Lecture 34 Lecture on Soil Physics, part 2

- Theory, Moisture Transfer
  - Water Potential, revisited
  - Moisture transfer, Darcy's Law and the Richard's Equation
  - Soil Release curve.
- Observations, Moisture profiles
  - Seasonal patterns
  - Influence of soil texture
- Soil Evaporation
  - measurements
  - model calculations

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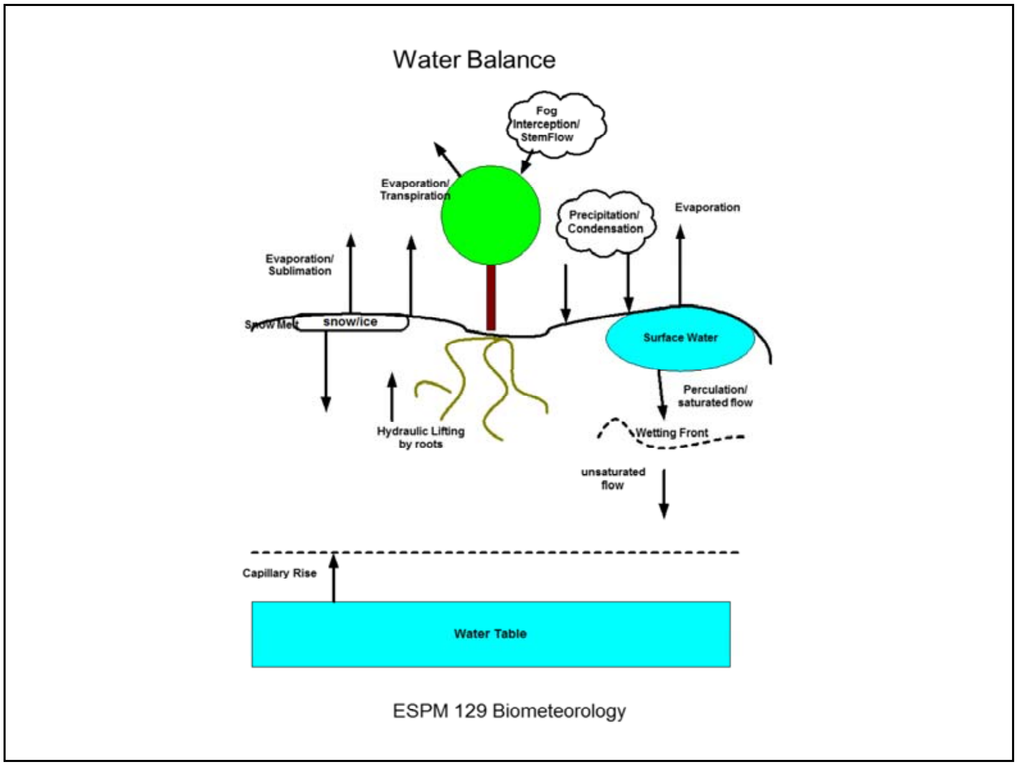
Here we discuss the transfer of water in soils and the storage of water in soils



Simple water balance considering pools and fluxes, inputs and outputs..inputs: rain, snow, fog and cloud interception. Outputs: evaporation, transpiration, sublimation..

Soil Water Potential

- Pressure
- Osmotic
- Gravitational
- Matric

$$\psi = \psi_p + \psi_o + \psi_g + \psi_m$$

Units: Energy/Volume =Pressure (Pa: kg m^{-1} s^{-2})

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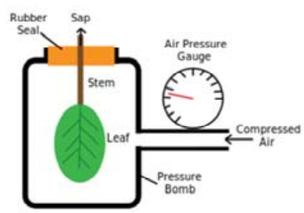
It is best to consider the energetics of water movement. This brings us to the concept of water potential

Measuring Water Potential



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We use a Scholander pressure ‘bomb’ to measure total leaf water potential. The leaf is placed in a sturdy metal chamber and the pressure of air is increased. At equilibrium sap will start to exude out the cut petiole. Domestic plants tend to wilt when the water potential is below -1.5 MPa, or -15 atmospheres. Drought adapted oaks can function as low as -6.0 MPa.

