The test contains 10 problems on six pages. Read the entire exam first.

**PART I: Multiple choice questions.**

**Problem 1.** (30 points)

Circle the most appropriate answer. By all other answers, briefly describe why they are less appropriate or inappropriate. 3 points each.

(a) Radioactive isotope of hydrogen (tritium) has

(1) three neutrons and no protons  
(2) two neutrons and one proton  
(3) one neutron and two protons  
(4) no neutrons and three protons  
(5) other configuration of neutrons and protons

(b) Darcy observed that flow in a column depends on

(1) temperature  
(2) porosity  
(3) pore size  
(4) column weight  
(5) none of the above

(c) Linear flow velocity is

(1) equal to the specific discharge  
(2) faster than the specific discharge  
(3) slower than the specific discharge  
(4) either faster or slower, depending on the medium  
(5) either faster or slower, depending on the Reynolds number

(d) Transmissivity tensor has

(1) one component  
(2) three different components  
(3) nine different components  
(4) six different components
(5) none of the above

e) In a phreatic aquifer the upper boundary is defined by
   (1) negative pressure head
   (2) positive pressure head
   (3) slow water velocities
   (4) zero hydraulic gradient
   (5) none of the above

(f) In a confined aquifer at the upper boundary
   (1) the pressure head is positive
   (2) the pressure head is negative
   (3) the pressure head is zero
   (4) the hydraulic gradient is zero
   (5) none of the above

(g) hydraulic head is
   (1) weight per unit density
   (2) energy per unit mass
   (3) energy per unit work
   (4) weight per unit mass
   (5) none of the above

(h) Specific storage coefficient has the same unit as
   (1) specific yield
   (2) Reynolds number
   (3) storativity
   (4) permeability
   (5) none of the above

(i) Specific yield measures
   (1) compressibility of water
   (2) compressibility of matrix
   (3) drainage of water from pore spaces
   (4) subsidence due to pumping
   (5) none of the above

(j) In flow through a tube maximum velocity (in the center of the tube) is
   (1) twice the mean velocity
   (2) four times the mean velocity
   (3) 16 times the mean velocity
   (4) infinitely faster than the mean velocity
   (5) none of the above
PART II: Short questions, short answers (use only the space provided).

**Problem 2.** (5 points)

What are dimensions and typical SI units for the following? For example: K, hydraulic conductivity: \([L/T]\), e.g., \([m/s]\)):

(a) T, transmissivity:

(b) \(\mu\), viscosity:

(c) \(S_y\), specific yield:

(d) \(\rho\), matrix compressibility coefficient:

(e) \(S_s\), specific storage coefficient:

**Problem 3.** (5 points)

A horizontal, confined aquifer has a homogeneous and isotropic hydraulic conductivity \(K=2\ m/d\) for water and a porosity \(n=25\%\). Two piezometers are placed 200 m apart along a typical flow path measure a head difference \(dh=1\ m\). How long will it take an ideal chemical tracer to be transported from one piezometer to the other?

**Problem 4.** (5 points)

Show mathematically that an impermeable boundary can be replaced by an image well. In other words, prove that a system consisting of a pumping well and an impermeable boundary is equivalent to a system consisting of a real pumping well and an image pumping well.
Problem 5. (5 points)

Pretend that you are to review a consulting report describing a model that was used in the investigation of a hazardous waste site. The authors claim that they studied two-dimensional migration of the contaminant, as the plume moved horizontally through the aquifer. They write the following equation describing their model of transient flow in the saturated zone:

\[ K \frac{\partial^2 H}{\partial x^2} + K_y \frac{\partial^2 H}{\partial y^2} = S \frac{\partial h}{\partial t} \]

where \( K \) is hydraulic conductivity, \( h \) is head, \( h=h(x,y) \), \( x,y \) are horizontal coordinates. Briefly evaluate this model (50 words or less). What would you change in it?

Problem 6. (5 points)

Show by dimensional analysis on the equation \( K=k g/\mu \) that hydraulic conductivity has the dimensions of velocity.

Problem 7. (5 points)

The water table of a phreatic aquifer drops 20 m over the area of 100 km\(^2\), yielding \( 10^8 \) m\(^3\) for irrigation. What is the specific yield of the aquifer?

Problem 8. (5 points)
Write the partial differential equations that describes transient, saturated groundwater flow in an isotropic, heterogeneous, phreatic aquifer with a horizontal bottom. Concisely define all terms. Consider two cases in which there is:

(a) essentially horizontal flow

(b) significant vertical flow

Problem 9. (5 points)

Concisely critique the following plot of hydraulic head distribution along the laboratory column that consists of two soils with different hydraulic conductivities.

PART III: Problem solving. Write your answers on separate paper. Show all work. Be brief and neat. Read the questions carefully.

Problem 10. (30 points)

Two well clusters are positioned 6000 m apart laterally. Each well cluster consists of a shallow well which taps the water table and a deep well which taps a confined aquifer below. At well cluster A, the land surface elevation is 1120 m. The deep well is screened at the bottom of its 500
m depth, and the depth to water is 63 m. The shallow well is 50 m deep, screened over its bottom 1 m, and has depth to water of 46 m. At well cluster B, the land surface elevation is 1260 m. The deep well is 640 m deep and depth to water is 209 m. The shallow well is 190 m deep and depth to water is 170 m.

The phreatic aquifer has isotropic and homogeneous hydraulic conductivity of \(10^{-3}\) m/s and porosity of 0.35. The aquitard between the two aquifer systems is horizontal, 1 m thick, and located at cluster A at depth between 120 and 121 m. Its hydraulic conductivity is \(10^{-6}\) m/s and porosity 0.2.

The confined aquifer is composed of solid granite with horizontal fractures; there is some vertical connection between horizontal fractures, also. The fracture density is 3 per meter of aquifer thickness. The fractures have different, but constant within single fracture, apertures (e). In each set of three fractures, fracture #1 has aperture \(e_1=4.62\times10^{-4}\) m, fracture #2 has \(e_2=6.94\times10^{-4}\) m, and fracture #3 has \(e_3=9.25\times10^{-4}\) m. The same set of fractures is repeated every 1 m of aquifer thickness. Assume that the granite is otherwise impermeable, i.e., the fractures are the only conduits for fluid flow in the horizontal direction.

(a) What is the vertical gradient at well cluster A? At well cluster B? Assume one dimensional vertical flow.

(b) What is the horizontal gradient in the phreatic aquifer? Of the confined aquifer? Assume essentially horizontal flow in the direction from A to B or vice versa.

(c) Through a sketch, suggest a realistic field situation of the above system that allows for two dimensional flow in the vertical cross section. Show directions of flow in your sketch. Neglect flow into or out of the page.

(d) A chemical spill was detected at the bottom of the phreatic aquifer at location A. The city has a deep municipal pumping well planned for location B. The well will be in operation for 20 years. Assume that the municipal well has no effect on the flow patterns in the aquifer/aquitard system. What is your assessment? Support it using calculations. Be careful in your calculations!

(e) Qualitatively, discuss how the municipal well can affect the flow pattern in the aquifer/aquitard system. Do you have to reconsider your assessment in part d? Why or why not?

(f) Devise a measure to prevent contamination of the proposed municipal well by the chemical. Be creative, but realistic. Discuss why your approach would be efficient.

(g) What is the total rate of leakage between the two aquifers. Report this rate per the entire 6000 m of aquifer length and per unit aquifer width (into the page). Neglect effects of pumping at the municipal well.