

CEE 1.72 -- Groundwater Hydrology
Professor Harvey

Final
12/2004

(1) Simplify the following sentence so it is a clear statement that preserves the obvious meaning. Your revision should contain the fewest words possible without losing meaning. Do not change any words, just eliminate (cross-out) unnecessary words. This is not a joke question. (10 pts.)

The ~~unchanging~~ steady-state water levels of the potentiometric surface in the ~~phreatic~~ zone of a ~~subsurface saturated~~ confined geologic groundwater aquifer indicated there was convergent flow of ~~moving fluid water~~ toward a ~~fully penetrating and fully screened~~ pumping ~~water~~ well.

(2) Describe the differences between the following terms. (12 points)

(a) Dispersivity, Dispersion Coefficient, and Diffusion Coefficient.

(b) Effective stress and total stress.

(c) Hysteresis and hystericalness.

(c) Langmuir isotherm and linear isotherm.

(3) Describe two different mechanisms that lead to overland flow. Contrast the conditions under which these two different processes occur. (10pts.)

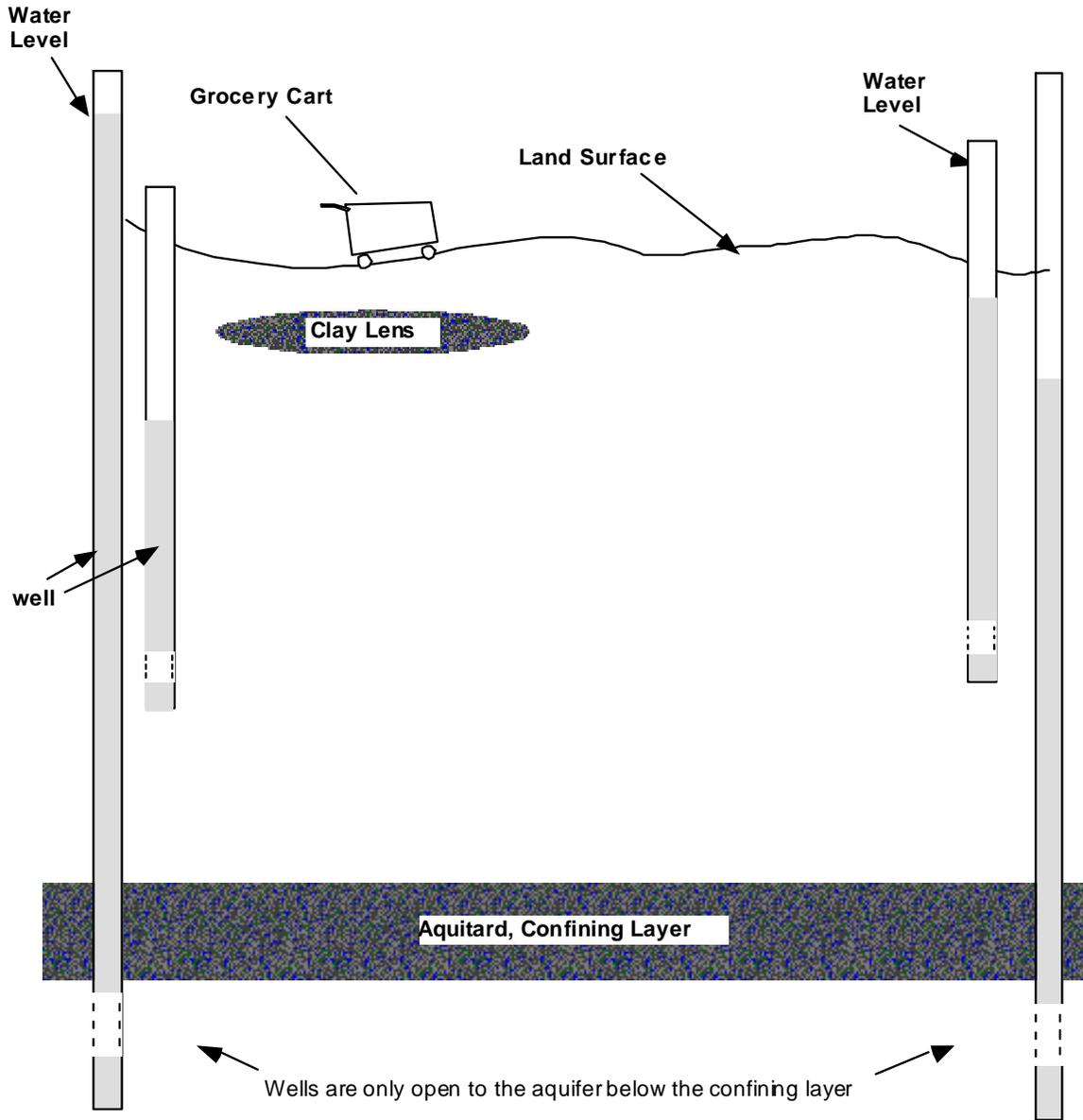
Saturation excess: occurs when the water table rises to the ground surface. Any additional effective precipitation will run off. This mechanism occurs near rivers and streams as well as during storms of long duration.

