Exam Hydrogeology – ACE080 June 3, 2022 (14.00 – 18.00)

Aids: calculator, pen, and paper

Examiner: Lars Rosen

Review of grading: will be carried out after making an appointment with Lars Rosén

In case of questions:

- A member of the teaching team will be present on-site for questions

General advice:

- Start every question on a new page!
- Geological processes are often most effectively described using both sketches and text.

1. Terminology (5p)

State the term that is described by the sentences below:

a. The maximum rate at which infiltration can occur (under specific conditions. soil moisture…)
b. The water in a stream that comes from effluent ground water. It sustains the stream during periods of no/little precipitation.
c. The soil moisture content below the limit at which plants can withdraw water in the unsaturated zone
d. A well where the hydraulic head in the well is above the upper limit of the aquifer.
e. The amount of evapotranspiration that would occur if there is at no time any water deficiency/shortage.
f. An imaginary well that is used to simulate the effects of a recharge/barrier boundary on a pumping well.
g. An area surrounded by a continuous topographic divide within which all runoff joins a single stream.
h. The condition under which one or more of the hydraulic properties of an aquifer vary according to the direction of flow.
i. The radial distance from the center of a pumped well to the point where there is no lowering of the water table or potentiometric surface (the edge of the cone of depression).
j. The volume of the void spaces through which water or other fluids can travel in rock or sediment divided by the total volume of the rock or sediment.

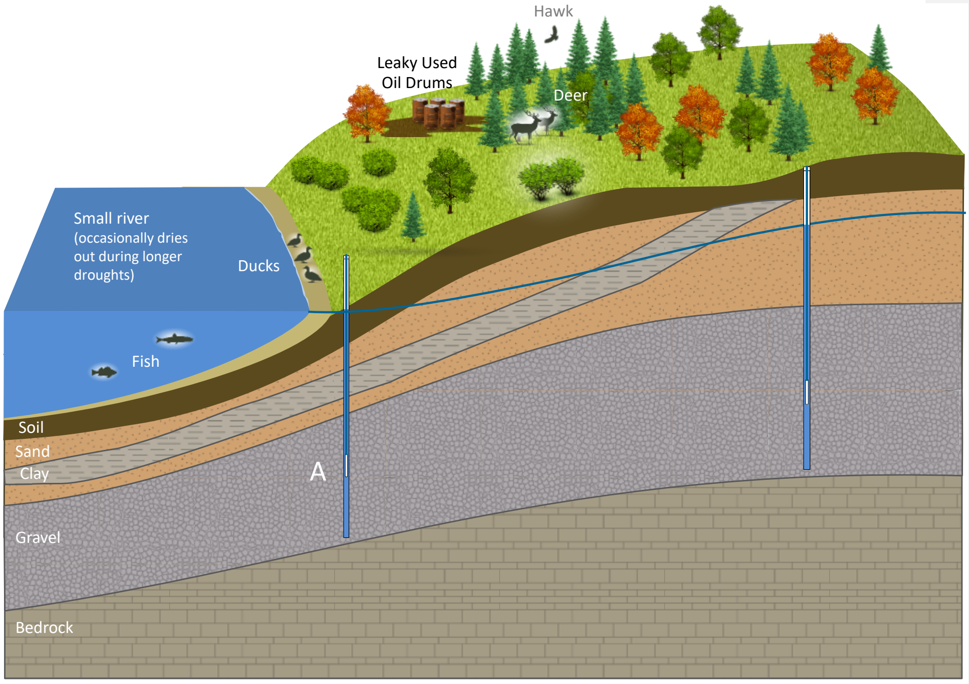
Solutions

a. Infiltration capacity
b. Baseflow
c. Wilting point
d. Artesian well
e. Potential evapotranspiration
f. Image well
g. Catchment area
h. Anisotropy
i. Radius of influence
j. Effective porosity

2. Aquifer properties (10p)

Commented [NG1]: Emrik posed this question last year. Should we just use it as it is? It was used during the second re-exam and we never published it.

