HWR 431 / 531
HYDROGEOLOGY LAB SECTION

LABORATORY 3

GROUNDWATER MODELLING

Introduction:
Several methods exist for solving groundwater flow problems. For simple geometries analytical solutions suffice. Complex problems may be difficult to solve analytically and so other methods are needed. Graphical solutions and analog models have been used extensively for a wide variety of problems, including those that involve heterogeneity and the vadose zone. The development of fast computers has allowed numerical models to become the most common method of solving groundwater flow problems. In this laboratory, you will explore and evaluate these different methods of solving groundwater flow problems.

Background:

A) Analytical Solutions:

An analytical solution is one that may be derived from the principles of groundwater flow. Consider the following diagram adapted from Freeze & Cherry (1979; Fig.2.25):

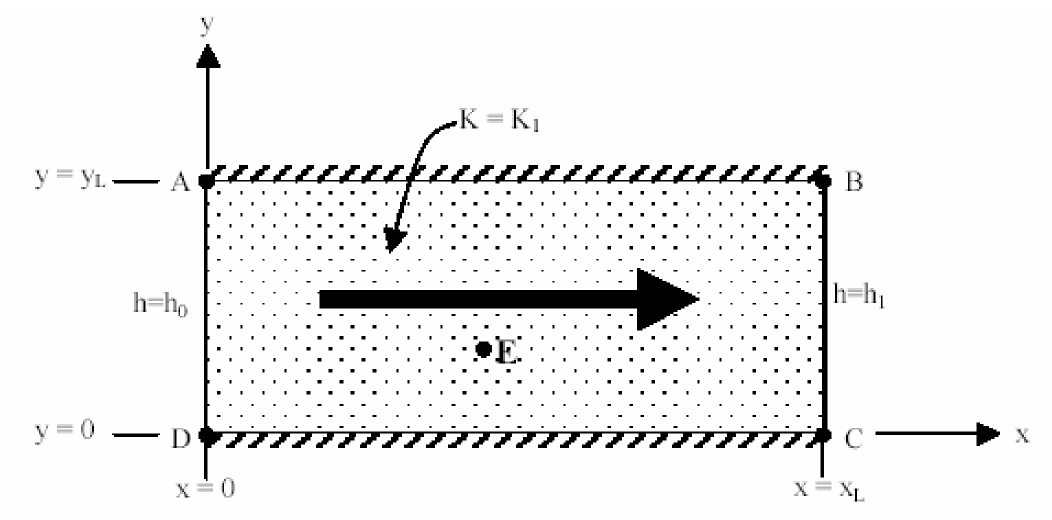


Figure 1 – A simple flow system. AD & BC are constant head boundaries and AB & DC are impermeable boundaries.

The physical setup of the system (i.e. geometry, hydraulic conductivity and location of prescribed head boundaries) is the defining characteristics of the flow domain. The following analytical solution for steady state flow defines the head at any point, E, within the domain (see Appendix 3, Freeze & Cherry, 1979):

$$h(x) = h_o - (h_o - h_1)\frac{x}{x_L}$$

It is evident that this solution is unique only if the heads at the boundaries, ho & h1, are known. If the boundary conditions are changed, the heads within the flow system will change accordingly.

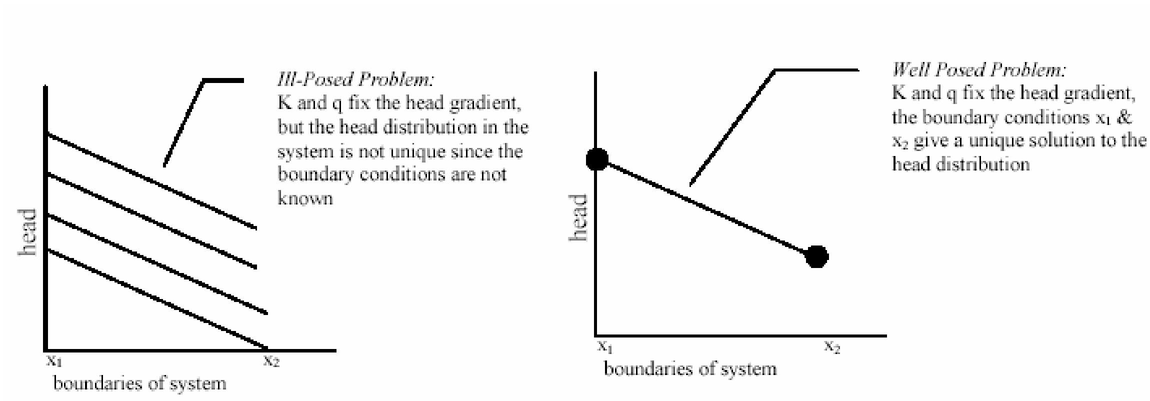


Figure 2 – The absolute value of head cannot be determined in a groundwater system unless the problem is well posed

B) Graphical Solutions: *(see Ch. 5 of Freeze & Cherry, 1979)*

The graphical representation of the head (i.e. equipotential lines) and flow direction (i.e. flowlines) is called a *flow net*. Groundwater flow problems may be solved quickly and easily (with practice) by sketching flow nets. Although they do not always offer the precision of other methods, flow nets do provide the opportunity to gain insight into complex systems with relatively little effort and are thus excellent conceptual tools for preliminary work.

Several ***assumptions*** underlie flow net construction:

1) Two dimensional flow. This implies no recharge or discharge perpendicular to the plan of the flow net.
2) Isotropic medium. Hydraulic properties (e.g. hydraulic conductivity) are independent of the direction of measurement.
3) Steady-state flow. At a point, velocity of flow does not vary in magnitude or direction.
4) Fixed physical characteristics of fluids. This implies constant temperature and density of the water.
5) Single phase flow.
6) Flow obeys Darcy's Law.

NOTE: Some of the above assumptions are necessary only for simple types of flow nets. Special techniques can be used to adjust for anisotropy, 3-D flow, etc.

If these assumptions are met, the following ***rules*** should be followed to sketch the flow net:

1) All flowlines are perpendicular to equipotential lines.
2) Impermeable boundaries are flow lines.
3) Flowlines terminate perpendicular to constant head boundaries.
4) Flowlines do not intersect except at stagnation points and singular points (eg. wells).
5) Equipotential lines do not close except around sinks and sources.
6) Equipotential surfaces refract into horizontal surfaces at the water table.
7) No two equipotential lines can intersect.
8) No equipotential lines can terminate except upon a boundary of the field of flow.
9) All squares must be curvilinear. (A circle will be tangent to all 4 sides.)
10) Partial stream tubes are acceptable near boundaries.