Infiltration excess: occurs when the effective precipitation rate exceeds the soil infiltration capacity. This mechanism many occur during storms producing extreme precipitation rates.

(4) Zeke , the well driller with a healthy curiosity, has a question for you. He had installed a set of wells in an aquifer he knows (accurately) to be confined. One of the wells was turned on and pumped continuously. Head measurements were taken at the surrounding wells. Playing around with Darcy's law, he noticed an "odd" phenomenon: based on his calculations from the heads of surrounding wells, the amount of water flowing toward the well appeared to increase over time. Yet the pumping rate at the well was constant. Explain to the well-driller what was happening. Draw cross-sections of the potentiometric surface around the well with time. (10pts.)

Darcy's law is a steady state law, and what Zeke is observing is the transient behavior of the potentiometric surface as it responds to pumping. Under transient conditions in a confined aquifer, water is withdrawn from storage through water expansion and aquifer compaction. Storage is the volume of water produced per aquifer volume per head decline. In this situation Zeke is essentially "mining" water or hydraulic head from the aquifer, so one would expect the drawdown to grow with time as water is continually pumped from storage and not replenished.

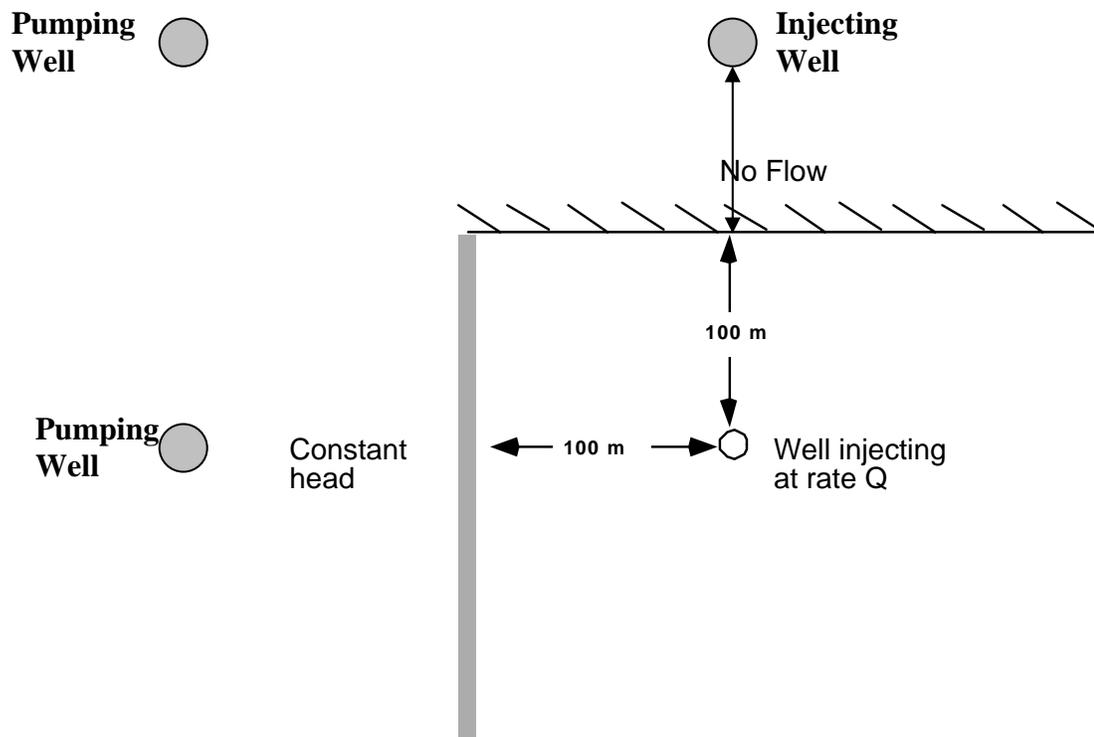
(5) Draw a cross-section of a subsurface water system (i.e., everything below ground level). Label the following: water table, phreatic zone, vadose zone, capillary fringe, unconfined aquifer, confined aquifer, potentiometric surface for the confined aquifer, perched water table, and, in the correct location, an artesian (flowing) well. Draw an arrow in both the top and bottom aquifers showing the direction of flow. The grocery cart and shape of the land surface are of no importance. (15 points)



(6) A well is injecting water in a confined aquifer with homogenous, isotropic S and T. This aquifer is bounded on the north side by an impermeable crystalline rock outcrop, and on the east by a lake. These two boundaries meet at approximately right angles as shown below.