Gravitational potential

- The force of gravity exerted on a water column produces the gravitation potential.

$$\psi_g = \rho_l g z \qquad \text{Pa} = \text{kg m}^{-1}\text{ s}^{-2}$$

$$\frac{\psi_g|_{head}}{\rho_l g} = z \qquad \text{m}$$

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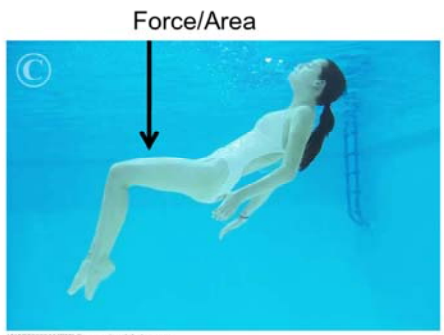
Gravitational potential is probably most well know. It takes energy to lift water and energy is released if it moves across a head, like the hydroelectric plant of a dam. Engineers prefer to work in terms of head, water potential devided by density and gravitational acceleration

Pressure, or Hydrostatic, Water Potential

Pressure exerted by an overlying water column on an infinitesimal cube of water



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Pressure potential can be positive or negative. Think of the case of the stomatal guard cells, the movement of water into these cells makes the turgid as pressure potential is positive. This leads to their opening. In the reverse case, they can experience negative pressure potential as they become water leaves and they become flaccid. The actual potential of a sample of pure water in water is defined as zero

Osmotic/Solute Water Potential

Change in Energy of Pure Water when Solutes are Added

Solutes reduce the free energy of water by reducing the mobility of water molecules as they are attracted to the charged or polar surfaces of the solutes

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Solutes in water reduce its free energy and make its water potential more negative. So a plant in salty water is exposed to a more negative water potential, hence it is harder for it to extract water for its biological use than if its roots were exposed to pure water.

Osmotic potential

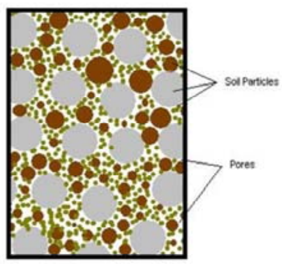
- Osmotic potential arises from the dilution of solutes in water, eg salts, sugars etc.
  - For the osmotic potential to drive water flow, a semi-permeable membrane must separate two bodies of water, such as cells, and pools of water.

$$\psi_o = -c\phi \nu RT$$

c is the concentration
ϕ is the osmotic coefficient
ν is the number of ions per mole

Matric Water Potential

Matric potential refers to the effect of a large polar or charged surface (e.g. soil matrix) on the water system



interactions between water and solid surfaces act to reduce the activity of water. Results from capillary and adsorptive (van der Waal's) forces

Matric effect reduces the free energy of water molecules through attractive forces that reduce their mobility

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Matric water potential is exerted on water in soils, as well as in cells and the plant xylem. So water can be tightly bound to the surfaces of soils. There is moisture there, but a low water potentials it is not biologically available. More over different soil textures will experience different water potentials at the same volumetric water content. This is why it is so important to think about water availability to microbes and plants in terms of water potential than water content. We will explore this later with the topic of water retention curves.