Given these rules, we can construct a flow net for the system in Figure 1. If all of the above rules are to apply, we can immediately see that the flow net must consist of straight equipotential and flowlines (Fig.3).

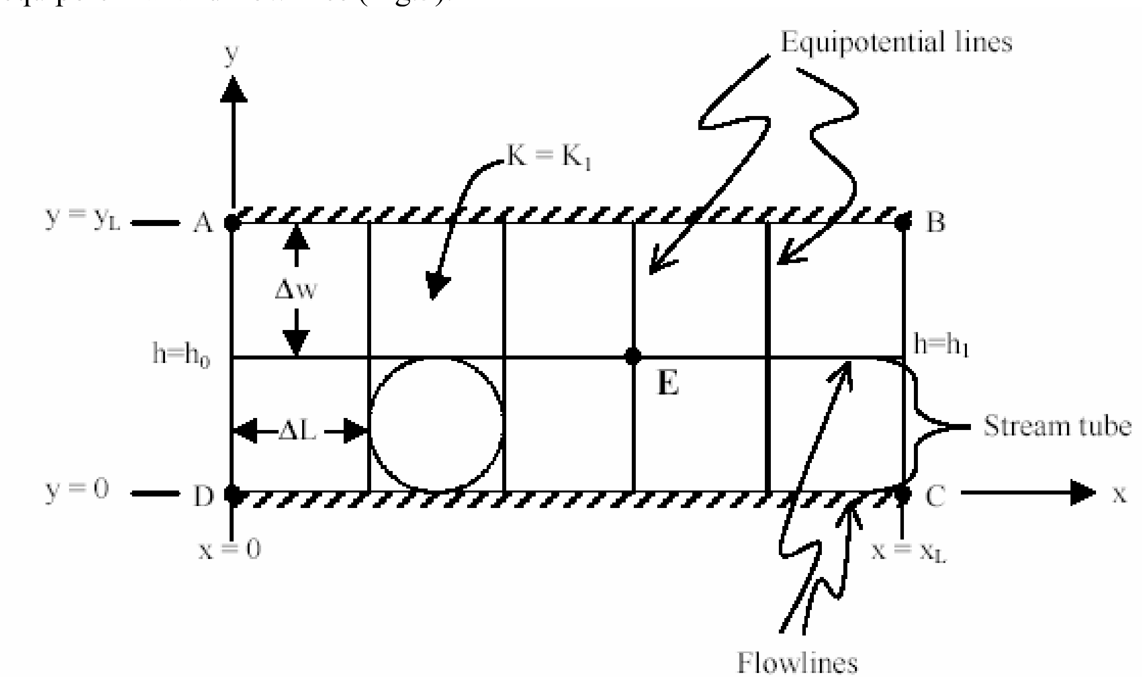


Figure 3 – Flow net for a simple flow system. Notice that all squares formed by equipotential and flowlines are curvilinear. (AD & BC are constant head boundaries and AB & DC are impermeable boundaries.)

Flow nets can be used to perform some simple calculations. If the flow net is constructed with equal head drops between equipotential lines, Darcy's law can be expressed as:

$$Q = nKb\Delta w \frac{\Delta h}{\Delta L}$$

Where:
Q = total discharge [L^3]
n = number of stream tubes (i.e. area between two adjacent flowlines)
K = hydraulic conductivity [LT^{-1}]
b = thickness perpendicular to flow net (i.e. into the page) [L]
Δw= width of stream tube [L]
Δh= head drop between equipotential lines [L]
ΔL= distance between head drops [L]

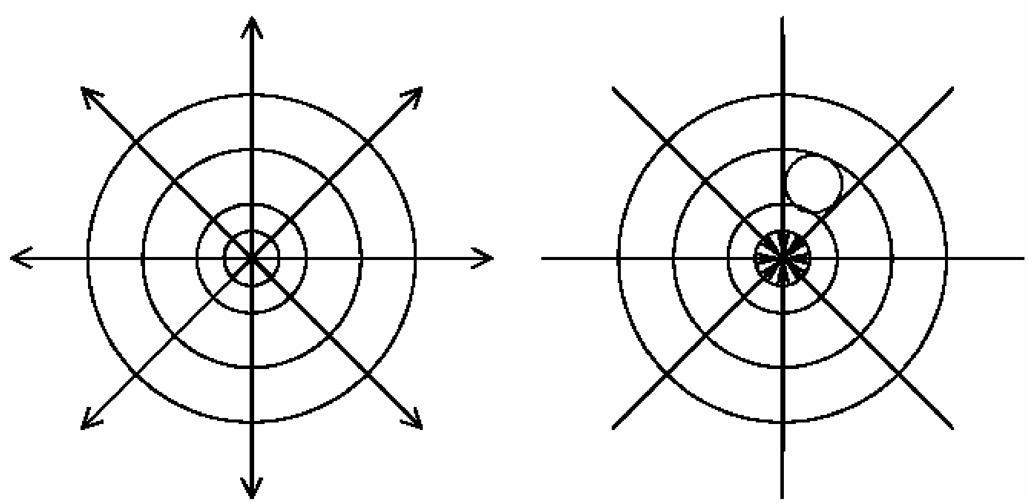
If the flow net is constructed such that Δw=ΔL (i.e. curvilinear) and recalling that Kb=T (*transmissivity*), then the equation simply becomes:

$$Q = nT\Delta h$$

Travel time can be estimated along a stream tube by the following equation:

$$\text{travel time} = \sum_0^i \Delta t = \frac{n_o}{K\Delta h}\sum_0^i (\Delta L)^2$$

Where ΣΔt is the sum of individual travel times across each distance, ΔL in the flow net and n_o is the effective porosity. To obtain the best estimate of total travel time, each Δt should be calculated individually along the flow path.