(a) Describe how changes in head in this aquifer may be calculated using image wells. Show the position of the image wells. (10 pts.)

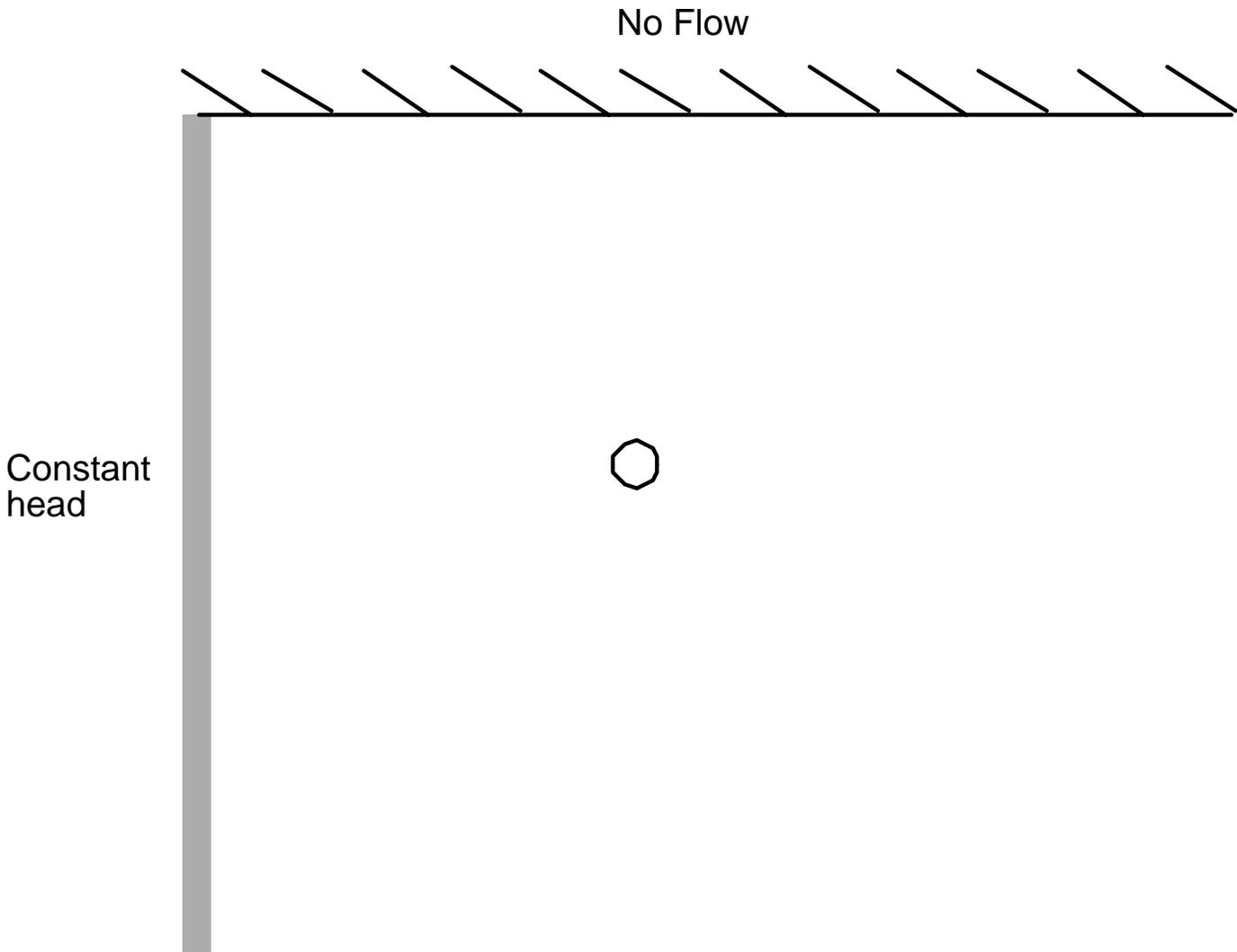
Locate the image wells as shown below, and use the principle of superposition to obtain the actual hydraulic head.



