Week twelve

I. soil moisture content

A. basic relations
   1. total sample volume
      a) \( V_t = V_s + V_v \)
   2. porosity
      a) \( n = \frac{V_v}{V_t} \)
   3. void ratio
      a) \( e = \frac{V_v}{V_s} \)
      b) \( e = \frac{n}{1-n} \)
      c) \( n = e/(1+e) \)
   4. saturation
      a) \( S = \frac{V_w}{V_v} \)
      b) note that this is a fraction not percentage
   5. moisture content
      a) \( \theta = \frac{V_w}{V_t} \)
      b) easier to measure in the field than saturation
      c) no knowledge of \( V_v \) is required
   6. field capacity - moisture content after gravity drainage
   7. wilting point – moisture content at which plants die
   8. Specific yield (Sy)
      a) fractional volume of water released from an aquifer under gravity drainage
      b) \( ne = Sy + Sr \) where \( Sr \) is specific retention, the water held back against gravity drainage

B. measuring moisture content or saturation
   1. take sample to the lab
   2. calibrated resistance block
   3. calibrated tensiometers
   4. time domain reflectometry
   5. neutron probe

II. wettability

A. hydrophilic materials
   1. attract water
      a) said to be water wet
      b) wettable
      c) water spreads out in a thin film
   2. includes most silicate materials
      a) common earth material

B. hydrophobic materials
   1. water is repelled
2. water beads up on the surface
3. many organic compounds

III. capillary rise
A. water will climb a hydrophilic surface
B. gravity restrains the amount of rise
   1. attractive force is proportional to interfacial length
   2. resistive force is proportional to
      a) volume of fluid being lifted
      b) density of fluid
C. in a tube
   1. attractive force decreases with the diameter
   2. resistive forces decrease with radius squared
   3. as diameter decreases
      a) weight of water that must be lifted
      b) decreases faster than the attractive force
   4. capillary rise increases with decreasing pore size
   5. \[ h_c = \frac{2\sigma \cos \alpha}{\rho gr} \]
D. in soils
   1. coarse sand ~ 4 cm
   2. silt ~80 cm
   3. fine grained rocks >10 m
E. capillary fringe
   1. capillary rise obscures location of the water table;
   2. rise can saturate soil above the WT
   3. capillary water is at a negative pressure < atmospheric
      a) water is not completely free to move
      b) held in place by capillary pressure
   4. water table is point where pressure = atmospheric

IV. moisture potential
A. vadose zone moisture is under tension
   1. capillary forces draw water into small pores
   2. assumes hydrophilic material
B. fluid pressures are negative
   1. less than atmospheric pressure
   2. tensions can be large, 10s (maybe 100s) of meters
   3. negative pressure is called moisture potential
      a) potential varies with moisture content
      b) zero at saturation
      c) small as the soil dries out
C. positive pressure must be applied to remove water
D. gravity can only apply so much force
1. gravity cannot fully drain a soil
2. limit is called field capacity

E. evaporation can remove water from the vadose zone
1. as moisture content decreases
   a) surface area of the water increases
   b) tension and hence activity decreases
   c) hard to dry soil without adding heat

F. measuring moisture potential
1. piezometer is useless
   a) adding water changes the system
      (1) moisture content
      (2) tension
2. tensiometer is used to measure negative soil pressures
   a) tube filled with water
      (1) capped on one end
      (2) porous ceramic on the other
      (3) tap to measure tension
   b) ceramic
      (1) very small pores
      (2) saturated with water
   c) how it works
      (1) soil water contacts water in ceramic
         (a) intermediary is often used
         (b) silica flower to make contact
      (2) soil water pulls on water in the ceramic
         (a) pores in ceramic are very small
         (b) water doesn’t leave the tensiometer
      (3) amount of pull is measured at tap
         (a) pressure transducer
         (b) gauge
         (c) mercury manometer

V. Hysteresis
A. the relationship between $S$ and $\psi$ is not simple
B. hysteresis
   1. means that the relationship is history dependent
   2. $S$ is not a unique function of $\psi$
C. 'ink bottle effect'
   1. picture a tube that is larger in the center
      a) to drain the center, entries must be drained first
         (1) entries are smaller
         (2) take more suction than center
      b) this process does not occur on refilling
   2. as a result drying curve is higher than wetting
D. scanning curves
   1. draw on board
   2. at any time, relation between $S$ and $\psi$ is path dependent

