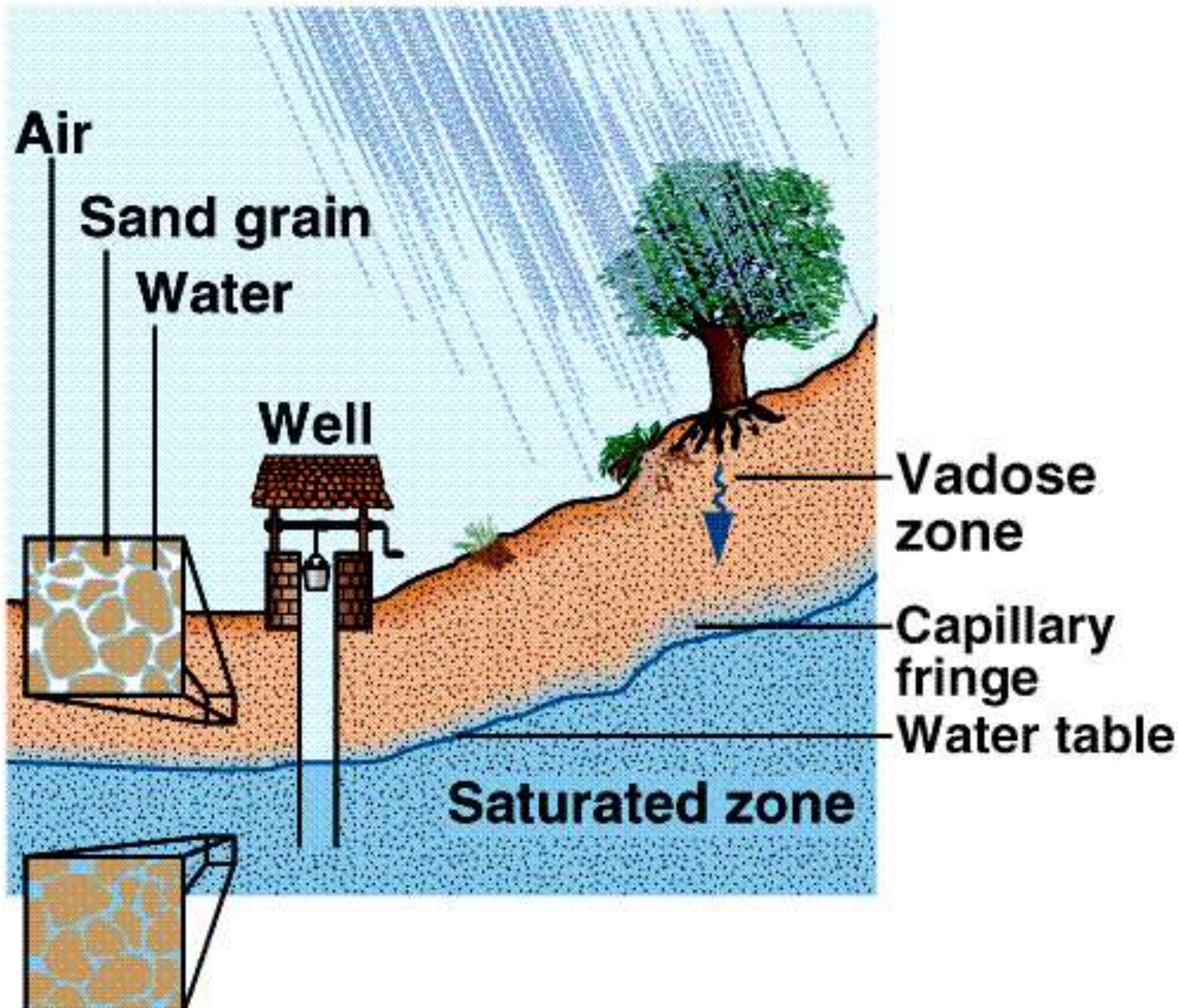
- The subsurface zone in which all rock openings are filled with water is the *saturated zone*
- The top of the saturated zone is called the *water table*
  - Water level at surface of most lakes and rivers corresponds to the water table
- Above the water table is a generally unsaturated region known as the *vadose zone*
- A *perched water table* is above and separated from main water table by an unsaturated zone
  - Usually produced by thin lenses of impermeable rock (e.g., shales or clays) within permeable ones



Water table

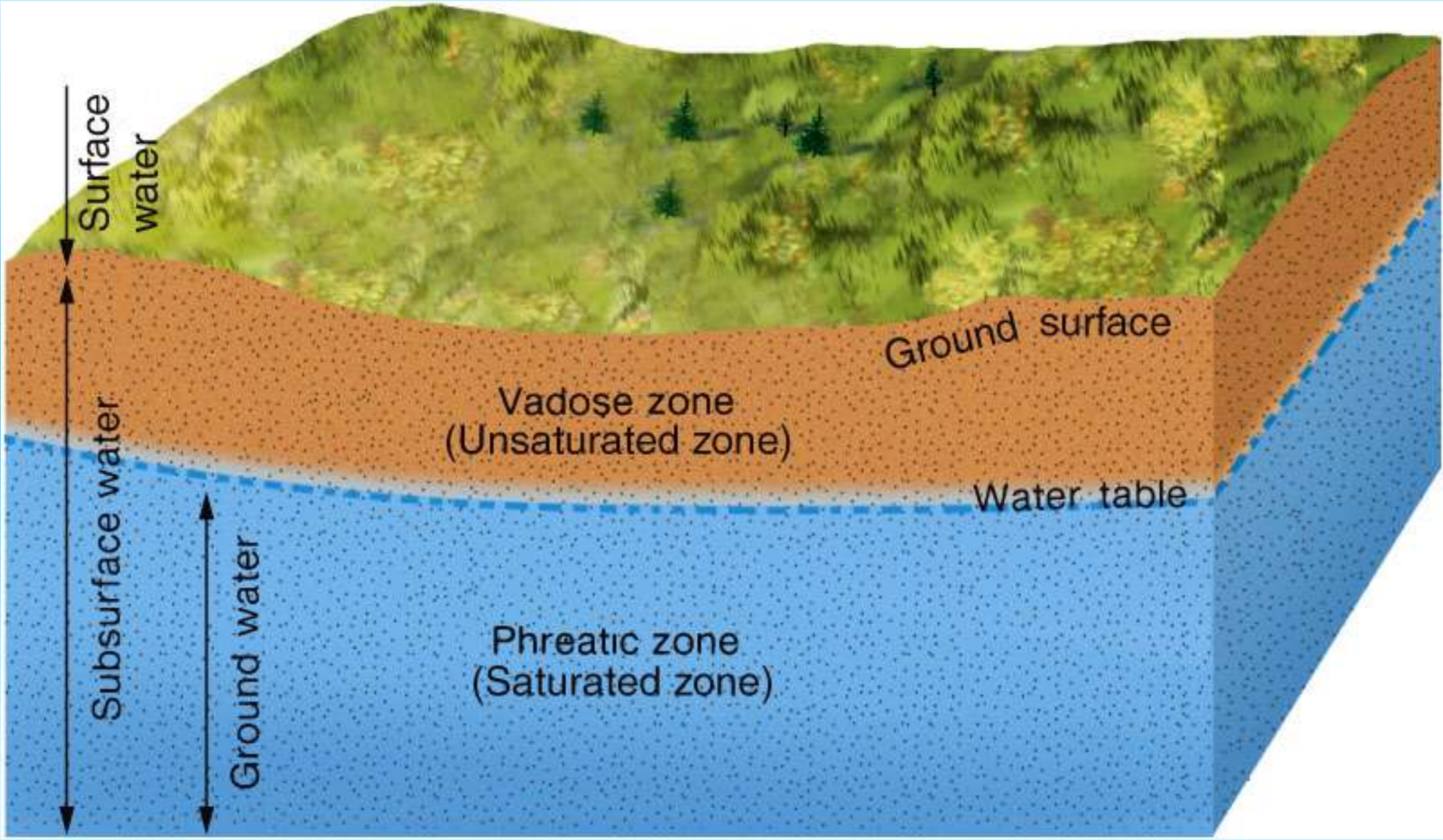

Well
Vadose (unsaturated) zone
Water table
Phreatic (saturated) zone

The Water Table



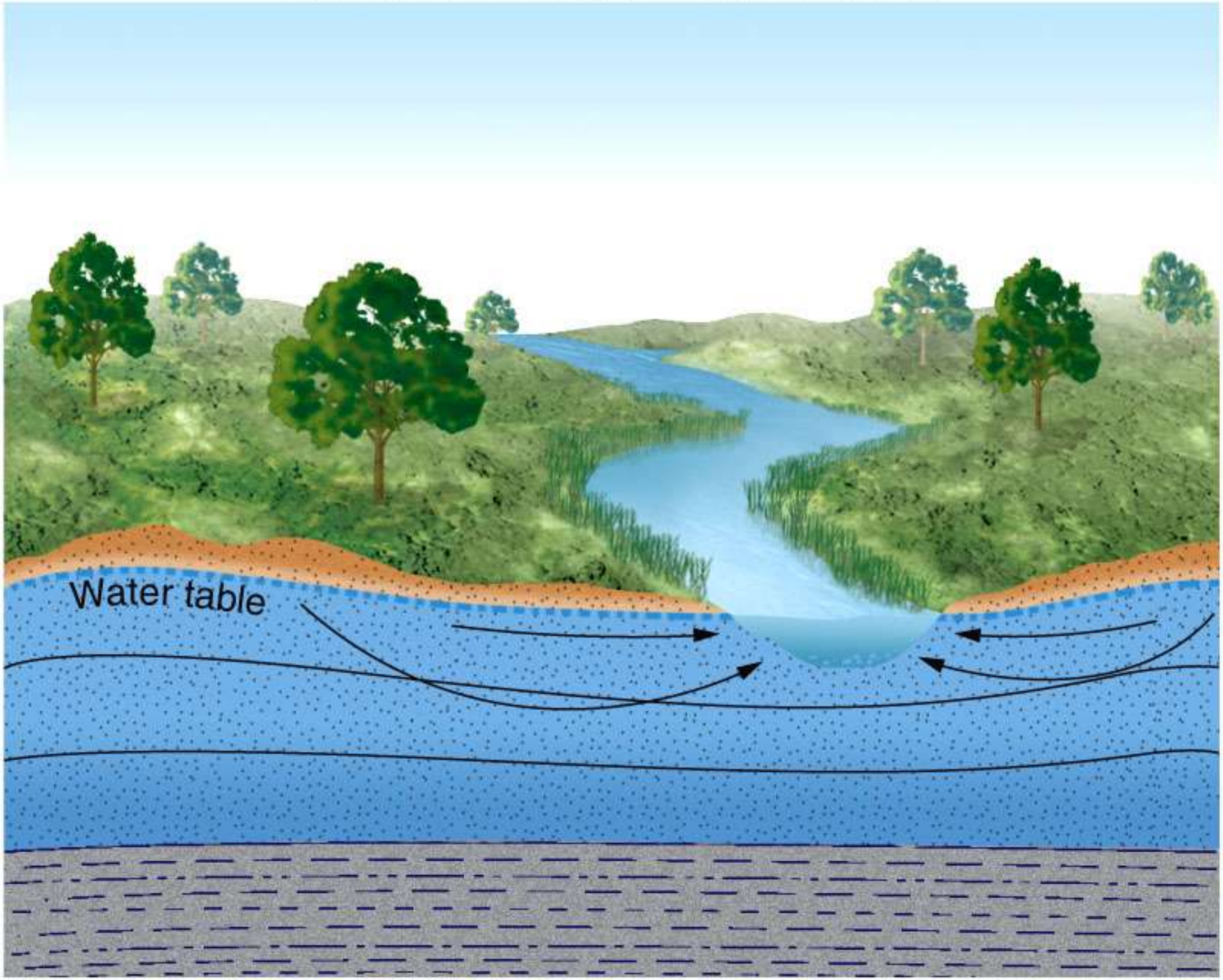
A

Water table



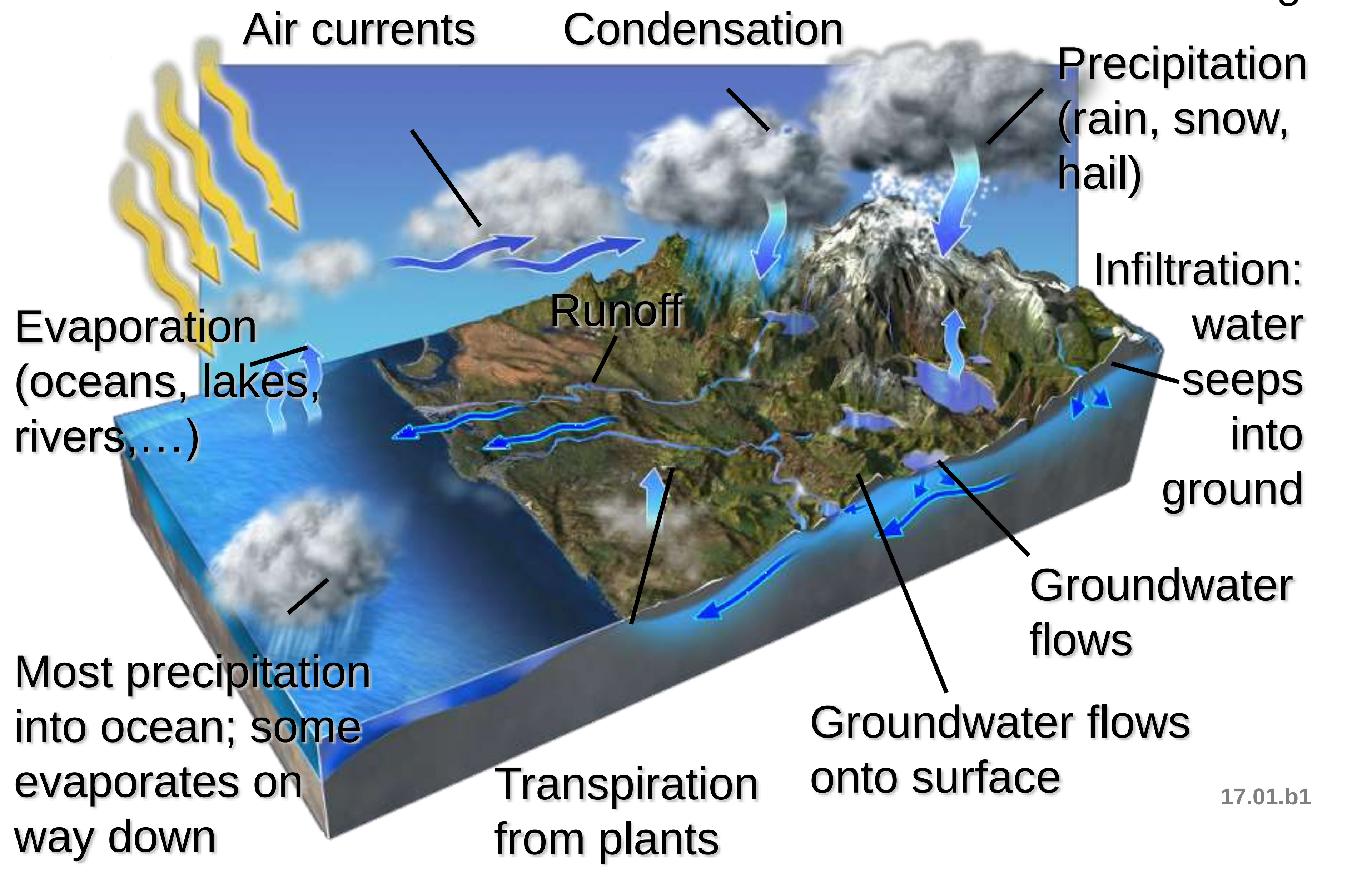
Surface water
Subsurface water
Ground water
Ground surface
Vadose zone
(Unsaturated zone)
Water table
Phreatic zone
(Saturated zone)

Flow from groundwater to rivers

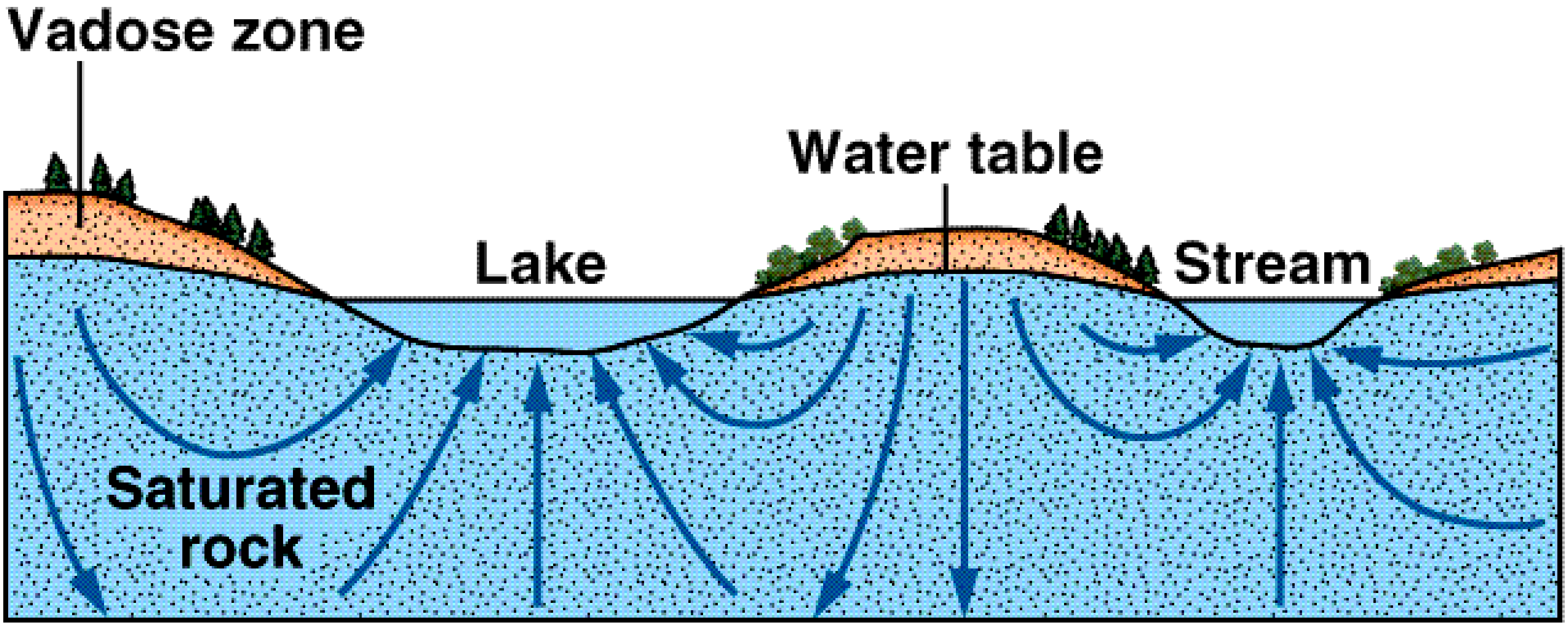


How Does Water Move?

Observe how water moves between settings

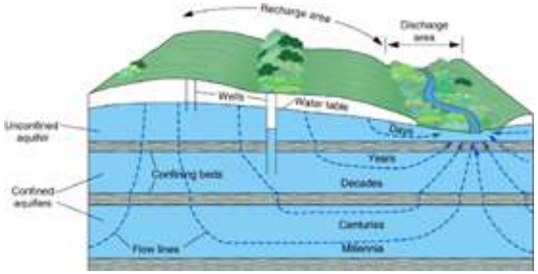


Ground Water Movement



Groundwater Movement

- Movement of groundwater through pores and fractures is *relatively slow* (typically centimeters to meters per day) compared to the rapid flow of water in surface streams
  - Flow velocities in cavernous limestones can be significantly higher (thousands of meters per day)
- Flow velocity depends upon:
  - *Slope* of the water table
  - *Permeability* of the rock or sediment

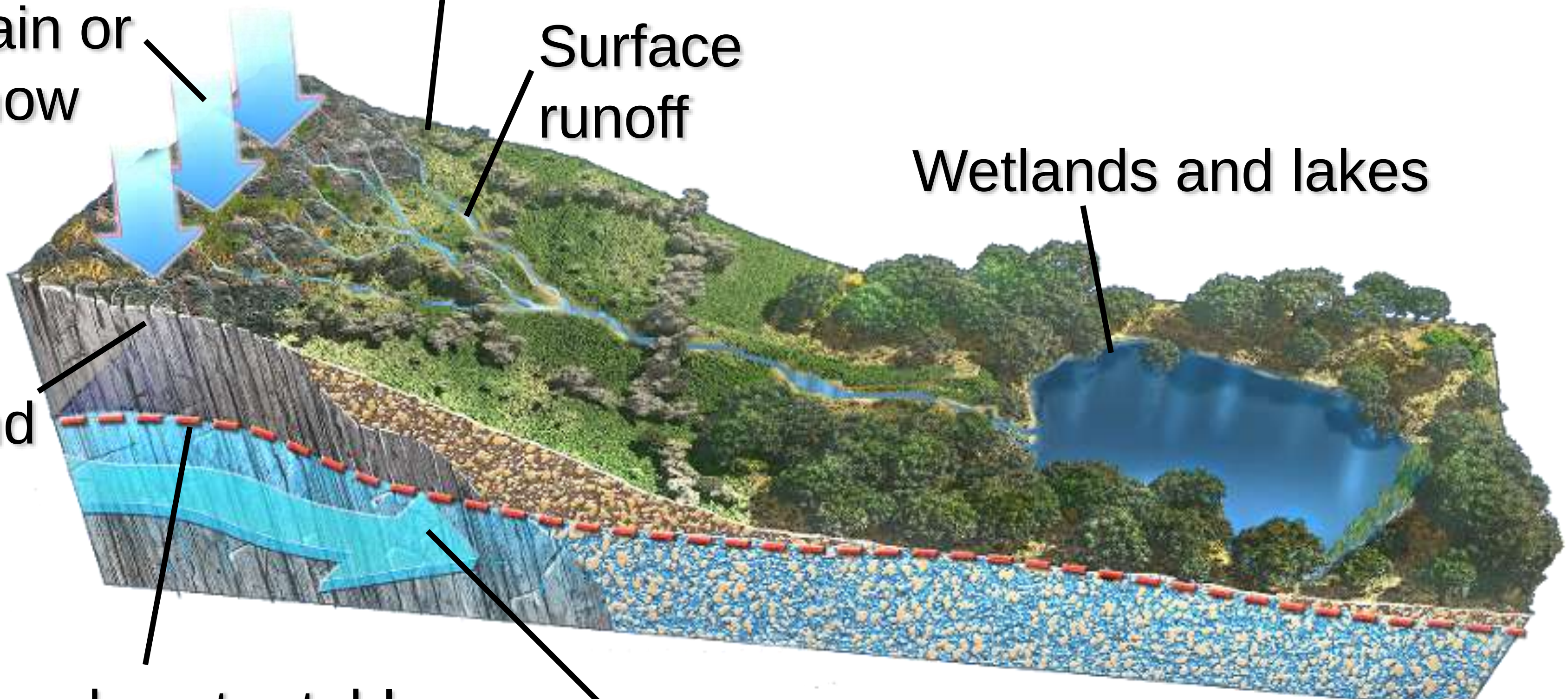


Aquifer Geometry and Groundwater Flow

- Geology and geometry of rocks and sediments will control the behavior of ground water
  - An aquifer without an aquitard above it is an **unconfined aquifer**
  - An aquifer with an aquitard above and below is a **confined aquifer**
  - A confined aquifer may see hydrostatic water pressure increase and form an **artesian system**
    - Drilling into a confined aquifer under pressure will see the water rise above the aquifer
    - In this system the **potentiometric surface** is the height to which the water would rise

How Does Groundwater Accumulate?

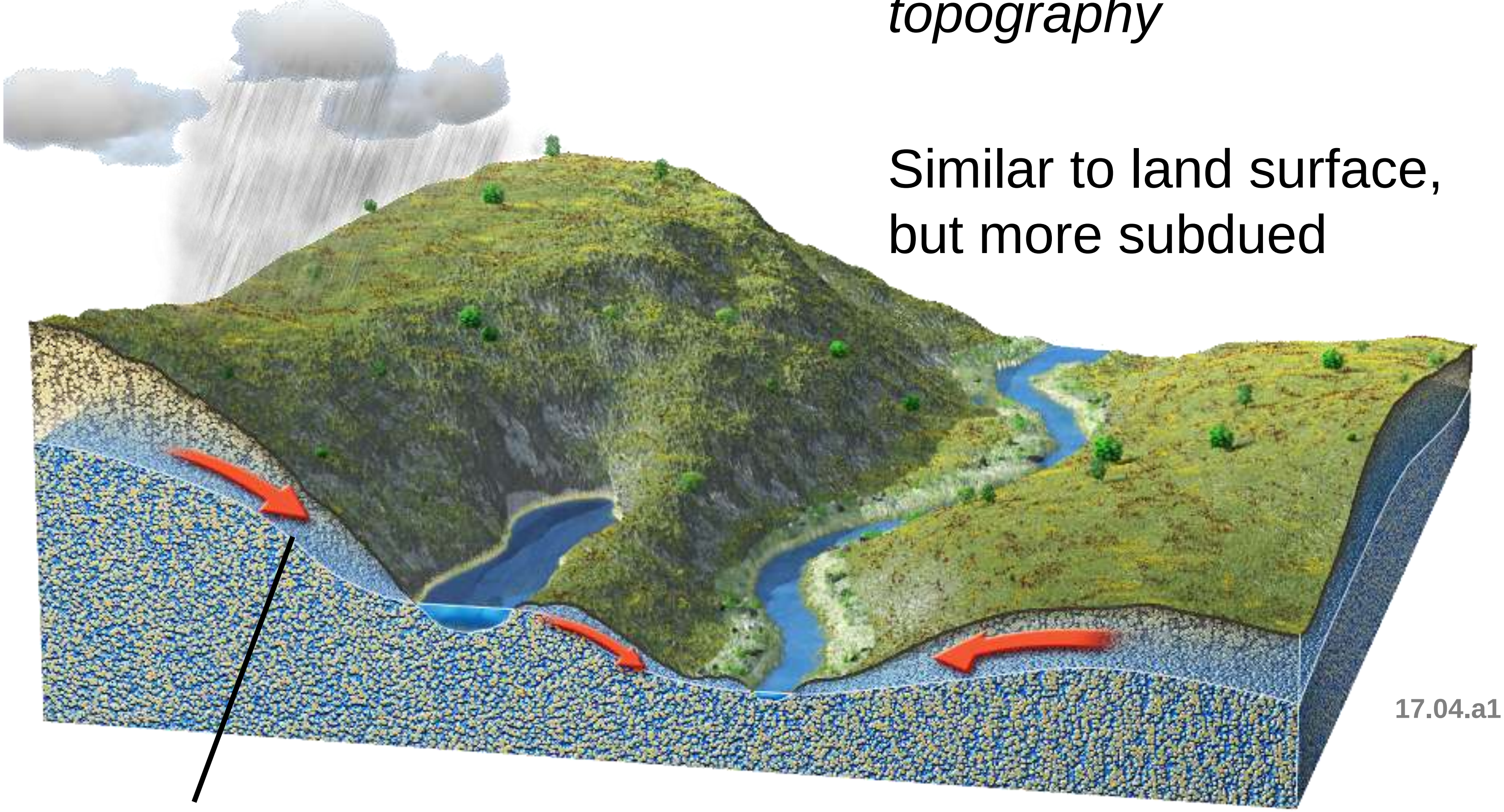
Observe this figure and note all the places where water could go



What is the Geometry of the Water Table?

Observe how the water table interacts with topography

Similar to land surface, but more subdued



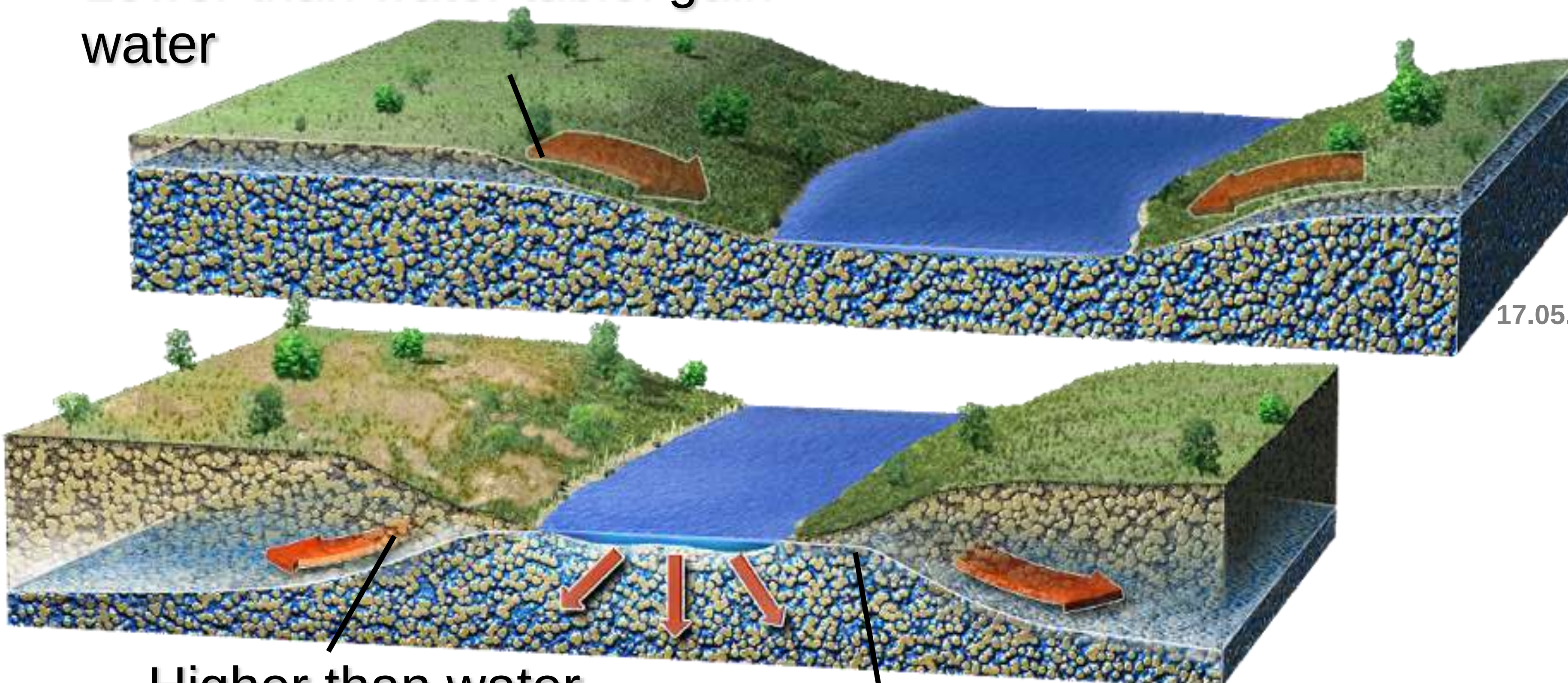
Groundwater flows down slope of water table

Water table cuts across rock units

How Do Rivers Interact with Water Table?

Observe how each river relates to water table and flow of groundwater

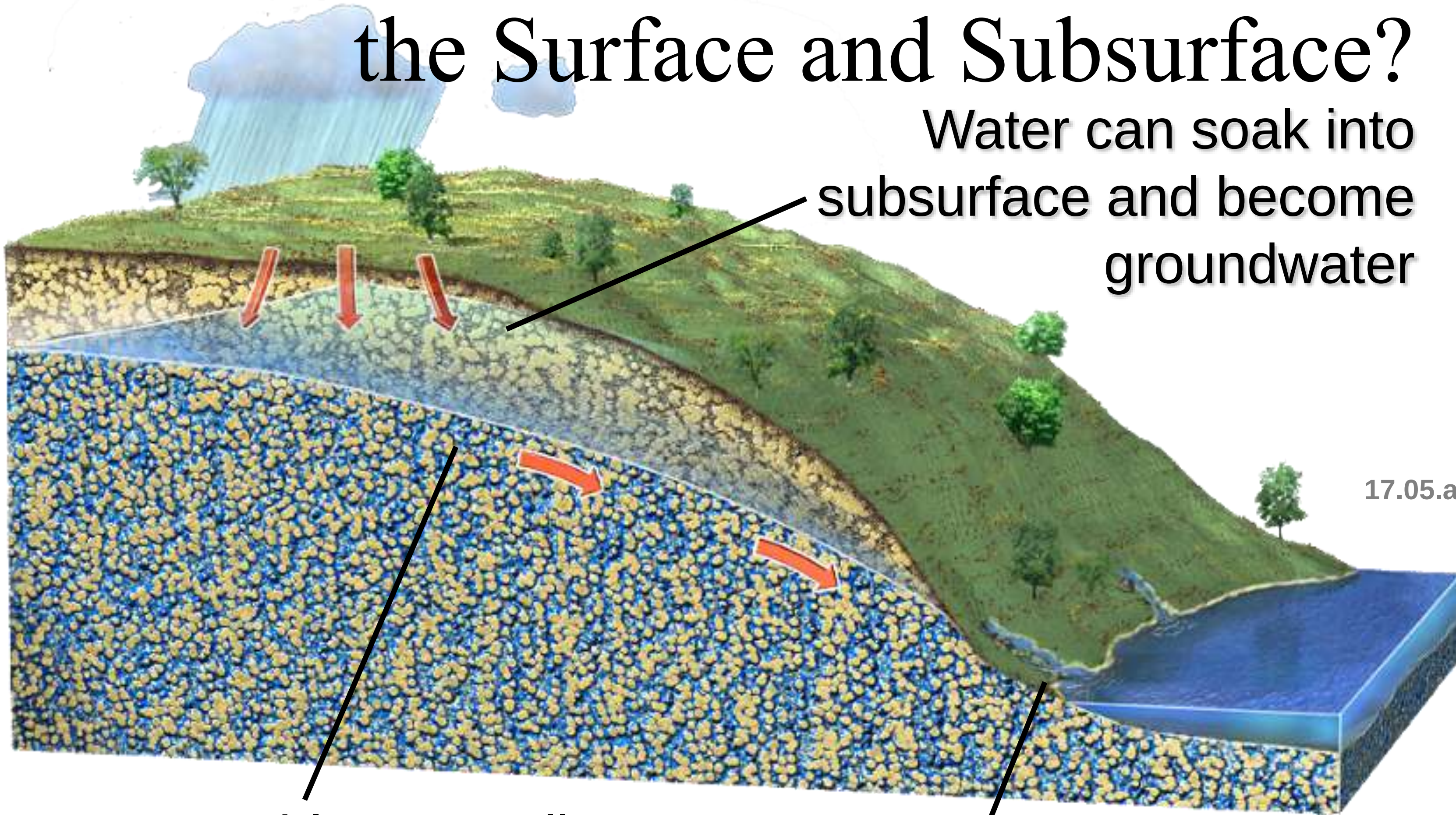
Lower than water table: gain water



Higher than water table: lose water

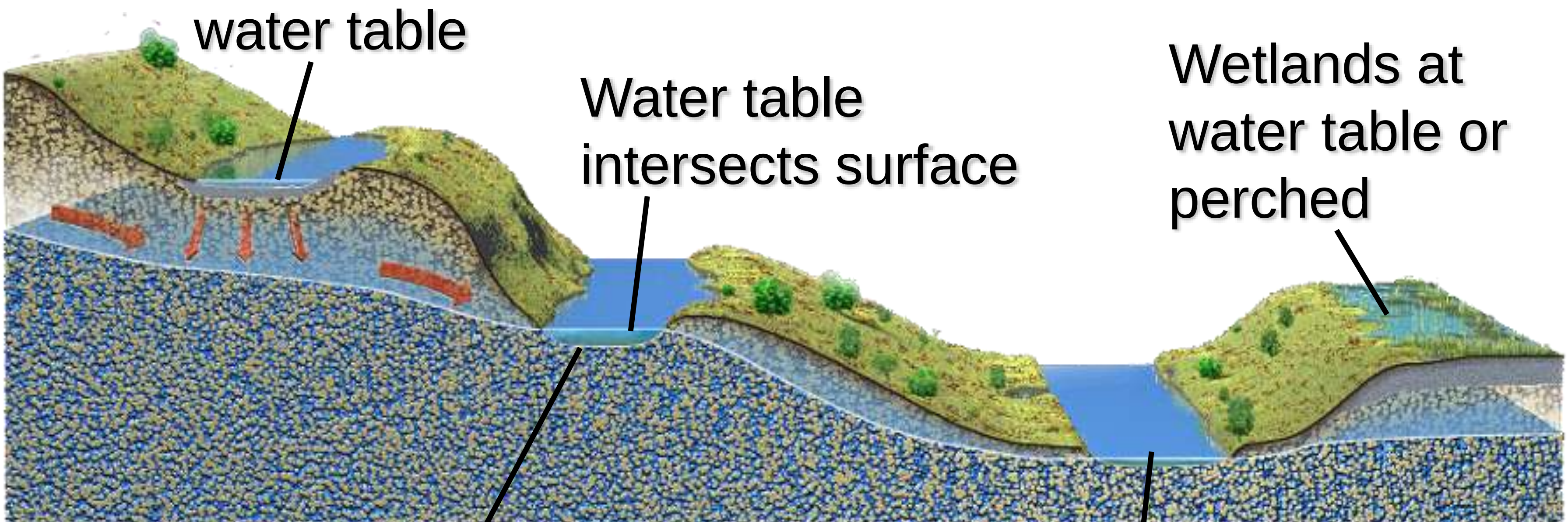
Mound of groundwater below river

How Does Water Move Between the Surface and Subsurface?

