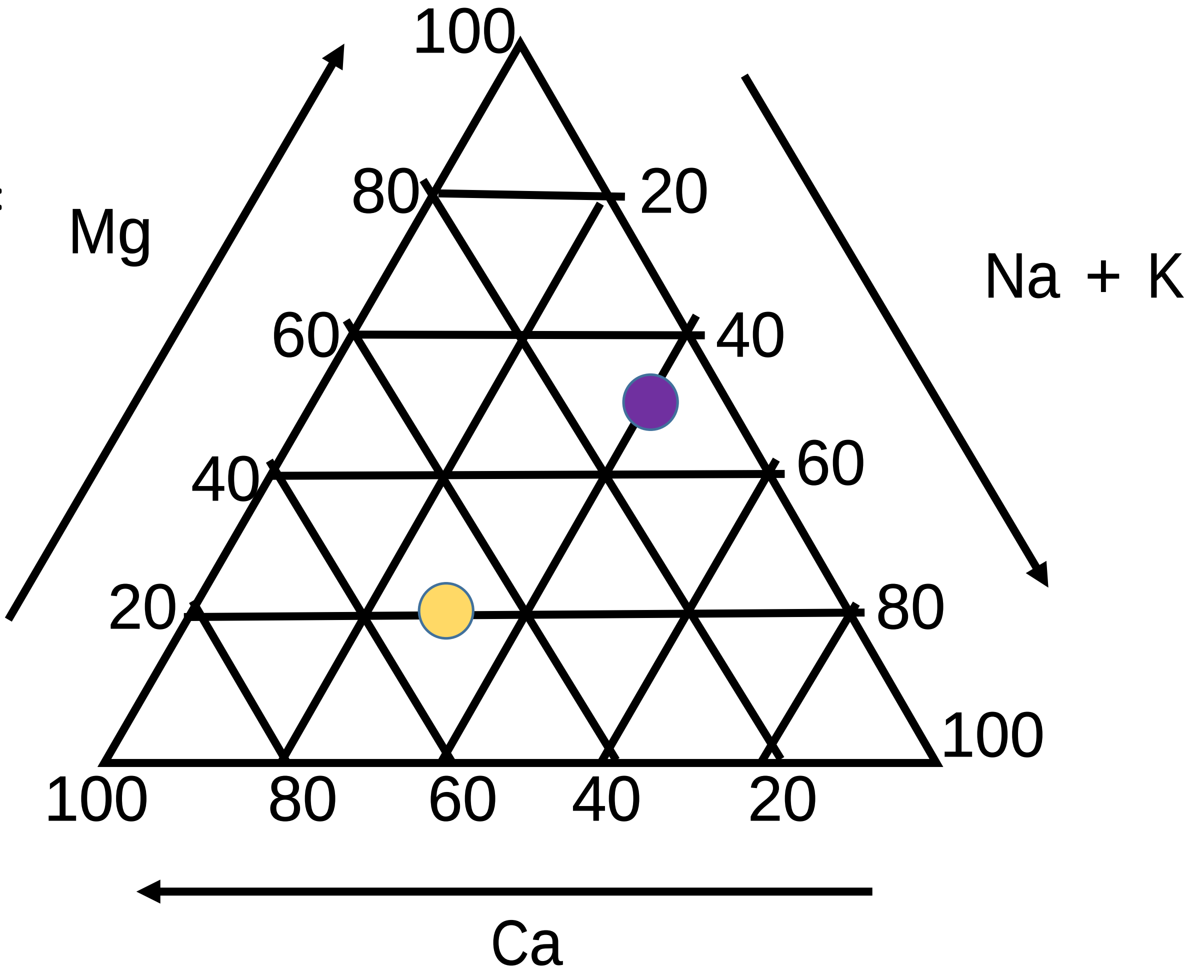
Tri-linear Plot

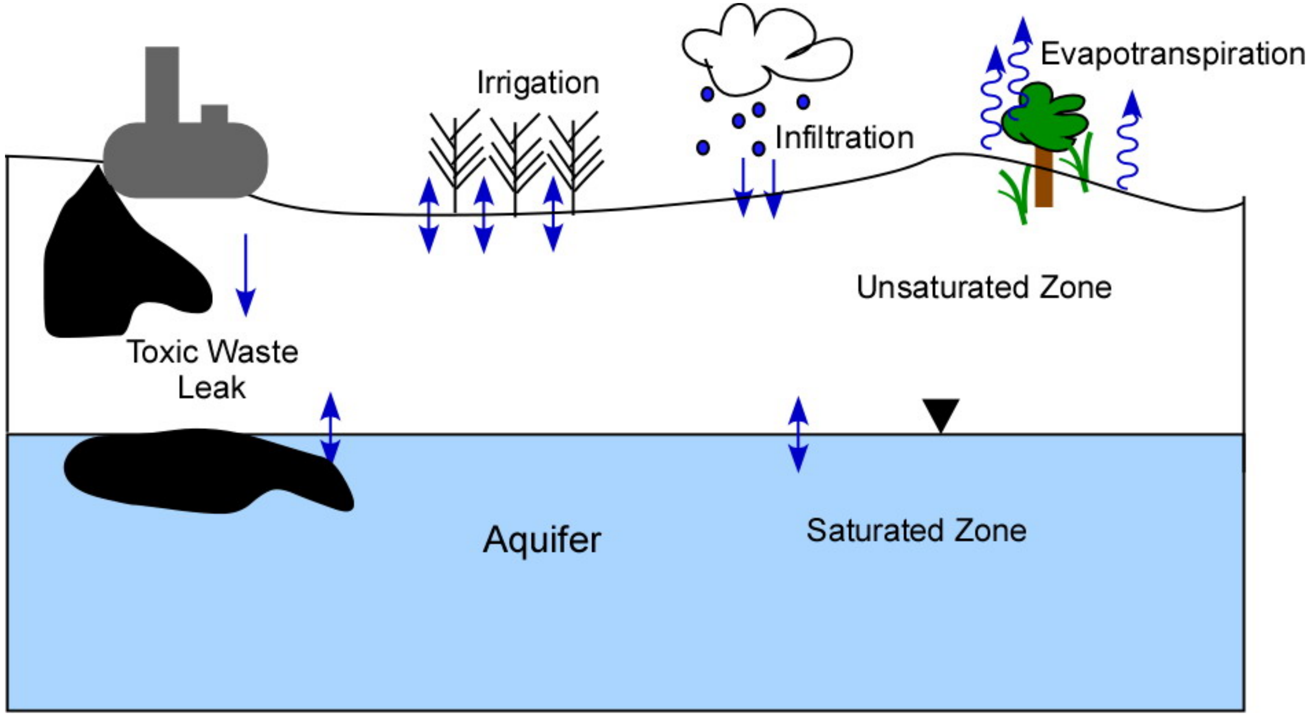
Mg, Ca, Na+K
100, 0, 0
0, 50, 50
33, 33, 33

More examples:
20, 50, 30
50, 10, 40



Unsaturated Flow

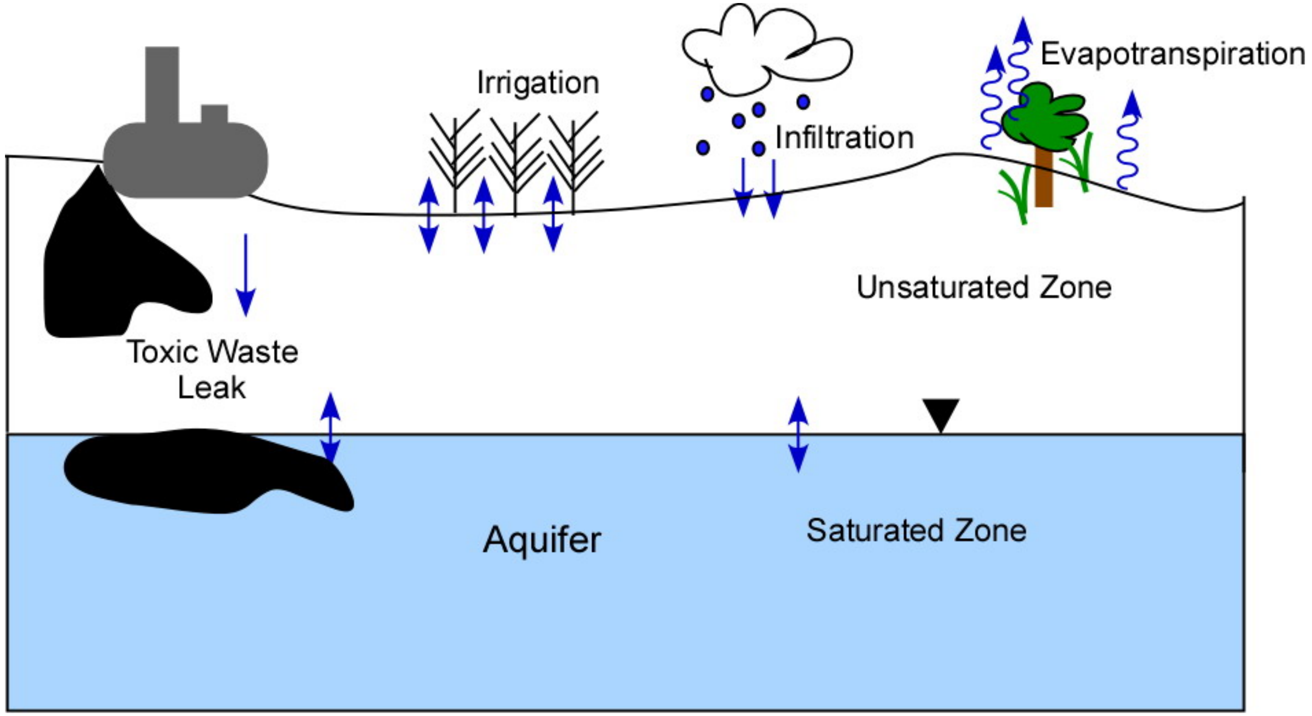
Why study the unsaturated zone?



The unsaturated or vadose zone:

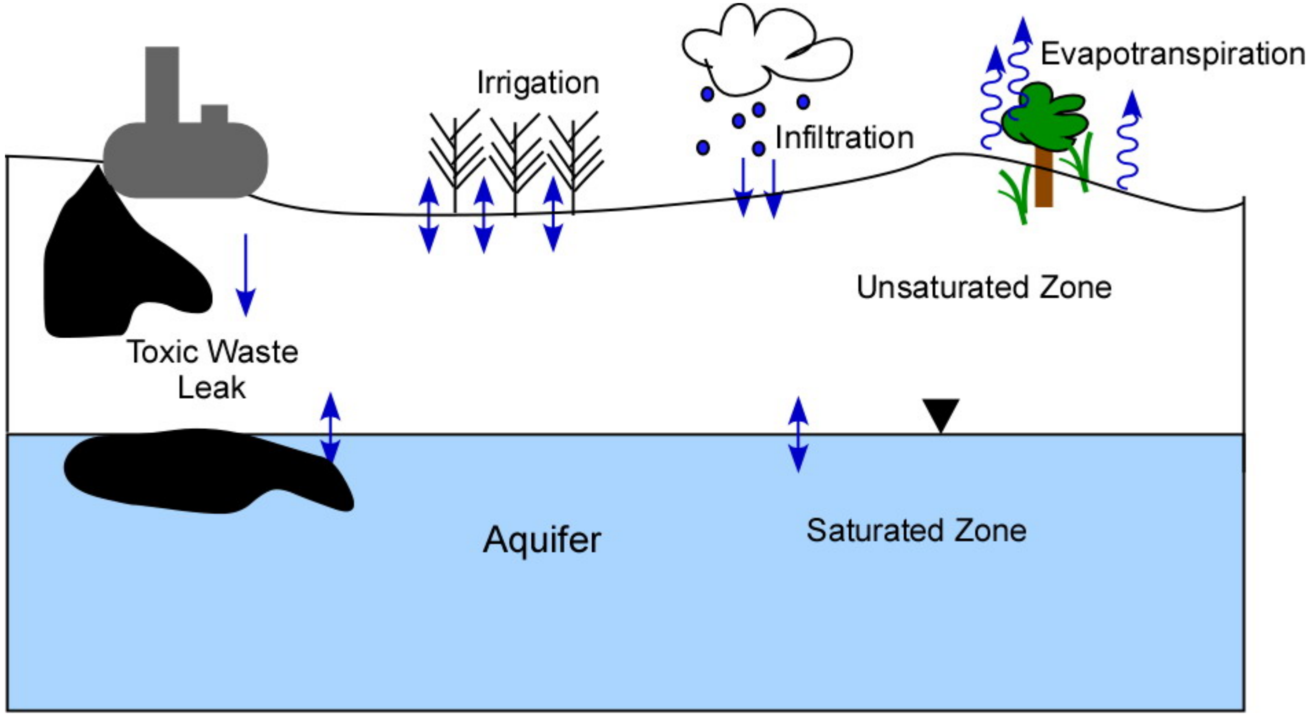
- Occurs above the water table
- Pores are only partially filled with water
  - the moisture content is less than the porosity
  - Three phases – liquid, ice, gas

Why study the unsaturated zone?



