

G202 GROUNDWATER AND KARST PROCESSES

I. GROUNDWATER OCCURRENCE AND PROCESSES

A. Introduction

1. Water contained within cracks, fractures and pore spaces of soil, sediment and rocks beneath the surface of the earth
2. Groundwater is much more voluminous and ubiquitous than surface water, commonly found within 2500 feet depth below land surface.
3. Groundwater flow path: atmospheric precipitation percolates into soil/bedrock directly or from surface lakes and streams, and generally flows downward under the force of gravity until it reaches some sort of physical barrier or impermeable zone, which either severely impedes flow or stops it altogether.

4. Types of Groundwater

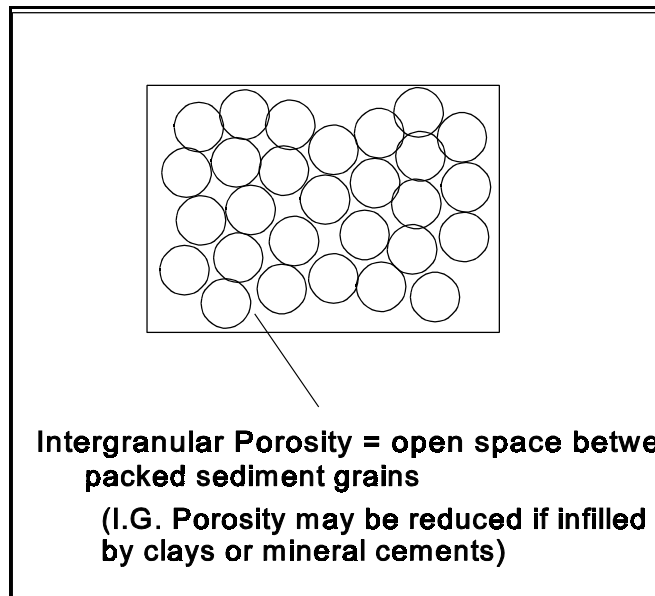
- a. Meteoric Water: water recently circulated from atmospheric cycle
- b. Connate Water: water that is entrapped with sediments when they are deposited, and subsequently gets buried and lithified with the sediments in form of sedimentary rock.
 - (1) I.e. connate water = fossil water.
- c. Juvenile Water: water freshly derived from deep within the interior of the earth via volcanic processes.

B. Groundwater Hydraulic Mechanisms

1. Porosity: ratio, in per cent, of the volume of void space to the total volume of sediment or rock

$$P (\%) = \frac{\text{total volume} - \text{volume of solids}}{\text{total volume}} \times 100$$

- a. Porosity is the primary governing factor influencing the ability of rock or sediment to store fluids (e.g. groundwater or hydrocarbons)
- b. Types of Porous Openings
 - (a) Intergranular Porosity = primary pore spaces present between particles of a sediment or rock deposit



- i) Intergranular Porosity influenced by:
 - a) sorting
 - b) grain packing
 - c) grain size

- (b) Fractured Porosity
- (c) Solution Cavities
- (d) Vesicles

c. Lithologic Control on Porosity

(1) Porosity of Unconsolidated Sediments

(a) function of grain size and packing

- i) uncompact clay and silt = very high porosity (up to 50%)
 - a) compacted clay and silt = decreased porosity to 15%
- ii) sand and gravel: porosity of 20-30% typically

(2) Porosity of Sedimentary Rocks

(a) Primary vs. Secondary Porosity

- (b) Sandstone and conglomerate may possess relatively high porosities (30%)

(c) Limestone and carbonates may be low or high depending on solution

- i) dissolved limestone ---- high secondary porosity
- ii) hard, dense limestone ----- low primary porosity

(3) Porosity of Crystalline Plutonic and Metamorphic Rocks

- (a) Very low primary porosity
- (b) Secondary "structural porosity"
 - i) joints, fractures, faults -----porous zones
 - a) may achieve 5-10% on avg, up to 50% porosity in some instances

(4) Porosity of Volcanic Rock

- (a) Vesicles and columnar jointing may create relatively high porosities

2. Permeability: the degree of interconnectedness between pore spaces and fractures within a rock or sediment deposit. A measure of the capacity of a porous material to transmit fluids

a. Permeability (K) is largely a function of:

- (1) grain size, size of pore space
- (2) shape of grains/shape of pore space
- (3) degree of interconnected pore space

b. Darcy's Law

$$Q = \frac{KA(P_2 - P_1)}{uL} \text{ where,}$$

Q = Volume Discharge Rate (cm³/sec)

K = Permeability (millidarcy = mD)

A = Cross-sectional area at perpendicular to flow (cm²)

L = length along which press. diff. is measured (cm)

(P₂-P₁)= pressure difference (atm) between two points separated by distance L

u = viscosity of fluid (centipoises)

Generally, well sorted sand and gravel display high porosity and permeability, however, a poor sorted sand with much matrix material will have a low permeability.

Unpacked clay, may have a very high porosity but very low permeability.

Generally clay/shale make for good permeability barriers, while sand and gravel readily transmit fluids. However secondary overprints such as structural deformation and diagenetic alteration (post-depositional changes in mineralogy) can drastically influence permeability and porosity.

c. Permeability Vs. Lithology

(1) Permeability of Unconsolidated Sediments

(a) Relationships to Grain Size

- i) Perm < with < Grain Size (and vice versa)
- ii) Perm < with < sorting (and vice versa)
 - a) Hence well sorted coarse sediment (sand, gravel) display the highest permeability
 - b) Poorly sorted or very fine sediment (clayey sand, or clay) generally display lowest permeability

(b) Permeability of Lithified Rocks = Function of interconnected nature of pore spaces

- i) Sandstone, Conglomerate = high primary permeability
- ii) Limestone = low primary permeability
 - a) Dissolved Limestone ----- high secondary permeability
- iii) Shale and Well-cemented Siltstone = low primary permeability
 - a) Fractured Shales and Siltstones = high secondary permeability
- iv) Crystalline Igneous and Metamorphic Rocks = low primary permeability
 - a) Fractured Shales and Siltstones = high fractured (secondary permeability)
- v) Volcanic Rocks = high primary permeability associated with vesicles

C. Subsurface Hydrologic Zones

1. Zone of Aeration or Vadose Zone:

- a. the uppermost portion of the groundwater environment, extends from a few cm's to hundreds of meters.
 - (1) Zone contains mixture of moisture and air held in pore spaces by molecular attraction.
- b. Much water flows downward through this zone into the underlying layer.

2. Zone of Saturation: or phreatic zone: zone below zone of aeration, in which all pore spaces, fractures and cracks are filled or saturated with water. (i.e. groundwater).
 - a. Water table: the top surface of the saturated zone, open to atmospheric pressure conditions via the vadose zone above.
 - b. Ground water flow: groundwater flows along permeable zones under the force of gravity, taking the path of least resistance. Ground water flows along porous paths from areas of higher water table elevation to areas of lower water table elevation.
 - c. Water table configuration: water table generally follows the surface topography of the land above, rising to higher elevations beneath hills, and lower elevations beneath valleys, generally water table deeper beneath hills, and coming closer to surface beneath valleys.
 - (1) intersection of water table with surface of the earth results in surface flow of water in form of springs or seeps, or perhaps manifested as a lake or swamp.
 - d. Pressure Relationships: the level of the water table is generally a surface of constant pressure or hydrologic head.
 - (1) A well dug to intersect the water table, will fill with water to the level of the water table, unless under some kind of hydrostatic pressure (artesian conditions)
 - (2) Groundwater Maps: elevations of top of water table can be mapped and contoured
 - i) Ground water elevations derived from measuring water levels in wells
 - ii) Hydraulic Gradient = rise/run or slope of water surface = (vertical difference/horizontal distance)
 - a) Groundwater flow generally parallel to lines of gradient (i.e. perpendicular to contour lines in downgradient direction under force of gravity)
 - (3) Cone of depression- if water is pumped from a well faster than it can be replaced, the level of the water table will be drawn down in the shape of an inverted cone.

D. Aquifer Types

1. Definitions

- a. Aquifer: porous rock/sediment units that have a capacity to contain water, pores can be formed by openings between grains (primary porosity) or by cracks and fractures in the rocks (secondary porosity)
 - (1) Common Aquifers: unconsolidated sand and gravel, sandstone, dissolved/fractured limestone, lava flows, fractured crystalline rocks.
- b. Aquiclude: Impermeable layers which will not transmit or store groundwater, tend to form the upper or lower boundaries of aquifers
- c. Aquitard = "leaky" aquiclude: low permeability layers which transmit groundwater at very slow rates in both vertical and/or horizontal directions.
 - (1) More permeable than aquiclude

2. Unconfined Aquifers: aquifers in vertical and hydraulic continuity with land surface.

a. Water Table Aquifers = Unconfined Aquifers

- (1) Water of saturated zone in open contact with atmospheric pressures
- (2) Water percolates through vadose zone to phreatic zone
- (3) Capillary Zone: layer immediately above water table where water moves upward under high surface tension and capillary forces

3. Confined Aquifers: aquifers that are separated from atmospheric pressures by impermeable zones or confining layers (water not referred to as "water table")

a. Confined aquifer and artesian conditions, relative to hydrostatic pressure

- (1) Potentiometric surface: analogous to water table, but is elevation of water of confined aquifer that rises to equilibrium in open well penetrating confined aquifer
 - (a) may contour elevations to form potentiometric contour map
 - i) confined aquifer groundwater flow generally perpendicular to contour of potentiometric surface.
 - (b) confined aquifers commonly under hydrostatic pressure in response to rock compaction and pore fluid pressures

b. Artesian Aquifer: identified as water in a well that rises under pressure above the saturated confined aquifer horizon

- (1) Conditions of formation:

- (a) confined aquifer between two impermeable layers
 - (b) exposure of aquifer to allow recharge/infiltration
 - (c) hydraulic flux into the aquifer from water cycle
 - c. Free-flowing artesian aquifer
 - (1) Artesian aquifer in which pressures are such that water freely flows out onto the ground surface.
 - d. Perched Aquifers: localized zone of upper level groundwater occurrence "perched" above a laterally discontinuous aquitard.
 - (1) forms a localized occurrence of groundwater above regional water table system (hybrid of confined and unconfined systems)
- E. Groundwater and Environmental Concerns
1. Resource Development
 - a. Groundwater use for urban and domestic needs prevalent throughout North America
 - (1) Residential use in rural areas off "plumbing grid" of public water supplies
 - (2) Residential and Industrial use in arid and semi-arid portions of U.S.
 - (a) Groundwater useage very prevalent throughout the Mid-west and Far-west.
 2. Environmental Hazards
 - a. Groundwater Contamination
 - (1) Industrial/Government Facilities
 - (2) Sewage/bacteria
 - (3) Mining
 - (4) Landfills
 - b. Ground Subsidence and Subsurface Fluid Withdrawal
 - (1) Extensive withdrawal of subsurface fluids
 - (a) groundwater
 - (b) Petroleum
 - (2) Fluid withdrawal results in decrease in pore pressure, leading to subsidence of land areas under lithostatic pressure

II. THERMAL SPRINGS AND GEYSERS

- A. Hydrothermal Regions
1. Basically groundwater plumbing systems that circulate in portions of the earth's crust associated with high heat flow... water circulated and heated by earth's internal heat
 - a. volcanic regions
 - (1) e.g. Yellowstone Park, WY
 - (2) Cascades / Eastern Oregon

- B. Hydrothermal Features on the landscape
 - 1. Hot Springs- hot water circulated to surface as discharge
 - a. Geyser- hot spring periodically erupting under pressure as hot water and steam.
 - (1) Pressure build-up in response to steam generation in constricted flow conduits
 - (a) Geyser eruptions cycle as hot chambers alternate between filling, heating and pressure escape cycles
- C. Geothermal Energy
 - 1. Harnessing of naturally occurring steam and hot water in areas of exceptional hydrothermal activity
 - a. steam-driven turbines for electricity production
 - b. hot water for circulation and heating of homes

III. KARST LANDSCAPES

- A. Introduction/Mode of Occurrence
 - 1. Groundwater as a modifying force of the landscape
 - a. Groundwater responsible for dissolution of soluble (dissolvable) bedrock beneath land surface
 - b. Common "dissolvable rock types"
 - (1) Limestone
 - (2) Evaporites (Gypsum, Halite)
 - 2. "Karst" topography = landscape formed by groundwater dissolution of subsurface bedrock
 - a. "Karst": slavic root = "waterless area"
 - b. Features:
 - (1) solution depressions
 - (2) caves
 - (3) collapsed ground
 - (4) diversion of surface runoff to underground cavern systems
 - (a) little free surface flow

c. Geographic Occurrence

- (1) Prevalent in Kentucky (Mammoth Cave Area), West Virginia, Virginia, Indiana, Florida, and localized areas in Tennessee, New Mexico, California.

3. Controls of Karst Formation

a. Climate:

- (1) Groundwater processes imply ample precipitation for recharge of groundwater system
 - (a) Abundant vegetation increases chemical weathering processes and karst development.
- (2) Karst common in humid climates of abundant rainfall
 - (a) Tropical Karst commonly observed
- (3) Arid karst observable but relatively poorly developed
 - (a) Carlsbad Caverns of New Mexico associated with percolating waters from great depth
 - (b) Residual karstic features associated with Past (wetter) Quaternary Climates
 - i) Relict karst features

b. Lithology and Structure

- (1) Karst extensively developed in areas underlain by soluble limestone
 - (a) Limestone = calcium carbonate (CaCO_3) primarily
 - i) dolostone = Magnesium variation = CaMgCO_3
 - ii) Limestone widespread and of common occurrence
 - (b) Rock Salt beds also highly soluble but not of widespread significance
- (2) Joints, Fractures and Faults Provide Secondary Porosity in Limestone
 - (a) fractures form secondary porosity and provide avenues for chemical reaction with groundwater and dissolution.

c. Ideal Conditions for karst development

- (1) Humid Warm Climate, high vegetative growth/organic activity
 - (a) promotion of rapid chemical weathering
- (2) Abundant and free groundwater flow (solvent)
- (3) Undisturbed limestone beds with fractured porosity

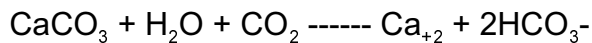
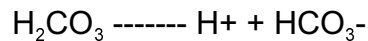
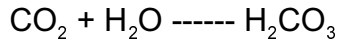
B. Limestone Solution Processes

1. Calcium Carbonate System

2. Important reactions involving CO₂, H₂O, CaCO₃, and pH.

- a. Dissolution of Carbon Dioxide (gas) in water results in production of Carbonic Acid, which subsequently dissociates into free H⁺ ions and the bicarbonate anion

(HCO₃⁻), hence increasing hydrogen ion activity, and by definition decreasing pH (becoming more acidic).



- b. In Sum: carbon dioxide in water creates carbonic acid and limestone dissolves. If carbon dioxide is decreased (lost) in groundwater system, pH > and calcite precipitates

C. Karst Landforms

1. Sinkholes

a. Characteristics

- (1) circular closed depressions of land surface formed by solution of limestone cavity
- (2) commonly occur in "fields" marking the landscape similar to craters of moon
- (3) Shapes
 - (a) cylinders, bowls, funnels
- (4) May fill with water or be associated with open water table to form sink hole lake

b. Solution Sinkholes

- (1) sinkholes formed by the downward dissolution of limestone from the surface
- (2) commonly fractured/joint controlled

c. Collapse Sinkholes

- (1) sinkholes formed by the dissolution of limestone at depth below surface with subsequent collapse of roof and ground above
 - (a) "solution cavities"

- (2) Sudden roof collapse common environmental hazard in Florida
 - (a) Associated with overwithdrawal of groundwater and subsidence
 - (b) loss of property

2. Solution Valleys

- a. Large-scale laterally extensive solution valleys
 - (1) widespread roof collapse and coalescence of sinkholes
 - (2) mixture of fluvial systems and alluvium fill the valleys and drain into subsurface caverns

3. Sinkhole Ponds/Karst Lakes

- a. Sinkholes filled with water
- b. Origins
 - (1) sediment-plug drain in sink with infill of surface water
 - (2) flooding of sinkhole by groundwater
 - (a) lake surface = water table level in open aquifer

4. Solution Processes and Rock Fractures

- a. Solution processes oriented and concentrated along fracture systems
 - (1) Solution Fissures
 - (2) Solution Canyons
 - (3) "Solution chimneys"

5. Fluvial-Karst Drainage Systems

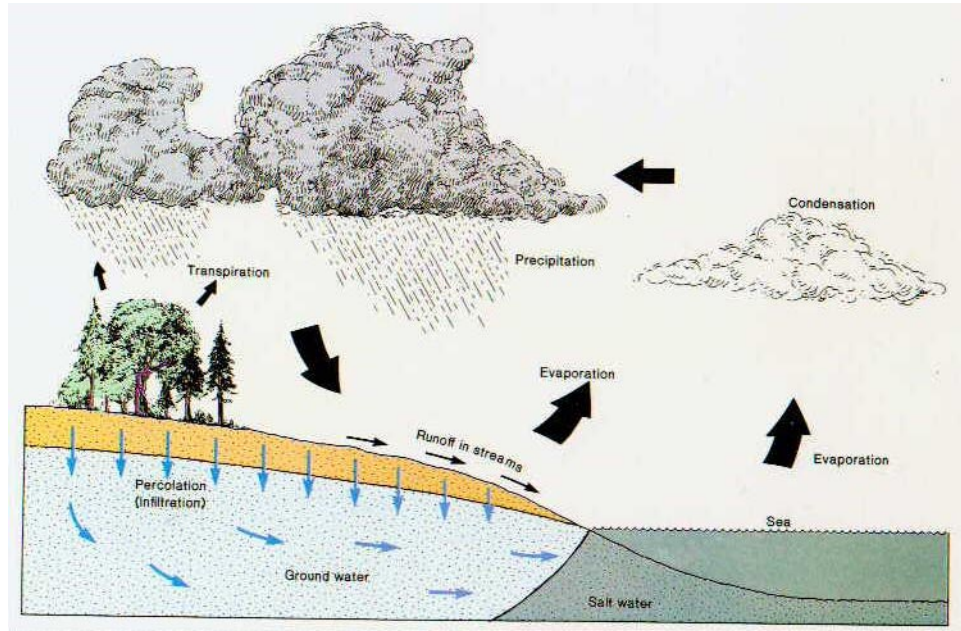
- a. Surface drainage complexly integrated with karst groundwater system
 - (1) Sinking Streams: surface streams abruptly flow into sinks and enter into subterranean hydrogeologic system.
 - (a) "Swallow Holes": sinks into which surface streams flow
 - (2) Karst Springs: sudden appearance of high discharge springs
 - (a) "underground rivers"
- b. Complex surface-groundwater interaction
 - (1) dye and tracer studies utilized to map subsurface flow conduits

6. Tropical Karst Landscapes:

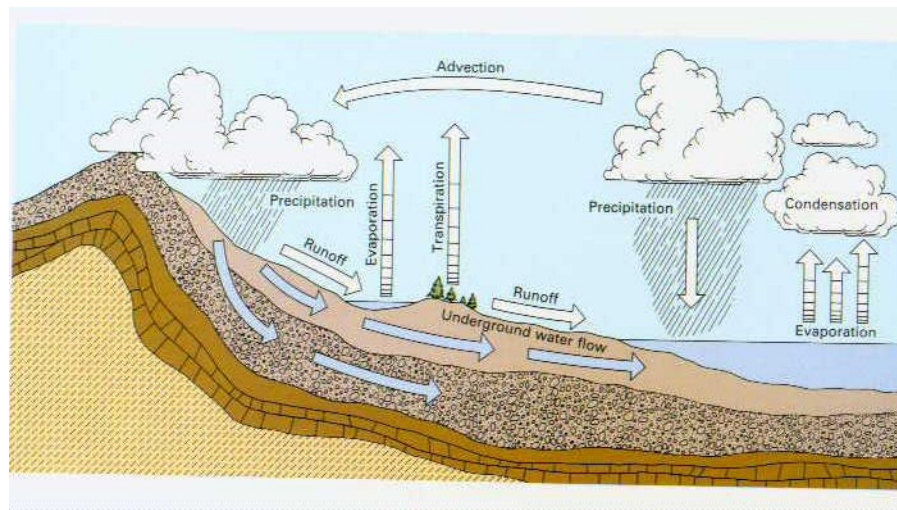
- a. Special consideration: intensely weathered limestone landscapes in warm, wet tropical climate
- b. Cockpits: very large bowl-shaped sinkholes >1 km in diameter formed in very thick limestone terranes (limestone > 1000 ft thick)
 - (a) e.g. Puerto Rico

- c. Cone and Tower Karst
 - (1) Extreme Karst development leads to very steep-sided cones or towers of limestone
 - (a) e.g. southern China Karst District
 - (2) Mogotes: extensive cone and tower topography found in Central America
- D. Cave Systems
1. Caves Defined
 - a. Elongate subsurface cavities formed by dissolution of limestone
 2. Origins of Caves
 - a. Common in limestone terrains
 - b. Groundwater flow with water-carbon dioxide equilibria and limestone dissolution
 - c. Cave conduit formation commonly structurally controlled
 - (1) fractures serve as flow conduits and avenues of dissolution by flowing groundwater
 - d. Theories of Origin (a bit controversial)
 - (1) Form in vadose zone above water table
 - (2) Form at fluctuating water table interface
 - (3) Form below water table in phreatic zone
 3. Conduit Systems
 - a. Complexly interconnected labyrinth of passage ways and conduits
 - (1) some continuous, some discontinuous and disconnected
 - b. groundwater occurrence variable and seasonal
 - (1) some conduits flooded, some dry
 4. Cave Entrances
 - a. Collapsed sinkhole
 - b. Karst windows- collapse hole open to surface
 - (1) able to view underground streams through window from surface
 - c. Natural outcrop of limestone and solution openings
 - d. Large percentages of caves inaccessible with no surface opening.
 5. Passages and Rooms
 6. Cave Deposits
 - a. Dripstone = Travertine = calcium carbonate formed by the precipitation of groundwater at low temp and press.

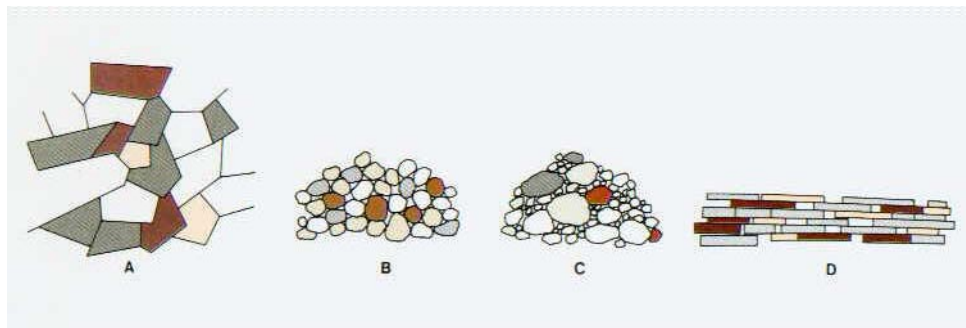
- (1) common in cave systems
 - (2) Deposition and solution of travertine a function of carbon dioxide content of water carrying ions
 - (a) as water percolates into cavernous opening, carbon dioxide in solution is liberated as gas (partial pressure of carbon dioxide decreases)
 - (b) release of carbon dioxide from solution results in $>pH$ and promoting the precipitation of calcium carbonate out of solution
- b. Stalactites: ice-cycle type travertine deposit hanging from ceiling
- c. Stalagmites: stump-like build-ups of travertine from cave floor
- (1) columns: coalescence of stalactites and stalagmites
 - (2) travertine terraces: table-like accumulations of travertine
 - (3) soda-straws: very delicate straw-like accumulations of travertine



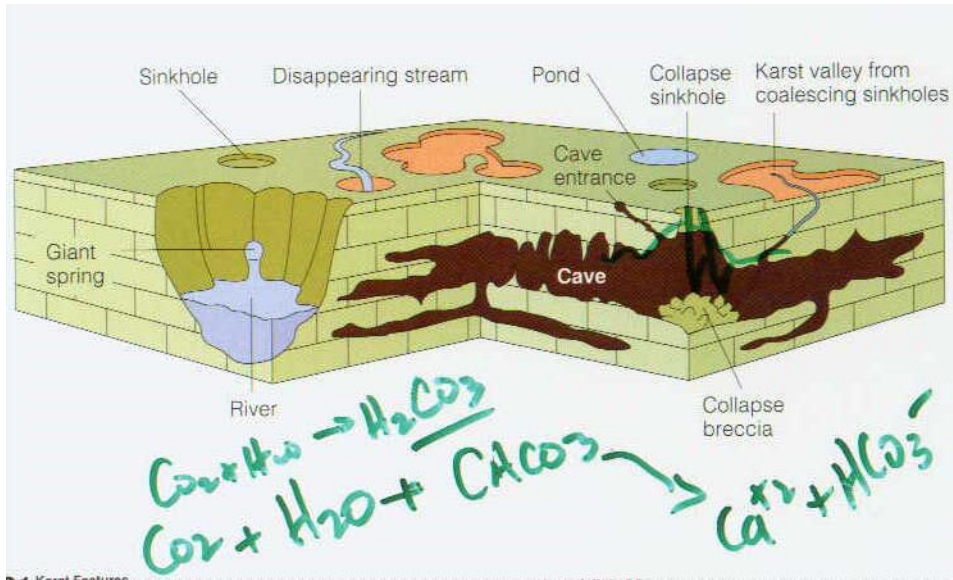
Water Cycle 1



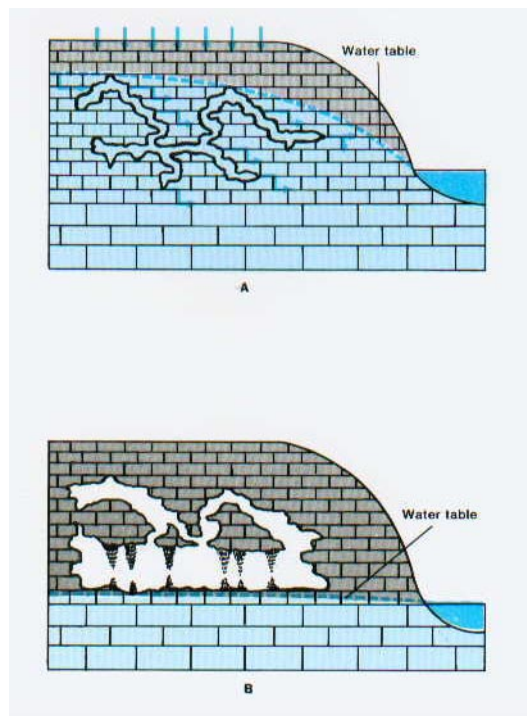
Water Cycle 2



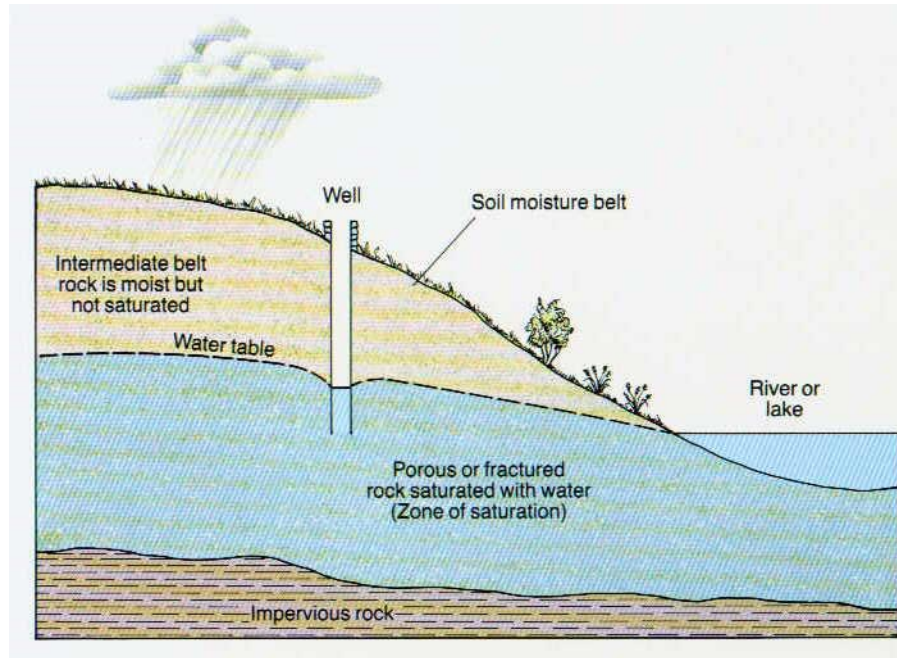
Degrees of Intergranular Porosity



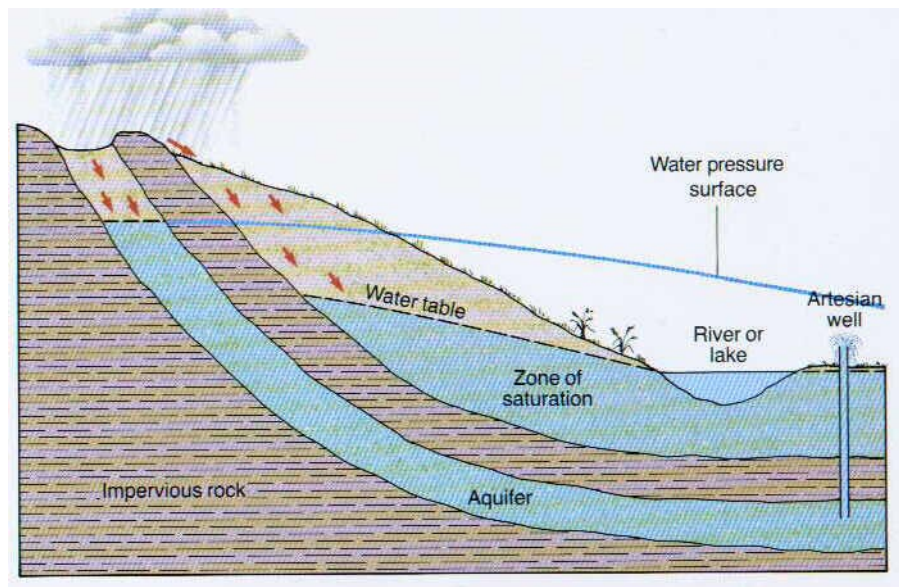
Karst Features