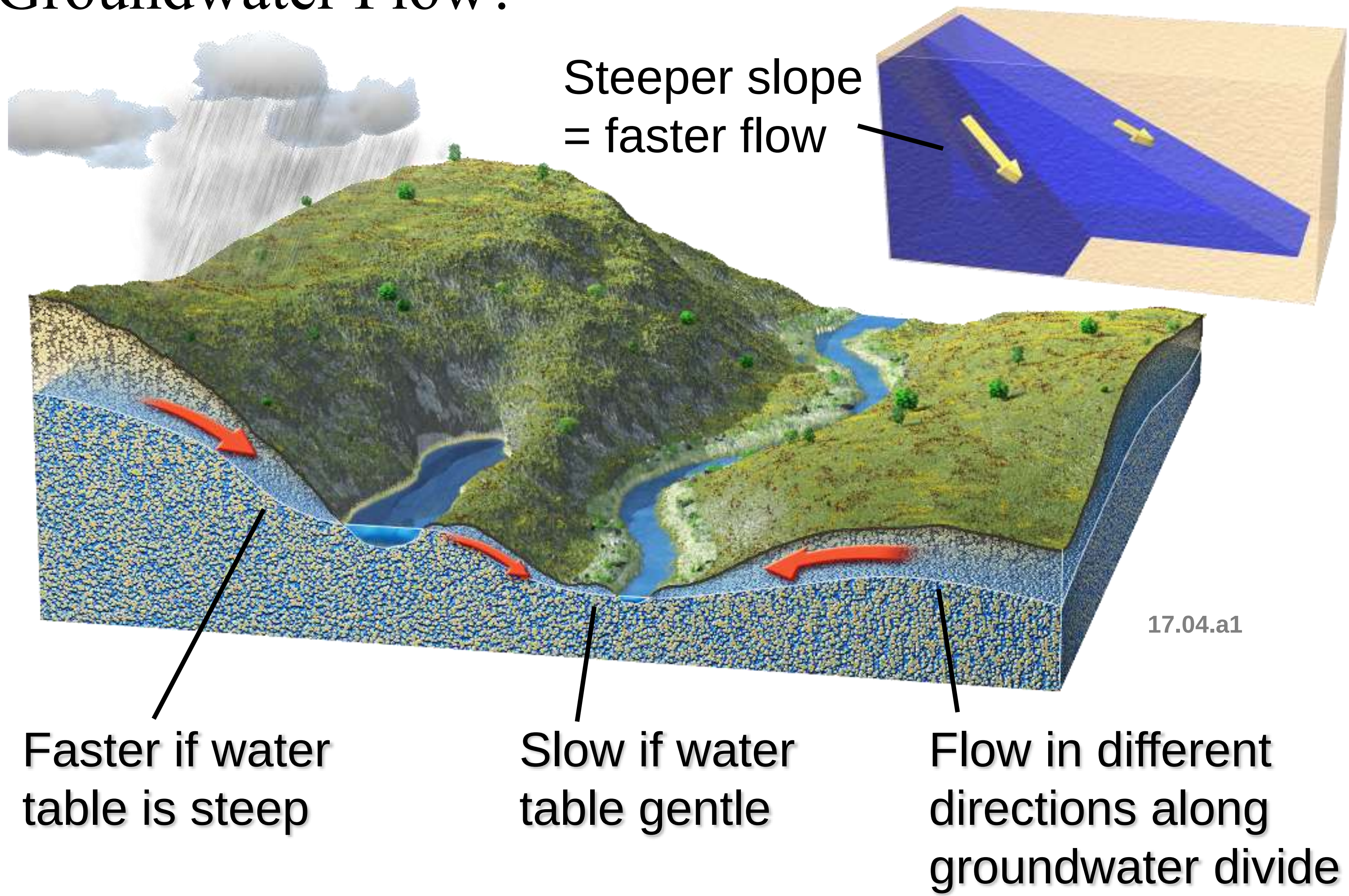


How Are Lakes and Wetlands Related to Groundwater?

Observe the settings of lakes compared to the water table



How Does Slope of the Water Table Influence Groundwater Flow?



Fluid Storage and Mobility

- **Rock type will impact porosity and permeability**
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- **Clastic sediments have more porosity and permeability**
  - **Sandstones are generally very porous**
  - **Clay and mud rich rocks are not porous or permeable**

Groundwater Flow

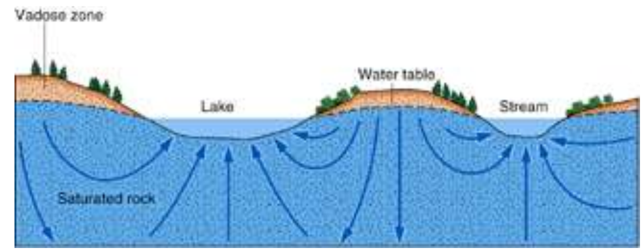
- **Hydraulic head** is potential energy in an aquifer
  - The height of water in an unconfined aquifer reflects the hydraulic head
    - The higher the water table the higher the head
  - The higher the potentiometric surface in a confined aquifer will equate to higher hydraulic head
  - Ground water flows spontaneously from areas of high hydraulic head to areas with low hydraulic head

Darcy’s Law

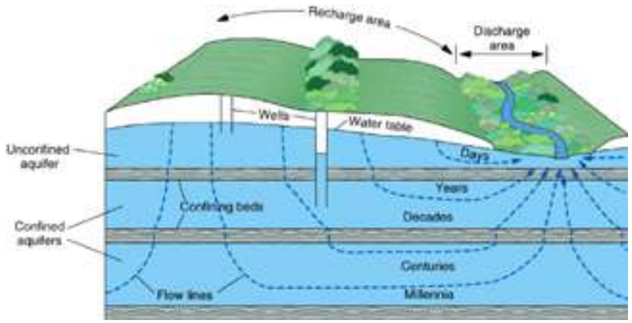
- Darcy’s Law is $Q = K \cdot A(\Delta h/\Delta l)$
  - Q = discharge
  - K = hydraulic conductivity
  - A = cross-sectional area
  - Δh = difference in hydraulic head
  - Δl = distance between well heads
- Discharge is the amount of water flowing past a point over a period of time
  - It is influenced by the porosity and permeability of the rock or sediment of the aquifer

Unconfined vs. Confined Aquifers

- *Unconfined Aquifer*
  - Has a water table, and is only partly filled with water
  - Relatively rapidly *recharged* by precipitation infiltrating down to the saturated zone from above

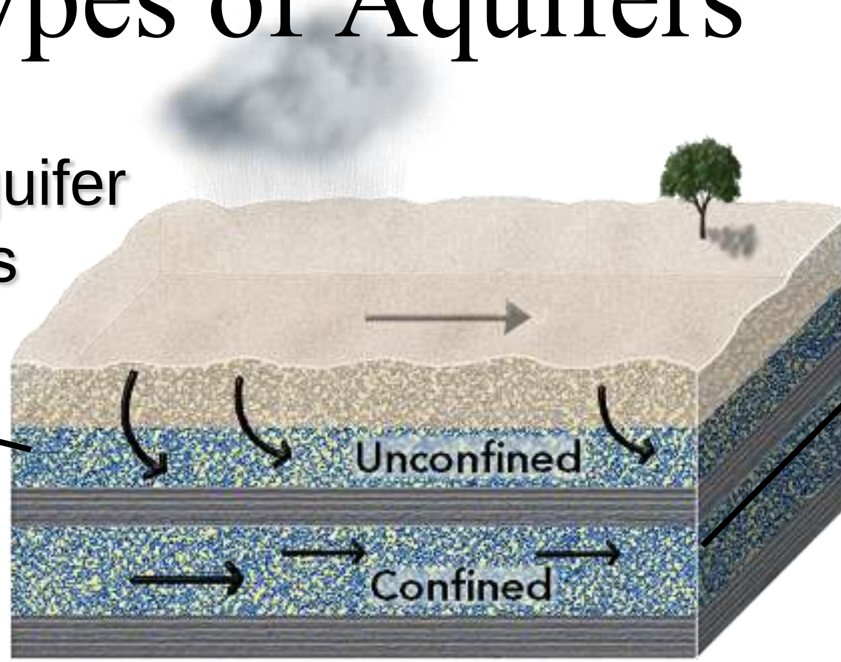


- *Confined Aquifer*
  - Completely filled with water under pressure (*hydrostatic head*)
  - Usually separated from the surface by a relatively impermeable *confining layer*
  - Very slowly recharged

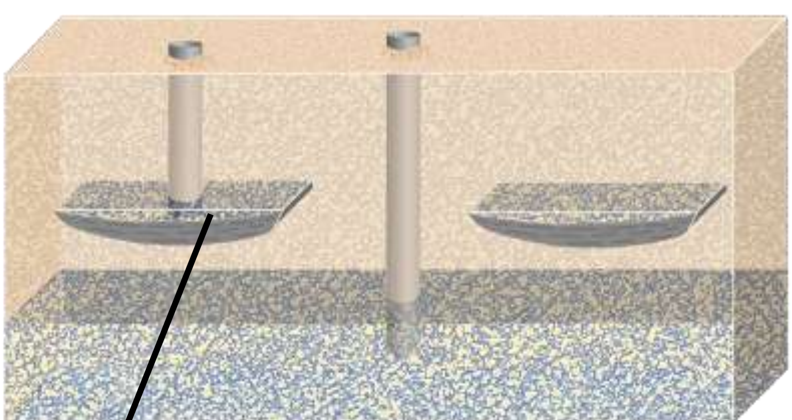


Types of Aquifers

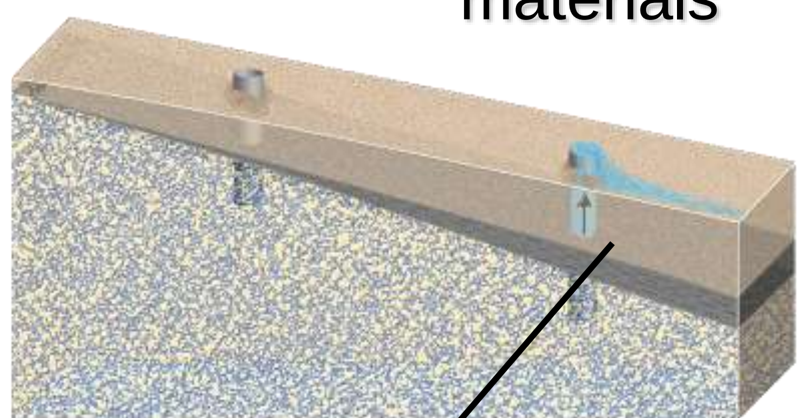
Unconfined aquifer open to Earth's surface and to infiltration



Confined aquifer overlain by less permeable materials



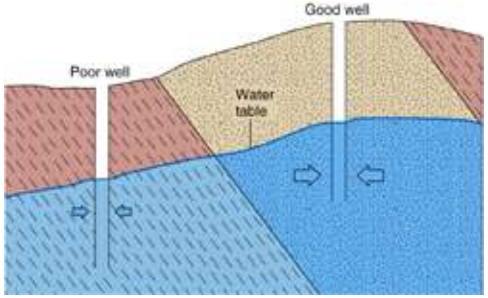
Perched aquifer underlain by low-permeability unit

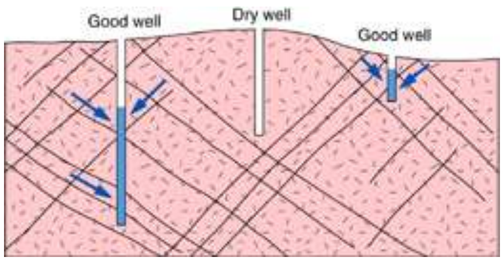


Artesian aquifer: water rises in pipe (maybe to surface)

Aquifers and Aquitards

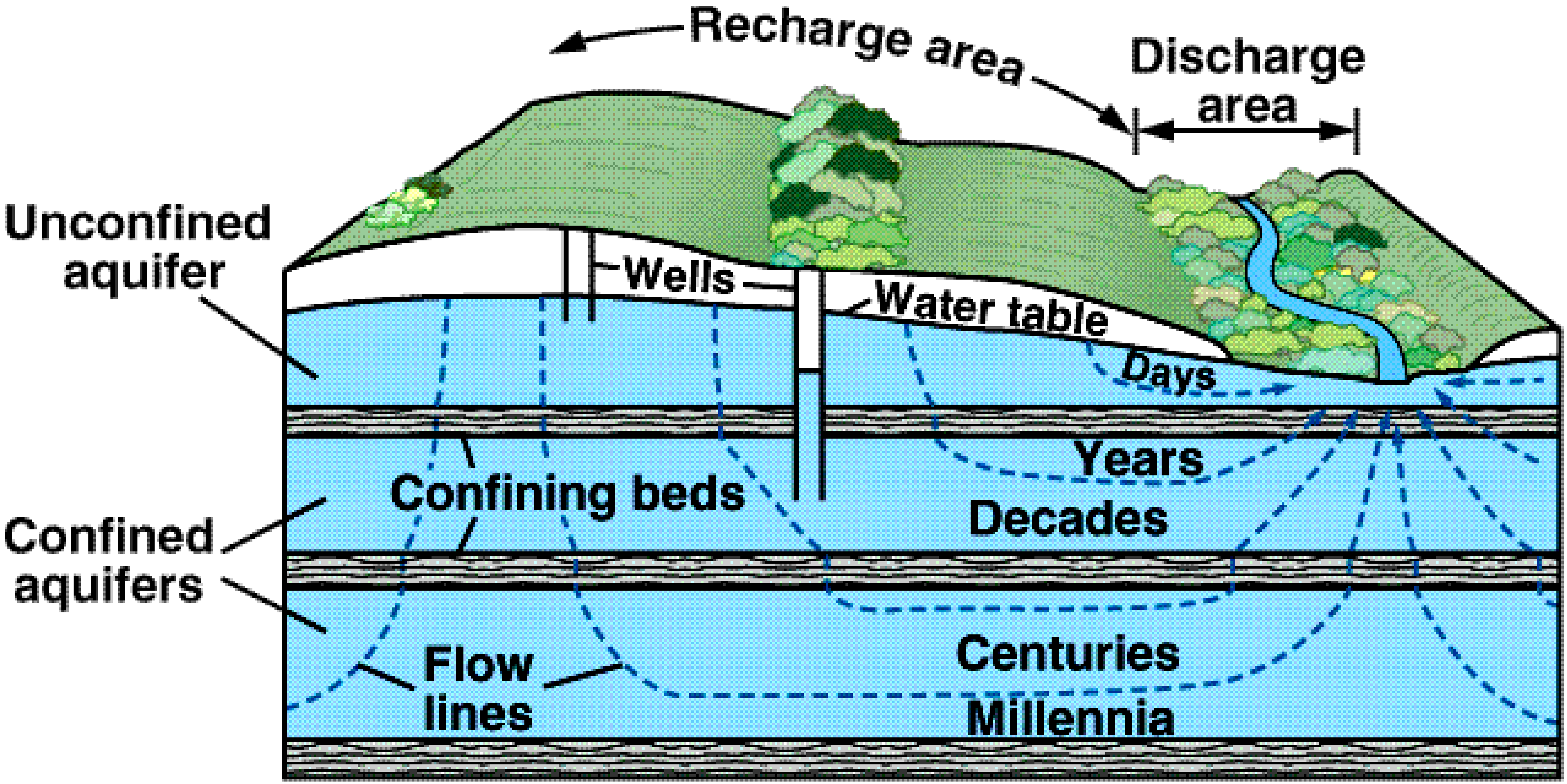
- *Aquifer* - body of saturated rock or sediment through which water can move easily
- Good aquifers include:
  - Sandstone
  - Conglomerate
  - Well-jointed limestone
  - Sand and gravel
  - Fractured volcanic rock



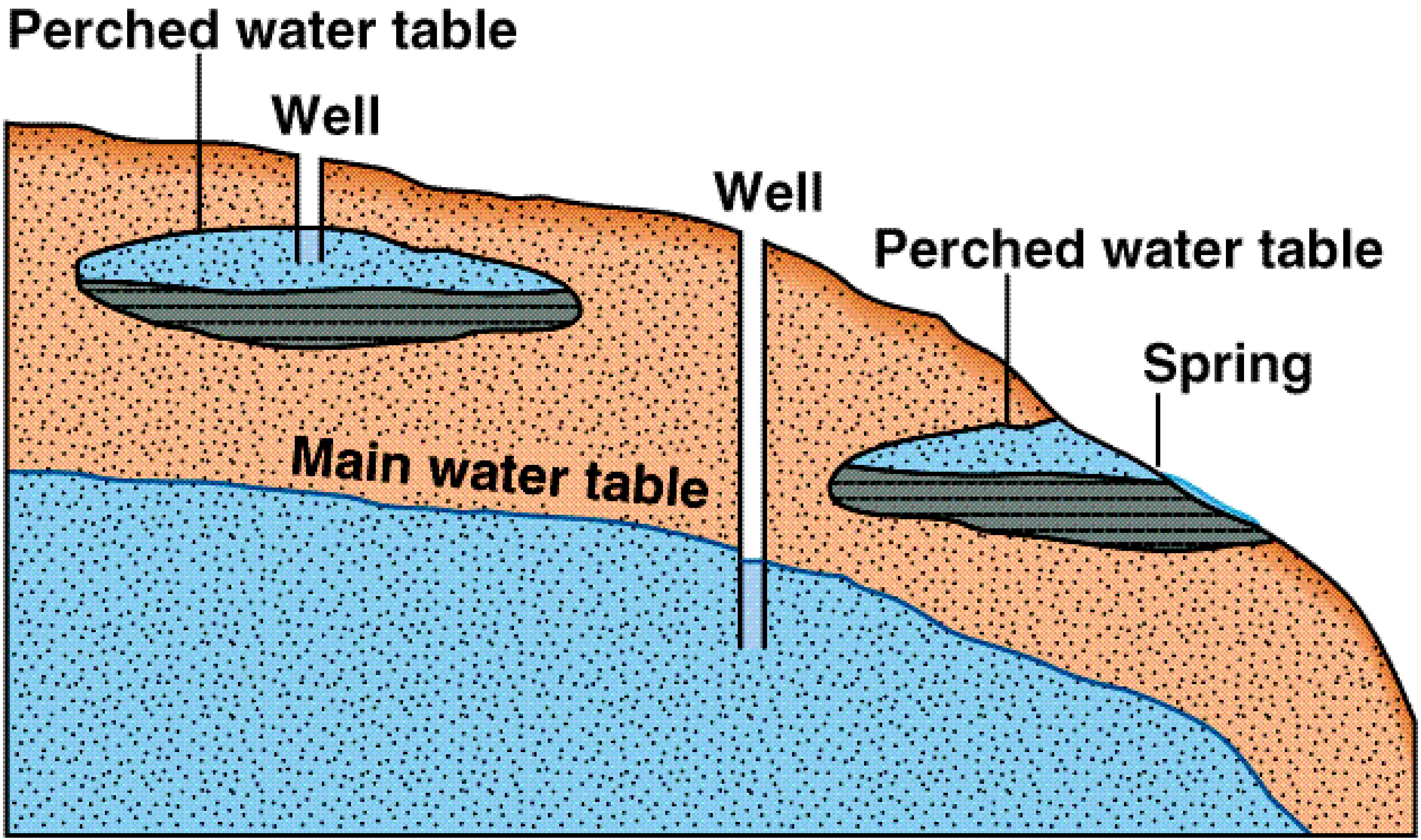


- *Aquitards* are rocks/sediments that retard groundwater flow due to low porosity and/or permeability
  - Shale, clay, unfractured crystalline rocks

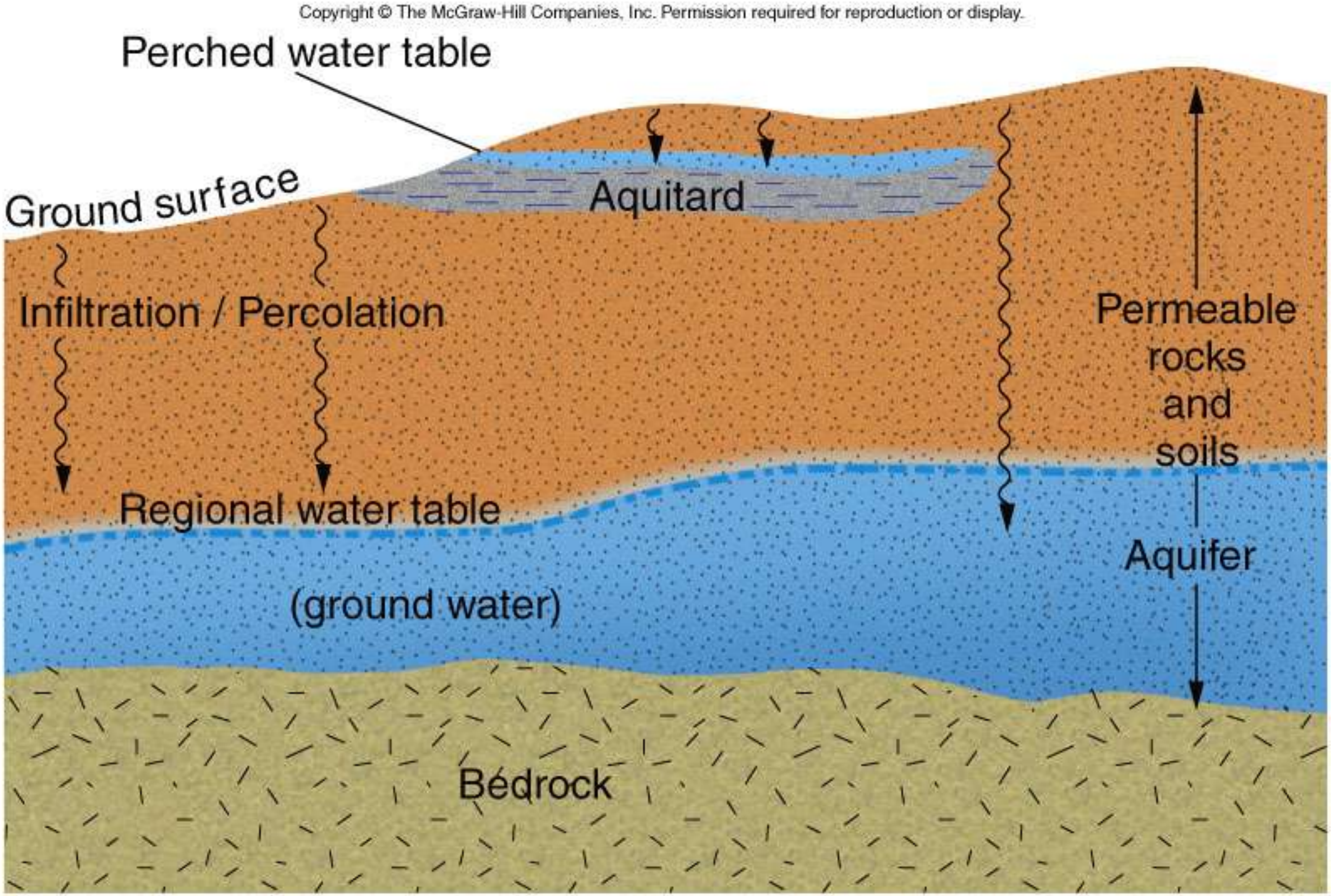
An Unconfined Aquifer



Perched Water Tables

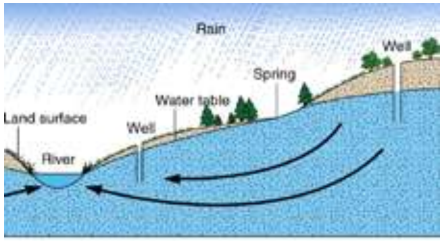


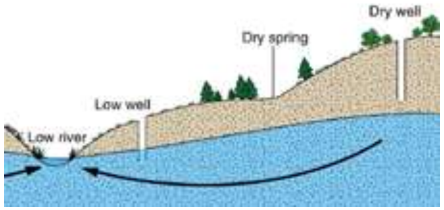
Perched water table



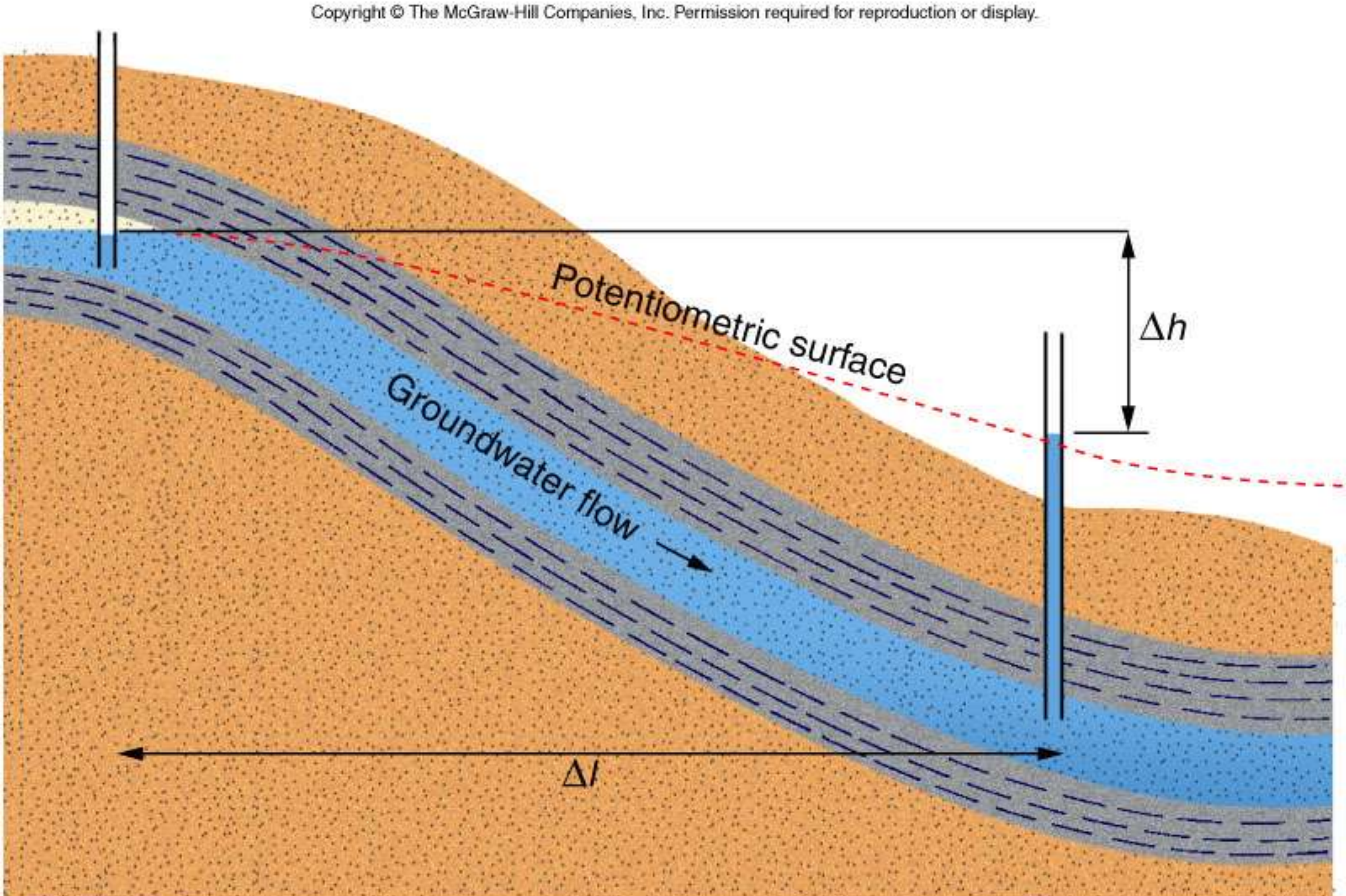
Wells

- *Well* - a deep hole dug or drilled into the ground to obtain water from the saturated zone of an aquifer
  - For wells in unconfined aquifers, water level before pumping is the water table
  - Water enters well from pore spaces within the surrounding aquifer
  - Water in wells (and surrounding aquifer) can be lowered by pumping of water, a process known as *drawdown*
  - Water under pressure in a confined aquifer may rise in a well to a level above the top of the aquifer to produce an *artesian well*

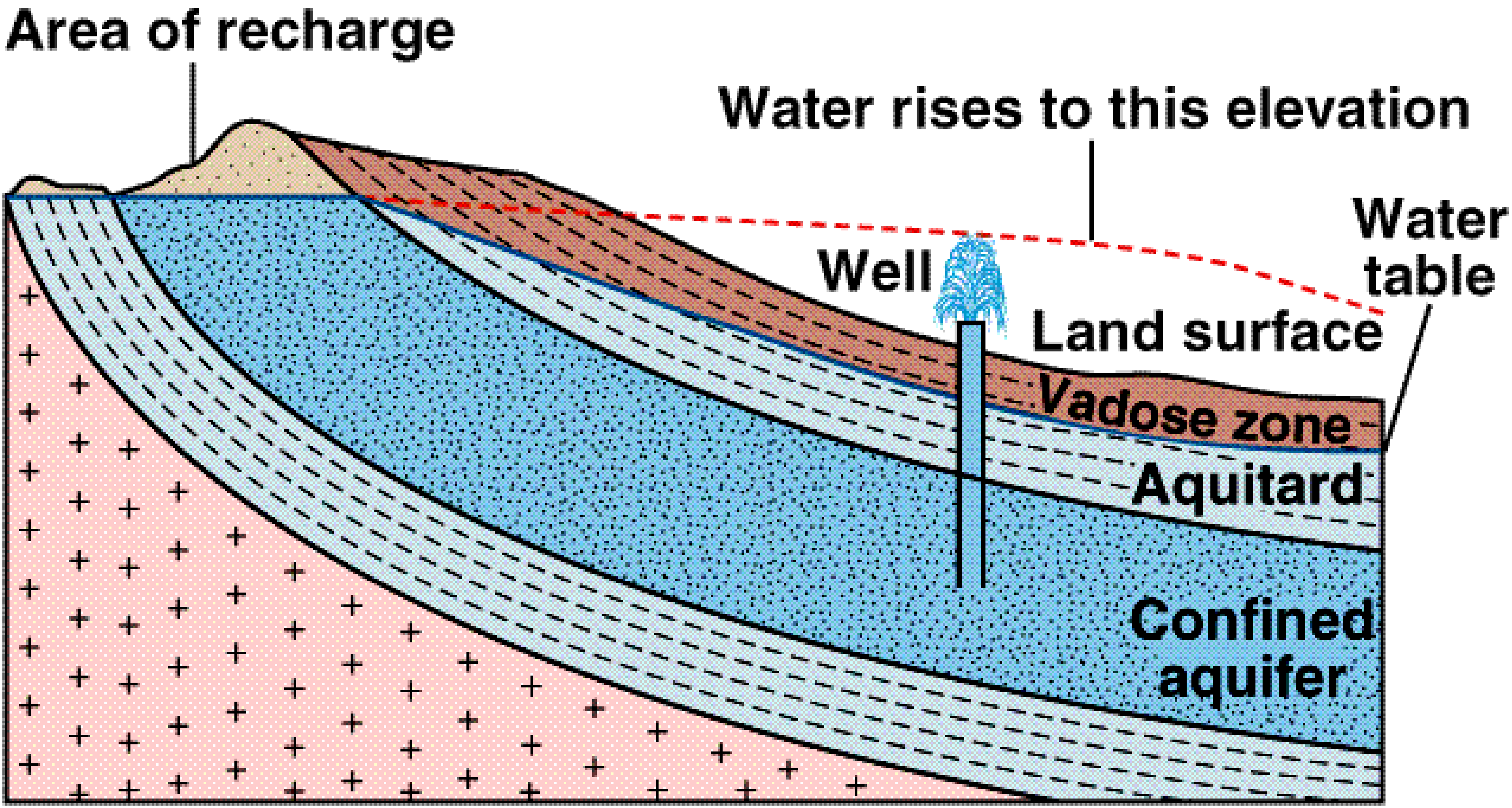




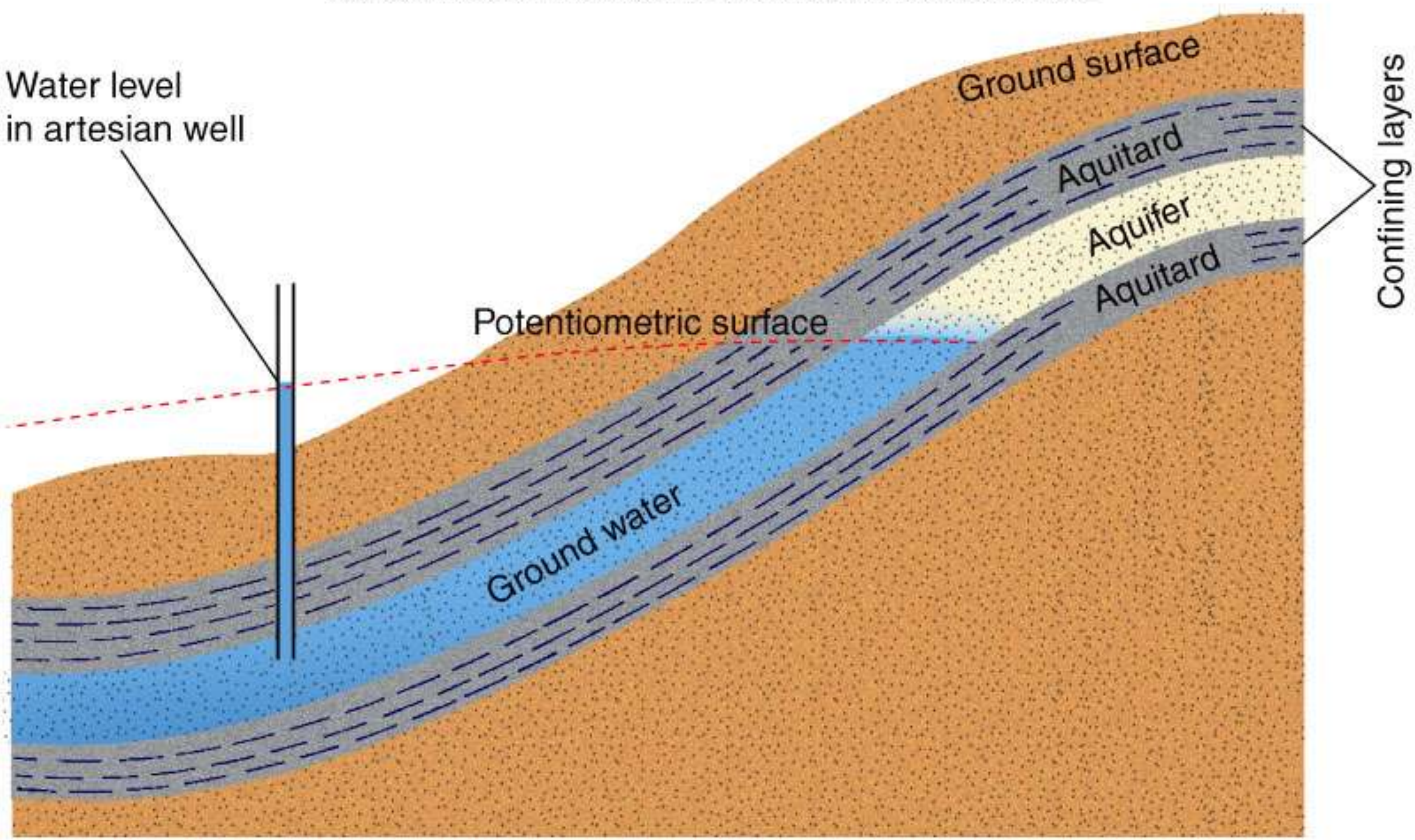
Artesian water



Dakota Sandstone



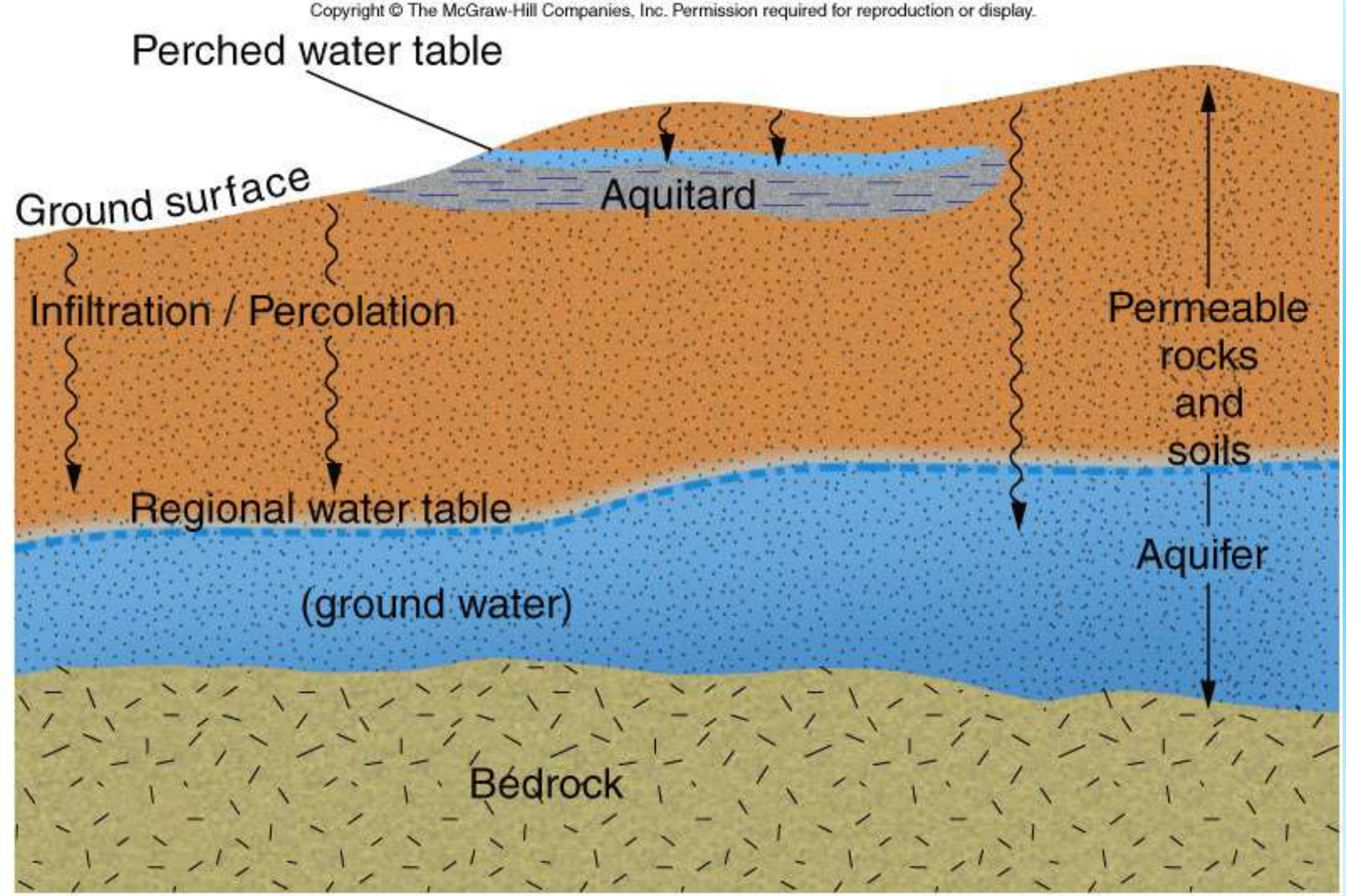
Artesian well – flows to surface without pumping