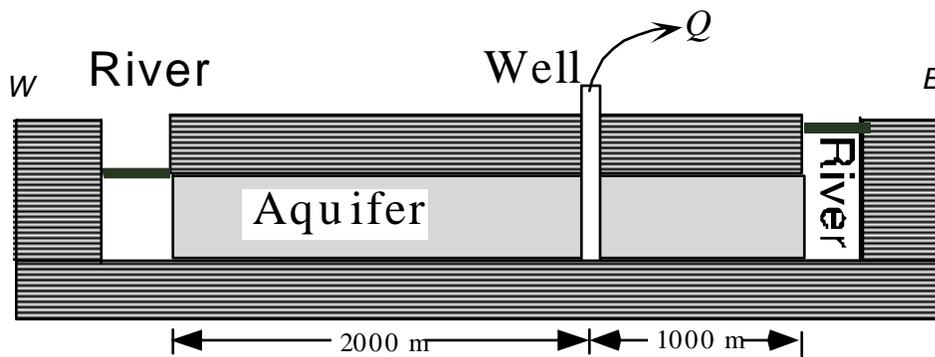
(b) Will the head change at the well be greater or less than it would be if the boundaries did not exist (i.e. if the well were in an infinite aquifer)? (1 point) Why? (9 points)

The head will be lower in the injecting well with the boundaries than without the boundaries. This is seen with the two pumping image wells compared to the one injecting image well. In this situation, the no-flow boundary will act to increase the head at the original injecting well compared to an infinite aquifer. The constant head boundary will act to decrease the head at the original injecting well compared to an infinite aquifer. These two effects do not exactly cancel each other out due to the non-symmetric geometry of the system.

(c) Once the system has reached steady state, the head at the well is 5 m above the head at the constant head boundary. Draw a flow net with head lines at 1 m intervals, and appropriate flow lines. Don't worry about being precise, just try to show the principles features of the system and avoid anything physically impossible. (15 points)



(7) The figure below shows a cross-section of a homogeneous, isotropic, confined aquifer with a large-capacity pumping well. The figure is not drawn to scale. The flows in the rivers are measured 5000 m upstream and 5000 m downstream of the well, and the difference between the upstream and downstream flows is due solely to discharge or recharge of this aquifer. (No flow goes to or from the other sides of the river.) Prior to pumping, the flow in West River increased by $1 \text{ m}^3/\text{s}$ along the 10,000 m reach, and the flow in East river decreased by $1 \text{ m}^3/\text{s}$ along the 10,000 m reach. (i.e the flow in and out of the rivers is $10^{-4} \text{ m}^3/\text{s}$ per meter length of river.) There is no other discharge or recharge to this aquifer. The head in the river remains constant over time and along the river. The aquifer remains confined. The clay of the confining unit, and of the unit beneath the aquifer is completely impermeable.



The following quantities are known:

Aquifer Porosity = 0.2.

Aquifer Thickness = 100 m.

Height of West River above aquifer top = 10 m.

Height of East River above aquifer top = 40 m.

(a) On the graph below sketch the head in the aquifer prior to pumping. (5 pts.)



(b) What are the values for transmissivity and conductivity of the aquifer? (5 pts.)

Darcy's Law: $q = -K \cdot dh/dx$;
 $T = K \cdot b$;
 $T = -q \cdot b \cdot dx/dh$

Flow out of the rivers is $1e-4 \text{ m}^3/\text{s}/\text{m}$, which is the darcy flux times the unit thickness of aquifer, i.e., $q \cdot b$

$T = (1e-4 \text{ m}^2/\text{s})[(3000-0\text{m})/(140-110\text{m})] = 0.01 \text{ m}^2/\text{s}$
 $K = T/b = 0.01/100\text{m} = 1e-4 \text{ m/s}$

(c) What is the groundwater velocity at the well location prior to pumping? (5 pts.)

$v = q/n = (1e-4 \text{ m}^2/\text{s})/(100\text{m})/(0.2) = 5e-6 \text{ m/s}$

(d) If everything were held constant (including the hydraulic conductivity), but the porosity was increased to 0.4, what would happen to recharge and discharge of the rivers? (5 pts.)

Recharge and discharge rates would remain the same because porosity has no effect on the hydraulic gradient or hydraulic conductivity. The only thing that would change is the average linear velocity.

(e) Using the table below, go back to part (a) and add plots of the head at years 2, 4 and 6. (The values of head are not important, but curves should have the correct shape and be placed correctly relative to each other.) The table below shows the discharge and recharge to the East and West rivers after the well is turned on, pumping at a constant rate of $0.4 \text{ m}^3/\text{s}$. The values are for the end of each year. (5 pts.)