a. Which geological formations form the most significant aquifers in Sweden regarding aquifer abstraction rates? (2p)
b. Give three important hydrogeological properties of the formations you identified in (a). (3p)
c. What aquifer properties (generally stated) do we expect at point A in the figure below regarding:
   1. Hydraulic conductivity? (1p)
   2. Drought sensitivity? (1p)
   3. Vulnerability to groundwater contamination? (1p)
   4. Recharge rate? (1p)
   5. Storativity? (1p)



Solutions

a. Glaciofluvial ekers and deltas (2p)
b. High effective porosity, high permeability and, large formations=large storage (3p)
c.
   1. High hydraulic conductivity. 10^{-5} to 10^{-2} m/s (1p)
   2. Less prone (1p)
   3. Less prone (1p)
   4. Not exceedingly slow or fast (1p). Confined aquifers usually have a slow recharge rate, however, in this case the length the water needs to go from the recharge area to point A is rather short, combined with high hydraulic conductivity
   5. Very low storativity (less than 0.01 upwards 10^{-5}) (1p)

3. Groundwater Flow - confined (5p)

a. Define Darcy's Law and outline in short the limits of its application in solving groundwater flow problems! (2p)

A confined aquifer assumed to be of infinite size and homogeneous is to be developed as a public drinking water supply from a borehole that fully penetrates the aquifer with a saturated thickness of 30 m. Test pumping of a newly drilled borehole is conducted until steady-state conditions are reached. At steady-state, the measured groundwater levels at two observation boreholes situated 100 m and 500 m from the pumping borehole are 58 m and 60 m above the top of the horizontal aquifer, respectively. During the test, the pumped borehole yielded a flow of 15 L/s.

b. Using the pumping test data, calculate the transmissivity and hydraulic conductivity of the aquifer. Comment on any assumptions made in your calculation. (3p)

Solutions

a. Darcy's Law is defined as q = -iK. Darcian flow applies when the Reynolds number is smaller than 10 and laminar flow conditions apply. In turbulent conditions, it does not apply, e.g., flow close to a pumping borehole or in a large karst conduit, flow with high groundwater velocities. Darcy velocity represents the average, macroscopic description of flow behaviour in a porous media.
b. Thiem equation:

$$Q = 2\pi Kb \frac{(h_2 - h_1)}{\log_e (r_2 / r_1)}$$

r1 = 100m; r2 = 500m; h1 = 58m; h2 = 60m; b = 30m; Q = 15 L/s
T = Kb
Kb = 0.015/(2Pi)*[ln(500/100)/(60-58)] = 0.015/(2Pi[ln(5)/2] =
Kb = T = 1.921 x 10-3 m2/s= 166.0 m/d

K = T/b = 1.921 x 10-3/30 = 6.40 x 10-5 m/s or 5.5 m/d

4. Flow in an unconfined aquifer (10p)

An unconfined aquifer outside of Gothenburg is in a flat area and has a hydraulic conductivity of 4.2 x 10^{-4} m/s. The aquifer is in a horizontal bed of sand with uniform thickness of 31 m, as measured from the land surface. There are two observation wells 315 meters apart. At well 1 the water table is 21 meters below the ground surface and at well 2 it is 24.5 meters below the ground surface.

a. Calculate the discharge per unit width of the aquifer in m^2/day (4p). Assume the aquifer is homogeneous and isotropic.
b. What is a reasonable value for recharge to the aquifer? (1p)

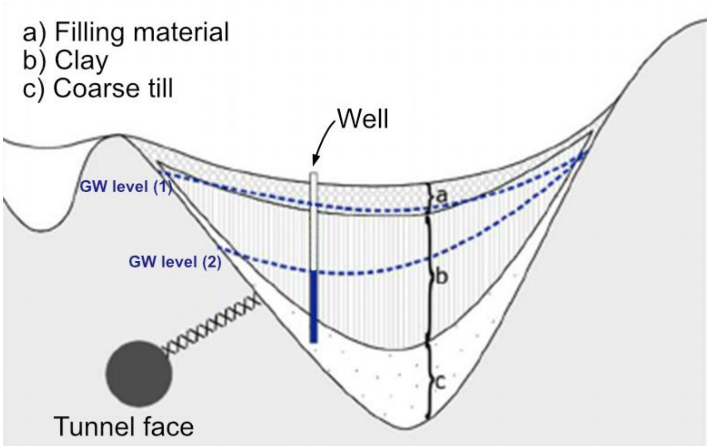
Solution:

a. $q' = \frac{1}{2}K\left(\frac{h_1^2 - h_2^2}{L}\right) = 2.1 \cdot \frac{10^{-4}m}{s} \cdot \frac{57.75m^2}{315\ m} = 3.85 \cdot 10^{-5}\ \frac{m^2}{s} = 3.33\ m^2/d$

b. Approximately 400-500 mm

5. Time Series Analysis (15p)

At a site in central Gothenburg, groundwater levels have been recorded in a well for three years using a dipper a couple of times a year and for the past months with a pressure transducer taking daily measurements. A tunnel is being built in the vicinity, and drilling commenced 6 months ago. The tunnel face is currently at roughly 100 m distance from the wells. You are in charge of warning the resident engineer of groundwater impacts and have received a flag that the groundwater level has dropped in a well penetrating the unconfined aquifer. A conceptualization of the site can be seen in the figure below, where groundwater levels are only known at the well (the dotted lines GW level (1) and (2) are only estimates of the groundwater head).



a) Given the information you were given, what are potential causes of the drop in groundwater. Name two different causes and explain the linked process(es). What are the uncertainties in the data and which further data could you gather to reduce uncertainties? (6p)
b) Which cause is represented by the drawdown pattern indicated by the dotted lines (GW level (1) to GW level (2)) in the figure above? Explain! (2p)
c) List the steps necessary to introduce a method to flag action and mitigation levels at your local site in the correct order, given the groundwater level data available. (7p)

Solutions:

a) Potential causes:
   - **a.** leakage from aquifer to tunnel construction, when tunnel face approached the site. Flow from confined aquifer through fractured rock to tunnel (where it is pumped out of the system). Drop in pressure head in the confined aquifer.(2p)
   - **b.** Spring is associated with falling groundwater levels due to precipitation not going to recharge but to vegetation and rising ET. This could be the reason for falling levels given that there is no reliable data (very few measurements, short time period) from previous seasons to verify the seasonal amplitude. (2p)
   - **c.** Alternative to a, b: e.g. impact from other construction site nearby, gw drought etc
   - **d.** Uncertainties are mainly in short and patchy time series and not sufficiently well understood hydrogeology. Adjacent wells in the same aquifer can be checked and a comparison could be made with reference wells. Alternatives: inflow data from tunnel, modelling with ts analysis or numerical models etc.. (2p)

b) The situation describes leakage to a tunnel from the unconfined layer through fractured rock. The drawdown is more pronounced close to the fracture zone, while groundwater recharge keeps levels up in the right corner of the aquifer. (2p)

c)

a. Find reference well from SGU's network with similar hydrogeology and close vicinity. (2p)

b. Correlate to check how well the behaviour of the reference well reflects the local well. If good proceed otherwise find new reference well. (1p)

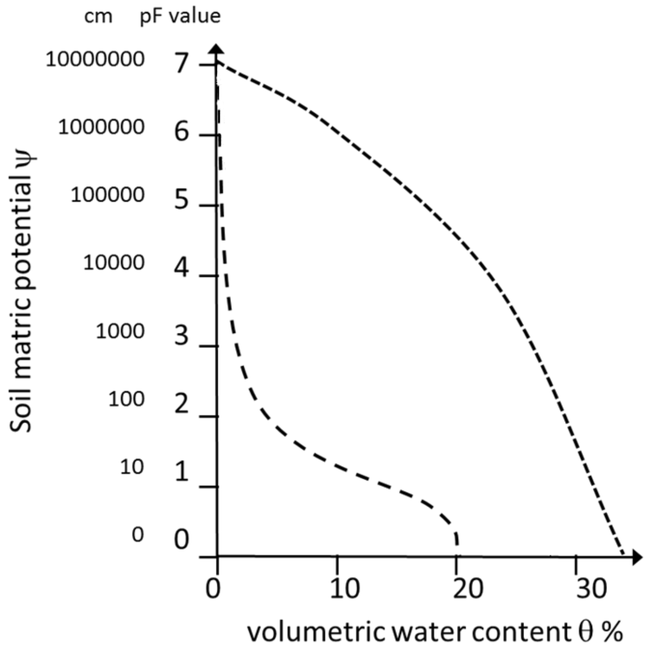
c. Build regression model to extend local time series based on reference well. (1p)

