WATER
Process, Supply and Use
Part 2: Groundwater \rightarrow Processes and Concepts

Read Chapter 10 in your textbook (Keller, 2000)
Chapter 10 in textbook (Keller, 2000)

For this section, and all sections in this course, look up and study all concepts and terms in various resources:
  • other textbooks
  • library books
  • journal articles
  • websites

**NOTE:** Always be prepared to discuss any of the concepts in class. Focus on **highlighted** terms.

Diagrams and information in this presentation are from various sources:
  • Keller (2000) textbook
  • Idaho Virtual Campus -- [Environmental Geology](#)
  • others by S. Hughes
Groundwater

The major source of all fresh water drinking supplies in some countries is groundwater. Groundwater is stored underground in aquifers, and is highly vulnerable to pollution.

Understanding groundwater processes and aquifers is crucial to the management and protection of this precious resource. Groundwater comes from precipitation. Precipitated water must filter down through the vadose zone to reach the zone of saturation, where groundwater flow occurs.

The vadose zone has an important environmental role in groundwater systems. Surface pollutants must filter through the vadose zone before entering the zone of saturation.

Subsurface monitoring of the vadose zone is used to locate plumes of contaminated water, tracking the direction and rate of plume movement.

S. Hughes, 2003
The vadose zone includes all the material between the Earth’s surface and the zone of saturation. The upper boundary of the zone of saturation is called the water table. The capillary fringe is a layer of variable thickness that directly overlies the water table. Water is drawn up into this layer by capillary action.

Essential components of groundwater

The rate of infiltration is a function of soil type, rock type, antecedent water, and time.

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S. Hughes, 2003
Aquifers

- An aquifer is a formation that allows water to be accessible at a usable rate. Aquifers are permeable layers such as sand, gravel, and fractured rock.

- Confined aquifers have non-permeable layers, above and below the aquifer zone, referred to as aquitards or aquicludes. These layers restrict water movement. Clay soils, shales, and non-fractured, weakly porous igneous and metamorphic rocks are examples of aquitards.

- Sometimes a lens of non-permeable material will be found within more permeable material. Water percolating through the unsaturated zone will be intercepted by this layer and will accumulate on top of the lens. This water is a perched aquifer.

- An unconfined aquifer has no confining layers that retard vertical water movement.

- Artesian aquifers are confined under hydraulic pressure, resulting in free-flowing water, either from a spring or from a well.
Groundwater -- Recharge and Discharge

- Water is **continually recycled** through aquifer systems.
- Groundwater **recharge** is any water added to the aquifer zone.
- Processes that contribute to groundwater recharge include **precipitation**, **streamflow**, leakage (reservoirs, lakes, aqueducts), and artificial means (injection wells).
- Groundwater **discharge** is any process that removes water from an aquifer system. Natural springs and artificial wells are examples of discharge processes.
- Groundwater supplies 30% of the water present in our streams. **Effluent streams** act as discharge zones for groundwater during dry seasons. This phenomenon is known as **base flow**. Groundwater **overdraft** reduces the base flow, which results in the reduction of water supplied to our streams.

S. Hughes, 2003
Perennial Stream (effluent)

(from Keller, 2000, Figure 10.5a)

- Humid climate
- Flows all year -- fed by groundwater base flow (1)
- Discharges groundwater
Ephemeral Stream (influent)

(from Keller, 2000, Figure 10.5b)

- Semiarid or arid climate
- Flows only during wet periods (flashy runoff)
- Recharges groundwater

S. Hughes, 2003
Groundwater -- Artesian Conditions

- Water pressure in buildings is maintained by a hydraulic head (h) and confinement of water beneath the pressure surface.
- Natural artesian conditions occur when an aquifer is confined by a saturated, impermeable clay layer (aquitard or aquiclude) below the sloping pressure surface.
- An artesian well flows continually. It is produced when a well penetrates the clay layer and the land surface is below the pressure surface.