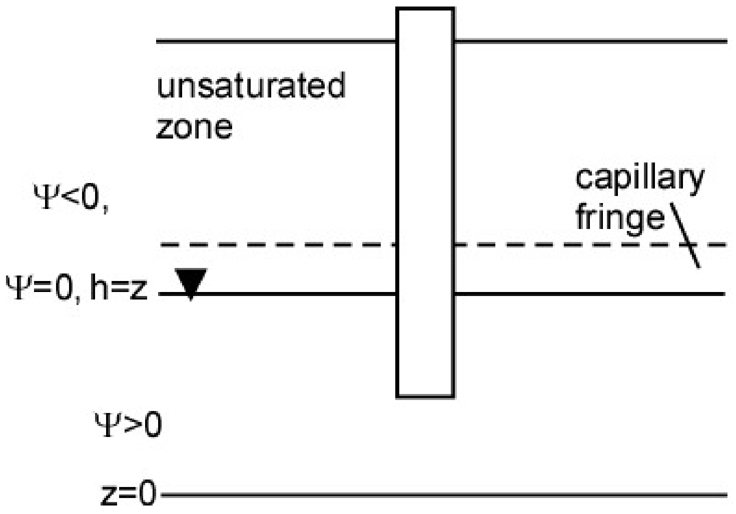
Important to:
- GW Recharge
- Agriculture
- Contaminant Transport
- Runoff generation
- Interface w/Atmosphere (GCM)

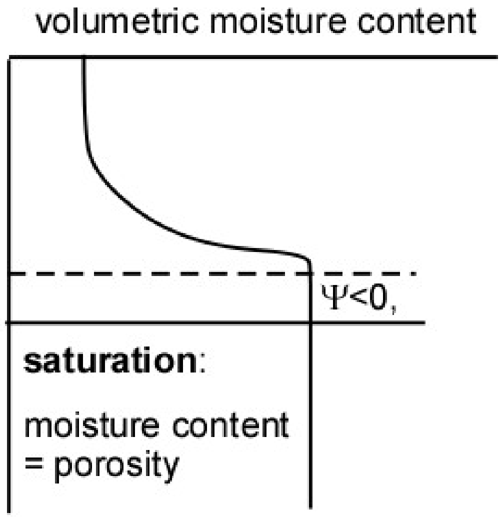
Why study the unsaturated zone?



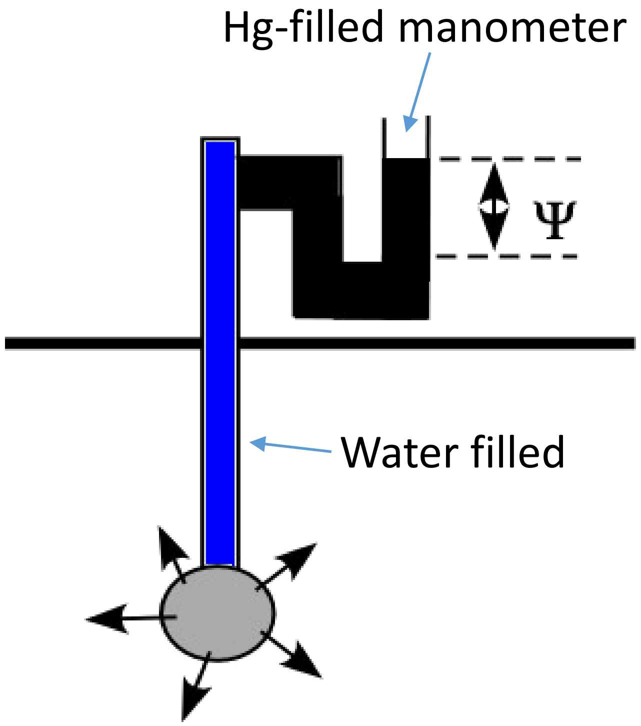
The unsaturated or vadose zone:

- Fluid pressure head, Ψ, is less than zero – under tension
  - Hydraulic head is measured with a tensiometer
- ➔ Flow is driven by suction
- Hydraulic conductivity, K, and moisture content, θ, are functions of the pressure head [or $K(\Psi)$, $\theta(\Psi)$].



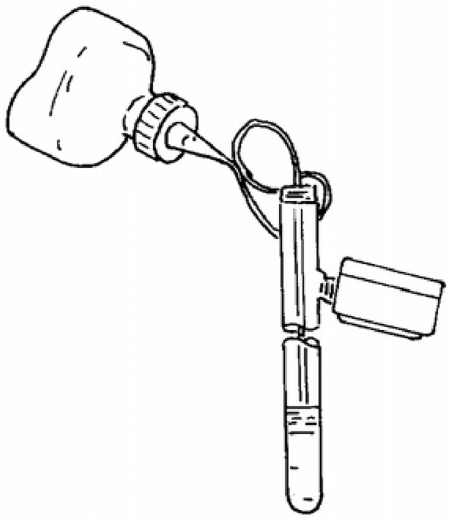


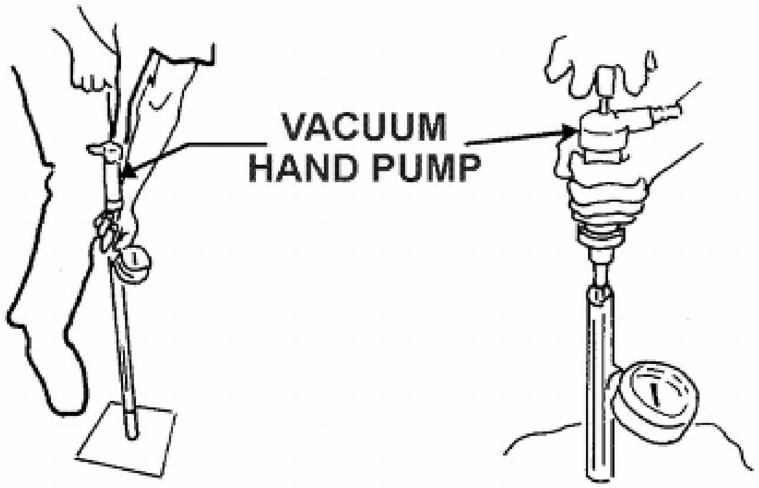
Ψ = *pressure head*

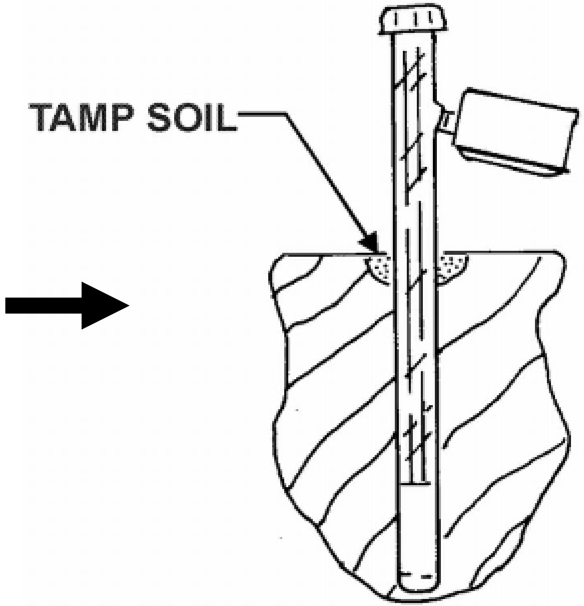


How to measure Ψ: Because pressure head is negative in the unsaturated zone, we can't use a piezometer to measure head – no standing water in the well above the water table.

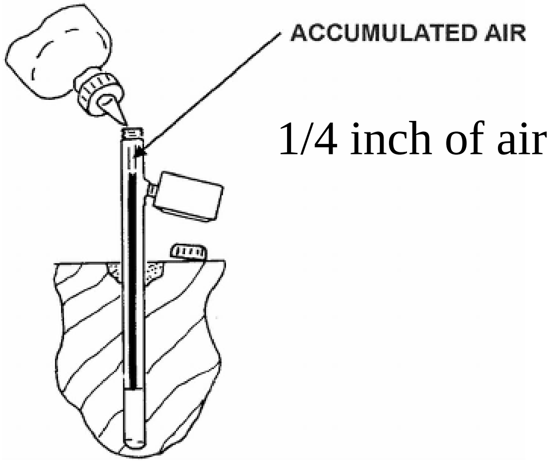
Tensiometer: Directly measures Ψ: A porous cup is attached to an airtight water-filled tube. Porous cup inserted into soil at a known depth where it comes into contact with the soil and reaches hydraulic equilibrium. The vacuum (negative pressure) created at the top of the tube is measured as Ψ.



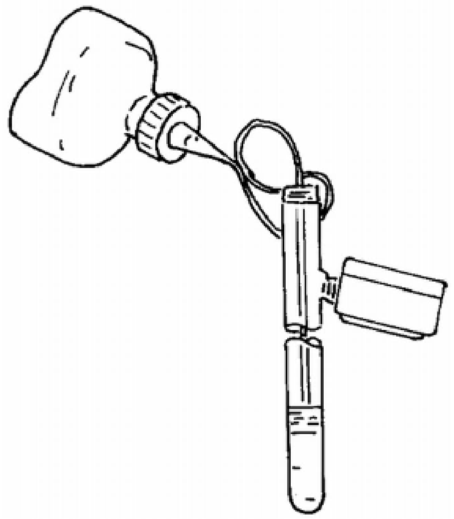


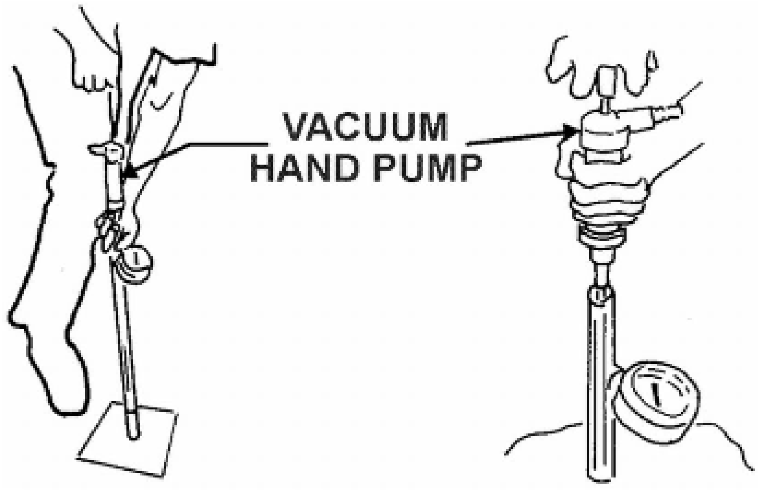


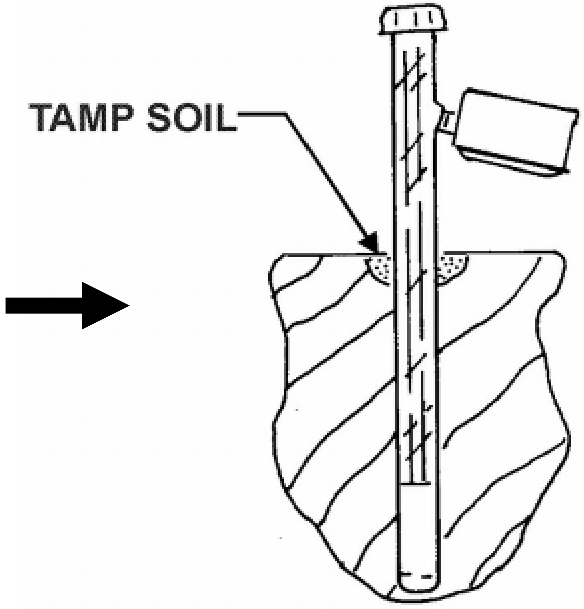
Tensiometers



Source: http://awqa.org/wp-content/toolkits/IrrigationScheduling/TensiometerDesciription_UnivFla.pdf