Zone of recharge (i.e. injection well)

Zone of pumping

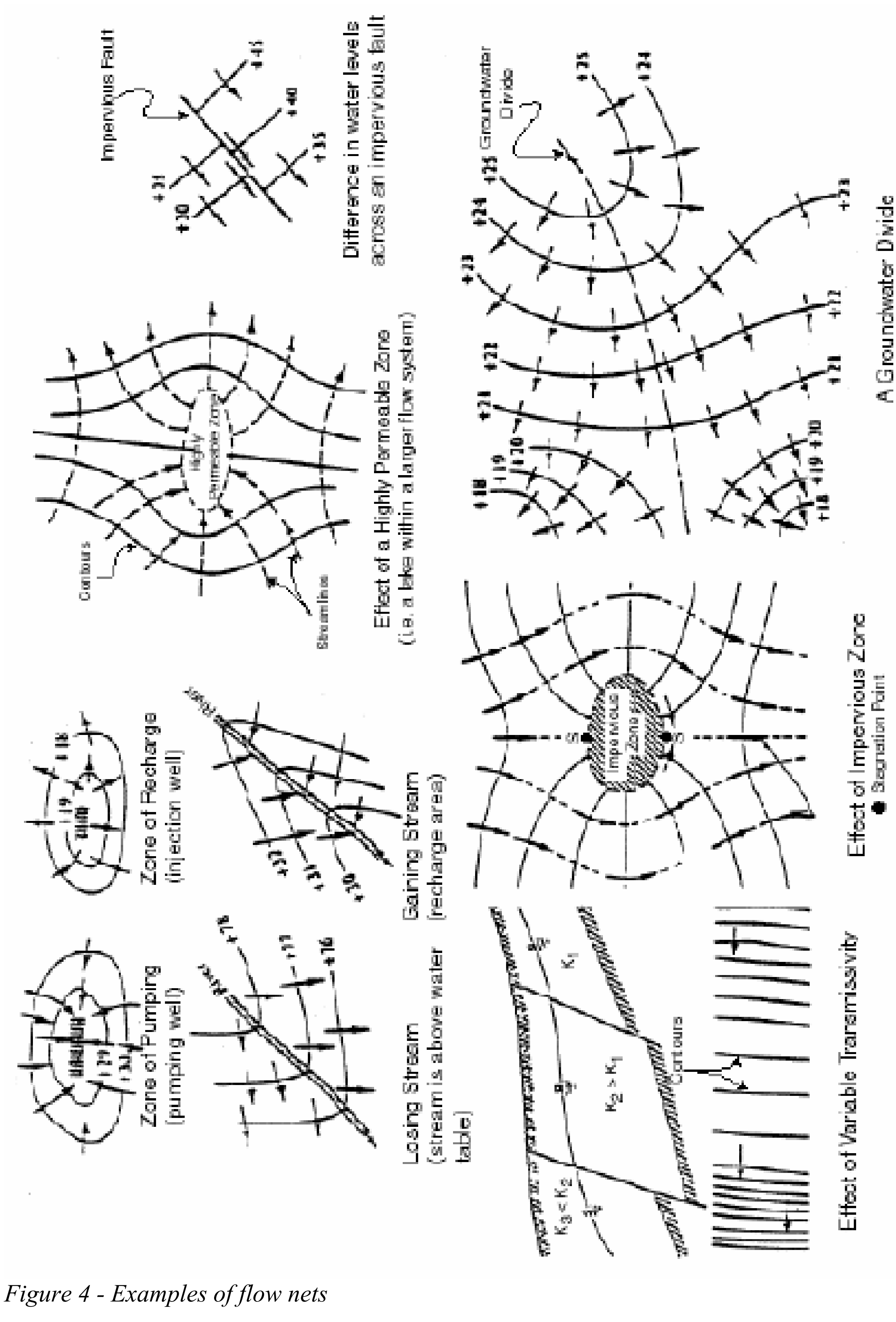


Figure 4 - Examples of flow nets

C) Electrical Analog Models:

Before the advent of computer simulation, a very common tool for predicting groundwater movement was the use of electrical analog models. Under steady state conditions the two dimensional movement of groundwater, electricity and heat are governed by Laplace's equation:

$$\frac{\partial^2 G}{\partial x^2} + \frac{\partial^2 G}{\partial y^2} = 0$$

Where: x,y represent the primary coordinate axis, G represents the quantity of interest (ex. head, voltage or temperature)

Using conductive-paper one may create an electrical system that has an analogous response to boundary conditions as an aquifer.

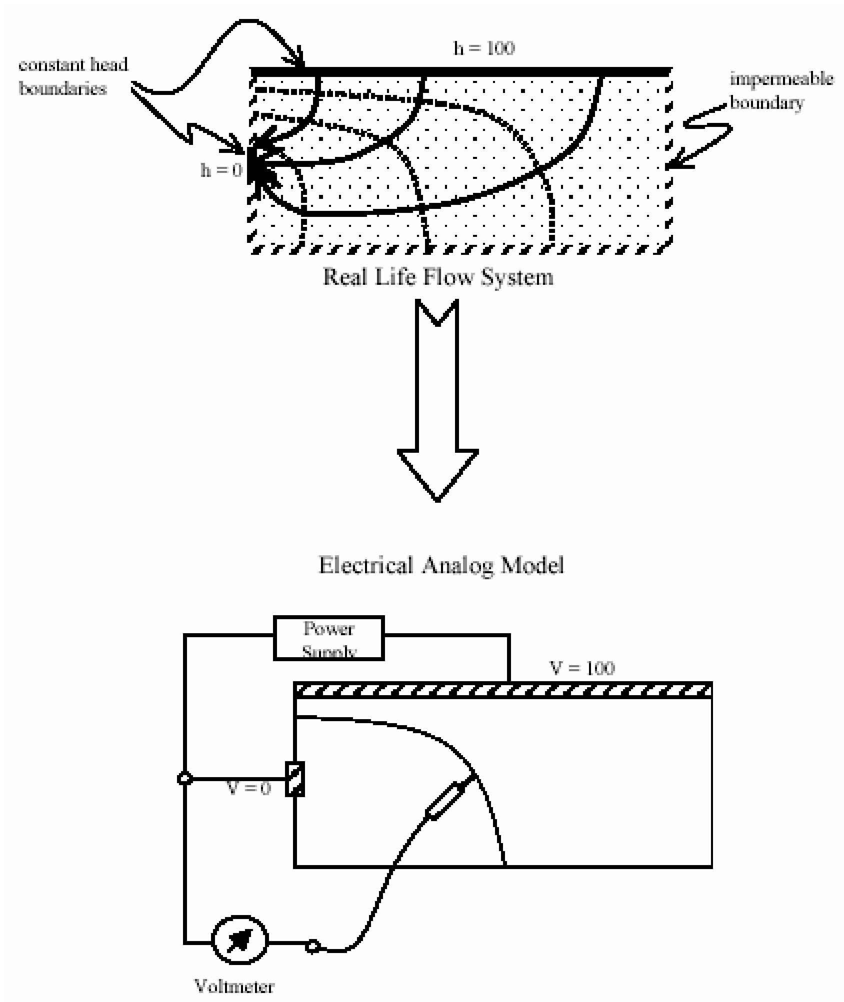


Figure 5 – Electrical Analog Simulation (after Freeze & Cherry, 1979)