(from Keller, 2000, Figure 10.7)
Springs generally emerge at the base of a hillslope. Some springs produce water that has traveled for many kilometers; while others emit water that has traveled only a few meters. Springs represent places where the saturated zone (below the water table) comes in contact with the land surface.

(from Keller, 2000, Figure 10.8)
Summary of Groundwater Systems

NOTE: Study each term, and the associated concepts and geologic processes.

(from Keller, 2000, Figure 10.9)
The water table is actually a sloping surface.

**Slope (gradient)** is determined by the difference in water table elevation \( (h) \) over a specified distance \( (L) \).

**Direction** of flow is downslope.

**Flow rate** depends on the gradient and the properties of the aquifer.

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(from Keller, 2000, Figure 10.6)

S. Hughes, 2003
Groundwater Movement

HYDRAULIC HEAD/ FLUID POTENTIAL  = h (length units)

• Measure of energy potential (essentially is a measure of elevational/gravitational potential energy)
• The driving force for groundwater flow
• Water flows from high to low fluid potential or head (even if this means it may go "uphill"!)
• Hydraulic head is used to determine the hydraulic gradient

Hydraulic head = the driving force that moves groundwater. The hydraulic head combines fluid pressure and gradient, and can be though of as the standing elevation that water will rise to in a well allowed to come to equilibrium with the subsurface. Groundwater always moves from an area of higher hydraulic head to an area of lower hydraulic head. Therefore, groundwater not only flows downward, it can also flow laterally or upward.

S. Hughes, 2003
Groundwater Movement

General Concepts

- **Hydraulic gradient** for an unconfined aquifer = approximately the slope of the water table.
- **Porosity** = fraction (or %) of void space in rock or soil.
- **Permeability** = Similar to hydraulic conductivity; a measure of an earth material to transmit fluid, but only in terms of material properties, not fluid properties.
- **Hydraulic conductivity** = ability of material to allow water to move through it, expressed in terms of m/day (distance/time). It is a function of the size and shape of particles, and the size, shape, and connectivity of pore spaces.
Groundwater Movement
Determine flow direction from well data:

Well #1 4252’ elev
depth to WT = 120’
(WT elev = 4132’)

Well #2 4315’ elev
depth to WT = 78’
(WT elev = 4237’)

Well #3 4397’ elev
depth to WT = 95’
(WT elev = 4302’)

1. Calculate WT elevations.
2. Interpolate contour intervals.
3. Connect contours of equal elevation.
4. Draw flow lines perpendicular to contours.

S. Hughes, 2003
Pumping water from a well causes a cone of depression to form in the water table at the well site.

S. Hughes, 2003
Groundwater Movement

POROSITY = Φ or n (units - fraction or %)

= fraction of void space (empty space) in soil or rock.

Represents the path water molecules can follow in the subsurface

Primary porosity - intergranular

Secondary porosity - fractures, faults, cavities, etc.

Porosity = volume of pore space relative to the total volume (rock and/or sediment + pore space). Primary porosity (% pore space) is the initial void space present (intergranular) when the rock formed. Secondary porosity (% added by openings) develops later. It is the result of fracturing, faulting, or dissolution. Grain shape and cementation also affect porosity.

S. Hughes, 2003
Groundwater Movement

PERMEABILITY is the capability of a rock to allow the passage of fluids. Permeability is dependent on the size of pore spaces and to what degree the pore spaces are connected. Grain shape, grain packing, and cementation affect permeability.

SPECIFIC YIELD \((S_y)\) is the ratio of the volume of water drained from a rock (due to gravity) to the total rock volume. Grain size has a definite effect on specific yield. Smaller grains have larger surface area/volume ratio, which means more surface tension. Fine-grained sediment will have a lower \(S_y\) than coarse-grained sediment.

SPECIFIC RETENTION \((S_r)\) is the ratio of the volume of water a rock can retain (in spite of gravity) to the total volume of rock.