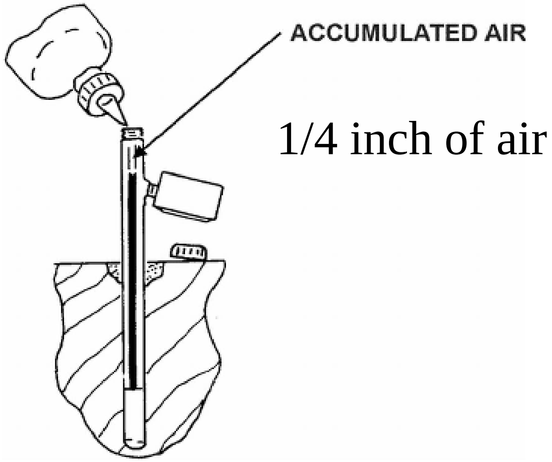






Tensiometers

- Rate of increase in soil tension at any given depth can be related to the density of the active roots
- Directly related to the ability of plants to extract water from soil. Automated!



Source: http://awqa.org/wp-content/toolkits/IrrigationScheduling/TensiometerDesciription_UnivFla.pdf

Definitions:

θ = *volumetric moisture content* or *volumetric water content* (decimal fraction)

= volume of water / bulk volume of soil [L^3/L^3]

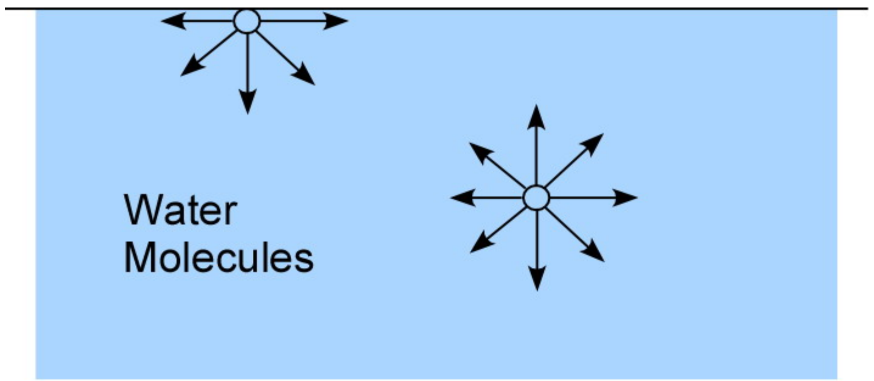
θ' = *degree of saturation* = θ/η [L^3/L^3]; η is porosity

Capillarity and movement of soil moisture:

Water molecules attract each other so that at the surface there is a net downward pull on the molecule. The net effect is **surface tension, σ.**

Surface tension depends on:

- The substances (fluid, solid, gas)
- Any solutes
- Temperature
- Gas pressure



These tensions, or attractions, cause capillary pressure: media draws in water, and a meniscus forms.

Capillarity and movement of soil moisture:

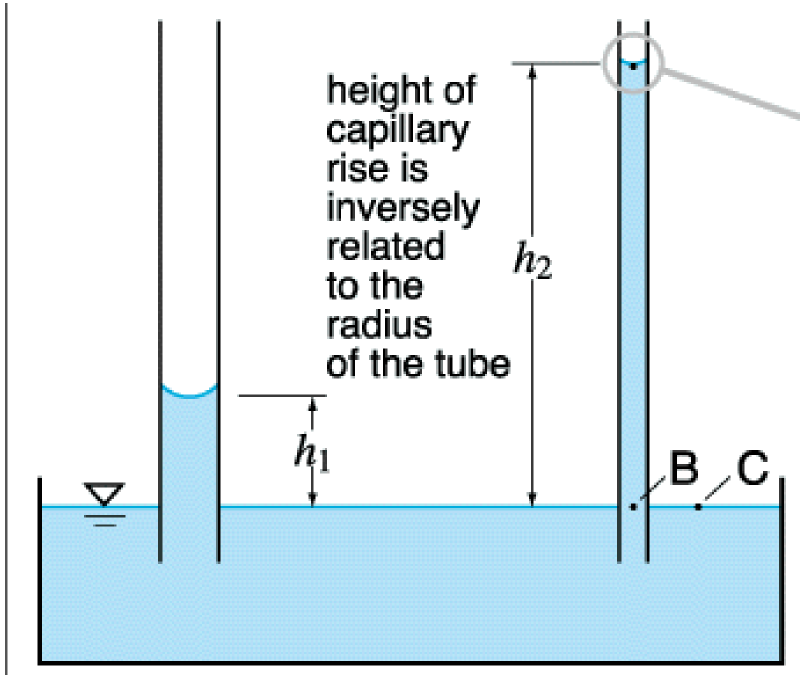
Capillary rise (idealized capillary fringe):

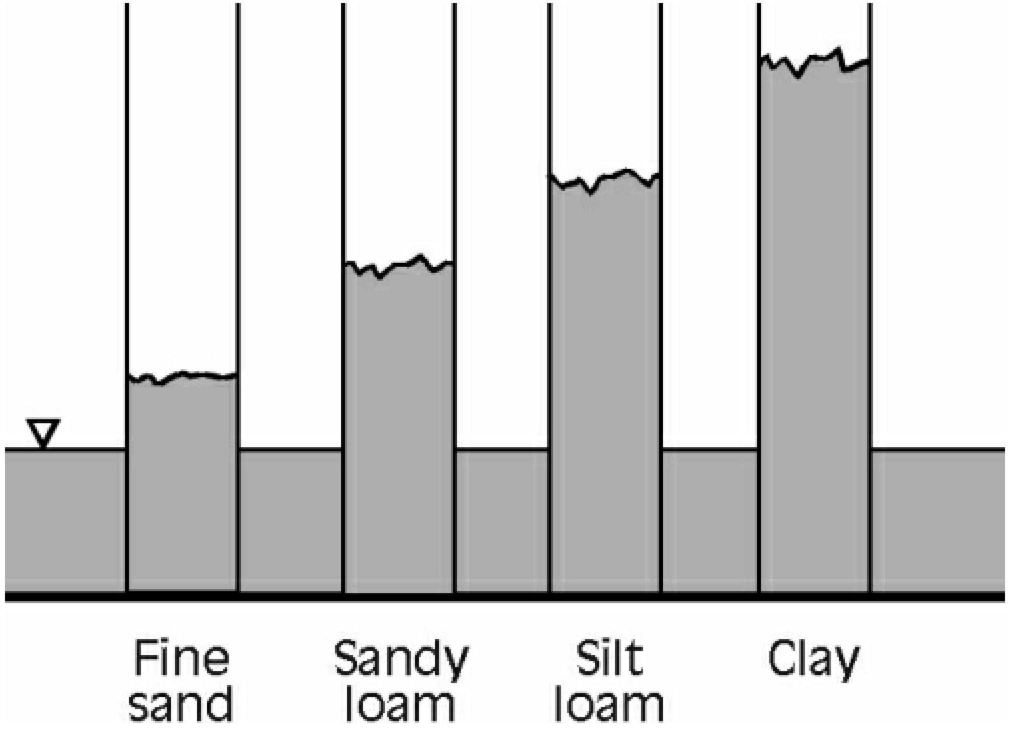
Capillary fringe is a few mm for coarse sediment and up to 1-2 meters for clays

Downward force: $F_d = (\pi r^2)\,\rho g h_c$ (weight of water)

Upward force: $F_u = (2\pi r)\,\sigma \cos\alpha$ (tension force)

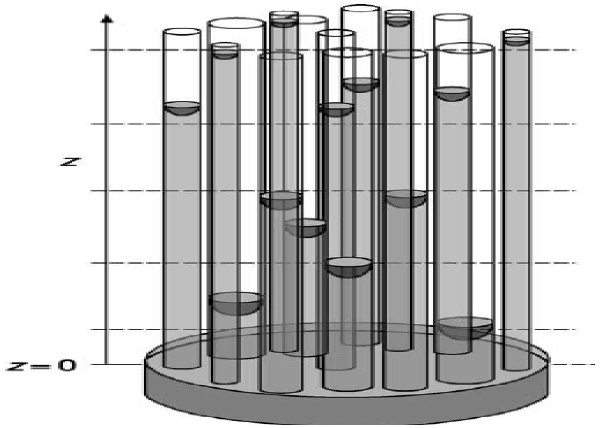
Setting up equality and solving for h_c : $h_c = 2\sigma \cos\alpha / \rho g r$

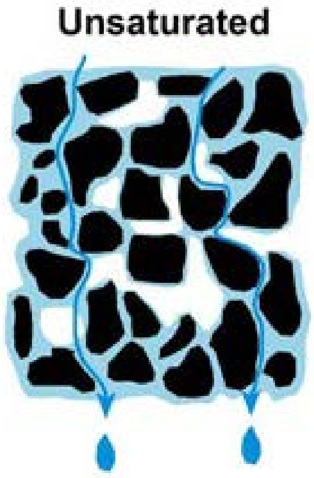




Capillarity and movement of soil moisture:

Soil water content, θ, is a function of the suction (or tension or moisture potential), Ψ. Pore space in rocks and soil is much more complex geometricallyto characteristic retention curves for a given sample material:





Capillarity and movement of soil moisture:

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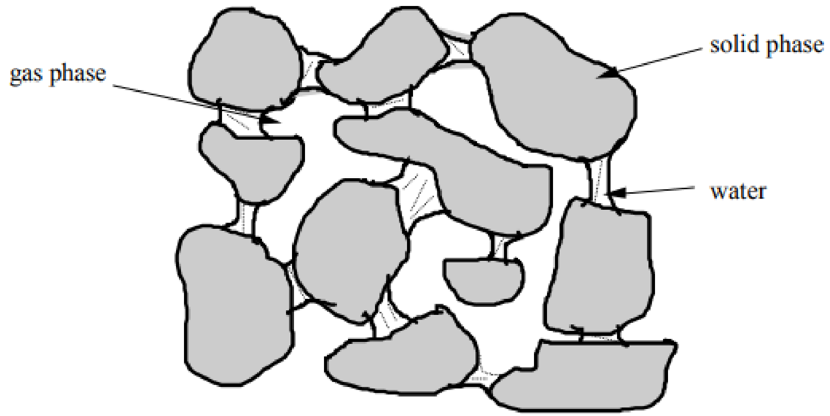
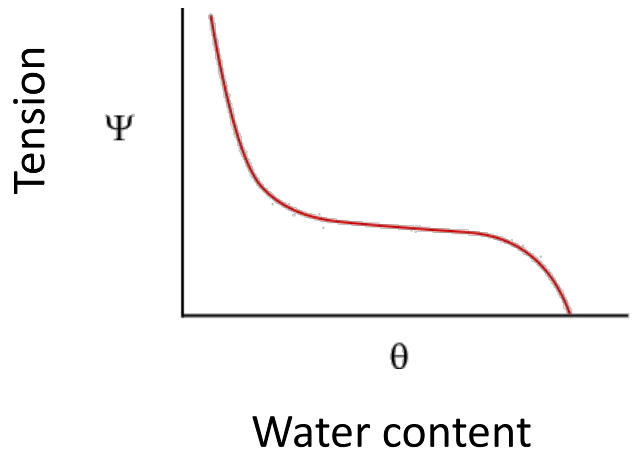
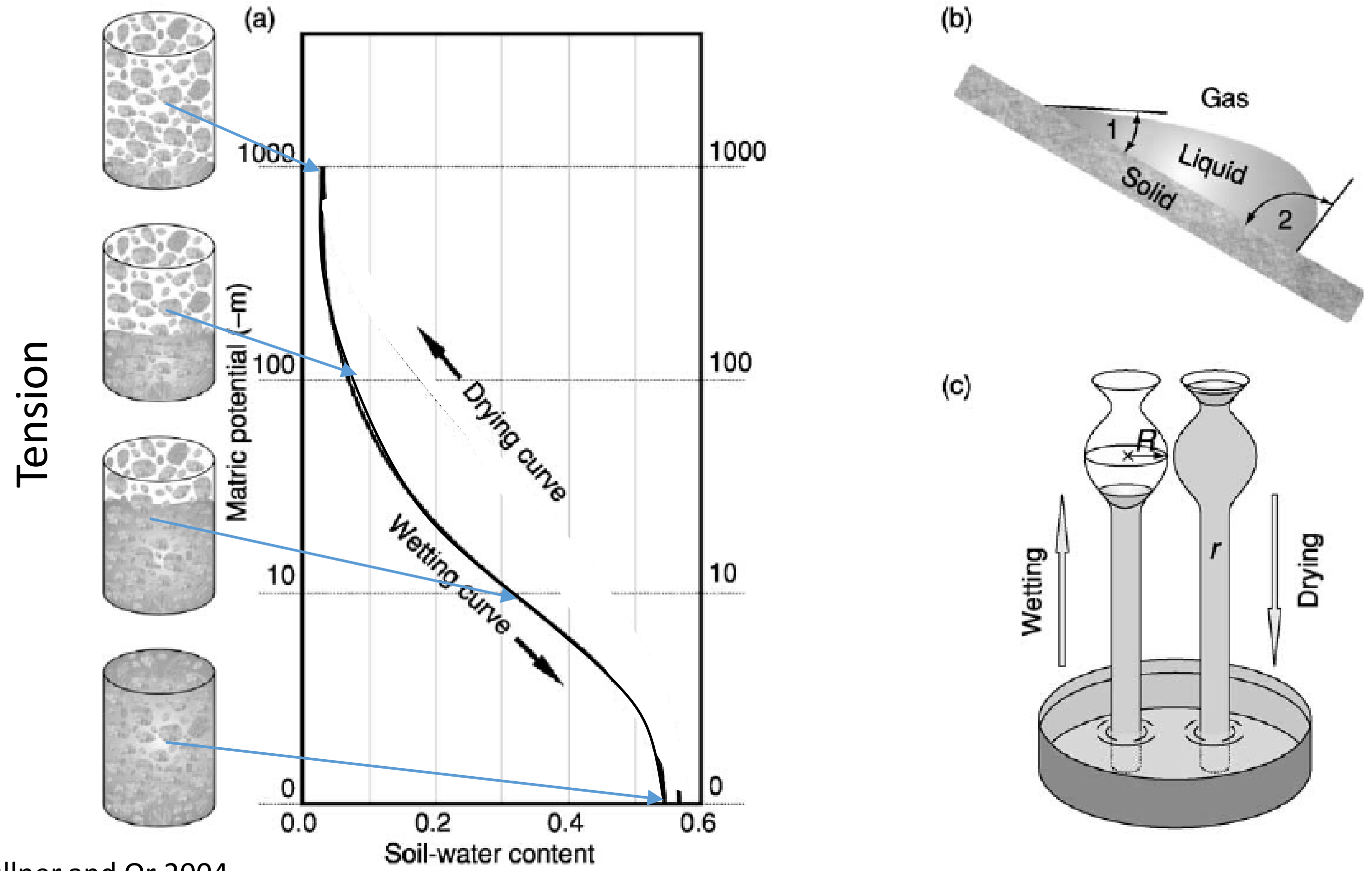
Pore space in rocks and soil is much more complex geometrically





Capillarity and movement of soil moisture:

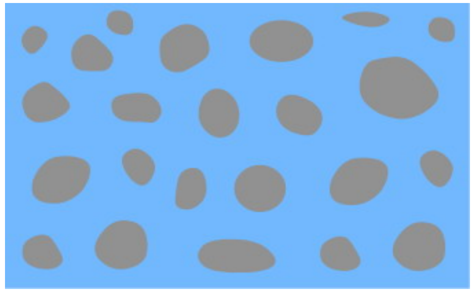
The shape of the retention curve:

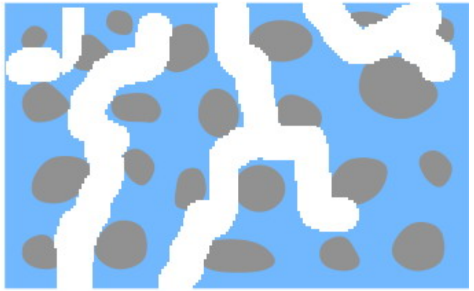


Tullner and Or 2004

Hydraulic conductivity in the unsaturated zone:

How would you intuitively expect K to differ between saturated and unsaturated cases?





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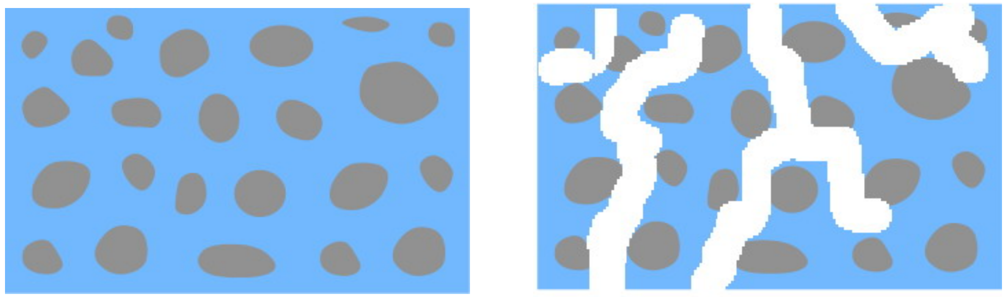


Hydraulic conductivity, K, depends on moisture content, θ, and pressure head, Ψ

$$K=K(\theta) \;\&\; K=K(\Psi)$$

Compared to saturated media:

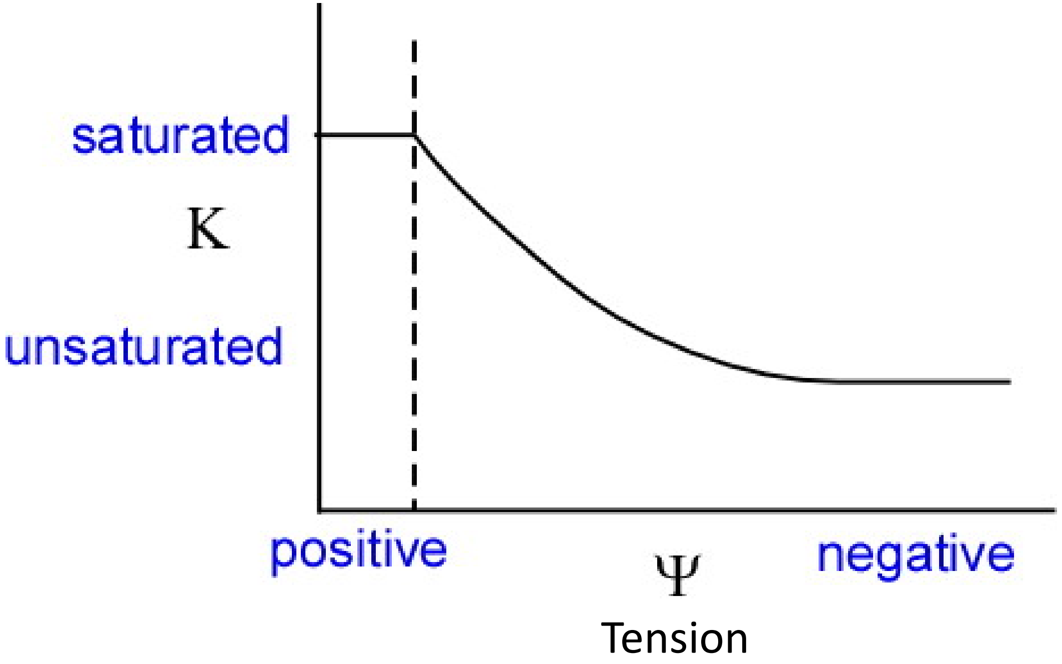
- When unsaturated (gas phase present), K will be lower.
- The more air, the smaller the cross-sectional area for flow of water.
- Large pores are empty and smaller pores remain filled.
- What will happen to K for declining water content (more air)?

Hydraulic conductivity in the unsaturated zone:

- What will happen to K for declining water content (more air)?

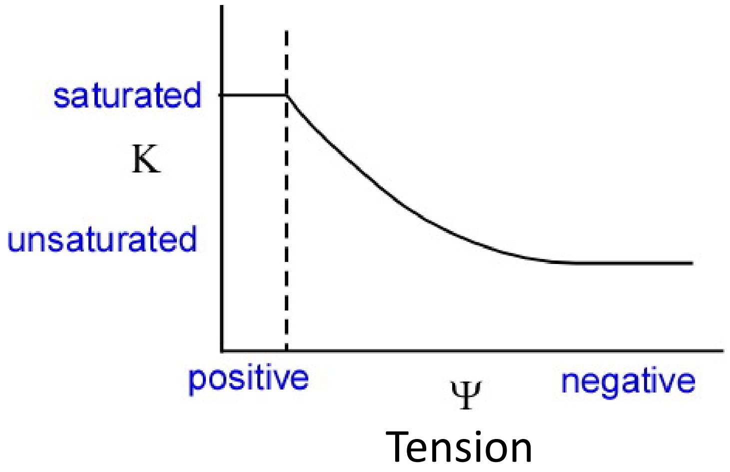
K is lower for smaller θ because:

1) Cross-sectional area remaining reflects only water-filled smaller pores. (What do you know about K in media with large pores vs small pores?)
2) There is greater tension because for a lower θ water is held tighter.
   Note that for saturation, there is no tension.



Hydraulic conductivity in the unsaturated zone:

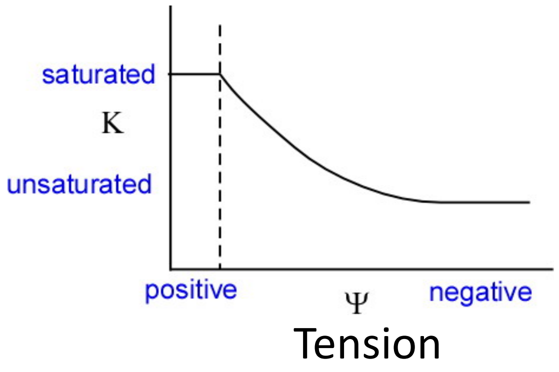
The K vs Ψ relationship differs for coarse vs. fine media. This is important when considering unsaturated flow through layered media.