Matric potential

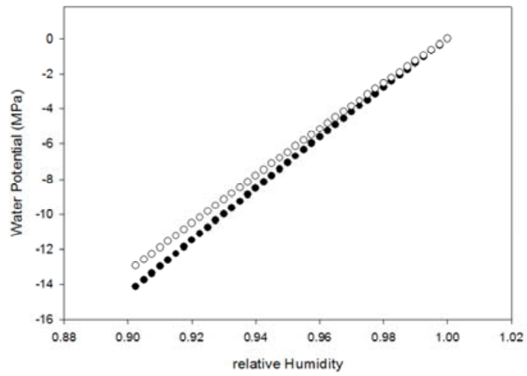
- It is water potential due to attraction between water and soils.
  - These interactions reduce the potential of water, giving it a negative sign.

$$\psi_m \sim a w^{-b}$$

w is relative water content
a and b are coefficients

Vapor potential of
The Atmosphere
And how to measure
Matrix Potential of Soils

$$\psi_v = \frac{R\,T}{V_w}\ln\left(\frac{e}{e_s}\right)$$



R is the universal gas constant (8.314 J mole-1 K-1)
V is the molal volume of water (18 l mol^{-1})

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We can quantify the water potential of the atmosphere by knowing the relative humidity, ea/es. We use this equation to evaluate matrix water potential of soil samples. We put a sample in a chamber and wait for equilibrium and measure the temperature of the sample and the dew point temperature. It takes very, very precise temperature measurements and intense temperature control. You can see from this figure, smally changes in RH translate into large differences in water potential

Gravity Potential
= Density of water times Acceleration of Gravity times Head Differential

$$\psi_g = \rho_w g h$$

It takes Energy to Lift water Up Hill
Energy is Released when Water Flows Down Hill

Conveyance, Storage and Treatment of Water accounts for 19% of CA electricity use

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We are most associated with gravitational potential. Its value depends on the position relative to a reference, known as head

Lifting Water by Suction, 10.3 m at sea level

$$P_{atmos} = -\psi_g = \rho_w g h = 101300\,Pa$$

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How does a Straw work? Does Paris suck the water out of the glass?; The technical answer is no. Sucking evacuates the atmospheric pressure acting on the water column under the straw. With it evacuated of air pressure, the pressure on the water exposed in the glass pushes it up the straw to a new equilibrium.

What are the Limits on Pumping Water from a Well?
How deep can the Water Table Be?

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This is an important limit as it also establishes the limit of lifting ground water with a suction pump. If you are interested in doing work for the Peace corp and bring water to underserved people you should know this fact. It is a reason companies like Jacuzzi develop submersible pumps.

What is the Maximum Height a Suction Pump can Lift water at Sea Level??

$$\frac{\psi_g |_{head}}{\rho_l g} = z = \frac{101300}{1000 \cdot 9.8} = 10.3 \quad \text{meters}$$

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Here are the computations for sea level. What happens if you are working in Tibet or the Andes?

Saturated Flow, Pure Water

$$\psi = \psi_p + \psi_g$$

$$0 = \psi_p + \psi_g;$$
$$\psi_p = -\psi_g$$

Takes Negative Pressure (suction) to lift water against gravity
The Gravitational Burden of Water Overhead Imposes a Positive Pressures

Dominated by Pressure and Gravity

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Let's deconstruct these ideas of water potential. Let's first consider pure water. By definition its water potential is zero. So if you are deep in a pool the pressure potential you feel is the opposite of the gravitation potential that is pushing down on you.