Specific yield plus specific retention equals porosity (often designated with the Greek letter phi): 

\[
S_r + S_y = \Phi
\]
Groundwater Movement

Movement of groundwater depends on rock and sediment properties and the groundwater’s flow potential. Porosity, permeability, specific yield and specific retention are important components of hydraulic conductivity.

**HYDRAULIC CONDUCTIVITY** = \( K \) (or \( P \))

units = length/time (m/day)

Ability of a particular material to allow water to pass through it

The definition of hydraulic conductivity (denoted "\( K \)" or "\( P \)" in hydrology formulas) is the rate at which water moves through material. Internal friction and the various paths water takes are factors affecting hydraulic conductivity. Hydraulic conductivity is generally expressed in meters per day.
Sorting of material affects groundwater movement. Poorly sorted (well graded) material is less porous than well-sorted material.
### Table 10.6 in textbook (Keller, 2000)

Porosity and hydraulic conductivity of selected earth materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Porosity (%)</th>
<th>Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unconsolidated</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>45</td>
<td>0.041</td>
</tr>
<tr>
<td>Sand</td>
<td>35</td>
<td>32.8</td>
</tr>
<tr>
<td>Gravel</td>
<td>25</td>
<td>205.0</td>
</tr>
<tr>
<td>Gravel and sand</td>
<td>20</td>
<td>82.0</td>
</tr>
<tr>
<td><strong>Rock</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>15</td>
<td>28.7</td>
</tr>
<tr>
<td>Dense limestone or shale</td>
<td>5</td>
<td>0.041</td>
</tr>
<tr>
<td>Granite</td>
<td>1</td>
<td>0.0041</td>
</tr>
</tbody>
</table>

S. Hughes, 2003
Groundwater Movement

The tortuous path of groundwater molecules through an aquifer affects the hydraulic conductivity. How do the following properties contribute to the rate of water movement?

- Clay content and adsorptive properties
- Packing density
- Friction
- Surface tension
- Preferred orientation of grains
- Shape (angularity or roundness) of grains
- Grain size
- Hydraulic gradient

S. Hughes, 2003
Groundwater Flow Nets

Water table **contour lines** are similar to topographic lines on a map. They essentially represent "elevations" in the subsurface. These elevations are the hydraulic head mentioned above.

Water table contour lines can be used to determine the **direction groundwater will flow** in a given region. Many wells are drilled and hydraulic head is measured in each one. Water table contours (called **equipotential lines**) are constructed to join areas of equal head. Groundwater flow lines, which represent the paths of groundwater downslope, are drawn **perpendicular** to the contour lines.

A map of groundwater contour lines with groundwater flow lines is called a **flow net**.

**Remember**: groundwater always moves from an area of higher hydraulic head to an area of lower hydraulic head, and perpendicular to equipotential lines.
Groundwater Flow Nets

A simple flow net
Cross-profile view

- Effect of a producing well
- Notice the approximate diameter of the cone of depression

S. Hughes, 2003
Groundwater Flow Nets

Water table contours

Water is flowing from Qal to granite

Water is flowing from granite to Qal

Distorted contours may occur due to anisotropic conditions (changes in aquifer properties).

Area of high permeability (high conductivity)

S. Hughes, 2003
Groundwater Flow Nets

Water table contours in drainage basins roughly follow the surface topography, but depend greatly on the properties of rock and soil that compose the aquifer:

- Variations in mineralogy and texture
- Fractures and cavities
- Impervious layers
- Climate

Drainage basins are often used to collect clean, unpolluted water for domestic consumption.

S. Hughes, 2003
Groundwater Flow Net

Water Flow Lines

Water Table Contours

Well
Groundwater Movement -- Darcy’s Law

\[ Q = KIA \] -- Henry Darcy, 1856, studied water flowing through porous material. His equation describes groundwater flow.

Darcy’s experiment:
- Water is applied under pressure through end A, flows through the pipe, and discharges at end B.
- Water pressure is measured using piezometer tubes.

