Lab 10: Groundwater and resource extraction

Groundwater
As many parts of the world are becoming increasingly aware, groundwater is an economic resource, as strategic and necessary as petroleum and hard-rock mineral deposits. In the Middle East, for example, the Israeli-occupied West Bank of the Jordan River is disputed territory in part because of the groundwater reserves there. Closer to home, the fossil Snoqualmie aquifer is being tapped heavily by the expansion of the towns of North Bend and Snoqualmie; as a fossil aquifer, it has no chance of being recharged and problems will ensue when that resource runs out.

In almost all cases, groundwater does not flow as “underground rivers”. Most commonly, it flows within the pore space between sediment grains. Groundwater can flow more rapidly through fractured rock or through cave systems in carbonate (mostly limestone) rocks. The amount of pore space in a rock is called its porosity; how well these pore spaces are connected to each other is defined as permeability.

1. Compare sediment samples W8 and W9 in the drawer.
   a. Describe the grain size of each.

   **W8**  **W9**

   b. Which sample is more porous?

2. Compare sediment samples W10 and W11 in the drawer.
   a. Describe the sorting (well-sorted to poorly-sorted) of each.

   **W10**  **W11**

   b. Which sample is more porous?

   c. Which sample is more permeable?

3. Based on your observations on the questions above, circle the characteristics of a good sediment for an aquifer:

   poorly-sorted       or       well-sorted

   coarse-grained      or       fine-grained

   poorly-cemented    or       well-cemented
Surface water seeps into a layer of sediment or rock below the ground surface (such as the glacial gravels in many North Seattle backyards) and becomes groundwater. The water continues to seep deeper into the ground until it reaches the saturated part of the sediment (remember the B soil horizon?) or rock unit. The top of the zone of saturated sediment or rock is called the water table. The water table often, but not always reflects the ground surface topography, lying at higher elevations under hills than under valleys (see the figure below).

![Figure 10-1](image-url). Diagram showing the relationship of the water table (shaded) with the ground surface (upper line). Barely visible curved arrows show direction of water flow.

Groundwater flow
Groundwater, like surface water, flows downhill, which in the case of groundwater is defined as the direction of the lower water table (recall that the water table is not flat, but is higher under hills than valleys). Unlike surface water, groundwater encounters far more friction and resistance to flow, and thus moves much more slowly than surface water, which is why the water table does not “level out”.

In the figure above, the groundwater will flow from under the hill toward the stream valley; some of the water will flow out of the ground and into the stream. The surface of the water table can be mapped using water wells — the height to which water rises in a well is the height of the water table there (note that you will need a pump to bring the water the rest of the way to the surface). Surface water features such as streams and lakes also show where the water table is — the shore of a stream or lake is coincidentally the water table elevation in that area. A spring or seep is an area where the water table is at ground level and thus water comes literally out of the ground.

The level of the water table depends on the amount of water soaking (percolating) into the ground versus the amount of water being removed via streams, springs and wells. If more water is removed than is recharged, the water table will drop. For example, irrigation projects have so depleted the Central Valley of California’s aquifer that the water table has dropped 100 feet in some places.

A body of rock or sediment that yields useful amounts of water is called an aquifer. Typically, aquifers are made of gravels, sands or sandstones. A body of rock or sediment through which water cannot flow is called an aquiclude. Typical aquiclude materials are clays, shales, igneous and metamorphic rocks. An aquifer that is at the surface is called an unconfined aquifer. An aquifer that lies below an aquiclude is called a confined aquifer. Note that a confined aquifer is not necessarily closed off from recharge by rain or snow; “confined” simply means that at some points, the aquifer is under an aquiclude, though the recharge area of the aquifer
may be open to the air (see the figure on the next page). A fossil aquifer is a confined aquifer with no recharge area.

Figure 10-2. The mechanics of a confined aquifer reveal how it can be confined and recharged at the same time, and where an artesian well might be drilled.

Because the recharge area of a confined aquifer may be many hundreds of feet in elevation above other parts of the aquifer, and because even groundwater tries to run “downhill”, the lower parts of a confined aquifer can build up a significant amount of water pressure. If a well were drilled through the aquiclude into the confined aquifer, it is quite possible that the pressure (called the hydraulic head) might be sufficient to bring water to the surface without a pump; this is called an artesian well. An artesian spring is a naturally-occurring artesian well.

The pressure of the confined aquifer can be measured by drilling a special type of well called a piezometer into the aquifer. By measuring the pressure in the well (really the level to which the water will rise in the well), a potentiometric surface or a hypothetical water table can be mapped, similar to a map of the unconfined water table.