Given this electrical model, the following properties are analogous:

Head (h) ~ voltage (V)
Flux (q) ~ current density (I)
Hydraulic conductivity (K) ~ specific electrical conductivity (σ)

The conductive paper can be cut to represent the shape of any two dimensional basin. The hydrologic properties of the basin are controlled by the properties of the paper; areas here the hydraulic conductivity is high can be represented in the model by conductive paint. Lining edges with conductive paint (and/or a wire) connected to a power source of a given voltage simulates prescribed head boundaries. The head at any point in the basin can be read directly using a voltmeter. Any two-dimensional basin subject to steady state flow can quickly and accurately be modeled using this method, making it is a powerful tool.

D) Numerical Models:

Numerical models of groundwater flow can be used to solve complex groundwater flow problems such as those that have irregular boundaries or complicated geological configurations. These models are based on the discretization of the flow field into a grid. At each intersection of gridlines exists a node. Equations such as Darcy's Law can be applied between each of the nodes to calculate unknown head values. Sections 5.3 & 8.7 in Freeze and Cherry (1979) provide a good introduction to this procedure.

These sections are required reading for this exercise.

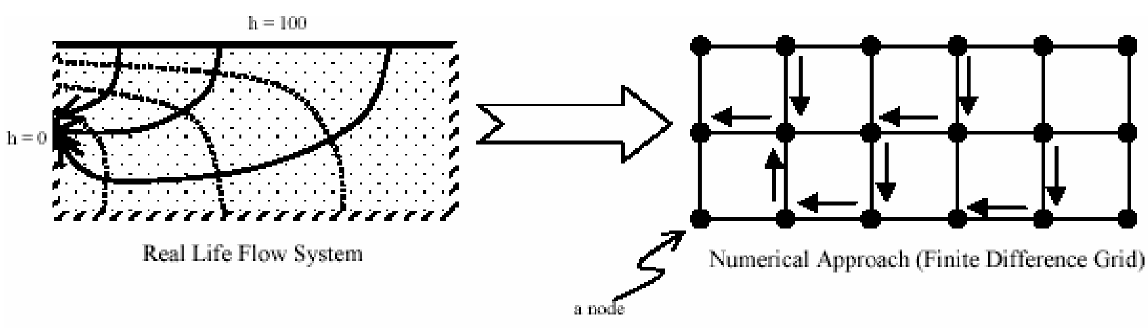


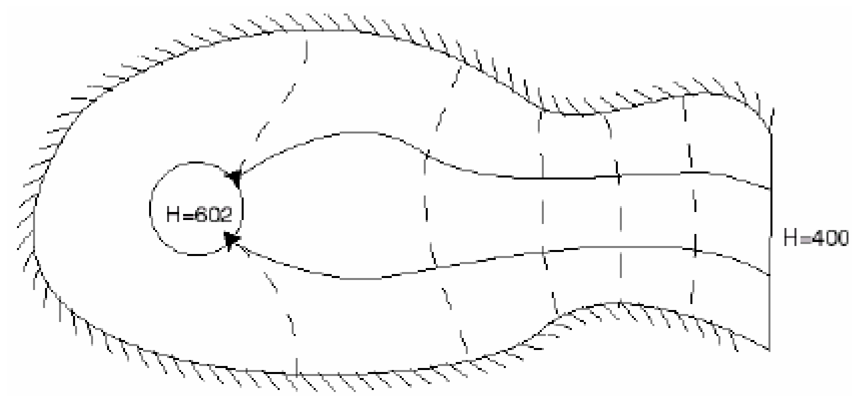
Figure 6 – Transformation of Flow System into a Grid for Numerical Simulation

Laboratory Assignment:
This lab is divided into two weeks. The first week will focus on flow nets. The second week will take place in the computer lab where you will design and run several flow models using GW Vistas.

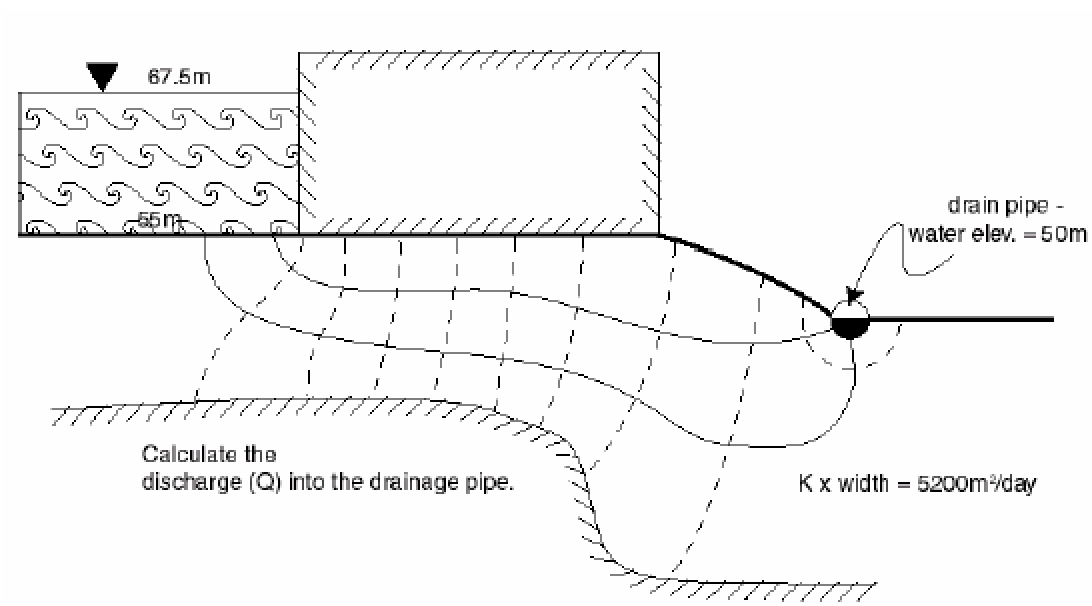
Week 1 – Flow Nets

There are nine questions for you to answer on the following pages. These should help you to understand the basic concepts behind the construction of flow nets. Lab time is allotted for you to begin this assignment but it should be completed at home. This activity must be completed during the lab period.

