Soils & Hydrology (3060 - Part II)

9. Soil Water
10. Precipitation and Evaporation
11. Infiltration, Streamflow, and Groundwater
12. Hydrologic Statistics and Hydraulics
13. Erosion and Sedimentation
14. Wastes in Soil and Water
Global Water Budget
Volumes in PL, Flows in PL/yr

Atmosphere (12.9)

Plants (1.1)

Soil Water (16.5)

Surface Water (104)

Ground Water (10,800)

Glaciers (24,000)

Oceans (1,340,000)

1 PL = 1 petaliter
= $10^{15}$ L = 1000 GL
• Residence Time: The time water spends in a reservoir:

\[ \tau = \frac{V}{Q} \]

- \( \tau \) (tau) is the residence time (years)
- \( V \) is the volume of the reservoir (liters)
- \( Q \) is the flow through reservoir (liters per year)

• Think of a bathtub...
  - If you start with an empty bathtub
    * \( \tau \) = how many minutes it takes to fill the bathtub
    * \( V \) = size of tub, (say 100 gallons)
    * \( Q \) = flow into tub, (say 10 gallons per minute)
    * \( \tau = \frac{V}{Q} = 100 / 10 = 10 \) minutes
  - If you start with a full bath
    * There is no inflow
      - And you let it drain at a constant rate
      - Will it take the same time to drain?
  - You add and drain water at the same rate
    * Will a tracer take the same time?
# Water on Planet Earth

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>% of Water</th>
<th>Residence Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global</td>
<td>Fresh</td>
</tr>
<tr>
<td>Salt Water</td>
<td>97.5</td>
<td>.</td>
</tr>
<tr>
<td>Glaciers</td>
<td>1.75</td>
<td>68.7</td>
</tr>
<tr>
<td>Ground Water</td>
<td>0.79</td>
<td>30.9</td>
</tr>
<tr>
<td>Surface Water</td>
<td>0.008</td>
<td>0.3</td>
</tr>
<tr>
<td>Soil Water</td>
<td>0.0012</td>
<td>0.05</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.0009</td>
<td>0.04</td>
</tr>
<tr>
<td>Plants</td>
<td>0.00008</td>
<td>0.003</td>
</tr>
</tbody>
</table>
• Soil surfaces have *negative* charge!
  – Water is a *polar* molecule
  – The H-side has a positive (+) charge
  – The O-side has a negative (-) charge

• Water is bound to:
  – other water molecules by
    • *cohesive* (water-water) forces
  – the soil surface by
    • *adhesive* (soil-water) forces

• Think of water as a bar magnet
  – soil is a negative box
  – it sticks to other water “magnets”
  – the positive end sticks the “box”
Soils = Air + Water + Solids
Capillary Rise:

- The *wick* effect caused by small pores
- Rise is greater in finer materials:
  - clays > silts > sands > gravels
- \( h = \frac{0.15}{r} \)
  - \( h \) is the height of rise in tube, cm
  - \( r \) is the radius of tube, cm
Energy:

• The driving force for water flow
• The **total energy** is the sum of three types of energy
  - \[ E = GE + KE + PE \]
    - \( GE \) = gravitational or potential energy
      - like a water balloon at the top of a building
    - \( KE \) = kinetic or inertial energy
      - like when the balloon is dropped and it’s picking up speed
    - \( PE \) = pressure energy
      - like when the balloon hits the ground before it explodes
  - Total Energy is expressed as a head, or height of water:
    - \[ h = z + p \]
      - \( z \) is the elevation head
      - \( p \) is the pressure head
Soil Tension

• *A negative* pressure that accounts for moisture held in the soil by capillary forces
  – A small tension means water is **not** bound tightly
  – A large tension means that water is bound tightly

• **We use the symbol** $\psi$ (psi) = - $p$ **to represent the tension:**
  – It’s a negative pressure, or suction...
  – Remember, dry soil sucks!
<table>
<thead>
<tr>
<th>Tension (bars)</th>
<th>Head (m)</th>
<th>Pore Radius (μm)</th>
<th>Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>∞</td>
<td>100.</td>
</tr>
<tr>
<td>0.1</td>
<td>-1</td>
<td>15</td>
<td>99.993</td>
</tr>
<tr>
<td>1</td>
<td>-10</td>
<td>1.5</td>
<td>99.93</td>
</tr>
<tr>
<td>15</td>
<td>-150</td>
<td>100</td>
<td>98.9</td>
</tr>
<tr>
<td>100</td>
<td>-1000</td>
<td>15</td>
<td>93.</td>
</tr>
<tr>
<td>500</td>
<td>-5000</td>
<td>3</td>
<td>70.</td>
</tr>
<tr>
<td>1,000</td>
<td>-10,000</td>
<td>1.5</td>
<td>48.</td>
</tr>
<tr>
<td>5,000</td>
<td>-50,000</td>
<td>3</td>
<td>2.6</td>
</tr>
<tr>
<td>10,000</td>
<td>-100,000</td>
<td>1.5</td>
<td>0.068</td>
</tr>
<tr>
<td>Condition</td>
<td>Water Film</td>
<td>Pressure</td>
<td>Pores</td>
</tr>
<tr>
<td>-----------</td>
<td>------------</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Wet</td>
<td>Thick</td>
<td>near zero</td>
<td>Full</td>
</tr>
<tr>
<td>Dry</td>
<td>Thin</td>
<td>very negative</td>
<td>Empty</td>
</tr>
</tbody>
</table>

![Diagram of soil and water films with pressures and labels](image-url)
Some Definitions

- **Bulk Density:**
  - \( BD = \text{Mass Soil} / \text{Volume Soil} \)

- **Porosity:**
  - \( PS = \text{Volume Voids} / \text{Volume Soil} \)
  - \( PS = 1 - BD / PD \)

- **Water Content (theta):**
  - \( \theta_v = \text{Volume Water} / \text{Volume Soil} \)
  - \( \theta_g = \text{Mass Water} / \text{Mass Soil} \)
  - \( \theta_v = \theta_g \cdot BD \)

- **Water Depth:**
  - \( D_w = \theta_v D_s \)
  - \( D_s \) is depth of soil

- **Relative Saturation (capital theta):**
  - \( \Theta = \text{Volume Water} / \text{Volume of pores} \)
  - \( \Theta = \Theta_v / PS \)
Classification of Soil Water

• Saturation = SAT
  – The water content when the pores are completely filled with water.
  – Saturation corresponds to pressure potentials of zero, and above (positive pressure).
  – This is the same as saying $p = 0$, $\psi = 0$
  – At saturation, the volumetric water content equals the porosity.
• **Field Capacity = FC**
  
  - The water content held after rapid gravitational drainage has occurred.
  
  - Field capacity is sometimes described as the amount of water a soil can hold against gravity.
  
  - This is not completely true, however, as water continues to drain slowly by gravity at pressures below field capacity.
  
  - The tensions associated with field capacity are between $\psi = 0.1$ and 0.3 bars, equal to 100 to 300 cm.
• Wilting Point = WP
  – The amount of water held when plant roots can no longer extract water from the soil.
  • This tension is usually assumed to be $\Psi = 15$ bars
  • Different plants have different wilting points
    – Xerophytes (dry-loving plant) can go down to $\Psi = 75$ bars
    – Phreatophytes (water-loving plants) can only go down to $\Psi = 5$ bars
• **Air Dry = AD**
  - The amount of water held by soil when it is exposed to the atmosphere.
    - Related to the relative humidity.
    - Soils left in moist air are wetter than soils left in dry air.
      - Soils in caves and greenhouses are moist
      - Soils in the desert are dry
    - $\psi$ varies from 75 to over 1000 bars depending on the RH

• **Oven Dry = OD**
  - The amount of water held once the soil has been dried in a 105°C oven for 48 hours.
  - $\psi$ is about 10,000 bars in the oven.
### Characteristic Curves