d. Run extreme value analysis and fit distribution to minimas, e.g. normal distribution (1p)

e. Decide action and mitigation levels, e.g. 50 and 100 year return levels and extract the values from plot or distribution function. (2p)

6. Groundwater recharge (5p)

The pF or water retention curve describes the relationship between the soil matric pressure (suction pressure) and water content and gives an understanding of the parameters involved that controls percolation from unsaturated to saturated zone. Below such a curve is shown for two different soils.



Determine the following for each of the soils:

a. The total porosity. (1p)
b. The available (soil) water content at the permanent wilting point (150kPa) and at field capacity (33 kPa). (3p)
c. Classify roughly the soil type (e.g. sand, loamy sand, …). (1p)

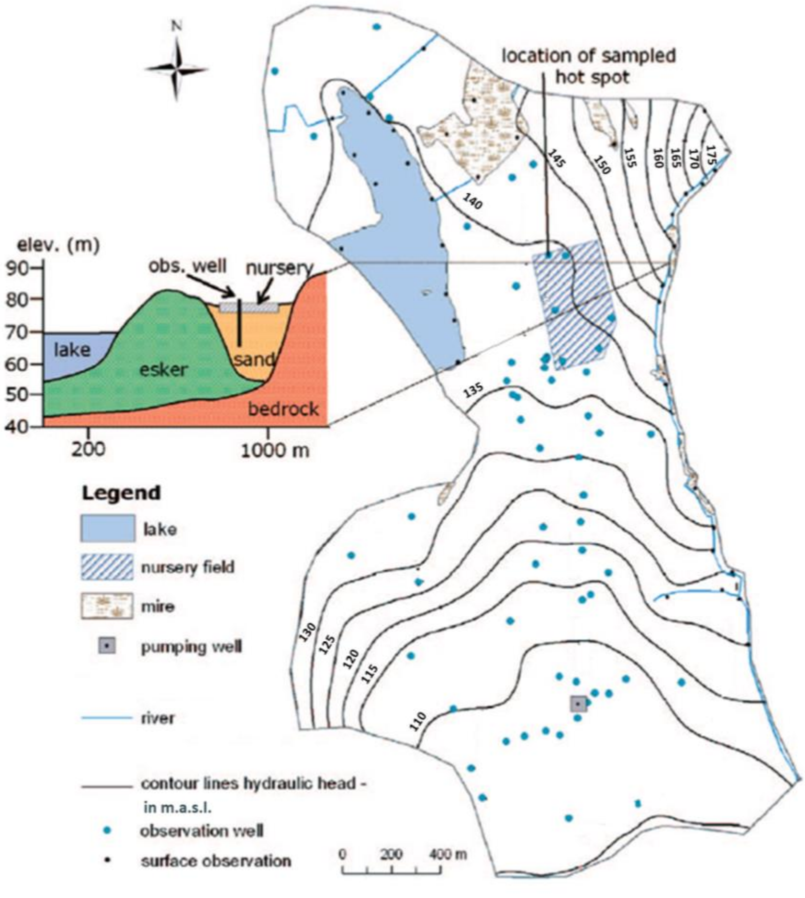
Solutions:
From left to right:

a) 20%, 33%
b) (~8, ~30) at field capacity, (~1,~27,) wilting point
c) Sand, clay

(0.5p each)