Hydraulic head = \( dh \) (change in height between A and B)
Flow length = \( dL \) (distance between the two tubes)
Hydraulic gradient \( (I) \) = \( \frac{dh}{dL} \)

S. Hughes, 2003
The **velocity of groundwater** is based on hydraulic conductivity \(K\), as well as the hydraulic head \(H\).

The equation to describe the relations between subsurface materials and the movement of water through them is

\[
Q = KIA
\]

- **Q** = **Discharge** = volumetric flow rate, volume of water flowing through an aquifer per unit time \(\text{(m}^3/\text{day)}\)
- **A** = **Area** through which the groundwater is flowing, cross-sectional area of flow \(\text{(aquifer width x thickness, in m}^2)\)

Rearrange the equation to \(Q/A = KI\), known as the flux \(v\), which is an **apparent velocity**

**Actual groundwater velocity** is higher than that determined by Darcy’s Law.

S. Hughes, 2003
**Groundwater Movement -- Darcy’s Law**

FLUX given by \( v = \frac{Q}{A} = KI \) is the **IDEAL velocity** of groundwater; it assumes that water molecules can flow in a straight line through the subsurface.

**NOTE:** Flux doesn't account for the water molecules actually following a tortuous path in and out of the pore spaces. They travel quite a bit farther and faster in reality than the flux would indicate.

DARCY FLUX given by \( v_x = \frac{Q}{An} = \frac{KI}{n} \text{ (m/sec)} \) is the **ACTUAL velocity** of groundwater, which DOES account for tortuosity of flow paths by including porosity (n) in the calculation. Darcy velocity is higher than ideal velocity.

**Darcy’s Law** is used extensively in groundwater studies. It can help answer important questions such as the direction a pollution plume is moving in an aquifer, and how fast it is traveling.

S. Hughes, 2003
Groundwater Overdraft

Overpumping will have two effects:

1. Changes the groundwater flow direction.
2. Lowers the water table, making it necessary to dig a deeper well.
   - This is a leading cause for desertification in some areas.
   - Original land users and land owners often spend lots of money to drill new, deeper wells.
   - Streams become permanently dry.

S. Hughes, 2003
Groundwater Overdraft

- Almost half the U.S. population uses groundwater as a primary source for drinking water.
- **Groundwater** accounts for ~20% of all water withdrawn for consumption.
- In many locations groundwater withdrawal exceeds natural recharge rates. This is known as **overdraft**.
- In such areas, the water table is drawn down "permanently"; therefore, groundwater is considered a **nonrenewable** resource.
- The **Ogallala aquifer** underlies Midwestern states, including Texas, Oklahoma, and New Mexico, while California, Arizona and Nevada use the Colorado River as their primary water source. All show serious groundwater overdraft.

S. Hughes, 2003
Groundwater Overdraft in the Conterminous U.S.

(from Keller, 2000, Figure 10.13a)
**Groundwater Overdraft**

- **Water-level changes** in the Texas--Oklahoma-High Plains area.
- The **Ogallala aquifer** -- composed of water-bearing sands and gravel that underlie about 400,000 km².
- Water is being used for irrigation at a rate up to 20 times more than natural recharge by infiltration.
- Water level (water table) in many parts has declined and the resource eventually may be used up.

(From Keller, 2000, Figure 10.13b)

S. Hughes, 2003
Groundwater Terms

- artesian aquifer
- aquifer
- cone of depression
- confined aquifer
- Darcy's Law (all terms)
- discharge
- effluent stream
- flow lines
- flow net
- groundwater
- hydraulic conductivity
- hydraulic gradient
- hydraulic head
- infiltration
- influent stream
- overdraft
- overland flow
- perched aquifer
- permeability
- pores
- porosity
- recharge
- residence time
- soil water
- specific retention
- specific yield
- spring
- unconfined aquifer
- vadose zone
- water table
- water table contour lines

S. Hughes, 2003