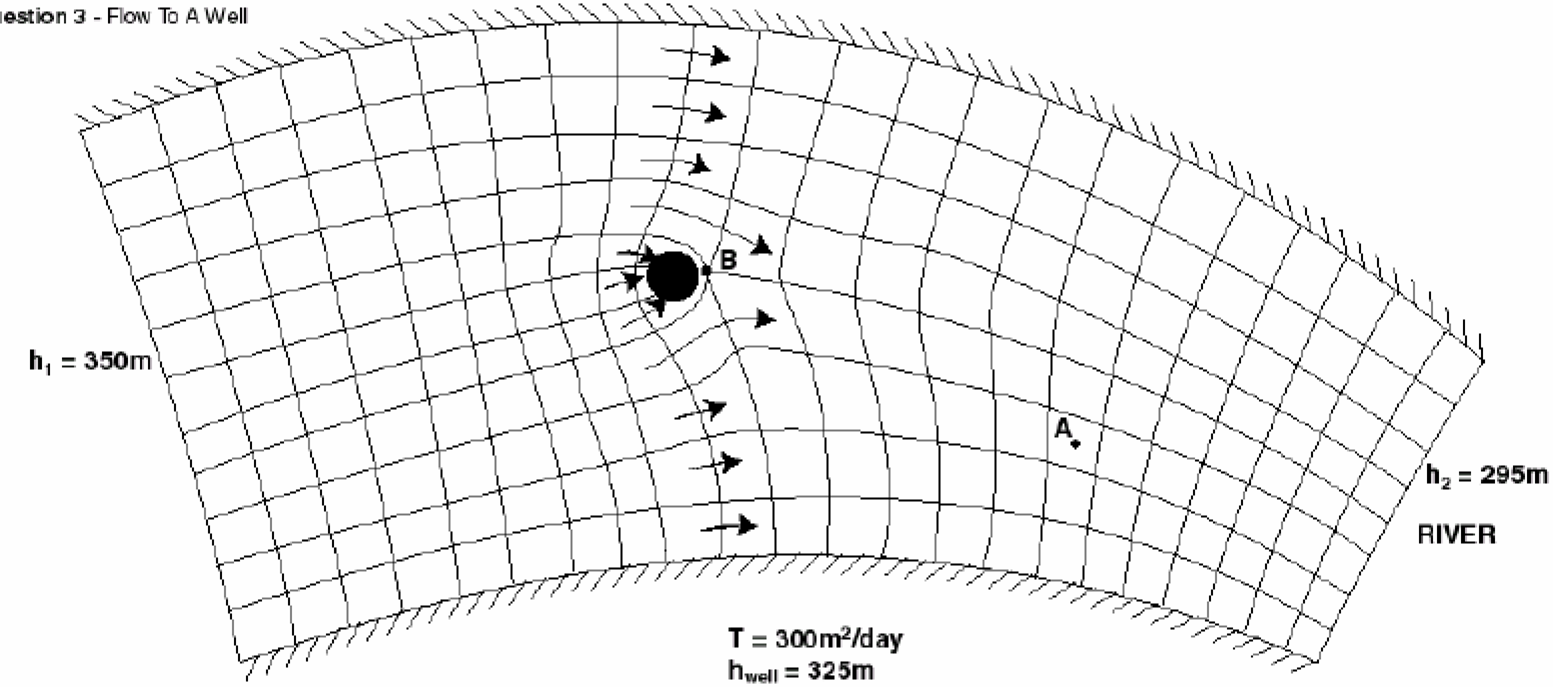
Q1) What is wrong with this picture? Circle and name at least 5 different things wrong with this flow net.



Q2)