Turgor or pressure potential

- Water potential exerted by the pressure, P, or weight of water

$$\psi_p = P$$

Sometimes expressed per unit density of water

$$\psi_p = \frac{P}{\rho_w} \qquad m^2\ s^{-2}$$

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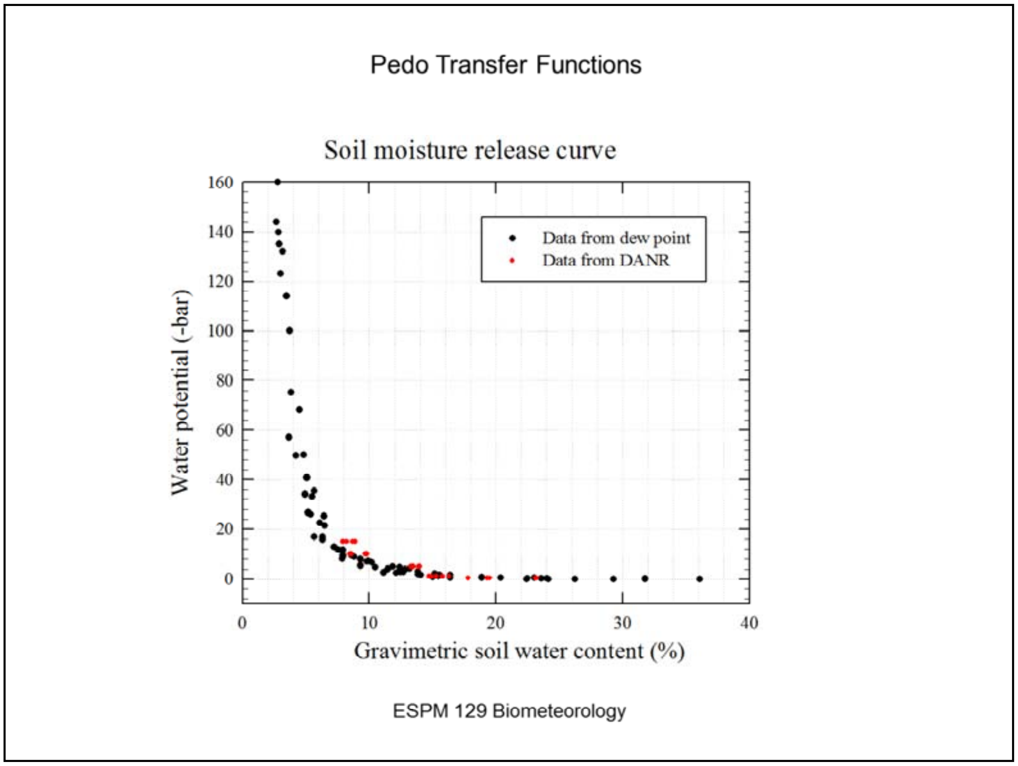
Unsaturated Flow

$$\psi = \psi_g + \psi_m$$

Dominated by Gravitation and Matrix Forces

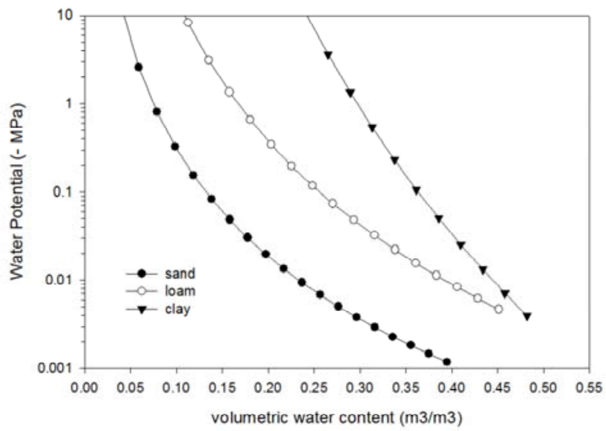
In fields we are more often dealing with unsaturated flows and movements of water. This will help us explain how water can move physically upward through the soil-plant-atmosphere continuum, because it must move downward energetically.



While gravimetric and volumetric water content is easiest to measure and measure routinely, It is important to quantify the water retention curve for your site and evaluate the water release curve for that soil. See how non linear it is.

Soil Water Retention Curve, f(volumetric water content)

