3. Physical Processes and the Fate of Contaminants

Textbook Chapter 5

Fig 5.2. Water in Soil

Fig 5.1 The Hydrologic Cycle and Movement of Pollutants

Units for Water Content

- By mass (weight)
  - θ_W = g g^{-1}, kg kg^{-1}, %
- By volume, volumetric water content
  - θ_V = cm^3 cm^{-3}, m^3 m^{-3}, %

Movement of Water

- Water in soil carries nutrients and contaminants.
  - Can flow in saturated soil
  - Can flow in unsaturated
  - Can flow down
  - Can flow up

Movement of Water

- Follows soil water potential energy, H

  H = gravity potential + pressure potential (matric potential) + osmotic potential (important in saline soils)
    - Osmotic potential is not discussed in the textbook and we will not deal with this effect.
    - H is called the soil-water potential.
  - If there is a difference in value of H between two points in a soil, water can move from the high to low potential.

Units of water potential

- The very basic unit of potential energy is joules (or ergs, calories, BTU etc)
- However, usually units of pressure or head of water (height of a water column) are used to express the energy status of water in soil.

Pressure potential in energy units

- What is the potential energy of water at 10 m above a surface (in relation to the surface)?
- Look 1 m^3 of the water 10 m above the surface
  - Water has a density of 1000 kg/m^3. Thus, the mass is 1000 kg.
    - The potential energy force times distance
    - (1000)(10) kg-m = 10,000 kg-m
      - Multiply by gravitational acceleration to convert kg to force; 98,000 N-m
  - 1 N-m = 1 joule so the potential energy of the water is 98,000 Joules.
    - Could express this as ergs or calories

Pressure potential in energy units (cont.)

- If this is expressed per unit volume, (98,000 J/m^3 or 98,000 N/m^2).
- The basic unit of pressure is force per unit area. I.0 Pascal = 1.0 N/m^2
  - The potential energy of the m^3 of water can be expressed as 98,000 Pascals (pressure unit) = 0.1 mega Pascal.
- Thus the potential energy per unit area can be expressed in units of pressure.
  - Use Pascals (or atmospheres).

Units for soil water potential

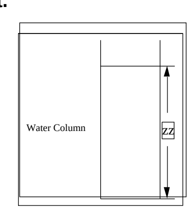
- 9.87 atm = 1 megapascal, MPa

Units for soil water potential

- Also can use the height of a of a column of liquid to define potential of water
- A column of a uniform liquid exerts a pressure proportional to the height of the column.
- 1 bar = 1000 cm of water (10 m)
- 1 bar = 0.987 atmospheres, atm

Gravity potential, z

- Gravity potential is a relative potential energy term.
  - Calculated relative to a height that is designated as the zero reference point.
- Using water column height
  - Gravity potential = head,
  - z is in cm or m



In Class Exercise

- ***What is the gravity potential of the surface water at the top of a 20 m column relative to the bottom of a the column. Express in bar, Mpa and atm.***

Answer

Water can rise up a soil column, or a sponge

- **How is water held in a soil column?**

Pressure potential (matric potential), h

- **Forces holding water in soil.(negative potential)**
  - **Capillary rise (This is effect of small pores in the soil. Soil minerals and organic materials are wetable.)**
  - **Strong adsorption of water by exchangeable cations and clay surfaces.**

h (or ψ) = Capillary potential + adsorptive potential

- **Capillary forces are usually dominant and we will only talk about this component of pressure potential.**

Capillary Rise, Fig. 5-3

Calculation of Capillary Rise

$$h_c = \frac{2s\cos\alpha}{Dgr}$$

- **h_C = capillary rise (m) = -h**
- **r = tube diameter or pore radius (m)**
- **D = density of water (Mg m^{-3}** or g cm^{-3}**)**
- **g = acceleration due to gravity**
- **α = contact angle of water on soil minerals.**
  - **(in degrees and is due to the wetability of the surfaces)**
- **s = surface tension of the water (N m^{-1})**

Calculation of Capillary Rise Continued

- In soils this equation can be reduced to:

$$h_c = \frac{3 \times 10^{-5}}{d}$$

- Where h_c = -h in m of water head and d = pore diameter in meters
  - This is a simplification
    - In real soils the pore sizes vary greatly

In Class Exercise

- ***What is the capillary rise in a silty glass bead material with a mean pore diameter of 30 µm.***

Answer

Combining gravitational and matric (pressure) potential

- Water potential, H.