Question 3 - Flow To A Well

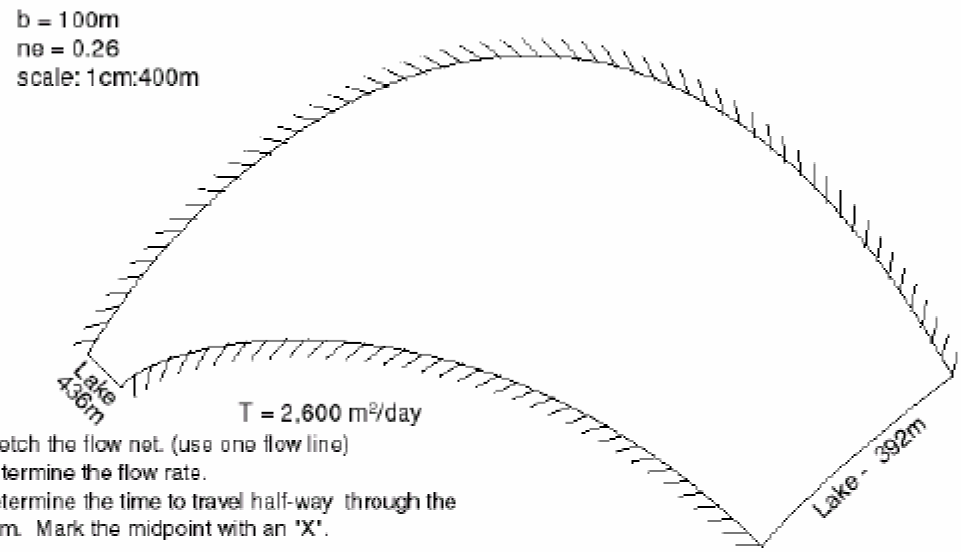


A. Calculate the flow to the well in m^3/day.

B. Calculate the flow to the river in m^3/day.

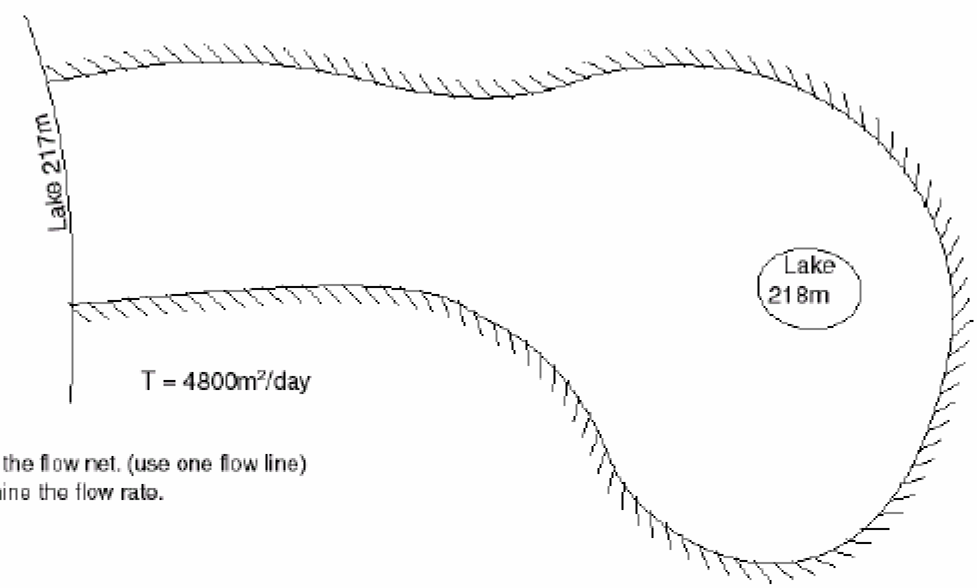
C. Find the head at point A.

Question 4



A. Sketch the flow net. (use one flow line)
B. Determine the flow rate.
C. Determine the time to travel half-way through the system. Mark the midpoint with an 'X'.

Question 5

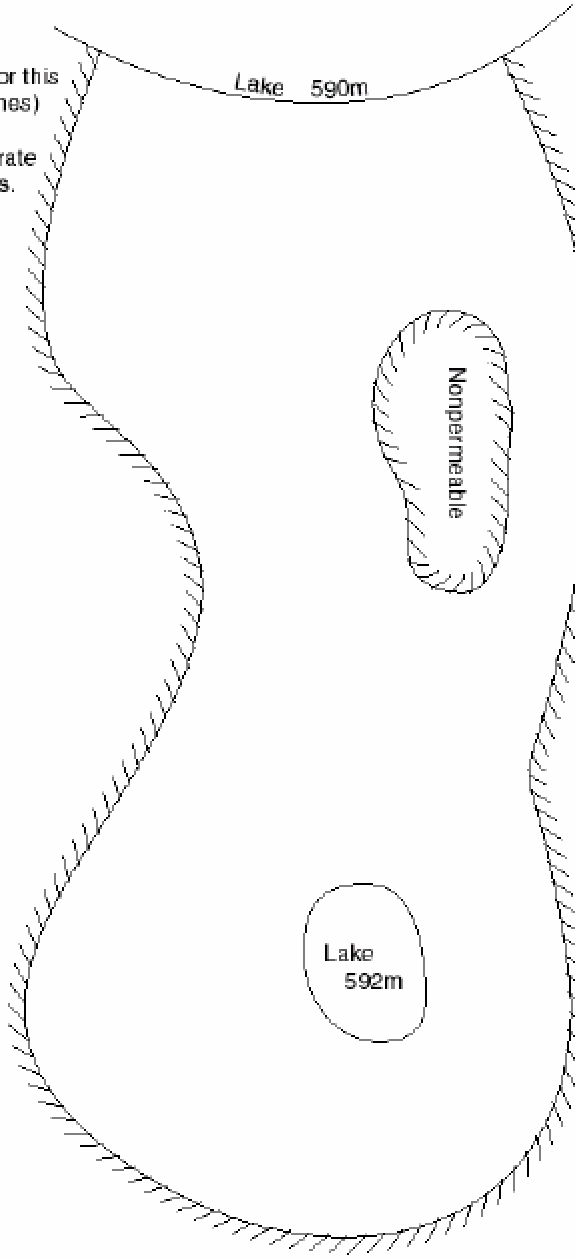


A. Sketch the flow net. (use one flow line)
B. Determine the flow rate.

Question 6

A. Sketch a flow net for this system. (use 2 flow lines)

B. Calculate the flow rate between the two lakes.

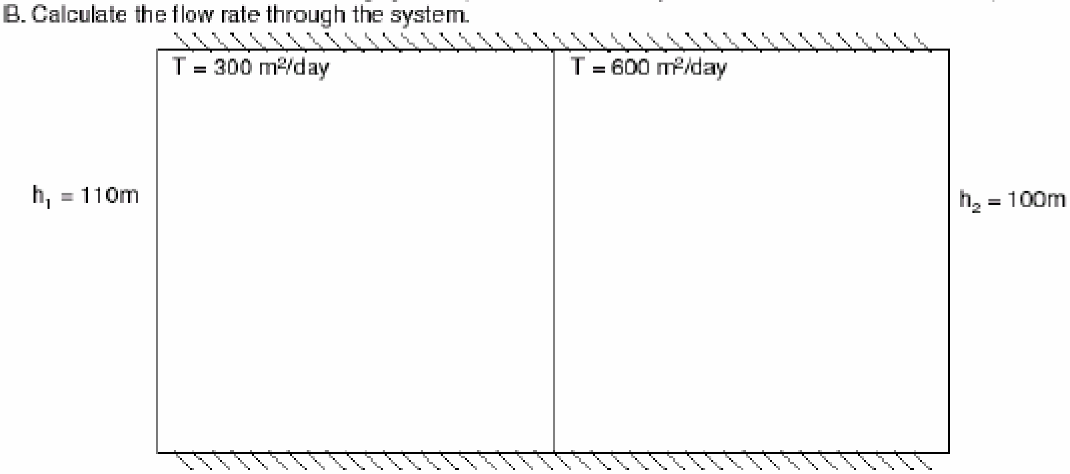


$T = 6300 m^2/day$

Question 7

A. Sketch a flow net for the following system (use 1 flow line/keep Q the same for both flow tubes)

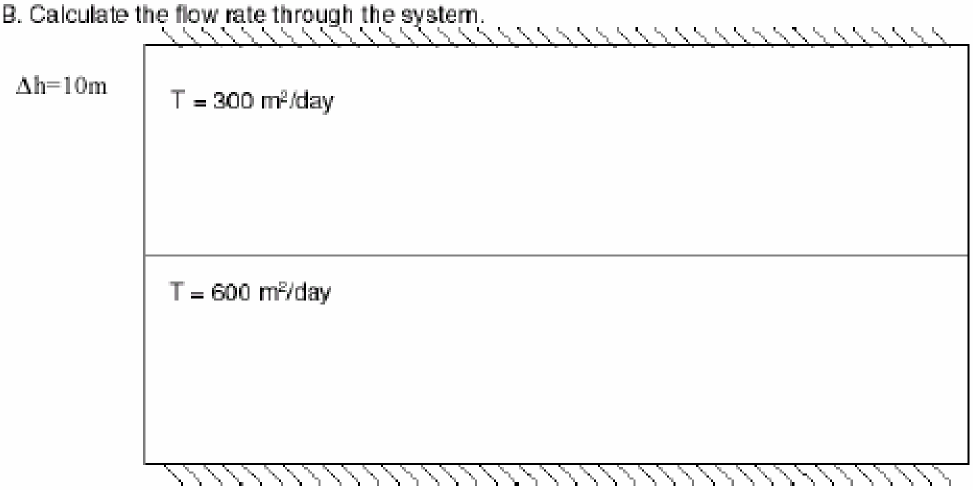
B. Calculate the flow rate through the system.