$$\Psi = \Psi_{sat} \frac{\theta}{\theta_{sat}}^{-b}$$



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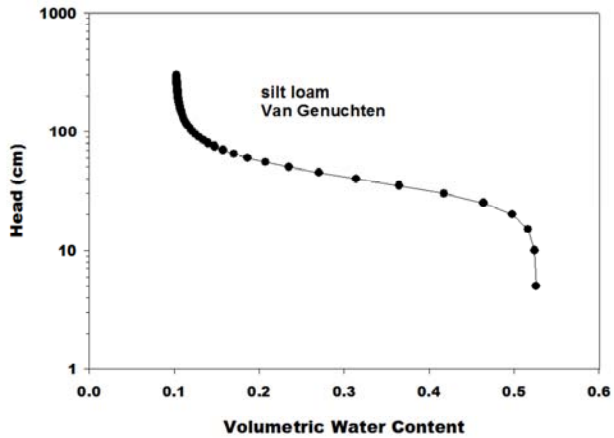
Knowing the texture one can apply simple water retention functions to compute water potential. Popular papers by Clapp and Hornberger are used in many climate and weather models.

PedoTransfer Function



$$\theta = \theta_{resid} + \frac{\theta_{sat} - \theta_{resid}}{[1 + (\alpha\psi)^n]^m}$$

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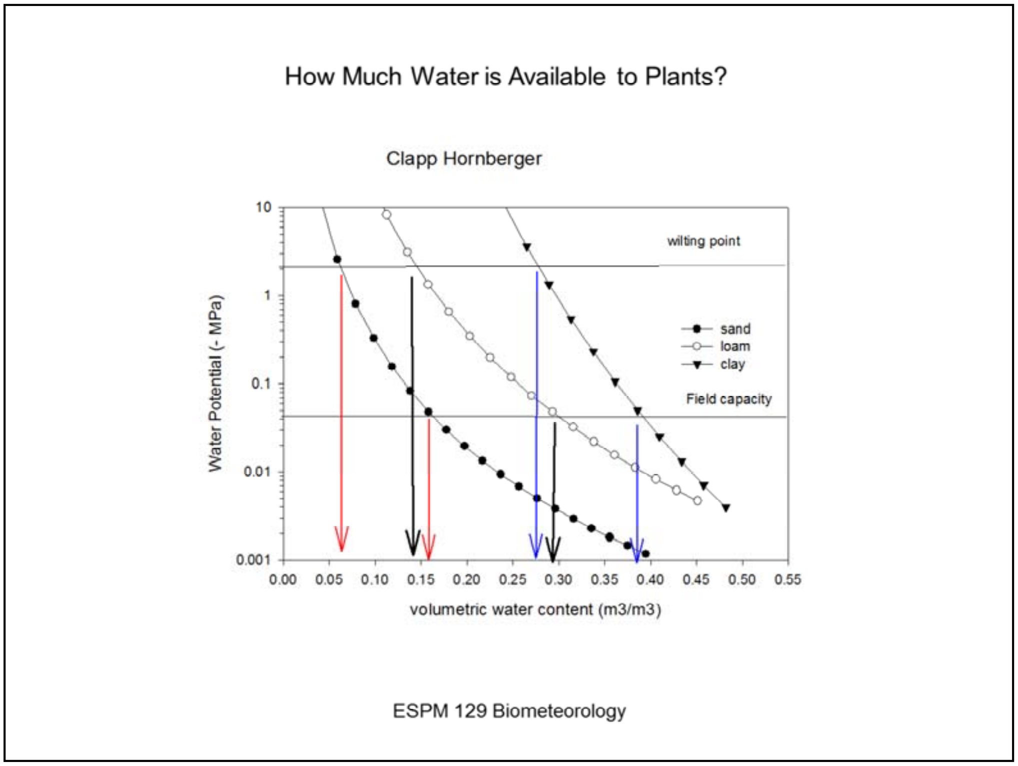
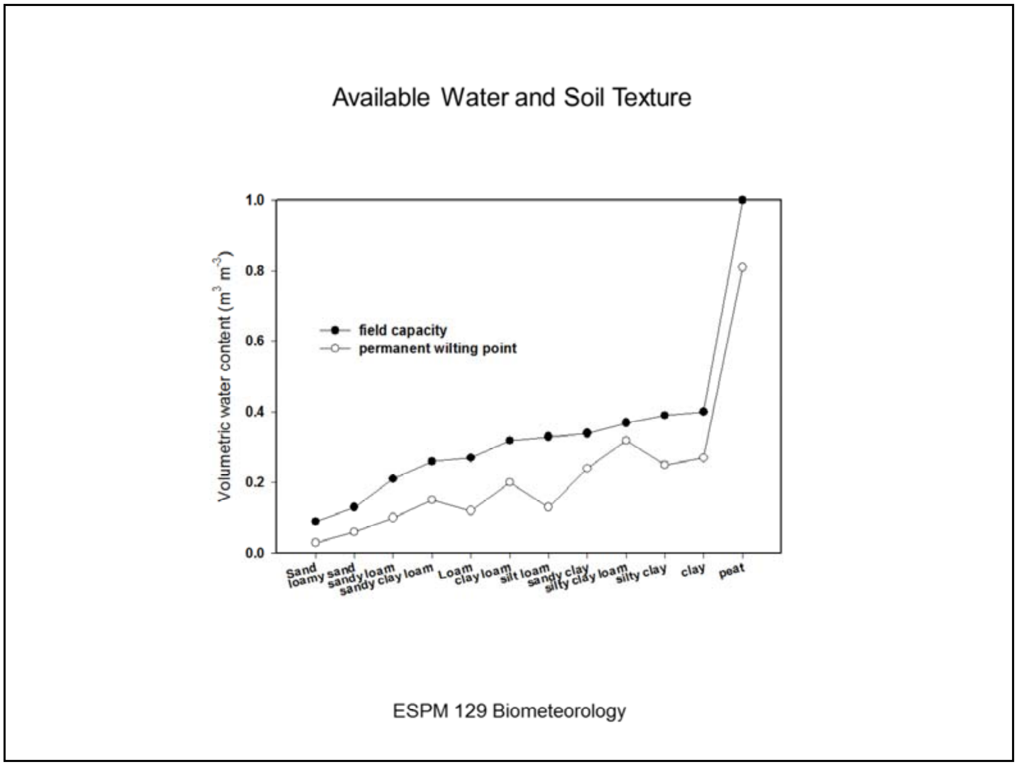
In recent years the functions of van Genuchten, as it deals more realistically with the drier and wetter ends. Yet it requires more parameters.

