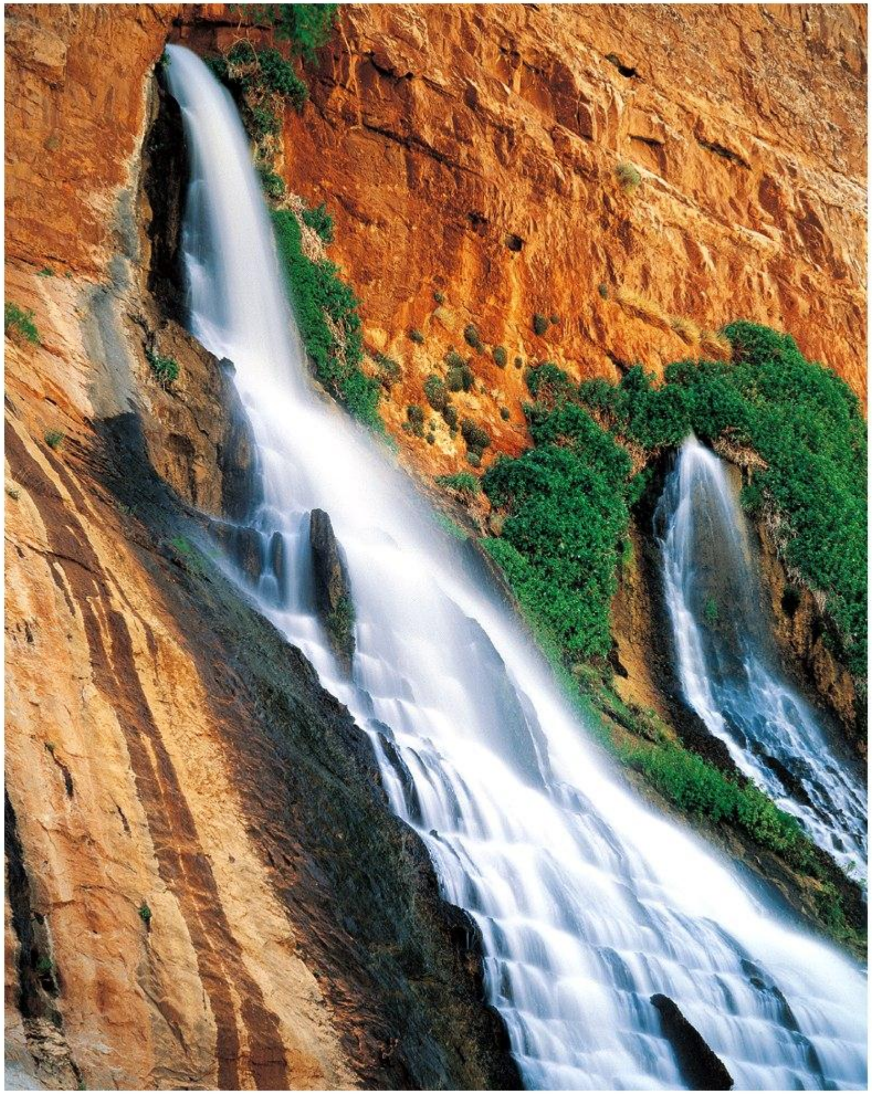
The Hydrosphere:
Lecture 8: Groundwater

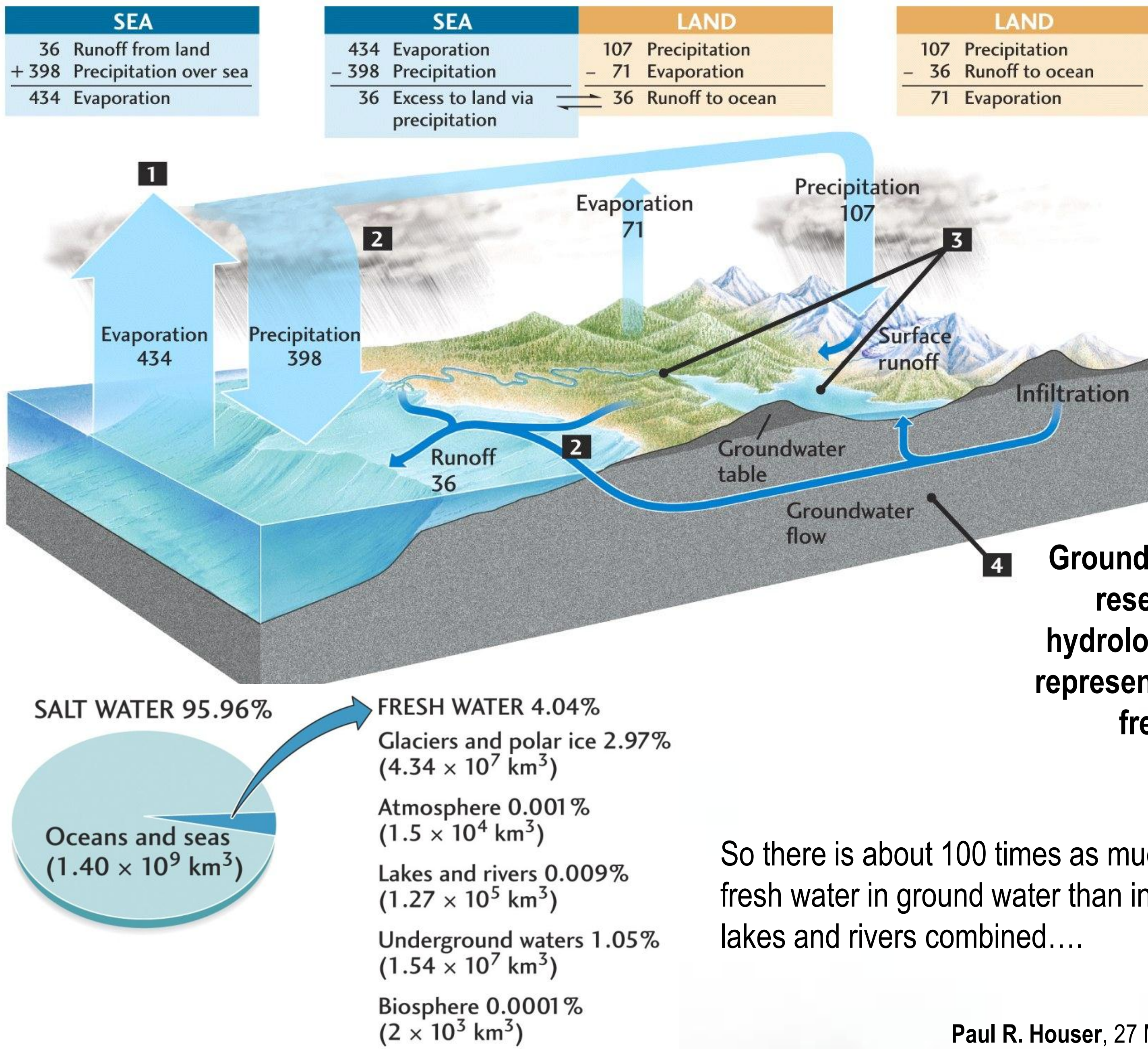
Groundwater



Vasey's Paradise: Groundwater discharges from the wall of Marble Canyon to form a series of natural springs. (Grand Canyon, Arizona)

- How is groundwater formed?
- What are the zones of subsurface water and their characteristics?
- What is a water table, and how is it configured in humid vs arid climates?
- How does ground water move? What is porosity? permeability? Primary vs seondary p and p?
- What is an aquifer, and what kinds are there?
- Be able to discuss the use of wells in ground water, including potential problems.
- What is karst topography?

The Hydrologic Cycle



Groundwater is one reservoir of the hydrologic cycle and it represents about 22% of fresh water.

So there is about 100 times as much fresh water in ground water than in lakes and rivers combined….

Porosity and **Permeability**.

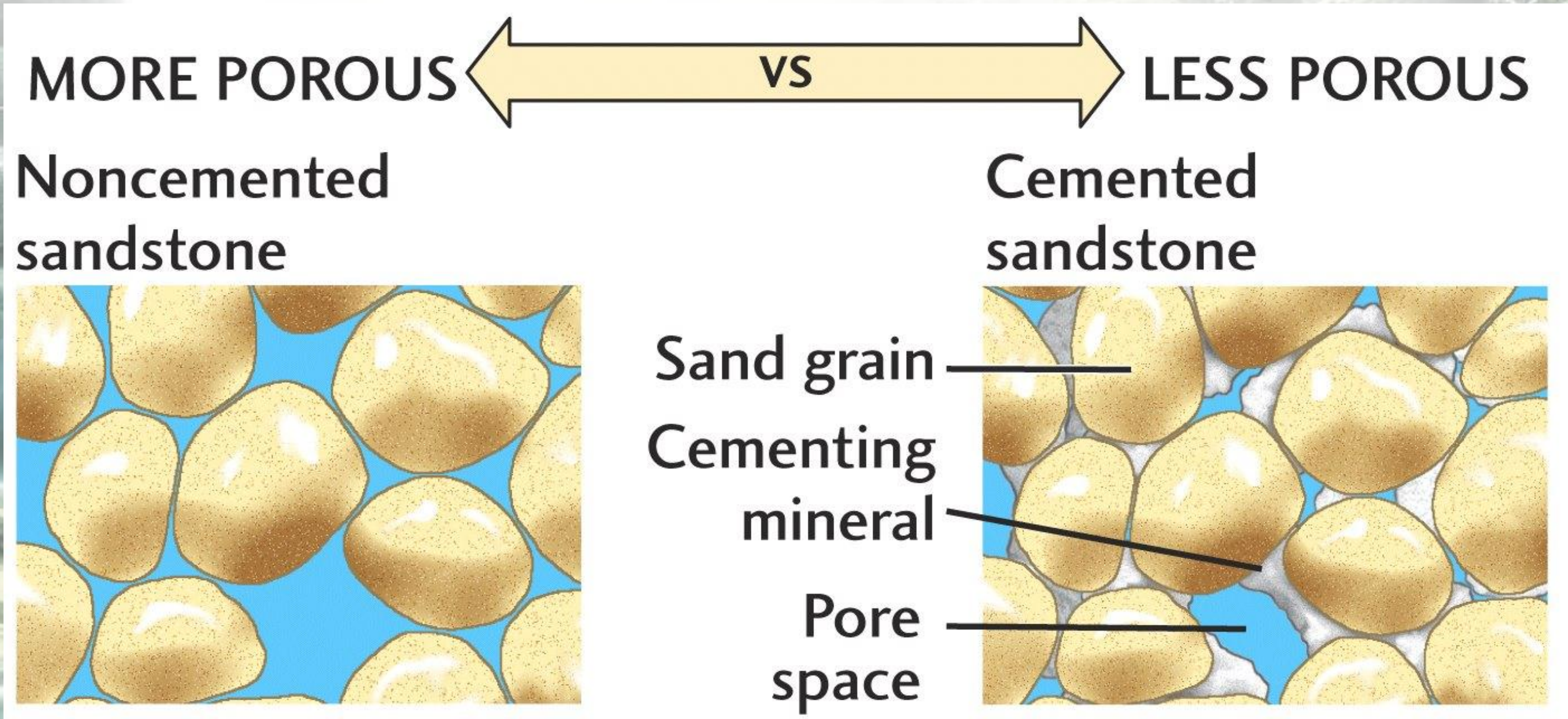
The amount, availability, and movement of groundwater depends largely on **Porosity** and **Permeability**.

With the exception of caves, there are no large open spaces for pools or rivers of water underground. The only space available for water is the ***pore space*** *between grains of sand and other particles that make up the soil and bedrock and the space in fractures.*

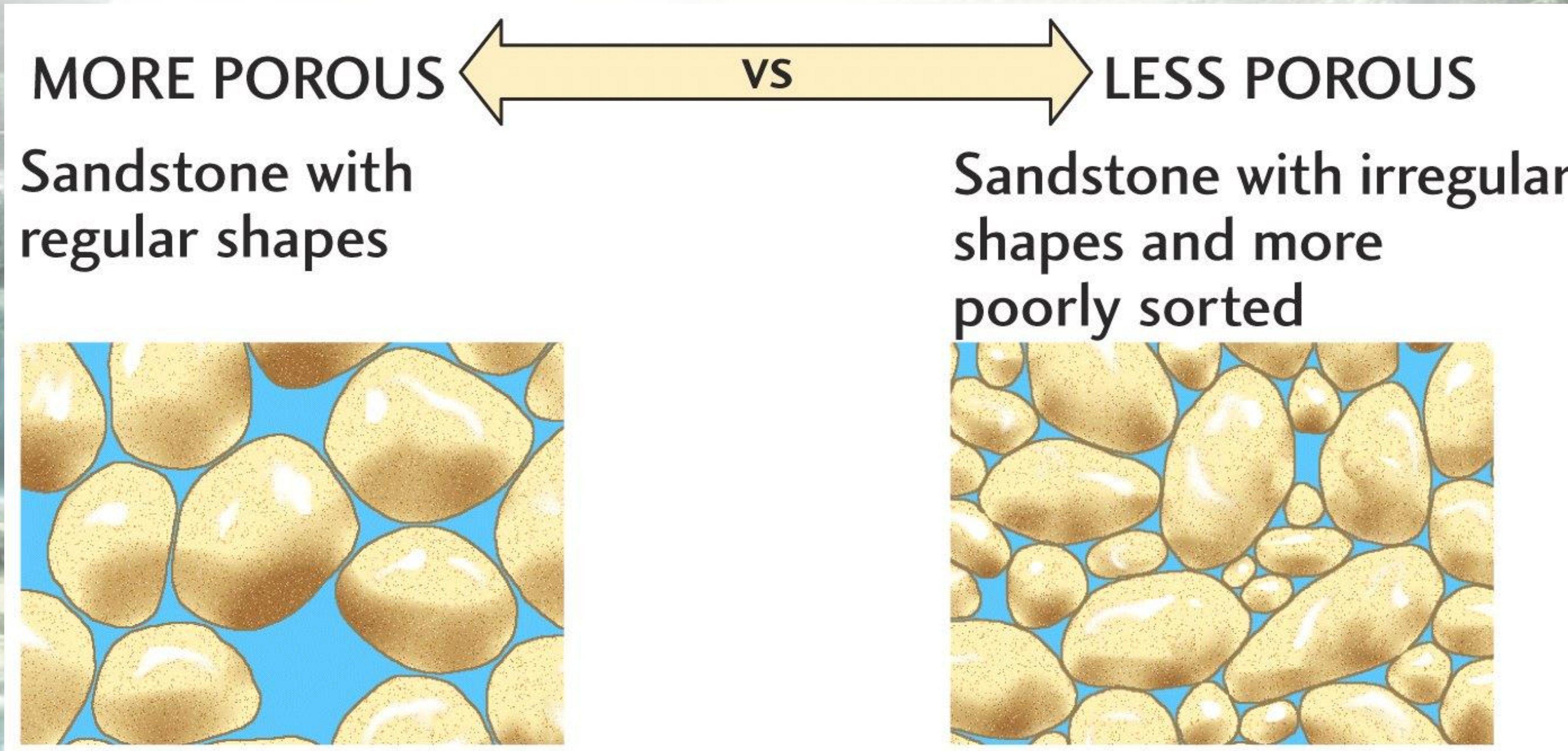
Porosity: *The percent void space in a rock or sediment. It is a measure of the potential volume of water that can be stored in a rock.*

Permeability: *The ability of a material to transmit a fluid. It is a measure of how fast the fluid can travel through the rock or sediment*