<table>
<thead>
<tr>
<th>Tension Term</th>
<th>Forces</th>
<th>Pores</th>
<th>Weight</th>
<th>$g$</th>
<th>$g/cm^3$</th>
<th>$\theta$</th>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bars</td>
<td>0</td>
<td>SAT gravity</td>
<td>all filled</td>
<td>60</td>
<td>0.20</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>FC available</td>
<td>macropores empty</td>
<td>55.5</td>
<td>0.11</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>WP capillary</td>
<td>mesopores empty</td>
<td>52.0</td>
<td>0.04</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>AD vapor</td>
<td>micropores empty</td>
<td>51.5</td>
<td>0.03</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>OD molecular</td>
<td>all empty</td>
<td>50</td>
<td>0.00</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Lab 9 - This week in lab...

- **Moisture Characteristic Curves**
  - Plot of tension (pressure) vs. water content (saturation)
  - Measure water content at various tensions
    - Saturated, Field Capacity, Wilting Point, Air Dry, Oven Dry
    - Determine plant available water content

- **Demonstrate some concepts**
  - Capillary rise – a function of particle and void size
  - How to measure field water tension and saturation
    - Tensiometer, Time Domain Reflectometry (TDR), Gypsum Blocks
Moisture Characteristic Curve

A plot of water content, $\theta$, vs soil tension, $\psi$. 

SOIL MOISTURE RELEASE (MOISTURE-SUCTION) CURVE

Soil A: at FC: 15%
at WP: 3%
Available: 12%
- Plant Available Water = \( AW = FC - WP \)
  - The water in the soil between \textit{field capacity}, \( \psi = 0.1 \) bar, and the \textit{wilting point}, \( \psi = 15 \) bars:
    - The water bound less tightly than the field capacity is termed \textit{gravitational} water because gravity easily drains this water before the plants can get it.
    - Water bound beyond the wilting point is \textit{unavailable}, because plant roots can not pull hard enough to overcome \textit{absorption} of the water to the soil.
Soil Tensiometer

- A small reservoir to hold water
- This dial gives soil tension (negative pressure)
- This part buried in soil
Time Domain Reflectometer

Used to measure soil moisture
An electrical pulse is sent down the rod
The pulse bounces off the end and returns to the source
The wetter the soil, the longer the delay in returning
Capillary Rise:

- The *wick*ing effect caused by small pores
- Rise is greater in finer materials:
  - clays > silts > sands > gravels
- \( h = \frac{0.15}{r} \)
  - \( h \) is the height of rise in tube, cm
  - \( r \) is the radius of tube, cm
Hysteresis: Caused by air blocking water in pores

"Ink Bottle" effect

![Diagram showing moisture content vs. matric potential with hysteresis loop and sorption and desorption phases]
Soil Water Movement

- **Hydraulic head:** \( h = z + p \)
  - \( h \) is total head, the driving force
  - \( z \) is elevation head, water moves from high to low elevation
  - \( p \) is pressure head, water moves from high to low pressure
  - \( \Psi \) is matric tension, which is a negative pressure (-p), so that water moves from low to high tension

- **Hydraulic gradient:** \( G = \Delta h / \Delta x \)
  - \( \Delta h \) is the change in head
  - \( \Delta x \) is the distance
  - This is the slope, or gradient, of the head.
  - The steeper the slope, the higher the gradient
Soil water can move from dry to wet
Darcy’s Law

• **Water Flux:** $q = - K \frac{G}{h} = - K \frac{\Delta h}{\Delta x}$
  - $K$ is the hydraulic conductivity, or how permeable the soil is
    • A big $K$ (sands, gravels) means that water flows fast
    • A small $K$ (clay, rock) means that water flows more slowly
  - $q$ is the flux, or flow per unit area
    • The negative shows that the flux is moving from high to low
    • It has a negative slope...