VI. Unsaturated hydraulic conductivity
A. function of saturation, $K(S)$ or $K(\theta)$
   1. steady flow does not change saturation
   2. water moves through the existing soil moisture
B. $K$ decreases much faster than moisture content
   1. reduction in cross-sectional area
   2. large pores drain first
   3. increased tortuosity
C. predicting $K(S)$
   1. if $S$ is a function of $\psi$, then so is $K(S), K(\psi)$
   2. usually
      a) develop curves for $S$ and $K$ as a function of $\psi$
      b) this is done in the laboratory
      c) measure $\psi$ in the field
   3. we can also measure $S$ in the field (actually $\theta$)

VII. Unsaturated Flow
A. driving force
   1. instead of head we talk about the soil water potential
      a) $\phi = \psi + Z$
      b) moisture potential + gravitational potential
      c) flow is usually assumed to be vertical
         \[ \frac{d\phi}{dz} = \frac{d\psi}{dz} + 1 \]
B. at any given point
   1. gravitational potential never changes
      a) gravitational gradient is 1
   2. moisture and total potential vary with $\theta$
      a) moisture potential is negative by definition
C. under moist conditions
   1. the soil moisture potential is small
   2. gravity may dominate
D. dry conditions
   1. moisture potential may be huge
   2. gravitational potential becomes insignificant
E. non-steady flow
   1. movement of water alters the system
      a) changes $K, \theta, \psi$
      b) this is very difficult to predict
   2. flow acts to reduce spatial differences in $\psi$
F. weirdness
1. highly negative moisture potentials (dry conditions)
   a) clay can become more conductive than sand
   b) hard to wet up material
      (1) some initial moisture is required

Investigation of Groundwater Geology

a hydrogeologic investigation has many things in common with a mineral or paleontology investigation, but also many differences

maps, air photos, outcrop studies, field observations, existing well logs are all tools used in a hydrologic investigation

the nature of the investigation will depend on the underlying problem; which may be water production, water table control, waste disposal, or remediation

in most cases the primary task is to understand how the subsurface materials transmit or block water flow

material formations are grouped into hydrostratigraphic units that may or may not coincide with the standard geologic or soil units

Groundwater in unconsolidated materials

unconsolidated materials are loose sediments, i.e., stuff that is rippable

if well sorted, unconsolidated sediments can have very high K, poorly sorted or fine grained sediments may have a very low K

granular sediments, like fine sand are good at filtering out bacteria, but don't have any mitigating effect on dissolved contaminants

Glacial terrain - glaciers covered much of the upper mid-continent region of the US, sediments may be very well or very poorly sorted, look for lake beds, sand stringers, moraines, well sorted glacial sand can be exceptionally productive, while till is typically poorly sorted and low K

till can act as a confining layer

note that many high K glacial features (e.g., eskers) are topographic highs and hence may be unsaturated
buried glacial features may be great productive zones, much of the mid-continent region of the US consisted of deeply incised bedrock stream valleys, glaciation buried many of these with loose sediment

**alluvial valleys** - shallow valleys with meandering streams, depending on the velocity streams will pick-up or deposit sediment, gravel gets dropped in stream channel, fines on banks and flood plain, at slow water, fines get dropped in channel

streams tend to move about in the valley leaving buried bars that are good sources of water

important to note that valleys formed during glacial or wetter times may be huge compared to what is there now

**tectonic valleys**- mountain fronts and fault blocks leave sharply defined basins (Nevada, Utah, Arizona), alluvial fans will have coarse deposits grading out into fines in the valley floor

can create confined aquifers by fingering of deposits

probably great depth to water on the fans, coarse material likely has high K

water is recharged in the mountains, discharge may be by ET or flow into regional system

ground water quality in tectonic valleys may exhibit significant spatial variation

because the subsurface is so complex, finding water is difficult, need to find a high K zone (coarse or fractured) where water is reasonable close to the surface

depth to water in basins can be shallow, or deep if it drains into a regional flow system, if the system does not drain, deep waters in the basin are likely to be brackish

Pleistocene glaciation made the climate of many valleys much wetter that it is today, as a result tectonic valleys often have lake bed clays near the surface, leading to artesian conditions

**regolith** - incoherent rock material covering the bedrock, typically weathered in place, may form aquifers in some locations

often shallow over top of fractured and weathered bedrock (sapprolite)

generally low K due to formation of clay minerals, often have drainage problems

may form leaky confining layer
Lithified sedimentary rocks

**depositional complexity** - for the most part these result from shallow seas

the sequences may change from near shore to marine, gradational change in a continuous unit

thickness may increase towards the center of the basin

layers may pinch out and inter finger

may be interrupted by unconformities

**folding** - beds can be tilted by regional uplift, or folded, most striking feature is confined aquifer formed at the center of a syncline in which erosion has exposed recharge/discharge areas

fractures may produce high K zones along the axis of anticlines

**faults** - strike-slip faults can be barriers or conduits depending on the material, fault gouge can be very fine grained and form a seal where breccia may be a conduit (conditions are reversed in vadose zone)

high pressures in fault zones can cause big danger for tunneling

overthrusts have the additional complexity in that different units are brought into contact, i.e., an igneous body is thrust up and abuts a sandstone forming a barrier