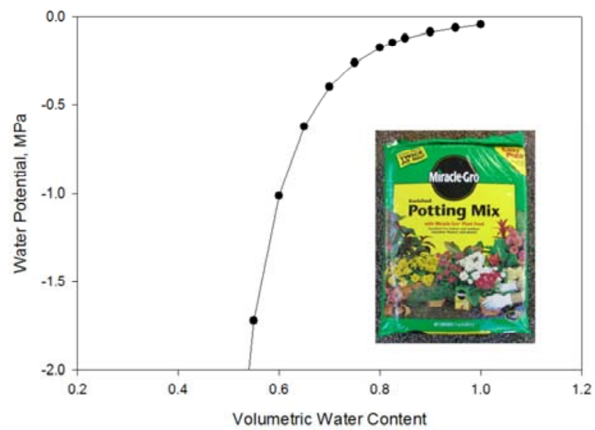


Water potential is critical to tell us how much water is available to a plant or microbe. Different soils will have different biological water holding capacities and different water contents that are deemed wet or dry. For example a wet sand is at a lower water content that a dry loam or clay, and vice versa



Here we can see the range between wilting point and field capacity for different soils. Loams tend to hold the most water. Peats are very wet, then very dry at high volumetric water contents. This water is just not available to plants. This is why I hate potting soil and see our basal wilt with relatively damp ‘soil’

Peat Water Retention Curve, Campbell Model, Data of Letts



Peat is either really Wet or Really Dry (in a Thermodynamic Sense)

Water Availability of Peat

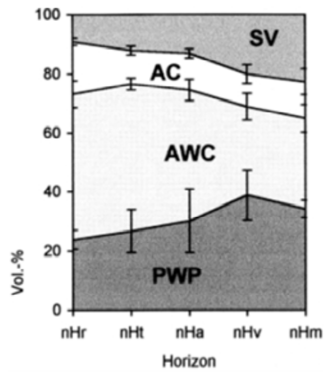


Figure 2: Influence of soil development on the soil-physical characteristics of peat soils.