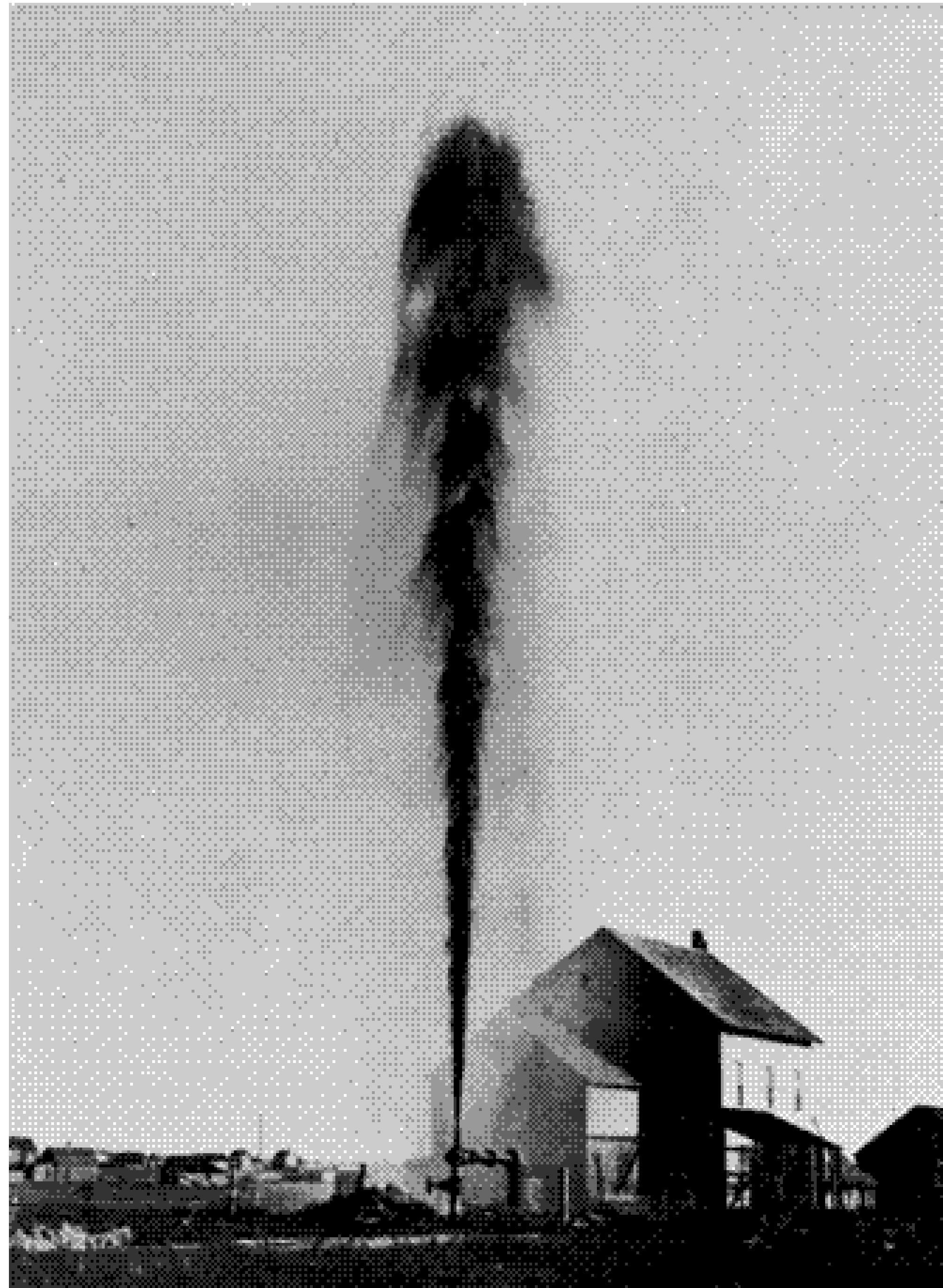
Groundwater Flow

- **Hydraulic head** is potential energy in an aquifer
  - The height of water in an unconfined aquifer reflects the hydraulic head
    - The higher the water table the higher the head
  - The higher the potentiometric surface in a confined aquifer will equate to higher hydraulic head
  - Ground water flows spontaneously from areas of high hydraulic head to areas with low hydraulic head

Perched water table



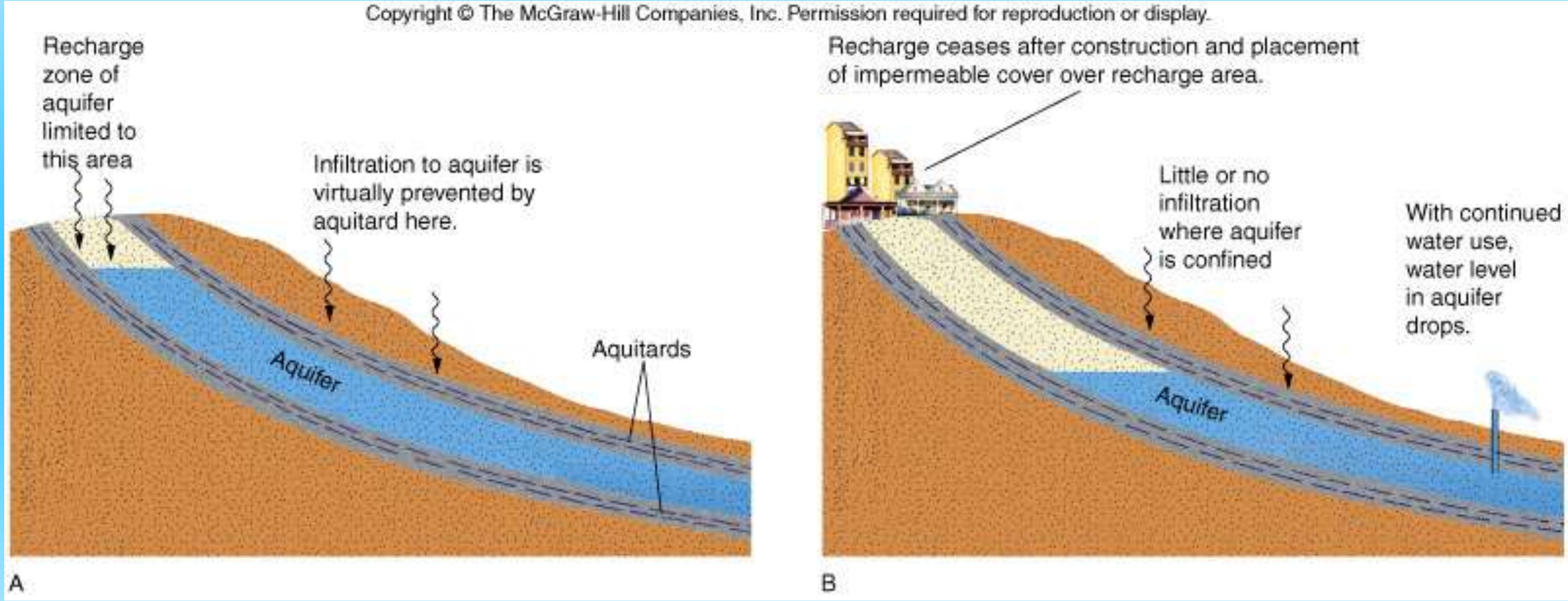
Artesian Well



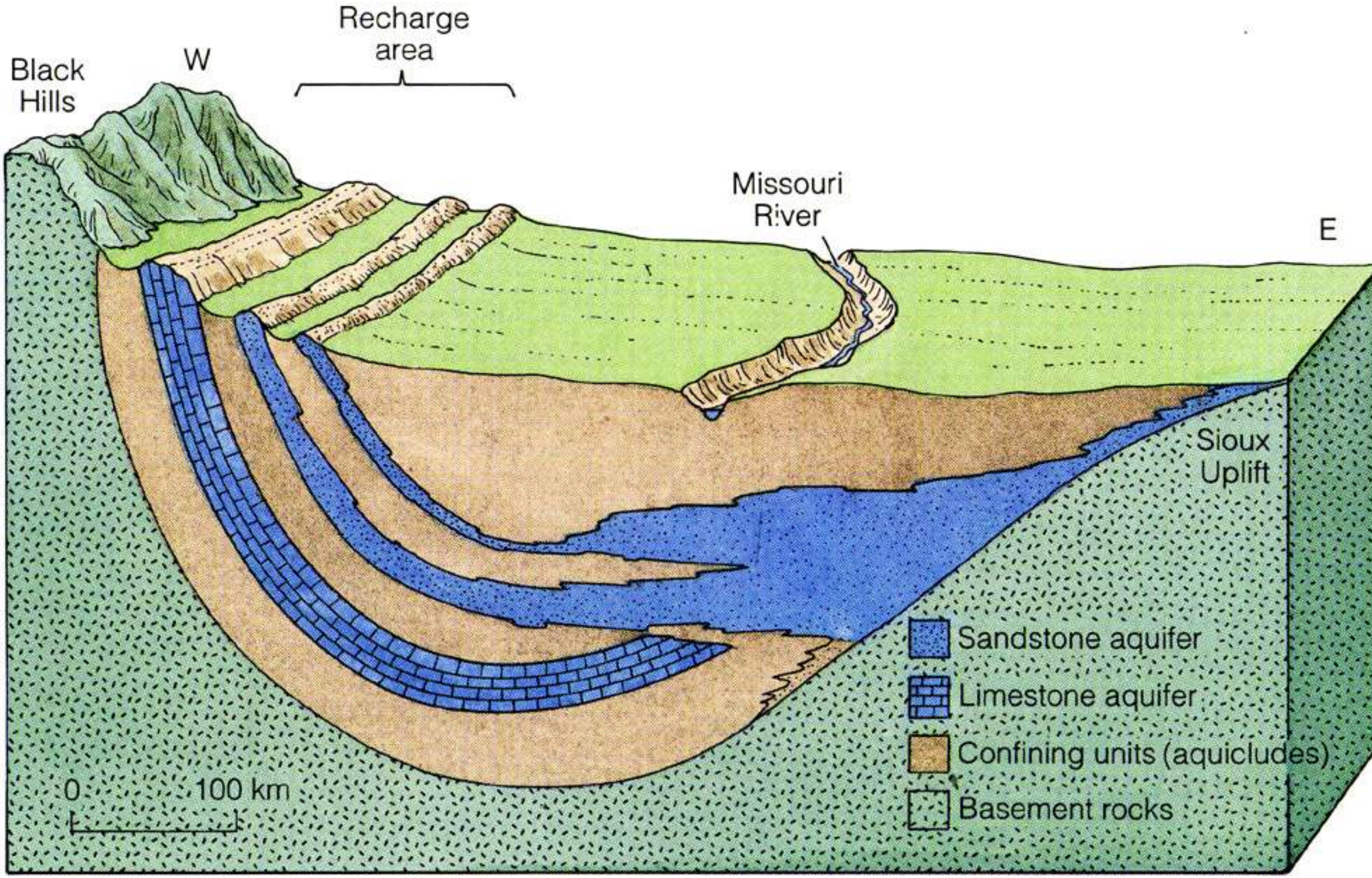
Other Factors in Water Availability

- Geometry of host rock units
- Distribution of aquitard lenses may form ***perched water tables***
- Local precipitation patterns and fluctuations
- Minerals in host rock
- Location of wells relative to recharge zones and discharge points

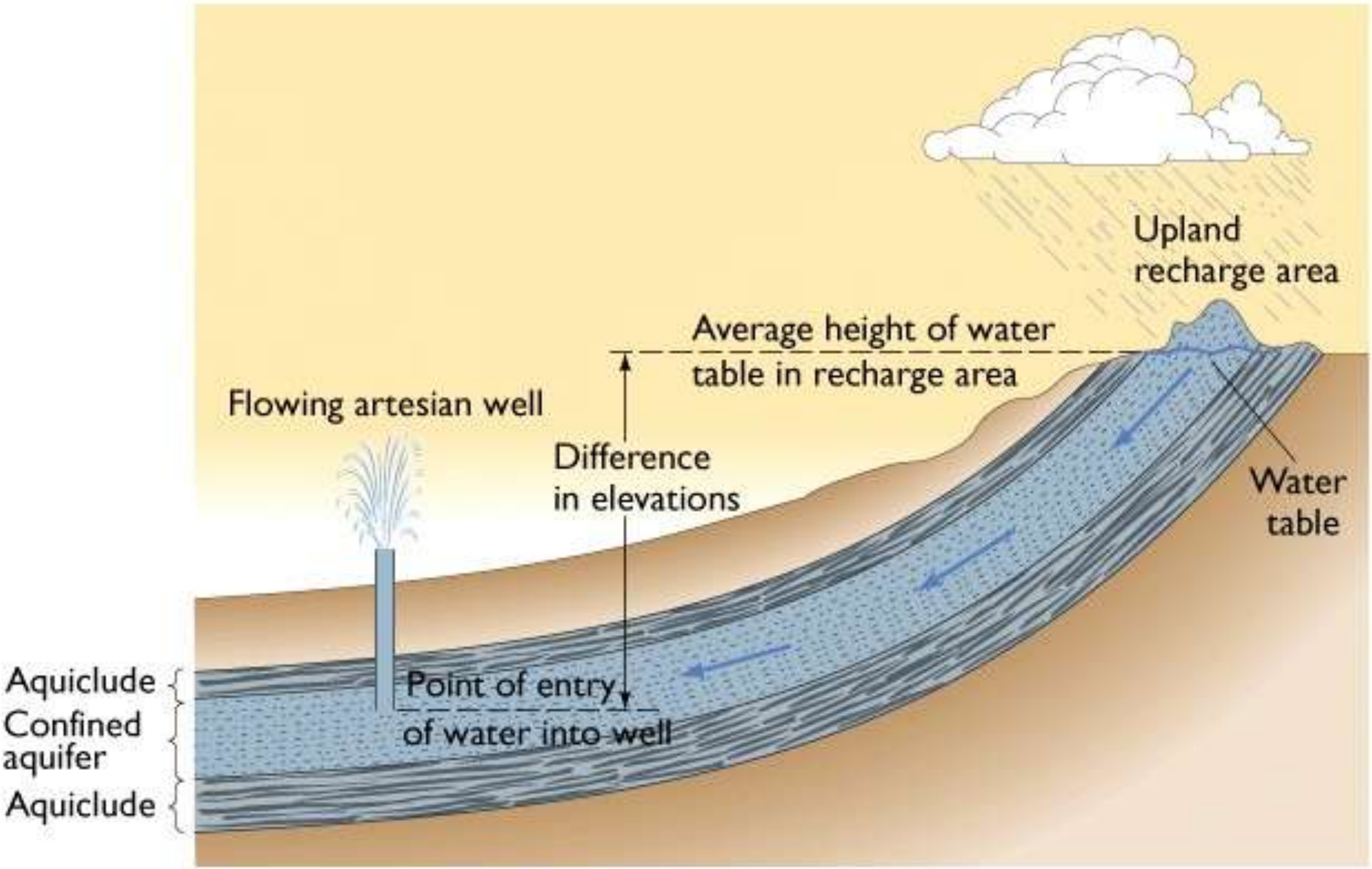
Artesian wells adjoining mountain ranges



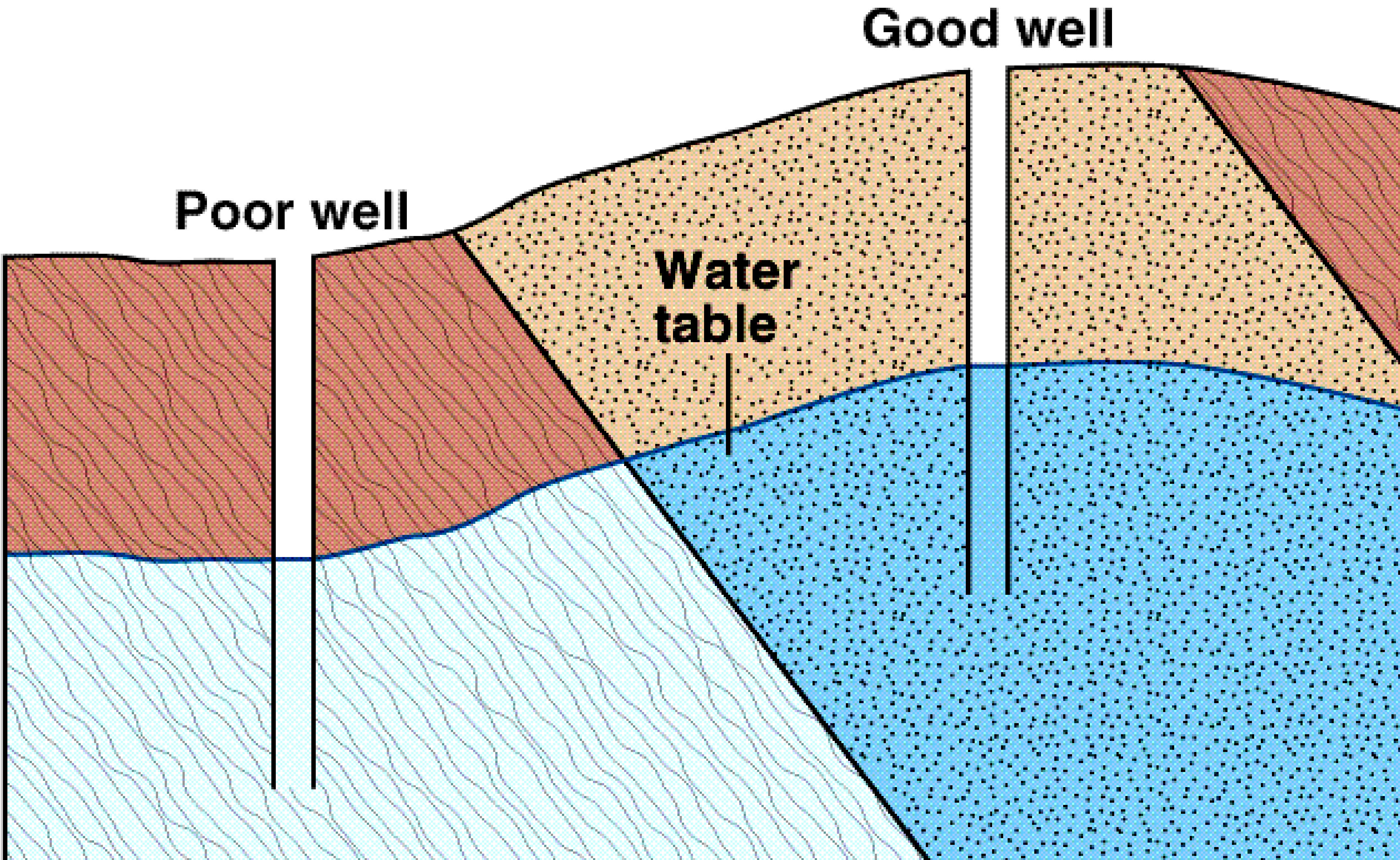
Mountain front artesian water



Confined flow paths — artesian water



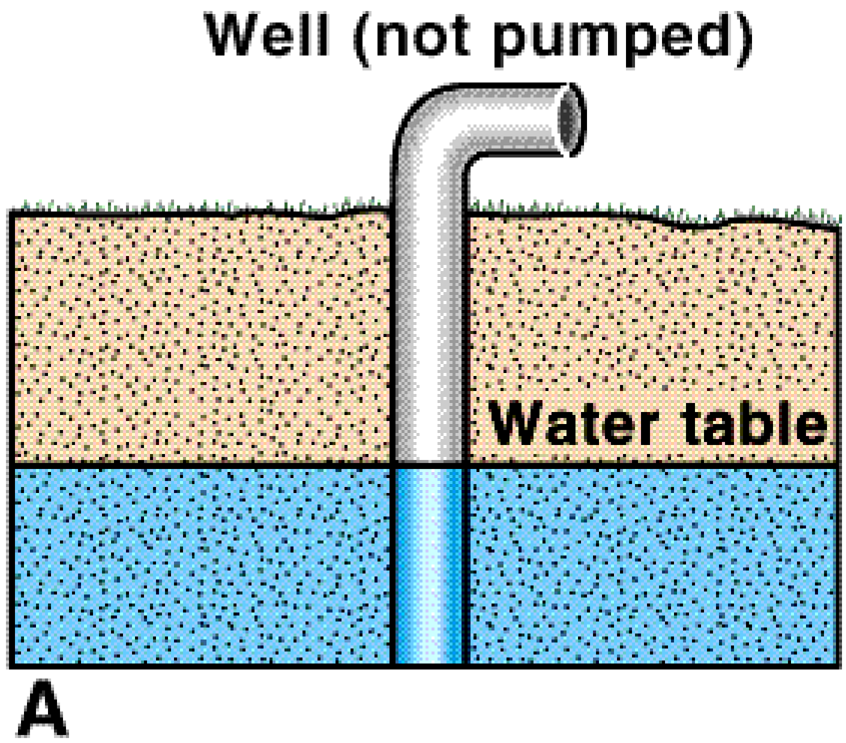
Obtaining Water from Aquifers

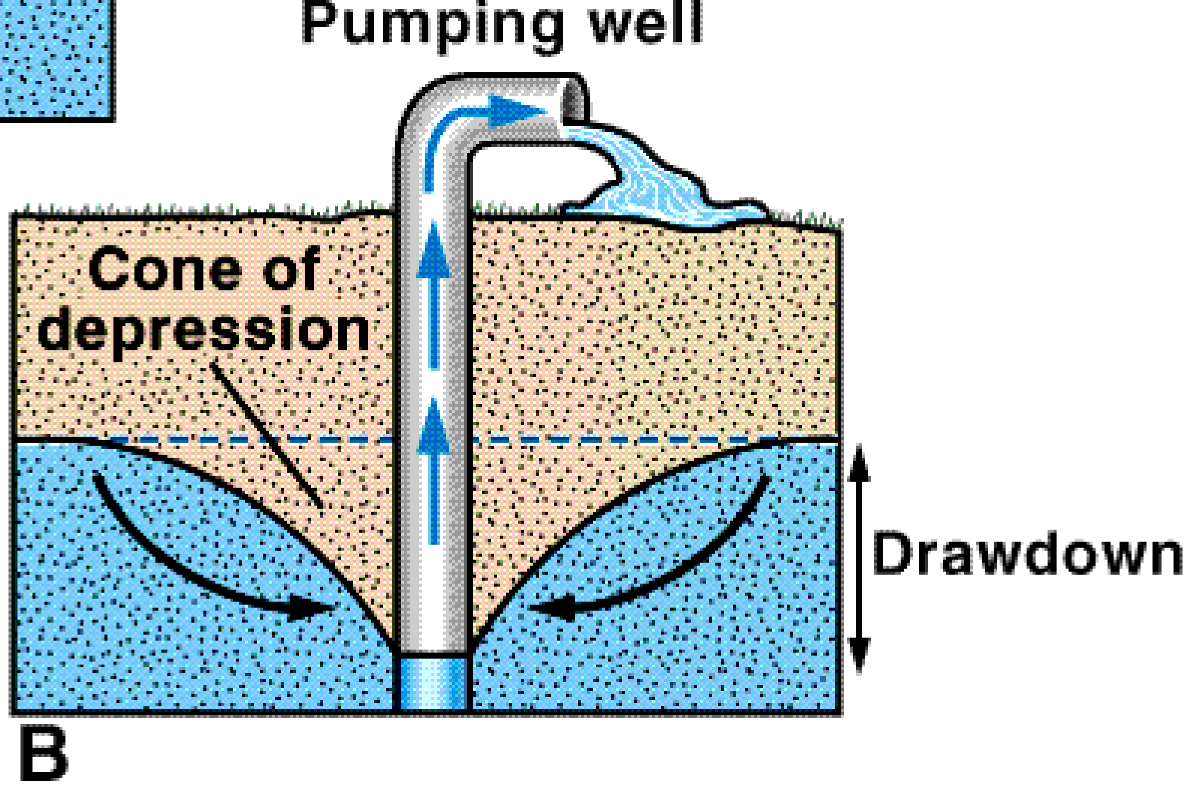


Aquifer Geometry and Groundwater Flow

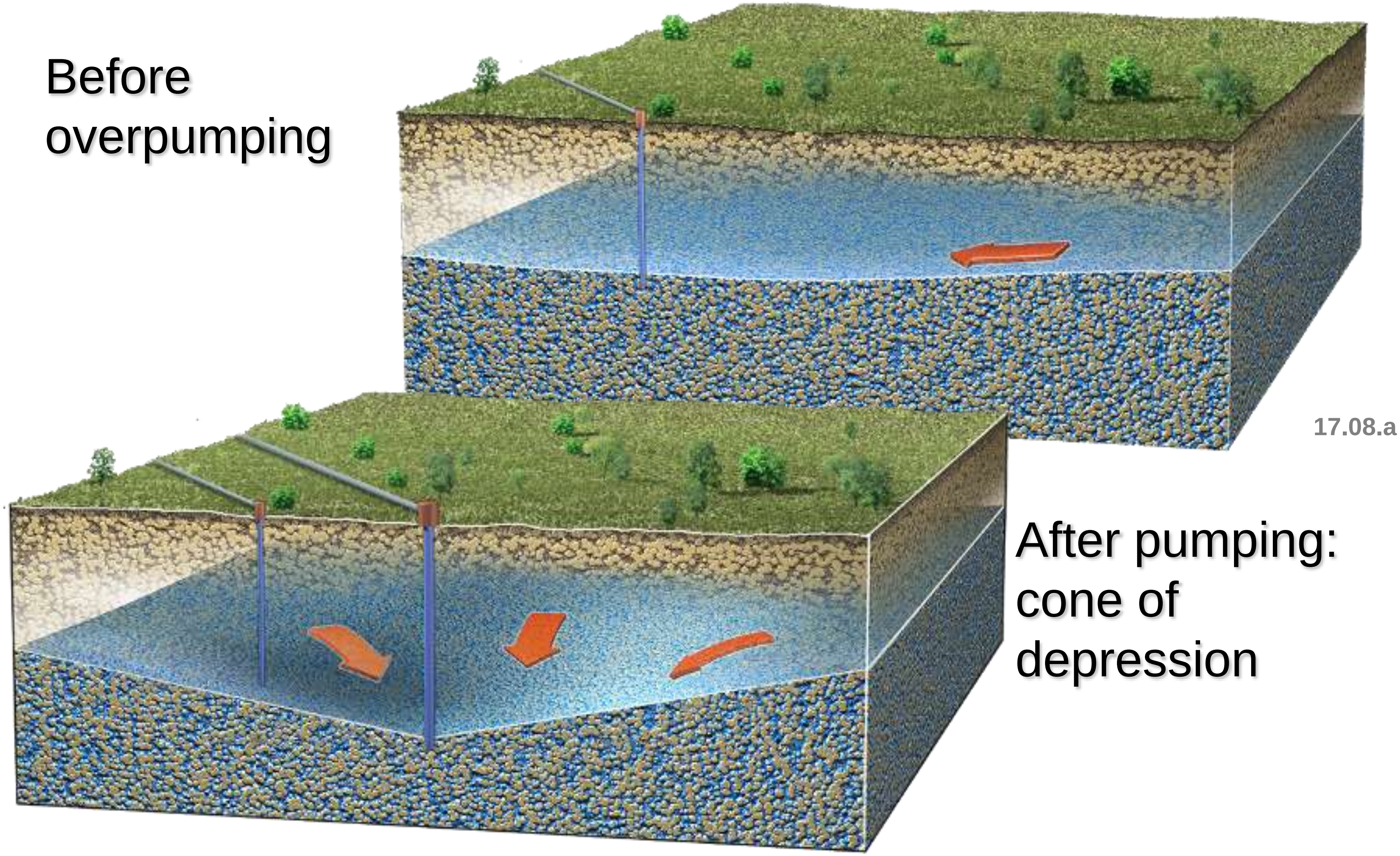
- Geology and geometry of rocks and sediments will control the behavior of ground water
  - An aquifer without an aquitard above it is an **unconfined aquifer**
  - An aquifer with an aquitard above and below is a **confined aquifer**
  - A confined aquifer may see hydrostatic water pressure increase and form an **artesian system**
    - Drilling into a confined aquifer under pressure will see the water rise above the aquifer
    - In this system the **potentiometric surface** is the height to which the water would rise

Cone of Depression

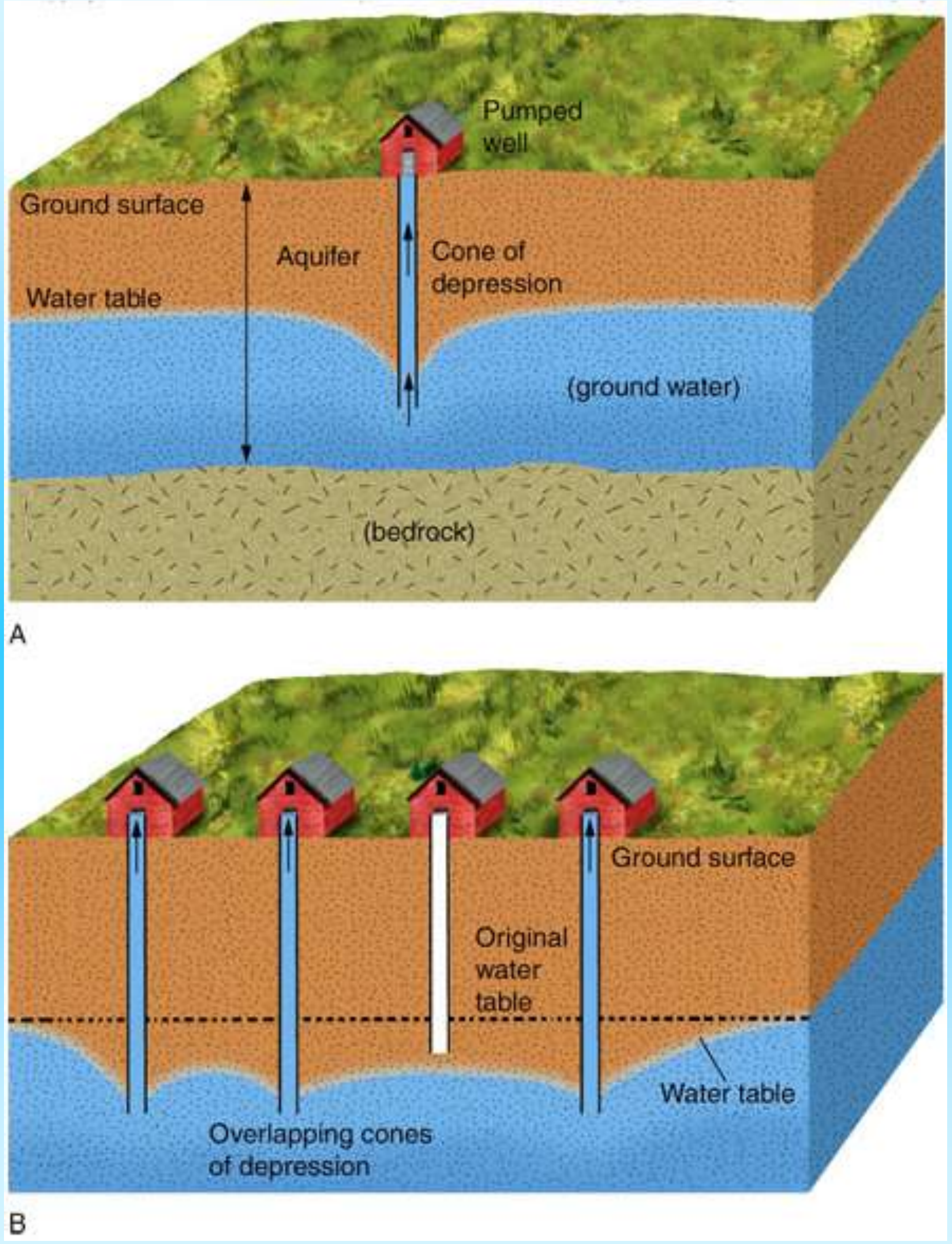




Effects of Overpumping Groundwater



Lowering the water table

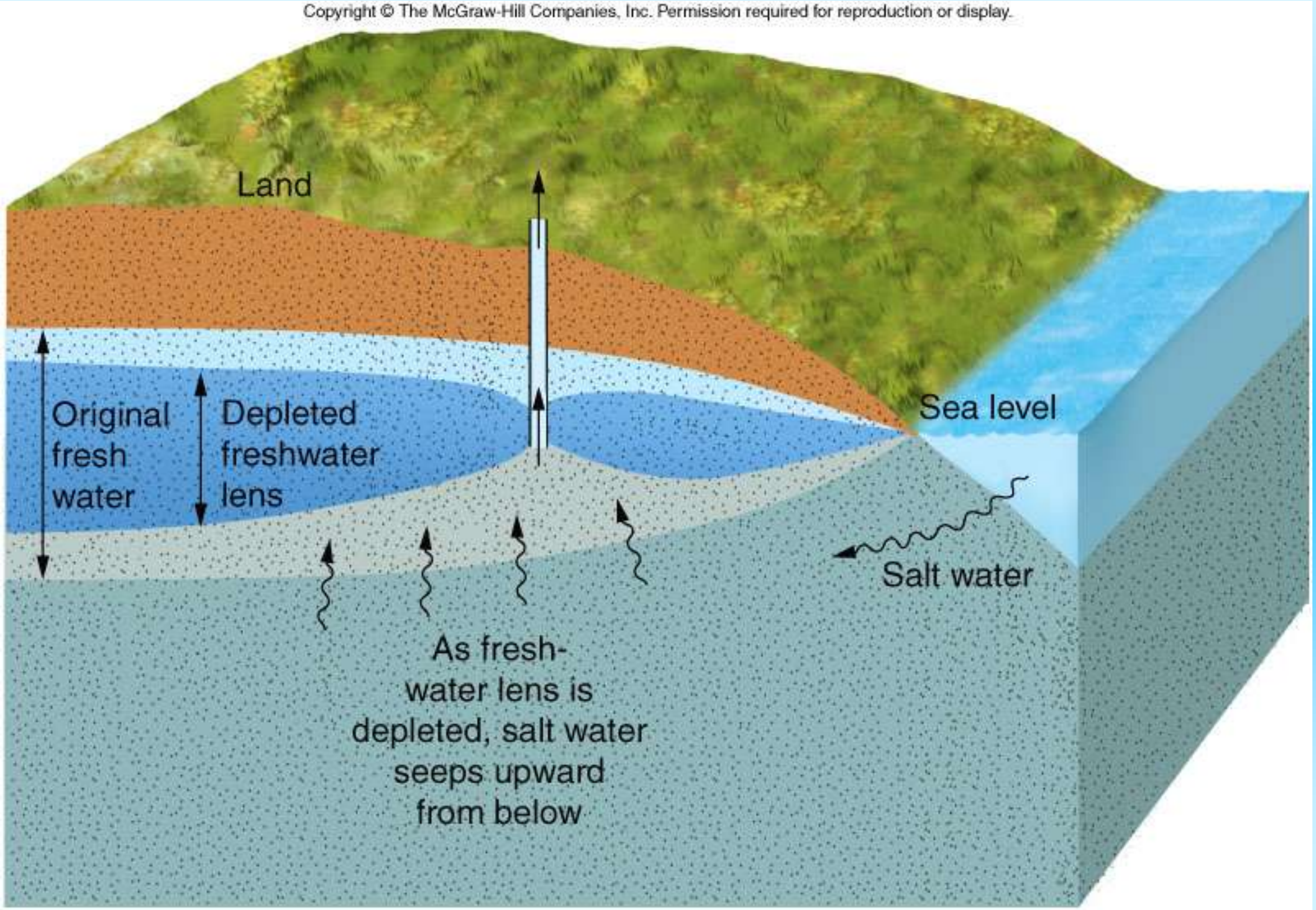


Ground subsidence related to pumping out grround water

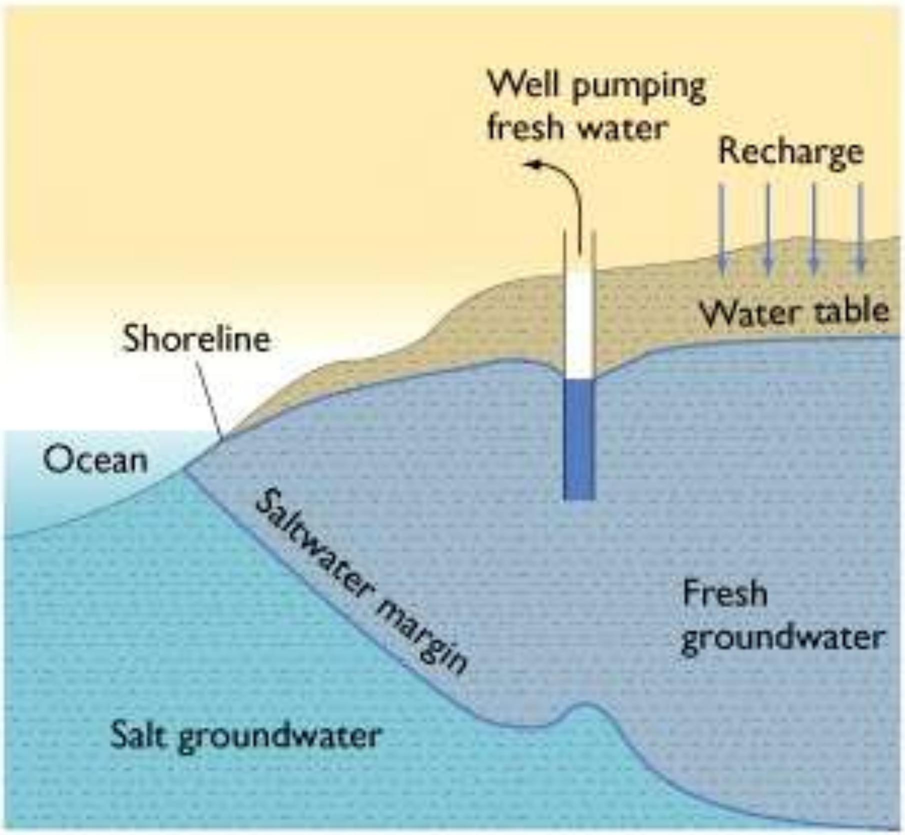
Consequences of Groundwater Withdrawal

- Pumping ground water will lower the water table and form a **cone of depression** around the well
  - This may impact local and regional ground water availability
- Aquifer rocks may re-adjust after ground water is withdrawn
  - Sediments may compaction and cause surface subsidence
  - An area of low elevation, relative to sea level, may be inundated by the sea
  - Sinkholes may also develop depending on the host rock
- Near coastlines saltwater intrusion may occur
  - Freshwater is less dense than saltwater
  - Saltwater near a coast line may push freshwater lenses back if recharge is not sufficient to force seawater toward the sea