Figure 10-3. Four wells drilled near Palm Springs, California.
4. On figure 10-3, water levels are shown in black for each of four wells in the Palm Springs, California, area. Assume the shale and granite are impermeable.

a. Label the confined aquifer, the unconfined aquifer, and the aquicludes.
b. Draw a solid line representing the water table of the unconfined aquifer.

c. Draw a dotted line representing the "hypothetical water table" (sometimes called the "potentiometric surface") of the confined aquifer.

d. In which direction is the water in the unconfined aquifer flowing?

e. In which direction is the water in the confined aquifer flowing?

f. In the summer, well A goes dry if it is pumped for more than a few hours. The owner of well A sues the owner of well B, who is pumping large volumes of water to irrigate her golf course, for damages. Does the suit have merit? Explain!

g. What simple, if expensive, solution does well owner A have?

5. In 1991, residents in Pierce County south of Puyallup became concerned about the construction of an aircraft parts manufacturing and painting plant in the town of Fredrickson. A cross-section of the area is shown on the next page.

a. Which unit is the aquifer, the till or the gravel?

b. Is the aquifer confined or unconfined?
c. With respect to the aquifer, what does the proposed plant area represent?

d. What was the concern of the residents (hint: their water supply is the wells)?

e. What are some strategies the aircraft company is designing in the plant to help ease the residents' concern?

Quantifying groundwater flow

You have now looked at a few sedimentary rocks and decided which make good aquifers qualitatively. Now you will quantify how good “good” is.

In the mid-nineteenth century, a French engineer in Dijon named Henry Darcy designed a water system for the town which required only gravity and a difference in elevation for the water to get from the source to the town. In fact, the results of his experiments resulted in the equation which bears his name:

\[ v = K \left( \frac{h_1 - h_2}{d} \right) \]

where \( v \) is the velocity of the groundwater, \( K \) is a measure of the permeability of the material the water flows through, \( h_1 - h_2 \) is the difference in elevation between the source of the water (the individual h's are sometimes called the hydraulic head of the groundwater) and its final destination and \( d \) is the horizontal distance over which the groundwater travels.

The square-bracketed part of the equation above, you may notice, represents merely the hydraulic gradient or slope of the "water table", and is sometimes represented by the symbol "I".

so Darcy's Law becomes \( v = K I \).

Note that if \( A \) represents the cross-sectional area of the groundwater flow, then \( v \) times \( A \) (the velocity of the flow times the area of the flow) equals \( Q \), the discharge of the groundwater (in other words, the volume of groundwater which flows forth at any given time).

Thus, the form of Darcy's Law you will use is

\[ Q = K I A \quad \text{or} \quad Q = K \left( \frac{h_1 - h_2}{d} \right) A \]
In this experiment, you will determine the validity of Darcy's Law and estimate the permeability of some uncommon soil grain sizes: **pea gravel**, **aquarium gravel** and **coarse sand**.

[Note to those of you in MAT 125 (or any other second-quarter calculus class): Darcy’s Law is a specific example of a second order partial differential equation (similar to heat transfer equations). It has the form:

\[
\frac{\partial u}{\partial t} = K \frac{\partial^2 u}{\partial x \partial y}
\]

where \( u \) is the volume of the flow (and therefore the time differential is called the flux), \( K \) is the permeability of the material and the scary second-order partial differential works out to be the hydraulic gradient.]

Some thoughts *before* you begin the experiment:

6. a. If the only thing you could change was \( I \) (which equals \((h_1-h_2)/d)\)), then what sort of relationship would I have with \( Q \), the discharge? In other words, if \( K \) and \( A \) were held constant, then how are \( I \) and \( Q \) connected?

b. In what **two** ways could you alter \( I \)? (Hint: look at the equation for \( I \) in the introductory part of this section for the two factors that can be changed)

7. a. Look at the experimental setup; what physical quantity is represented by \( h_1 \)? How will you keep it constant?

b. What physical quantity is represented by \( h_2 \)? And what about \( d \)?

c. So when you change the quantities above, what are you "really" affecting? In other words, how are you changing the experimental setup?
8. a. How will you measure $Q$, the discharge? Remember, you will need **two** pieces of equipment because the discharge is measured in $\text{cm}^3/\text{s}$ (cubic centimeters per second)

b. How will you calculate $A$?

c. How do you think the $K$ (permeability) of the coarse sample will compare to that of the fine sample? More? Less? The same?

9. Okay, now go take the measurements. On the following pages, you will find tables which are headed by the phrase "Grain size". Choose one of the prepackaged "canisters" and note the grain size written on the side. Assemble the equipment as demonstrated and assign tasks.

<table>
<thead>
<tr>
<th>Grain size</th>
<th>______________________</th>
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<table>
<thead>
<tr>
<th>Trial</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
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<tbody>
<tr>
<td>$h_1$ (cm)</td>
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<td>$h_2$ (cm)</td>
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<td>$h_1-h_2$ (cm)</td>
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<tr>
<td>$d$ (cm)</td>
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<tr>
<td>$I = (h_1-h_2)/d$</td>
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<td>Volume collected (cm$^3$)</td>
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<td>Time (s)</td>
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<tr>
<td>$Q$ (cm$^3$/s)</td>
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</table>
Go up to the computer room and open Excel. On the spreadsheet, enter two column headings in A1 and A2 respectively: "I (hydraulic gradient)" and "Q (discharge in cubic centimeters per second)" (don’t worry about the words not fitting into the column completely; use the “resize” function of Excel). Enter the appropriate data from each trial into the columns, and then use the "Chart Wizard" to plot I versus Q. Don’t print the graph out yet.

10. a. Was your prediction in question 6a accurate? How does your graph show this relationship?

Make another set of measurements using a different "canister"; note its grain size. Use the same I’s as you did for the first "canister".

Grain size _______________________

<table>
<thead>
<tr>
<th>Trial</th>
<th>#1</th>
<th>#2</th>
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<tbody>
<tr>
<td>h₁ (cm)</td>
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<td>h₂ (cm)</td>
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<td>h₁-h₂ (cm)</td>
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<tr>
<td>d (cm)</td>
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<tr>
<td>I = (h₁-h₂)/d</td>
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<td>Volume collected (cm³)</td>
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<td>Time (s)</td>
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<tr>
<td>Q (cm³/s)</td>
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In A3, write "**Q (discharge in cubic centimeters per second)**" and use the "Overlay" function in Chart Wizard to put both sets of data on the same graph. Once the title (think of an appropriate one) and the axes labels are right and the graph looks nice, print it out and attach it.

b. Does the graph of the coarser material canister have a steeper or shallower slope than the graph of the finer material canister? Is this consistent or inconsistent with your prediction in question 8c?

**Petroleum resources**

Petroleum (oil) is a multi-component liquid refined to generate different hydrocarbons, such as heptane (a component of gasoline) and waxes. For the industrial world, petroleum is not only a source of energy, but also a key starting material for making plastics. Because petroleum is a fluid, geologists use the principles of groundwater flow to narrow the possible locations of this economic resource. The areas which produce petroleum are called oil fields. If they generate natural gas (methane, ethane and propane) as well, they are called gas fields.

Many geologic factors determine where oil fields occur and the quality of the oil within that field. Though some components of oil are denser than water, oil and natural gas are typically less dense than water and thus will float on top or bubble through water. This means that oil and gas will rise to the surface using fractures and pore spaces within rocks. If the oil and gas reach an impermeable layer can no longer move upward, they are said to be “trapped” and the structure in which they are stuck is called an oil trap.

Three necessary factors for generating and trapping oil and gas are:

- A hydrocarbon **source rock** where the oil is made. A typical source rock is a marine limestone with plenty of organic material (mostly dead single-celled plankton). The sediments that will become this rock are covered, lithified, pressurized and heated by the burial. By excluding oxygen gas, the trapped organic material becomes more carbon-rich (water is driven out of the remains) through a series of chemical reactions. Organic-rich siltstones and shales also make good source rocks.

- A porous and permeable **reservoir rock** into which the oil and gas can migrate away from the source, accumulate and later be pumped out. These rocks include arenitic and greywacke sandstones, limestones and other carbonate rocks.

- An impermeable **cap rock** which acts like an aquiclude to prevent the oil and gas from escaping to the surface (once oil reaches the surface, the lighter molecular weight components simply evaporate!). Shale, evaporites (rock salt) and other fine-grained rocks are good cap rocks.

Note that the source rock is usually not the reservoir rock and that the cap rock is, of course, different from those two.
11. Look at rock samples R45, R46 and R47 and classify each as a good **source** rock, a good **reservoir** rock or a good **cap** rock.

R45

R46

R47

*Geologic map cross-section A-A’ of the La Habra and Whittier Quadrangles*

12. The major **reservoir** rock in this area is the Tfl strata. According to the explanation, what rock is Tfl made of? How well-cemented is this rock, in order that it be a **good** reservoir rock?

13. Which formation is the **source** rock? (Hint: it can be only one of the formations listed and remember that most of the oil may have migrated to the reservoir rock, so that very few wells would try to tap into the source rock). What **must** the source rock **contain**?

14. a. Which formation is the **cap** rock? Hint: again, it can be only one of the formations listed. What characteristic should the cap rock have? Find a **two-word** phrase which is this characteristic.

b. In areas where there is no cap rock but ample reservoir rock, what would you expect to see on the surface? (Hint: this happens in the La Brea district of Los Angeles. Also, R46 is actually from such a surface feature near Ojai, California)
15. Note the large number of vertical lines in the cross-section; these represent oil wells. The ID number of the well is given in parentheses above the well (for instance, the furthest west well on A-A' is #133). The depth of each well is given at the bottom of the well (Well #133 is 7832 feet deep).

a. What is the **number** and the **depth** of the deepest well in the cross-section?

b. Look for A-A’ on the geologic map and note that the wells are now represented by open or filled circles. Using the explanation to figure out what the open and filled circles mean, is the **deepest** well a **producing** well or a "dry" well? What does this suggest to you about the continued potential of this area as an oil-producing site?

16. Recalling how **anticlines** and **synclines** are represented on geological maps, are the producing wells concentrated on anticlines or on synclines? Why is this so?