Names: **ESS 315**

Lab #5 Groundwater

In this lab, we will consider several aspects of groundwater flow and their relationship to geologic materials through which the groundwater moves. The most fundamental property of those geologic materials is the permeability: deposits with a high permeability are called aquifers; those that slow the movement of groundwater, with a low permeability, are termed aquitards (moderately low permeability) and aquacludes (very low permeability). The divisions between aquifers, aquitards, and aquicludes are relative and not precise, but in general aquifers are almost exclusively sand and/or gravel. Aquitards and aquicludes may slow the movement of groundwater by factors of 1000 or more (in some places, much more), but they do not necessarily block water flow altogether.

The movement of groundwater is determined by the hydraulic head, which is measured at any point in an aquifer by the height to which water will rise in a well installed at that point. Water moves from areas of high head (i.e. water in a high level of the well) to areas of lower head. The average rate at which the water moves through the aquifer is proportional to the head gradient, the difference in heads in two separate wells divided by the distance between those wells, and the permeability of the intervening aquifer. This relationship is "Darcy's Law" (as explained in Part IV):

$$V_d = K \frac{\Delta H}{\Delta L}$$

where V_d is the darcian area-averaged velocity, k is hydraulic conductivity, $\Delta H/\Delta L$ is the slope of the water table (or potentiometric) surface.

Groundwater movement is typically calculated within a single aquifer; however, if two aquifers are separated by an aquitard or aquiclude, a vertical head gradient can be similarly calculated between the aquifers and a rate of "leakage" between them can be predicted.

Although Darcy's Law does account for the permeability of the aquifer in determining average groundwater flow, it does not tell us how rapidly each individual water droplet must be moving in its path through the material. Imagine 3 cars passing a traffic light every minute on a 3-lane road. If, now, 2 lanes are blocked off, but the same 3 cars pass by in the same amount of time, then each individual vehicle must be moving three times as fast to achieve the same rate of traffic flow. This is analogous to water flow in aquifers-the darcian velocity (V_d) is the average flow rate, but because only a fraction of the aquifer is pore space, and so can transmit water, the actual velocity of the moving water (V_{actual}) must be greater. Adjusting for the porosity (n) accounts for this difference (see part IV) of this lab.

Finally, we will investigate the localized effects on the water table from pumping a well, and the subsequent changes to groundwater flow paths (see part V).

Part I-Aquifer Characteristics

Problem 1 (Note: this first problem may be familiar to those who took ESS 101. Consider it a "warm-up" for the rest of the lab)

Water levels are shown in black for each of four wells in Palm Springs (see diagram below). Assume the shale is impermeable. All wells are open only at their base.

a) On the diagram
- ✓ Label the confined and unconfined aquifers
- ✓ Draw and label the water table of the unconfined aquifer
- ✓ Draw and label the piezometric surface of the confined aquifer

b) Towards which direction is water flowing in the upper aquifer (west or east)?

c) Towards which direction is water flowing in the lower aquifer (west or east)?

d) In the summertime, well A goes dry if it is pumped for more than a few hours. The owner of well A blames the owner of well B, who is pumping lots of water. Do you agree? Explain.

e) What simple, though expensive, solution would you recommend to the owner of well A?
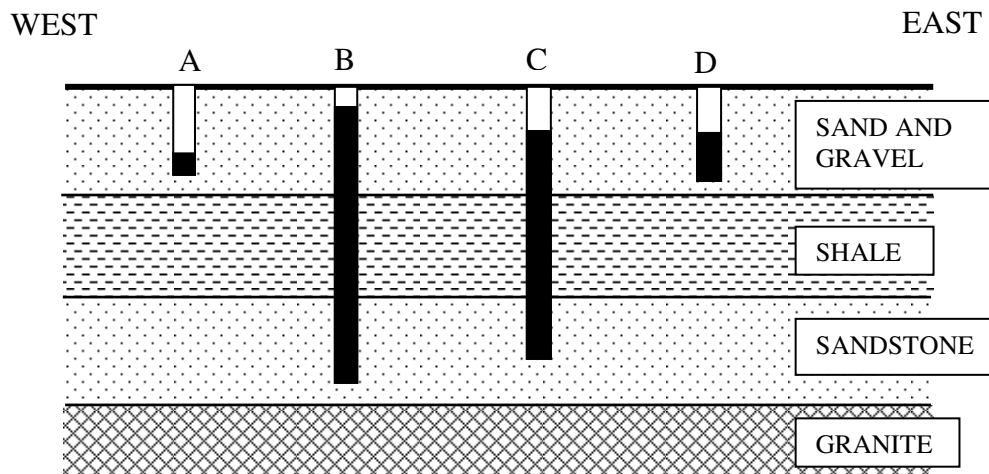
Part II-Well Log Interpretation

In this problem you will use information from "well logs". These are forms filled out by well drillers every time a well is drilled. These well logs are available for public inspection at US Geological Survey offices, as well as state agencies in charge of water resources (in Washington, Dept. of Ecology). All depths are measured from the ground surface down.

WELL LOG DATA

Well A		Well B	
Water depth: 75 ft		Water depth: 25 ft	
*Screened section: 85-100 ft		Screened section: 20-45 ft	
Depth (feet)	Formation	Depth (feet)	Formation
0-70	brown sand	0-2	soil
70-83	hardpan, some gravel	2-38	sand, gravel
83-95	gray sand	38-43	mixed shale, clay
95-100	blue clay	43-45	hard shale

*The screened section of a well is where the pipe or casing is porous instead of solid, allowing water to flow into the well only in that location.

Problem 2
Using the water levels given and your knowledge of the permeability of various earth materials, determine the following information for each of the wells:
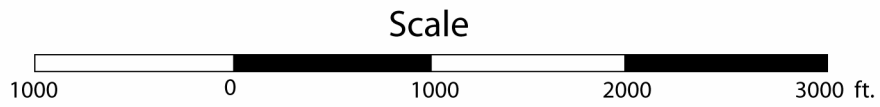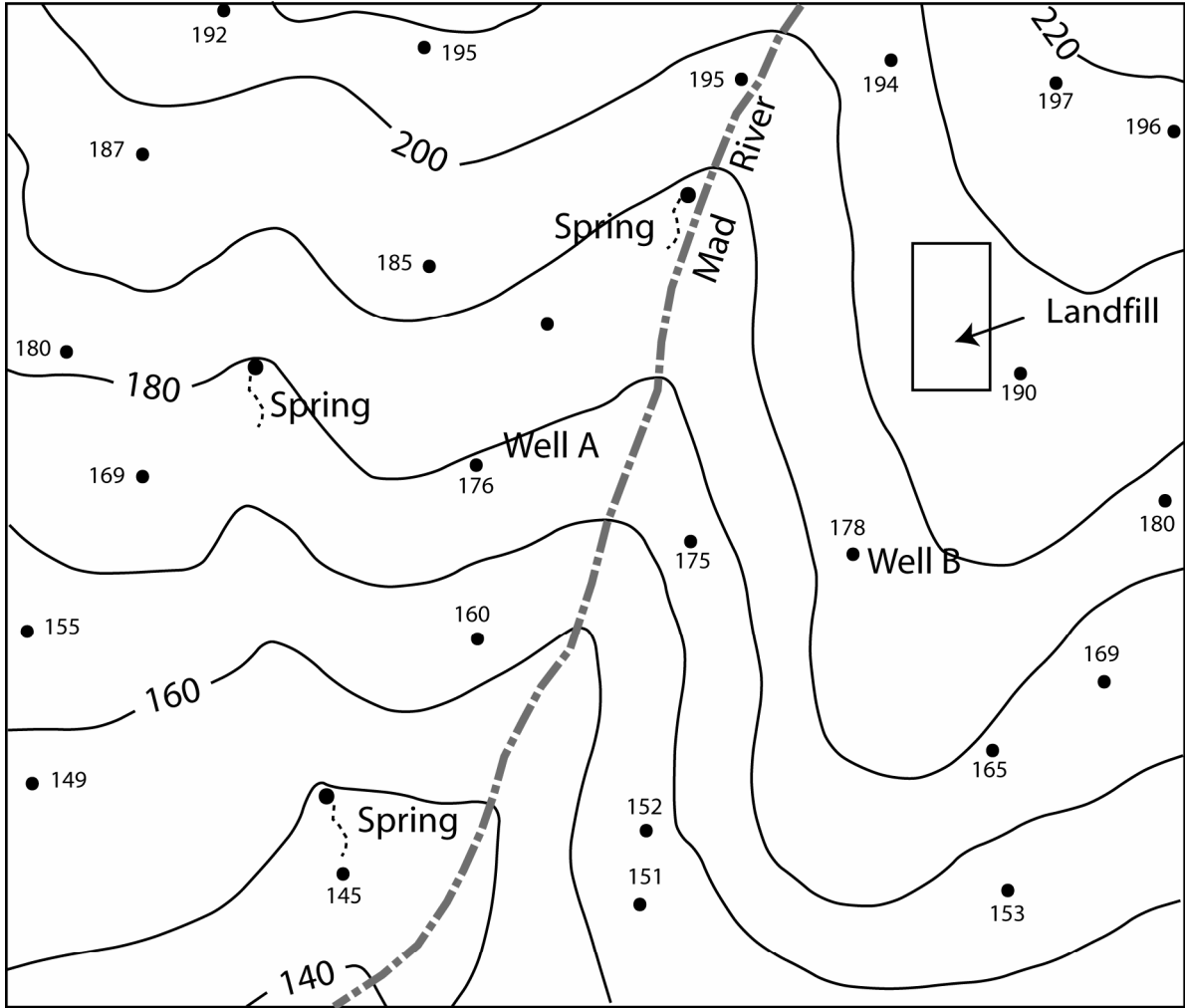
	WELL A	WELL B
Aquifer location (feet below ground surface)	_____	_____
Aquifer material	_____	_____
Type of aquifer (confined or uconfined)	_____	_____
How deep you have to drill to get water	_____	_____

Part III-Direction of Groundwater Flow

Problem 3
It has just been reported in the newspaper that hazardous waste was illegally dumped in 1985 in the landfill on your map (next page). Local residents are upset because the public water supply well (Well A) is a short distance downhill from the landfill. They have hired you to investigate the situation. You find the topographic map provided, gather all the well logs for the area, and get to work.

a) The contours on your topo map show the elevation of the ground surface. Your first task is to construct a contour map of the water table. Draw your contours at 10 foot intervals (150, 160, etc.). Use the following 3 sources of data:

- ✓ Water elevations in the wells, shown as dots on the map (note that these are elevations, not depths!)
- ✓ Spring locations (water table = ground surface elevation)
- ✓ Locations where the river crosses a contour line (water table = ground surface elevation)

b) Just like water on the ground surface will flow in the direction of steepest descent (perpendicular to topographic contours), groundwater will flow "downhill" relative to the water table or hydraulic head. Throughout your map, using a different color of pencil from the groundwater contours, draw arrows in the direction of groundwater flow.

c) Will leachate (contaminated liquids leaking from a waste site) from the landfill likely affect Well A? Why or why not?

d) Could leachate eventually reach Mad River? Well B?

192

195

220

195

194

197

196

187

Spring

Mad River

185

Landfill

180

180

Spring

Well A

190

169

176

178

Well B

180

175

155

160

169

160

149

165

Spring

152

153

145

151

Scale

| 1000 | 0 | 1000 | 2000 | 3000 ft. |

Water Elevation ● 197

Contour Interval: 10 ft.

Part IV-Groundwater Velocity

In this problem you will use Darcy's Law to determine the area-averaged velocity (V_s) of the groundwater moving through the subsurface. You will then adjust this velocity to account for the porosity (n) of the material, which is not considered in the equation. This will give you the true velocity of the groundwater (V_{actual}).

Darcy's Law: $$V_d = K\frac{\Delta H}{\Delta L}$$

V_d = darcian velocity of groundwater (ft/sec)
K = hydraulic conductivity (ft/sec)
ΔH = change in hydraulic head (ft)
ΔL = length of flow path over which dH is measured (ft)

To adjust for porosity: $V_{actual} = \dfrac{V_d}{n}$

Problem 4
The unconfined aquifer in the previous problem consists of sandstone with a porosity (n) of 0.40 and a hydraulic conductivity of 2×10^{-4} ft/sec.

a) Assuming the leachate travels at the same speed as the groundwater*, determine how long it would take the hazardous waste from the landfill to reach Well B (a bit south of the landfill). Use Darcy's Law to find V_d and adjust for the porosity to find V_{actual}. *NOTE: Time of travel = distance traveled divided by velocity of the moving water (1 day = 86,400 seconds)*

b) How far might the water have traveled already, assuming the worst case scenario in which it started leaking immediately after being dumped in 1985?

* This is not actually a very good assumption. Contaminants travel by diffusion (moving from areas of high to low concentration) as well as advection (physically carried by the water itself). Contaminants that diffuse rapidly can travel faster than the groundwater flow. The movement of contaminants can also be retarded by several processes, including adsorption (sticking) to the aquifer materials, and by chemical and biological degradation. Different chemicals behave differently; for example, acetone (a common solvent) is highly soluble in water and can move very quickly in groundwater. Conversely, PCB's are very insoluble and cling strongly to soils, and thus move very slowly, if at all, in groundwater.

Part V. The effects of pumping on the water table, a.k.a. the "cone of depression"

When a well is pumped, the surrounding water table will usually be lowered around the well, forming what is called a "cone of depression." This creates a gradient that causes water to flow toward the well. The radius (distance outward) and vertical extent of this cone is a function of the pumping rate of the supply well (Q) and the hydraulic conductivity (K) of the aquifer. In an unconfined, homogeneous aquifer, the cone of depression is defined by the Theim equation:

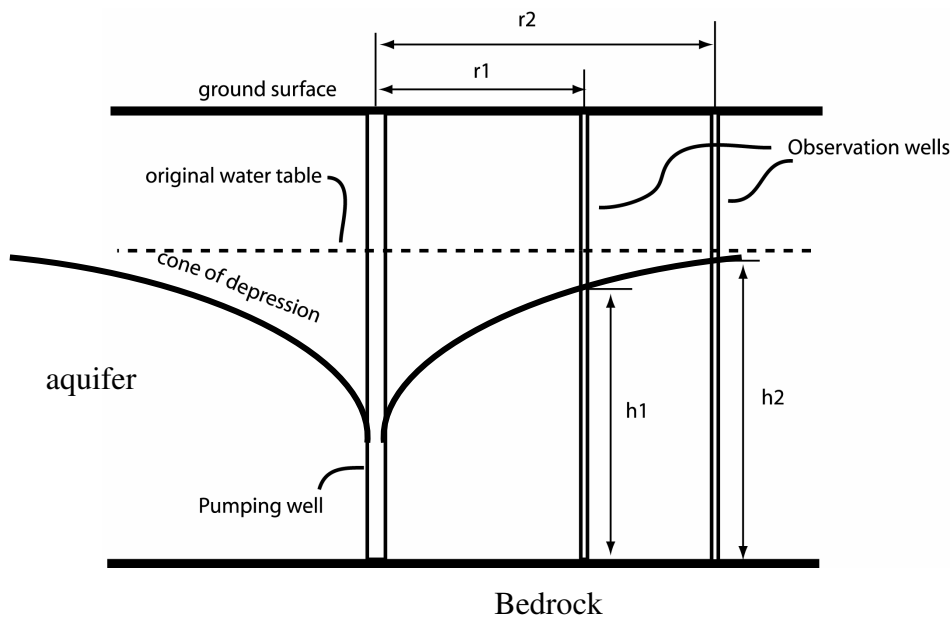$$K = \frac{Q}{\pi\left(h_2^2 - h_1^2\right)} \ln\left(\frac{r_2}{r_1}\right)$$

where:

K is the hydraulic conductivity (ft/day)
Q is the pumping rate (ft^3/day)
h_1 is head at distance r_1 from the pumping well (ft)
h_2 is head at distance r_2 from the pumping well (ft)
$\pi = 3.14$

The Theim equation is commonly used to determine the hydraulic conductivity of an aquifer. However, if K is known, this equation can also be used to determine or predict the drawdown in nearby wells resulting from pumping another well. Some assumptions required by this equation are that the aquifer is unconfined and underlain by a horizontal aquiclude, that the pumping well is pumped at a constant rate, and that the system has reached "equilibrium," i.e. there is no further change in drawdown with time.

Problem 5a. You have been hired by local sheep ranch to solve a water supply problem. Since 1995, when a large agricultural irrigation well (Well 1) was drilled nearby, the ranch's 100 ft-deep well (Well 2) has run dry in the summer (see the map below of the area). You study the geology of the area and figure out that the region is underlain by 500 ft. of silty sand on top of solid granitic bedrock. The silty sand forms the unconfined aquifer in which the wells are seated. When no wells are pumping, the water table is about 75 feet below the surface, and the water table dips slightly (~1 foot per mile) towards the east. The hydraulic conductivity of this aquifer is 1 ft/day. You study the records from the large agricultural irrigation well and determine that it is designed to pump a maximum of 20,000 ft^3/day, and it does so constantly during the summer. Well 1 is not used at all in the winter. You find out from the owners of another well (Well 3) that their water level drops 25 feet when Well 1 is pumping at maximum capacity. Both Well 2 and Well 3 are low-capacity wells, and when pumping form cones of depression that extend out less than 500 ft.

Your job is to calculate how deep of a well the sheep ranch needs to reach water in the summertime, when the cone of depression from Well 1 has drawn down the water table. You will also investigate the effects of the cone of depression on contaminant transport in the area. The next few pages will lead you through these analyses.

Map of Sheep Ranch site and nearby wells
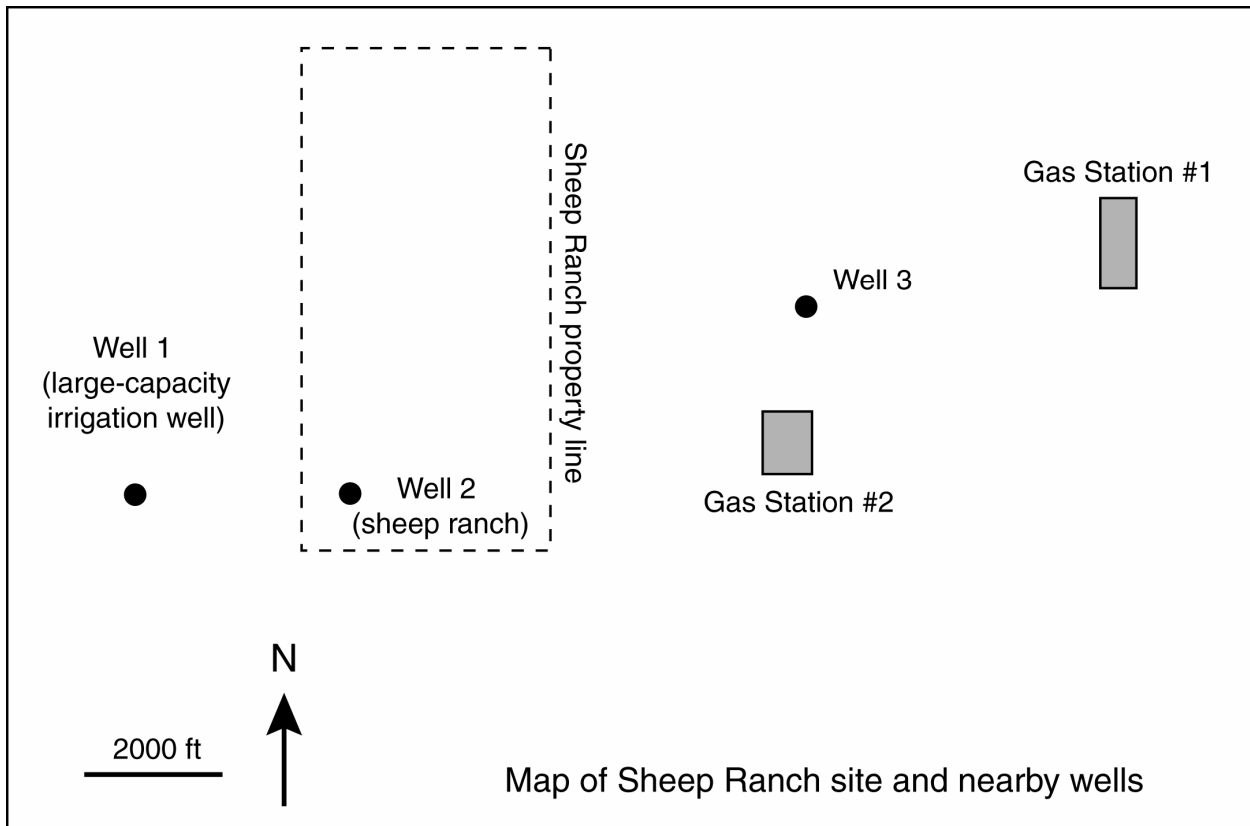
$$K = \frac{Q}{\pi\left(h_2^2 - h_1^2\right)} \ln\left(\frac{r_2}{r_1}\right)$$

a. First, determine which variable of the Theim Equation represents the height of the water table (head) above bedrock at Well 2 during maximum Well 1 drawdown (use the diagram on page 7 to figure this out). Rearrange the Theim Equation (above) to solve for this variable and write the rearranged equation below.

b. Determine the parameters in the Theim equation for when Well 1 is pumping at maximum capacity (leave the unknown variable blank). Refer to the diagram on Page 7 if necessary. Assume for this calculation that both the underlying granite and the surface of the initial water table are horizontal.

Q = _____ K = _____ r₁ = _____ r₂ = _____ h₁ = _____ h₂ = _____

c. Now, calculate the water table depression. When Well 1 is pumping at maximum capacity, *how much is the water table at Well 2 lowered from its initial level?* Show your math.

d. If the sheep ranch's new well needs to be in the same location as the old one and the bottom of the well needs to extend 20 ft. below the water table at maximum Well 1 drawdown, how deep does the new well need to be?

Problem 5b.

In the course of your investigations and study of the local groundwater for the sheep ranch, you discover that in the summer of 2003, the pollutant MTBE (methyl tertiary butyl ether) started showing up in the water collected from Well 3. [Note: MTBE is a water-soluble gasoline additive often found in groundwater as a result of leaking underground gasoline storage tanks at gas stations]. Because MTBE smells and tastes bad (and may be toxic), the owners of Well 3 are now monitoring MTBE concentrations on a monthly basis. They notice that MTBE concentrations are higher in the summer. There are two gas stations near the ranch, and both have sold MTBE-containing gasoline for many years (see the map on Page 8). These are the only two gas stations in the area.

    a. Which gas station is the most likely source for the MTBE in Well 3? Explain.

    b. Why has the MTBE only shown up recently, and why do MTBE concentrations increase in the summer?

    c. Using two different colored pencils, indicate on the map the direction of groundwater flow during A) summertime, and B) wintertime. (If you haven't figured it out by now, this directly relates to the previous two questions).

    d. Knowing that sheep dislike the taste of MTBE, and that deeper wells are more expensive to drill than shallower wells (drillers charge per foot, and deeper wells need bigger pumps), is there a better location for a new well on the ranch property? If so, where would you put it? Mark this new location on the map, labeling it "New Well." Give at least two reasons why the new location is better.