K *decreases* with *decreasing* saturation

→ Flow in the unsaturated zone can be quite complicated.

Calculating Fluid Flow in the Unsaturated Zone: Richard's Equation



Darcy's Law for unsaturated flow (3D, isotropic):

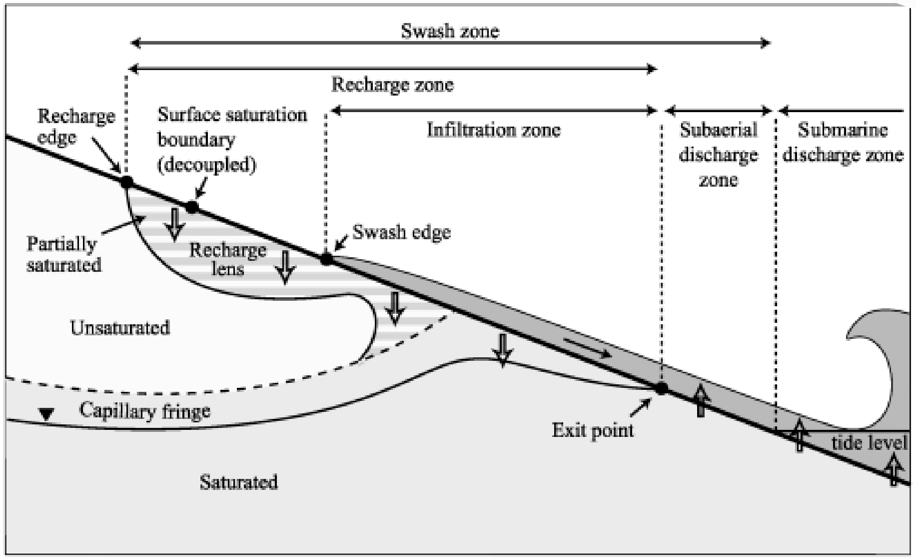
$$q_x = -K(\psi)\frac{\partial h}{\partial x}$$

We don't want h to be the dependent variable, since tension is measured as a pressure head, so we substitute h= Ψ+z. We can re-derive the flow equation to get ***Richard's Equation***:

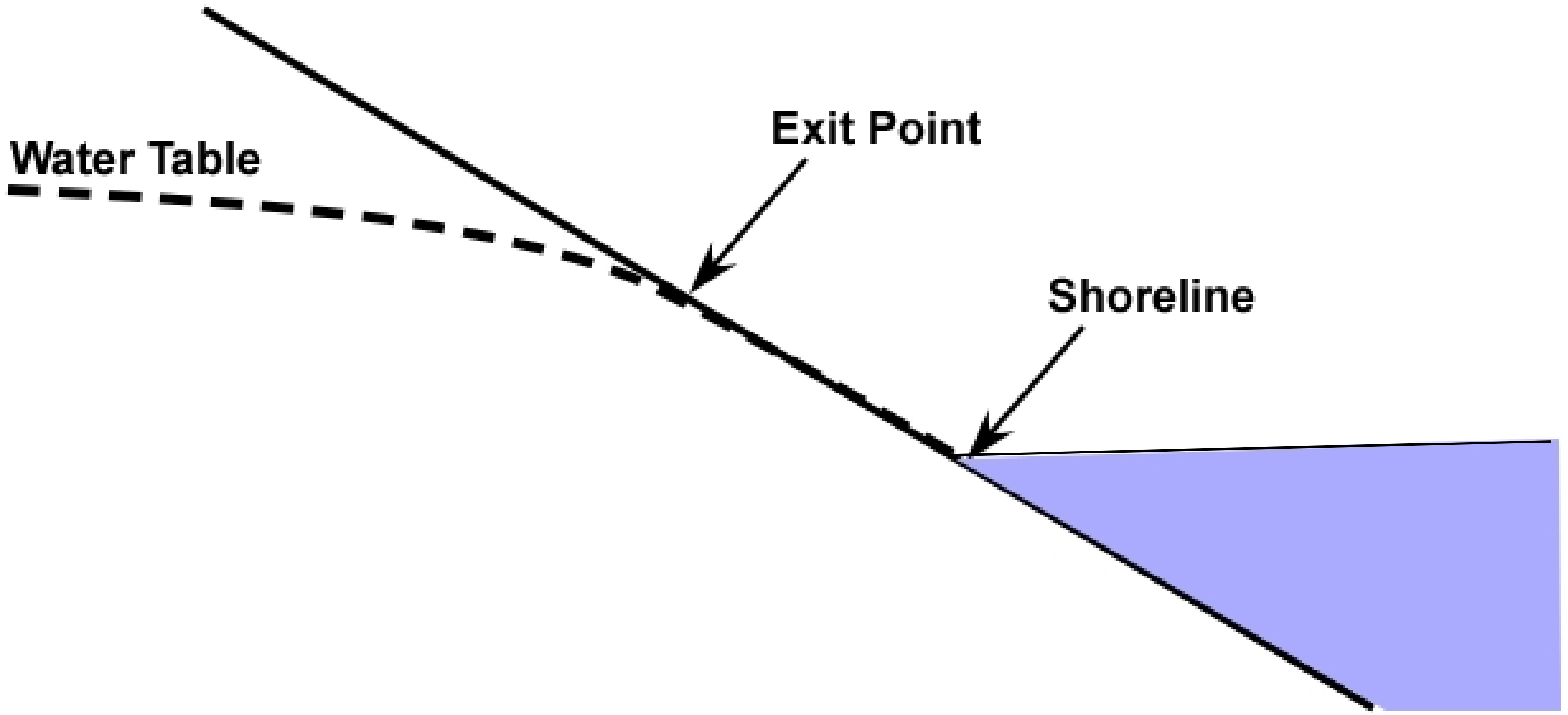
$$C(\psi)\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x}\left(K(\psi)\frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K(\psi)\frac{\partial \psi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K(\psi)\frac{\partial \psi}{\partial z}\right)$$

Solution Ψ(x,y,z,t) requires characteristic curves: relationships K(Ψ) and C(Ψ).

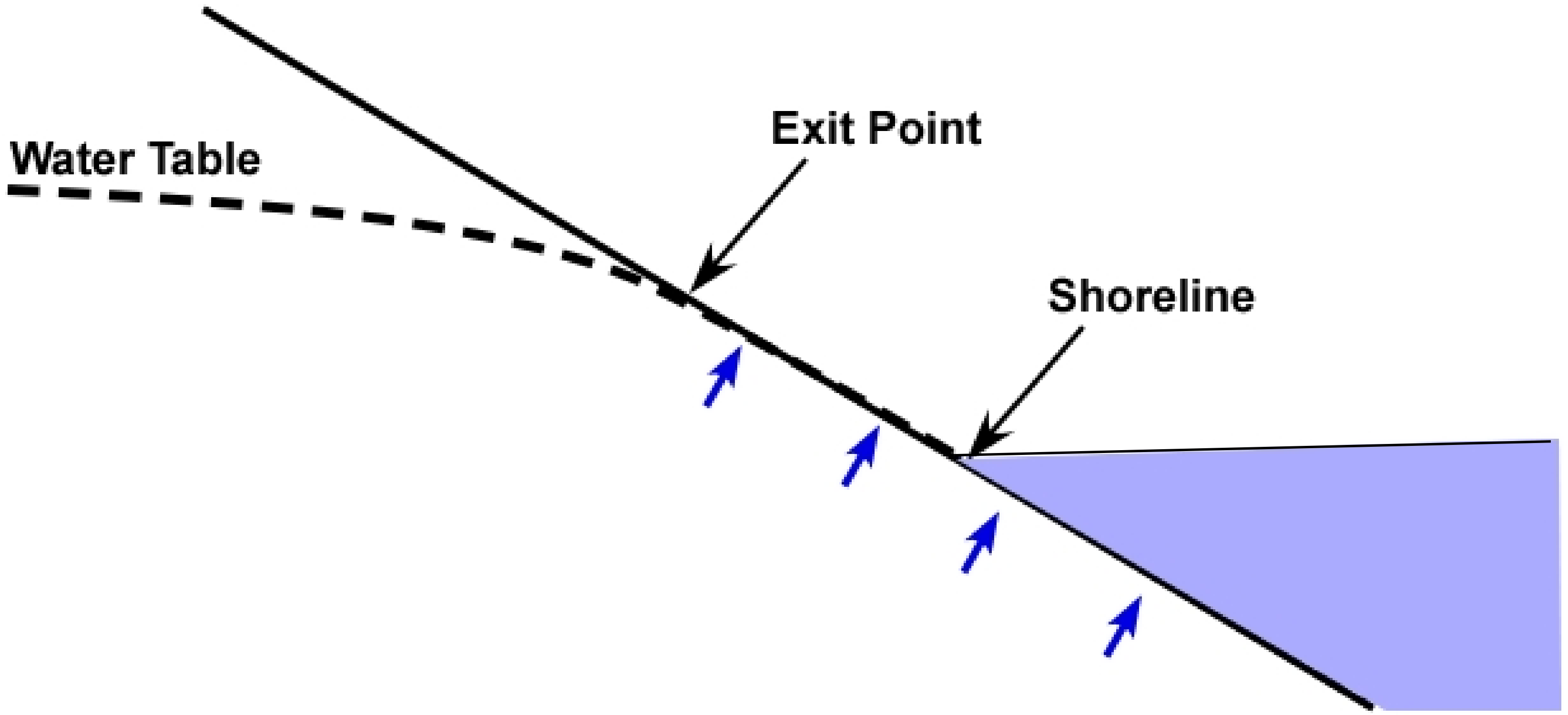
Coupled surface-subsurface hydrologic measurements reveal infiltration, recharge, and discharge dynamics across the swash zone of a sandy beach



Water Resources Research
Volume 51, Issue 11, pages 8834-8853, 6 NOV 2015 DOI: 10.1002/2015WR017395
http://onlinelibrary.wiley.com/doi/10.1002/2015WR017395/full#wrcr21759-fig-0001