Question 8

A. Sketch a flow net for the following system (use 2 flow line/keep Q the same for all flow tubes)

B. Calculate the flow rate through the system.

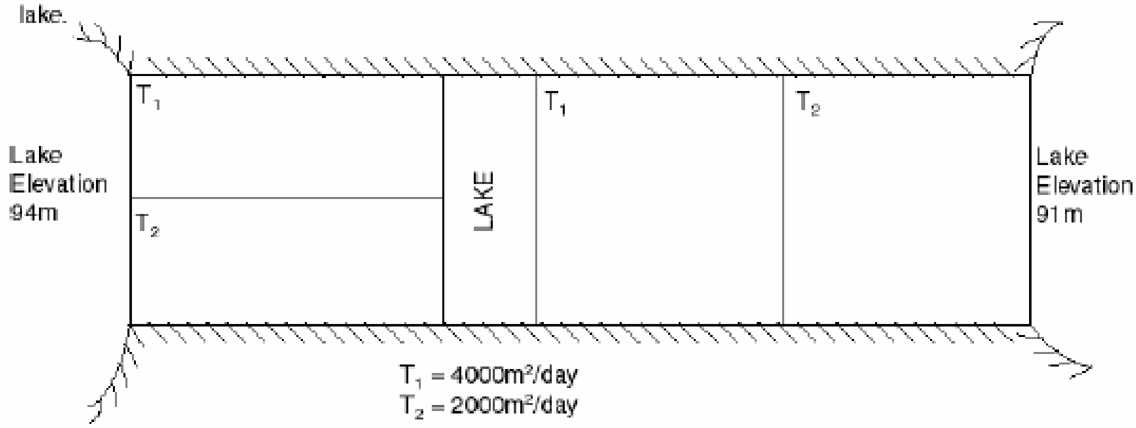


Question 9:

A. Construct a flow net for the following diagram.

B. Calculate the discharge from one lake to the other.

C. Determine the elevation of the water surface in the small rectangular lake.



Week 2 – Groundwater Flow modeling with GW VISTAS

This week's lab will be in the computer lab (HWR Room # 110). If you don't have an account to use the lab, please ask TA or James Broermann (james@hwr.arizona.edu) at HWR Room # 324H.

For this assignment, you will prepare and run groundwater flow models for systems which you prepared flownets last week and more complicated real life problems.

The program you will be using is "Groundwater Vistas" which is one of several commercially available interfaces which make easier to prepare MODFLOW input files and to display MODFLOW outputs. MODFLOW is the program that performs the actual flow calculations.

You can download student version of Groundwater Vistas from www.groundwater-vistas.com . This is a demo version. It allows only up to 50 x 50 grid size

Before Programming

1. Login to your accounts
2. Go to directory X:\. (This is the directory that you should save all your files. Otherwise you can not reach your files from other computers)
3. Go to X:\ My Documents and create a new folder named "hwr431"
4. Copy the entire disk which is given by TA to your class folder. These are the maps that you will need for problems
4. If you don't have a shortcut for GW Vistas (GWV) on your desktop or in start menu>All Programs, then go to C:\gwv4 and make a shortcut to your class folder
5. Click the shortcut to start the program

Problem 1: *Prepare a MODFLOW model for Question 5 from last week. Print out your final map and shortly discuss how your flownet drawings from last week and model results from this assignment are similar and/or different. Discuss your findings.*

1. Open Groundwater Vistas
2. Go to File>New
3. Choose followings in the "Initialize Model Grid" window
    - Number of rows = 30
    - Number of columns = 50
    - Model Bottom Elevation = 215
    - Model Top Elevation = 220
    - Don't change other parameters
    - Click OK.
4. Now you will see the grid 30x50
5. Go to File>Map>GW Vistas
6. Browse the "Sitemaps" folder on your class folder and chose *Problem1.map*
7. Now you see the outlines of the problem 5 from last week.
8. Click "View Full Grid" button on the toolbars to see the complete map
9. Go to Props>Set Value or Zone>Window
10. Draw a complete window on the grids from upper left corner to lower right corner
11. Click OK on the Window parameters
12. Set zone number as 1 and click OK

13. Go to Props>Property Values>Database
14. Make number of zones 1 and click update. Change Hydraulic properties of Zone 1 to 48. We know that T=4800 m^2/day for this problem and assume the aquifer is isotropic and the thickness of the aquifer is 100 m. Thus, K_x=K_y=K_z=48 Then, Click OK

Define the No flow boundaries

15. Go to BCs>No Flow (make sure you have √ sign)
16. Click "Digitize Polygon" button on the toolbars and draw a polygon outside of the aquifer area. When you finish drawing, double click to stop. Another way to assign BCs is clicking right button of your mouse for each cell.
17. Do not fill the cells on the left hand side of the model where the constant head boundary will be
18. You will now see the no flow areas are black.

Set the constant head boundaries

19. Go to BCs>Constant Head/Conc.
20. Click "Digitize Polygon" button on the toolbars and draw a polygon on the outline of the lake area. When you finish drawing, double click to stop.
21. On window of "Constant Value Boundary Condition", make head boundary 218 which is the head at the lake.
22. If you still have missing squares around the lake, right click the mouse, and assign 218 head value.
23. Go to BCs>Constant Head/Conc.
24. Click "Digitize Polygon" button on the toolbars and draw a polygon on the left side where the other lake is. Make the head boundary 217. You can change the color of this BC if you wish. Click OK
25. Now it is a good time to save your work. Save the file to your class folder.