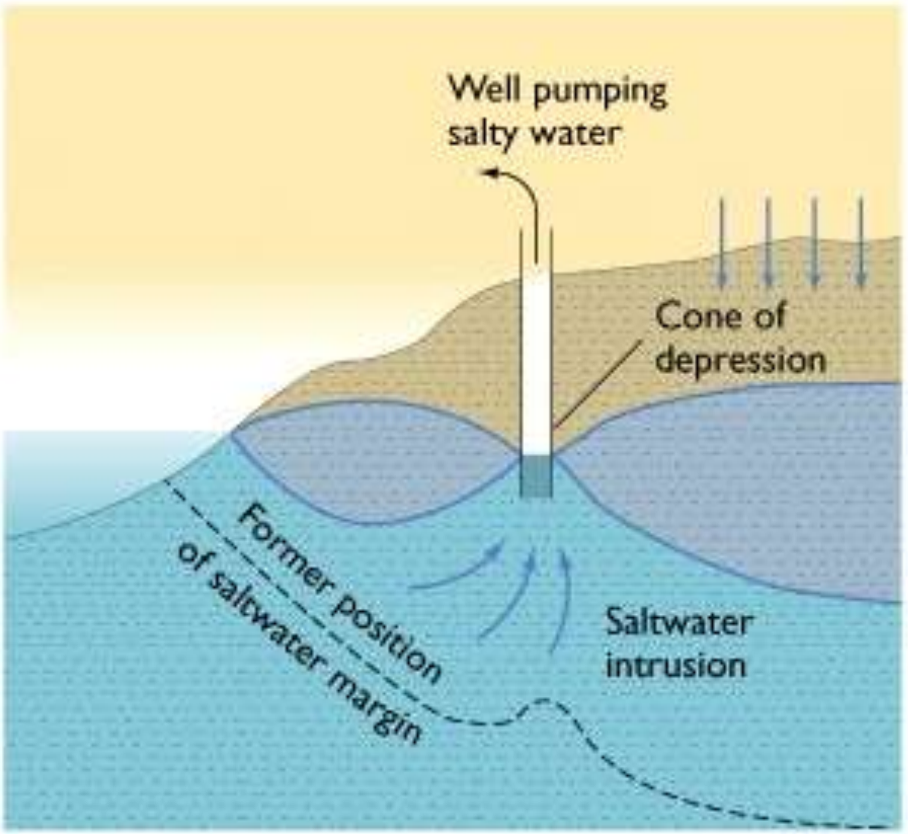
Salt water incursion due to cone of depression



Aquifer degradation by saltwater incursion



(a) Before extensive pumping



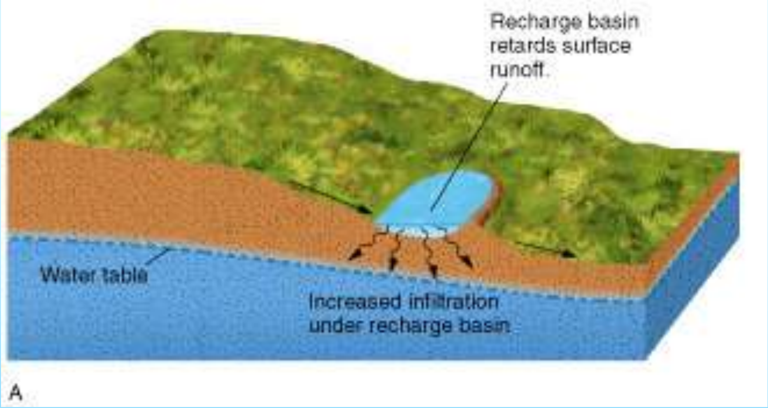
(b) After extensive pumping by many wells

Other Impacts of Urbanization on Groundwater Systems

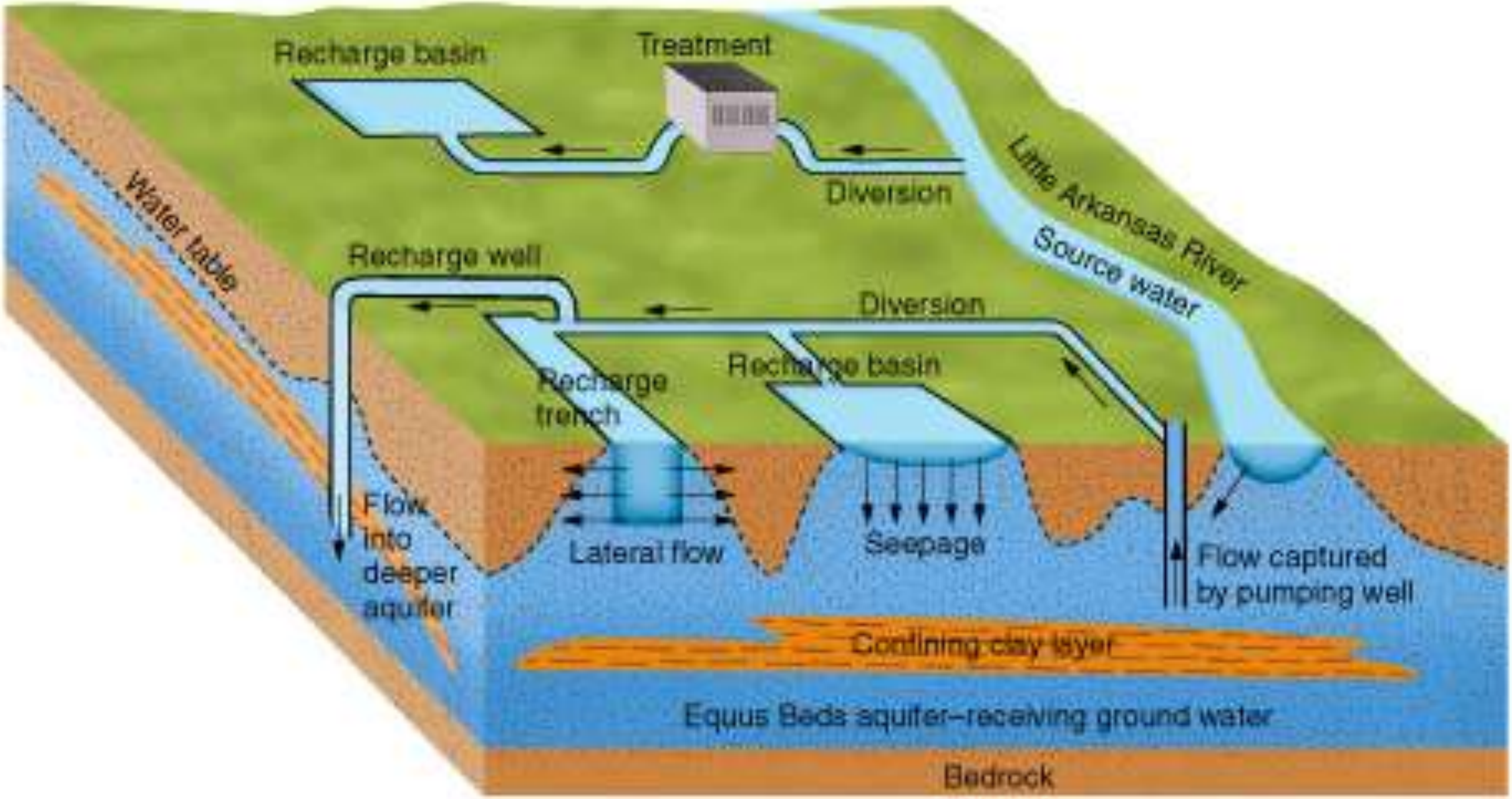
- An increase in people in an area may cause ground water supplies to be exhausted or **loss of recharge** to occur
  - Pavement and parking lots reduce the effectiveness of water infiltrating into ground water
  - Building on wetlands reduces recharge, water storage, and water quality
- Ground water recharge can be enhanced by incorporating various artificial recharge strategies
  - Build artificial recharge basins
  - Employ any method to slow down run off and increases surface water infiltration

Other Features Involving Subsurface Water

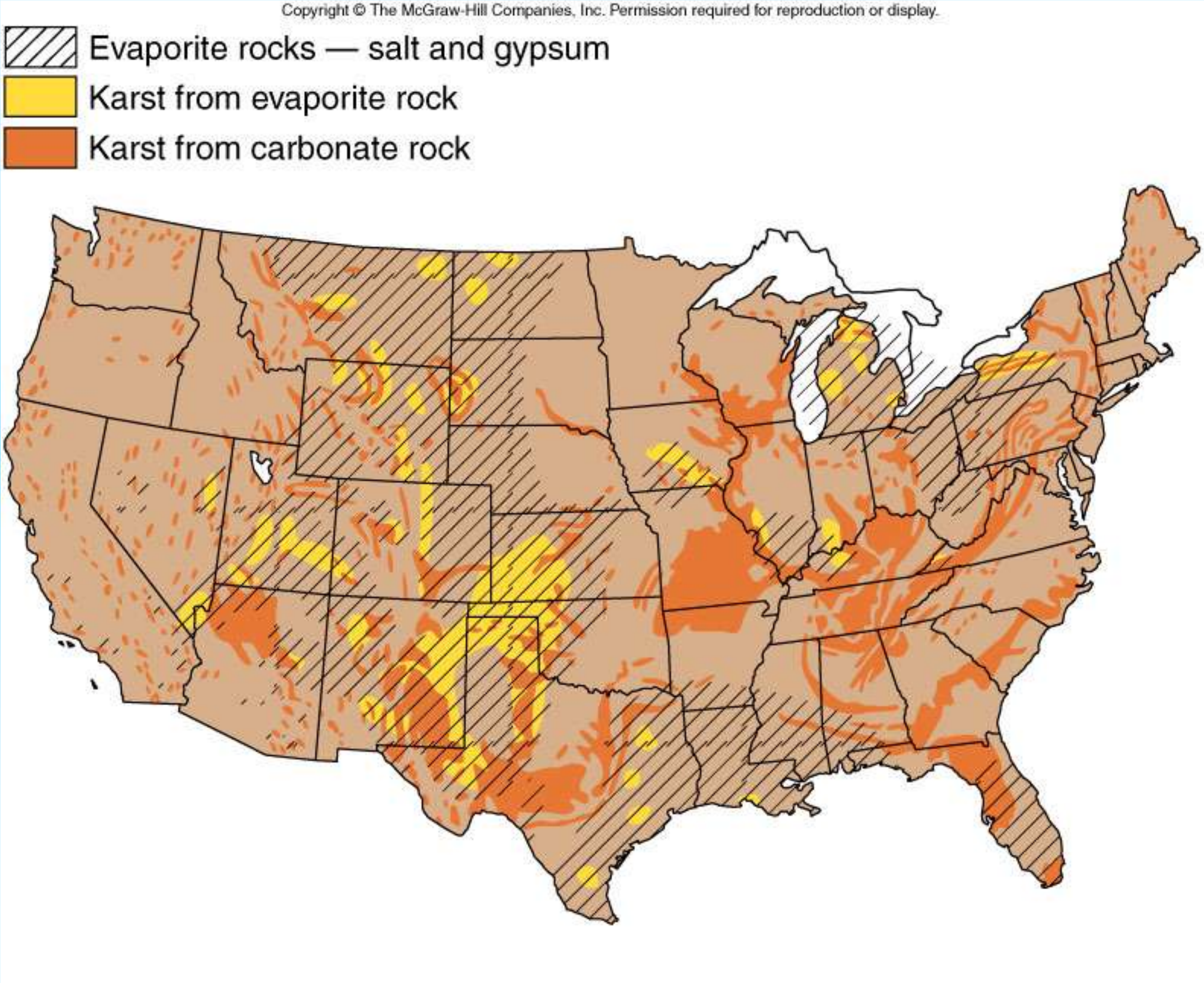
- Ground water may dissolve large volumes of rock (soluble rock)
  - Collapse of the surface rock may result in **sinkholes**
  - Caverns may also be enlarged
- **Karst** is a type of land form associated with many sink holes in soluble bedrock such as limestone, dolomite, or gypsum
  - Water removes the minerals of the rock and carries the ions off in solution
  - Ground water flow rates will increase in karst areas
    - Ground water flows faster without sediments and rock in the flow path
    - Pollutants move faster through ground water systems in karst areas



Karst topography



Soluble rock areas and Karst areas



Sink holes caused by collapse of cave roof

A

B

Florida sinkhole formed by collapse of cave roof

Internal and disrupted stream drainage

A

B

Water Quality

- Measures for expressing Water Quality
  - Parts per million (ppm)
  - Parts per billion (ppb)
  - Total Dissolved Solids (TDS)
    - The sum of dissolved solid chemicals in the water
    - It is important to know what chemicals are dissolved!
  - **Hard Water** contains substantial amounts of calcium and magnesium
    - Greater than 80 to 100 ppm

Concentrations of Some Dissolved Constituents in Rain, River Water, and Seawater

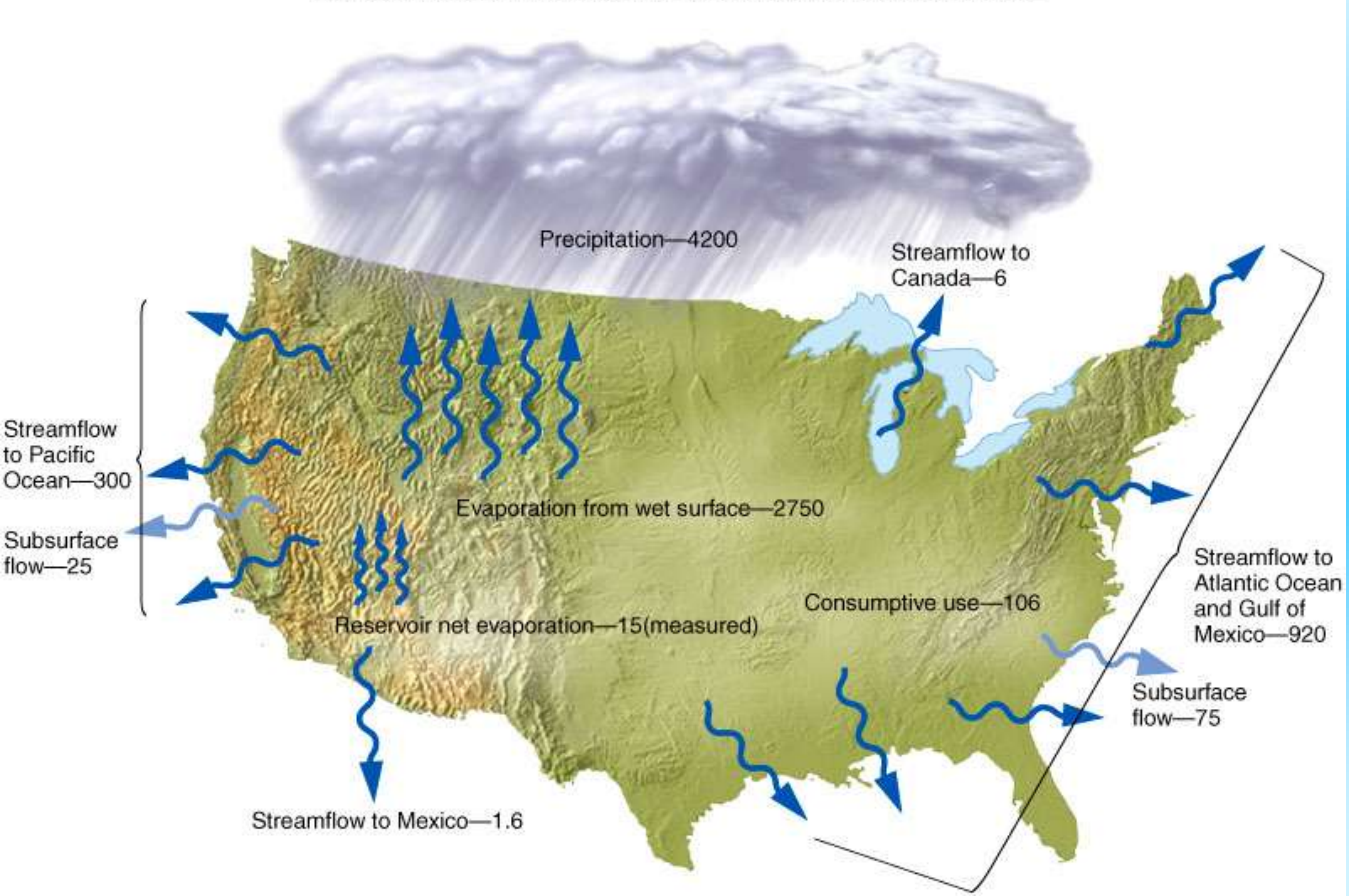
Constituent	Concentration (ppm)						
	Rainwater			River Water			
	1-year Avg., Mid-Atlantic States	Single Storm, California	1-year Avg., Inland U.S.	Amazon River	Mississippi River	World Avg. (est.)	Average Seawater
silica (SiO_2)	—	0.3	—	7.0	6.7	13	6.4
calcium (Ca)	0.65	0.8	1.41	4.3	42	15	400
sodium (Na)	0.56	9.4	0.42	1.8	25	6.3	10,500
potassium (K)	0.11	0.0	—	—	2.9	2.3	380
magnesium (Mg)	0.14	1.2	—	1.1	12	4.1	1350
chloride (Cl)	0.57	17	0.22	1.9	30	7.8	19,000
fluoride (F)	—	—	—	0.2	0.2	—	1.3
sulfate (SO_4)	2.18	7.6	2.14	3.0	56	11	2700
bicarbonate (HCO_3)	—	4	—	19	132	58	142
nitrate (NO_3)	0.62	0	—	0.1	2.4	1	0.5

Source: J. D. Hem, *Study and Interpretation of the Chemical Characteristics of Natural Water*, U.S. Geological Survey Water-Supply Paper 1473, 1970, pp. 11, 12, and 50. (Ground water composition is so variable that representative analyses cannot be determined.)

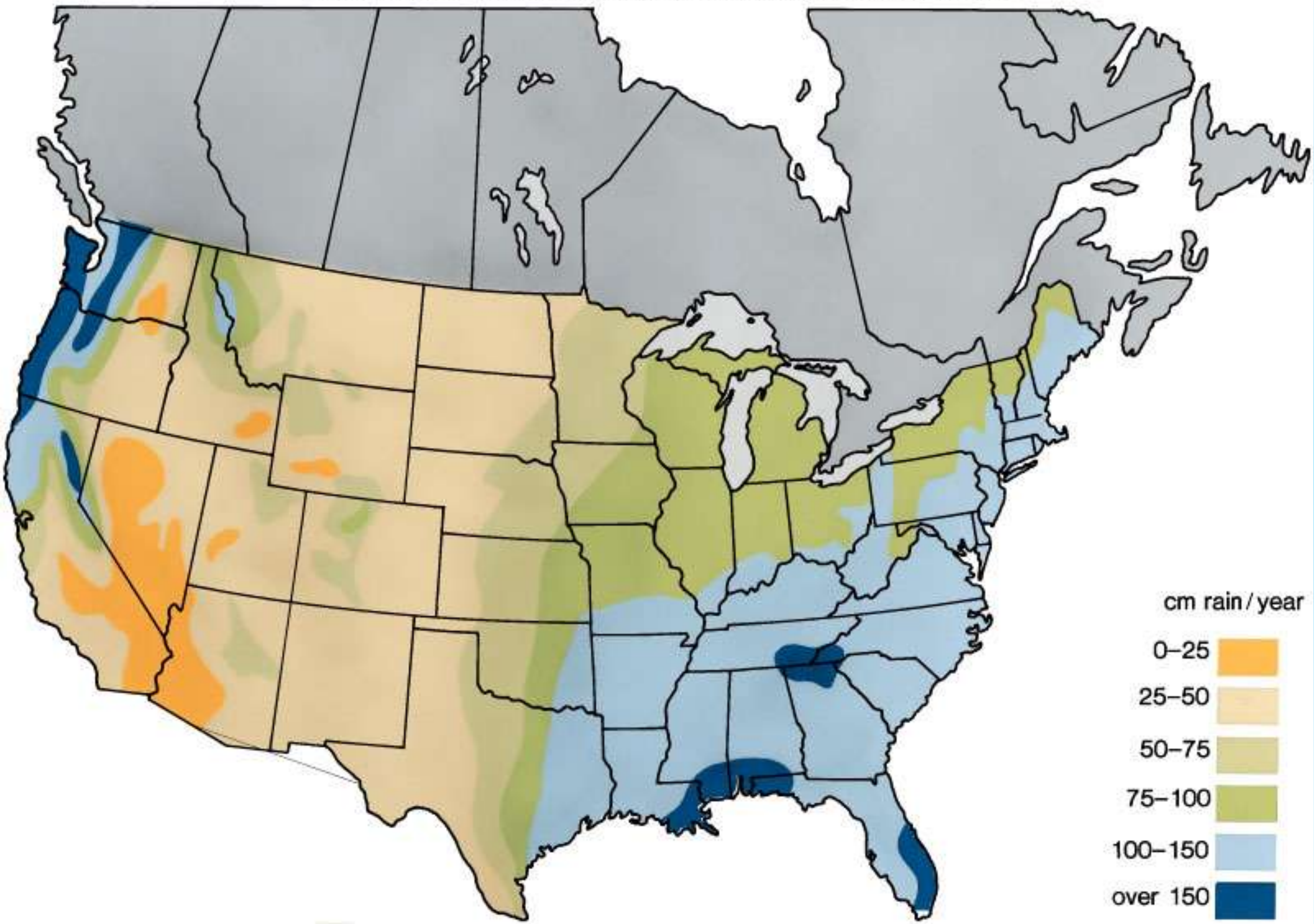
Water Use and Water Supply

- In U.S. the east is generally humid
  - More dependence is on surface water
- In the west more arid condition are found
  - More dependence is on ground water and impounding surface water for storage
- Global water usage
  - Too many people
  - Too much demand
  - Not many places to find more water

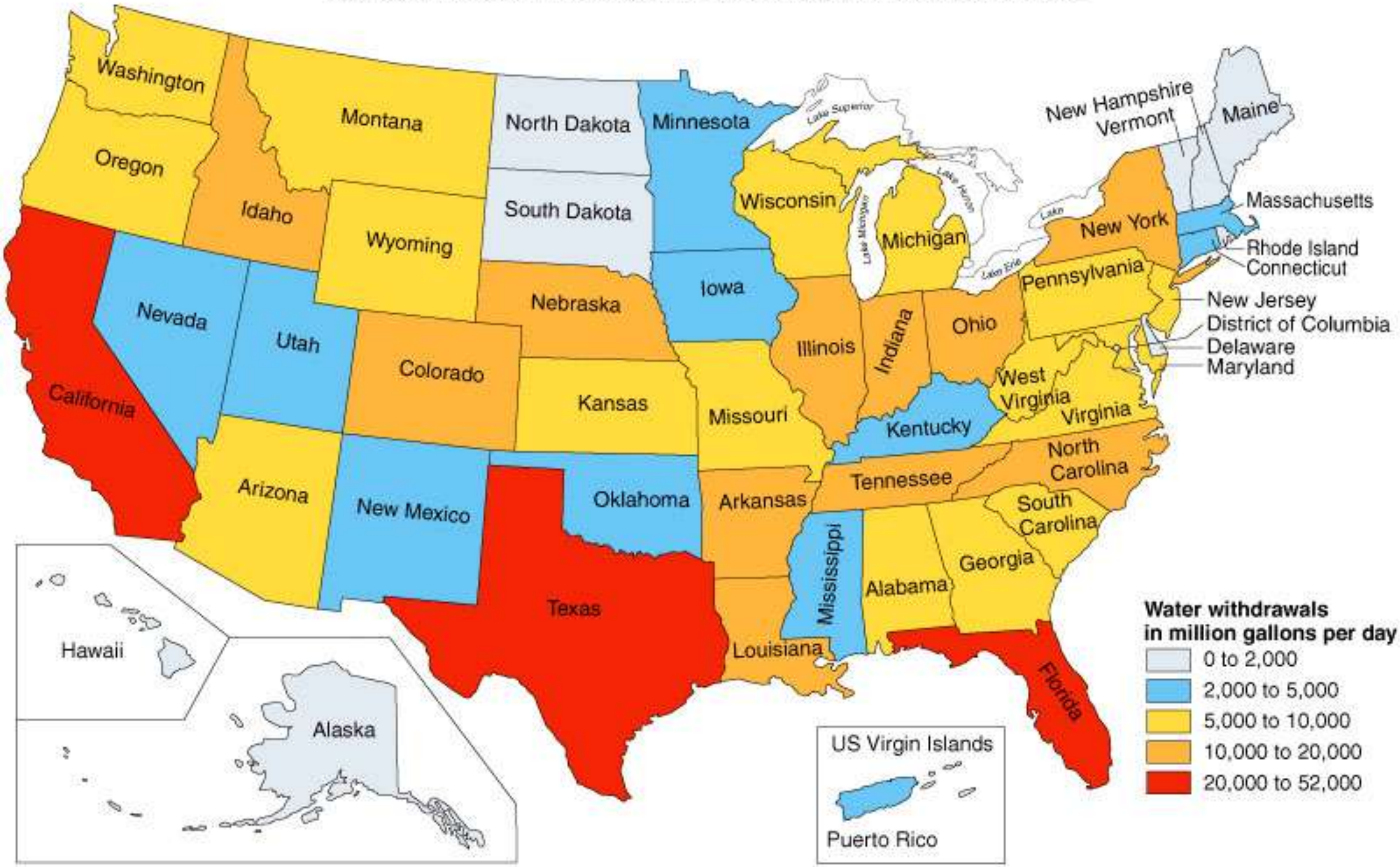
Water flows in US



Precipitation – rain & snow



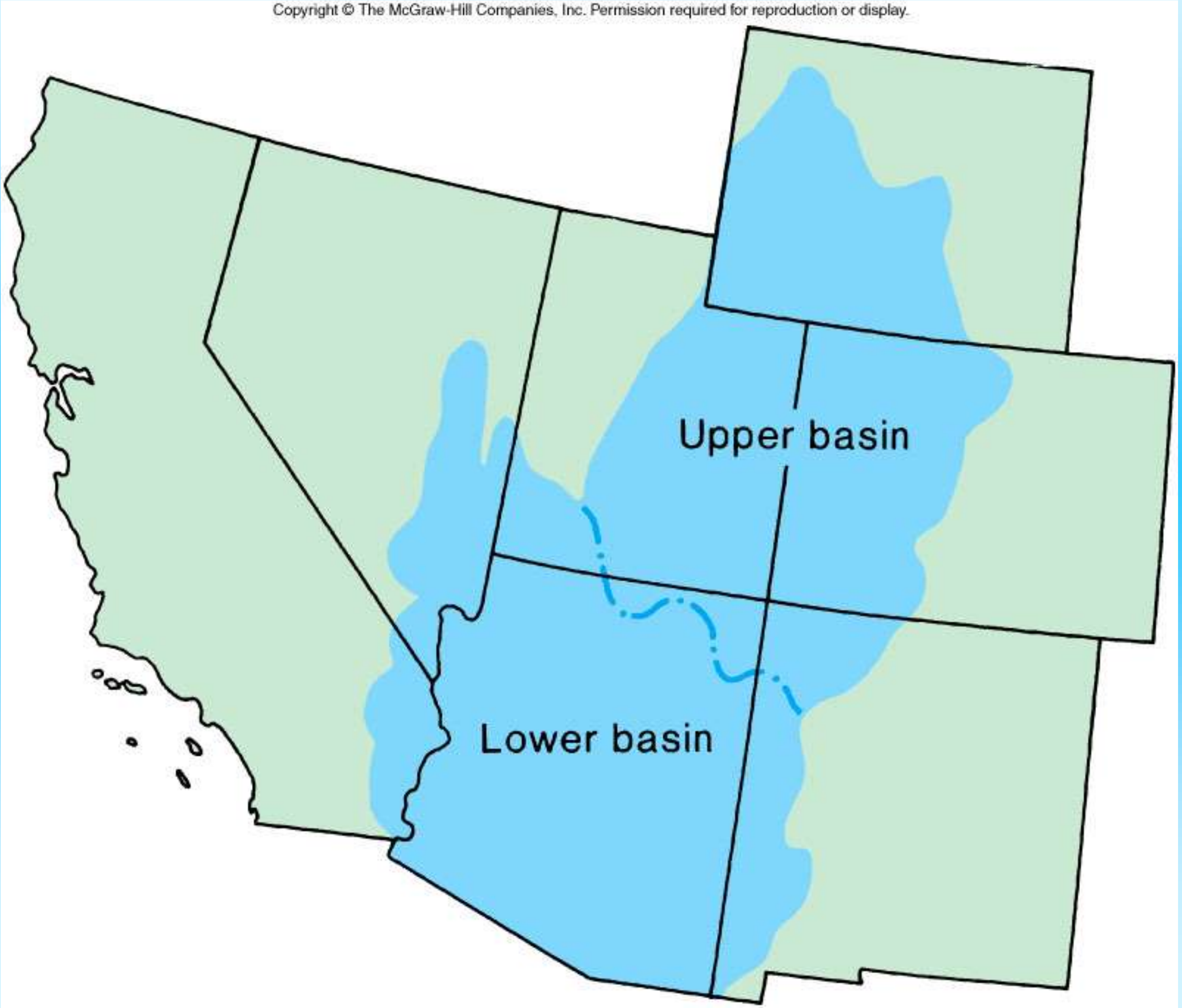
Water withdrawals



Case Studies in Water Consumption

- Plenty of water-supply problems: lakes, streams, or ground water
- The Colorado River Basin
  - Drains portions of seven western states and many of these states have extremely dry climates
- The High Plains (Ogallala) Aquifer System
  - The Ogallala Formation, a sedimentary aquifer, underlies most of Nebraska and sizeable portions of Colorado, Kansas, and the Texas and Oklahoma panhandles
  - The most productive units of the aquifers are sandstones and gravels
- The Aral Sea, a disappearing lake
  - Lies on the border of Kazakhstan and Uzbekistan
- Lake Chad
  - A disappearing lake on the edge of the Sahara Desert

Colorado River basin




NICE SHOT. KID!....C.A.P. WATER-- NO DOUBT...

Case Studies in Water Consumption

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Agriculture and the "mining" of groundwater

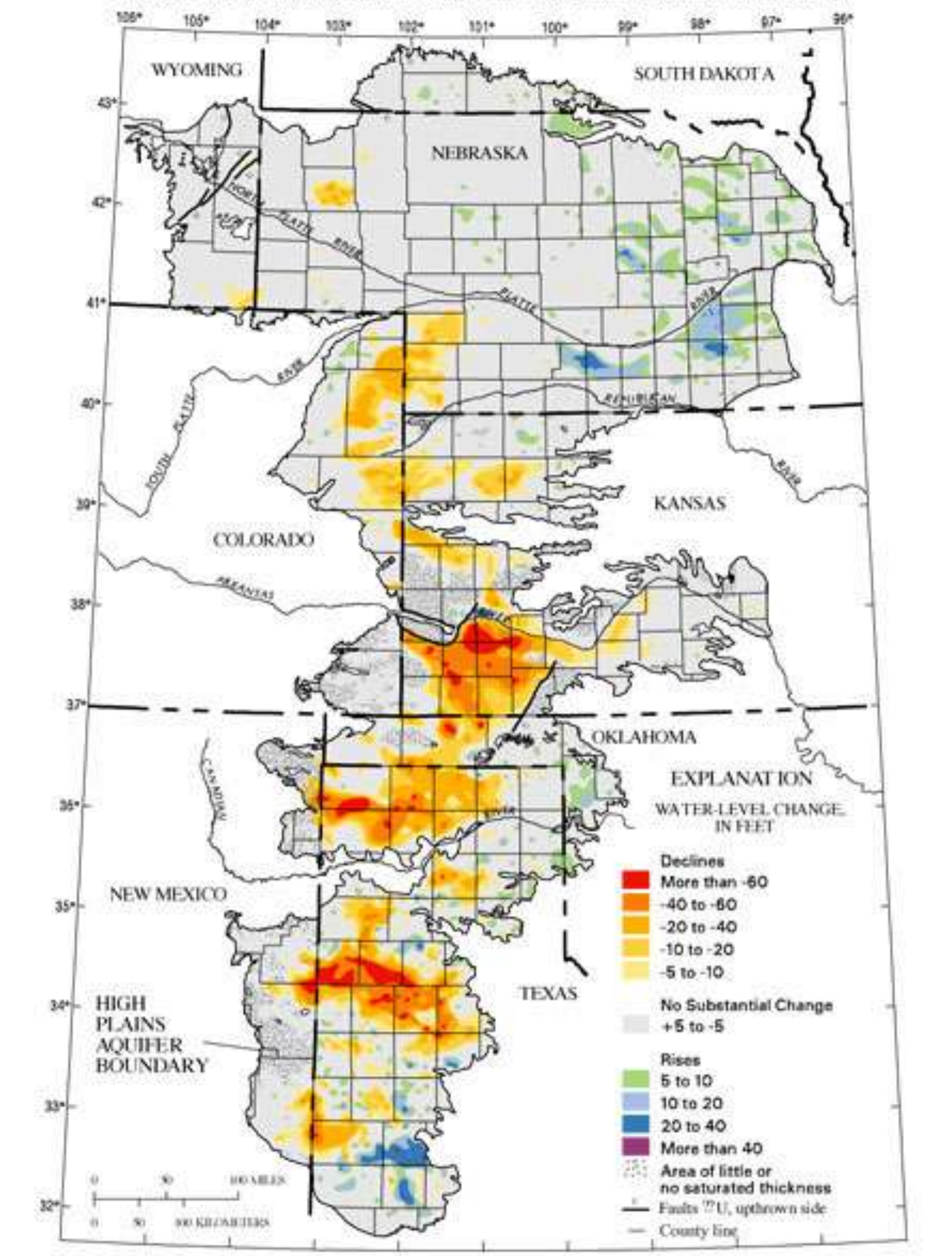
The Ogallala Aquifer

Ogallala Sandstone:

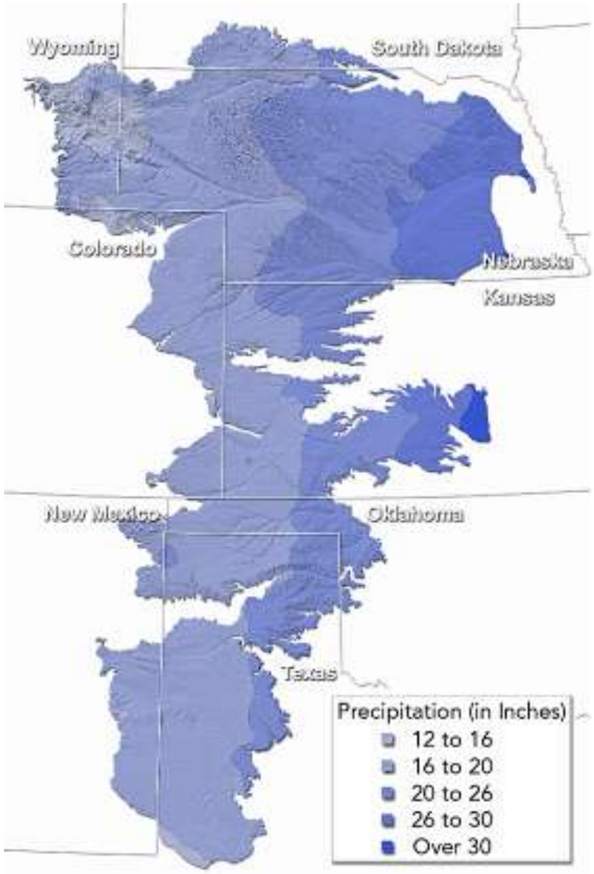
- serves as aquifer to most groundwater underlying the midwest, worth $32 billion/year in food.
- 60-400m thick sandstone derived from Rocky Mountains
- 170,000 wells drilled 1930-1980; 65-95% overdrafts; half of water gone; 1/4 remaining by 2020!
- remedies:

1. more efficient agriculture
2. use treated waste water
3. cloud seeding (but who looses??
4. El Nino!