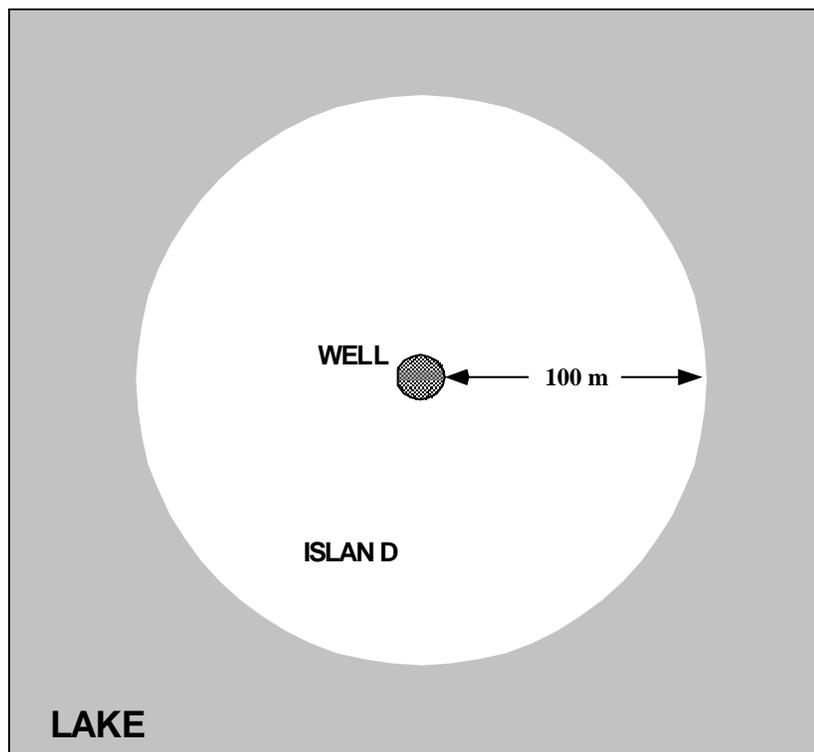
Time (Year)	Aquifer discharge to West River along 10,000 m reach m^3/s	Aquifer recharge along 10,000 m from East River m^3/s
0 (prior to pumping)	1	1
1	0.99	1.06
2	0.93	1.19
3	0.87	1.25
4	0.85	1.25
5	0.85	1.25
6	0.85	1.25

(f) Explain why the amount of water flowing into the aquifer (recharge - discharge) increases until year 4, then stops increasing. (10 pts.)

Up until year four, water is being extracted from storage. At year four and beyond, the difference in discharge is exactly equal to the pumping rate.

Year	Recharge - Discharge (m^3/s)
0	0
1	0.07
2	0.26
3	0.3
4	0.4
5	0.4
6	0.4

(8) The diagram below shows a confined, homogeneous, and isotropic aquifer beneath a circular island of radius 100 m in a lake. A pumping well is located in the middle of the island. Flow is steady state. In the picture below the hatched circle in the middle is the well, which is fully screened across the entire aquifer. Flow is horizontal to the well. The confined aquifer is 8 m thick. The extraction rate is $75.4 m^3/day$. The hydraulic conductivity of the aquifer is 30 m/day. The porosity is 0.3. Assume no flow through the confining layer and steady-state conditions.



- (a) What is the gradient of hydraulic head at the edge of the island? Assume no flow through the confining layer and steady-state conditions. (10 points)
- (b) The lake contains $1 \mu\text{g/L}$ bromide (not enough to significantly change the density). Bromide is a conservative tracer (i.e. no chemical reaction, or sorption), and does not exist in the groundwater before pumping. If we assume that both diffusion and dispersion are negligible how long does it takes for the bromide to reach the well after pumping commences? Still assume steady state. (10 points)
- (c) The lake also contains $1 \mu\text{g/L}$ lithium. Lithium sorption may be accurately modeled with a linear equilibrium isotherm. From a line of sampling wells you determine that just when the bromide reaches the pumping well, the lithium has traveled only 29.3 m from the edge of the island towards the pumping well. What is the retardation factor for lithium?(10 points)
- (d) Plot the breakthrough curves at the well for bromide and lithium. Also show a breakthrough curve for bromide when dispersion occurs. Is the breakthrough time of $0.9 \mu\text{g/L}$ and $0.1 \mu\text{g/L}$ of bromide increased or decreased compared to the arrival time of the solute front with no dispersion? (10 points)