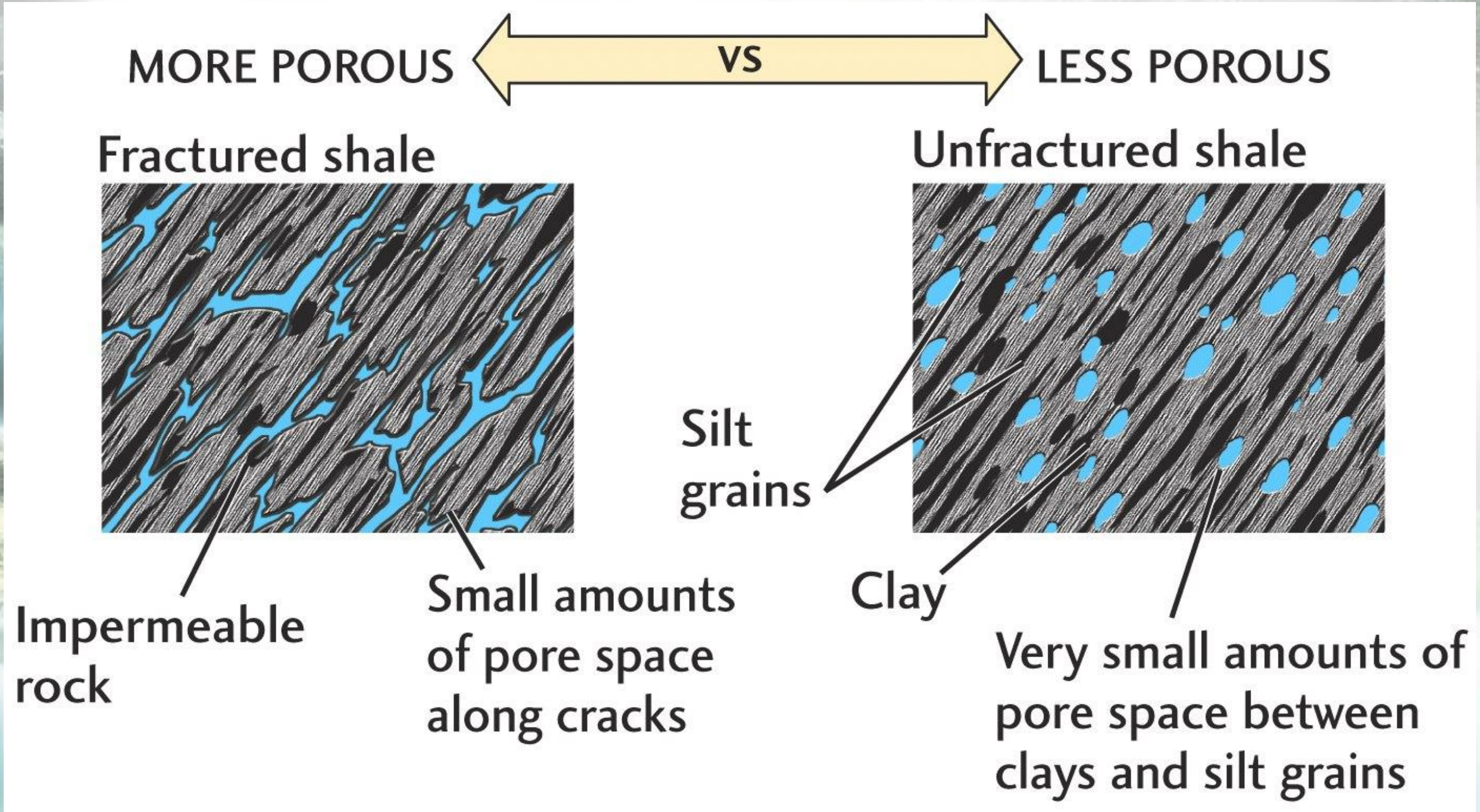
Porosity Varies with % Cement



Porosity Varies with **Sorting**



Porosity Varies with Fracturing



Permeability depends on **Pore Connectivity**

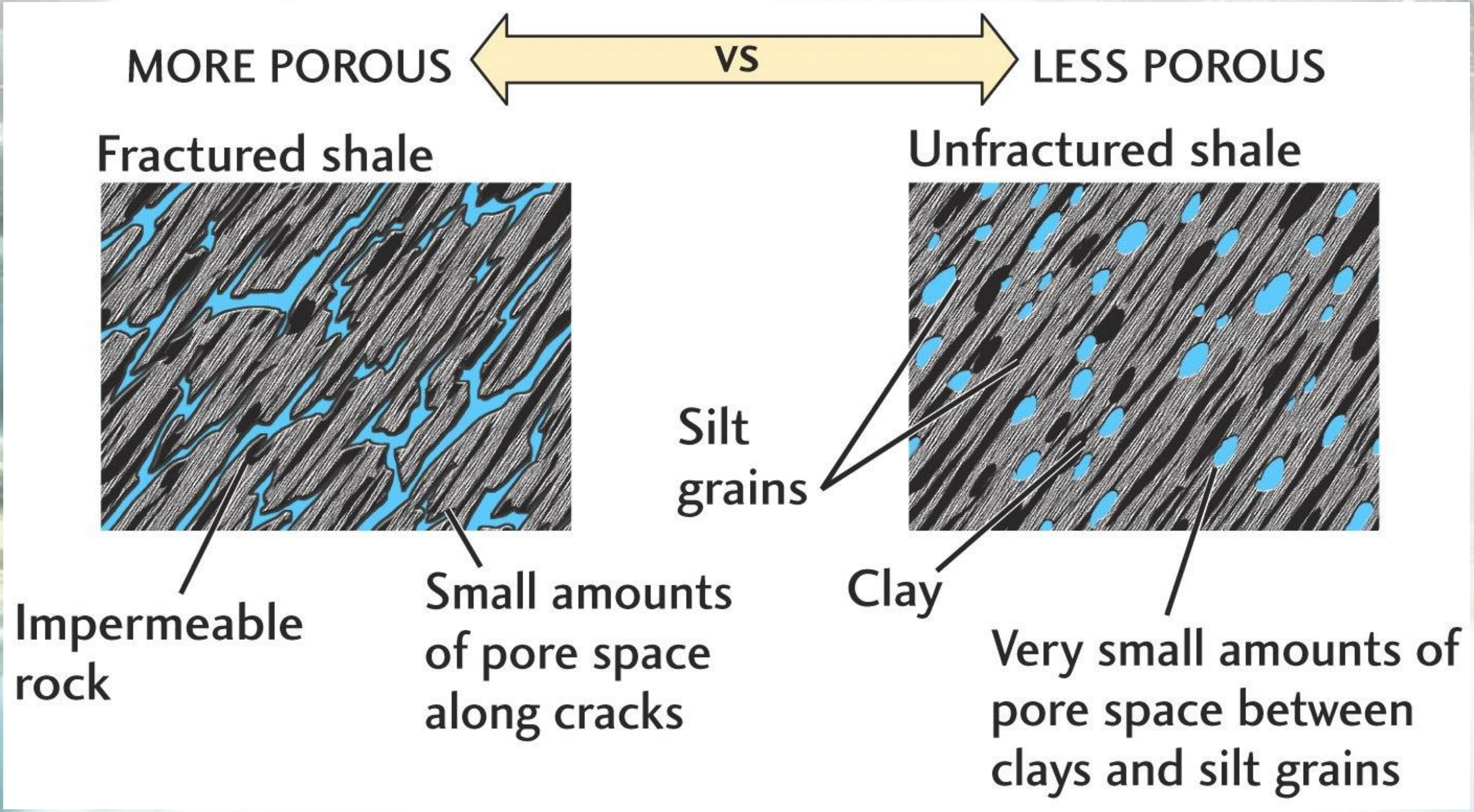
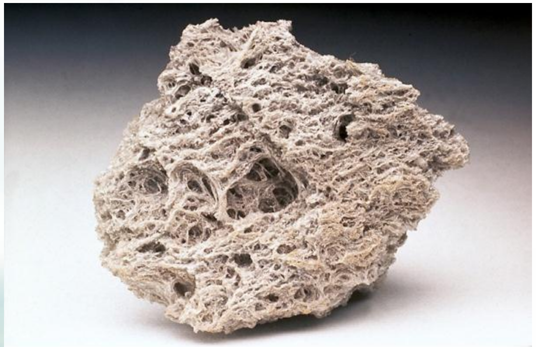


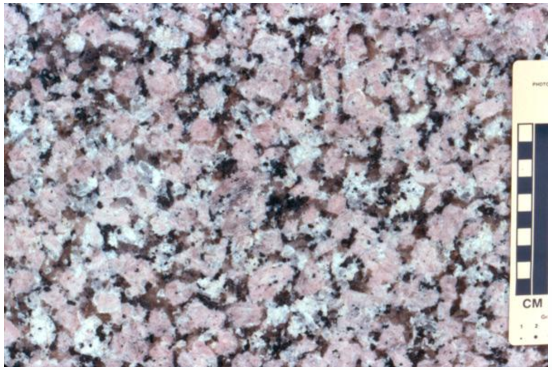
Figure 13.7

Relative Porosity and Permeability of Different Aquifer 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

Generally, permeability correlates with porosity, ***but not always.***





Secondary porosity and permeability

- Secondary porosity developed after the material was formed . Depends upon:
- Primary porosity and permeability were created by the same processes that formed the material.

  - degree of fracturing
  - amount of solution (for limestone)

Aquifers

Aquifer: A geologic unit capable of storing and transmitting water in sufficient quantities to supply wells.

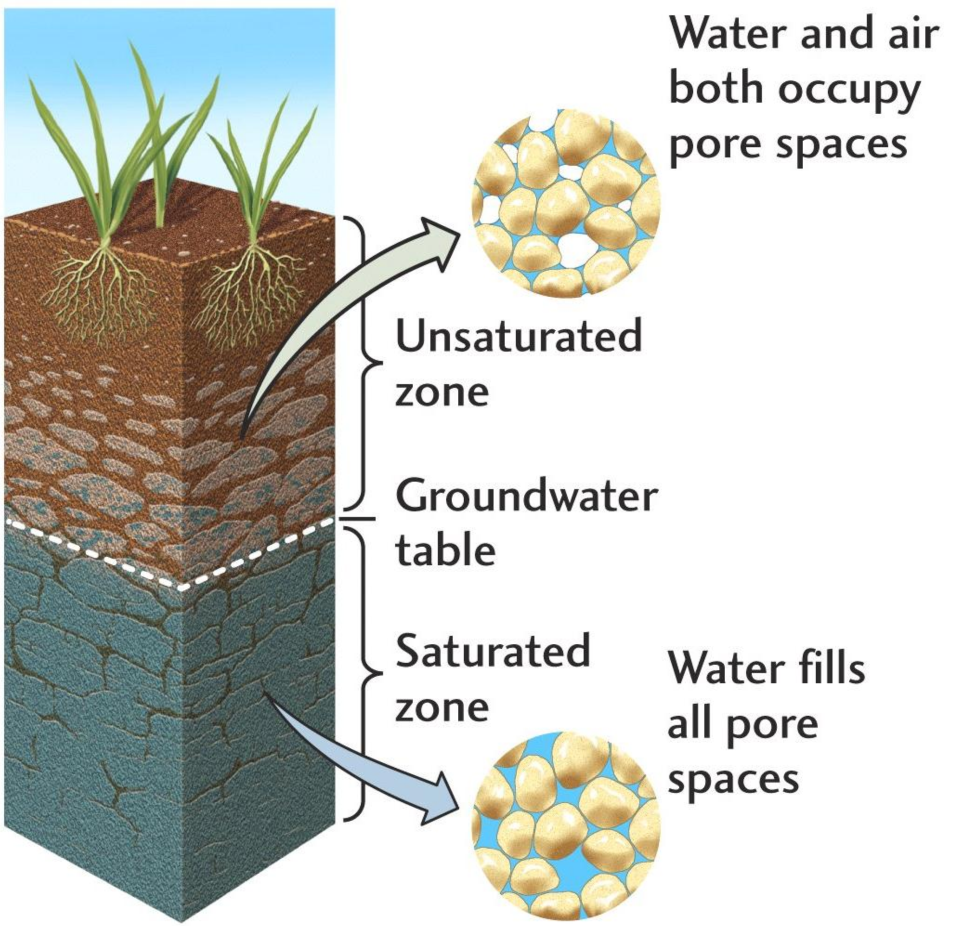
Aquiclude (Aquitard): A geologic unit that resists water flow (relative to an aquifer).

Unconfined Aquifer: the permeable layer extends to the surface. It consists of an **unsaturated** zone separated from the **saturated** zone by the **groundwater table**.

Confined Aquifer : the permeable layer is overlain and underlain by a less permeable layer (aquiclude)

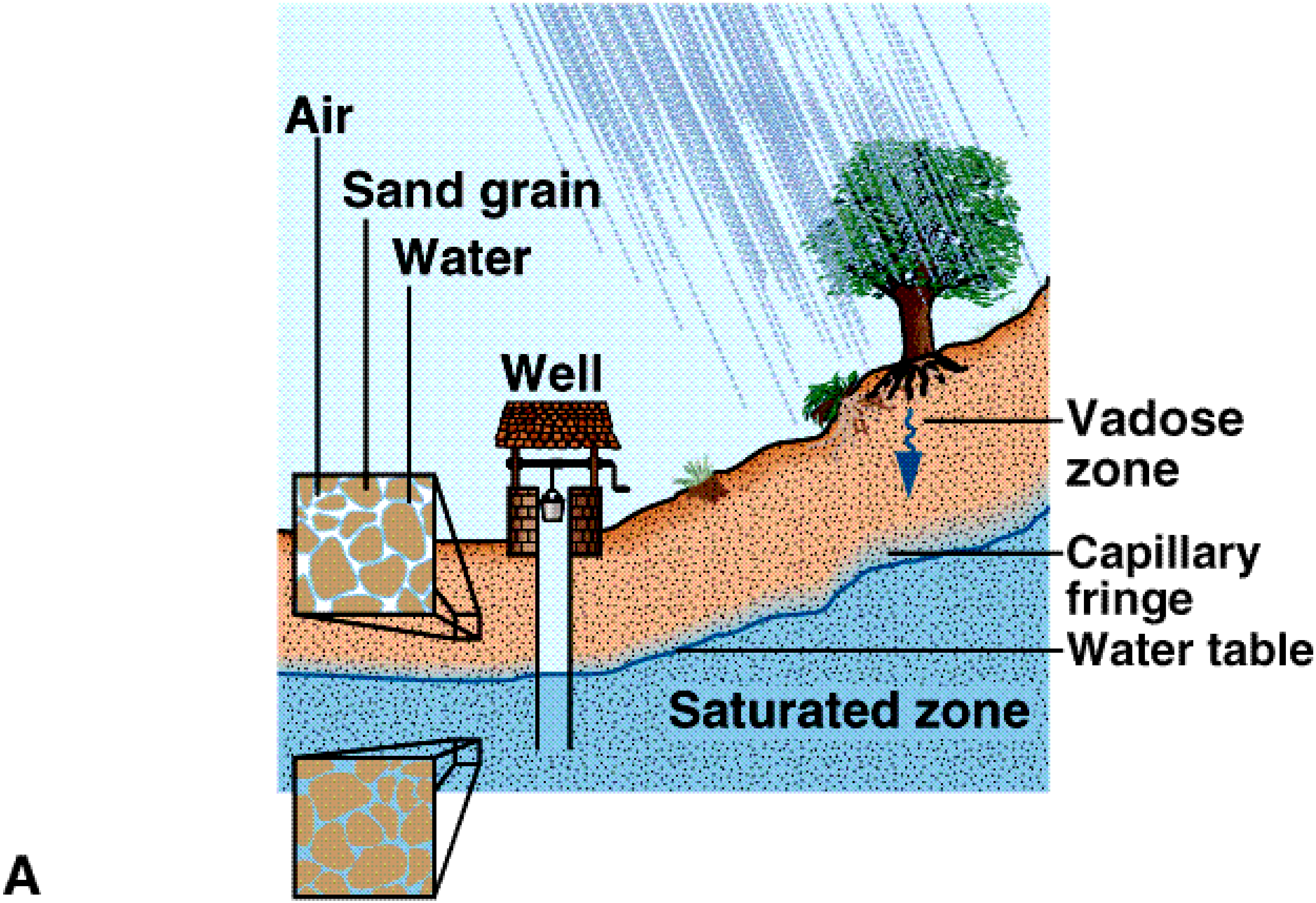
Water Table:

- the top of the saturated zone of groundwater
- the level to which water will rise in a hole
- the level to which water will rise in an unconfined aquifer
- Groundwater moves downward due to the force of gravity - some water in unsaturated zone is on way to saturated zone - the rest is held by surface tension.



The ground water table is not stable:
Modifications of the ground water table may result in lowering of the water table, saltwater incursion, subsidence, and contamination.

The Water Table

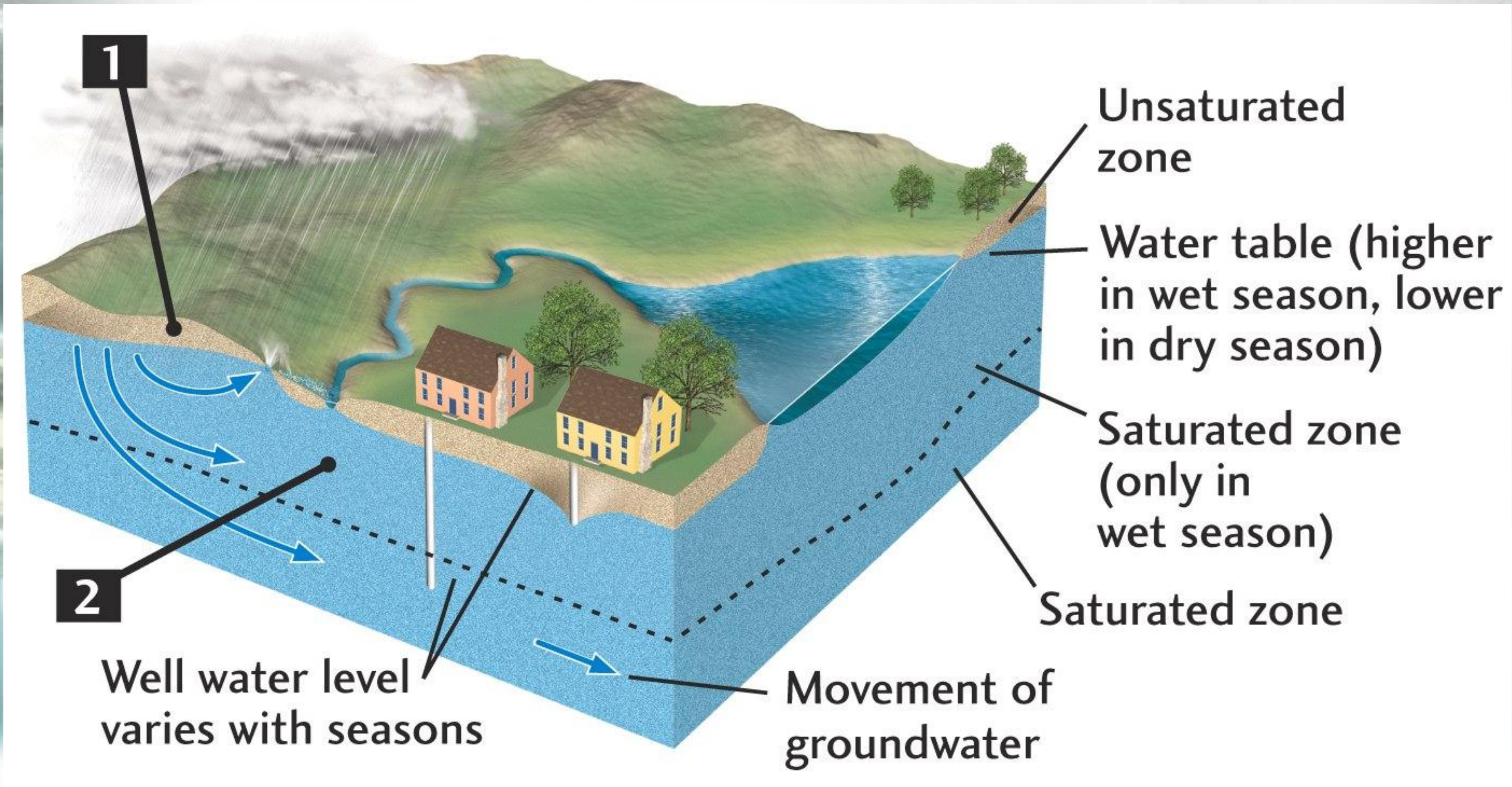


- **<u>Groundwater recharge</u>** – any process that adds water to an aquifer
  - Can be natural or human induced

- **<u>Groundwater discharge</u>** – any process that removes water from an aquifer
  - Can be natural – natural springs
  - Or human induced – pumping water from a well

Dynamics of an Unconfined Aquifer in a Temperate Climate

Rainwater infiltrates
porous soil & rocks ….