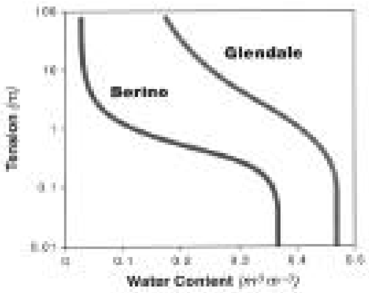
  H = z + h

Going back to the capillary rise question

- ***What is the water potential, H, of water at the top of the column relative to the free water surface at the bottom if the capillary rise is 1 m.***

Answer

Soil moisture retention curve: Tension (- matric potential, -h) vs. water content. Fig 5-5



Role of soil texture

- Berino is a loamy sand.
- Glendale is a clay loam.

In Class Exercise

- ***What is the matric potential in a soil that is saturated with water.***

Answer

In Class Exercise

- ***A. What is the typical pore space in a mineral soil? (Capacity for soil to hold water)***
  - ***Assume bulk density = 1.3 g/cm^3***
  - ***Assume density of particles = 2.6 g/cm^3***

Answer

-

Summary of Components of Soil Water Potential

- 1. Gravity potential, z, (relative to a given height)
  - Positive or negative
- 2. Matric potential, h

  h is also called pressure potential or ψ
  - Negative (zero in saturated soil)
    - Capillary
    - Adsorptive forces

Summary of Components of Soil Water Potential (cont.)

- Water potential
  - Soil-water potential, H = h + z
    - h = adsorptive potential
    - z = gravity potential
- Difference in H will result in water movement from higher to lower potential.

In Class Exercise

- Consider the Berino soil the with a water table at 5 m. The surface soil has a water content of 20%. Will water move from the surface to the water table (unsaturated flow) or not. Compare to the Glendale.
- Hint use the water table surface as the reference level for gravity head.
  - First define z, h, and H at the water table.

Fig 5.2. Water in Soil

Answer

Pressure (matric) Potential in Field Soils

- Field capacity, h = - 1/3 atm = -1/3 bar = -3.3 m = -.033 MPa
- Potential when water can't be taken up by plants is - 15 bar = - 15 atm
- Plant available water
  - - 15 to - 1/3 atm

Measurement of matric (pressure) potential

- Pressure plate
  - Place a sample of a known moisture content on a porous plate and apply pressure until water just begins to squeeze from the soil.
    - Record the pressure (pressure potential)
- Tensiometer (can measure *in situ*)
  - Porous cup on end of a pipe with pressure gauge.

Measure of Matric Potential with a Tensiometry, Fig 5.4

In class exercise

- What is the gauge reading on a 1 m long tensiometer set in water with just enough water to cover the porous cup.
  - The meter measures pressure potential, h.
  - What is H at the cup?
  - What is H at the meter?

Answer

Correcting tensiometers to zero

- To get h at the cup must correct for length of water column in tensiometer.
- However, many tensiometers can be set to correct for the length the of the water column.
  - Zero gauge in with the porous cup in water.

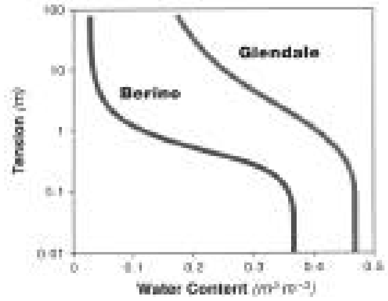
Alternative Methods for Determining Soil Water Content

- Take to lab and dry at 105 ^{0}C
- Field
  - 1. Tensiometry
    - Need to have soil moisture tension graph.
  - 2. Neutron Probe.
  - 3. Time domain reflectometry (TDR).