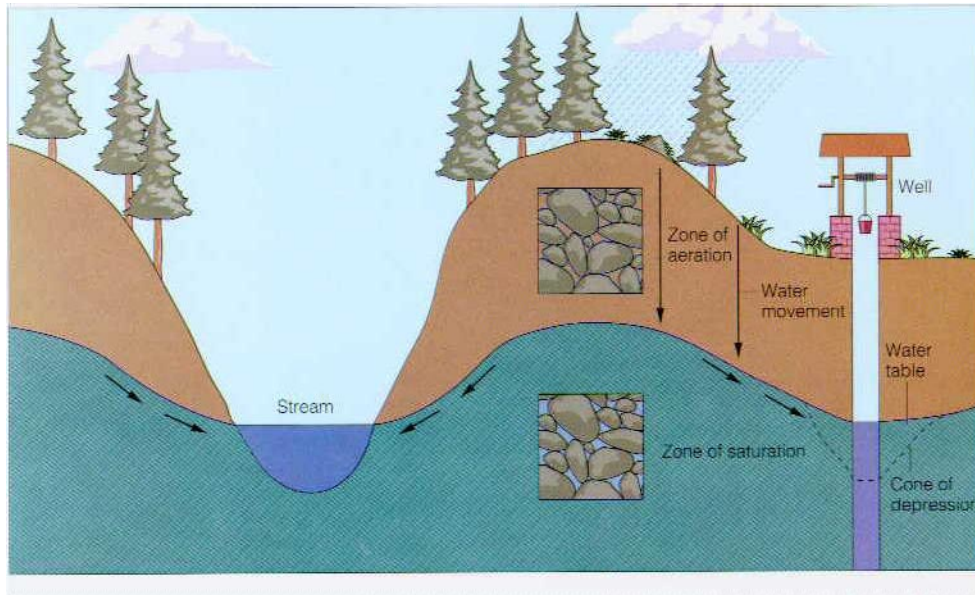
Cave Formation



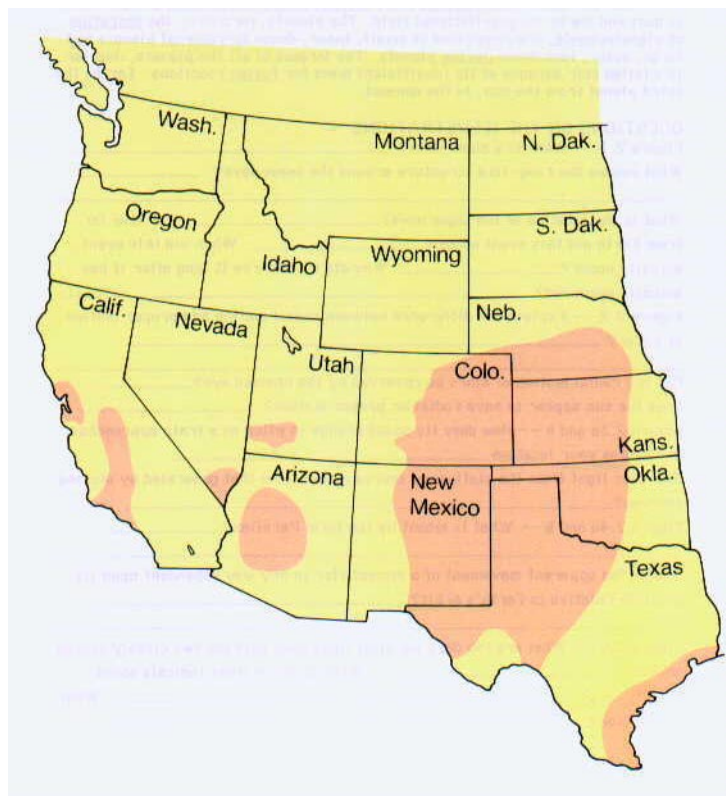
Unconfined Aquifer



Confined (Artesian) Aquifer



Well Dynamics in Unconfined Aquifer



Areas of Extensive Groundwater
Withdrawal in Western U.S.