7. Groundwater Modeling (15p)

The water authority wants to develop a new well (see grey rectangle 'pumping well' in the illustration below) for providing drinking water to the municipality. Investigations in the area revealed a former forest plant nursery, where the pesticide *dichlobenil* was used from the late 1970s to 1991. The nursery is shut down, but potential groundwater contamination should be considered. The former forest plant nursery is situated on deep sandy sediments in contact with a north-south–oriented esker. The esker, which consists of glaciofluvial sand and gravel, accommodates large quantities of groundwater. The aquifer is homogenous and isotropic. The equipotential lines are displayed on the map in meters above sea level (m.a.s.l.). The Swedish Geological Survey (SGU) assumes 400 mm/year net groundwater recharge. (*Annotation: A mire is a wetland area dominated by living peat-forming plants.*)



a. What is the direction of the groundwater flow? Sketch it in the figure. (1p)
b. Where in the case study area do you expect the highest groundwater velocity, and where is the lowest groundwater velocity? (2p)
c. List the boundary conditions (BC) in the case study area. Assign to each BC the corresponding type and give a short explanation for the choice of BC. (3p)

d. During a first meeting on the site, someone claims that 500L/s can be abstracted without managed aquifer recharge. You doubt those claims and quickly approximate the groundwater flow with Darcy's Law. You can use the information from the map, the cross-section, and the text description to calculate the groundwater flow. (2p)
e. The municipality asks you to build a numerical model of the area to get a more detailed picture of the groundwater flow and the potential contamination. (4p)
   - What are the steps for setting up a numerical groundwater model?
   - What kind of data do you need for building such a model? List the parameters (min 3)!
   - What data would you use to calibrate your numerical model?
f. After successfully calibrating your numerical model, you are asked to investigate if the former forest nursery poses a risk to the drinking water well. You decide to use forward and backward particle tracking with MODPATH. (3p)
   - Describe forward and backward particle tracking in your own words!
   - Where in the model do you release the particles for forward particle tracking? Where do you release the particles for backward particle tracking? Remember that you aim to investigate if the former forest nursery poses a risk to the drinking water well.

Solutions:

a. Flow towards the well, perpendicular to the equipotential lines
b. High gradient → high velocity, low gradient → low velocity
c. Boundary conditions can be named in the scientific name (Dirichlet/Neumann or as BC Type 1, 2 or as constant head/constant flow/head-dependent flux:
   - River = constant head or head-dependent flux
   - Lake = constant head or head-dependent flux
   - Well = constant flow
   - Recharge = constant flow
   - Wetland = dependent if the lake or the groundwater recharges it; it can be BC1, 2 or 3

d. Approximation with Darcy's Law
   - Q=K*i*A
   - A=600*35m2=21000m2; K=10-4 m/s; i=20/900=0.02
   - Q=46L/s

e. Steps for building a model:
   - Purpose definition
   - Conceptual model
   - code selection
   - Data collection
   - Model design
   - Calibration
   - Verification

   Data type + unit (here are just some examples):

   - CHD river/lake: m; HDF river/lake
   - aquifer thickness: m;
   - K = m/s;
   - recharge: mm/a;

- pumping well flow = m^3/s
- information on mire

Calibration option:

- Equipotential lines, observation wells

f. Definition of backward and forward particle tracking:
   - Forward: particles placed at the source, see where they go
   - Backward: Particles placed at the sink, see where they came from

   Position of particles for forward/backward particle tracking:

   - Backward: At the well
   - Forward: At the nursery

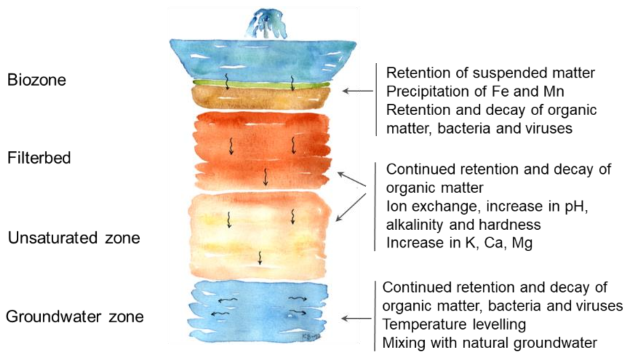
8. Managed aquifer recharge or groundwater chemistry/contamination (5p)