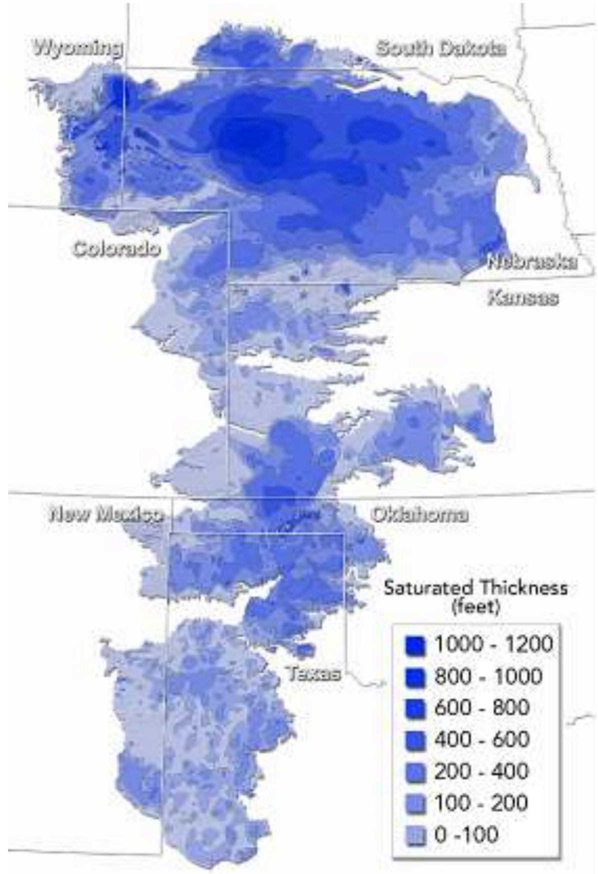
Ogallala Formation aquifer



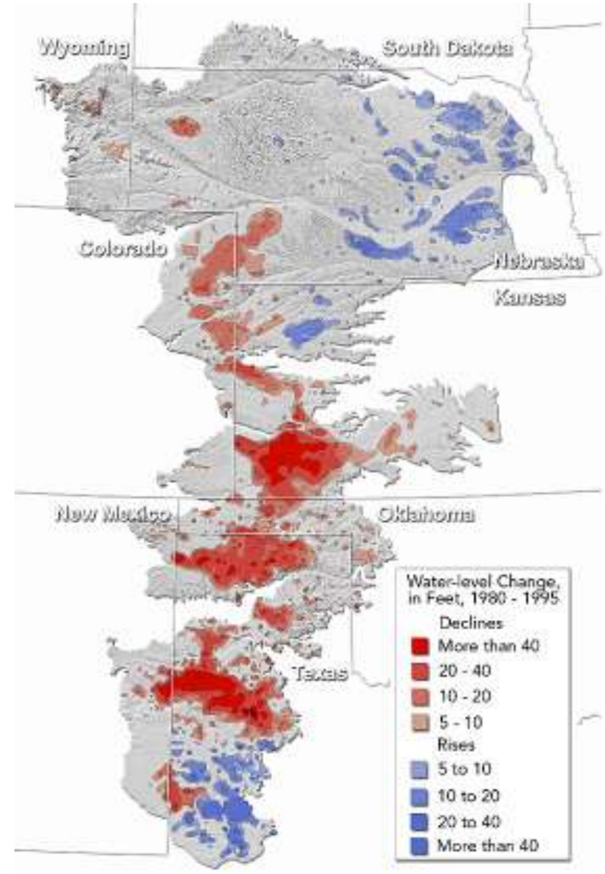
Ogallala Water Supplies and Usage



More rain in east

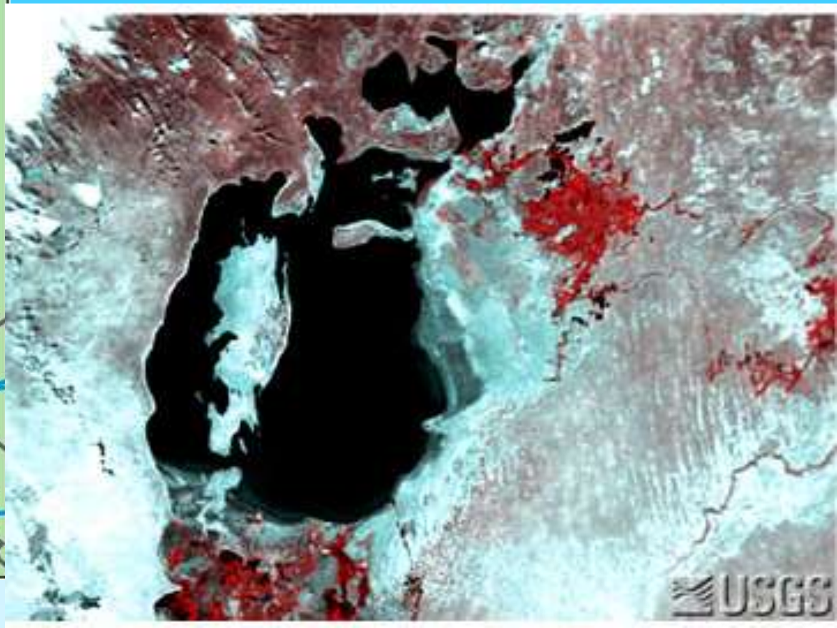


Thickest in north

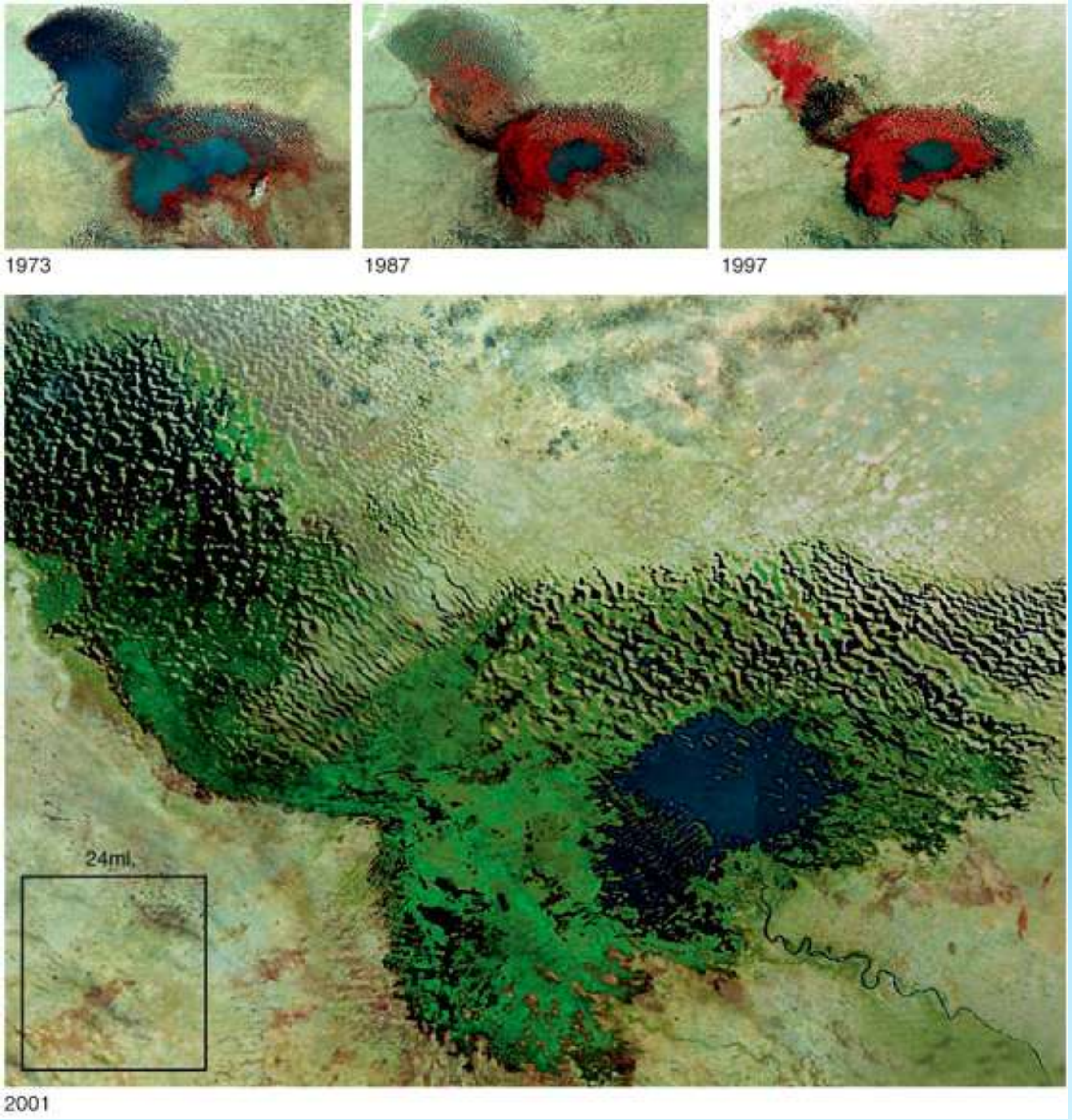


Water table decline greatest in south (Kansas & Texas)

Drying up of Aral Sea



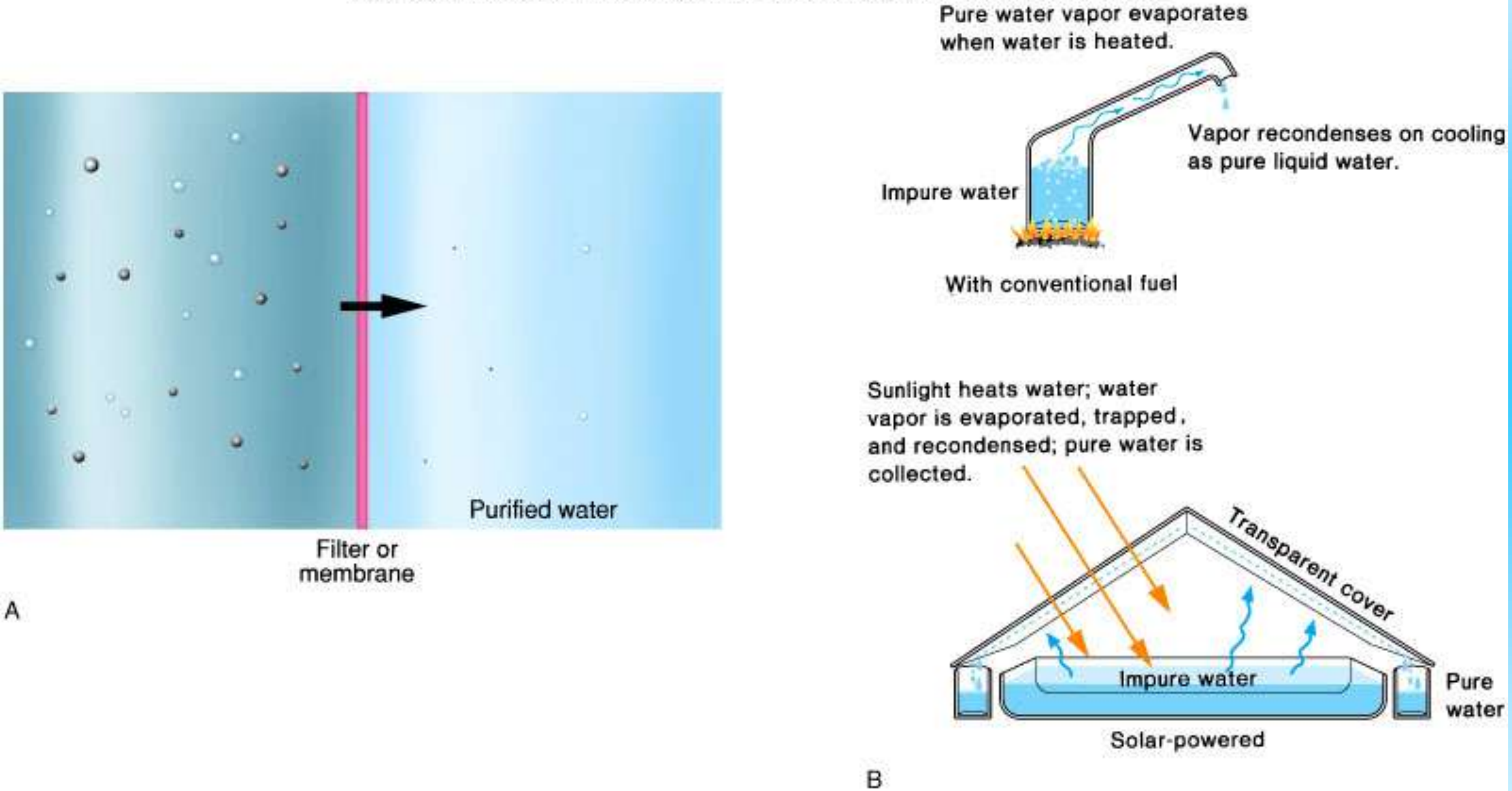
Reduction in size of Aral Sea



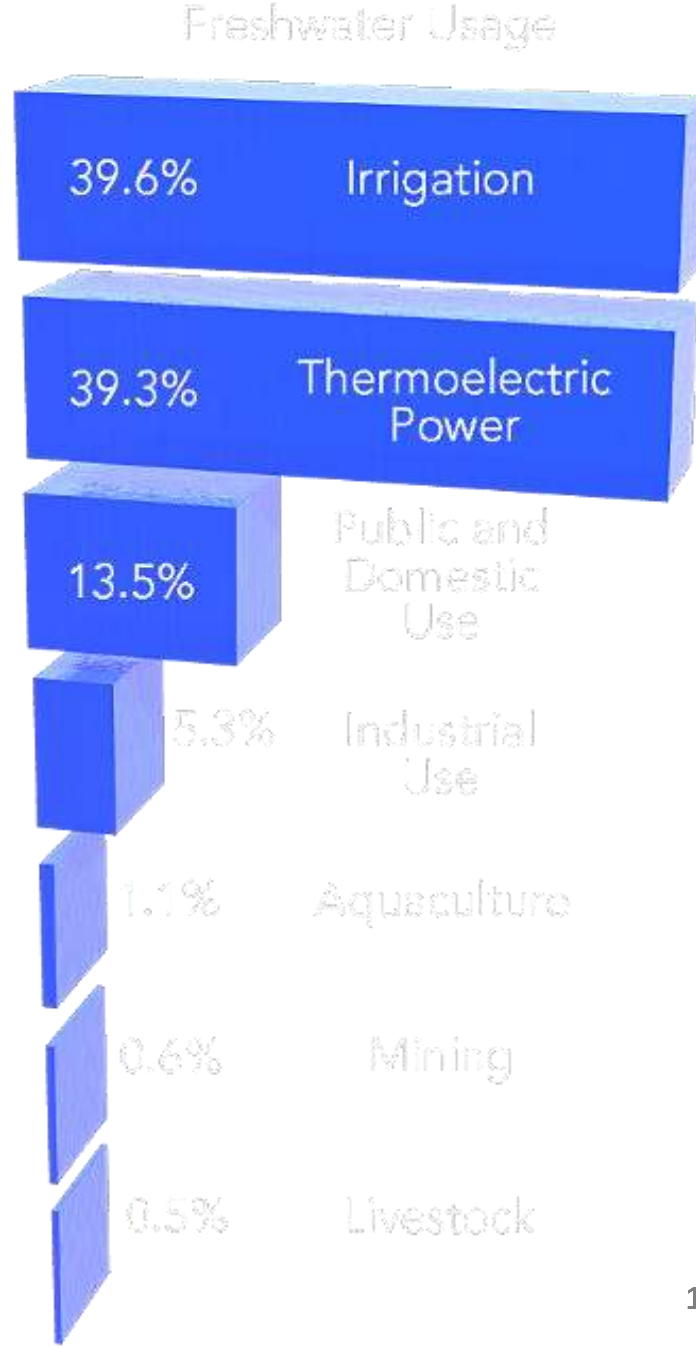
Extending the Water Supply

- Conservation – a must do strategy in U.S.
  - Water is wasted every day in different ways
- Interbasin Water Transfer
  - Conservation alone will not resolve the imbalance between demand and supply
  - Moving surface waters from one stream system’s drainage basin to another’s where demand is higher
- Desalination
  - Improve and purify waters not now used and make them usable

Reverse Osmosis water purification

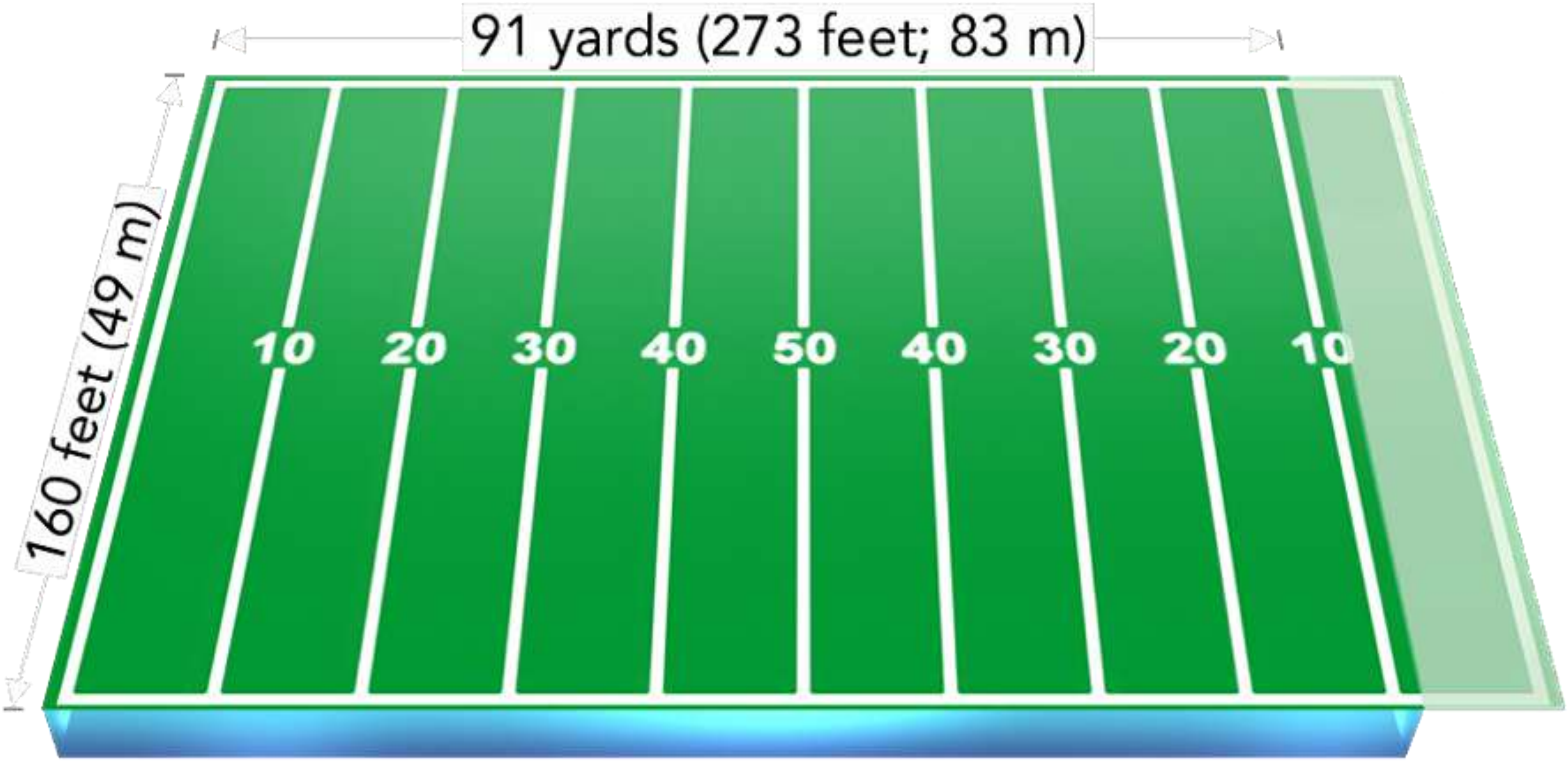


Water Use in U.S.



17.02.a

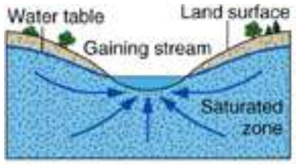
Measuring Volumes of Water

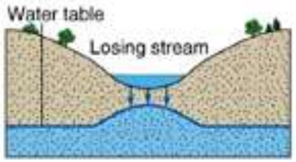


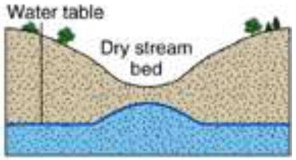
Acre-foot: amount of water to cover one acre (nearly a football field) to a depth of 1 foot

Springs and Streams

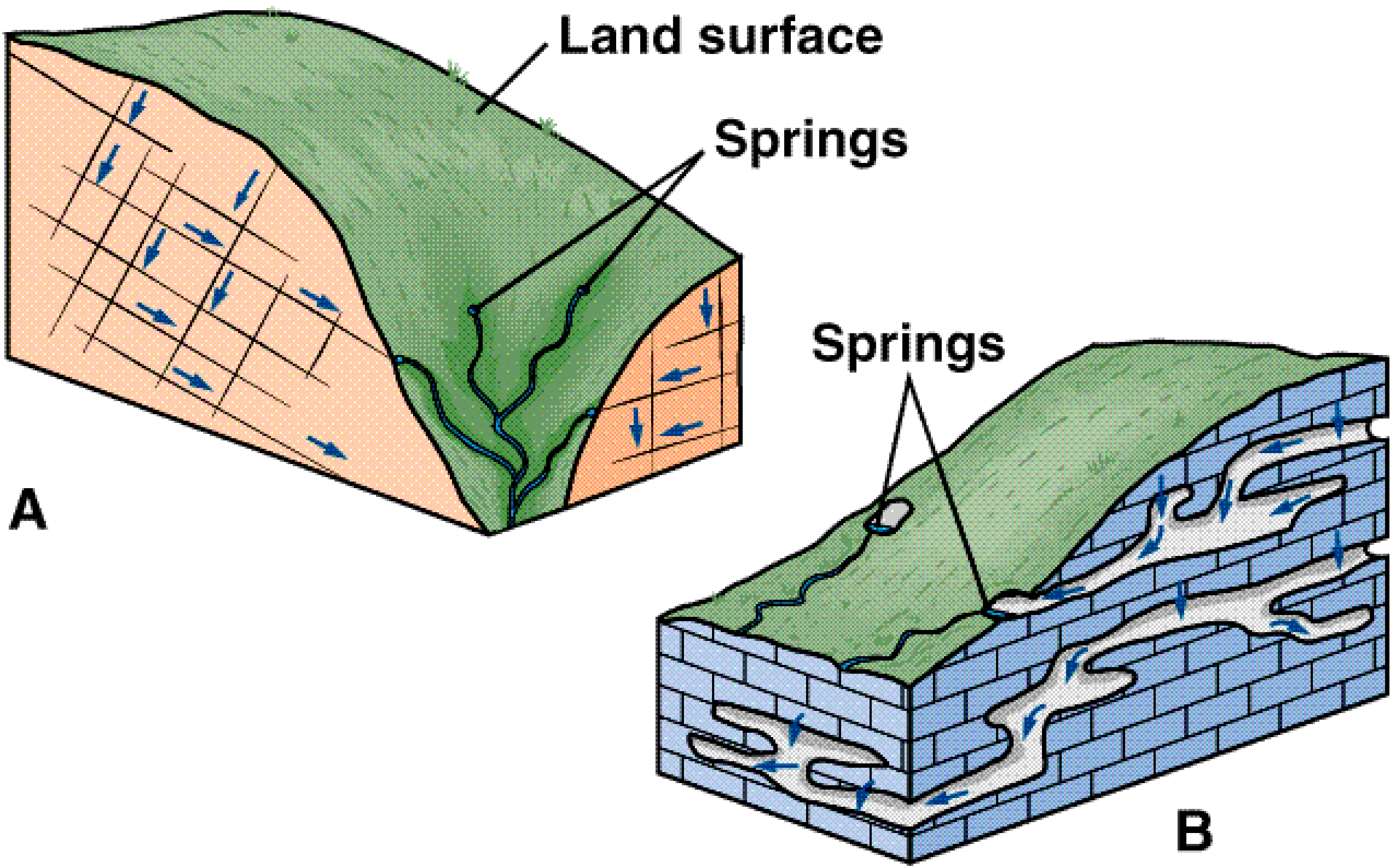
- *Spring* - a place where water flows naturally from the rock or sediment onto the ground surface
- *Gaining streams* - receive water from the saturated zone
  - Top of a gaining stream corresponds with the local water table
- *Losing streams* - lose water to the saturated zone
  - Stream beds lie above the water table
  - Maximum *infiltration* occurs through streambed, producing a permanent "mound" in the water table beneath the dry channel