Exit Point
Water Table
Shoreline


Exit Point
Water Table
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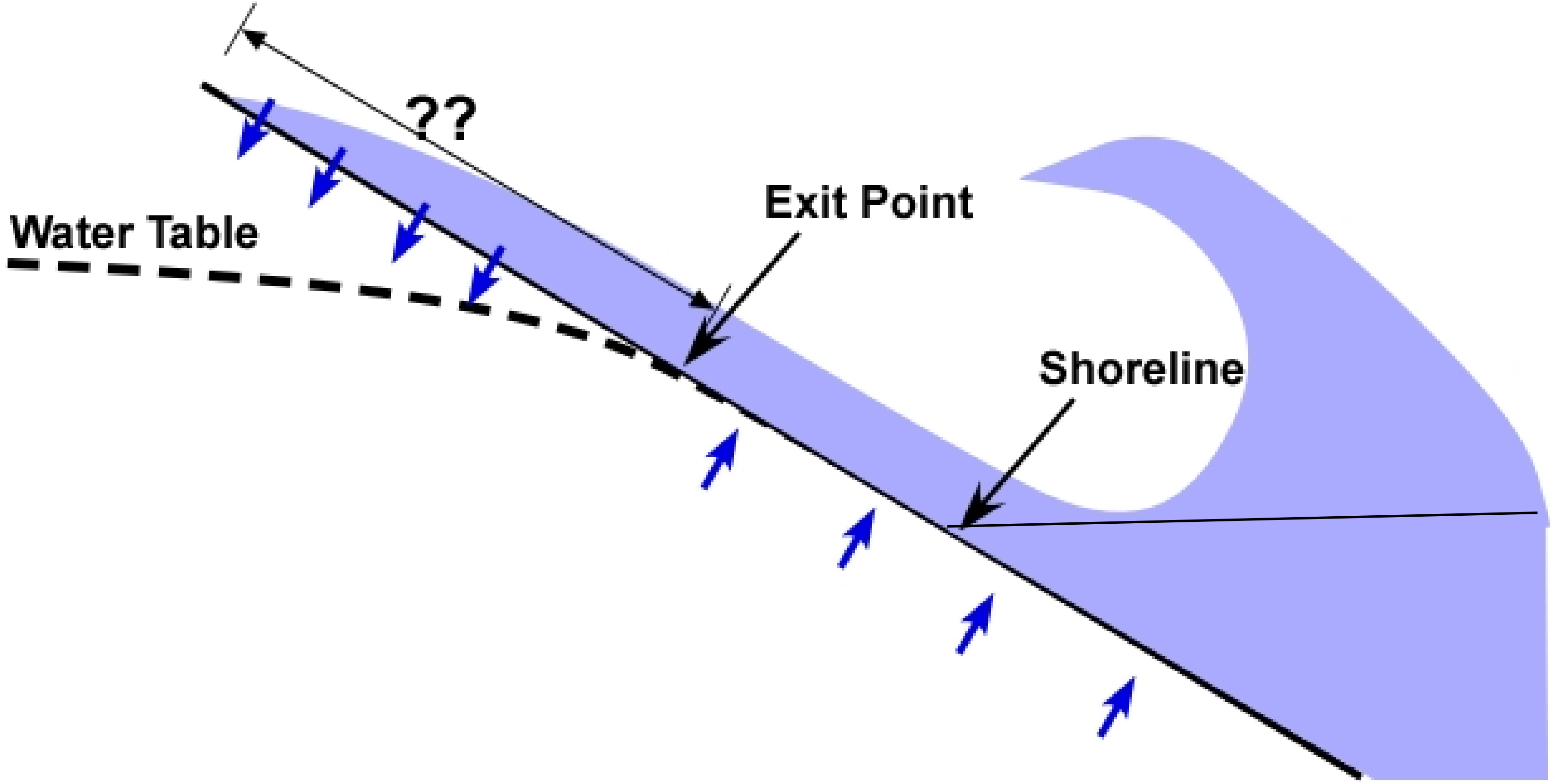
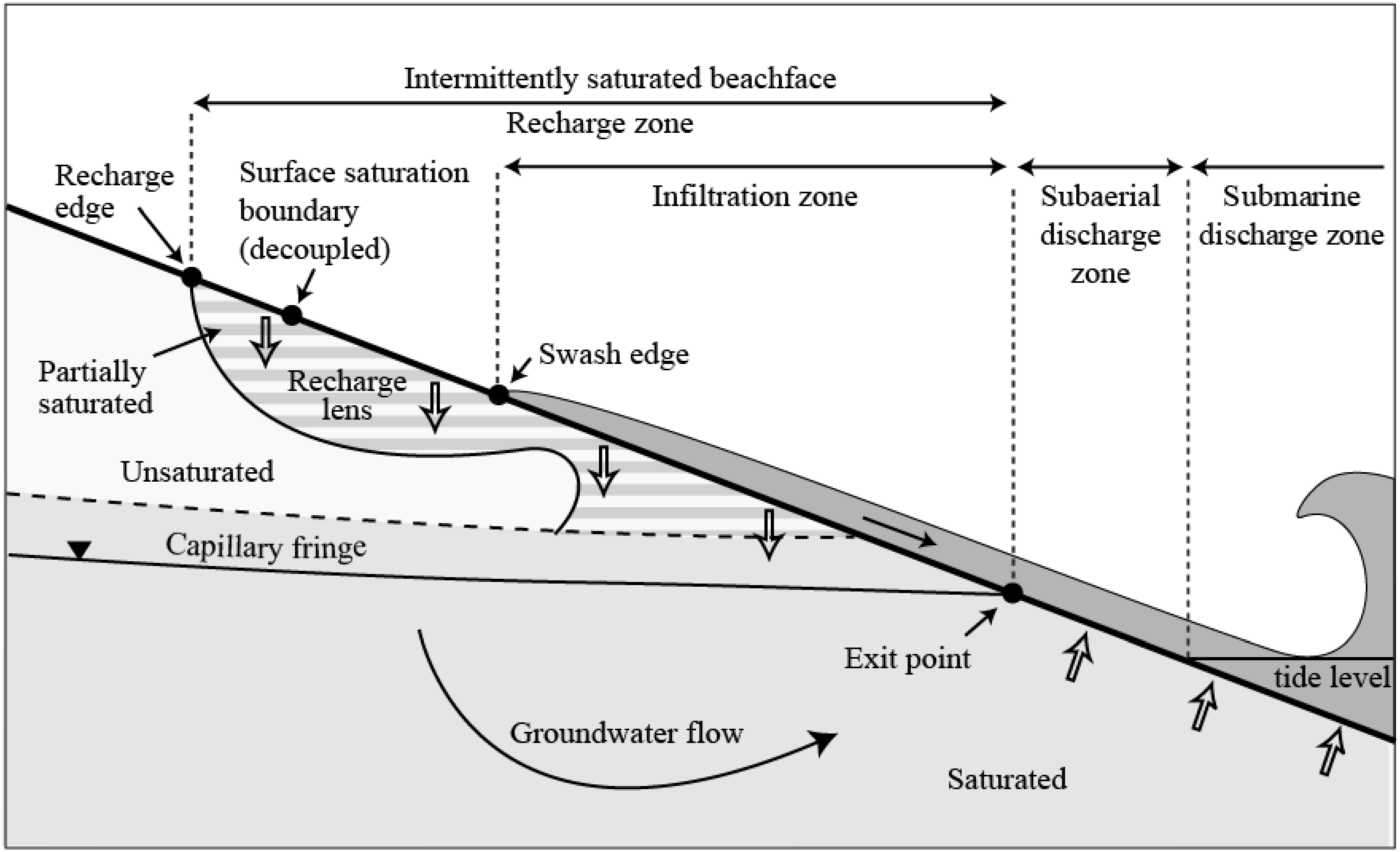
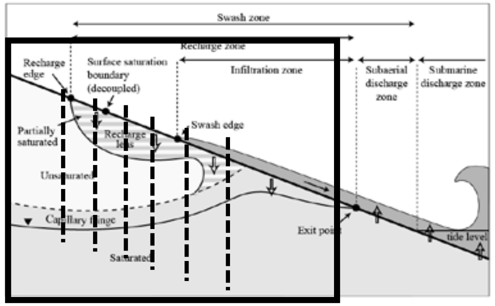
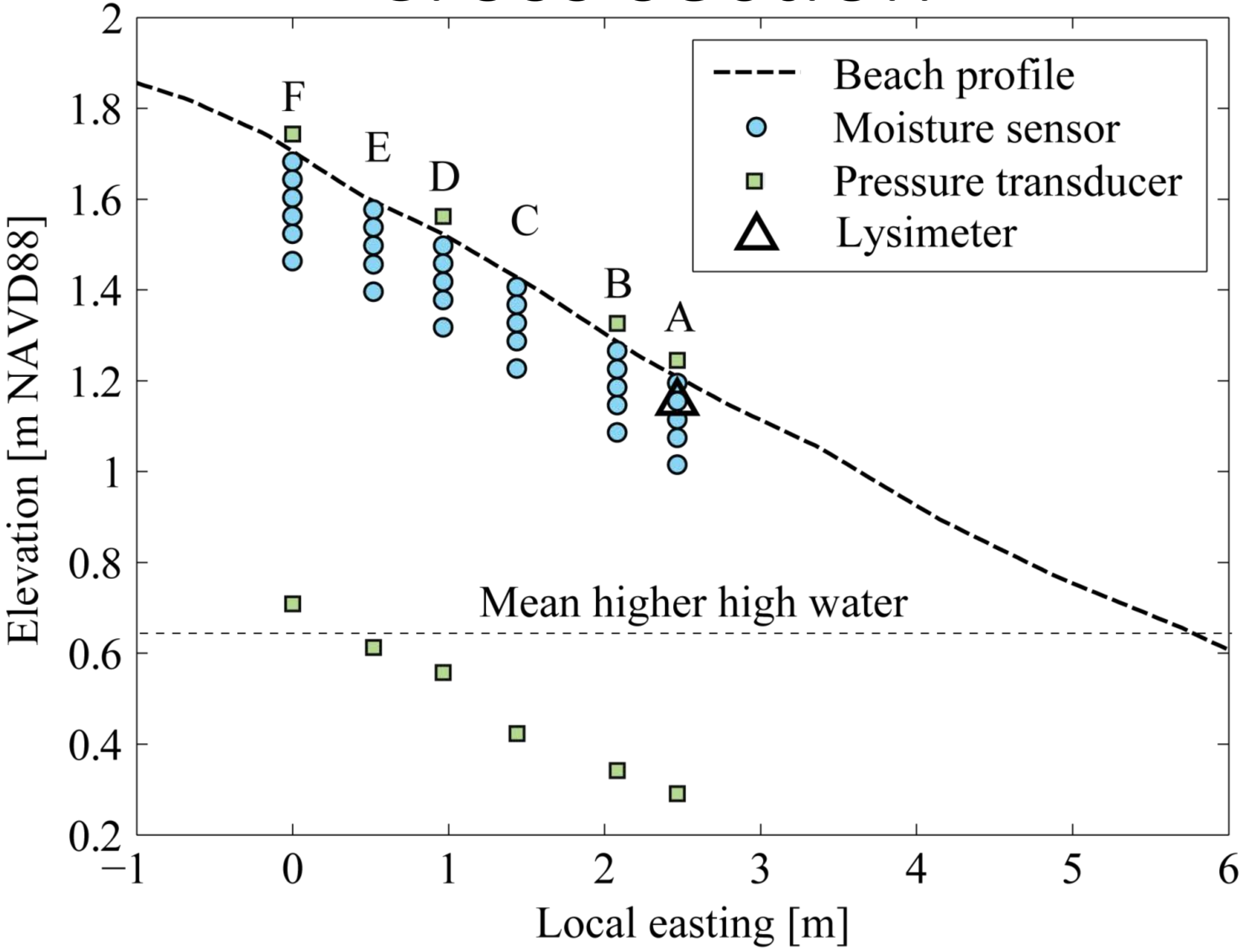
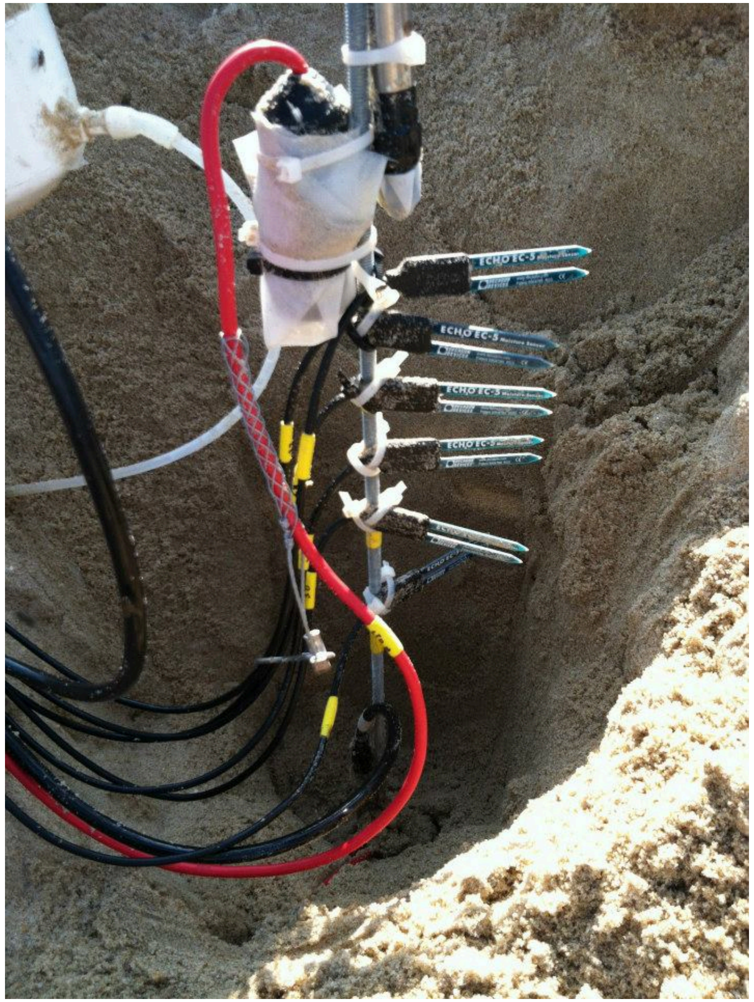

??
Exit Point
Water Table
Shoreline


Intermittently saturated beachface
Recharge zone
Recharge edge
Surface saturation boundary (decoupled)
Infiltration zone
Subaerial discharge zone
Submarine discharge zone
Partially saturated
Recharge lens
Swash edge
Unsaturated
Capillary fringe
Exit point
tide level
Groundwater flow
Saturated

Instrument transect
Cross section



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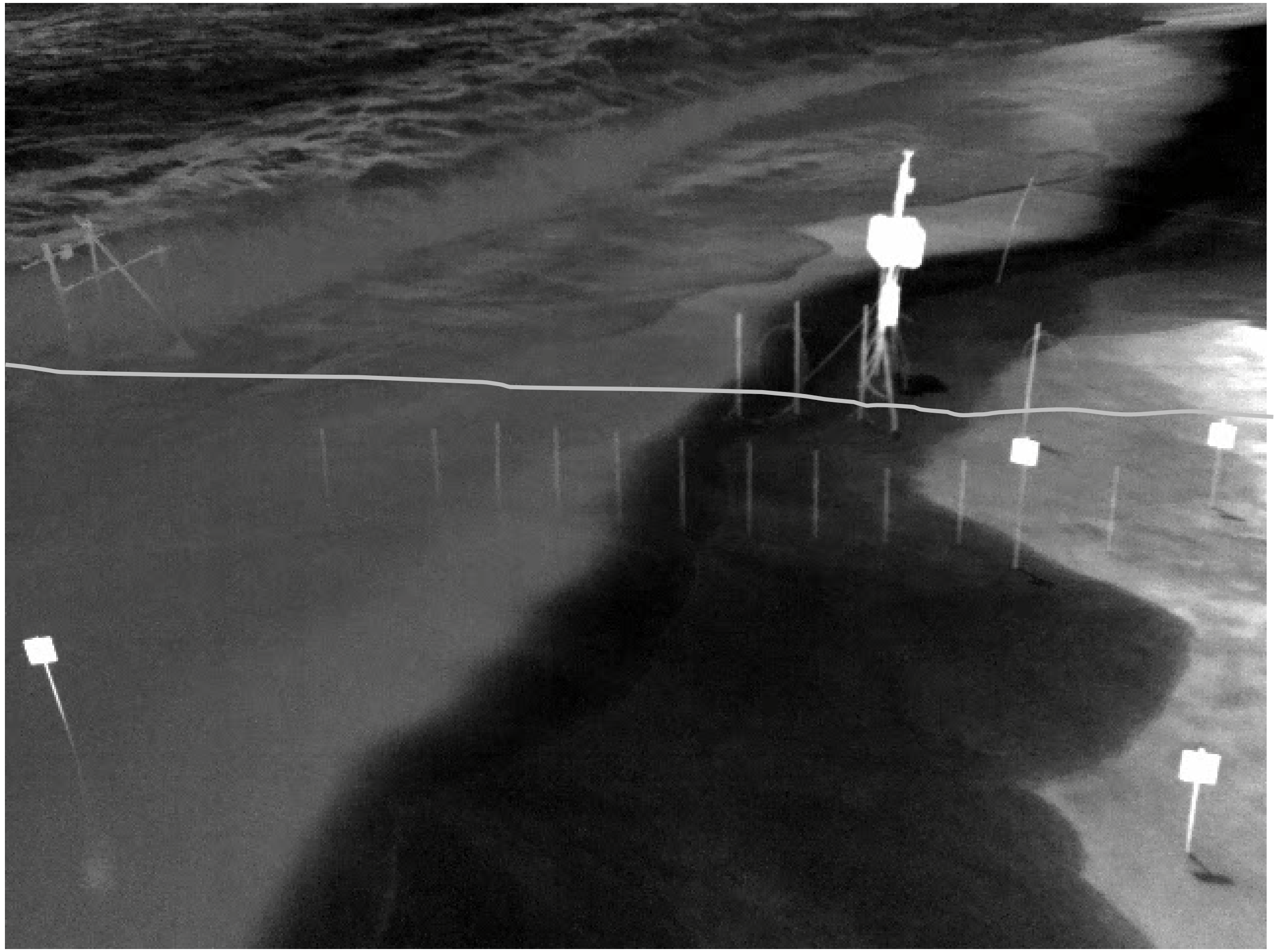
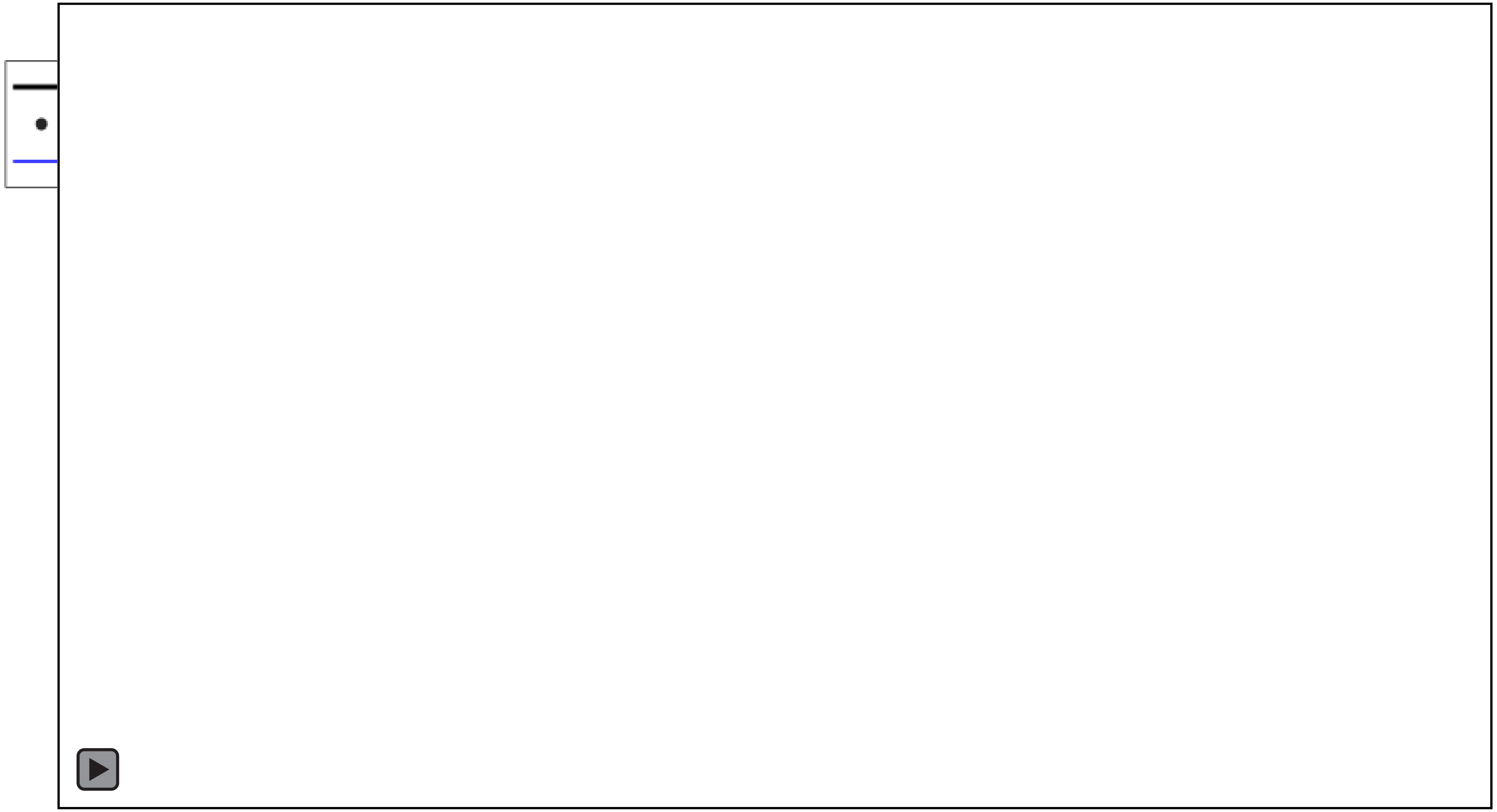
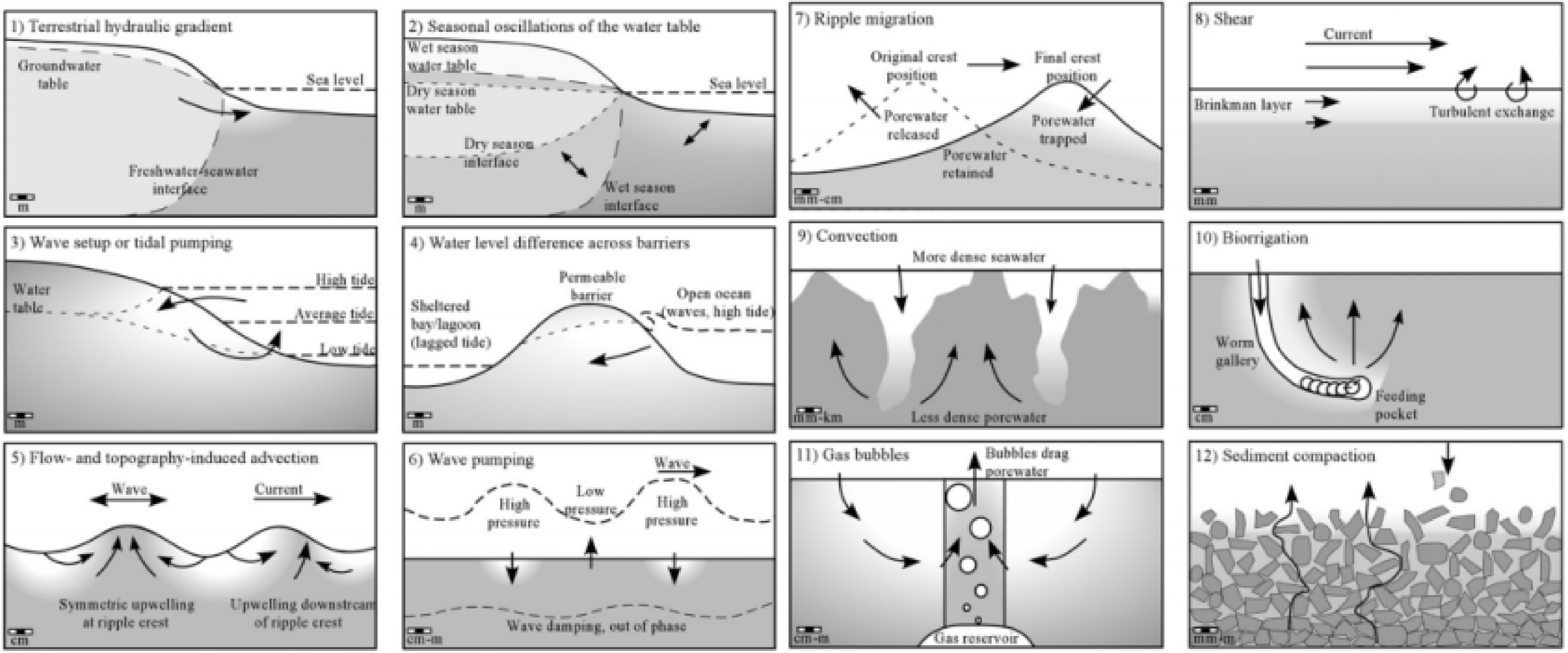
Thermal imagery



Saturation dynamics: Tidal cycle

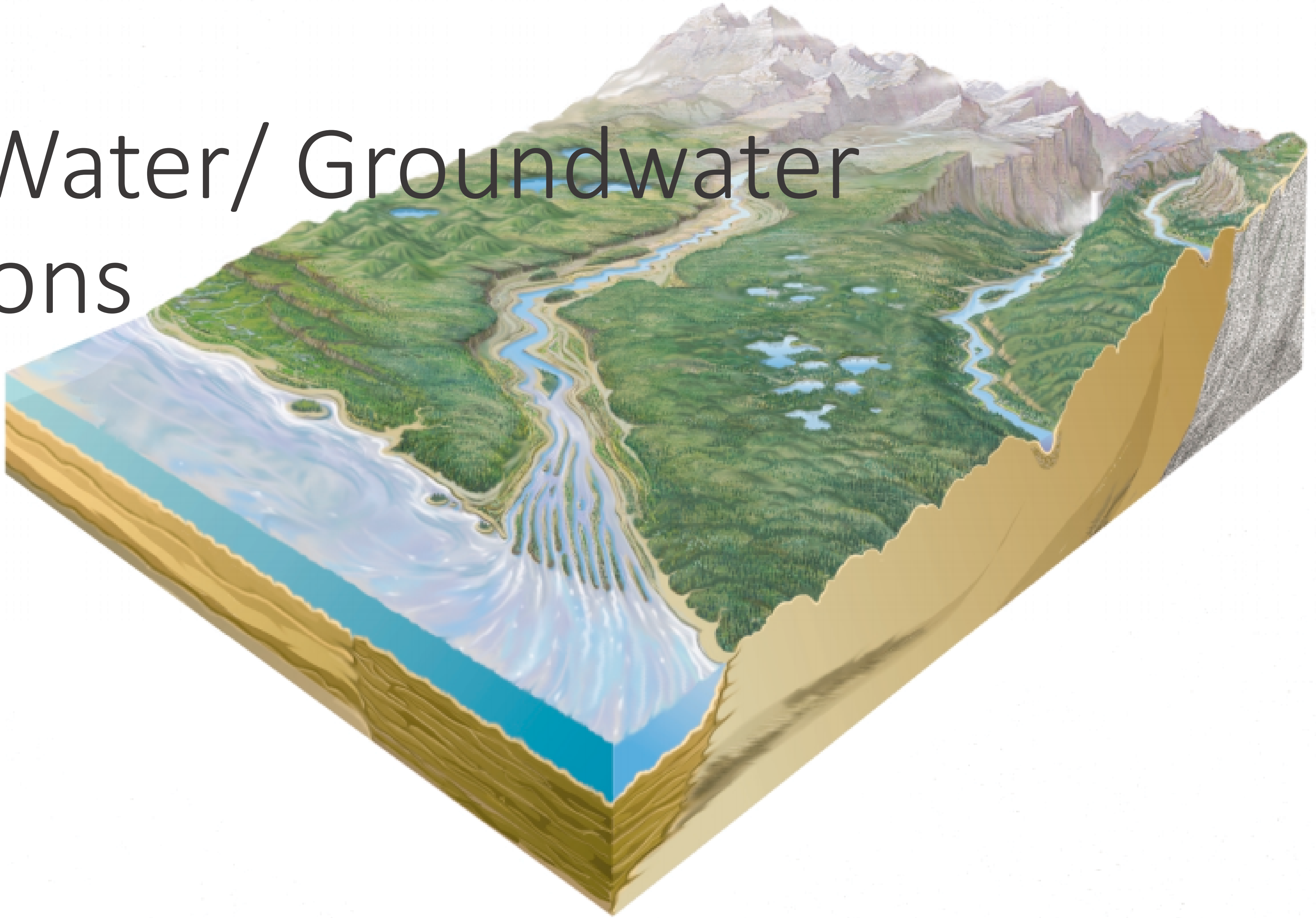


Groundwater-surface water interactions



Santos et al, 2012

Surface Water/ Groundwater Interactions

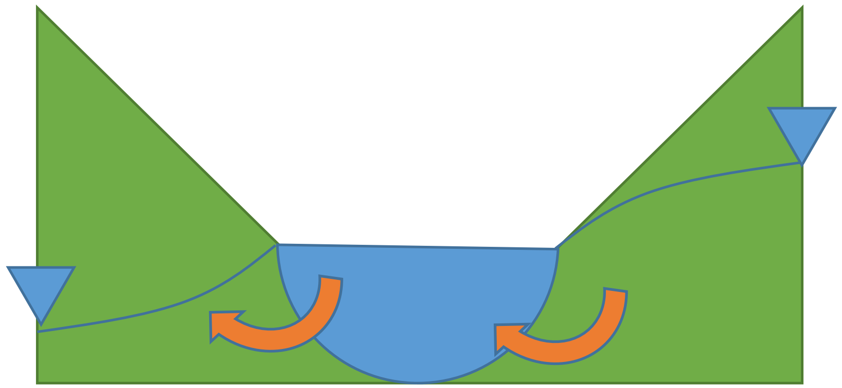


Why do we care?

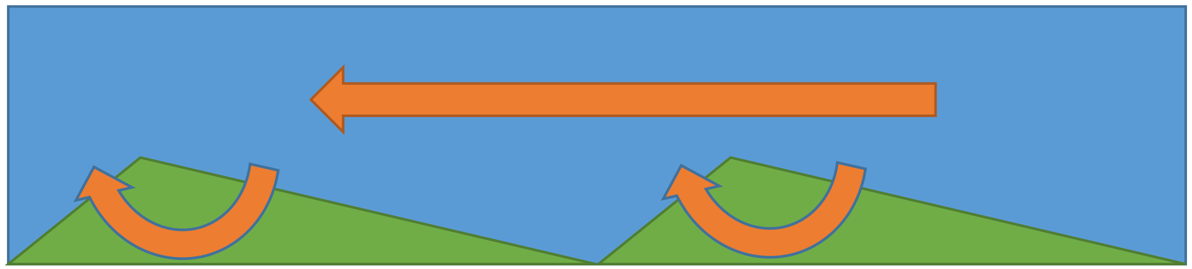
- “Traditionally, management of water resources has focused on surface water or ground water as if they were separate entities…
- “Nearly all surface-water features (streams, lakes, reservoirs, wetlands, and estuaries) interact with ground water…
- “Effective land and water management requires a clear understanding of the linkages between ground water and surface water as it applies to any given hydrologic setting.
- \- Robert M. Hirsch, Chief Hydrologist, USGS
  From USGS Circular 1139: Ground Water And Surface Water: A Single Resource

What is SW/GW interaction

- Varies Spatially
  - Range of scales
    - > Kilometers
    - Millimeters
      - Bedforms, waves, pores



Currents over bedforms



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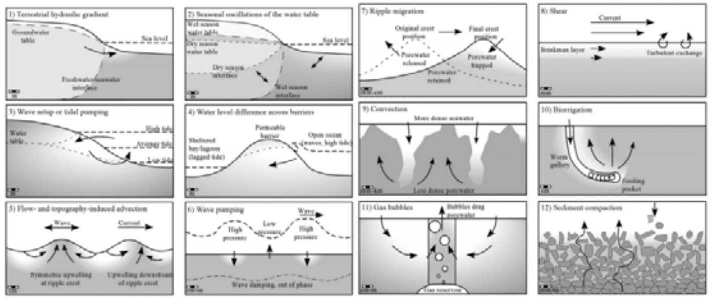
Santos et al, 2012

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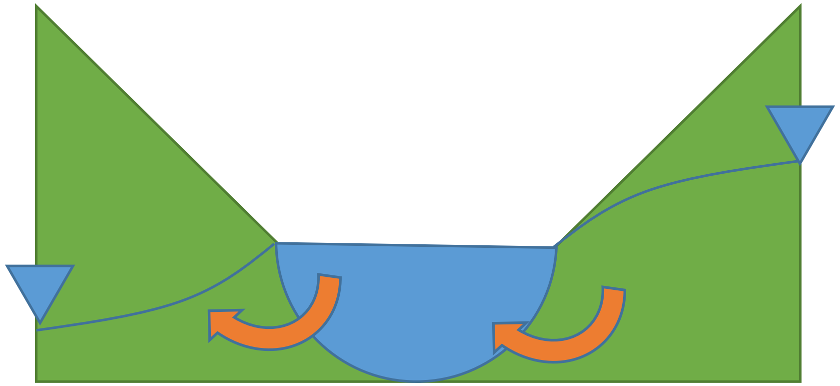
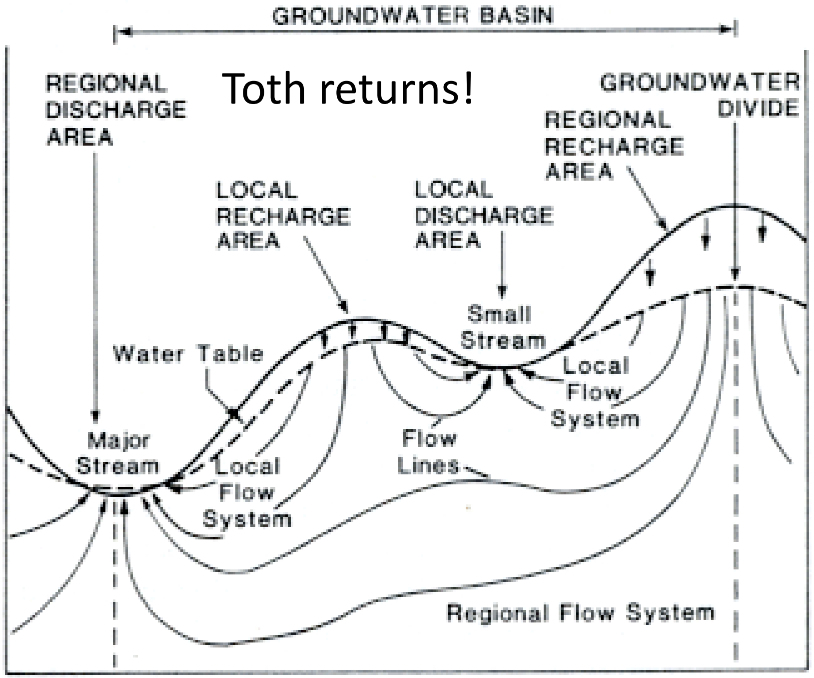
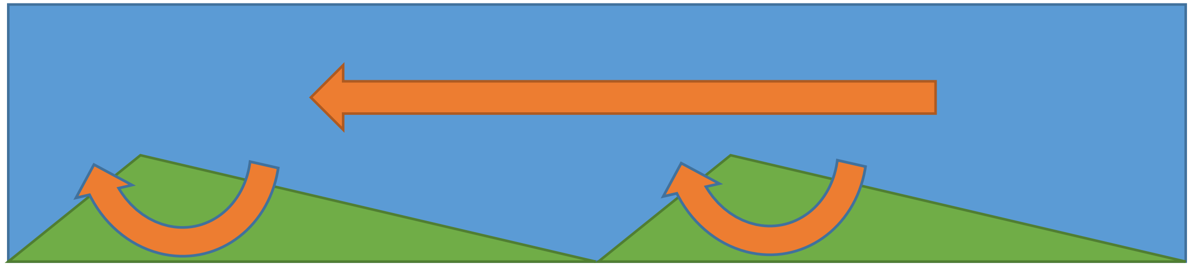
res





Toth returns!

Currents over bedforms



What is SW/GW interaction

- Varies Temporally
  - Range of scales
    - Annual/Seasonal
    - Daily
      - Tides, Storms
    - Seconds