Schwartzel et al. 2002. J Plant Nutrition and Soil Sci

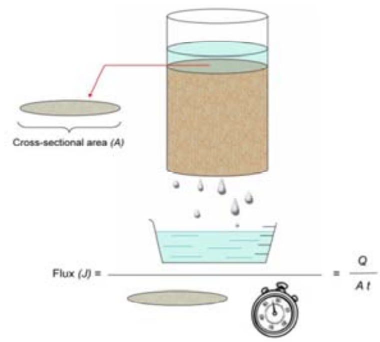
Darcy's Law

Henry Darcy

The volume of water, V, passing through a bed of sand per unit time is a function of the cross-sectional area, A, the thickness of the bed, L, the depth of water on top of the bed, Δh, and the hydraulic conductivity of the sand, K:

$$\frac{V}{t} = K\frac{A\Delta h}{L}$$

$$J = \frac{V}{At} = K\frac{\Delta h}{L}$$



ESPM 129 Biometeorology soils.usda.gov/.../note6fig2_lowres.jpg

Now lets look at water movement through soils. The theory started during the Napoleonic wars of the early 19th Century by French Engineers like Darcy

ABSTRACT

Henry Darcy (born 1803, died 1858) is known to soil physicists as the founding father of the science of fluid flow in soils. This illustrated account of a short visit to Dijon, his native town, reveals little-known aspects of Darcy's character, life, and work. The central square and town gardens are named after Darcy, as are numerous commercial and public undertakings: a cinema, bus stop, a garage, a multistory car park, a pharmacy, and a shopping arcade. Inquiry revealed that Henry Darcy himself has been forgotten by the citizens of Dijon, and that his name persists only as a ubiquitous geographical label. It was not always thus. Darcy, with great vision and skill, designed and built a pure water supply system for Dijon, in place of previous squalor and filth. Dijon became a model for the rest of Europe. Darcy selflessly waived fees due to him from the town, corresponding to about $1.5 million today. Medals were struck recognizing his skill and selflessness; and a monument celebrates his great work. Dijon gave him a public funeral, the whole population lining the streets, and the council renamed the central square in his honor. His simple tomb is in good condition in Dijon cemetery. His letters to Henri-Emile Bazin reveal him as intelligent, witty, and sceptical, and quite devoid of pretension.

Philip JR (1995) Desperately Seeking Darcy in Dijon.
Soil Sci Soc Am J 59:319-324

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While Darcy is famous to US, one of our leading scientists John Philip wrote a wonder story of his search for Darcy's grave in Dijon, mustard country. Sadly no one seemed to know of him. And John Philip met his early demise being struck by a trolley car in Amsterdam, not looking across the street before he walked, like LOTS OF BERKELEY STUDENTS…Look both ways, please

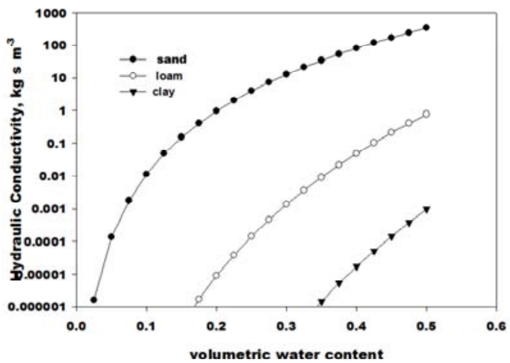
Darcy’s Law: Conditions of Use

- valid for
  - **low** Reynolds numbers, where flow is laminar
  - viscous forces dominate (Re <1).