In class exercise

- At equilibrium what is the moisture content of a Berino soil at 2 m above the water table?
- Compare to Glendale soil.

Moisture Tension Graph, Fig. 5.5 (volumetric water content)



Answer

Rate of Water Flow

- Saturated flow
  - In saturated soil the matric potential, h, is zero. H = z = height of water column and water flows in response to gravity potential.
- Unsaturated flow
  - Water flows in response to H = z + h

Saturated Flow
Note here z = thickness, Fig. 5-6

Darcy's Law

$$\text{Flow rate} = \frac{(\text{pressure difference})}{(\text{resistance})}$$

- Like Ohm's Law

$$I = \frac{E}{R}$$

- I = current in amperes
- E = voltage
- R = resistance in ohms

Darcy's Law Continued

$$\text{resistance} = \frac{\text{thickness}}{K(\text{area})}$$

- K = hydraulic conductivity

Darcy's Law Continued

- Flow in volume per unit time

$$\text{Flow rate} = \frac{Q}{t} = \left(\frac{KA}{z}\right)\Delta H$$

  - Q = accumulated flow, m^3
  - t = time
  - K = hydraulic conductivity
  - z = thickness of the water column
  - ΔH = head
  - A = area
- See equation 5.5 in textbook.

Darcy velocity

- Flow in meters per day:

$$q = \frac{Q}{At} = \left(\frac{K}{z}\right)\Delta H$$

- A = the cross sectional area of the column

Unsaturated Flow

- Water can flow in soils even if the soil is not saturated
- Use Darcy's Law
- Unsaturated conductivity, K, is a function of water content

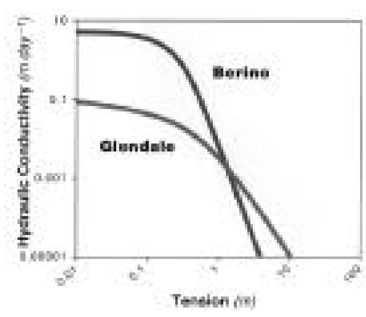
$$K_h = ke^{\alpha h}$$

- Where ∝ is a soil constant and h is the matric (pressure) potential

Water flow in unsaturated soils

- If water is content is greater than for the equilibrium potential, water flows to the ground water. This flow can transport pollutants
- If water is content is less than for the equilibrium potential water can move up from the water table.
- However, during very dry weather the surface soil can get very dry because of the slow rate for unsaturated flow.

Unsaturated Flow Continued, Fig. 5.7



Unsaturated Flow Continued

- Berino is a loamy sand.
- Glendale is a clay loam.
- At tension ≤ 1 m (0.1 bar) or greater, conductivity is very low.

In Class Exercise

- What is the flow rate through, in m/day for a 2 m thickness of Glendale soil given saturated conditions and total head of 3 m? 10 m ?

Answers

In Class Exercise

- Unsaturated flow.
  - What is the flow rate through 2 m of Glendale soil given a suction at the bottom of - 0.1 atm and a thickness of 1m.
  - Water is added to the top of of the column to maintain the matric potential 0, just saturated.
  - Assume most of the column has a matric potential of - .1 atm.

Set up for Column Studies of Unsaturated Flow, Fig 5-10

Answer

Mass transport of dissolved materials in soil water

- Mass flow with water predicted by Darcy's Law.
- Flux density (mg m^{-2} d^{-1})
  - 1 m^3 = 1000 L

$$J_m = qC$$

  - q = Darcy velocity (m day^{-1})
  - C = concentration (mg m^{-3})

In Class Exercise

- Flow in an aquifer.
  - What is the Darcy velocity for saturated flow in a loamy sand aquifer like the Berino soil assuming a distance of 100 m with a 1.0 m drop in aquifer surface.