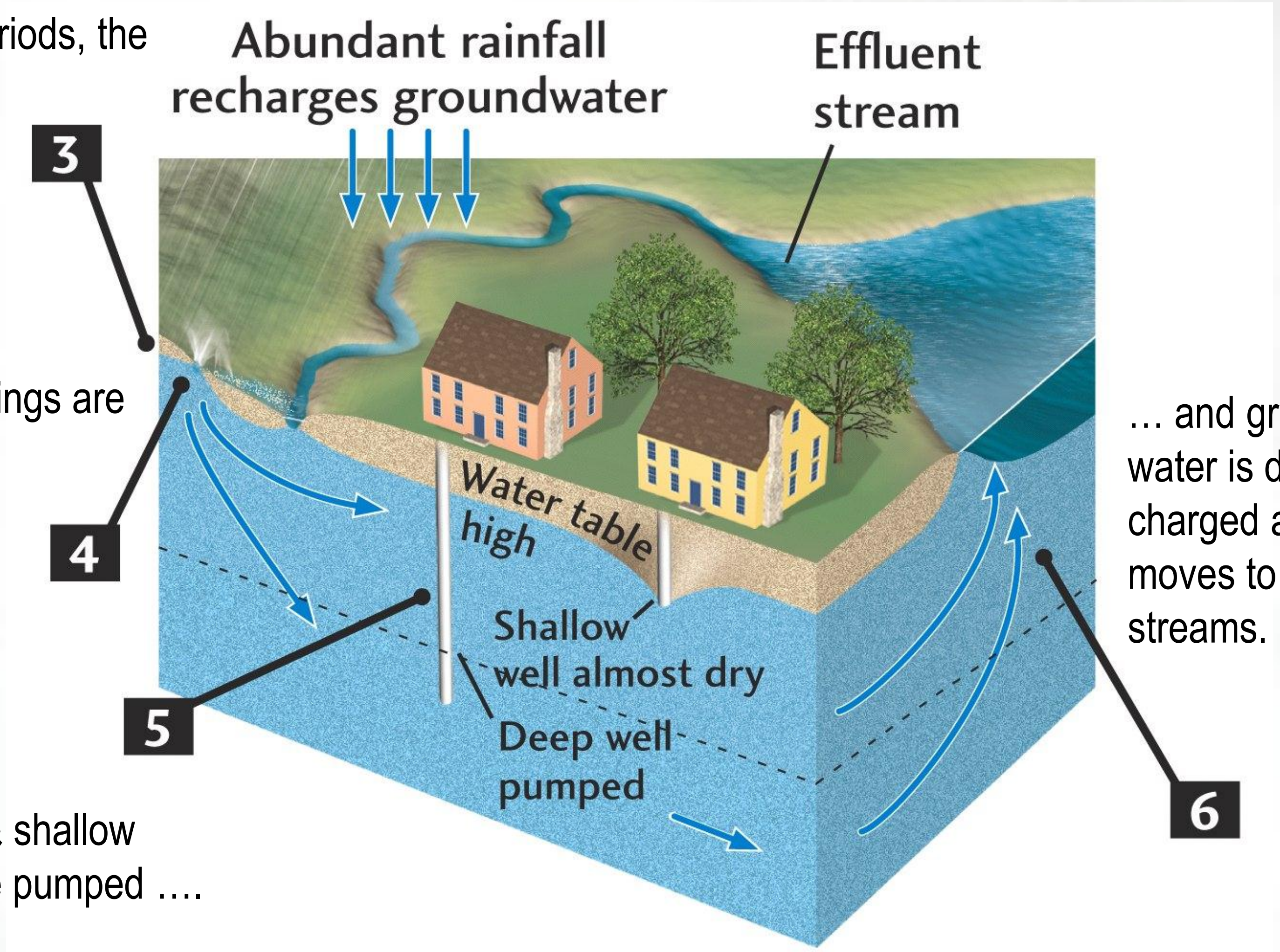
… and flows underground towards
lakes and streams.

During the Wet Season…

During wet periods, the water is high

Natural springs are flowing.

Both deep & shallow wells can be pumped ….



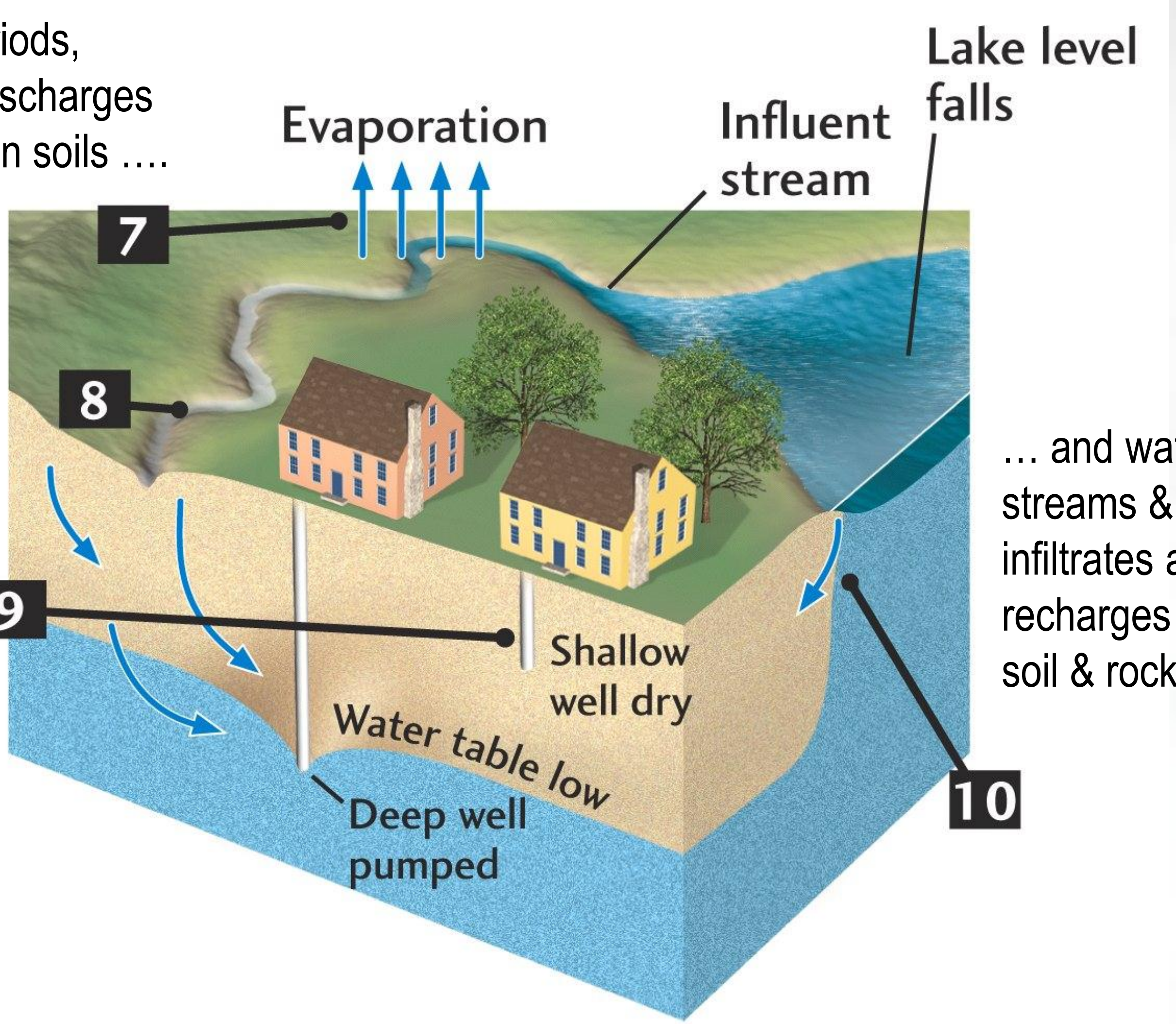
… and ground water is dis-charged as it moves to lakes & streams.

During the Dry Season…

During dry periods, evaporation discharges ground water in soils ….

… springs stop flowing, river dries up …

… the water tables falls, shallow wells dry up ….

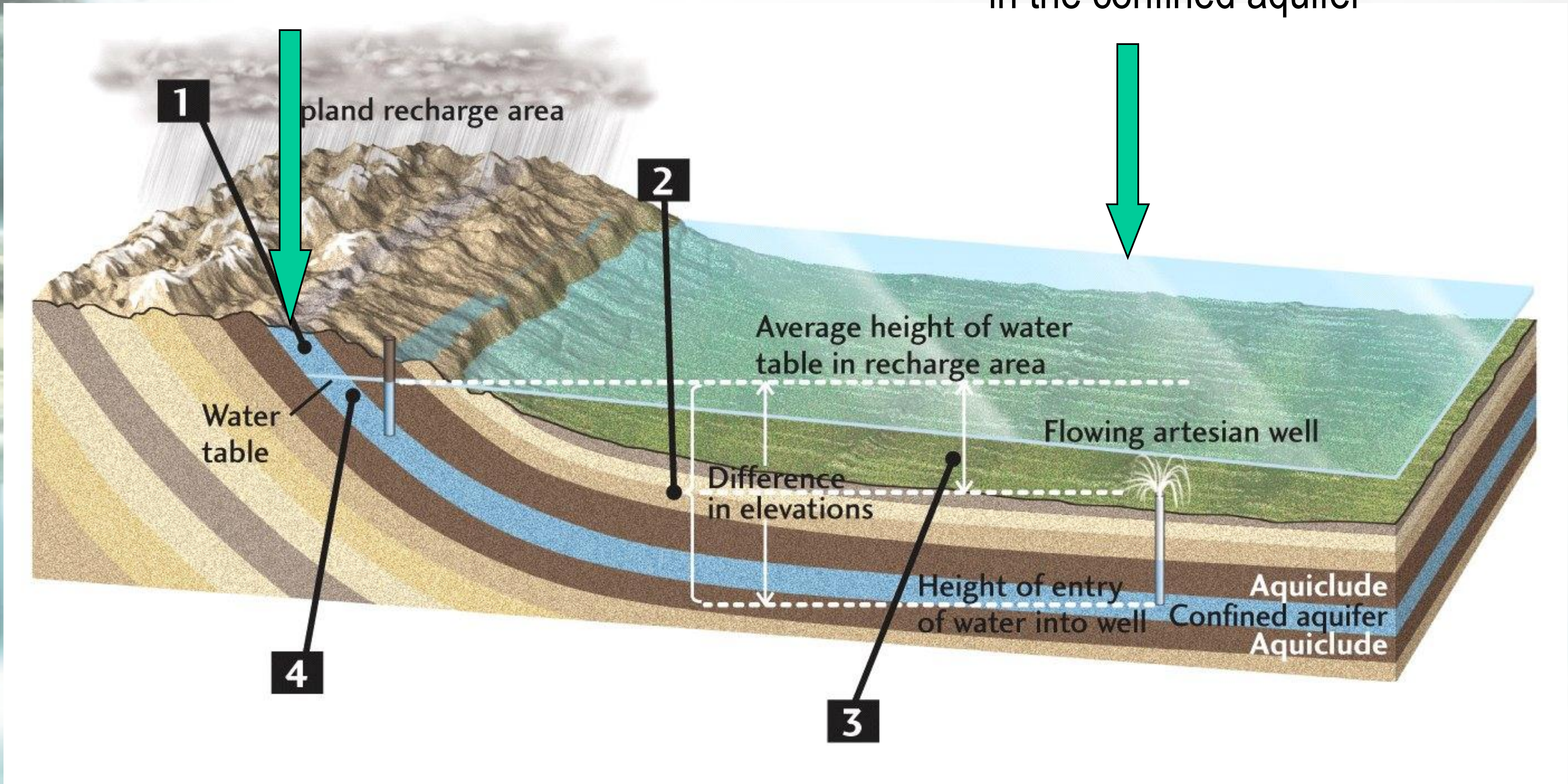


… and water from streams & lakes infiltrates and recharges the surface soil & rock.

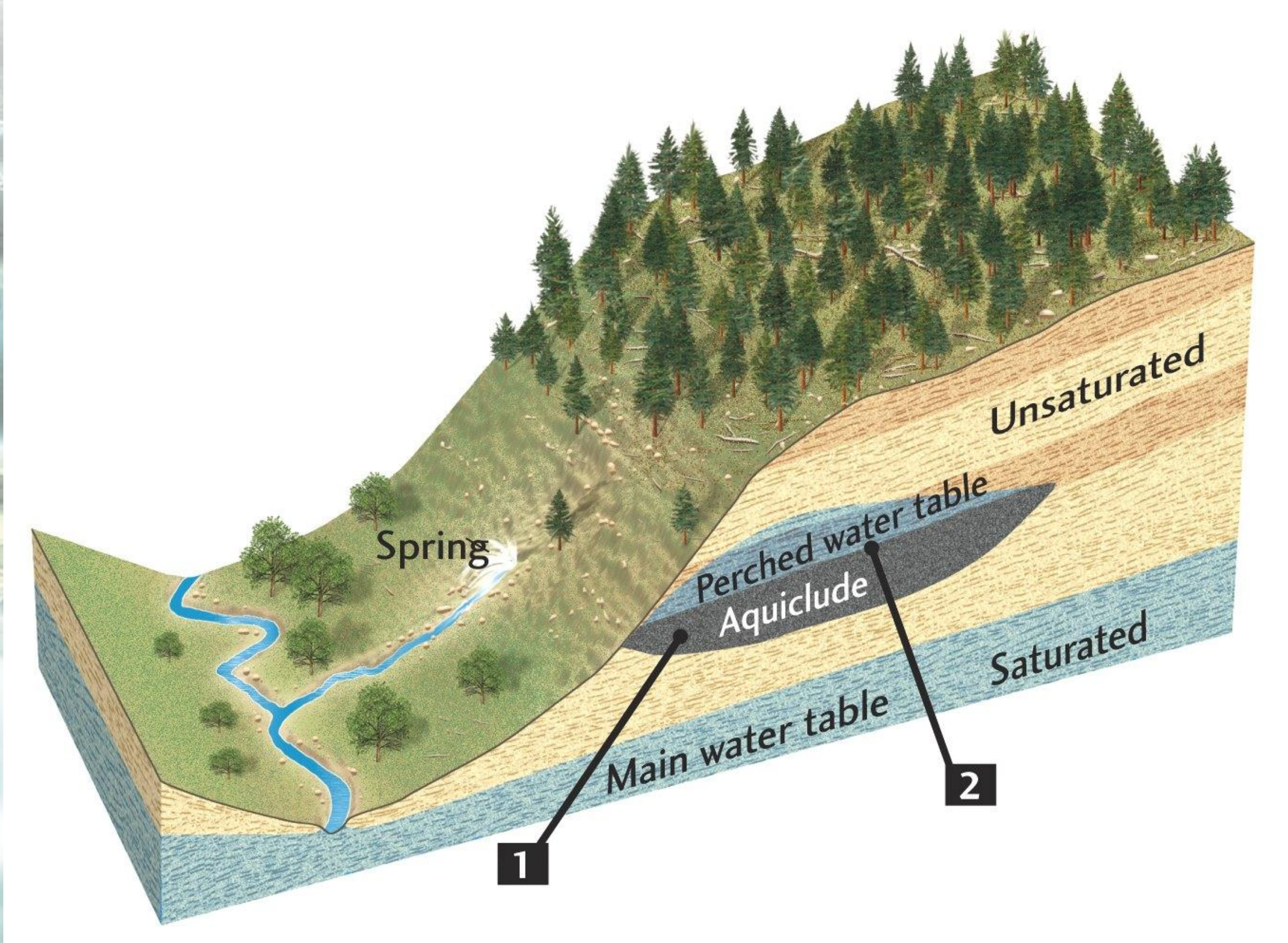
Confined Aquifer

Recharge Area:
where the confined aquifer
is recharged by infiltration

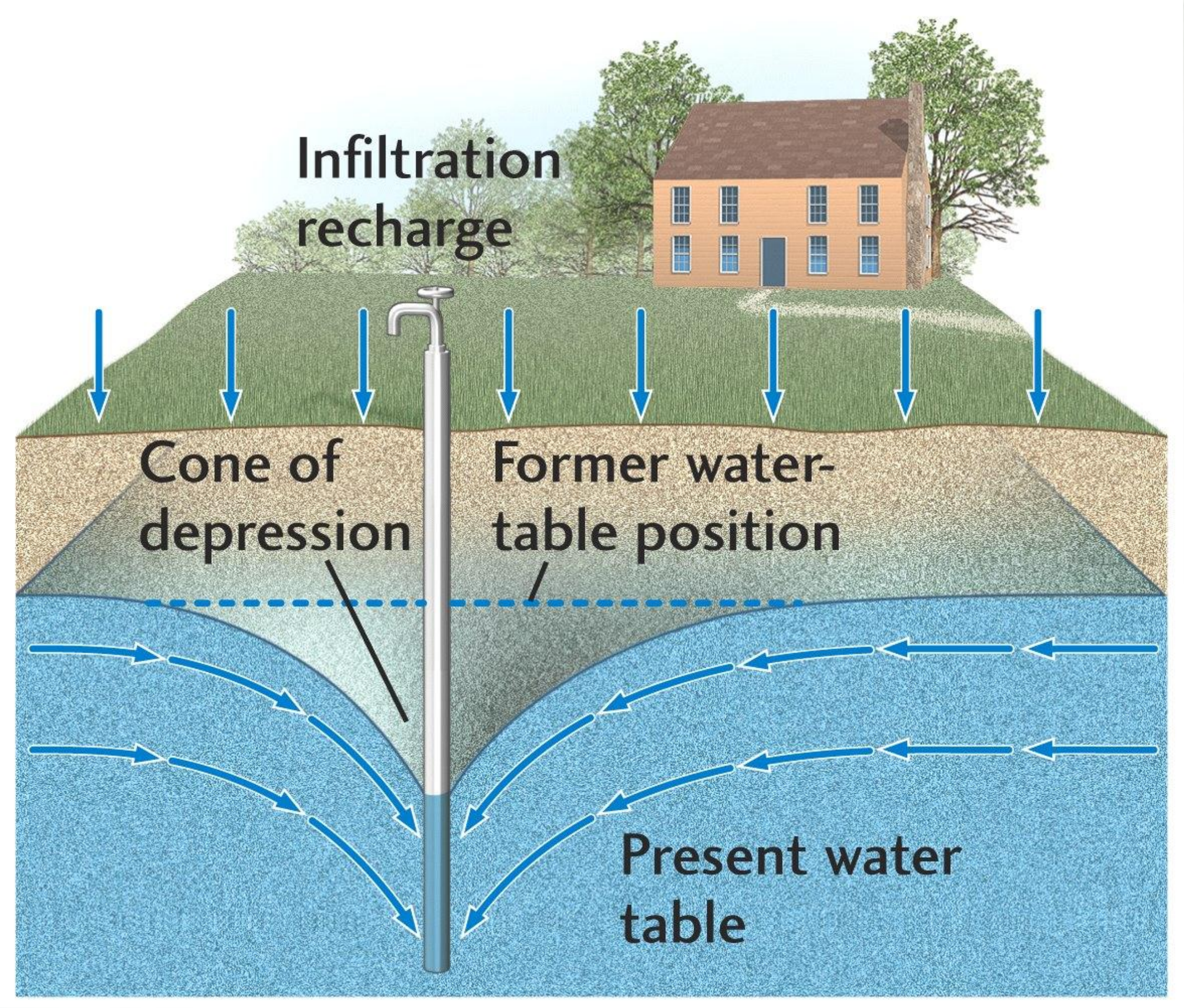
Pressure Surface:
Height to which water will rise
in the confined aquifer