• **Total Flow:** $Q = q A$
  - $A$ is the cross-sectional area
    • For example, the cross-sectional area of a pipe is $\pi r^2$
    • The bigger the pipe, the more the flow
  - $Q$ is the total flow
Soil Water Movement

- **Total Head:**
  - \( h = z + p = z - \Psi \)

- **Hydraulic Gradient, G**
  - change in energy w/ distance
  - \( G = \frac{\Delta h}{\Delta x} \)

- **Hydraulic conductivity, K**
  - a function of pore size \((d)\) and connectivity
  - \( K = f(d^2) \)
Hydraulic Conductivity

- Typical Values
  - Gravel, lava, caves
    - $K = 10 \text{ cm/s}$
  - Sands
    - $K = 20 \text{ cm/hr}$
  - Soils
    - $K = 5 \text{ cm/day}$
  - Clays
    - $K = 0.9 \text{ cm/yr}$
Darcy’s Law, \( Q = A \cdot K \cdot G \)
- \( A \) = The area of flow
  - The greater the area, the greater the flow.
- \( K \) = The hydraulic conductivity or permeability
  - The higher the conductivity, the greater the flow.
- \( G = \Delta H / L \) = The magnitude of the driving force (\( L = \Delta x \))
  - The steeper the water slope, the greater the flow.

\[ Q = A \cdot K \cdot G \]

![Diagram of Darcy’s Law](image_url)
Unsaturated Hydraulic Conductivity

- *Less* than the *Saturated* Conductivity!!
  - \( q = K_u \, G = K \, K_r \, G \)
  - \( K_u = K \, K_r \) = unsaturated hydraulic conductivity
  - \( K_r \) = relative hydraulic conductivity
Plant Water Uptake

- Water is *pumped* through plants partly by the *pull* or *tension* of the atmosphere
- The tension in the atmosphere is generally hundreds of bars
- The moisture in the soil is only weakly bound.
- We can measure the tension in the plant, and find the tension is lowest in the roots, and highest in the leaf
Plant Water Uptake

- **Plant Available Water**
  - Soil water that is potentially used by plants
  - Limited by soil tension, from wilting point to field capacity
  - \( \text{PAW} = \text{FC} - \text{WP} \)
Soil Available Water (AW) for various soils

<table>
<thead>
<tr>
<th></th>
<th>Δz</th>
<th>OD</th>
<th>BD</th>
<th>FC</th>
<th>WP</th>
<th>AW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
<td>g</td>
<td>g/cm³</td>
<td>g/g</td>
<td>g/g</td>
<td>g/g/cm³/cm³</td>
</tr>
<tr>
<td>$A_p$</td>
<td>15</td>
<td>212</td>
<td>1.485</td>
<td>259</td>
<td>0.224</td>
<td>227</td>
</tr>
<tr>
<td>$B_A$</td>
<td>30</td>
<td>240</td>
<td>1.684</td>
<td>312</td>
<td>0.303</td>
<td>275</td>
</tr>
<tr>
<td>$B_t$</td>
<td>45</td>
<td>230</td>
<td>1.613</td>
<td>333</td>
<td>0.452</td>
<td>280</td>
</tr>
</tbody>
</table>

Soil samples were collected in a ring with:

\[ w = 2 \text{ g} \quad r = 3 \text{ cm} \quad h = 5 \text{ cm} \quad V = \pi r^2 h = 141 \text{ cm}^3 \]

Water contents calculated using:

\[ BD = \frac{OD-w}{V} \quad FC_g = \frac{C-OD}{OD-w} \quad WP_g = \frac{WP-OD}{OD-w} \]

\[ AW_g = FC_g - WP_g \quad AW = AW_g \cdot BD \quad D_w = D_s \cdot AW \]
Chapter 9 Quiz – Soil Water

1. Adhesion – Cohesion (circle one) is the attraction of the water to the soil surface.

2. What is the volumetric water content if the bulk density is 1.33 kg/L (same as g/cm$^3$) and the gravimetric water content is 0.25?

3. What is the depth of water in a foot of soil if the volumetric water content is 0.10 (10%)?

4. Is available water primarily held in:
   ___ Macropores (greater than 100 μm)
   ___ Mesopores (between 0.1 and 100 μm)
   ___ Micropores (smaller than 0.1 μm)

5. Which soil type has the greatest plant available water? Least?
   ___ Clay  ___ Sand  ___ Silt  ___ Loam  ___ Clay Loam