Run your model

26. Before running your model, make sure that your working directory is your class folder. Go to Model>Paths to Models and change the working directory to your class folder. Check the box below the browse line to make this directory default and click OK
27. To run the model, click on the "Recalculate" button that look like a calculator on the toolbar.
28. Click yes for "Create Data files first?"
29. Click no for "Display Error/Warning File?"
30. Click yes for "MODFLOWwin32 is finished! Processes the results? "
31. In the "Import Model Results" window, check the box for Cell-by-Cell Flow on the right side. Click OK
32. Now, you will be able to see the isochrones and if you draw your mouse on the map, you will see the changing head values on the lower bar
33. Go to Plot>What to Display
34. Check the box for "Display Velocity Vectors" and print the model includes head distributions and the flow vectors for your assignment
35. Play with the "What to Display" window to see different display options.
36. Go to Plot>Contour>Parameters (Plan) and change counter interval to 0.01 to see the head distribution around the lake
37. To see the cross sectional view of the model in any row or column, go to XSect>Selection and change the row number/column number which you would like to see.

Problem 2: *Prepare a MODFLOW model for Question 7 and 8 from last week. Print out your final maps and shortly discuss how your flownet drawings from last week and model results from this assignment are similar and/or different. Discuss your findings.*

Follow the same direction from above. However,

- Don't import any map. Instead make grid of 6x14 for question 7 and 8.
- Your bottom elevation should be lower than your minimum head and top elevation should be higher than your maximum head.
- For question 7:
    - Assign zone 1 for the left half (Column 1 through 7) of the grids and zone 2 for the right half (Column 8 through 14) of the grids
    - Assume the thickness of the aquifer is 1. Thus, for zone 1 K_x=K_y=K_z=300, for zone 2 K_x=K_y=K_z=600 (Look at steps 9 to 14 above)
- For question 8:
    - Assign zone 1 for the upper half (Row 1 through 3) of the grids and zone 2 for the lower half (Row 4 through 6) of the grids
    - Assume the thickness of the aquifer is 1. Thus, for zone 1 K_x=K_y=K_z=300, for zone 2 K_x=K_y=K_z=600 (Look at steps 9 to 14 above)

Look at different display options and try to see that flow velocities and head distributions are different in different zones.

Bonus Problem: *Prepare a MODFLOW model for Question 9 from last week. Just print out your final map.*

Hint: For the lake in the middle, go to BC>lake and set the "maximum stage value" 93

Problem 3:

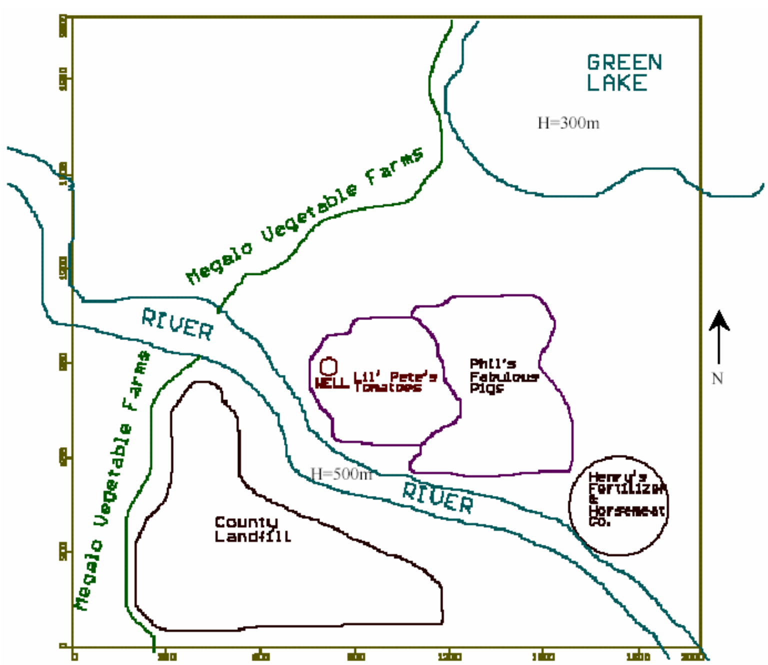
Trouble is a brewin' in the valley. Lil' Pete is darn tooting mad 'cause he thinks his well water is being contaminated by Phil's-not-so-fabulous pigs. He is getting ready to sue Phil to cover the losses he faced on last year's bumper crop of mutant tomatoes and he wants to get the facts right before he hires Johnnie Cochran and turns this thing into a national scandal. He hires you to model the groundwater hydrology of the basin to corroborate his theory. Don't forget the other characters in this story. Could the culprit really be Megalo Vegetable Farms (you've heard that they are not organic farmers as they claim)? Maybe it is dear sweet Henry and his Fertilizer & Horsemeat Co. (you've heard that he dumps assorted horse parts and effluent into the river)! Perhaps it is a government conspiracy perpetrated by the County Landfill?

You should prepare a one page report on your findings. Discuss your decisions for preparing the model the way you did and outline your findings with regards to responsibility for the contamination.

You have the following information:

- Make a 50x50 grid by 450x450 uniform spacing
- Dimension of your model is 2km x 2km. So, each cell represents 40m x 40m

- The river runs west to east
- The head in the Green Lake is 300m
- The head in the river is 500m
- The head in the south-west corner of the grid is 250m
- The basin has a uniform transmissivity of 200m^2/day. Assume unit thickness. So, K=200m/day
- The boundaries of the basin where head is not yet specified should be constant head boundaries which change in a linear fashion between known boundaries. Use the polyline tool on the toolbar. First give a beginning head and then ending head. Computer will linearly assign heads on the line.



Problem 4:

Farmer Buck wants to install a new pump to aid in the irrigation of his crop of… (Well, we couldn't tell you that or Farmer Buck would be in a lot of trouble!). Buck's neighbor Willie doesn’t want the new well to interfere with his own well's production. Willie has said that he doesn't care how much Buck pumps as long it doesn't draw down the existing well by more than 0.5m. It is up to you to maximize Buck's pumping rate without making Willie go dry.

Write a one page report that describes how you set up your model and discusses your results. Attach your final maps before and after pumping.

Hint: Make sure you establish the equilibrium baseline flow before you turn on Buck's well!

You have the following information about the area:

- Make a 50x50 grid by 2000x2000 uniform spacing
- Dimension of your model is 2km x 2km. So, each cell represents 40m x 40m

- There are 3 constant head boundaries and 3 impermeable boundaries on the sides of the model
- The basin is heterogeneous with 5 different units - each unit is homogenous and isotropic inside