Perched Water Table



Cone of Depression due to Withdrawal



- **<u>Cone of depression</u>** – forms in the water table when water is pumped from a well

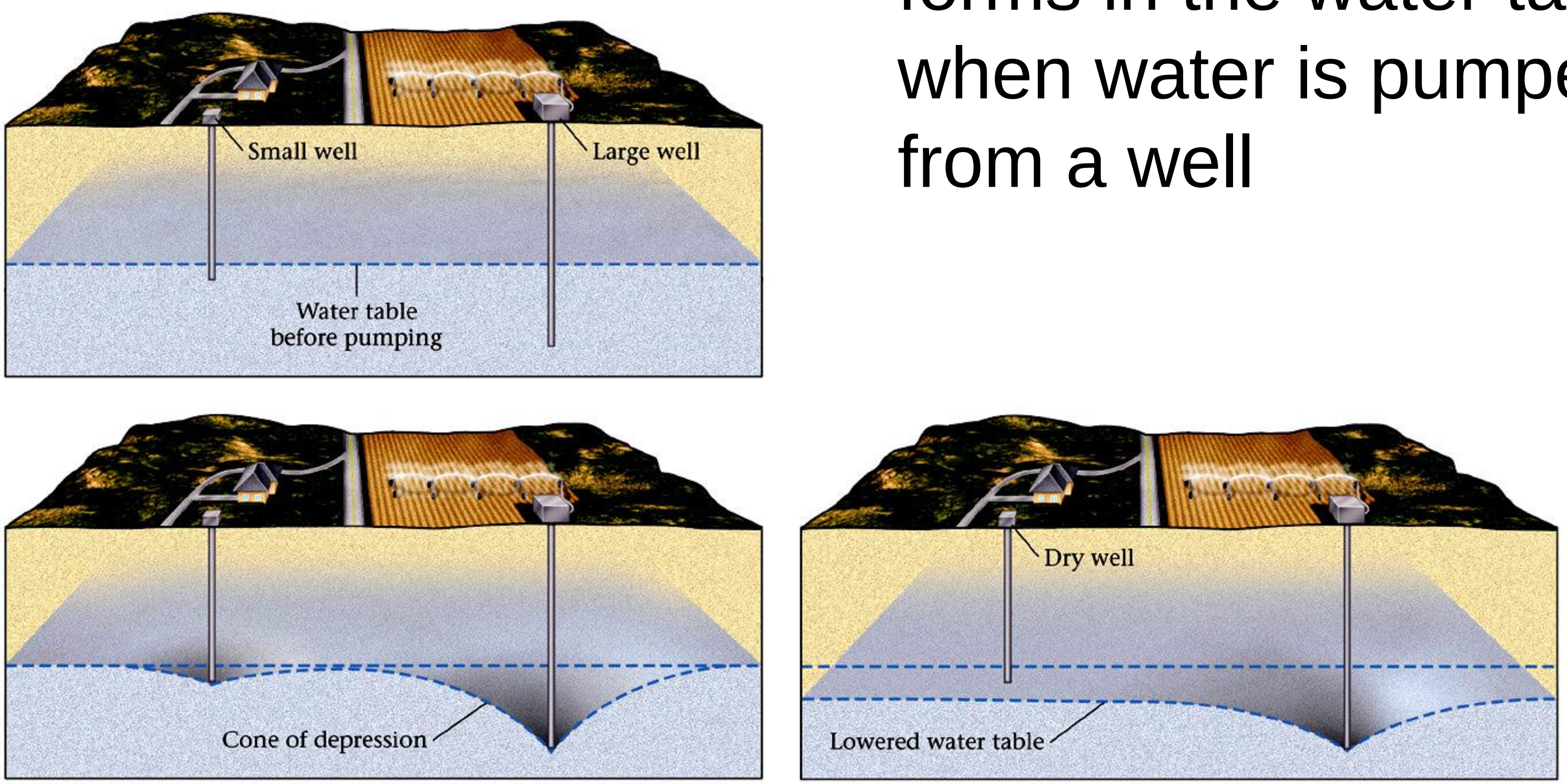


FIGURE 19.13

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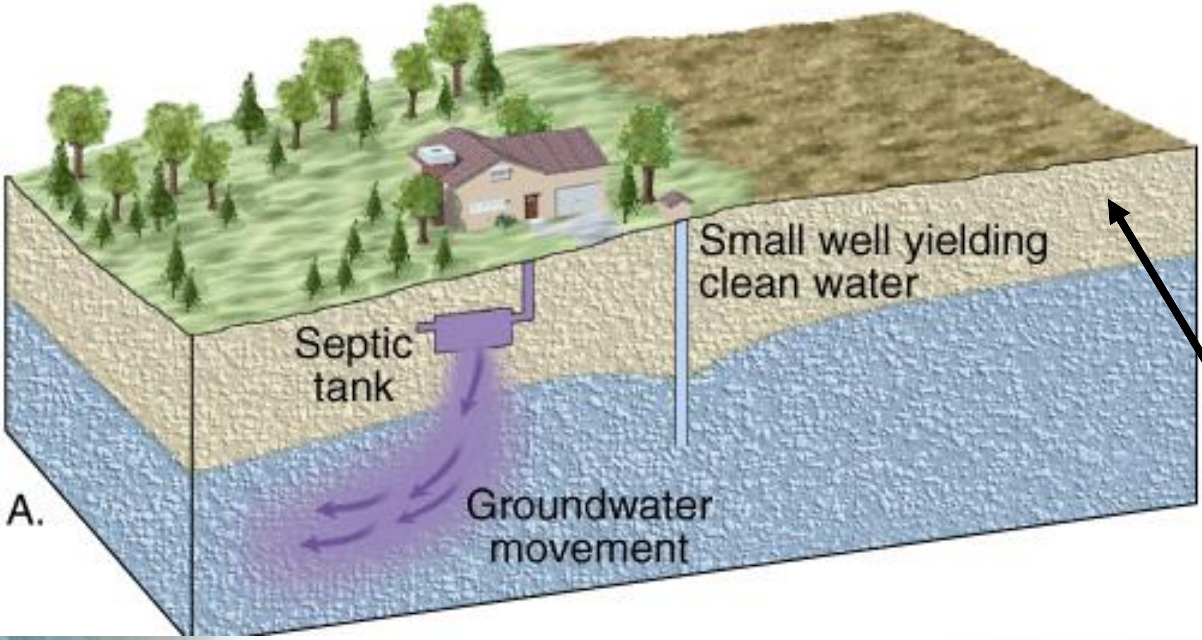
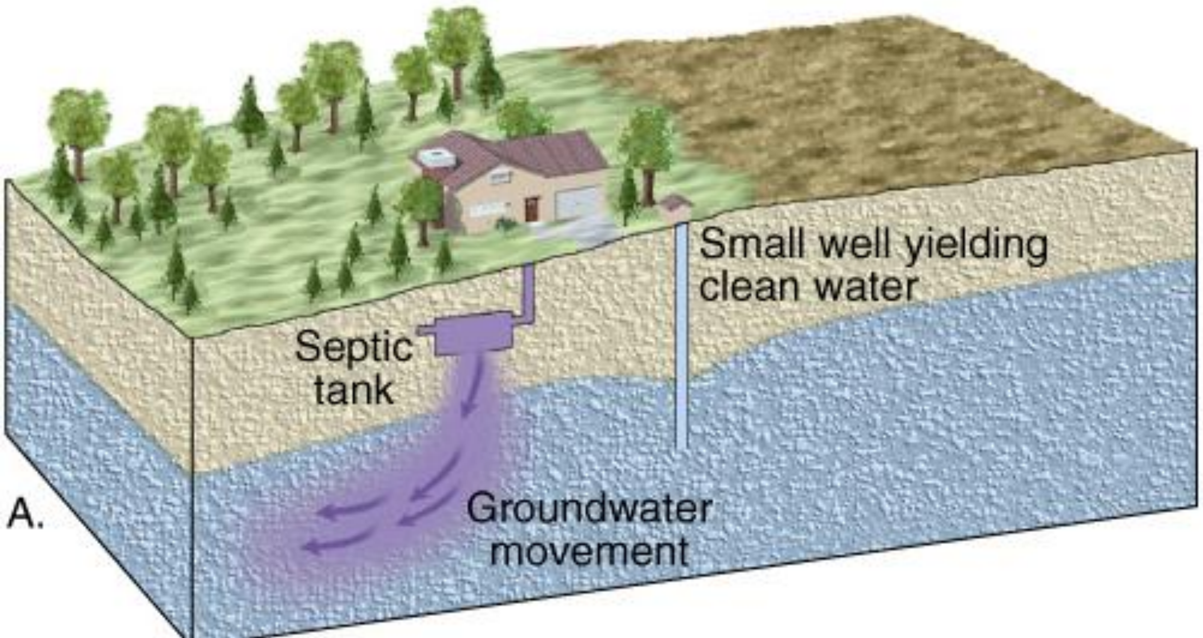
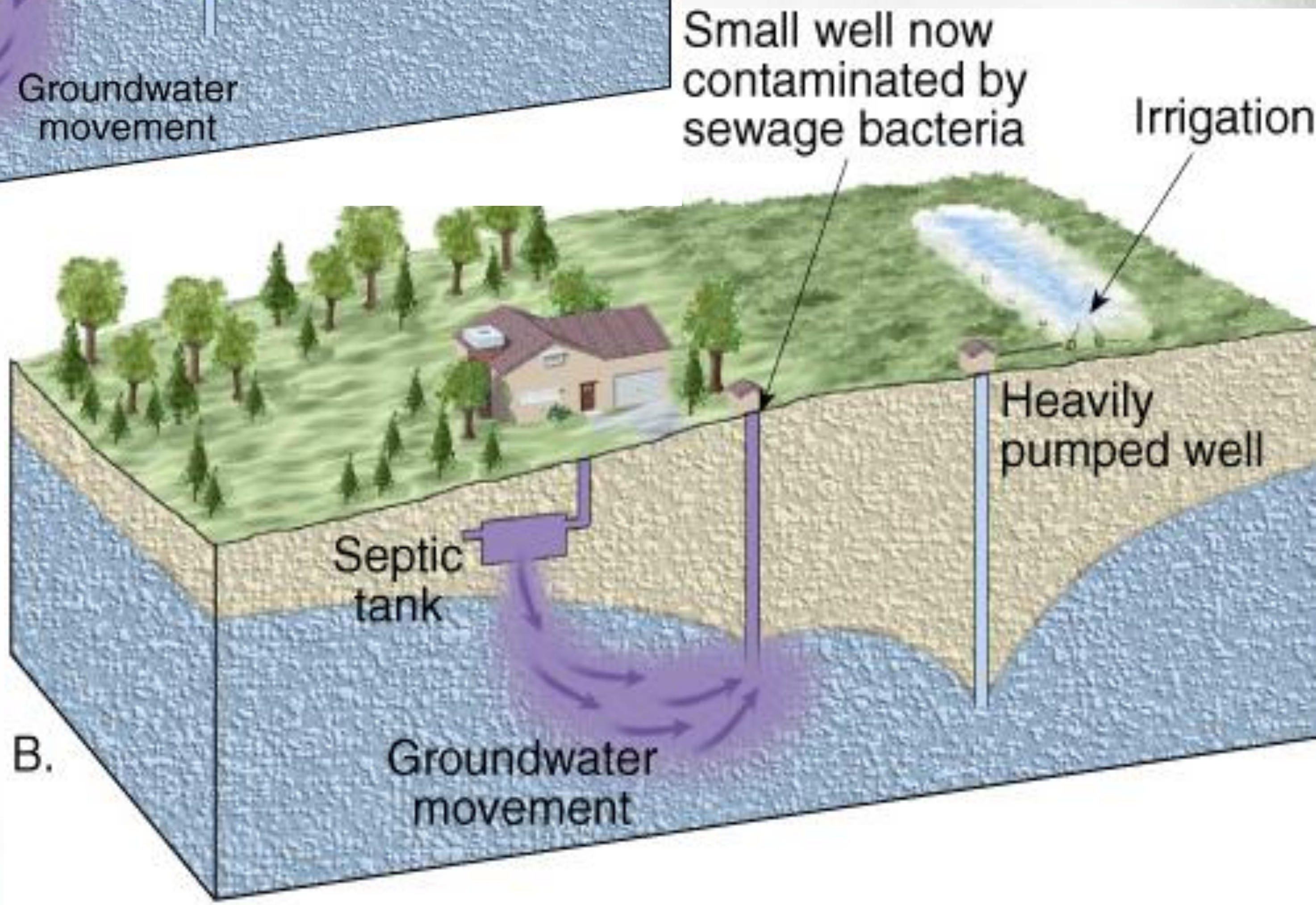


- What happens when a new well here is heavily pumped?

Flow direction can change

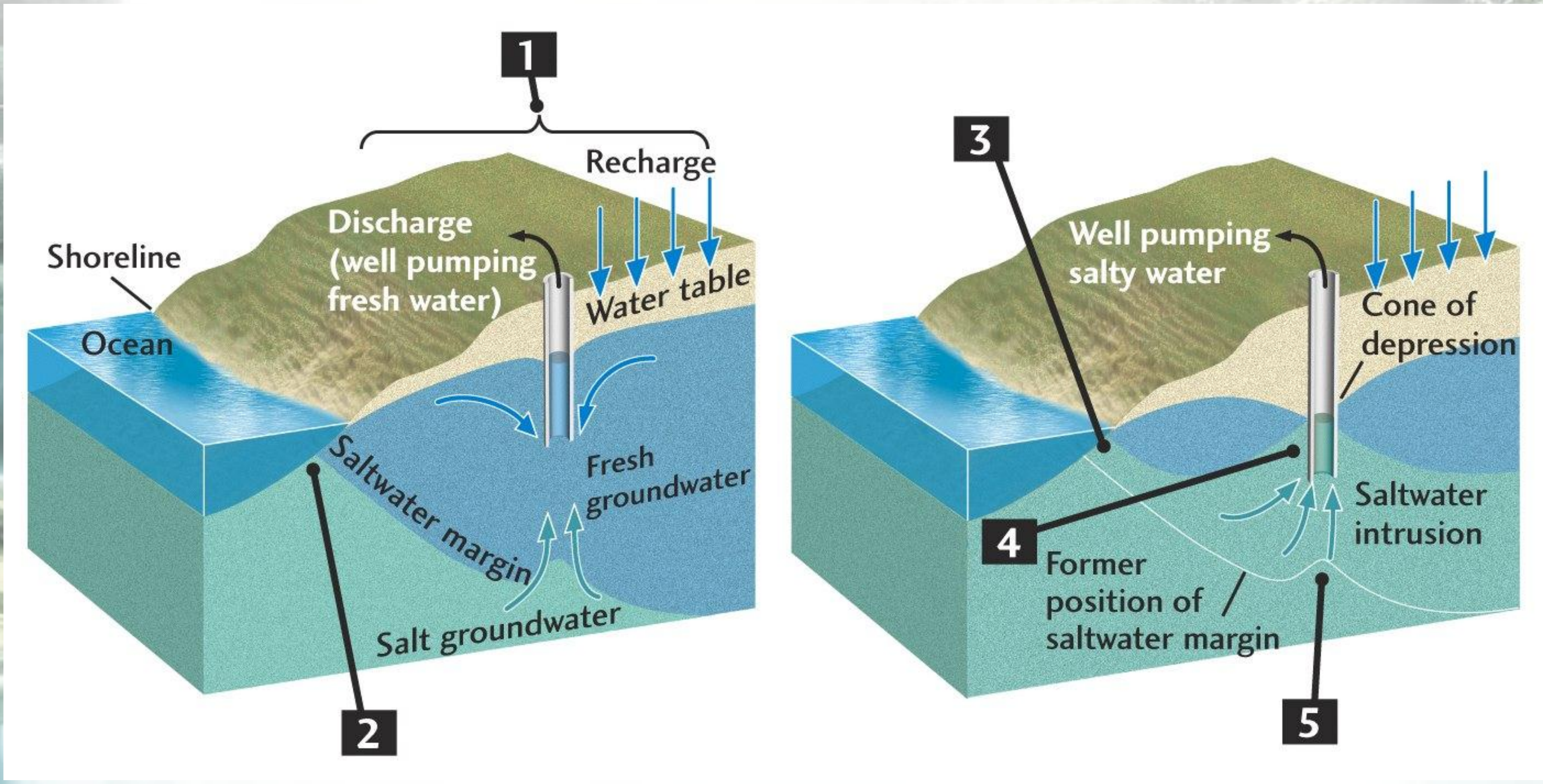




Karst topography

- Topography with features relating to underground solution.
- Collapse may also be involved.
- Surface waters diverted underground.
- Features: sinkholes, sinking streams, rises, caves.