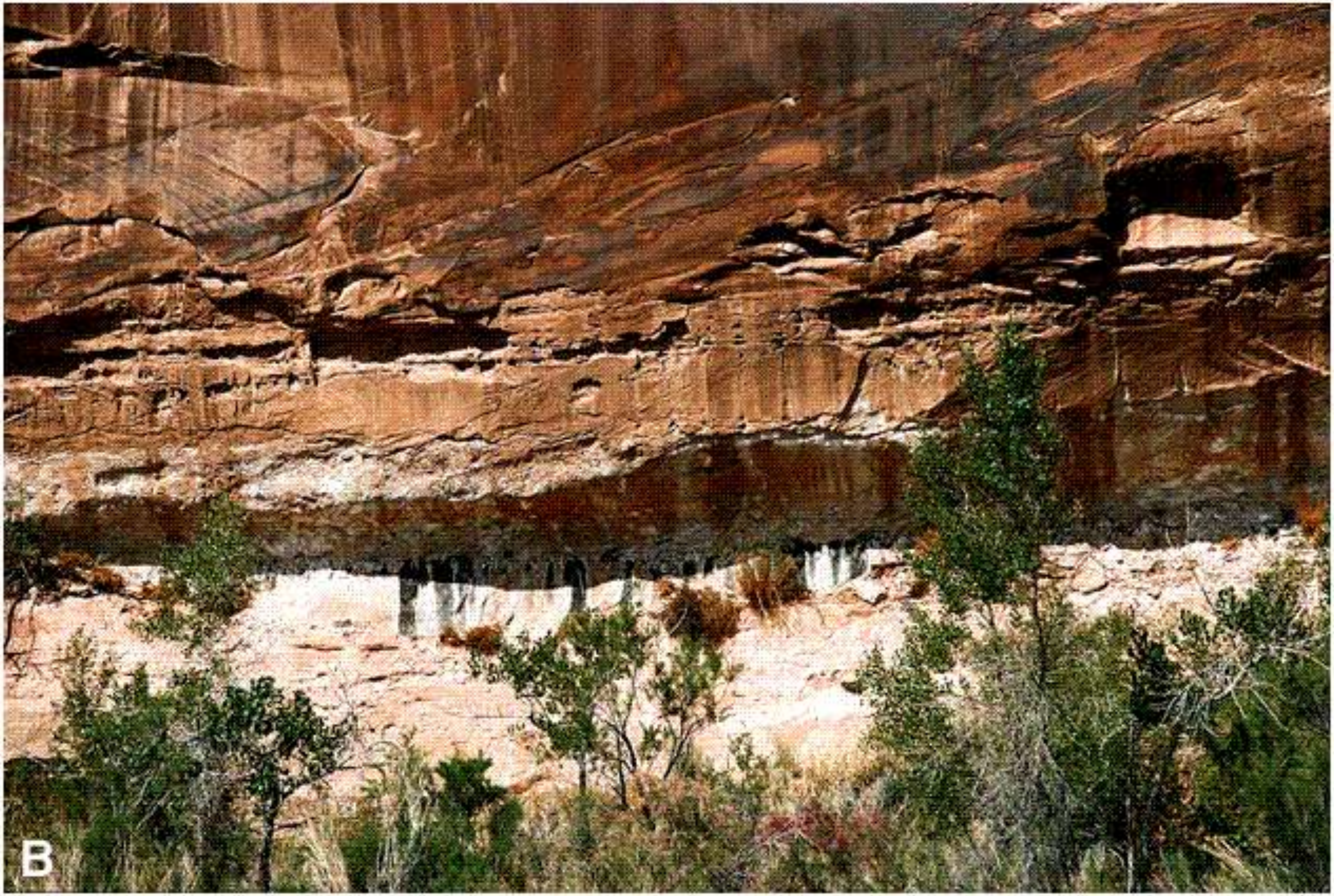


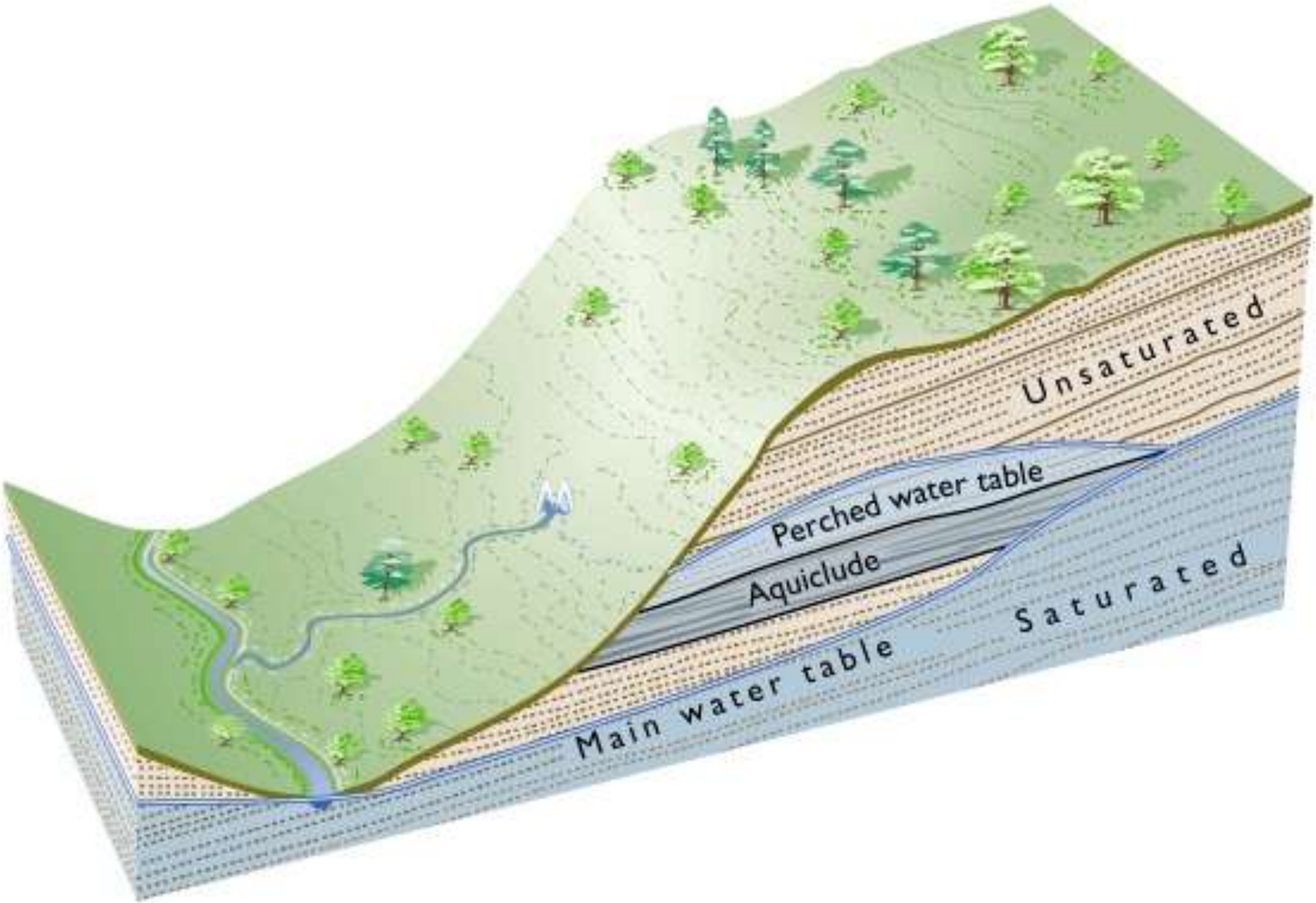


Formation of Springs



Line of Springs




Unsaturated
Perched water table
Aquiclude
Saturated
Main water table

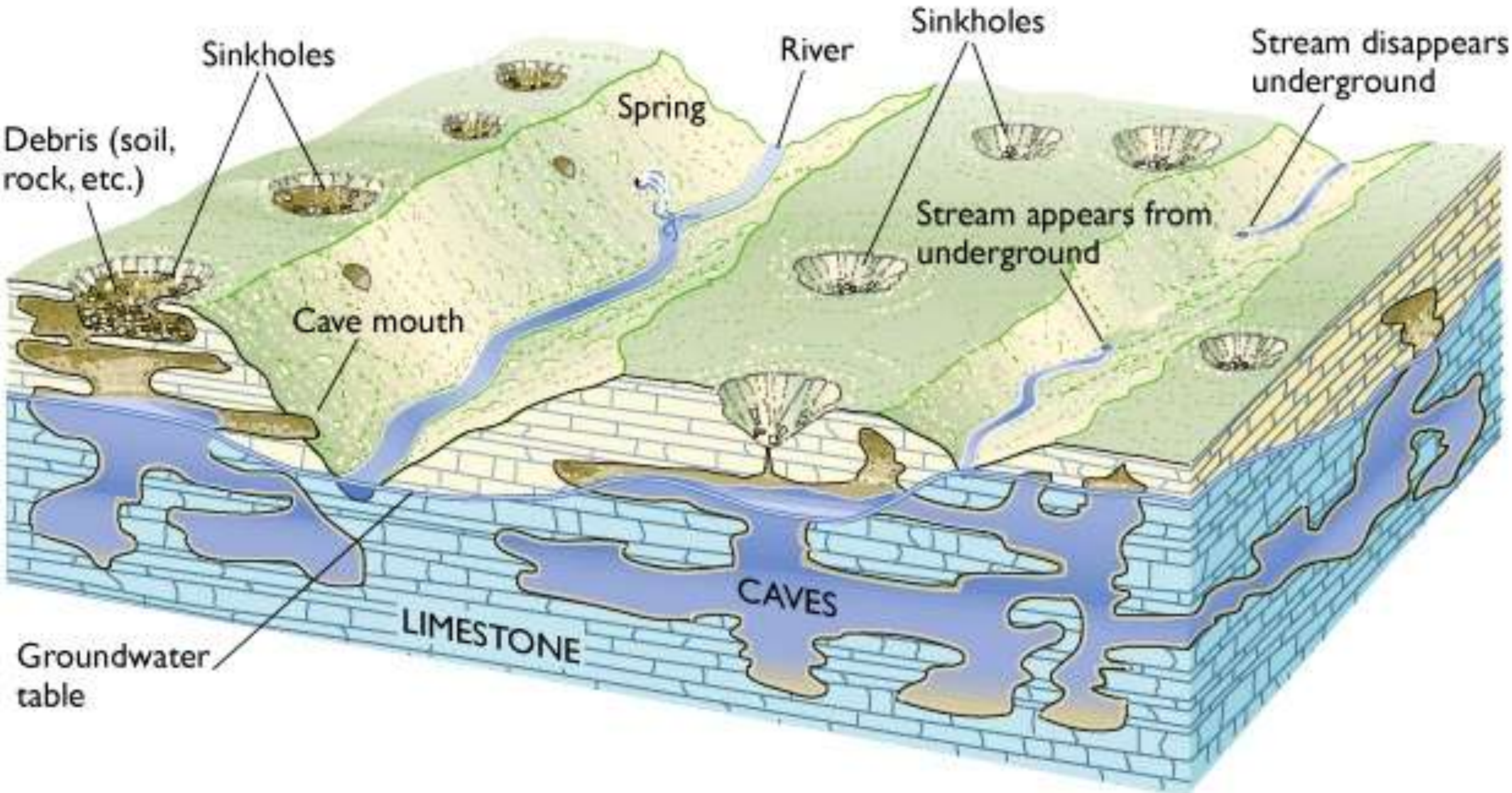
Large Spring, Canada

A

Other Features Involving Subsurface Water

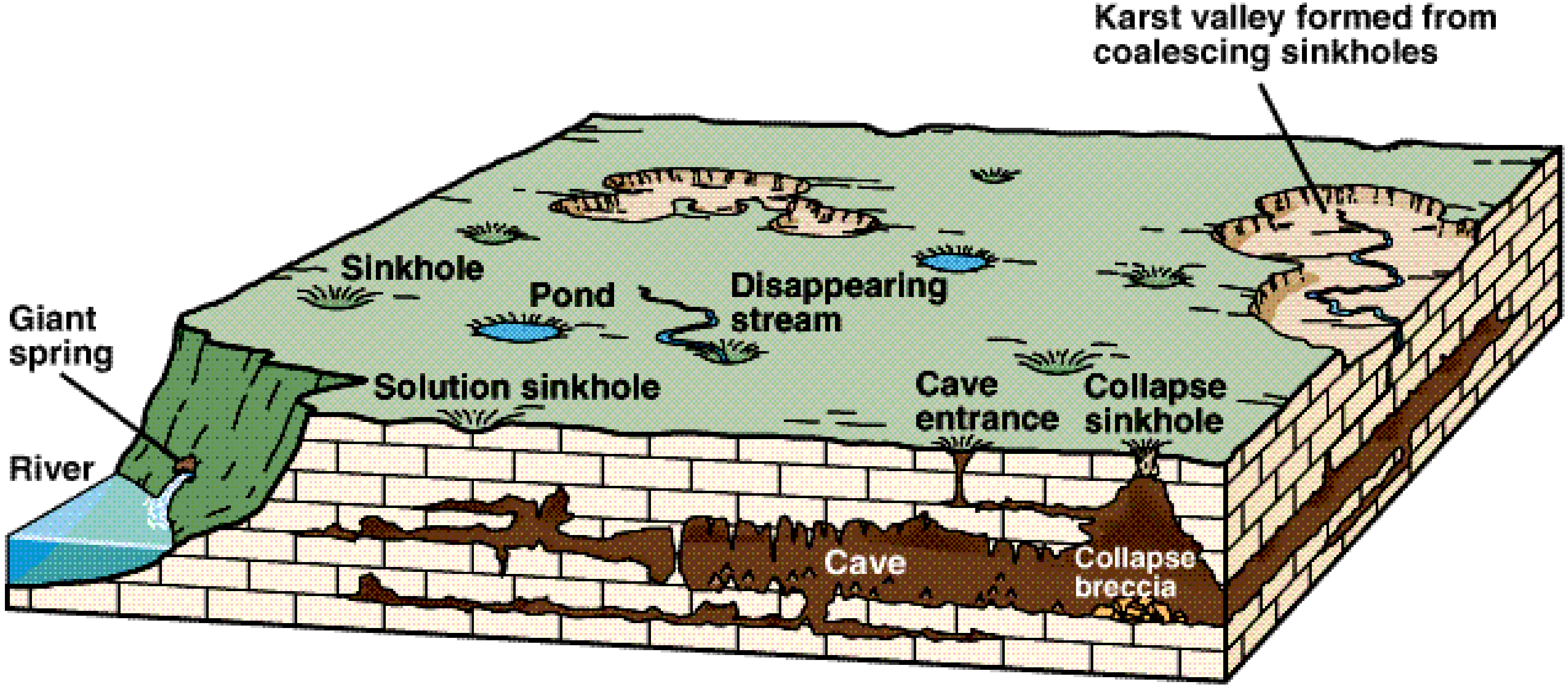
- Ground water may dissolve large volumes of rock (soluble rock)
  - Collapse of the surface rock may result in **sinkholes**
  - Caverns may also be enlarged
- **Karst** is a type of land form associated with many sink holes in soluble bedrock such as limestone, dolomite, or gypsum
  - Water removes the minerals of the rock and carries the ions off in solution
  - Ground water flow rates will increase in karst areas
    - Ground water flows faster without sediments and rock in the flow path
    - Pollutants move faster through ground water systems in karst areas

Fluid flow in carbonate bedrock (karst)



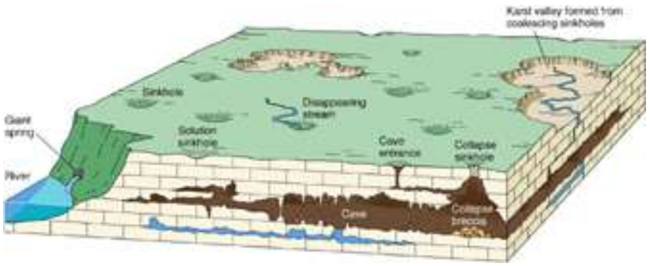
Vasey's Paradise
Grand Canyon –
from caves in the
Redwall
Limestone

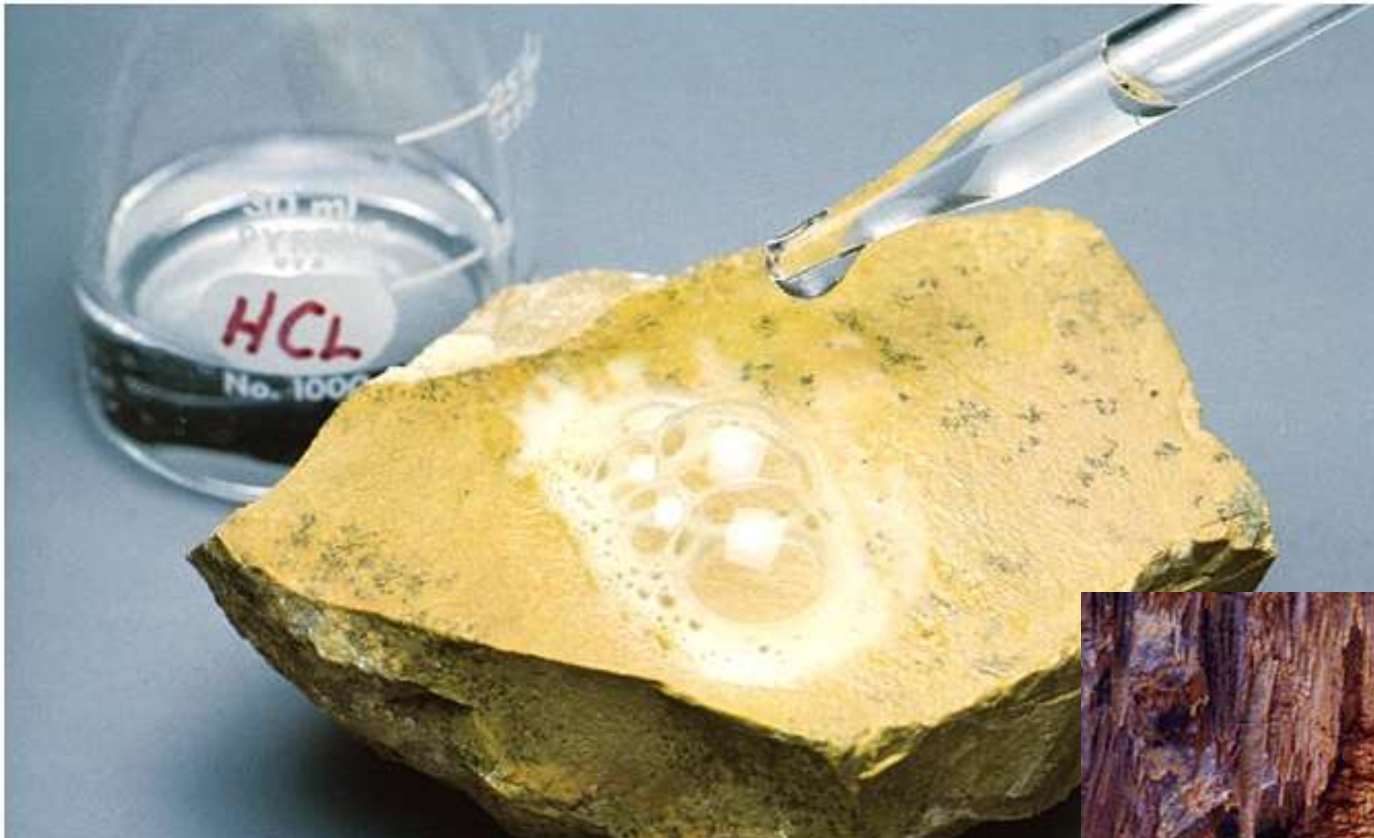
Karst Topography

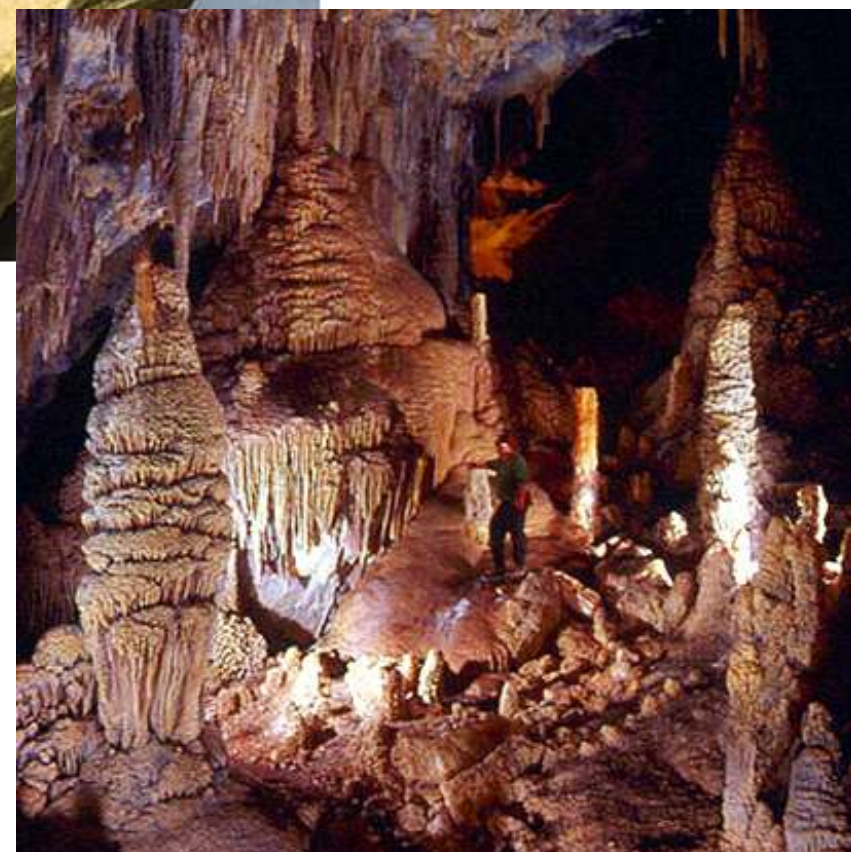


Caves, Sinkholes, and Karst

- *Caves* - naturally-formed underground chambers
  - Usually formed when slightly acidic groundwater dissolves limestone along joints and bedding planes
- When caves near the surface collapse, often due to drawdown of the local water table, the resulting crater at the surface is known as a *sinkhole*
- When rolling hills, disappearing streams, and sinkholes are common in an area, the resulting landscape is known as *karst topography*

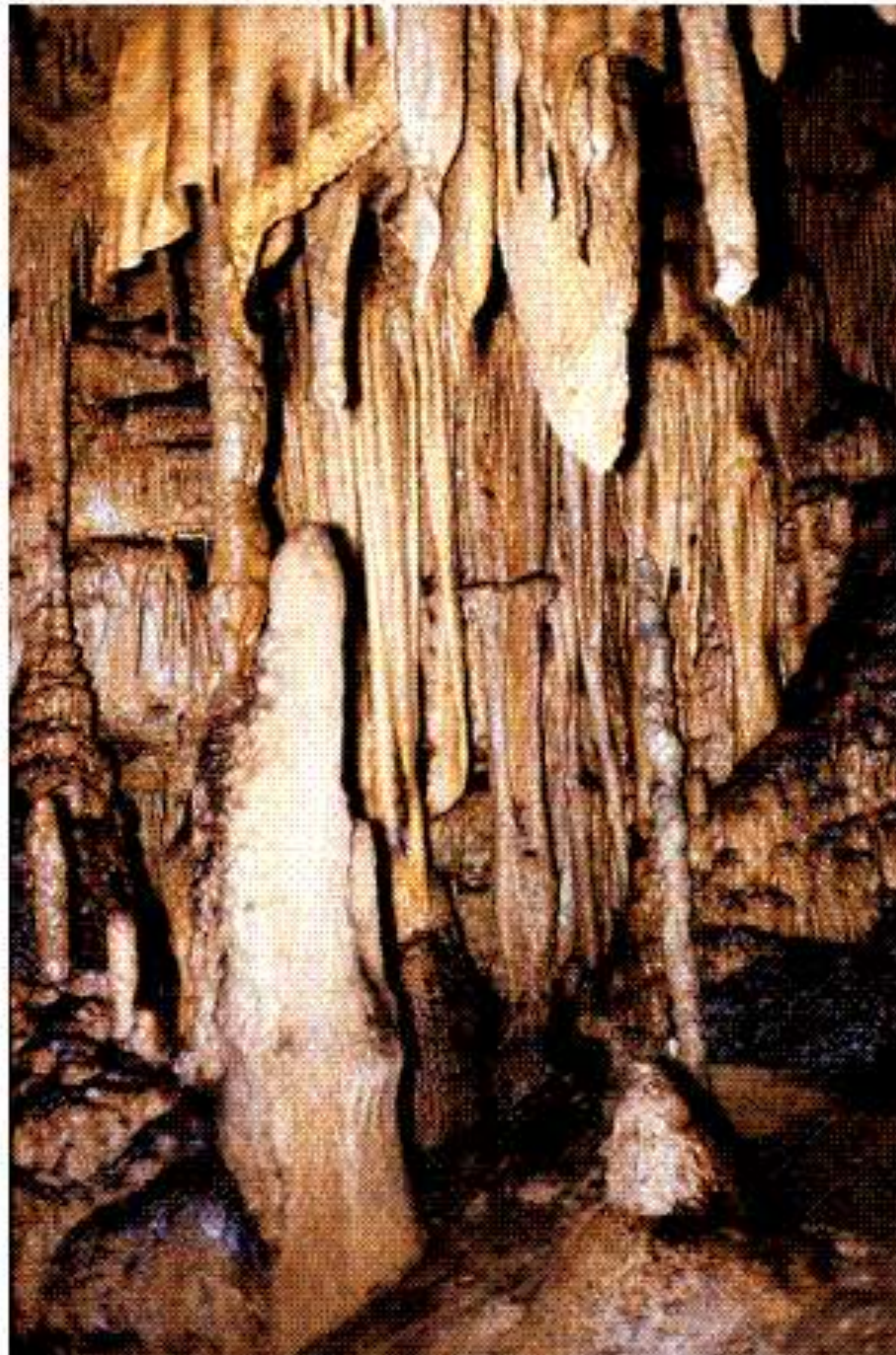




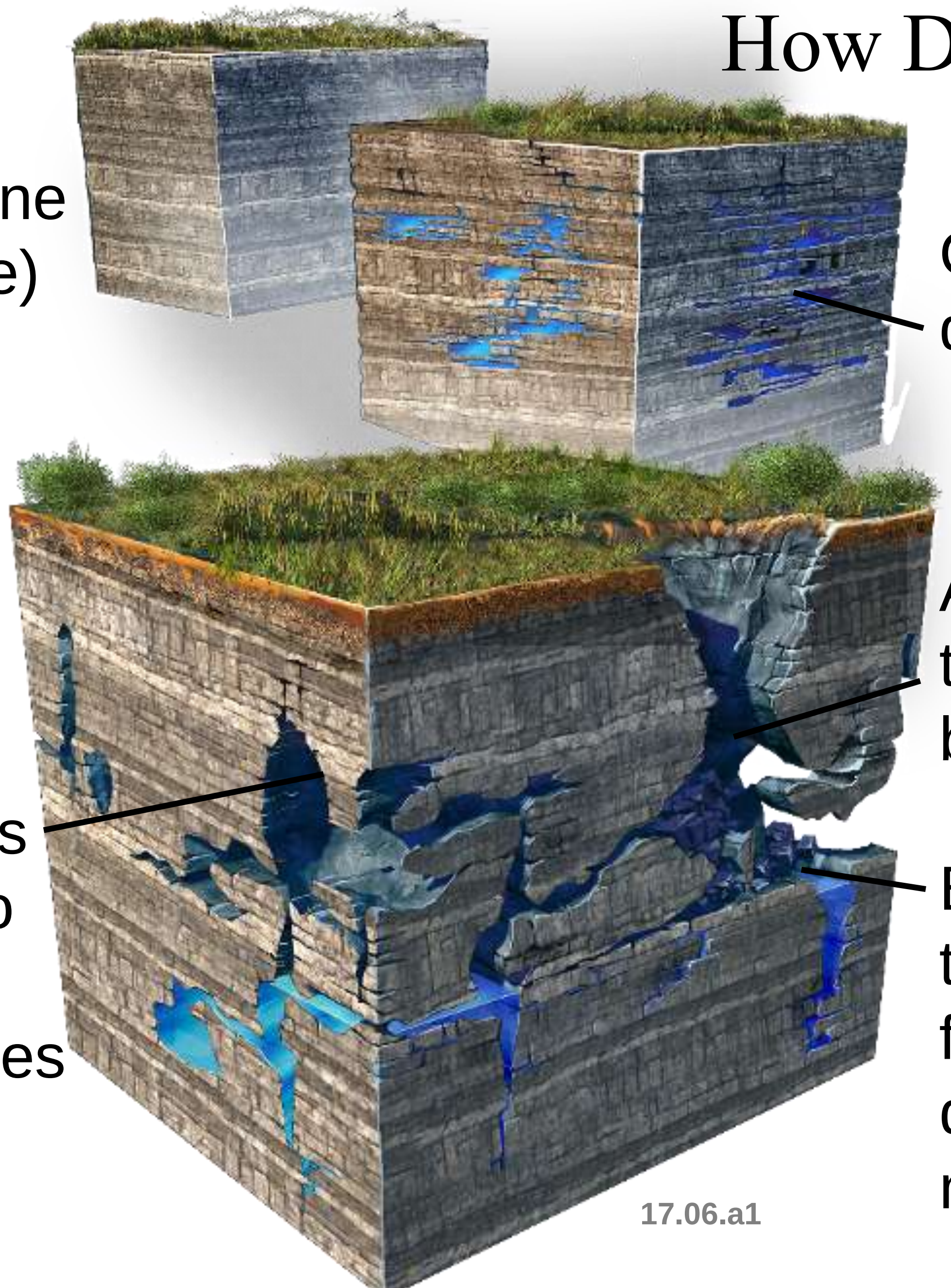


$$CaCO_3 + 2H^+$$
$$=$$
$$Ca^{+2} + H_2O + CO_2$$

Stalactites, Stalagmites and Flowstone



How Do Caves Form?



What Features Accompany Caves?

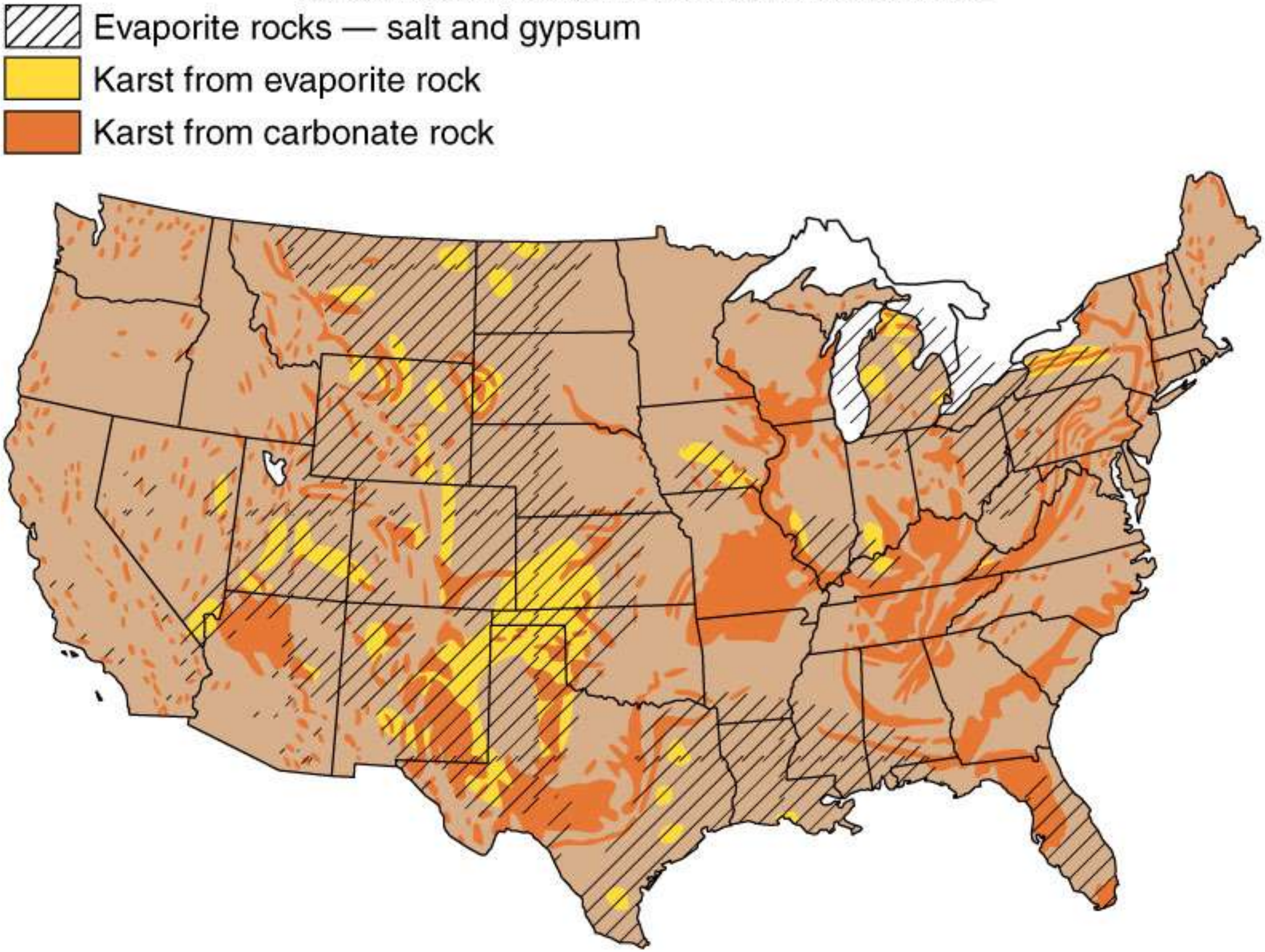
Roof collapse can form sinkhole on surface

Dripping water evaporates, precipitates calcite

Cave formations on roof, floor, and walls

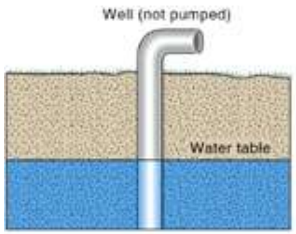
Surface with sinkholes, limestone pillars, disappearing streams = *karst topography*

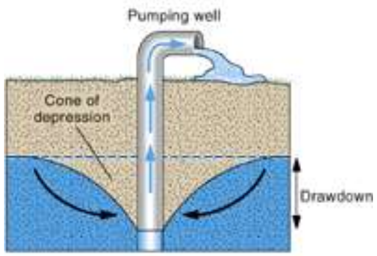
Karst areas in US



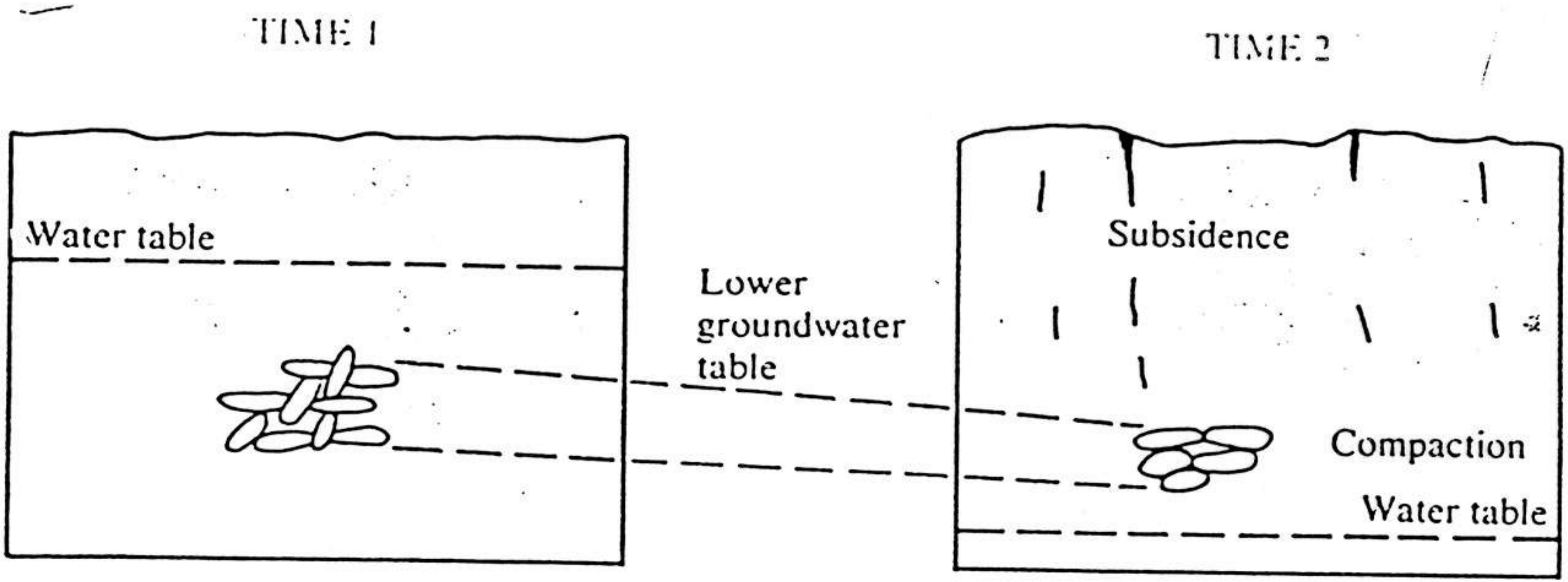
Balancing Withdrawal and Recharge

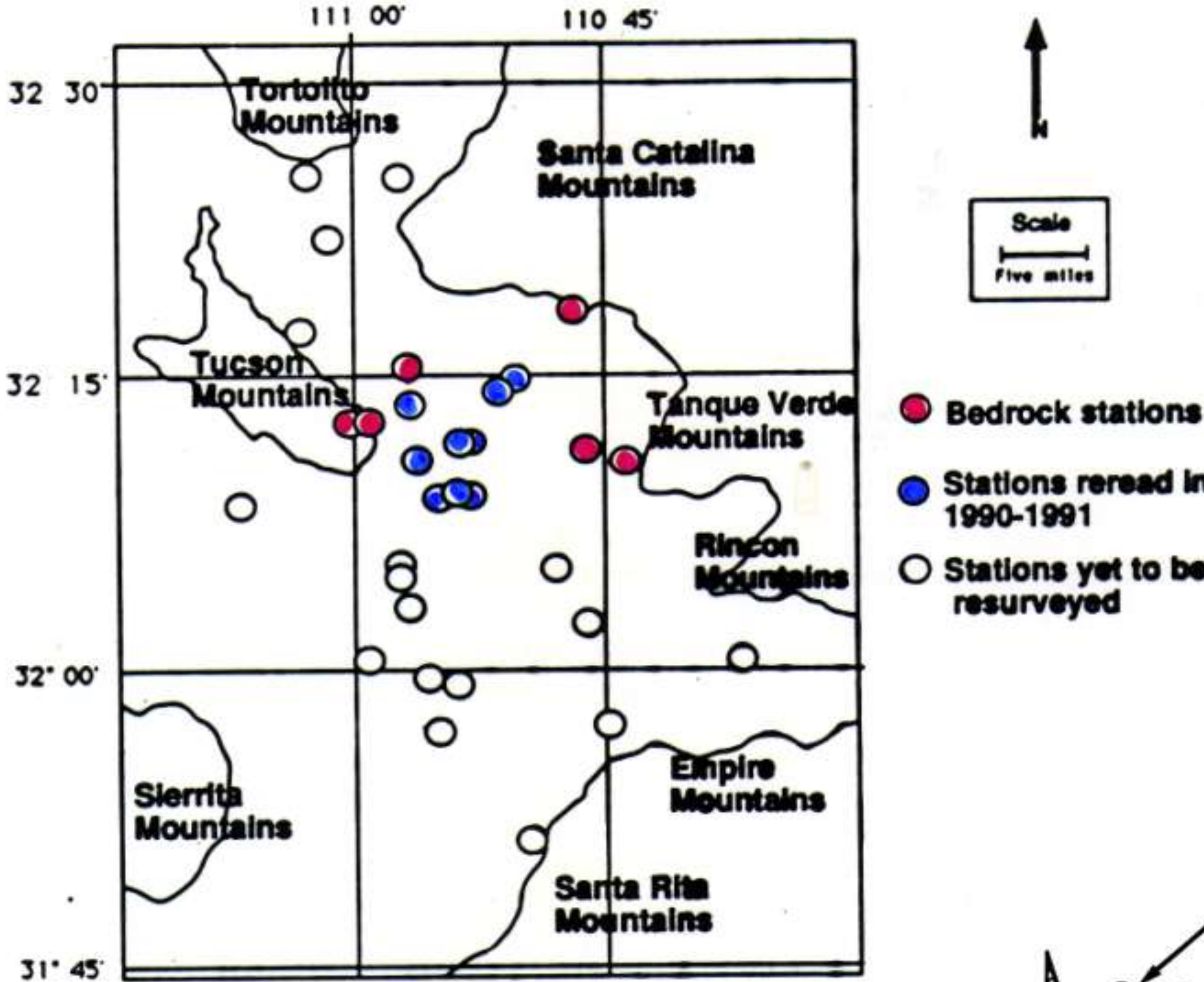
- If groundwater is withdrawn more rapidly than it is recharged, the *water table* will drop
  - Dropping water table can lead to ground *subsidence*, where the surface of the ground drops as the buoyancy from groundwater is slowly removed, allowing rock or sediment to compact and sink
  - Subsidence can crack foundations, roads and pipelines
  - Areas of extremely high *groundwater pumping* (such as for crop irrigation in dry regions) have subsided as much as 7-9 meters over several decades





Compaction and subsidence — an irreversible process





Tucson Subsidence

a) 0.027 - 0.054 m/yr (1-2 inches)

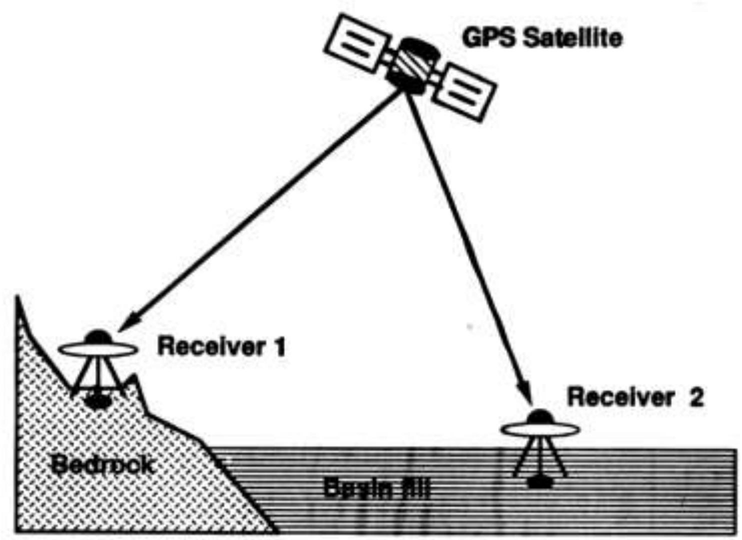
∴ 30 years = 1 meter

b) will continue until aquifers refilled

Phoenix

– up to 5' in places

– several feet common.



Typical setup for Differential GPS
Survey to get centimeter accuracy

Subsidence in clastic sediments

FIELDNOTES

From The Arizona Bureau Of Geology And Mineral Technology

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A VIEW OF SUBSIDENCE

by Carl C. Winikka
Assistant State Engineer
Arizona Department of Transportation

Figure 1. Giant earth fissure near Chandler Heights, Arizona. Earth fissures begin as tiny cracks, but become enlarged by water erosion and collapse of adjacent soils. This fissure is related to subsidence due to ground-water withdrawal. Photo taken on October 21, 1983 by Larry D. Fellows.

INTRODUCTION

Subsidence, the gradual settling or sinking of the earth's surface, is occurring in many areas of Arizona as a result of declining ground-water levels. Rates of subsidence have exceeded 0.6 foot per year and earth fissures, or cracks in the earth's surface, are proliferating (Figures 1, 2, and 3). In some areas, the total amount of subsidence has increased from 12.5 feet, measured in 1977, to about 16 feet.

Subsidence can be caused by natural geologic processes or by man's activities, such as the removal of subsurface fluids. In Arizona, subsidence is mostly due to large-scale withdrawal of ground water from subsurface reservoirs. The fluid pressure of ground water partially supports the material above. As the water is pumped out, that support is lost, causing compaction of the grains of earth material and lowering, or subsidence, of the earth's crust.

Earth fissures usually form around the margins of subsiding areas and may be related to distribution and thickness of basin-fill sands and gravels, buried bedrock topography, or other factors. It is not possible to predict specifically where fissures will form. It may be possible, however, to identify zones where fissures *might* form.

Land-elevation changes caused by subsidence can be determined by repeated, precise, survey leveling to fixed reference points or bench marks. Bench marks are usually brass caps encased in concrete and set a few inches above the ground surface. Precise surveys determine elevations of bench marks within the subsiding area by comparing them with stable bench marks set in bedrock *near* the subsiding area. Reference bench marks must remain stable to provide an accurate, common base for all measurements; therefore, they are located in bedrock.

Problems related to subsidence, especially differential subsidence and the formation of earth fissures, have been known for years. The issue itself is complex; numerous papers have been published to explain causes, identify problems, and offer solutions. A list of papers that describe specific subsidence areas and problems in Arizona is included at the end of this article.

It is not the purpose of this article to summarize or describe the extent of subsidence throughout Arizona, although a plan for monitoring subsidence in the State is discussed. This article does, however, describe the results of the National Geodetic Survey (NGS) precise leveling conducted in the Phoenix metropolitan area from 1980 through 1981 (Winikka, 1981). It also identifies subsidence areas and discusses uses of the NGS level datum.

THE PHOENIX AREA

The NGS Level Line

The 1980-81 NGS retracement of the 1967 NGS level line in Arizona was done as a segment of the current network of NGS transcontinental leveling, which extends through all States from coast to coast. In the Phoenix area, where several subsidence areas were crossed, numerous new bench marks were established in bedrock to preserve the precise leveling results. Consequently, more convenient stable elevations are now available to all users, particularly those who measure or monitor subsidence. The 1980-81 NGS leveling identified and measured subsidence that had occurred since 1967.