Answer

Factors Altering Chemical Transport in Soil

- Diffusion in water.
- Retardation by retention on soil particles.
- Dispersion due variation in pore size in soils.

Dispersion and Diffusion in Soil

- As water is moving by saturated or unsaturated flow, diffusion in 3-dimensions is occurring.
- Dispersion due variation in pore size and slower flow rate through smaller pores.

Molecular Diffusion

- Causes dissolved chemicals to slowly move in three dimensions.
- Greater diffusion at higher temperatures.
- Results in a spreading of a "plume" of contaminants in groundwater and the vadose zone.
- Can be calculated by Fix's Law

Fick's Law of Diffusion

$$J_D = -\theta D_m \frac{\partial C}{\partial z}$$

- J = diffusion rate
- D_m = porous medium diffusion coefficient
  - In groundwater ≈ 10^{-4} m^{-2} day^{-1}
- θ = water content
- Z = distance

Mechanical Dispersion

- Water flows at different rates through different sizes of pores.
- Causes some of the water and dissolved solute to be transported more slowly.

Retardation

- Chemical interaction between solute and particles can slow the movement of solutes.
- Examples:
  - Movement of K^+ through a soil is retarded greatly by cation exchange sites.
  - Organic solutes like components in gasoline can be adsorbed to some extent by soil organic matter.

One-Dimensional Flow in Columns

- Simple column studies are useful in determining diffusion and retardation coefficients for various solutes.
- Get "breakthrough" curves.

Measurement of Flow and Dispersion Without Retardation

- Use ^3H_2O, tritiated (radioactive) water.
  - Tritium is a radioactive isotope of H
- Can track water flow.

Set up for Column Studies of Unsaturated Flow, Fig 5-10

Dispersion of Tritiated ^3H Water in Unsaturated Flow, Fig. 5-12

- At time zero add a pulse of radioactive water.
- Sampling at different depths in column.
- Notice effects of dispersion and diffusion.

Different Types of Saturated Flow, Fig 5-12

- Sample end of column, report pore volumes instead of time
  - I. Piston flow
  - II. Dispersion plus diffusion
  - III. Dispersion plus diffusion plus retardation

Field measurements using large monoliths, Fig. 5-8

Field measurements using trenching, Fig. 5-9

Field measurements using wells and suction lysimeters

- Sampling wells strategically placed can be used to follow movement of contaminants.
- Suction lysimeters (porous ceramic cups) can be used to follow movement in unsaturated zones.
  - Use suction to extract water from unsaturated soil.
  - Limited to about minus 0. 75 atm water.

Movement of tritiated water applied on the surface of a soil, Fig. 5.13.

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Movement of chloride plume in sand aquifer, Fig 5-14.

Plume of trichloroethene down gradient from the Twin City Army Ammunition Plant

Summary

- Soil water moves from higher to lower potential.
- Water potential in atm, bar, or Pascals.

  H = h + z

  - z = gravity potential
  - h = ψ = matric (pressure potential) due to capillary and hydration forces
- Water flows in both saturated and unsaturated soil materials.
- Rate of water movement is calculated by Darcy's law.

- Conductivity decreases greatly in unsaturated soil as soil dries.
- Diffusion and mechanical dispersion causes plumes of contaminants to spread with time and distance.

Daily assignments

- For Sept. 12
  - Using the data in Fig 5.5 in estimate the minimum water content in the Bernino soil for water to flow from the surface toward the water table if the water table is at 5.0 m. Assume the soil water characteristic curve is the same for all of the vadose zone
    - Hint: First calculate the equilibrium matric potential then use the Figure to get the equilibrium water content.

- For Sept. 15
- What is the Darcy velocity for saturated flow in a Glendale soil column. A 0.5 m head of water is maintained on a 1.0 m column of of soil?
  - Get the K value from Figure 5.7