Dynamics of the Saltwater - Fresh Water Interface



Can we predict these changes?

We need to understand how water flows through the subsurface:

- *What drives flow: gravity, pressure*
- *What resists flow: low permeability, lack of recharge (no pressure)*

Darcy's Law: An equation by which the discharge (rate of flow) of groundwater can be calculated.

$$Q = A\,(K \times S)$$

Q = Discharge

A = Cross-sectional area of flow

K = Permeability (hydraulic conductivity)

S = Slope of water table = h/l

h = vertical drop

l = flow distance

Darcy's Law

Rate of flow is directly proportional to drop in water table:

- the greater the drop, the higher the flow.

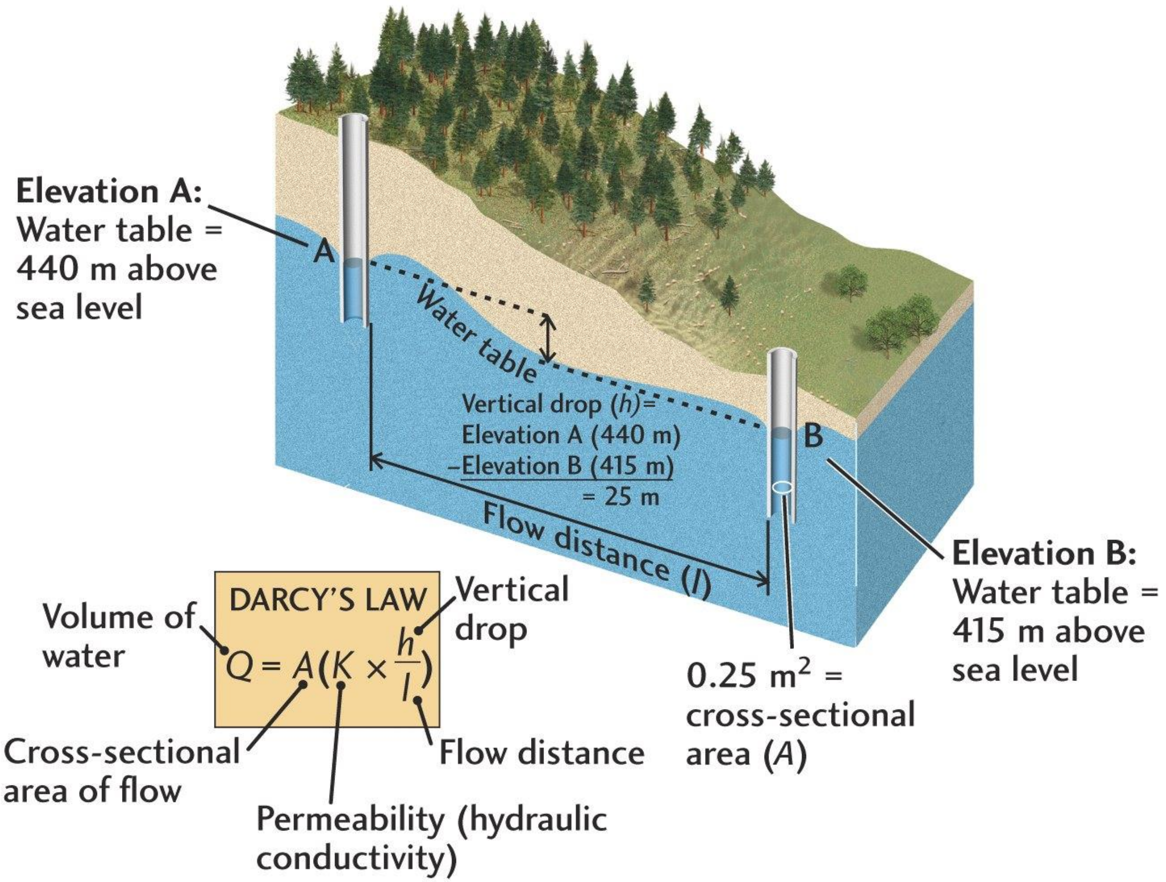
Rate of flow is indirectly proportional to flow distance:

- the greater the distance, the lower the flow.

Hydraulic Gradient: h/l

Groundwater flow also affected by permeability, k

$$Q = A\,(K \times h/l)$$



Darcy's Law for flow through a porous medium

$$\frac{Q}{A} = -K\frac{\Delta h}{\Delta s}$$

Q discharge ($m^3 s^{-1}$)

A cross-sectional area (m^2)

K hydraulic conductivity (of medium)

h head (m)

s distance in direction of flow

$$\frac{Q}{A} = -K\frac{dh}{ds}$$

- Negative sign because flow direction is down the gradient (i.e. in opposite direction to it)
- Yet another example of a diffusion process

In 4D: $$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K_h}\frac{\partial h}{\partial t}$$

Hydraulic conductivity (*K*)

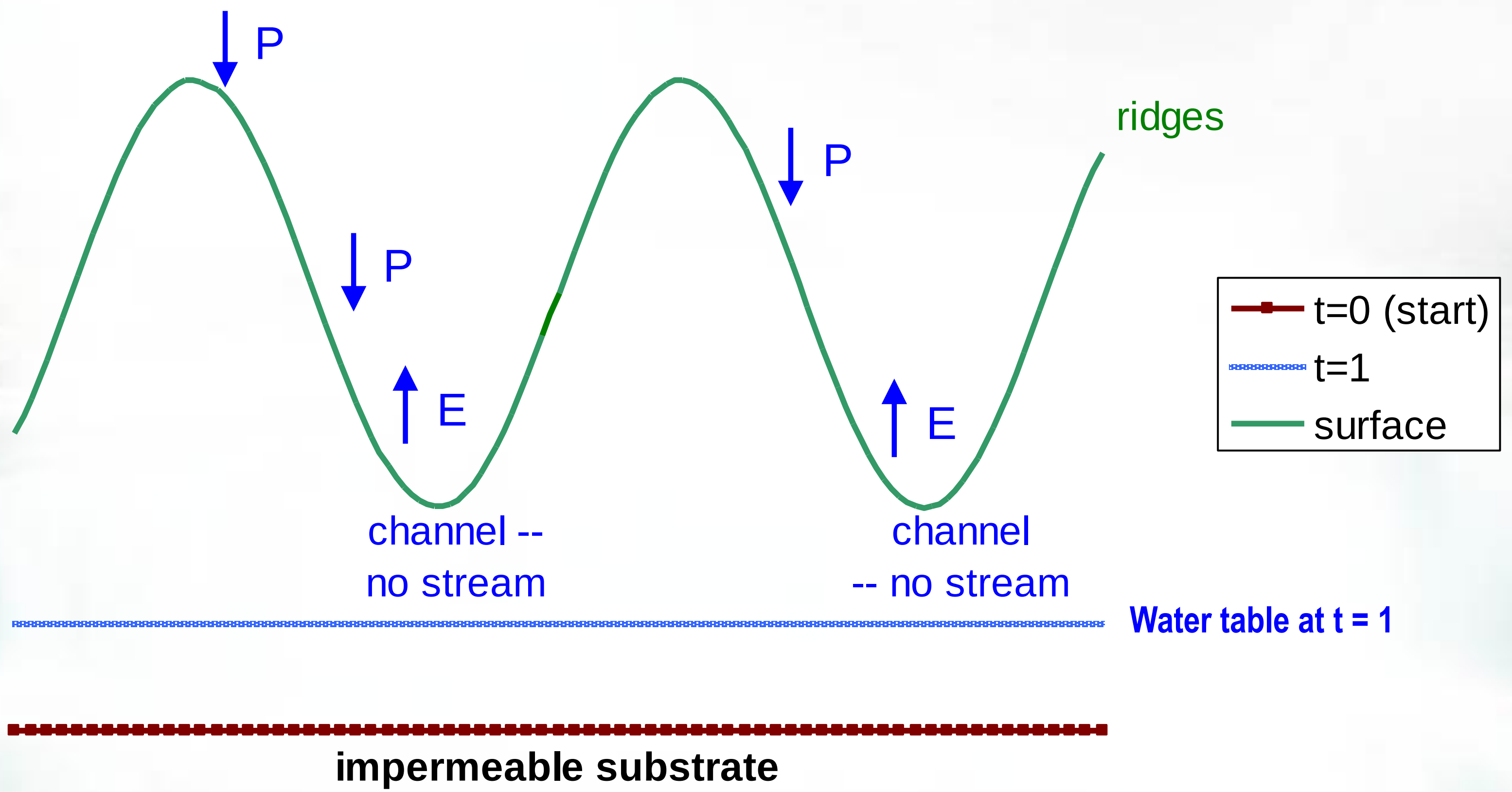
- For a given fluid and temperature (i.e. viscosity and density) the hydraulic conductivity *K* reflects the properties of the soil or rock containing the groundwater

- Hydraulic conductivity correlates roughly with the 2nd-3rd power of the radius of the largest pores or fractures in the medium, though it is not easy to specify exactly which fraction of the largest of these conduits

  - Gravel 10,000-100 m/day
  - Sands 100-1 m/day
  - Silts, glacial till 1-0.001 m/day
  - Clays < 0.001 m/day

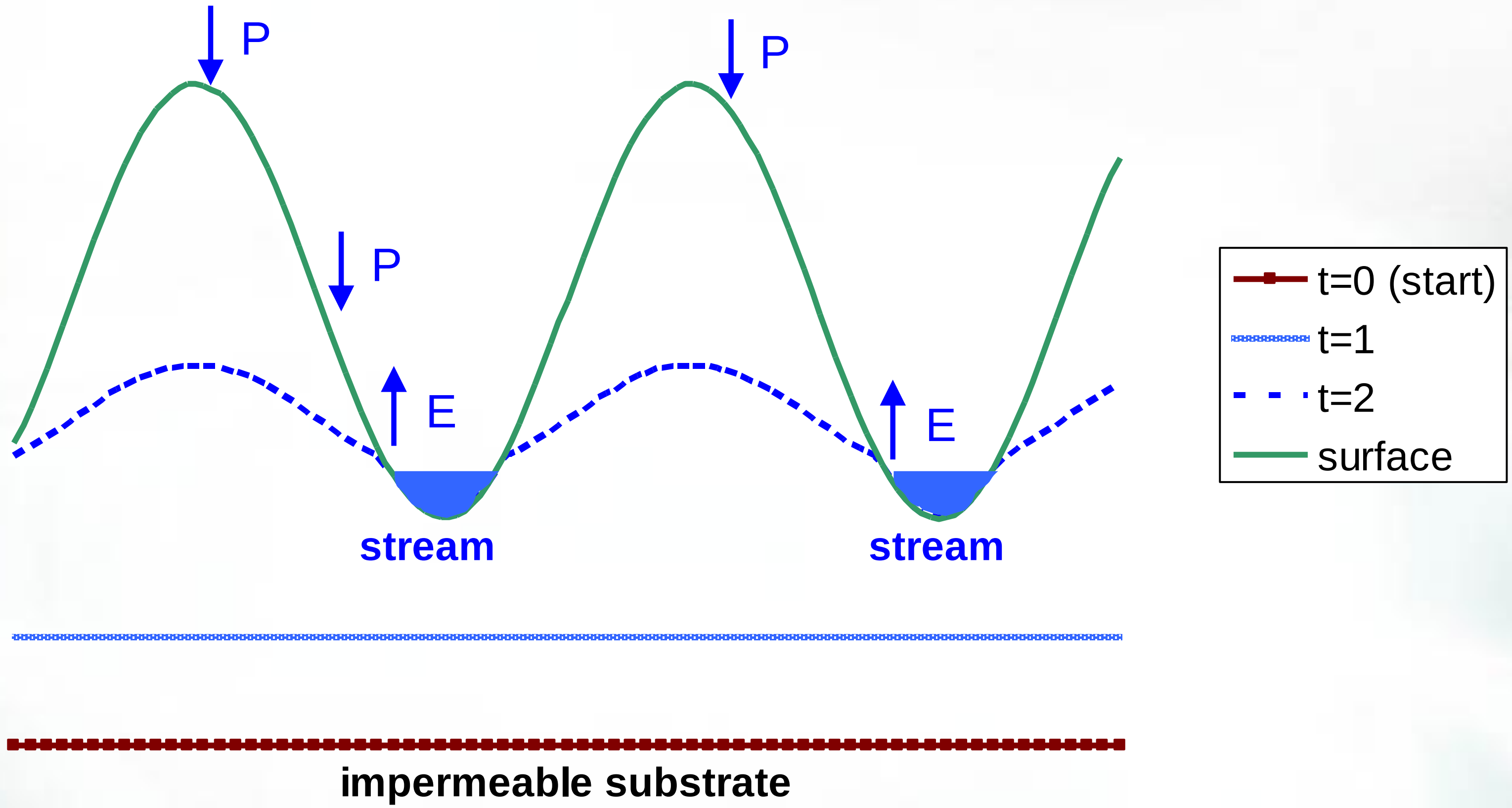
Formation of a groundwater body, early stage (*t* = 1)

Water table has not yet risen to stream channels, so no outflow



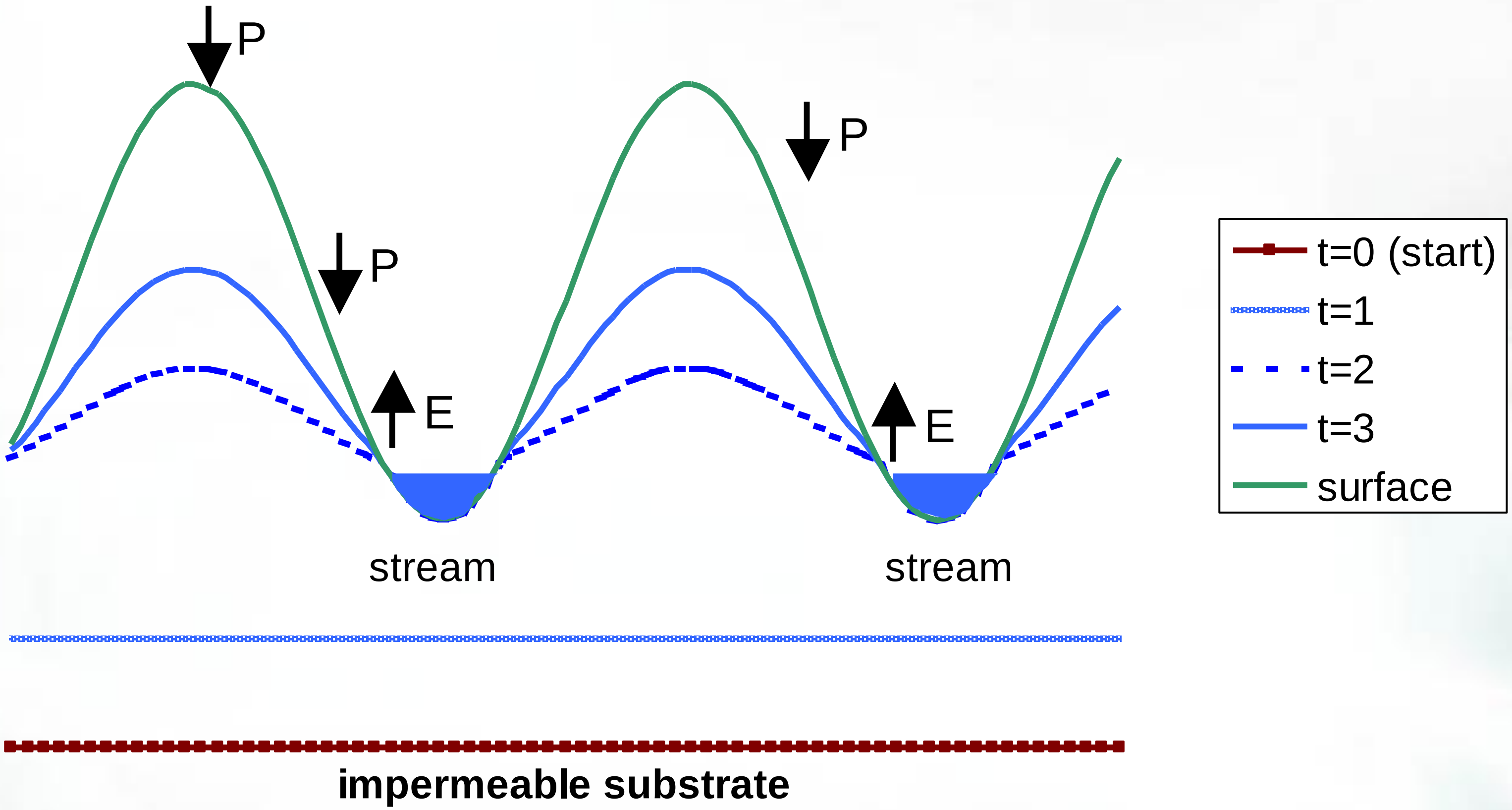
Formation of a groundwater body (*t* = 2)

Water table rises to stream channels, which drain water away, but still at a rate lower than areal sum of (P-E) because the water table gradients are low



Formation of a groundwater body, *t* = 3

Water table (fixed at stream channels) has continued to rise due to recharge until the gradient is sufficient to increase the outflow to equal the areal sum of (P-E)

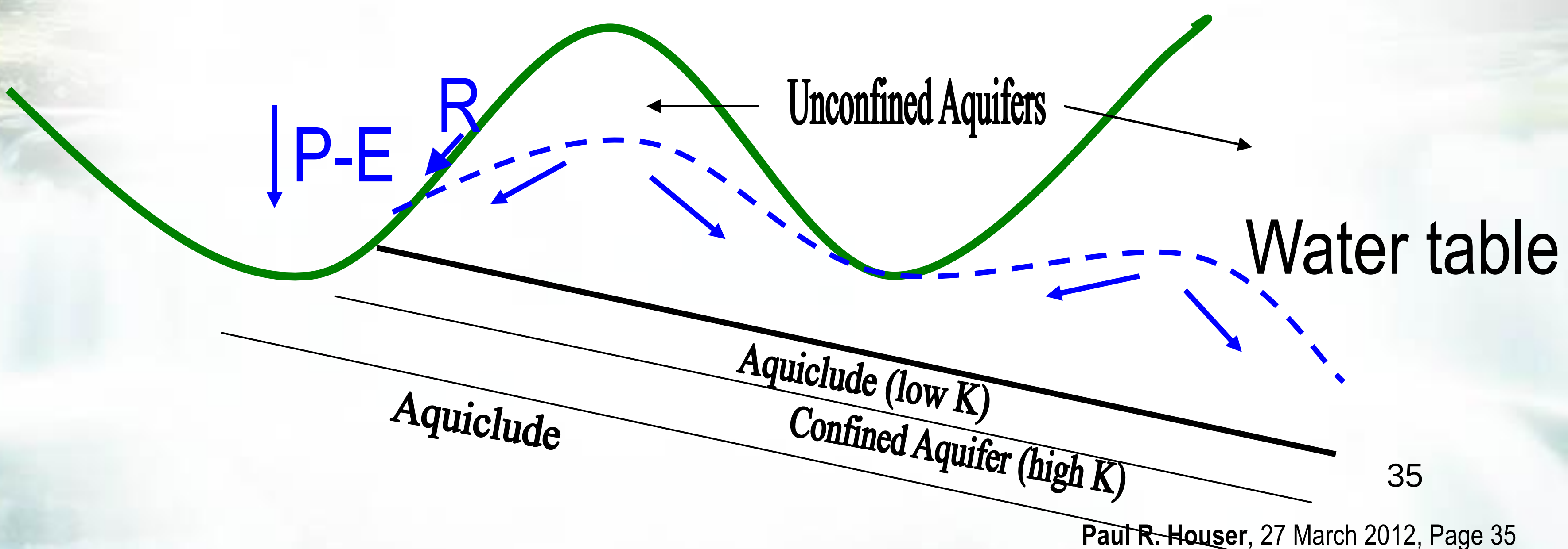


(in words)

- Equilibrium state occurs when outflow of groundwater to streams (Darcy's law) balances *P-E* on the land surface
- Water table is a diffuse mimic of the topography
- The lower the value of *K,* the steeper the water table must be to convey the water
- If (P – E) varies seasonally, the water-table gradient and therefore height and outflow rate will also change

Effects of lithologic heterogeneity

- Rocks/soils have *very* heterogeneous *K* values (14 orders of magnitude)
  - Therefore, the arrangement and orientation of the rocks also affect the volume, direction, and speed of groundwater flow



Groundwater Sustainability

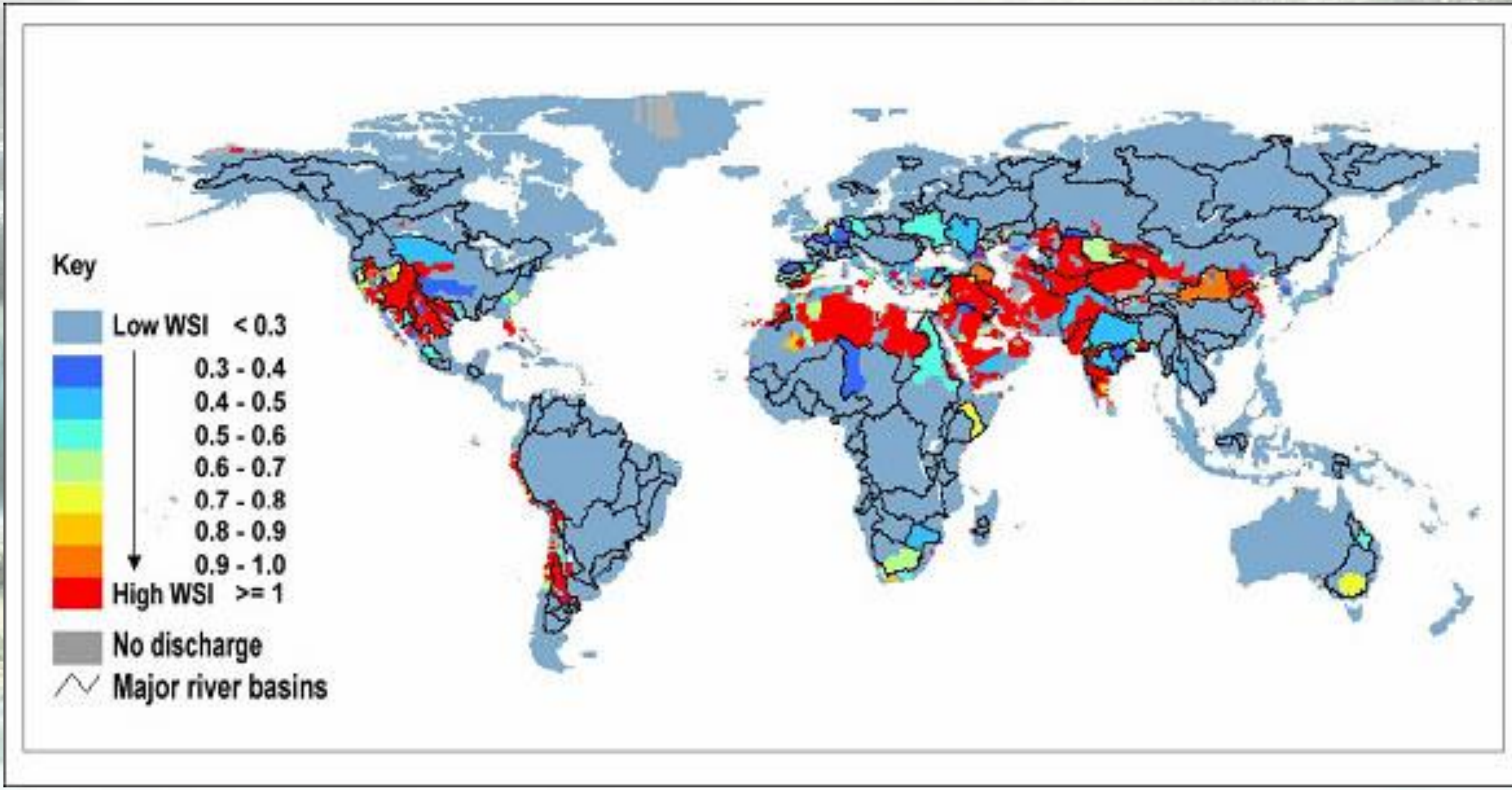
To Maintain the Water Table, Discharge MUST be Balanced by Recharge

If imbalance Exists:

- *Decrease discharge, i.e., water usage*
- *Increase recharge, i.e., pump recycled water*
- *Increase permeability??*

Groundwater Depletion: When groundwater removed from an aquifer exceeds the amount produced (i.e., demand > supply).

- Main causes
  - Too much demand
  - Too little rainfall.
- Where are the biggest problems?
  - Northern and Eastern states – adequate groundwater supplies – usually not a problem
  - Southwest U.S. – inadequate supplies – can be a big problem



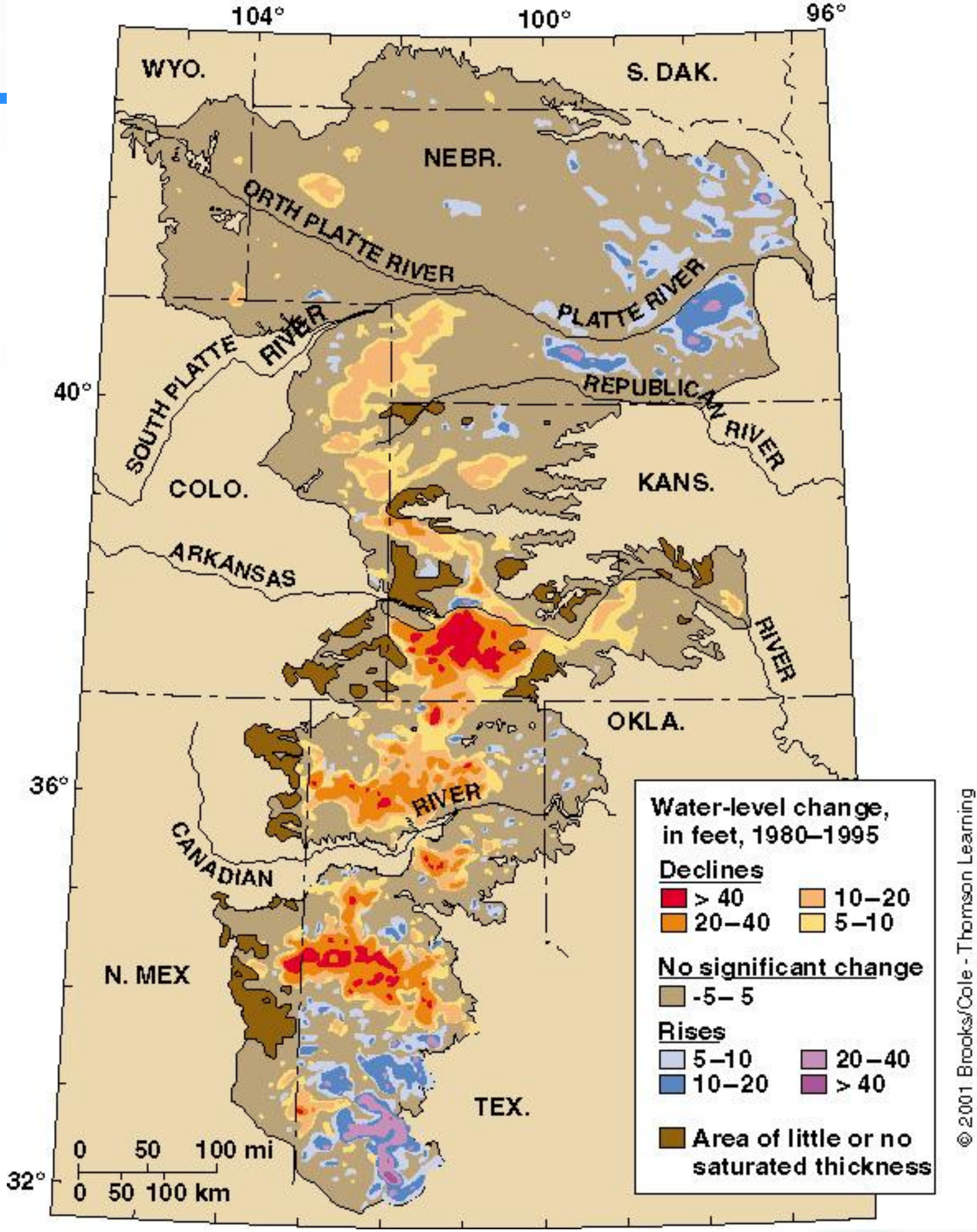
Map of water stress indicator (International Water Management Institute (IWMI))

Case Study - Ogallala Sandstone/High Plains Aquifer

- The Ogallala Sandstone (High Plains Aquifer) is a very large confined aquifer that underlies much of the High Plains (NE, KS, OK, TX) and is used for irrigation.

- It was filled (recharged) following the Ice Age
  - The aquifer contains “fossil” water, the product of a wetter ancient climate associated with the end of the last ice age
  - There is no sufficient contemporary source for water to recharge the whole aquifer

- Today = little recharge and demand <u>greatly</u> outweighs supply.
- In the 1940's (before groundwater pumping occurred) the average saturated zone was > 60 meters thick.
- By 1980 the average saturated zone ~3 meters thick.
  - 30-60 meter decline in some areas



- **Problems:**
  - Currently water is being extracted at 100 times the natural replacement rate
  - Poor irrigation practices
    - Losing substantial water to evaporation
  - Little incentive to conserve water
    - Government prices support the farming of water-hungry crops
    - Lose water-use rights if a minimum amount of groundwater is NOT extracted each year

- In the 1980's, the situation improved due to:
  - better water management (well meters, waste water reuse)
  - heavy rains
  - new technologies - new irrigation nozzles that decrease evaporation loss by up to 98% over previous methods.

- Projection - 25% of the water in Ogallala will be used by 2020. <u>UNSUSTAINABLE USAGE</u>

Question:

If groundwater systems are at equilibrium, how can we extract *any* water without depleting the volume stored?

- To a first approximation, we can't. If we pump (Q, volume of water per unit area of aquifer), then $R=P-E-Q$
- The maximum value of Q (per year over the long term) cannot exceed (P-E) without reducing the volume in storage and the runoff, which must ultimately → 0
- But, we can "choose" to reduce R by pumping and live with the new "equilibrium" R in the rivers
- In other cases, there is a feedback of Q reducing E. For example by drawing down water tables, we can reduce water "loss" by E and absorb the ecological changes. Demise of some riparian forests in Central California. 1960s UN proposal for the Sahara.
- In other cases, pumping can lower the water table and induce recharge from rivers
- In many cases, we pump at Q > (P-E) and "mine" water emplaced in a wetter or cooler climate (upto 100,000s of years ago)

How much water do we use per capita in the U.S. per day?

- Choose 1:
  - 2 liters?
  - 10 liters?
  - 300 liters?
  - 6000 liters?

6000 liters….

A human can survive on just 2 liters a day. How do we use so much?

Personal use per capita per day without conservation:

Shower/bath:	60 liters
Toilet:	80 liters
Faucet:	45 liters
Dish/clothes washer	75 liters
Other domestic	40 liters
TOTAL	**300 liters**

Personal use per capita per day with conservation:

Shower/bath:	50 liters
Toilet:	40 liters
Faucet:	45 liters
Dish/clothes washer	50 liters
Other domestic	25 liters
TOTAL	**210 liters**

Still just a few percent of 6000 liters…

Main uses of water

Table 2.1 Global water use in the 20th century

Although we are withdrawing only 10% of renewable water resources, and consuming only about 5%, there are still problems for human use. Water is unevenly distributed in space and in time—and we are degrading the quality of much more water than we withdraw and consume.

Cubic kilometres

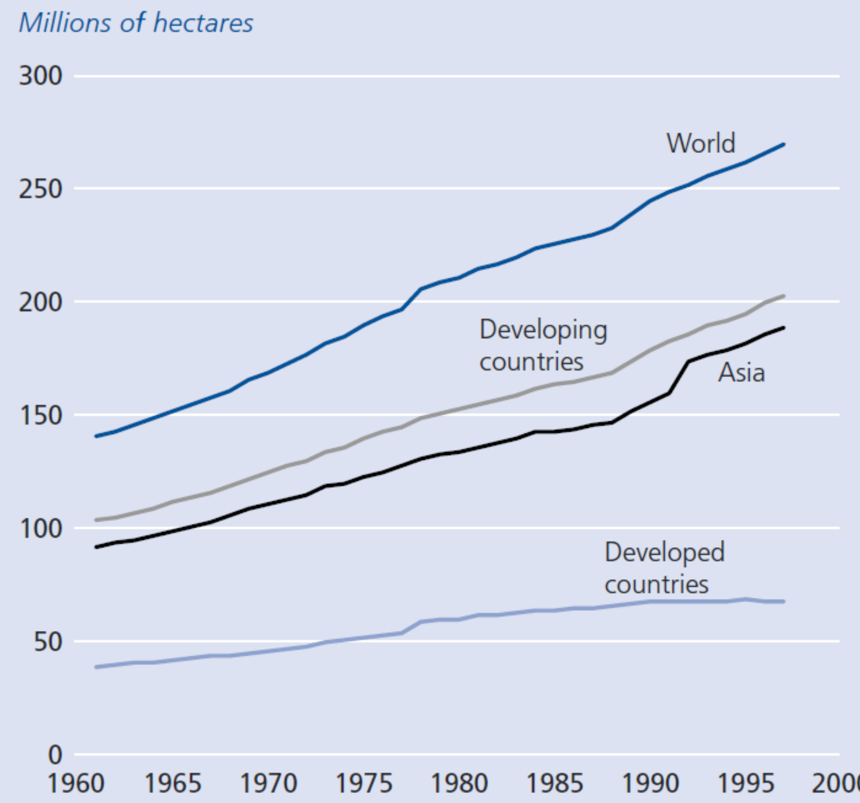
Use	1900	1950	1995
Agriculture			
Withdrawal	500	1,100	2,500
Consumption	300	700	1,750
Industry			
Withdrawal	40	200	750
Consumption	5	20	80
Municipalities			
Withdrawal	20	90	350
Consumption	5	115	50
Reservoirs (evaporation)	0	10	200
Totals			
Withdrawal	600	1,400	3,800
Consumption	300	750	2,100

Note: All numbers are rounded.

Source: Shiklomanov 1999.