Tucson basin

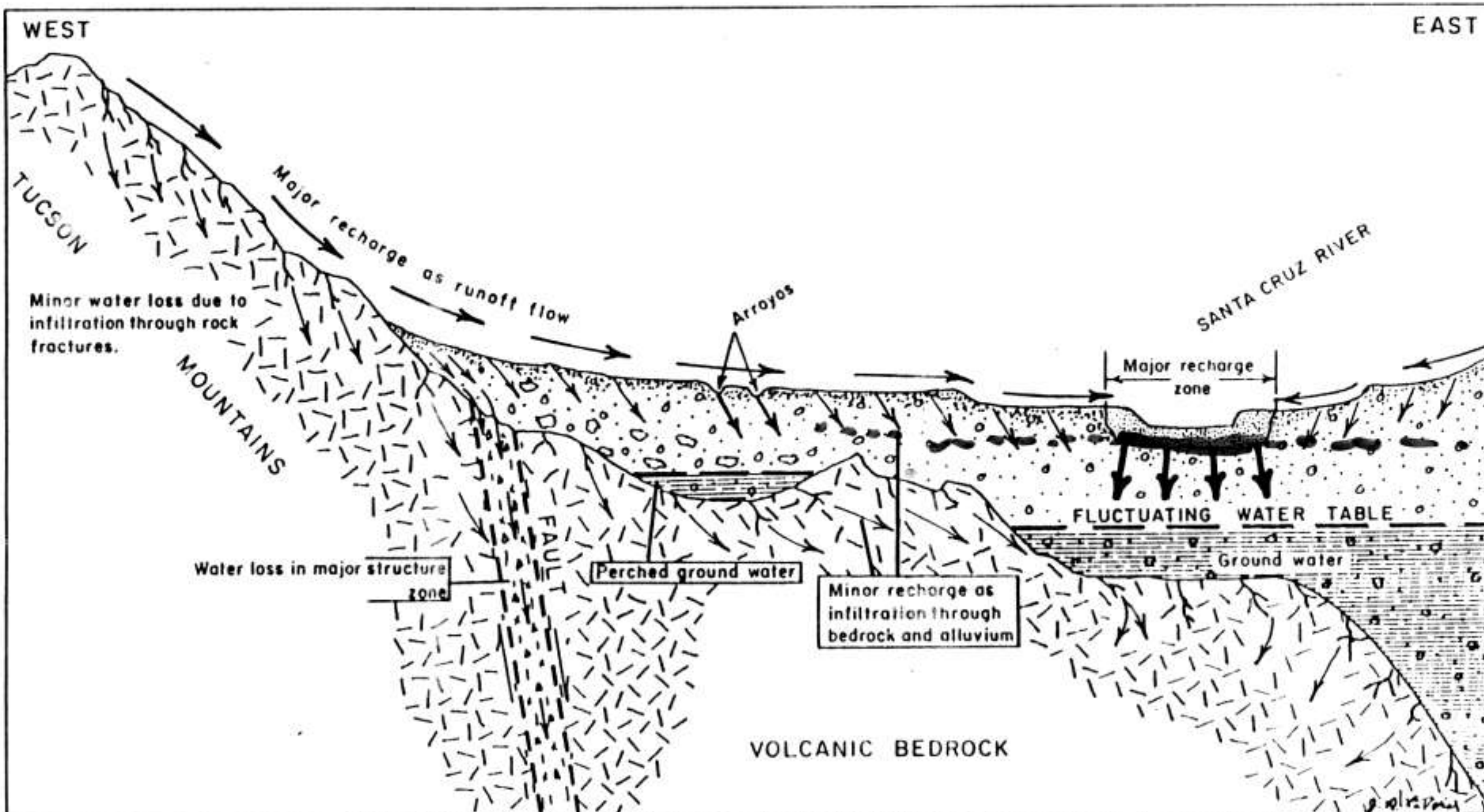
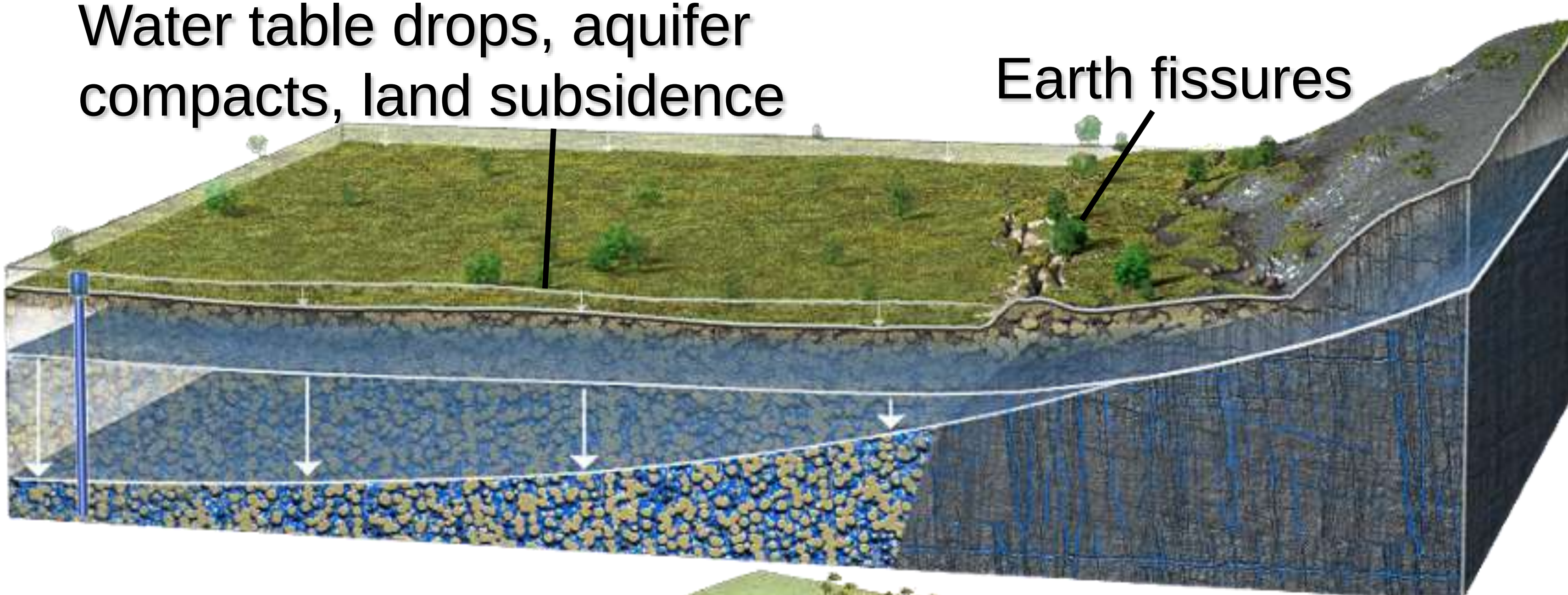
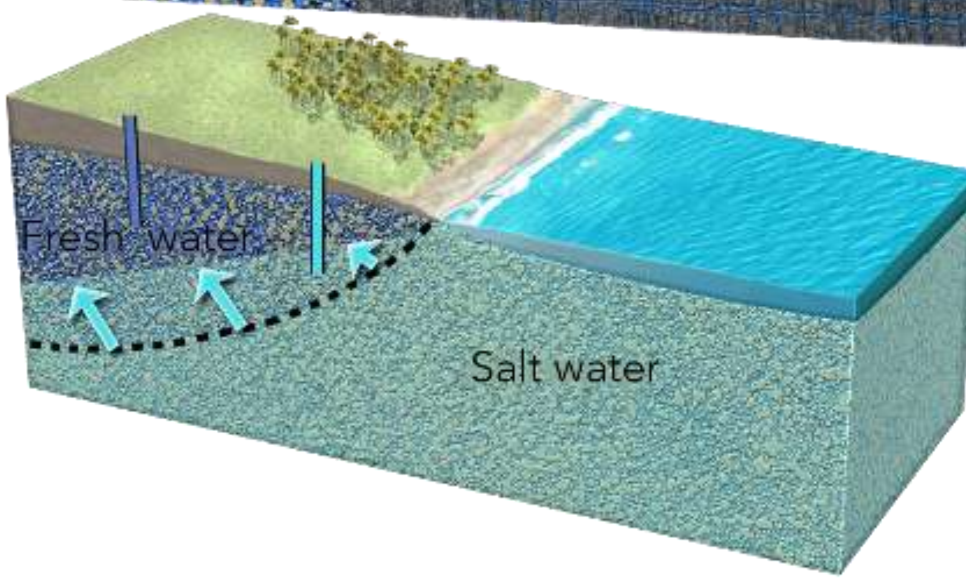


Fig GEOLOGIC FACTORS THAT INFLUENCE THE AMOUNT OF RUNOFF REACHING GROUND RECHARGE ZONES.

Other Problems of Overpumping



Along coast: freshwater floats on saltwater, so draw in saltwater

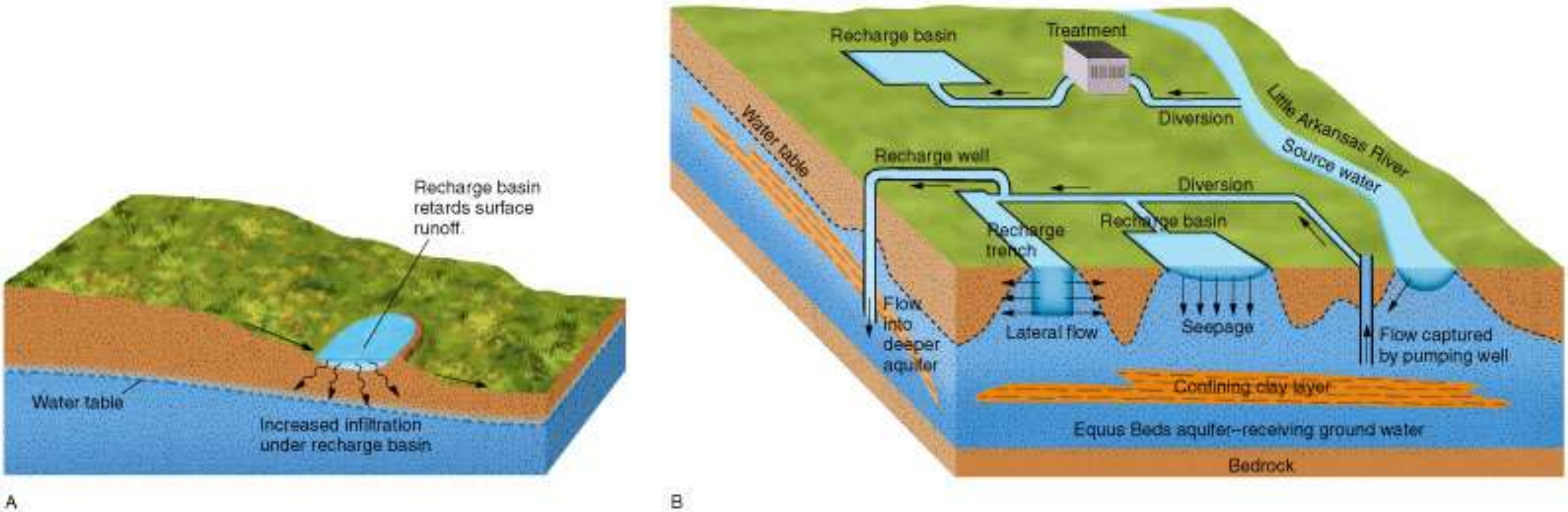


17.08.b

Other Impacts of Urbanization on Groundwater Systems

- An increase in people in an area may cause ground water supplies to be exhausted or **loss of recharge** to occur
  - Pavement and parking lots reduce the effectiveness of water infiltrating into ground water
  - Building on wetlands reduces recharge, water storage, and water quality
- Ground water recharge can be enhanced by incorporating various artificial recharge strategies
  - Build artificial recharge basins
  - Employ any method to slow down run off and increases surface water infiltration

Recharge basins



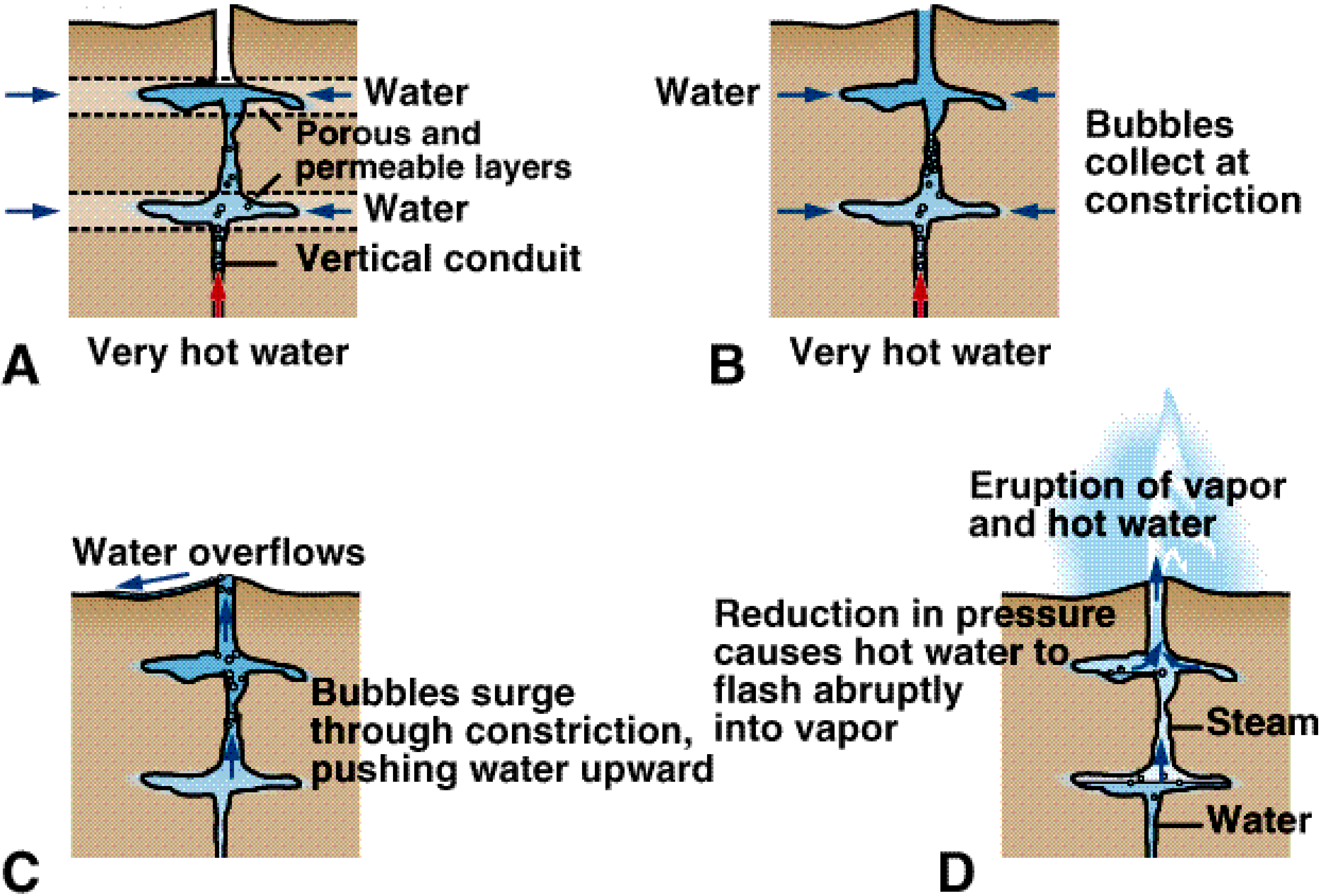
Hot Water Underground

- Hot springs
  - Near magma or cooling igneous rocks
  - Deep-circulating groundwater or
- Geyser
- Precipitation of dissolved ions
  - Travertine- calcite
  - Sinter- silica
- Mudpot
- Geothermal Energy

Hot Water Underground

- *Hot springs* - springs in which the water is warmer than human body temperature
  - Groundwater can be heated by nearby magma bodies or circulation to unusually deep (and warm) levels within the crust
  - Hot water is less dense than cool water and thus rises back to the surface on its own
- *Geysers* - a hot spring that periodically erupts hot water and steam
  - Minerals often precipitate around geysers, as the hot water can contain many more dissolved ions than cooler water
  - As the hot water cools in the air, minerals are precipitated rapidly

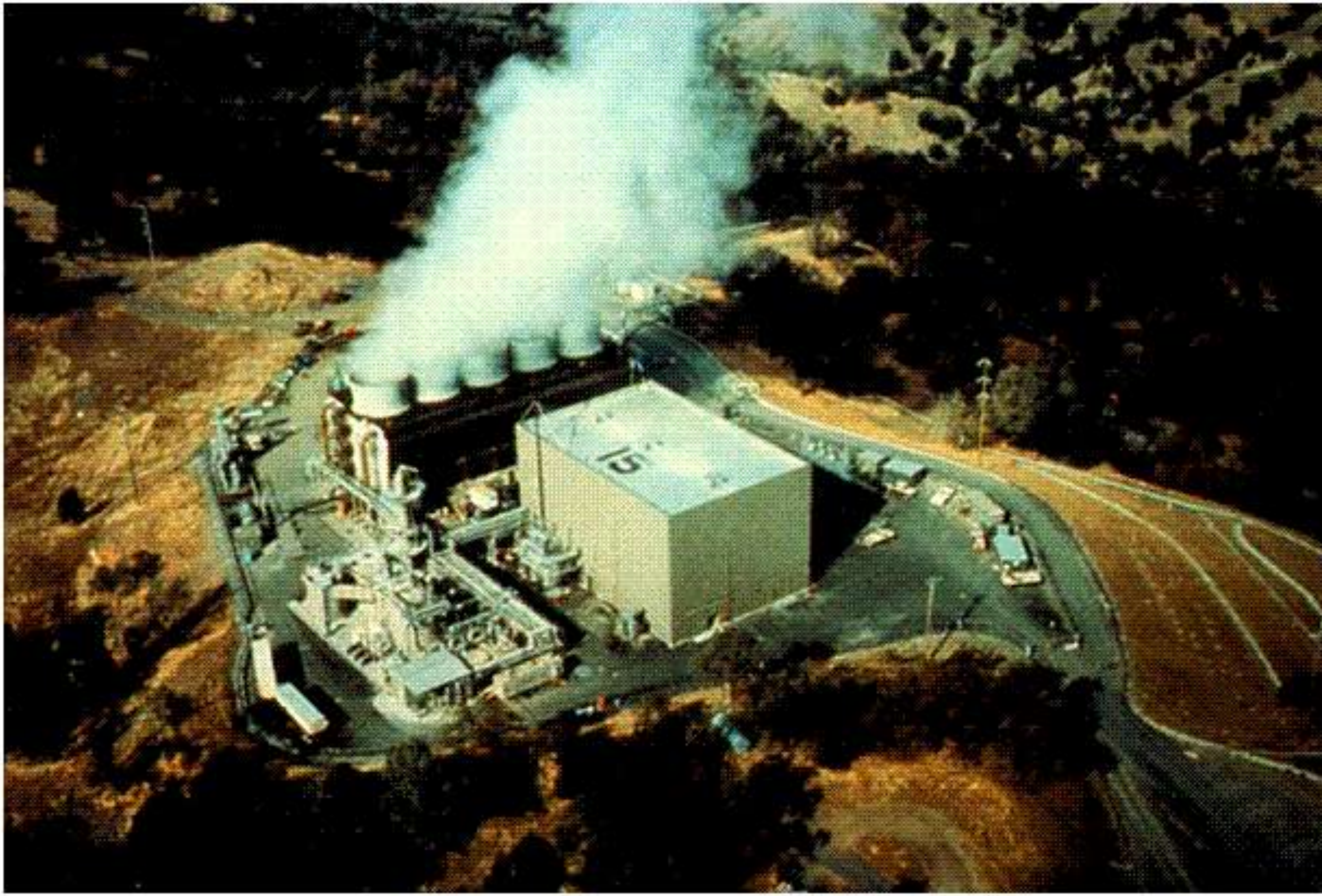
Hot Spring Formation



Geothermal Energy

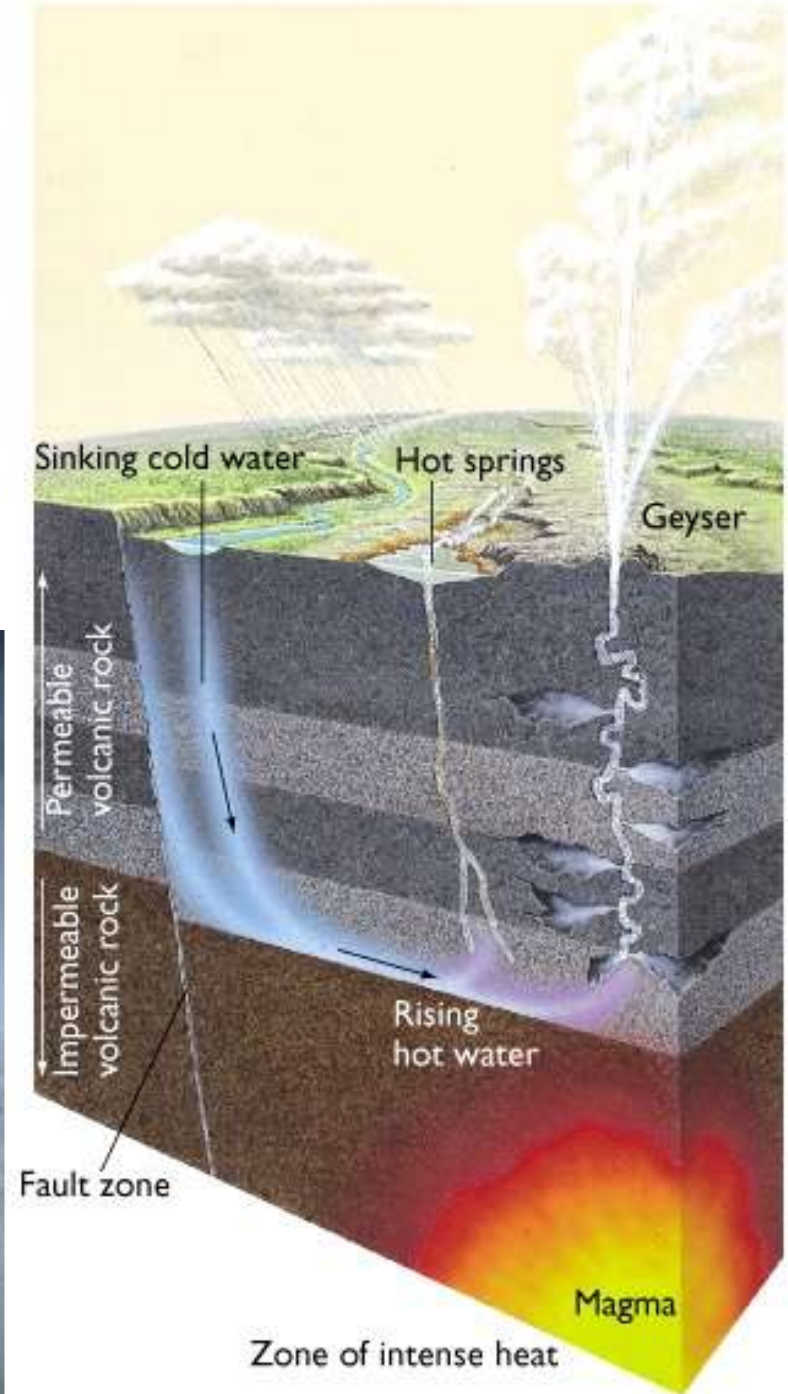
- Energy produced by harnessing natural steam or superheated water (than can be converted to steam) to produce electricity is known as *geothermal energy*
  - No fossil fuel burning needed, such that no CO_2 or acid rain are produced (*clean* energy source)
  - Some toxic gases given off (esp. sulfur compounds)
  - Superheated water can be quite corrosive to pipes and equipment
  - Can be used directly to heat buildings

Geothermal Power Plant



Geothermal fluid flow

- Driven by magmatism, metamorphism, and deformation in many settings



Travertine Terraces

Geodes

Concretions Weathered from Shale

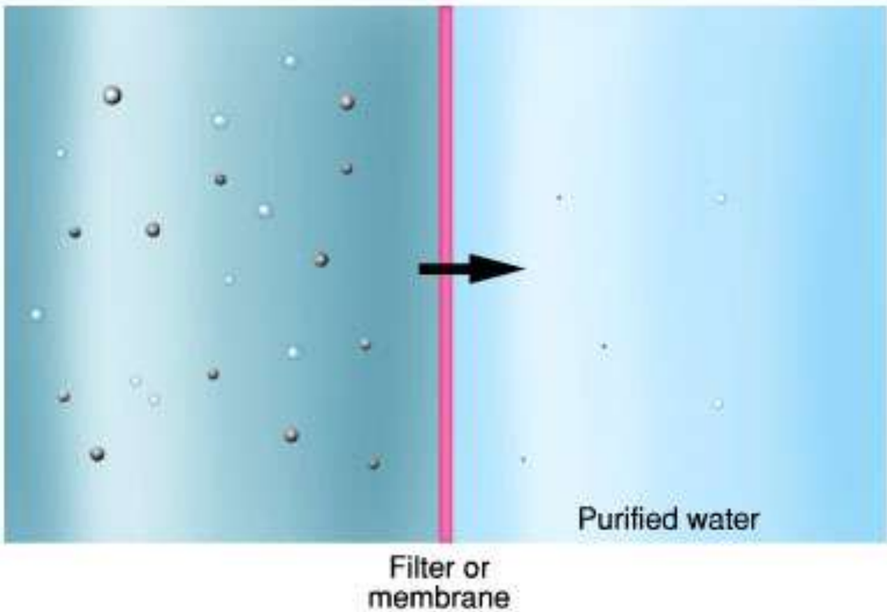
Extending the Water Supply

- Conservation – a must do strategy in U.S.
  - Water is wasted every day in different ways
- Interbasin Water Transfer
  - Conservation alone will not resolve the imbalance between demand and supply
  - Moving surface waters from one stream system's drainage basin to another's where demand is higher
- Desalination
  - Improve and purify waters not now used and make them usable

Water Quality

- Measures for expressing Water Quality
  - Parts per million (ppm)
  - Parts per billion (ppb)
  - Total Dissolved Solids (TDS)
    - The sum of dissolved solid chemicals in the water
    - It is important to know what chemicals are dissolved!
  - **Hard Water** contains substantial amounts of calcium and magnesium
    - Greater than 80 to 100 ppm

Reverse osmosis water purification



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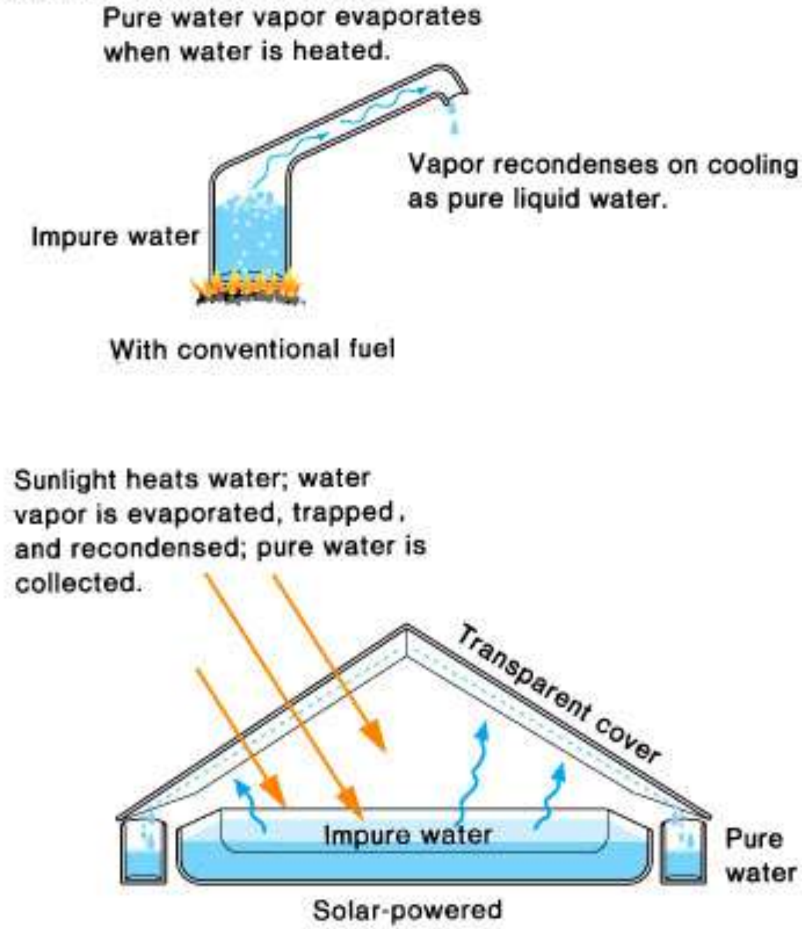
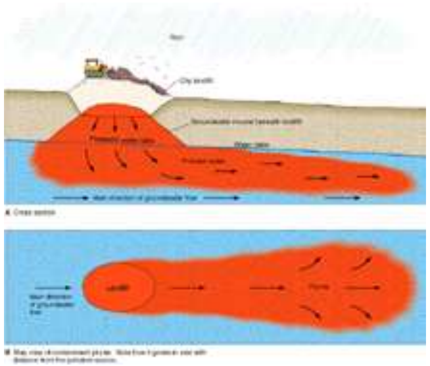


B

Groundwater Contamination

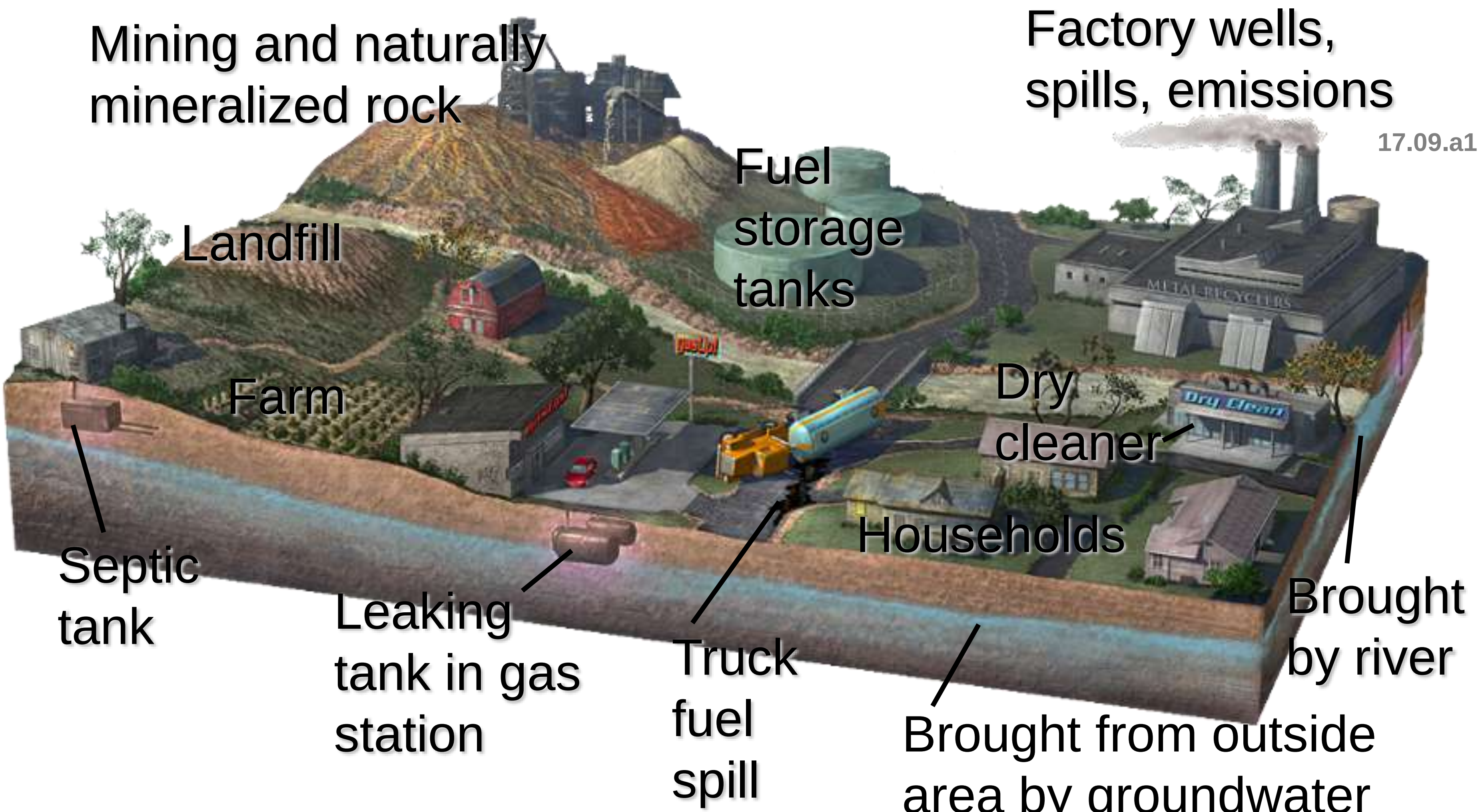
- *Infiltrating* water may bring contaminants down to the *water table*, including:
  - Pesticides/herbicides
  - Fertilizers
  - Landfill pollutants
  - Heavy metals
  - Bacteria, viruses and parasites from sewage
  - Industrial chemicals (PCBs, TCE)
  - Acid mine drainage
  - Radioactive waste
  - Oil and gasoline



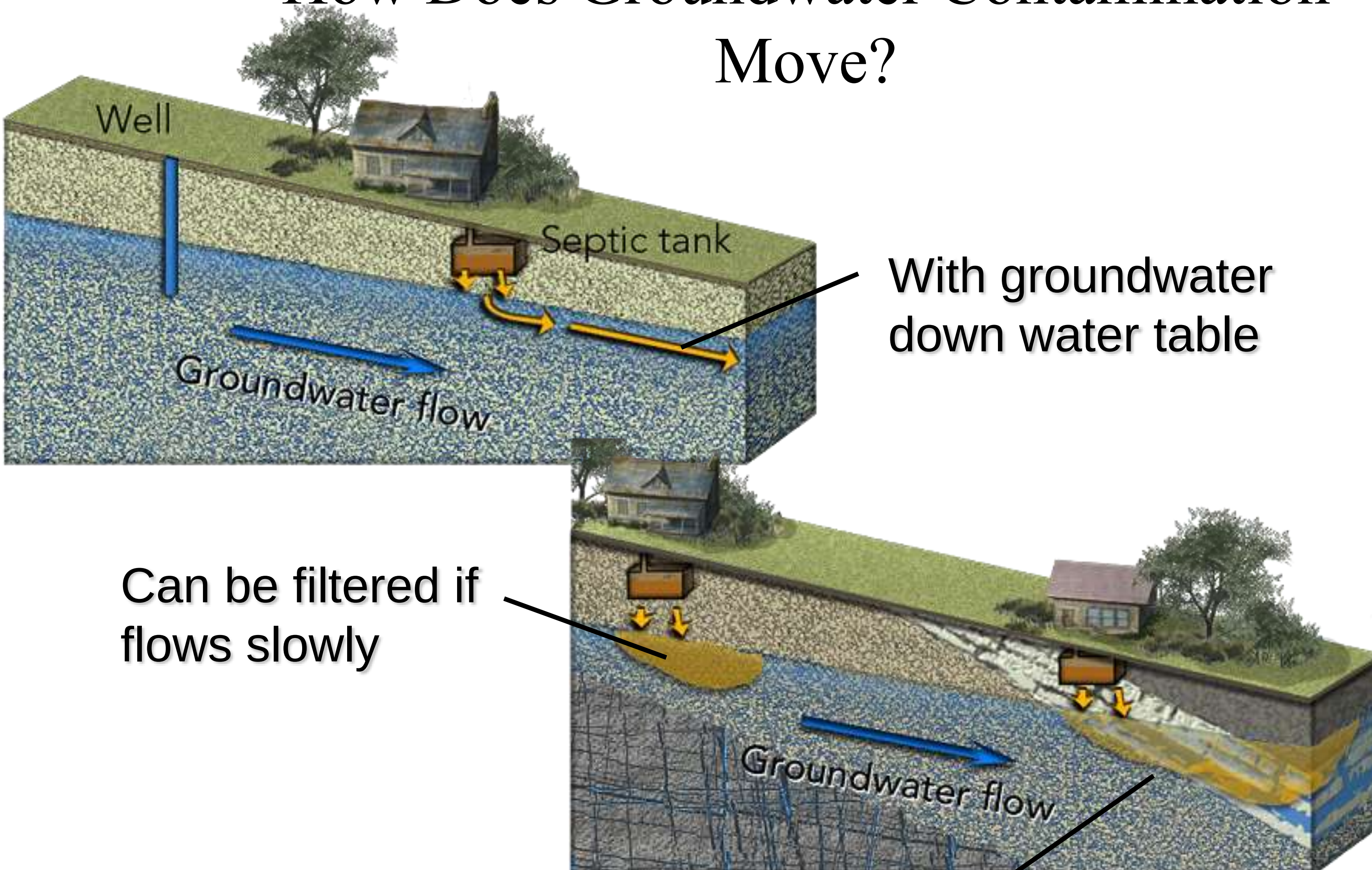
- *Contaminated groundwater* can be *extremely difficult and expensive* to clean up

How Can Water Become Contaminated?