Clastic rocks

primary porosity will result from original particle size, shape, and packing

cementation or dissolution may alter porosity

fractures (secondary porosity) resulting from tension release or tectonic activity may significantly impact permeability

sandstone is an important aquifer material, it is often between layers of shale that act as confining layers
Carbonate rocks - limestone, dolomite are special cases of sedimentary rocks, both are soluble in acidic water, solubility is a function of water chemistry, mineral composition, and temperature. Solubility is much lower for dolomite and dirty limestones.

Chemical precipitated rocks have a low primary porosity so flow tends to be focused in secondary porosity (fractures, bedding planes), fluid flow reinforces connection along these features. Initial orientation of fractures has a major impact on cave development, for example water flowing through vadose fractures can form vertical features. Karst topography forms over limestone, producing caves, sinkholes etc. Because of high K in the tunnels, water table tends to be flat with respect to the dominant regional stream, if stream is downcutting, water table will drop, leaving caves at a variety of levels. Rainwater is the least saturated with calcite so most solution occurs about the water table, contrary to most substances, calcite tend to have a higher solubility in cold water than in warm water, solubility is a function of dissolved carbon dioxide.

Coal

Flow through coal occurs along fractures called “cleat”, water quality from coal can be very poor and acidic.

Igneous and metamorphic rocks

Flow is pretty much confined to secondary porosity (fractures, weathering) both of which decrease with depth, angled boreholes may increase likelihood of hitting a vertical fracture. Saprolite - highly weather rock that retains its structure, may have porosity of 40-60%. Volcanics - fractures, flow tops, buried stream beds are good fluid sources. Lava flows on Hawaii are highly permeable, flows are cut by intersecting igneous dikes of low K which act as groundwater dams.

Permafrost
permanently frozen ground (maximum temperature of 0), active layer is the top 1-2 m
which may thaw in warm months, frozen depth may reach 400 m

shallow lakes (< 2 m) freeze to bottom, but deeper lakes insulate the ground and form
either depressions or breaks in the 'permafrost table', as do glaciers and ice sheets

permafrost act as a confining layer, perched water on poorly drained surface land

water leaking upward through cracks in the confining layer can form conical ice filed
hills called pingos

if the permafrost is continuous the water below tends to be brackish from lack of
movement

alluvial valleys of large rivers may be the only good source of water

**Coastal plains**

units tend to slope towards the sea, grade in porosity, increase in thickness, and get
younger, these units also tend to be in fingered layers

can get fresh water a fairly large distance out to sea

historic changes in sea level may have brought salt inland (sea level rise) or put fresh
water to great depth (sea level lowering)

**salt-water intrusion (encroachment)**

fresh water is generally discharging through aquifers, as the on-land potentiometric
surface is sufficiently above MSL to force flow in that direction

however pumping or diversion can change the situation

if the groundwater flow is reduced, salt water creeps in (passive encroachment)

this would result from pumping a long ways from shore, reduction of infiltration, general
lowering of the water table, etc.

if the gradient is reversed (active encroachment) it floods in

this is what ruined the aquifer under Brooklyn in the 1930's

Drainage of swamps in Florida for sugar cane lowered the general water table and
brought in salt water, also big problems with karst aquifers

once the salt gets in it's difficult to flush
we can also get salty water in deep onshore aquifers due to its age

show upconing, in an unconfined aquifer, active encroachment in a confined aquifer, and use of recharge wells to form a barrier

**Salt/fresh water relationship**

in some cases dissolved solids effect the flow system, this is particularly true near the interface between oceanic and fresh water

it is typically assumed that the interface is sharp, but in reality it is a mixing zone, diffusion, tidal fluctuation, barometric pressure, seasonal flow, etc.

however, if the thickness of the mixing zone is small with respect to the aquifer thickness we can assume a sharp boundary, this makes the math much easier

**Ghyben-Herzberg relationship**

implies that depth to an interface will be about 40 times the height of the water table above MSL, assumes that both groundwater and sea water are static, i.e. in the case of an island a freshwater lens is floating on the sea water

\[ z = \frac{\rho_w}{\rho_s - \rho_w} h \]

\[ z \]  = depth of interface below MSL

\[ \rho_w \] = fresh water density

\[ \rho_s \] = salt water density

\[ h \] = height of fresh water above MSL

this relationship does not allow for any flow to occur, Glover and others have extended this relationship to account for a seepage face