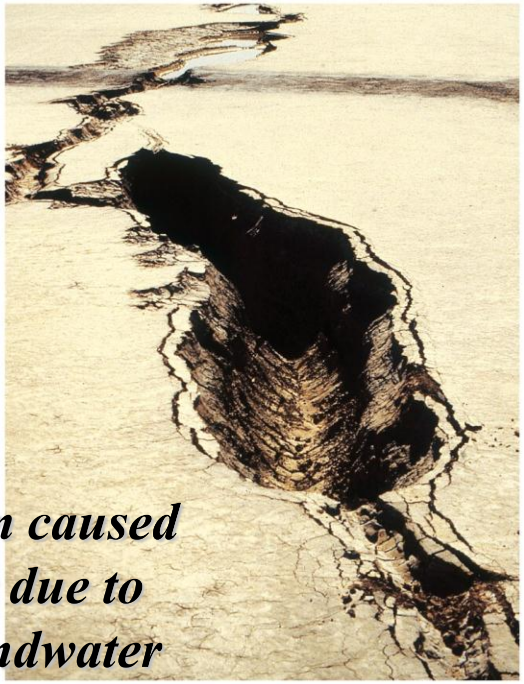
Figure 2.1 Net irrigated area, 1961–97

Irrigated area nearly doubled in the last four decades of the 20th century, mostly in Asia (China, India, Pakistan) and the United States, with the pace of development slowing after 1980 in the developed world.



SUBSIDENCE

- Subsidence - a sinking or downward settling of the earth's surface
  - Typically irreversible
  - Subsidence is observed in 45 US states, estimated damage is $125 million per year.
  - Usually not associated with loss of life



Fissures and depression caused by ground subsidence due to over-pumping of groundwater (Edwards Air Force Base)

Areas where subsidence has been attributed to ground-water pumpage (Land Subsidence in the United States, USGS Circular 1182)

Deep Subsidence

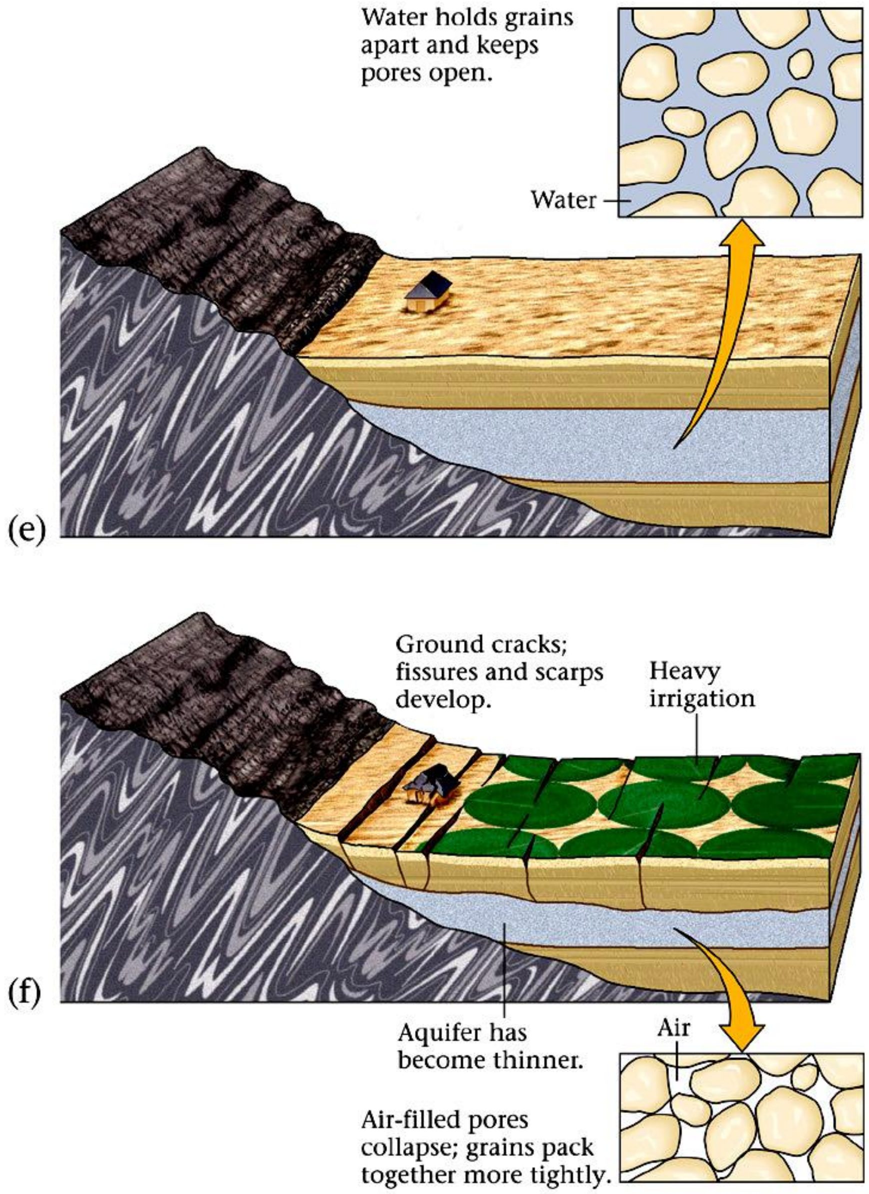
– Gradual compaction of sediment caused by withdrawal of fluids (groundwater or oil) from the subsurface over large regions

– Usually human-induced

– Late recognition

– Example regions:
  - San Joaquin Valley, CA;
  - Houston / Galveston, TX;
  - Venice, Italy;
  - Mexico City, Mexico

- Pore Collapse
  - When groundwater fills the pore space of a rock, it holds the grains of the rock or sediment apart
    - Water cannot be compressed
  - The extraction of water from a pore eliminates the support holding the grains apart
    - The air that replaces the water **can** be compressed
  - As a result, the grains pack more closely together
  - This **pore collapse** permanently decreases the porosity and permeability of a rock
    - Porosity = the ability to hold fluid
    - Permeability = the ability to allow fluids to pass through



- Land Subsidence
  - Pore collapse can also decrease the volume of the aquifer
  - The result is that the land above the aquifer sinks
  - This **land subsidence** may cause
    - fissures at the surface to develop
    - and the ground to tilt
  - The Leaning Tower of Pisa, in Italy, tilts because the removal of groundwater caused its foundation to subside
  - The effect of land subsidence is most severe for **clay- and organic-rich sediments**

(g)

– In coastal areas, land subsidence may even make the land surface sink below sea level

- The flooding in Venice, Italy, is due to land subsidence

(i)

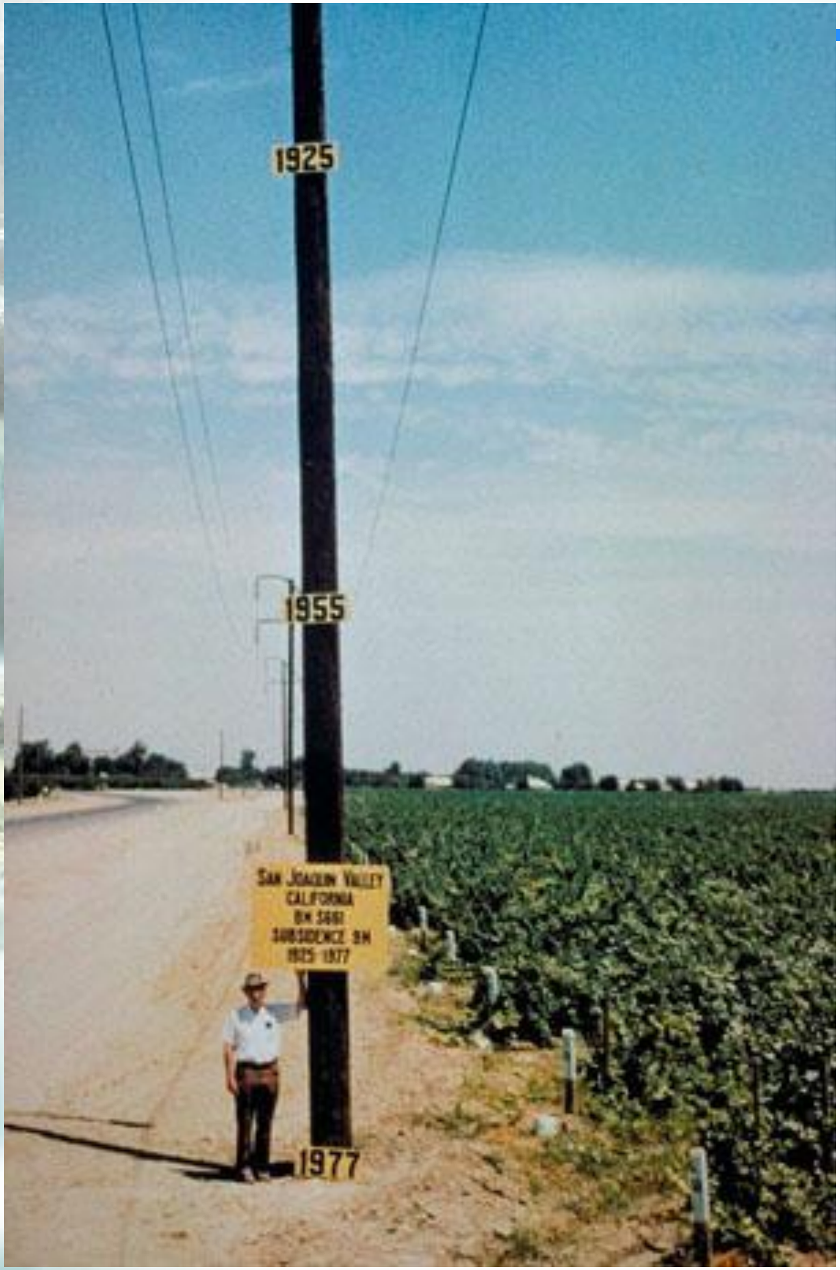

FIGURE 19.21

Damaging Effects of Subsidence

- Construction damage (buildings, roads, dams, etc.)
- Alteration of landscape
- Increased risk of flooding (lowered land surface)

Case Study - Groundwater extraction

- San Joaquin Valley, CA (1925-1975)
  - **Location** - flat basin between two mountain ranges - Sierra Nevada Mountains (E) and Coast Range (W)
  - > 5000 km^2 in central California subsided up to 8.93 meters
  - **Cause** - overuse of groundwater (for agriculture) over a period of 50 years, linked to declining water table


1925
1955
SAN JOAQUIN VALLEY
CALIFORNIA
SUBSIDENCE BM
1977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- **Effect** - subsidence was greatest on the west side (underlain by finest-grained sediment - easiest to compact)
  - Reduced porosity and permeability (loss of aquifer!)
- **Mitigation** - greater use of *surface water* for agriculture
- **Conclusion** - region is still subsiding today (but much more slowly)

Saltwater Intrusion

- In coastal areas, fresh groundwater lies in a layer above the saltwater that entered the aquifer from the adjacent ocean
  - Saltwater is denser than freshwater
  - Therefore, fresh groundwater floats above the saltwater
- If water is pumped out of the aquifer too quickly, the boundary between the saline water and the fresh groundwater rises

- If the boundary between the fresh groundwater and the saline water rises above the base of the well, the well will start to yield useless saline water

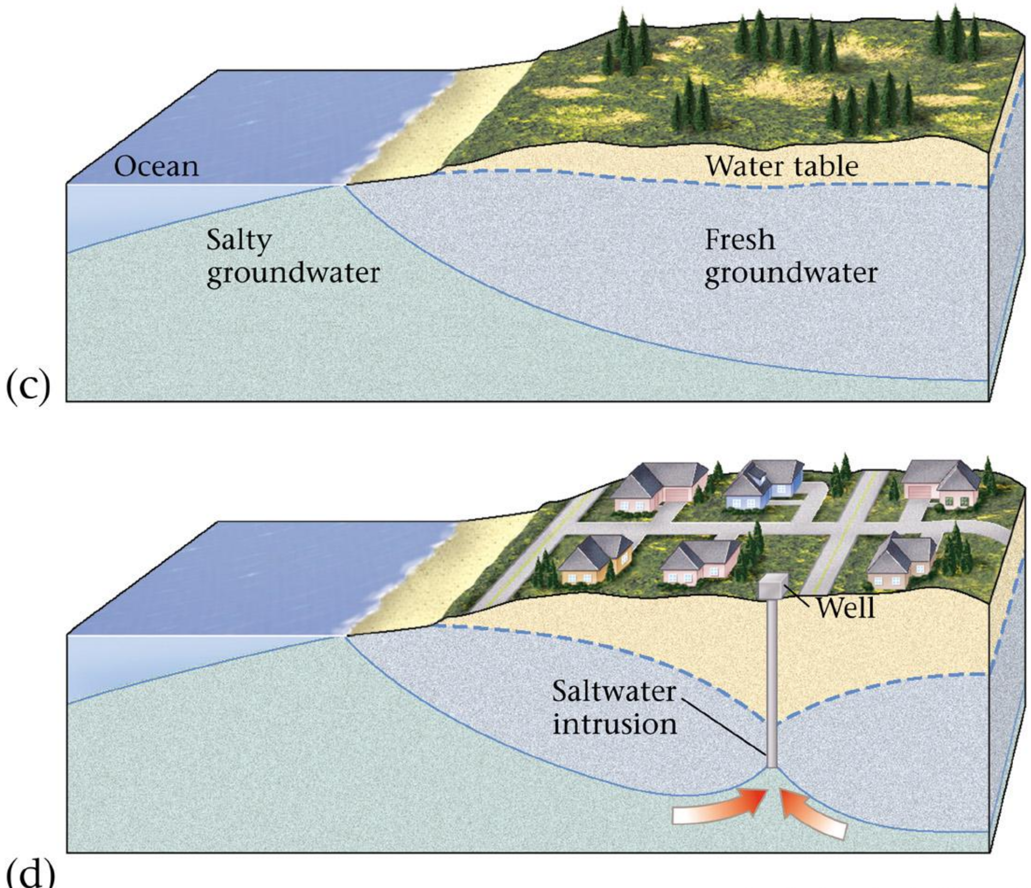

FIGURE 19.21

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Groundwater Pollution

- Pollutants and sources that contaminate surface waters can also pollute groundwater
- Examples
  - Leaky landfills
  - Industrial waste lagoons
  - Agricultural activities
  - Underground storage tanks
- Groundwater pollution may go unnoticed and undetected for a long period of time
  - Groundwater moves **very** slowly

- Groundwater contamination
  - Rocks and sediments are natural filters capable of efficiently removing suspended solids (mud and solid waster) from groundwater
    - These solids get trapped in the tiny pathways between pores
    - Clay flakes can remove certain ions from the water
      - They have electrically charged surfaces
  - However, invisible organic and inorganic chemicals may be carried along with the flowing groundwater
    - Some dissolved chemicals are toxic – arsenic, mercury, lead
    - Others are not – salt, iron, lime, sulfur

- In recent decades, human activity has increasingly introduced contaminants into aquifers

- These contaminants include
  - Agricultural waste – fertilizers, pesticides, and animal wastes
  - Industrial waste
  - Effluent from “sanitary” landfills and septic tanks
  - Radioactive waste – from weapons manufacture, power plants, and hospitals
  - Acids leached from sulfide minerals in coal and mineral mines

– Some of these contaminants
    - Seep into the ground from subsurface tanks
    - Infiltrate from the surface
    - Are intentionally forced through injection wells

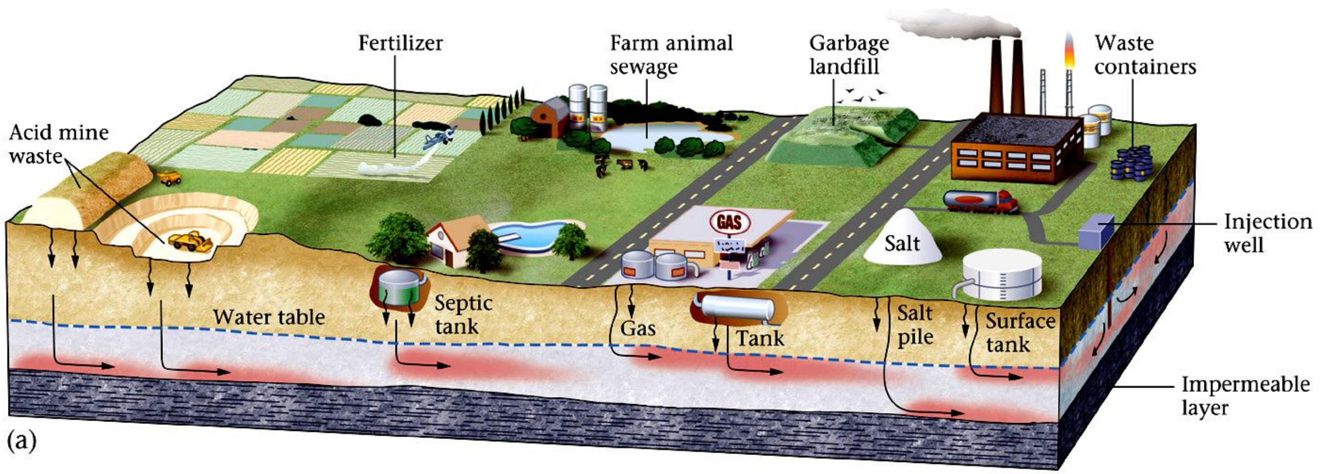

FIGURE 19.23

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– The cloud of contaminated groundwater that moves away from the source of the contamination is called a **contaminant plume**