Identify possible sources of surface water and groundwater contamination



How Does Groundwater Contamination Move?



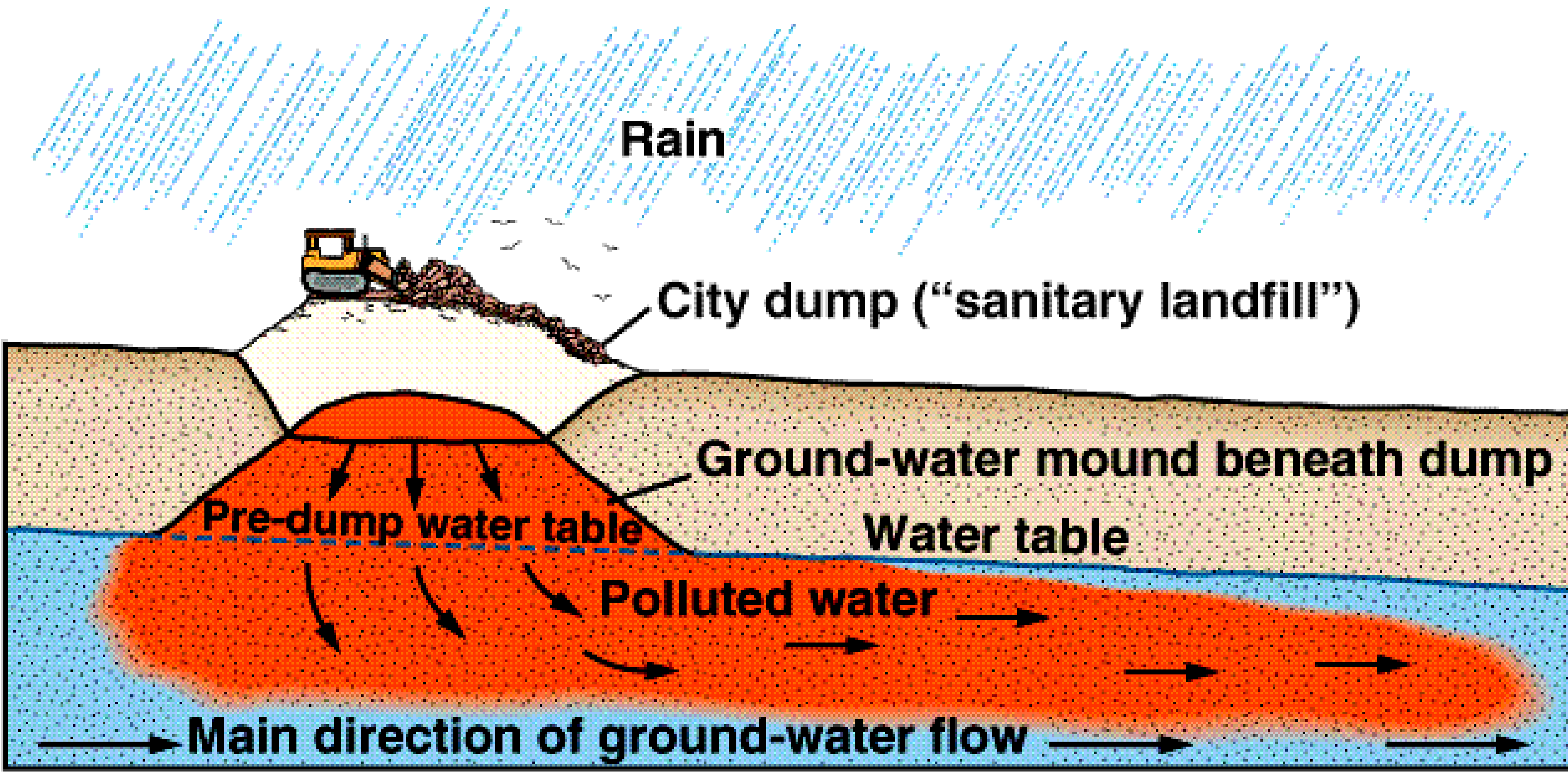
With groundwater down water table

Can be filtered if flows slowly

Not filtered if flows rapidly, like in limestone caves

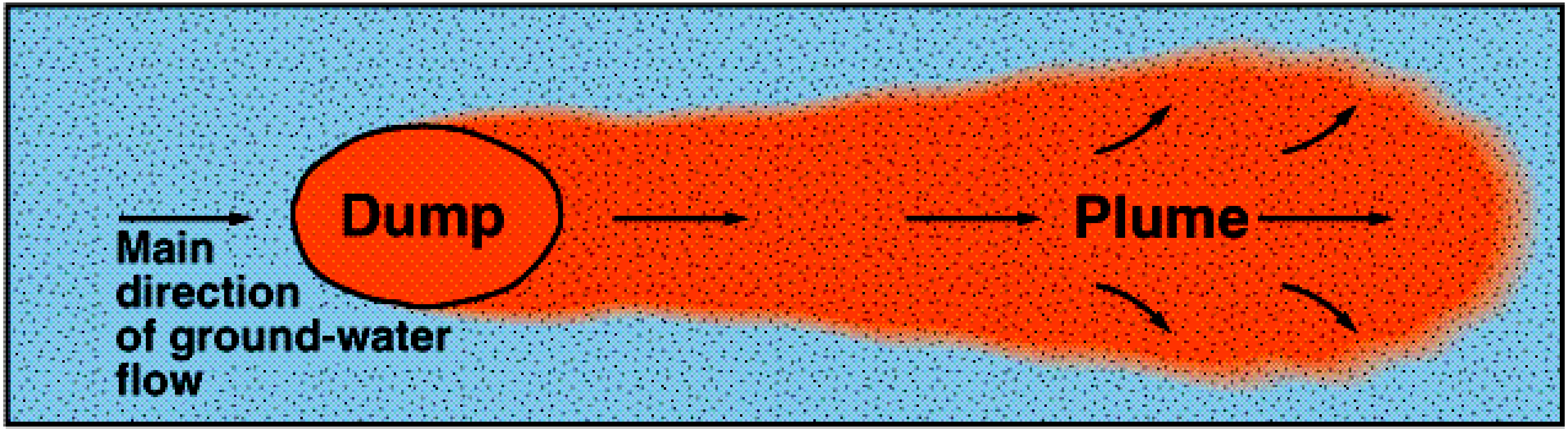
17.10.a

Ground-Water Mound



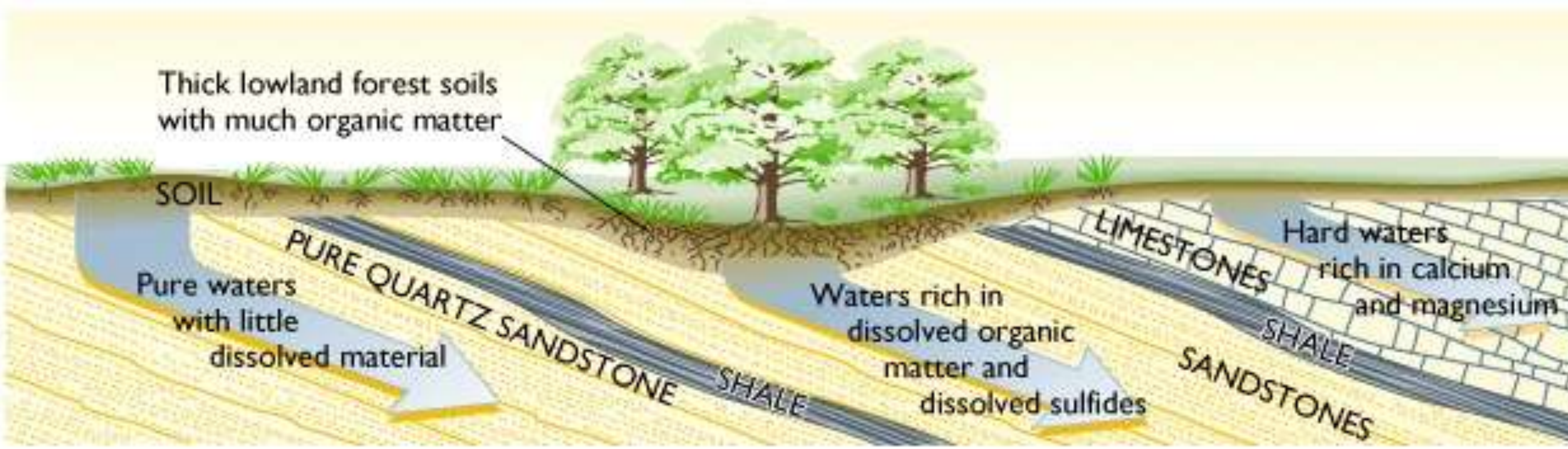
A Cross section

Map View of Contaminate Plume

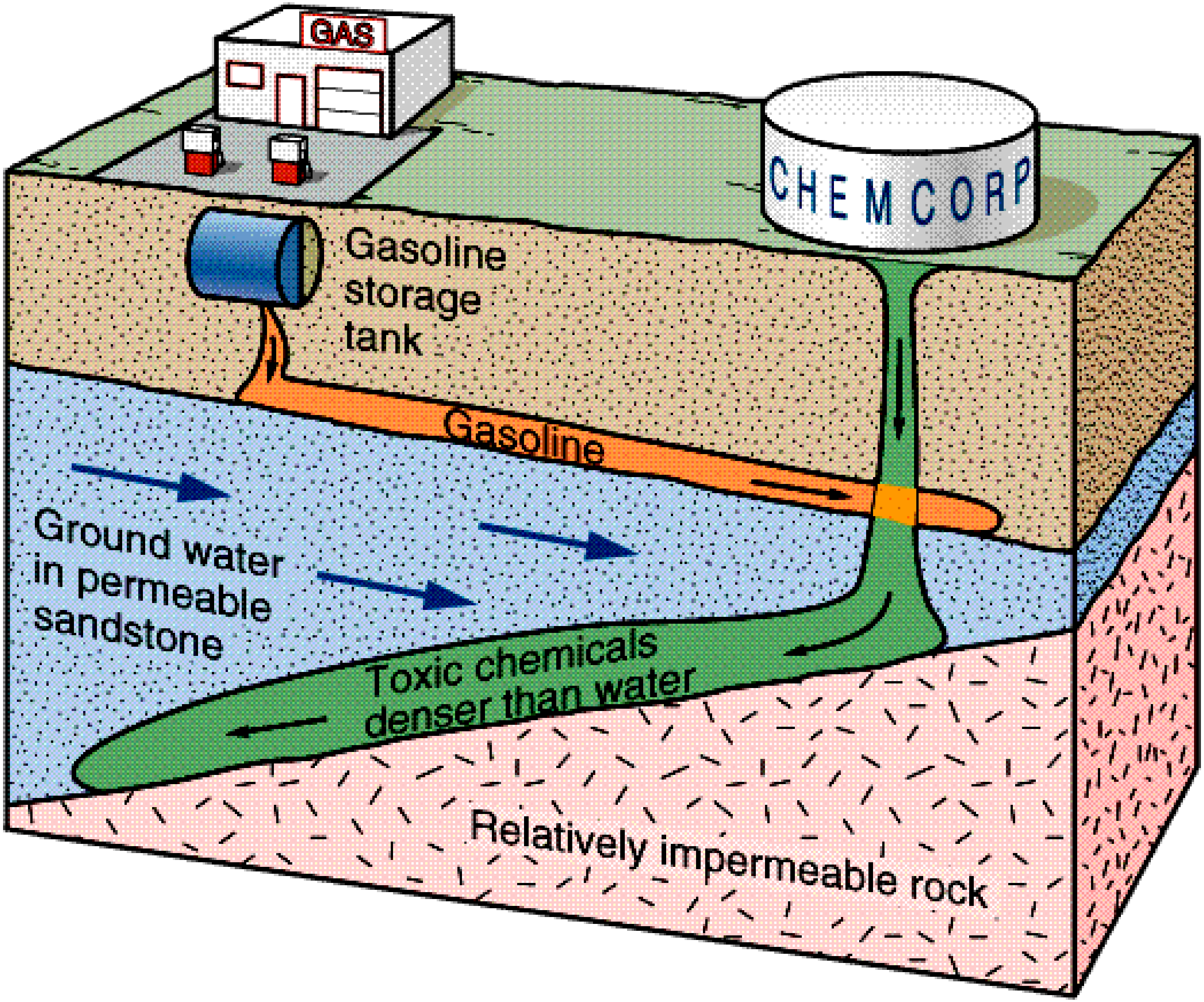


B Map view of contaminant plume. Note how it grows in size with distance from the pollution source.

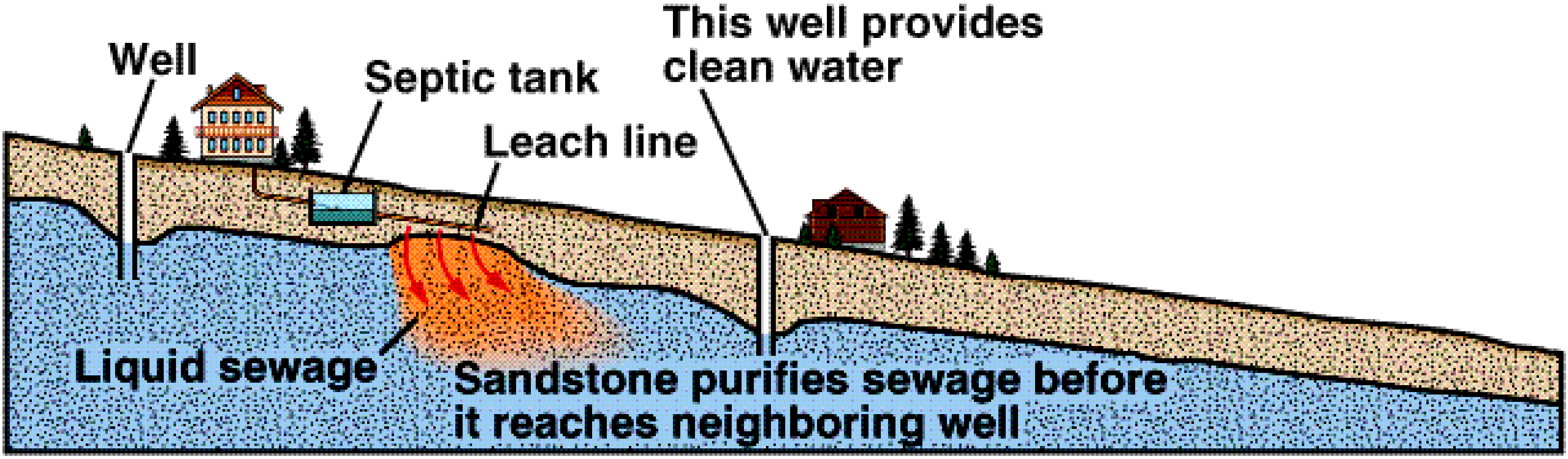
Groundwater chemistry — A function of surface source and subsurface flow path



Pollutants within Saturated Zone



Sewage Contamination



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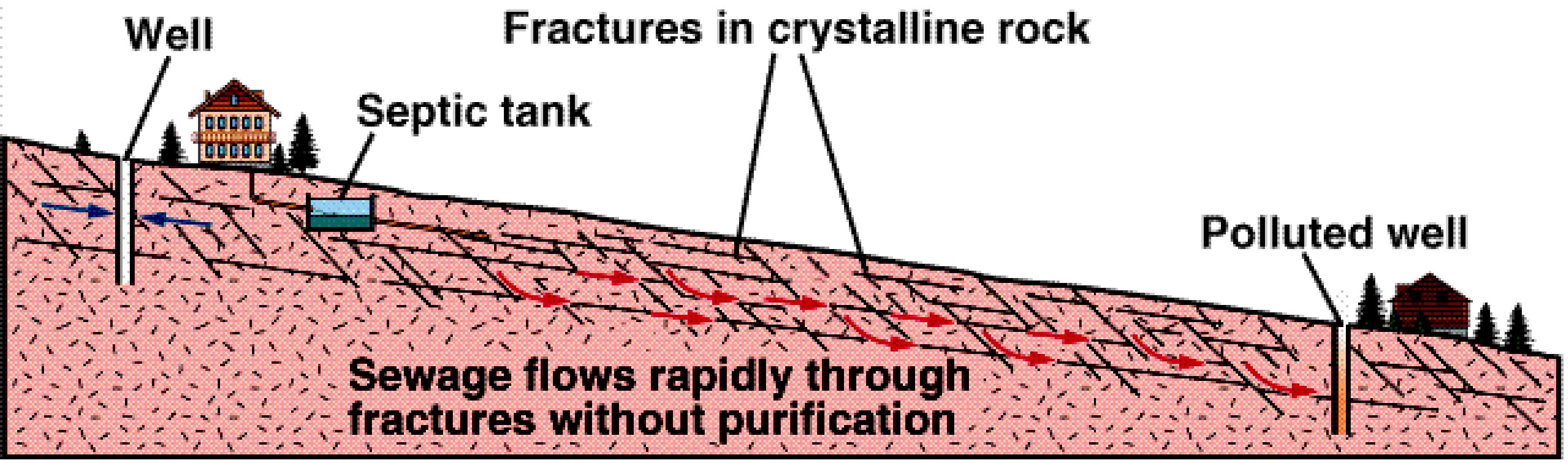
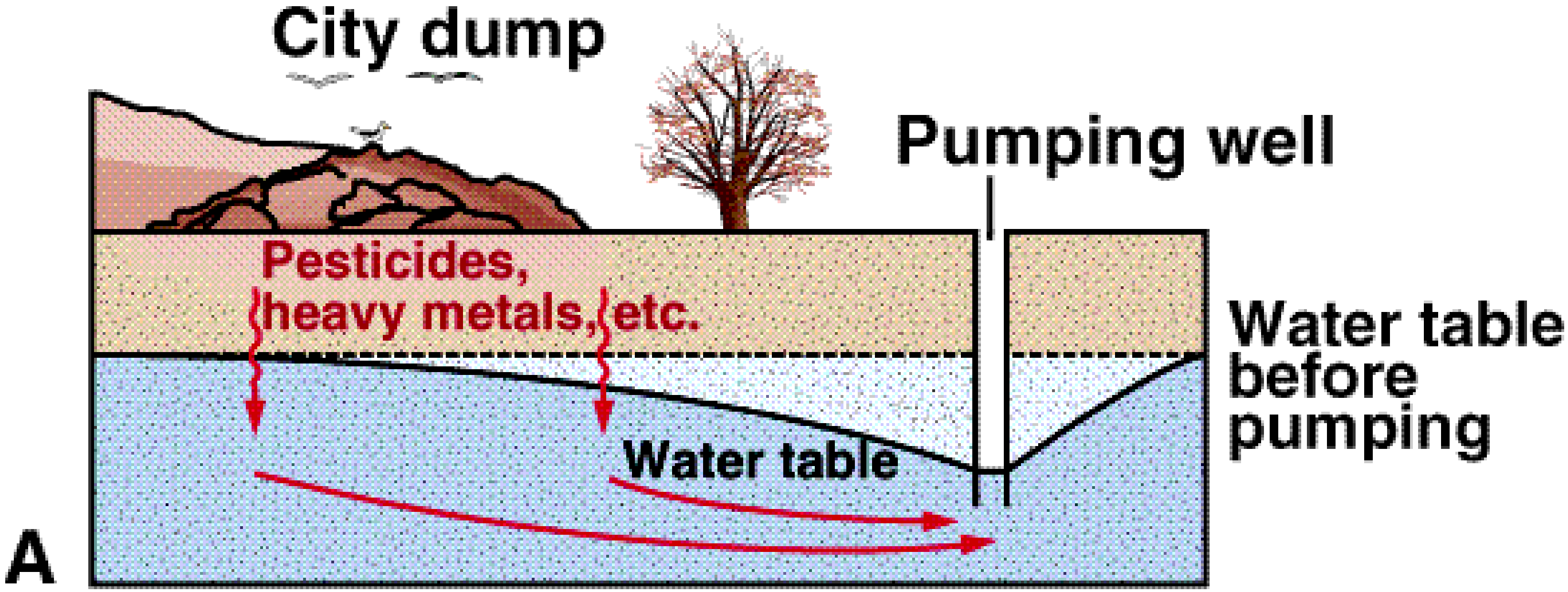
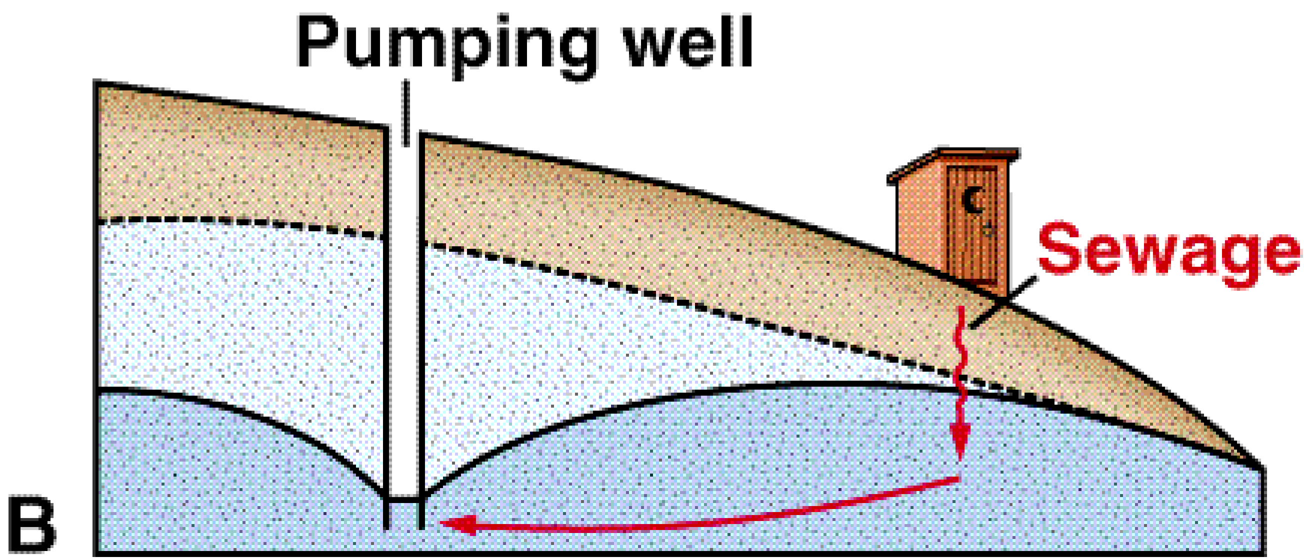
Contamination from Open Fractures



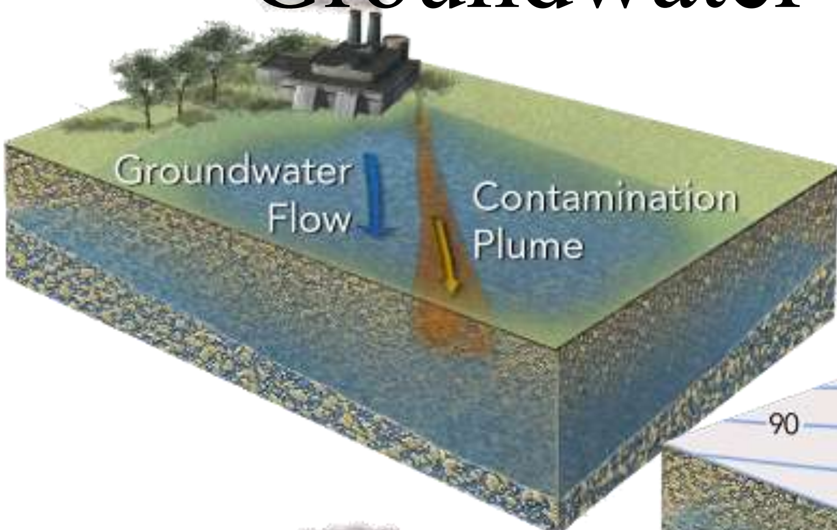
B

Ground-Water Pollution

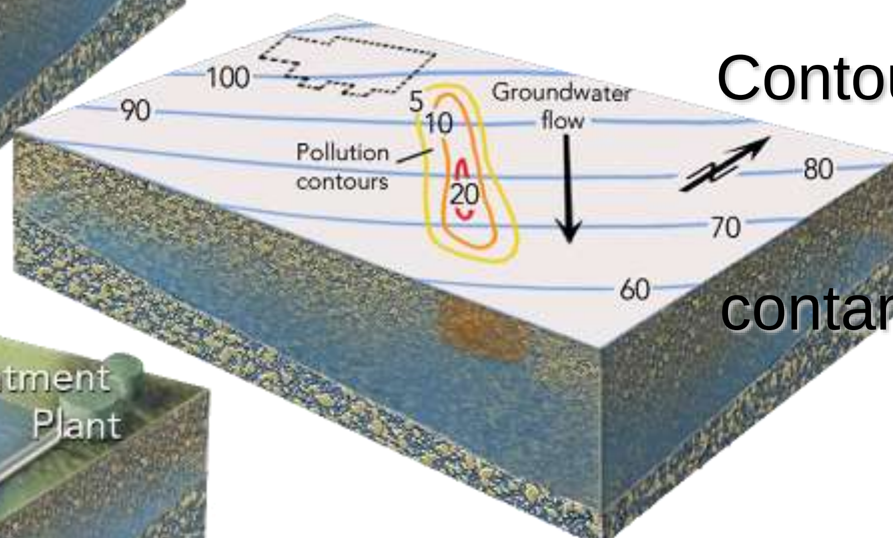




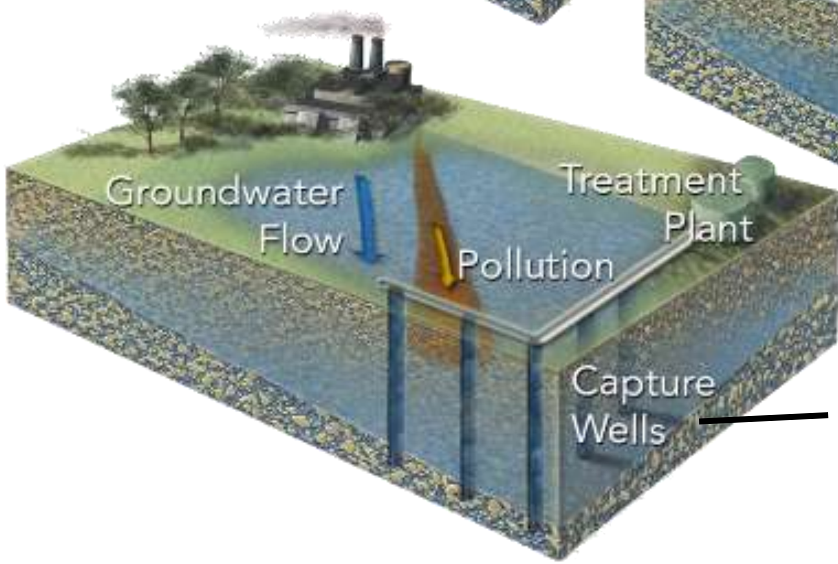
How Do We Track and Remediate Groundwater Contamination?



Spreads out due to diffusion and mixing, forming *contamination plume*



Contour water table and contamination



Drill wells to intercept plume, pump and treat water

Consequences of Excessive Groundwater Withdrawal

1. Jeopardizes our long-term dependable supply.

2. More expensive to pump deeper water.

3. Water quality decreased with time.

4. Salt water intrusion along coastlines.

5. Ground subsidence and associated compaction of the aquifer.

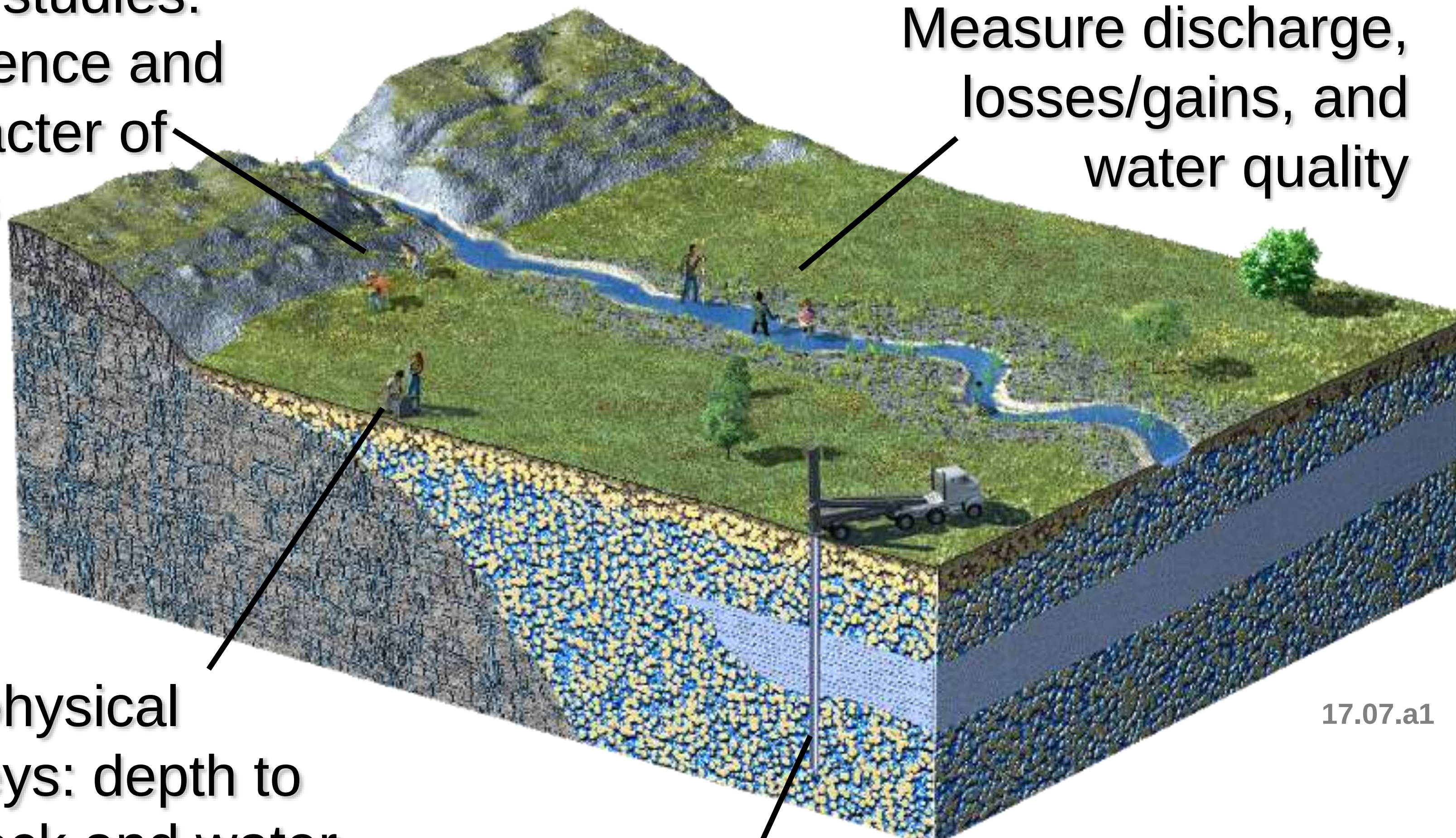
Tucson Water Supply

- Tucson ground water averages 4-5,000 years old — nearly all of current supply
- Much was accumulated during last Ice Age
- Horizontal recharge only ~100 meters per year
- Water table drops ~1 meter per year in areas of intense pumping — consequently, compaction & subsidence are major problems in Arizona
- Requires other water sources — CAP (Colorado River water via the Central Arizona Project)

How Do We Study Groundwater?

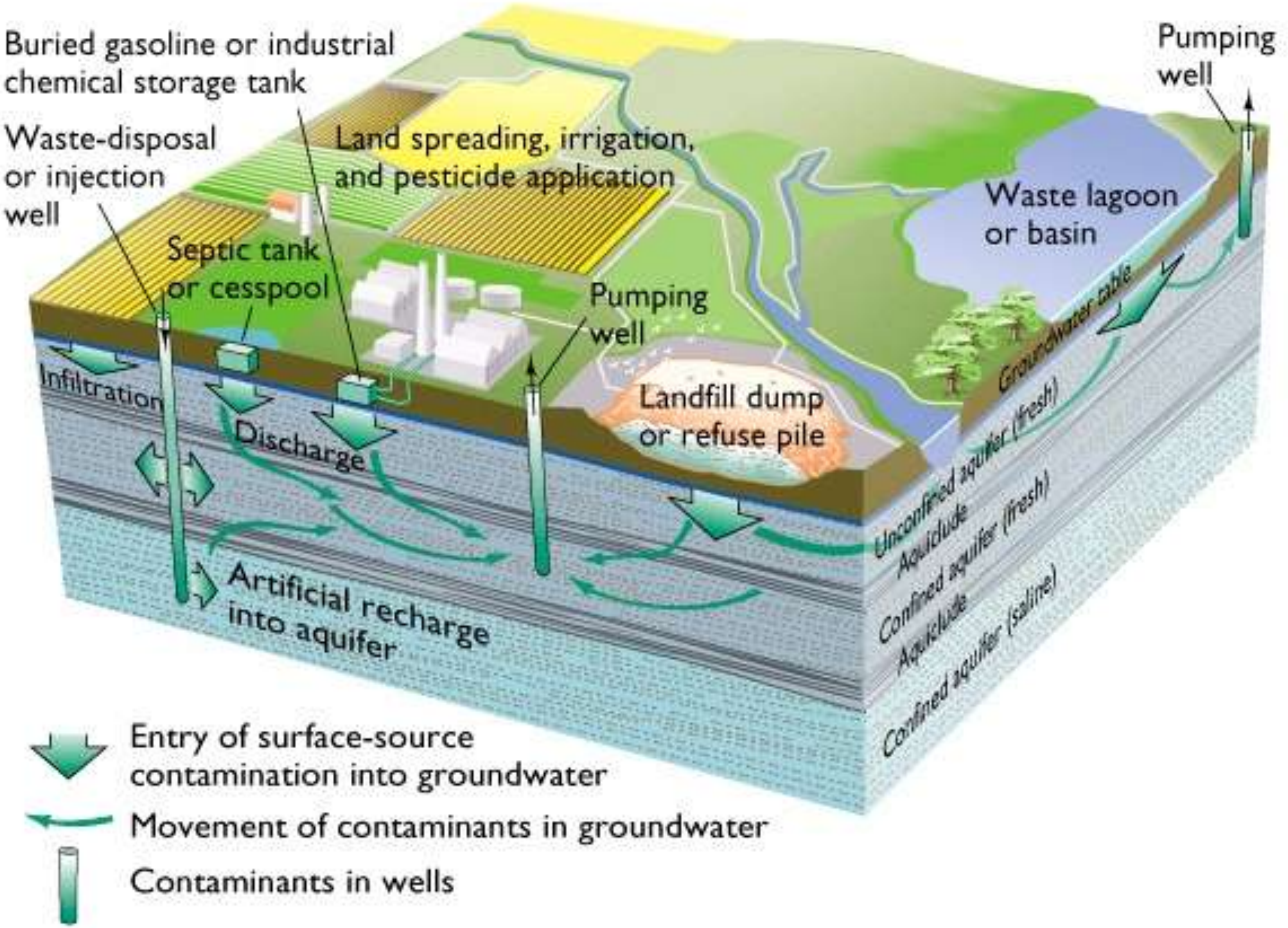
Field studies: sequence and character of rocks

Measure discharge, losses/gains, and water quality



Geophysical surveys: depth to bedrock and water

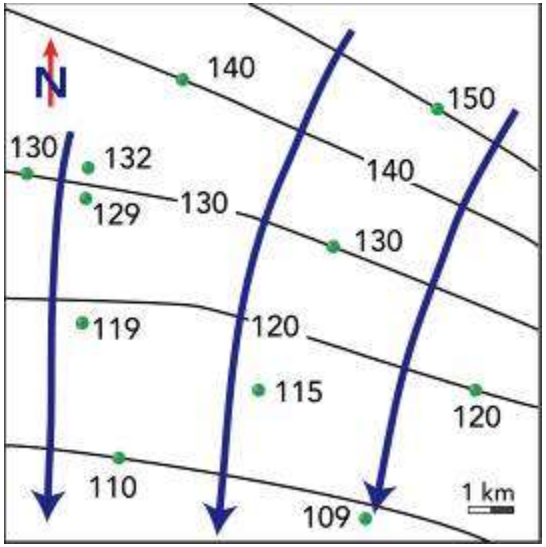
Drilling: verify geology, depth to water table, provide samples, pump tests


Buried gasoline or industrial chemical storage tank
Waste-disposal or injection well
Land spreading, irrigation, and pesticide application
Pumping well
Waste lagoon or basin
Septic tank or cesspool
Pumping well
Infiltration
Discharge
Landfill dump or refuse pile
Groundwater table
Unconfined aquifer (fresh)
Aquiclude
Confined aquifer (fresh)
Aquiclude
Confined aquifer (saline)
Artificial recharge into aquifer
Entry of surface-source contamination into groundwater
Movement of contaminants in groundwater
Contaminants in wells

How Do We Depict the Water Table?

Numbers show elevations of the water table: *what is the pattern?*

Contours: water table at same elevation; blue arrows show flow



Compare water table to other features