- invalid for:
  - Conditions where K is a function of head
    - e.g. unsaturated soils, karst limestone and dolomite soils.
  - dense clay soils, which have low permeability.

Hydraulic Conductivity is a Function of Soil Moisture

$$K = \frac{VL}{At\Delta h}$$



$$K(\Psi_m) = K_s(\frac{\Psi_e}{\Psi})^{2+3/b}$$

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Mass Flux of Water and Its Budget Equation

$$F_m = -D_{mass} \frac{\partial (m_{water} / V)}{\partial z} = -D_\theta \frac{\partial (\rho_w \theta)}{\partial z} \qquad \text{kg m}^{-2}\ \text{s}^{-1}$$

$$\rho_w \frac{\partial \theta}{\partial t} = -\frac{\partial F_\theta}{\partial z} = \rho_w \frac{\partial}{\partial z}\left[D_h \frac{\partial \theta}{\partial z} \right]$$

Richards Equation for Unsaturated Soils

Describes the time rate of change of soil moisture in a soil column

Classic Form, in terms of Head, h

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right) \right]$$

Richards equation is for unsaturated flow. It is complicated as K is a function of head. Note in our study of turbulence K was not a function of itself.

In Terms of Water Potential

$$F_w = -D_\psi(\psi)\frac{\partial \psi}{\partial z}$$

the flux density of **Energy** is a product of the energy density (J/V) times a velocity:

(J m^{-3}) m s^{-1} =J m^{-2} s^{-1}= (kg m^2 s^{-2}) m^{-2} s^{-1} = kg s^{-3} = Pa m s^{-1}

$$\frac{\partial \psi}{\partial t} = \frac{\partial q}{\partial z} = \frac{\partial (K(\psi)^{\partial \psi}/_{\partial z})}{\partial z}$$

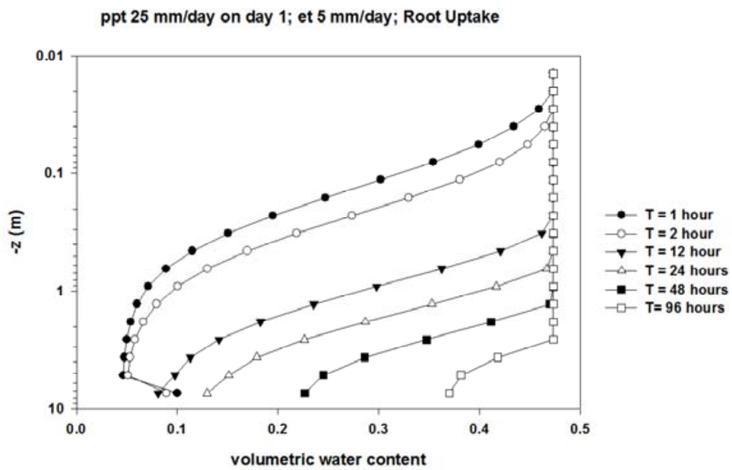
Water Transfer In Terms of Water Potential

$$q = -K(\psi) \partial\psi / \partial z$$

$$q = -K(\psi_m) \partial\psi / \partial z = -K(\psi_m)\frac{\partial \psi_m}{\partial z} - K(\psi_m)\frac{\partial \psi_g}{\partial z}$$

$$\frac{d\theta}{d\psi_m}\frac{\partial \psi_m}{\partial t} = \frac{\partial \theta}{\partial t} = \frac{K_h(\psi)}{\rho_w g}\frac{\partial^2 \psi_m}{\partial z^2} + \frac{\partial K_h(\psi_m)}{\partial z}[\frac{1}{\rho_w g}\frac{d\psi_m}{dz} + 1]$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\rho_w g}\frac{\partial K_h(\psi_m)}{\partial z}\frac{d\psi_m}{dz} + \frac{K_h(\psi)}{\rho_w g}\frac{\partial^2 \psi_m}{\partial z^2} + \frac{\partial K_h(\psi)}{\partial z}$$



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