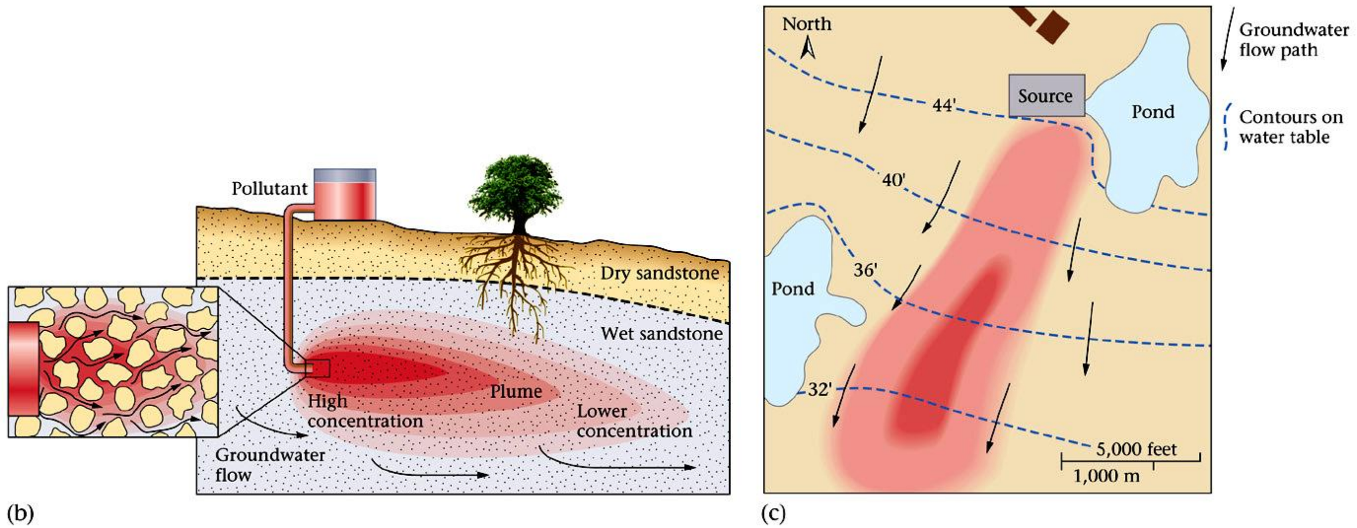
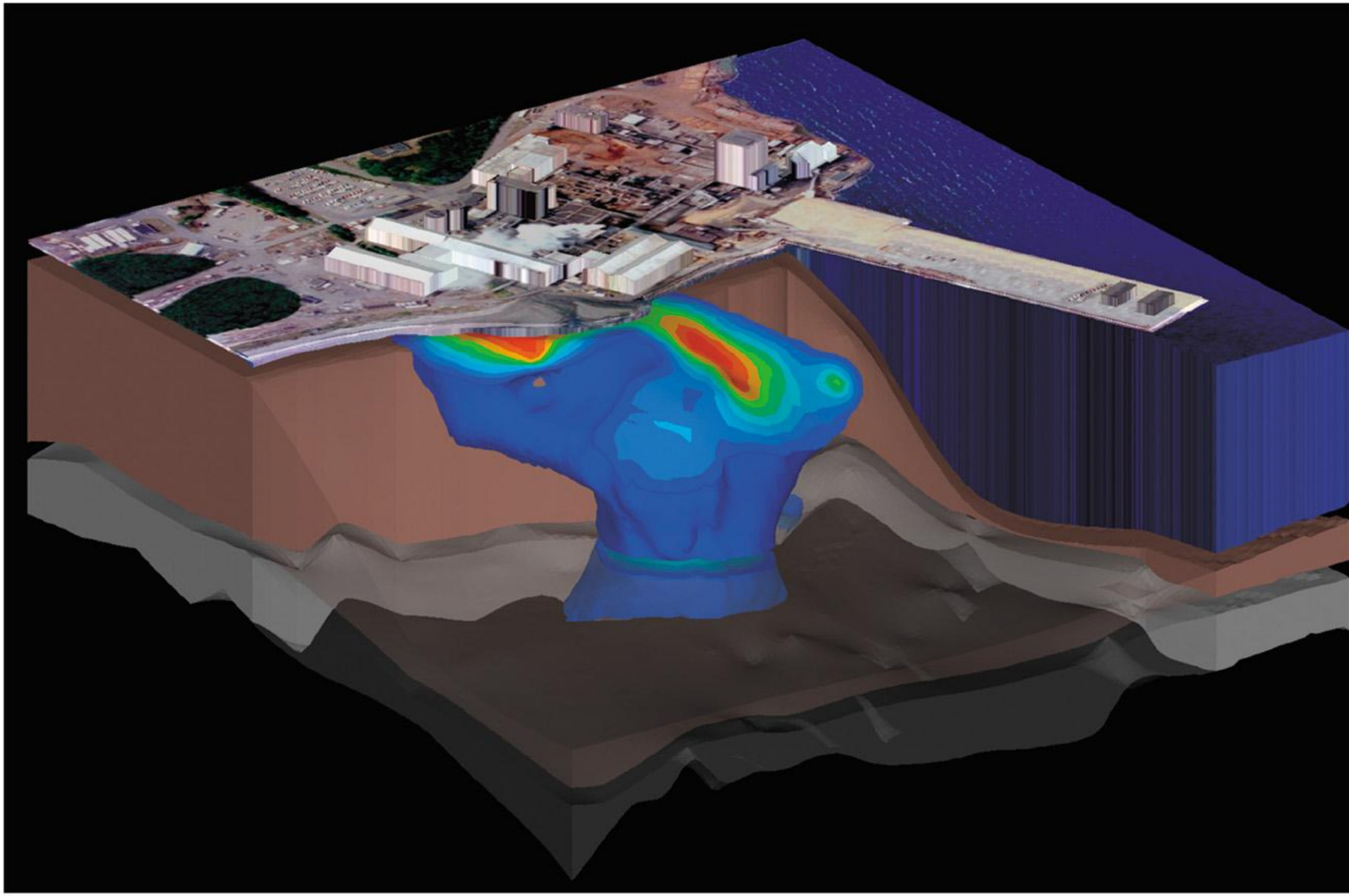


FIGURE 19.23

3-D image of a contaminant plume



(d)

FIGURE 19.23

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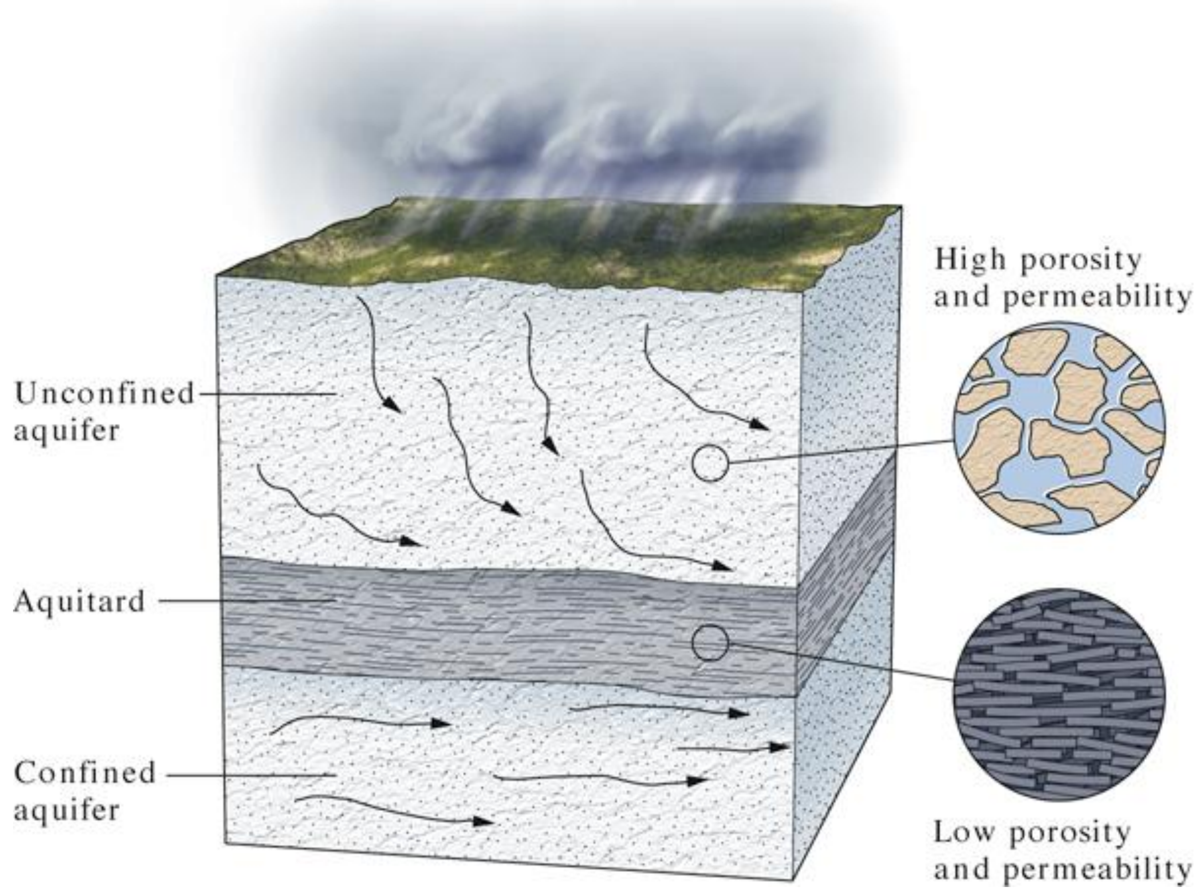
- Most groundwater contamination occurs in **<u>shallow unconfined aquifers</u>** located near a contaminant source.

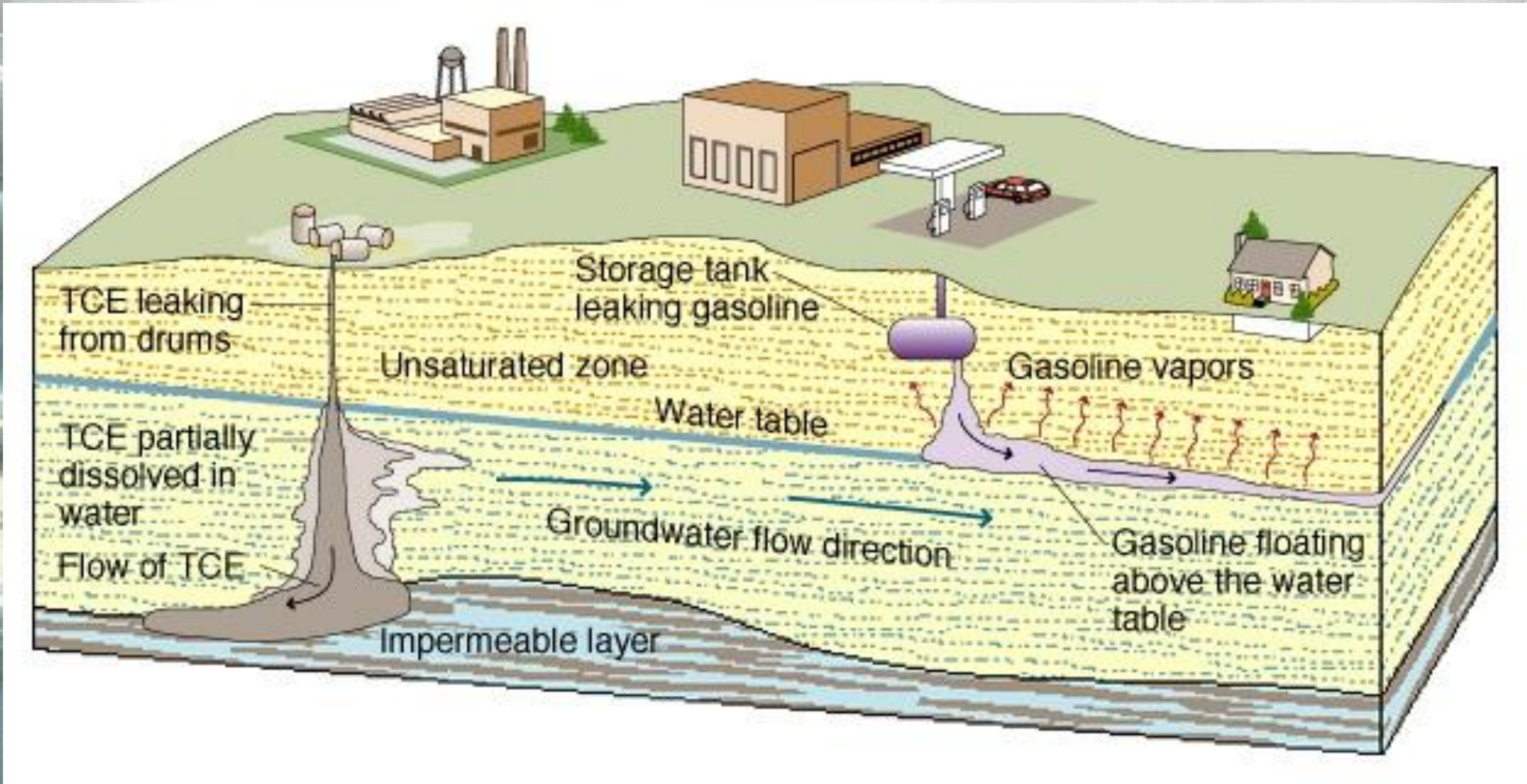


Common Sources of Groundwater Pollution

- Leaking underground storage tanks (gasoline stations)
  - Before 1980, these tanks were made of metal and tended to corrode and leak pollutants into the soil and groundwater.
  - Now, leak detectors are required, old storage tanks are being dug up and replaced, and the soil has to be cleaned up or destroyed (incinerated).
  - In Denver, 80 liters of organic solvents contaminated 4.5 trillion liters of groundwater, affecting an area 5 km in length!

- Septic tanks - bacterial/chemical pollution can be released when
  - there are heavy rains and clay-rich soils cause the water to float the raw sewage to the surface
  - extremely permeable or fractured bedrock does not effectively filter the waste as it passes through

Light and heavy immiscible contaminants

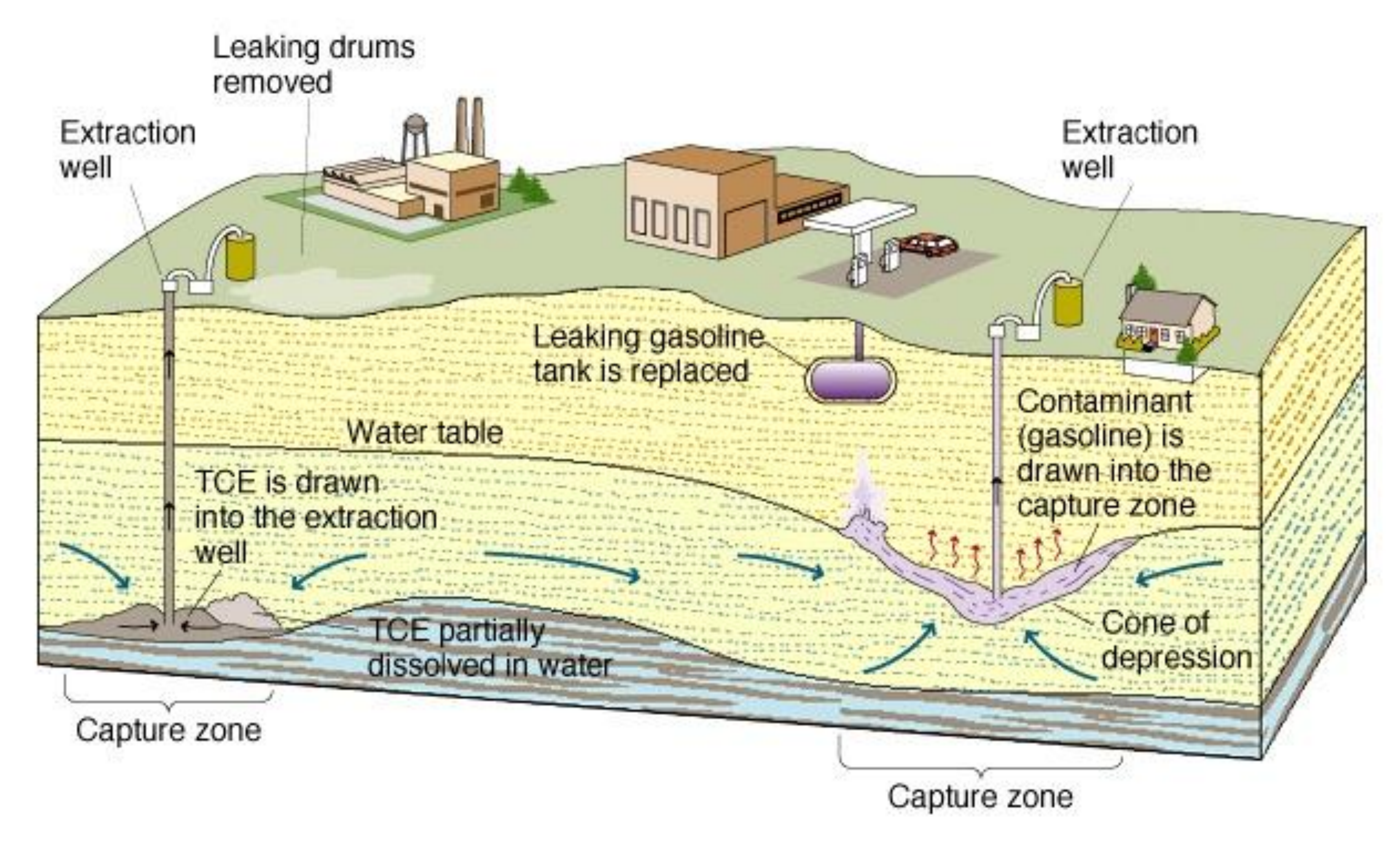


Heavy: TCE (trichloroethene) Light: gasoline

Groundwater treatment

- Reduce or stop input and then wait for nature to remove or destroy pollutants
  - Easiest and least costly, but SLOW and a long-term hazard to the environment.
- Extract groundwater
  - Pump out the contaminated water and try to treat it, remove the soil and treat or destroy it.
  - Problem - extraction is not very efficient or productive

Extraction wells - remediation



- In-situ
  - add chemicals to immobilize heavy metals
  - add oxygen or nutrients along with microorganisms to stimulate them to munch on the pollutants
    - common approach for oil spills