You have been assigned to design a public drinking water supply, with managed aquifer recharge using basin (pond) infiltration.

a. Describe shortly the different layers in a recharge basin (from bottom of the basin and into the saturated zone) and the filtering processes of each layer (5 p).
b. Many artificial recharge facilities in Sweden use a residence time (between infiltration and abstraction in wells) of at least 2 months. What is the main purpose for using this residence time? (2p)
c. What would be potential problems if you use a very long residence time of e.g., several months? (3p)

Solution:

a.



(after Hanson, 2000)

b. Many pond infiltration facilities in Sweden designed to provide ≥ 2 months residence time

- To provide good enough microbiological quality
- To provide good enough reduction of organic content (to avoid taste and odor problems)

c. If residence time is too long => the organic content can lead to depletion of oxygen => Fe, Mn and other metals go into solution => more extensive post-treatment (and may also give technical problems with clogging of wells)

9. Pumping test (10p)

A well in a confined aquifer is pumped with a discharge of 21 l/s for 500 minutes. The time-drawdown in an observation well located 130 meters from the pumping well can be found in the table below.

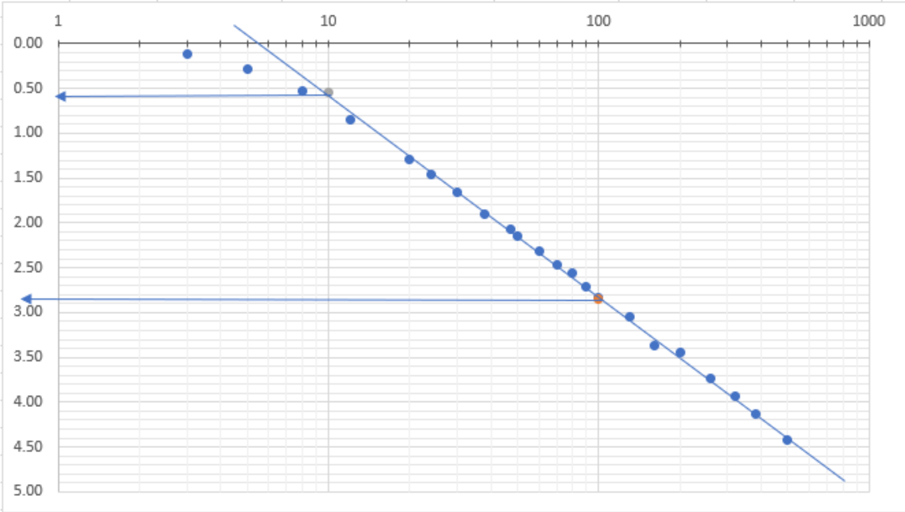
Time (min)	Drawdown (m)
3	0.12
5	0.28
8	0.53
12	0.85
20	1.30
24	1.46
30	1.66
38	1.91
47	2.07
50	2.15
60	2.31
70	2.47
80	2.55
90	2.72
100	2.84
130	3.04
160	3.36
200	3.45
260	3.73
320	3.93
380	4.13
500	4.42

a) Calculate the transmissivity and the storativity for the aquifer using the Cooper-Jacob straight-line time-drawdown method (lin-log).

b) This method is only valid for $u<0.01$. How many minutes must the aquifer be pumped for this method to be valid?

Solution:

a)



T=$1.67 * 10^{-3} m^2/s \ = \frac{0.183 * 0.021}{2,3}$

$S = 7.34 * 10^{-5} = \frac{135 * 0.00167 * 5.5}{130^2}$

b)

$309\ min = \frac{130^2 * 7.34^{-5}}{4 * 1.67^{-3} * 0.01}$

Equations sheet:

Thiem:

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

$K = \frac{Q}{\pi(b_2^2 - b_1^2)} \ln\left(\frac{r_2}{r_1}\right)$ (unconfined)

