Groundwater Movement, The Unsaturated Zone, Flow of Non-Aqueous Phase Liquids (NAPL)

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Unsteady Storage and Flow

• Everything we have talked about to date regarding storage and flow of groundwater is based on a steady state model. But, very often (for instance) the magnitude of well pumping will change quickly over time- resulting in unsteady or transient flow. In unsteady or transient flow - flow will thus vary over time and in unsteady flow both the amount of water stored in an aquifer and the head at various points will change over time.

• We need to know what happens between the time that a well is not pumped and the aquifer is at steady state and after a long period of pumping has occurred resulting in a stable cone of depression. This is a dynamic phase in which there is an association between the change in water storage and change in hydraulic head.
**Specific Yield $S_y$ and Storivity**

- **Used for an unconfined aquifer to describe the amount of water stored.** $S_y$ is the ratio of the change in depth of water stored (in water $L^3$/aquifer surface area in $L^2$) to the unit decline in hydraulic head in $L$. $S_y$ can be estimated by:
  1. The change in head from a known amount of rainfall (recharge).
  2. The porosity $n = V_{voids}/V_{total} = V_{voids}/V_{solids} + V_{voids}$, when we have a coarse porous medium.

- **Storivity** – S- describes the amount of water stored in a confined aquifer and is proportional to aquifer thickness. When large volumes of water are removed from confined aquifers we can have **significant ground subsidence.**
The Thies Equation

- The Thies Equation can be used to determine the time varying drawdown near wells when wells are pumped at constant rate. Can be used for confined aquifers and also for unconfined aquifers for the dynamic periods.

- \[ s(r,t) = \left(\frac{Q_w}{4\pi T}\right) W(u) \]

- where \( s \) = drawdown L at radius \( r \) and time \( t \) from the well; \( Q_w \) = The rate of well pumpage; \( T \) = Aquifer Transmissivity; \( W(u) \) = The well function – a value for the exponential integral presented in 3-10; and \( u = \frac{r^2 * S}{4*T*t} \).

- Important because this theoretical calculation can be compared with field tests to:

  ⑩  Determine if there is evidence of recharge from a lake or river.

  ⑩  If drawdown occurs more rapidly than predicted – this can indicate a limited geographical boundary of the aquifer.

  ⑩  Can determine the fluctuating drawdown in an aquifer by an intermittently pumped well.
Dispersion –

• Mixing that occurs as a result of the winding torturous path that water travels through a porous medium. This is Fickian transport by dispersion. Fickian mass transport is driven by the concentration gradient and is described by Fick’s First Law.

• Here: \( D = \alpha \ast v \), where \( D \) is the mechanical dispersion coefficient in \([L^2/T]\), \( \alpha \) is the dispersivity of the aquifer (the median grain diameter of the aquifer \([ L]\) and \( v \) is the seepage velocity in \( L/T \).

• So this can be inserted into \( J = -D(dC/dx) \) to determine flux density knowing the change in chemical concentration per distance change.
The Unsaturated Zone – also called the vadose zone.

- Soil – soil formation is called diagenesis and the layers of soil are called horizons.
- This region of the subsurface environment is above the saturated zone and it consists of:
  - 0 horizon – organic material
  - A horizon – high humus, partially leached of minerals.
  - B horizon - Zone of illuviation, deposition of minerals
  - C horizon – Parent material.
- This is a critical region for the transport and fate of contaminants because they must go through the unsaturated zone to get to the saturated zone. (and recharge of contaminants can be stopped here before aquifer contamination).
- Water movement (conductivity) depends on moisture content between the pores (percent saturation).
- In the unsaturated zone the pressure of pore water is less than atmospheric pressure.
Pressure Head in the Unsaturated Zone

- Use $\Psi = \frac{p}{\rho g}$ where $\Psi$ is the pressure head, $p$ is the pressure of the pore water, $\rho$ is the density of water and $g$ is acceleration due to gravity.
- $\Psi$ is often called the soil suction – this occurs because of the interaction of the water and soil grains and is greatest in fine media because the menisci between the pore water and soil gas have their smallest radii thus producing the greatest pressure differential.
- This phenomena is no different than water raising the highest in glass capillary tubes of the smallest diameter.
- Flow in the unsaturated zone generally moves downward in response to gravity---but in arid areas the pressure term overwhelms the elevation term in the Darcy equation and water moves according to the spatial variability in the porous material.
Flow of Non-Aqueous Phase Liquids (NAPL) –

• This is a third fluid phase introduced such as in a leaking underground storage incident or a spill of TCE on soil. This phase moves and behaves differently than both the air and water phases.

• This flow is complicated because
  1. Each have different viscosities.
  2. Different interfacial tensions with each other and
  3. Different capillary interactions with soil grains.

• **Residual Saturation**- This is the amount of a contaminant NAPL present in the porous media when flow stops because of discontinuous NAPL. As the NAPL spreads out it can become discontinuous this prevents the NAPL to flow from one area to another.------This is the problem of recovery of oil.

• NAPL can be recovered if the vapor pressure is high enough by removal of air – this is known as **vacuum extraction**.

• NAPL can also be removed if large quantities of water are inserted into the vadose zone in one place and removed in another. This is known as **dissolution**.
Flow of Non-Aqueous Phase Liquids (NAPL) –

• If contaminant NAPL gets to the saturated zone and the NAPL is less dense than water it floats and is called a bolus. It can be removed by installation of a well below the spread out film and pumping to form a cone of depression under the bolus so that it is taken into the well.

• For dense NAPL (DNAPL) the process of recovery may be difficult and may lead to further disturbance of a pool. If a pool of DNAPL can be found under the surface of an aquifer a well can be placed in the zone of the saturated media to remove it. This is a big problem for chlorinated materials such as PCB’s which are not very soluble and small quantities can contaminate an aquifer for a long period