Theis:

$$h_0 - h = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

Jacob, distance-drawdown:

$$T = \frac{\ln(100)Q}{4\pi\Delta(h_0 - h)} = \frac{0{,}366Q}{\Delta(h_0 - h)}$$

and $S = \frac{2{,}25Tt}{r_e^2}$

Jacob, time-drawdown:

$$T = \frac{2{,}3Q}{4\pi\Delta(h_0 - h)} = \frac{0{,}183Q}{\Delta(h_0 - h)}$$

and $S = \frac{2{,}25Tt_0}{r^2}$

Walton, leaky:

$$h_0 - h = \frac{Q}{4\pi T} W(u, r/B)$$

$u = \frac{r^2 S}{4Tt} \quad B = \sqrt{\frac{Tb'}{K'}}$

Darcy's Law:

$$Q = -KA\frac{dh}{dl}$$

Darcian velocity:

$$v = -K\frac{dh}{dl} = \frac{Q}{A}$$

Average linear velocity:

$$V_x = \frac{Kdh}{n_e dl} = \frac{Q}{n_e A}$$

Dupuit equation:

$$q' = \frac{1}{2}K\left(\frac{h_1^2 - h_2^2}{L}\right)$$

Head in unconfined aquifer:

$$h = \sqrt{h_1^2 - \frac{(h_1^2 - h_2^2)\,x}{L} + \frac{w}{K}(L - x)\,x}$$

Average horizontal hydraulic conductivity:

$$k_h avg = \sum_{m=1}^{n} \frac{k_{hm} b_m}{b}$$

Average vertical hydraulic conductivity:

$$k_v avg = \frac{b}{\sum_{m=1}^{n} \frac{b_m}{K_{vm}}}$$

Hazen's formula:

$$\boldsymbol{K = C(d_{10})^2}$$

K is hydraulic conductivity (cm/s)

d_{10} is the effective grain size (cm)

C is a coefficient based on the following table:

Very fine sand, poorly sorted	40–80
Fine sand with appreciable fines	40–80
Medium sand, well sorted	80–120
Coarse sand, poorly sorted	80–120
Coarse sand, well sorted, clean	120–150

Hvorslev:

$$K = \frac{r^2 \ln\left(\frac{L_e}{R}\right)}{2L_e T_0}$$

Appendix 1 Values of the function $W(u)$ for various values of u

u	$W(u)$	u	$W(u)$	u	$W(u)$	u	$W(u)$
1×10^{-10}	22.45	7×10^{-8}	15.90	4×10^{-5}	9.55	1×10^{-2}	4.04
2	21.76	8	15.76	5	9.33	2	3.35
3	21.35	9	15.65	6	9.14	3	2.96
4	21.06	1×10^{-7}	15.54	7	8.99	4	2.68
5	20.84	2	14.85	8	8.86	5	2.47
6	20.66	3	14.44	9	8.74	6	2.30
7	20.50	4	14.15	1×10^{-4}	8.63	7	2.15
8	20.37	5	13.93	2	7.94	8	2.03
9	20.25	6	13.75	3	7.53	9	1.92
1×10^{-9}	20.15	7	13.60	4	7.25	1×10^{-1}	1.823
2	19.45	8	13.46	5	7.02	2	1.223
3	19.05	9	13.34	6	6.84	3	0.906
4	18.76	1×10^{-6}	13.24	7	6.69	4	0.702
5	18.54	2	12.55	8	6.55	5	0.560
6	18.35	3	12.14	9	6.44	6	0.454
7	18.20	4	11.85	1×10^{-3}	6.33	7	0.374
8	18.07	5	11.63	2	5.64	8	0.311
9	17.95	6	11.45	3	5.23	9	0.260
1×10^{-8}	17.84	7	11.29	4	4.95	1×10^{0}	0.219
2	17.15	8	11.16	5	4.73	2	0.049
3	16.74	9	11.04	6	4.54	3	0.013
4	16.46	1×10^{-5}	10.94	7	4.39	4	0.004
5	16.23	2	10.24	8	4.26	5	0.001
6	16.05	3	9.84	9	4.14		

Log-log-paper:

Semi-log-paper: