GEGN583/483
Groundwater modeling
Eileen Poeter
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go to
inside.mines.edu/~epoeter/583CSM

click on Syllabus – download and open
under January 12 click on Introduction-ConceptualModel-BC.pdf
– download and open

If you do not have a login – please ask me for help

ALL GROUND-WATER HYDROLOGY WORK IS MODELING

A Model is a representation of a system. Modeling begins when one formulates a concept of a hydrologic system, continues with application of, for example, Darcy's Law or the Theis equation to the problem, and may culminate in a complex numerical simulation.

All models are wrong, but some are useful. - George Box

MODELS can be used BENEFICIALLY and for DECEPTION

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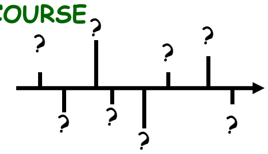
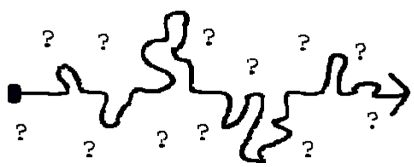
SHORT COURSE



It would be nice, but there is no MODFLOW knowledge "pill". Learning MODFLOW takes lots of time, patience and persistence. We only scratch the surface in a short course.

LONG COURSE



A semester course gets us a little deeper, but every new model is a puzzle even after 30 years of modeling. Experience helps you identify the problems faster and find creative solutions quickly.

LIFE The ultimate long course!

Our goal for the semester is to prepare you to continue to learn on your own, that is, to arm you with the concepts you will need to puzzle things out in your own projects.

Goal: to be able to use any viable groundwater modeling software manual to set up a simulation, calibrate the model and make predictions

Visit the class web site each week http://inside.mines.edu/~epoeter/583CSM
non-class related support material http://inside.mines.edu/~epoeter/583

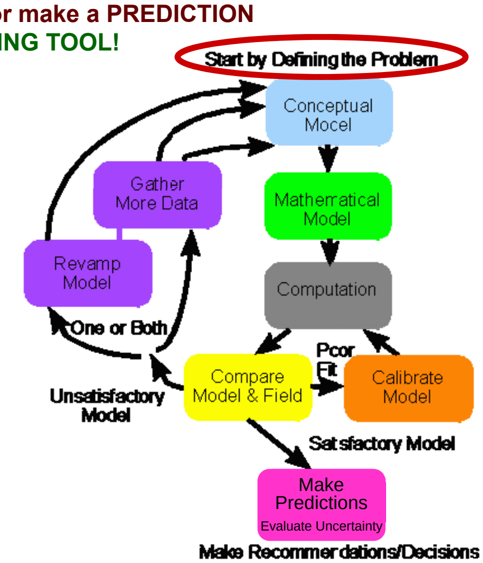
Format:
- **Each student chooses a modeling project for the semester**
- **Sessions start with a lecture followed by work sessions**
- **Assignments lead you through the modeling process phase by phase**
- **On average, plan approximately 6 hours per week outside of class**
- **Start each study session by reviewing this document, syllabus and web page to recall:**
  1) **what topic to study**
  2) **what is due next week**
  3) **submission directions for each assignment (rejected if not met)**
- **Meet all submission deadlines with the best product you can provide. You will be allowed to resubmit one week after I return the assignment to improve your grade based on my comments. If you want the grade reconsidered, you must submit** 1) the paper that I marked up
  2) your revised paper and associated computer files

Assignments:

Assignment #1 Conceptual Model
Assignment #2 Finite Difference Calculation & Grid
Assignment #3 Analytical Model
Assignment #4 Finite Difference Spreadsheet
Assignment # 5 Steady State Numerical Models
Assignment # 6 Model Calibration
Assignment # 7 Transient Modeling
Assignment # 8 Analytical Transport Modeling
Assignment # 9 Numerical Transport Modeling
Assignment # 10 Final Presentation

Review the description in the syllabus as you start each. Use the outlines provided for guidance on your submission

WHY MODEL?
SOLVE a PROBLEM or make a PREDICTION
A Model is a A THINKING TOOL!



ALL IMPORTANT MECHANISMS & PROCESSES MUST BE INCLUDED IN THE MODEL, OR RESULTS WILL BE INVALID. KEEP AN OPEN MIND !

Ground Water Models impose boundary conditions and solve the governing equation of Ground Water Flow:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W=S_s \frac{\partial h}{\partial t}$$

Geometry

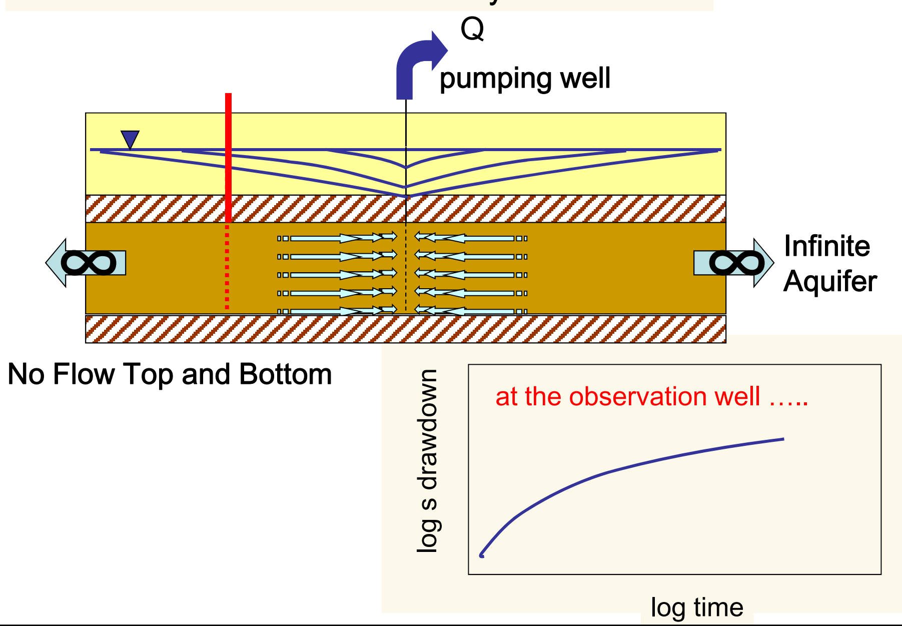
Material Properties (K, S, T, Φ_e, D, R, etc)

Boundary Conditions (Head, Flux, Concentration etc)

Stresses (changing boundary conditions)

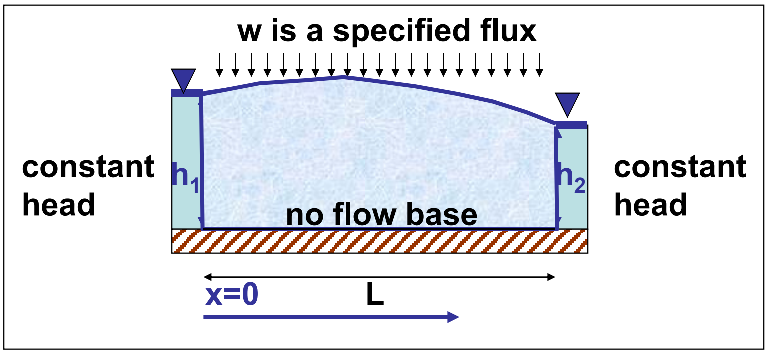
EXAMPLE CONCEPTUAL MODEL:

1D flow to a well with Theis Boundary Conditions



EXAMPLE CONCEPTUAL MODEL:

1D Unconfined flow with recharge and constant heads



$$h_x = \sqrt{h_1^2 - \frac{(h_1^2 - h_2^2)x}{L} + \frac{w}{K}(L-x)x} \quad \mathbf{d} = \frac{\mathbf{L}}{\mathbf{2}} - \frac{\mathbf{K}}{\mathbf{w}} \frac{\mathbf{h}_1^2 - \mathbf{h}_2^2}{\mathbf{2L}}$$

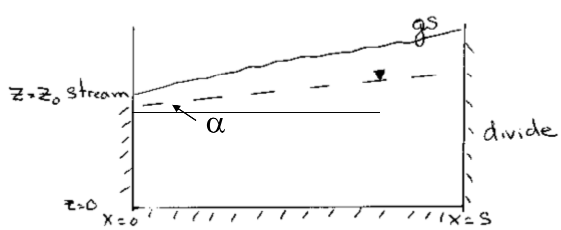
$$\mathbf{q_x} = \frac{\mathbf{K}(\mathbf{h}_1^2 - \mathbf{h}_2^2)}{\mathbf{2L}} - \mathbf{w}\left(\frac{\mathbf{L}}{\mathbf{2}} - \mathbf{x}\right)$$

EXAMPLE CONCEPTUAL MODEL:

2D flow from a divide to a stream

Toth solved the Laplace Equation

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2} = 0$$



boundaries

left $\frac{\partial \mathbf{h}}{\partial \mathbf{x}}(\mathbf{0}, \mathbf{z}) = \mathbf{0}$ **right** $\frac{\partial \mathbf{h}}{\partial \mathbf{x}}(\mathbf{s}, \mathbf{z}) = \mathbf{0}$

lower $\frac{\partial \mathbf{h}}{\partial \mathbf{z}}(\mathbf{x}, \mathbf{0}) = \mathbf{0}$

upper water table $\mathbf{h}(\mathbf{x}, \mathbf{z_o}) = \mathbf{z_o} + \mathbf{cx} = \mathbf{z_o} + \tan(\alpha)\mathbf{x}$

Toth's result:

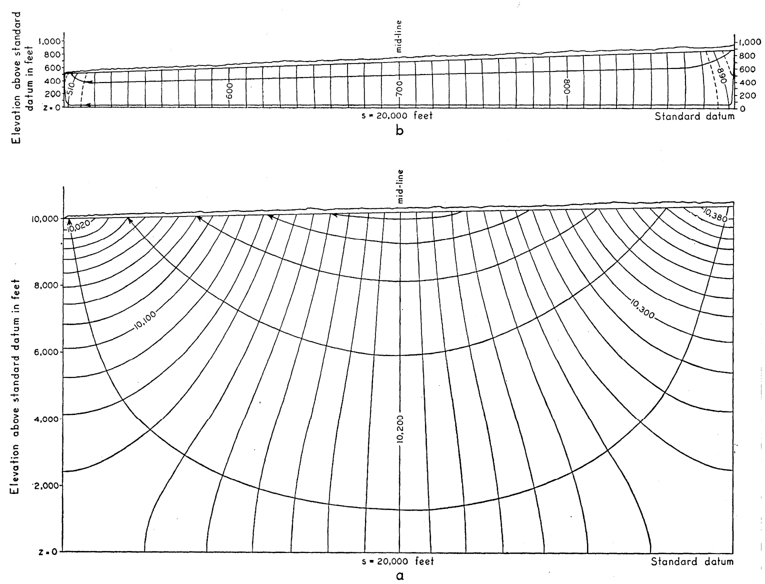
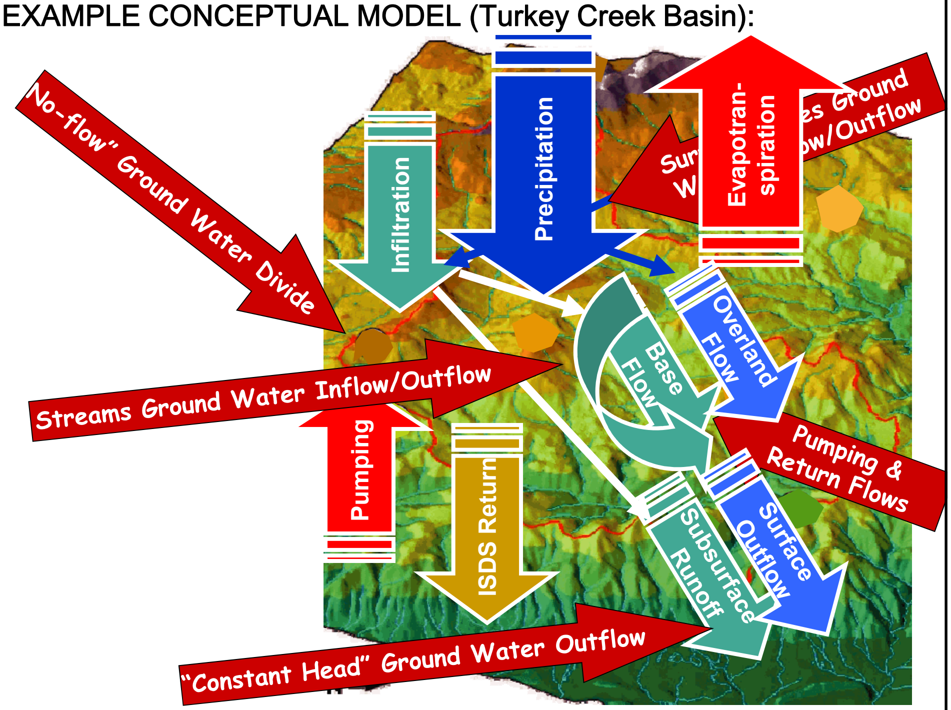


Fig. 3. Two-dimensional theoretical potential distributions and flow patterns for different depths to the horizontal impermeable boundary.

EXAMPLE CONCEPTUAL MODEL (Turkey Creek Basin):



CRITICAL STEPS IN MODELING PROCESS

* DEFINE THE PROBLEM
* CONCEPTUAL MODEL DEVELOPMENT
* DEFINING MATERIAL PROPERTIES
* DEFINING BOUNDARY CONDITIONS
* DEFINING INITIAL CONDITIONS, IF TRANSIENT
* SELECTING APPROPRIATE EQUATION / CODE
* CALIBRATION
* CHECKING IF RESULTS MAKE SENSE
* INTERPRETING RESULTS
* DEALING WITH UNCERTAINTY

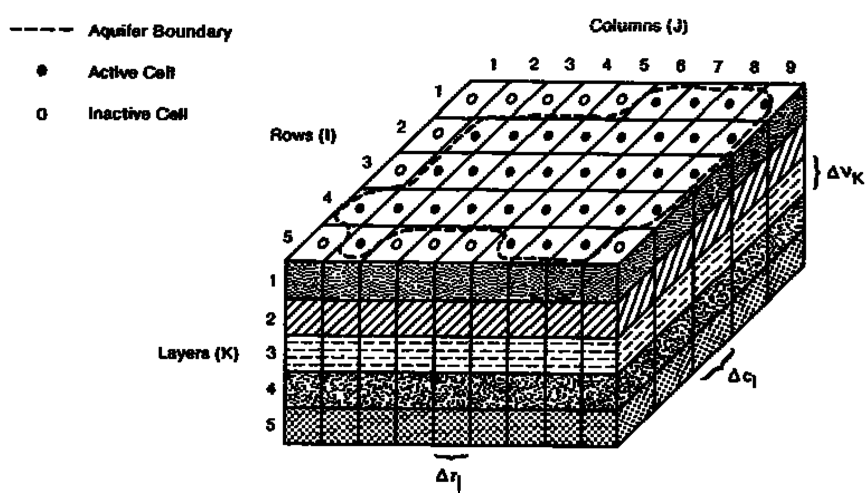
AFTER EACH STAGE OF MODELING ASK

DOES MY RESULT MAKE SENSE?
HAS MY QUESTION BEEN ANSWERED SATISFACTORILY?

IF YES, STOP! WHAT WILL MORE MODELING GAIN?
IF NO, USE RESULTS TO GUIDE FURTHER DATA COLLECTION

EXAMPLE OF A SIMPLE NUMERICAL MODEL

- Complex geologic material distributions are simplified to discrete blocks
- Numerical values define each block to represent geometry, properties, boundary conditions, initial conditions and stresses to represent a groundwater system
- Properties may vary between and within layers
- BLOCKS may be INACTIVE (e.g. open circles) NO FLOW BOUNDARIES
- BLOCKS may have SPECIFIED HEAD or SPECIFIED FLOW



BOUNDARY CONDITIONS

Boundary Types

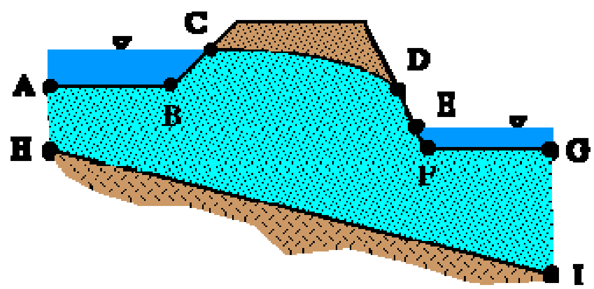
Specified Head: head is defined as a function of space and time (ABC, EFG)
Constant Head: a special case of specified head (ABC, EFG)

Specified Flux: could be recharge across (CD) or zero across (HI)
No Flow (Streamline): a special case of specified flux where the flux is zero (HI)

Head Dependent Flux: could replace (ABC, EFG)

Free Surface: water-table, phreatic surface (CD)

Seepage Face: h = z; pressure = atmospheric at the ground surface (DE)



Specified Head / Constant Head

Implication: *Supply Inexhaustible, or Drainage Unfillable*

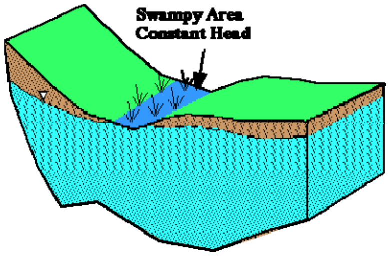
Specified Flux / No Flow

Head Dependent Flux

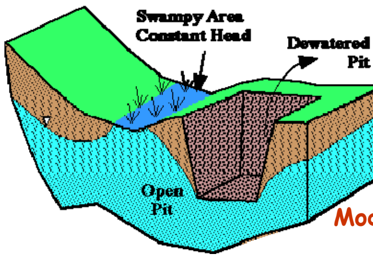
Free Surface

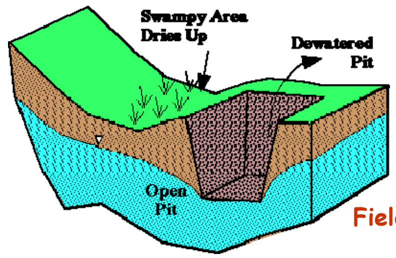
Seepage Face

Example of Potential Problems
From Misunderstanding/Misusing
a Constant Head Boundary



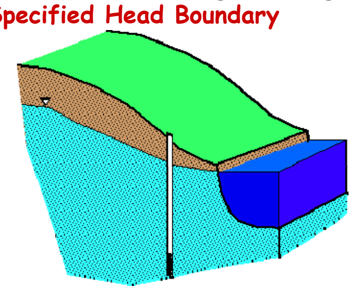
If heads are fixed at the ground surface to represent a swampy area, and an open pit mine is simulated by defining heads in the pit area, to the elevation of the pit bottom, the use of constant heads to represent the swamp will substantially overestimate in-flow to the pit. This is because the heads are inappropriately held high, while in the physical setting, the swamp would dry up and heads would decline, therefore actual in-flow would be lower. The swampy area is caused by a high water table. It is not an infinite source of water.



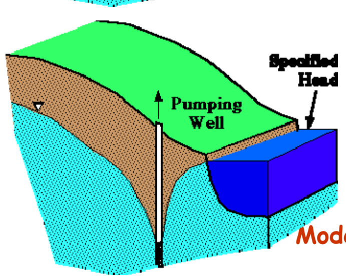


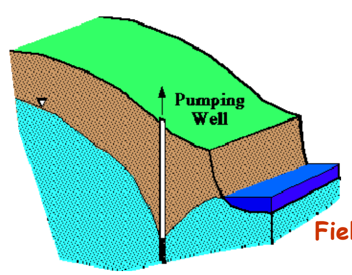
Lesson: Monitor the in-flow at constant head boundaries and make calculations to assure yourself the flow rates are reasonable.

Example of Potential Problems
From Misunderstanding/Misusing
a Specified Head Boundary



When a well is placed near a stream, and the stream is defined as a specified head, the drawdown may be underestimated, if the pumping is large enough to affect the stream stage. The specified flux boundary may supply more water than the stream carries, and drawdowns should be greater, for the given pumping rate. The stream stage, and flow rate, should decrease to reflect the impact of the pumping.





Lesson: Monitor the in-flow at specified head boundaries. Confirm that the flow is low enough relative to the stream flow, such that stream storage will not be affected.

Specified Head / Constant Head

Implication: *Supply Inexhaustible, or Drainage Unfillable*

Specified Flux / No Flow

Implication: *H will be calculated as the value required to produce a gradient to yield that flux, given a specified hydraulic conductivity (K). The resulting head may be above the ground surface in an unconfined aquifer, or below the base of the aquifer where there is a pumping well; neither of these cases are desirable.*

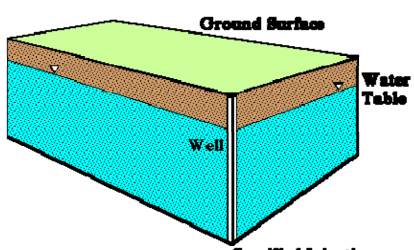
Head Dependent Flux

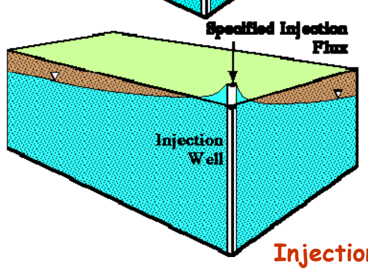
Free Surface

Seepage Face

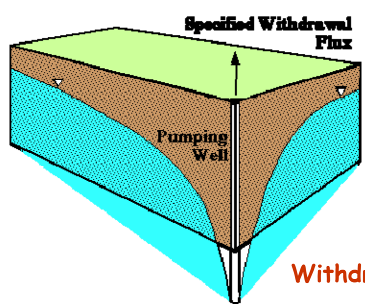
Example of Potential Problems From Misunderstanding/Misusing a Specified Flux Boundary

In a simple unconfined aquifer with one well. If the injection flux is too large, calculated heads may be above the ground surface in unconfined aquifer models. If the withdrawal flux is too large, calculated heads may fall below the bottom of the aquifer, yet the model may still yield water.





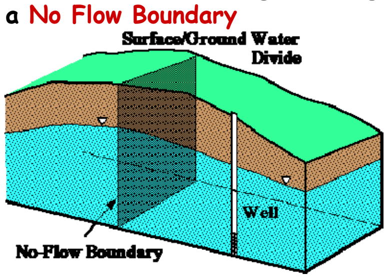
Injection



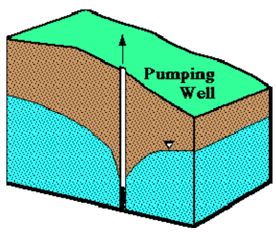
Withdrawal

Lesson: Monitor calculated heads at specified flux boundaries to ensure that the heads are physically reasonable.

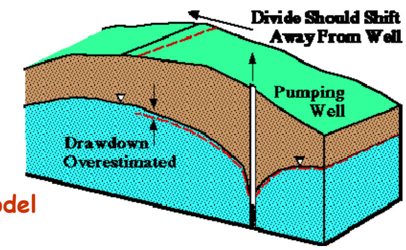
Example of Potential Problems From Misunderstanding/Misusing a No Flow Boundary



When a no flow boundary is used to represent a ground water divide, drawdown may be overestimated, and although the model does not indicate it, there may be impacts beyond the model boundaries. When a ground water divide is defined as a no-flow boundary, the flow system on the other side of the boundary cannot supply water to the well, therefore predicted drawdowns will be greater than would be experienced in the physical system. The no-flow boundary prevents the ground water divide from shifting, implying the drawdown is zero on the other side of the divide.



Model



Field

Lesson: Monitor head at no flow boundaries used to represent flow lines or flow divides to ensure the location is valid even after the stress is applied.

Specified Head / Constant Head

<u>Implication</u>: *Supply Inexhaustible, or Drainage Unfillable*

Specified Flux / No Flow

<u>Implication</u>: *H will be calculated as the value required to produce a gradient to yield that flux, given a specified hydraulic conductivity (K). The resulting head may be above the ground surface in an unconfined aquifer, or below the base of the aquifer where there is a pumping well; neither of these cases are desirable.*

Head Dependent Flux

<u>Implication</u>: *Supply Inexhaustible, or Drainage Unfillable*

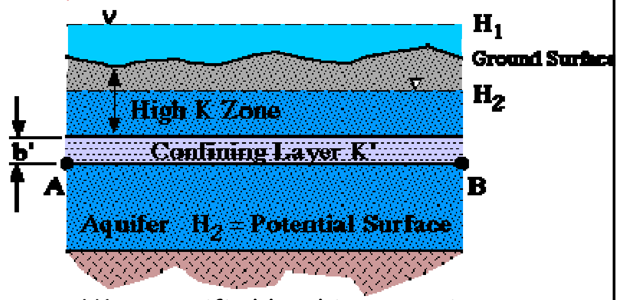
Free Surface

Seepage Face

Example of Potential Problems
From Misunderstanding/Misusing
a Head Dependent Flux Boundary

Flux into aquifer =

$$q = \frac{H_1 - H_2}{b'} K'A$$

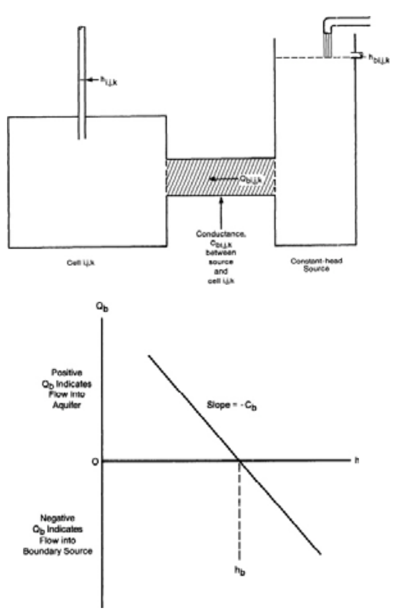


H1 = Specified head in reservoir
H2 = Head calculated in model

Implications:

- If H_2 is below AB, q is a constant and AB is the seepage face, but model may continue to calculate increased flow.
- If H_2 rises, H_1 doesn't change in the model, but it may in the field.
- If H_2 is less than H_1, and H_1 rises in the physical setting, then inflow is underestimated.
- If H_2 is greater than H_1, and H_1 rises in the physical setting, then outflow is overestimated.

Head-dependent Flux: General Head Boundary Q + or -



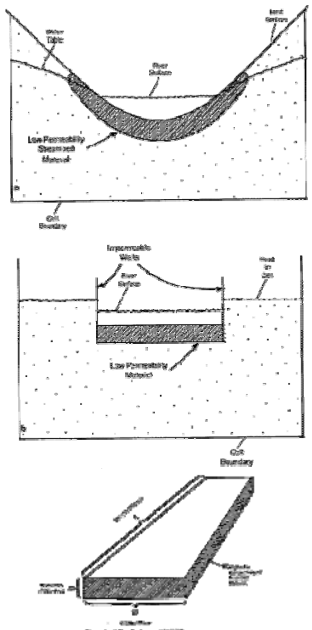
Conductance (is all of Darcy's Law except the head difference)

Q = KA dh/dl

Conductance = KA/thickness
Q = Conductance dh

Conductance of the ghb is calculated as:
K * Area / thickness

Head-dependent Flux RIVER



Using River Stage and River Bed Conductance

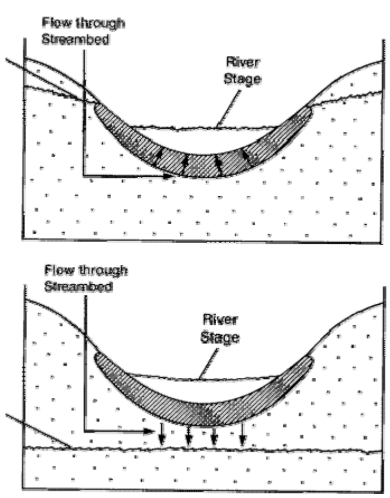
Q = KA dh/dl

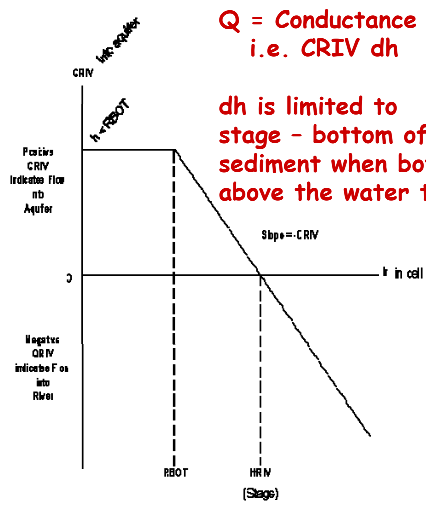
Conductance = KA/thickness

Q = Conductance dh

Conductance of the river bed is calculated as:
Kv * Area(the plan view area,L*W) / thickness

Head-dependent Flux RIVER

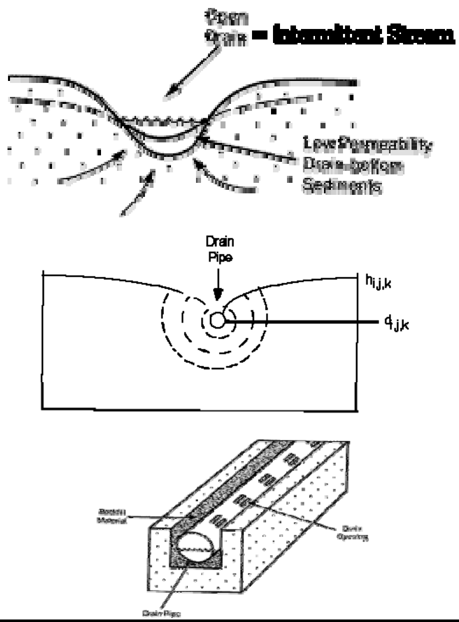




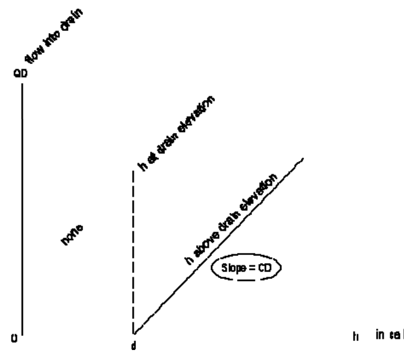
Q = Conductance dh
i.e. CRIV dh

dh is limited to stage – bottom of sediment when bottom is above the water table

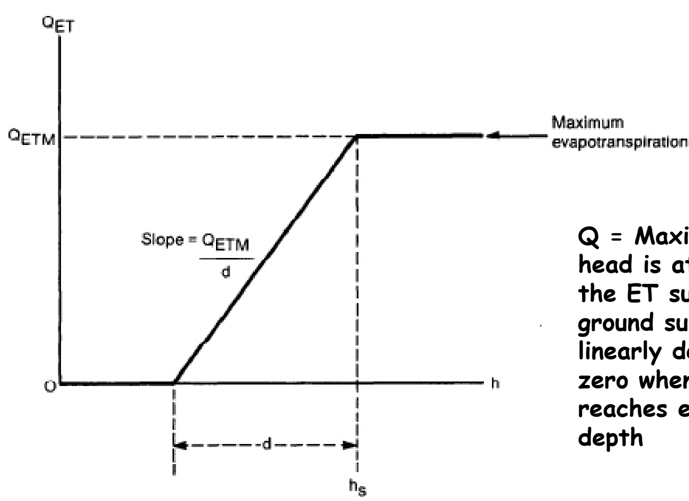
Head-dependent Flux DRAIN (outflow only)



Q = KA dh/dl
Q = Conductance dh
Conductance of the drain is calculated as:
$K_{\text{of material over which gradient is calculated}}$ * Area/thickness
Area may be the cylindrical area midway between where the heads used for the gradient are located* length of the drain



Head-dependent Flux: ET only outflow



Q = Maximum when head is at or above the ET surface (usually ground surface) and linearly declines to zero when head reaches extinction depth

Specified Head / Constant Head

Implication: *Supply Inexhaustible, or Drainage Unfillable*

Specified Flux / No Flow

Implication: *H will be calculated as the value required to produce a gradient to yield that flux, given a specified hydraulic conductivity (K). The resulting head may be above the ground surface in an unconfined aquifer, or below the base of the aquifer where there is a pumping well; neither of these cases are desirable.*

Head Dependent Flux

Implication: *Supply Inexhaustible, or Drainage Unfillable*

Free Surface

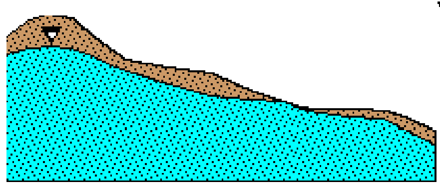
Implication: *Head is a function of elevation.*
Parameters are a function of head. Problem is nonlinear.

Seepage Face

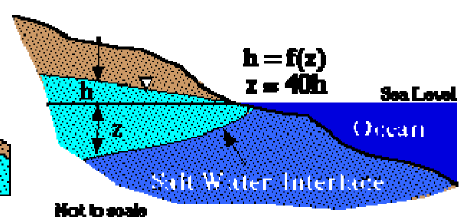
Example of Free Surface Boundary

•Free Surface: h = Z, or H = f(Z)

e.g. the water table h = z



or a salt water interface



Note, the position of the boundary is not fixed!

Implications: Flow field geometry varies so transmissivity will vary with head (i.e., this is a nonlinear condition). If the water table is at the ground surface or higher, water should flow out of the model, as a spring or river, but the model design may not allow that to occur.

Specified Head / Constant Head

Implication: *Supply Inexhaustible, or Drainage Unfillable*

Specified Flux / No Flow

Implication: *H will be calculated as the value required to produce a gradient to yield that flux, given a specified hydraulic conductivity (K). The resulting head may be above the ground surface in an unconfined aquifer, or below the base of the aquifer where there is a pumping well; neither of these cases are desirable.*

Head Dependent Flux

Implication: *Supply Inexhaustible, or Drainage Unfillable*

Free Surface

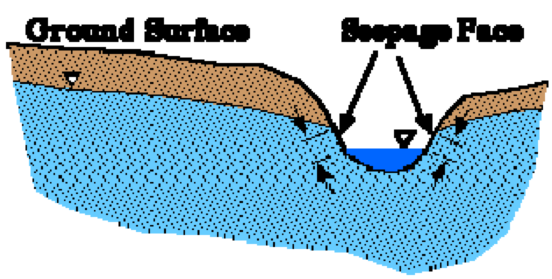
Implication: *Head is a function of elevation.*
Parameters are a function of head. Problem is nonlinear.

Seepage Face

Implication: *Outflow occurs as needed given the problem parameters.*

Example of Seepage Face Boundary

The saturated zone intersects the ground surface at atmospheric pressure and water discharges as evaporation or as a overland flow.



Note, the location of the surface is fixed but its length is not and is not know before solution of the problem.

Implications: *A seepage surface is neither a head or flow line. Often seepage faces can be neglected in large scale models.*

Common Designations for Several Important Boundary Conditions

After:
Definition of Boundary and Initial Conditions in the Analysis of Saturated Ground-Water Flow Systems – An Introduction,
O. Lehn Franke, Thomas E. Reilly, and Gordon D. Bennett, USGS - TWRI Chapter B5, Book 3, 1987.

BOUNDARY CONDITION NAME	BOUNDARY TYPE & GENERAL NAME	FORMAL NAME
Constant Head & Specified Head	Type 1 specified head	Dirichlet
No-Flow & Specified Flux	Type 2 specified flux	Neumann
Head-dependent Flux	Type 3 mixed condition	Cauchy

Natural and Artificial Boundaries

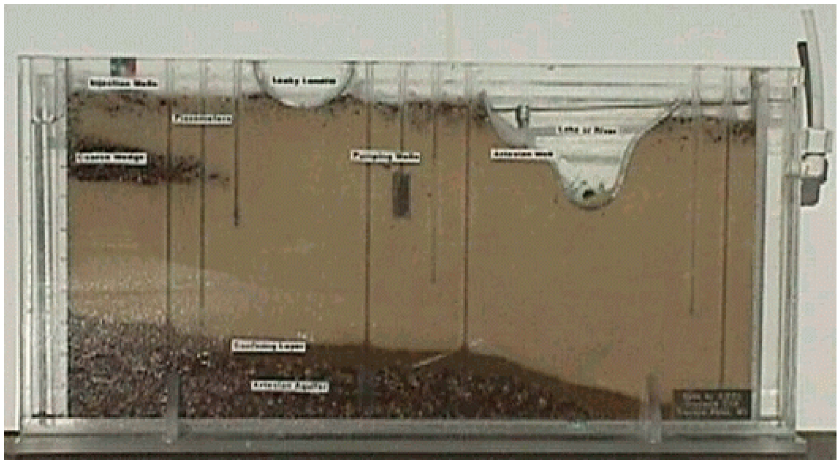
It is most desirable to terminate your model at natural geohydrologic boundaries.

However, we often need to limit the extent of the model in order to maintain the desired level of detail and still have the model execute in a reasonable amount of time. Consequently models sometimes have artificial boundaries. For example, heads may be fixed at known water table elevations at a county line, or a flow line or ground-water divide may be set as a no-flow boundary.

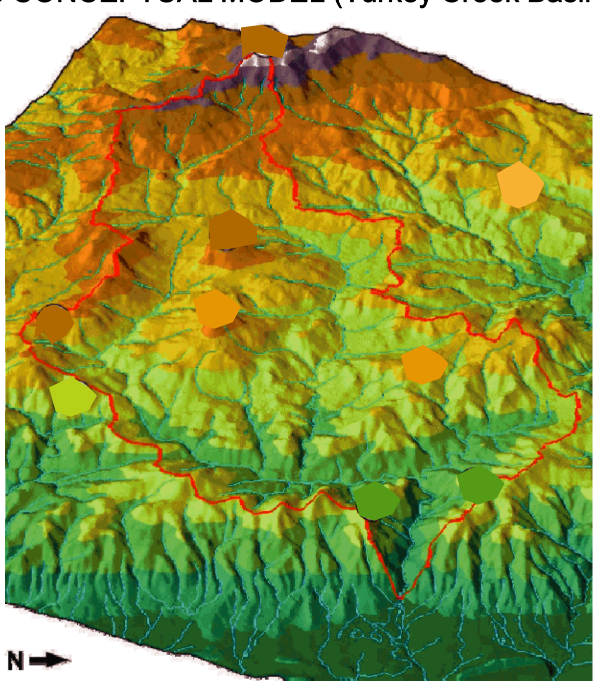
BOUNDARY TYPE	NATURAL EXAMPLES	ARTIFICIAL USES
CONSTANT or SPECIFIED HEAD	Fully Penetrating Surface Water Features	Distant Boundary (Line of unchanging hydraulic head contour)
SPECIFIED FLUX	Precipitation/Recharge Pumping/Injection Wells Impermeable material	Flow line Divide Subsurface Influx
HEAD DEPENDENT FLUX	Rivers Springs (drains) Evapotranspiration Leakage From a Reservoir or Adjacent Aquifer	Distant Boundary (Line of unchanging hydraulic head contour)

DESCRIBE THE CONCEPTUAL MODEL

Geometry
Materials
Boundary Conditions

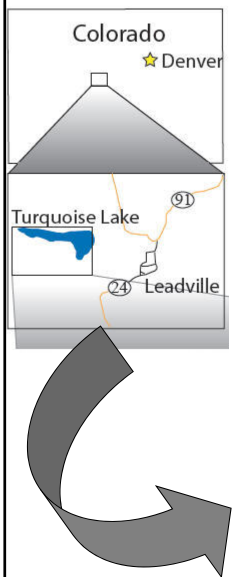


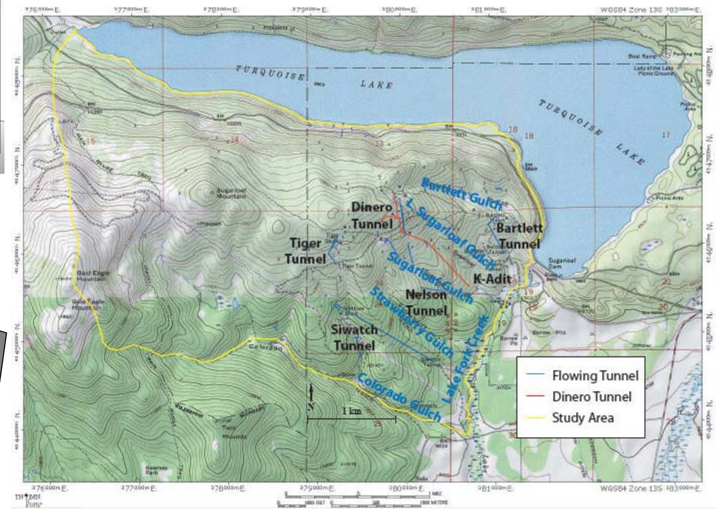
Describe the CONCEPTUAL MODEL (Turkey Creek Basin):



DESCRIBE THE CONCEPTUAL MODEL

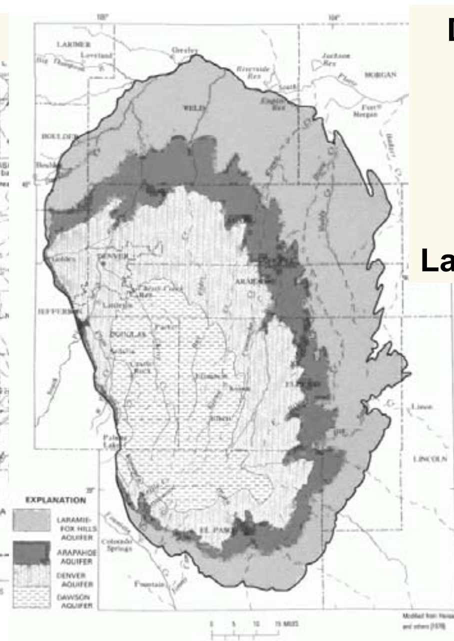
Geometry
Materials
Boundary Conditions





Describe the Conceptual Model in a familiar location

NE corner of CO

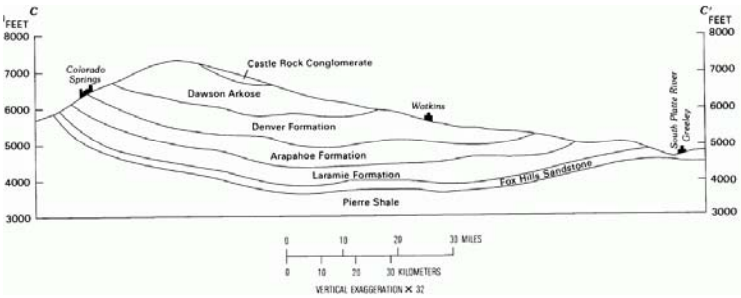


Denver Basin Aquifers:

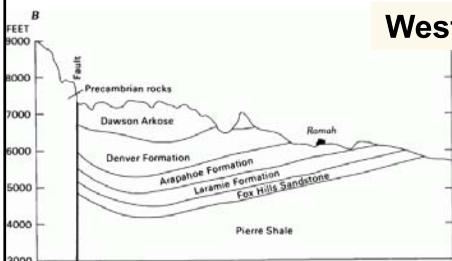
Dawson
Denver
Arapahoe
Laramie-FoxHills

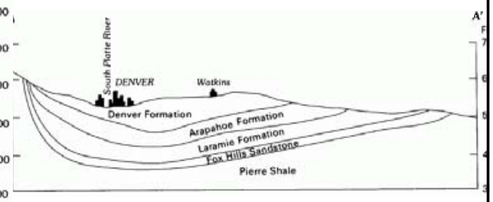
Denver Basin

South - North



West - East

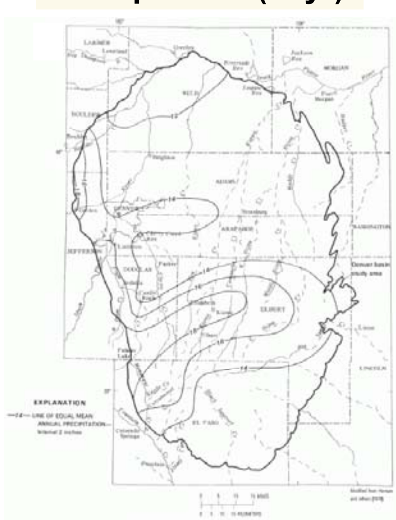




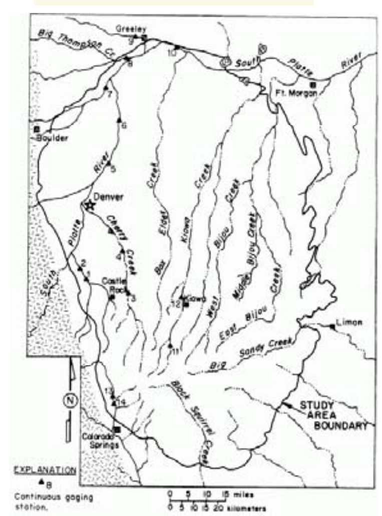
further south **further north**

Denver Basin

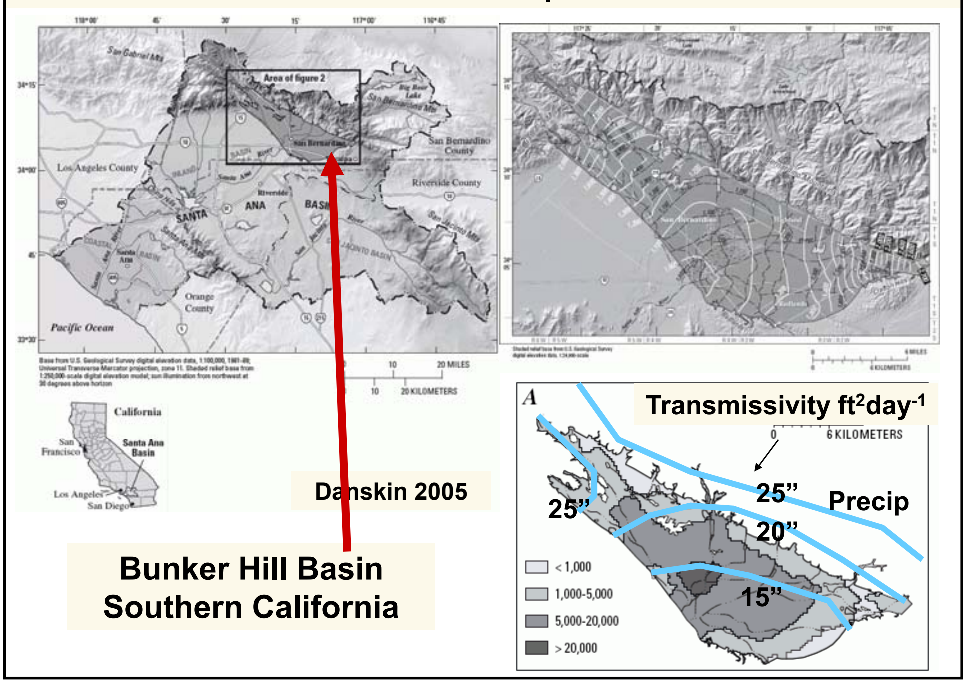
Precipitation (in/yr)



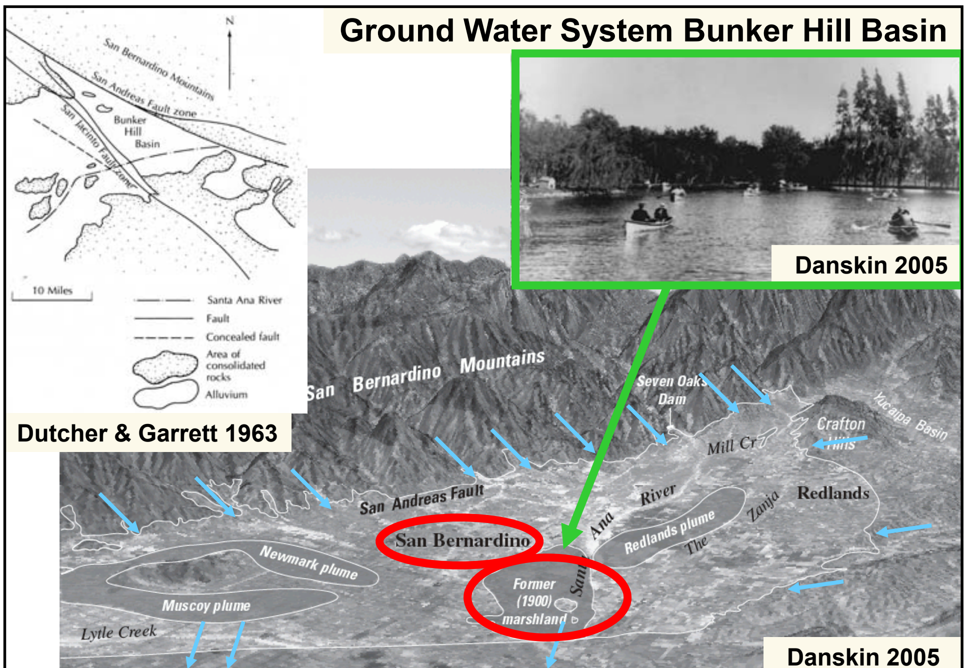
Streams



Describe the Conceptual Model



Ground Water System Bunker Hill Basin



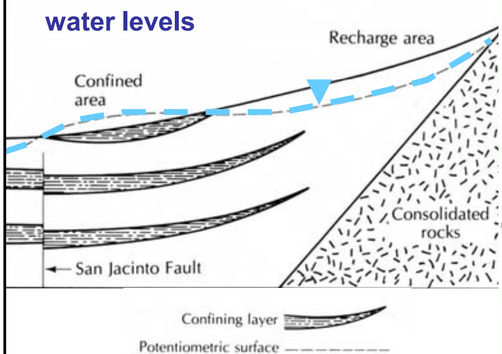
Ground Water System Bunker Hill Basin

current water levels

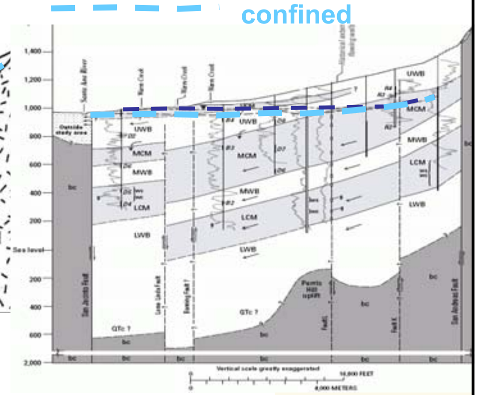
water table

confined

1940's confined water levels



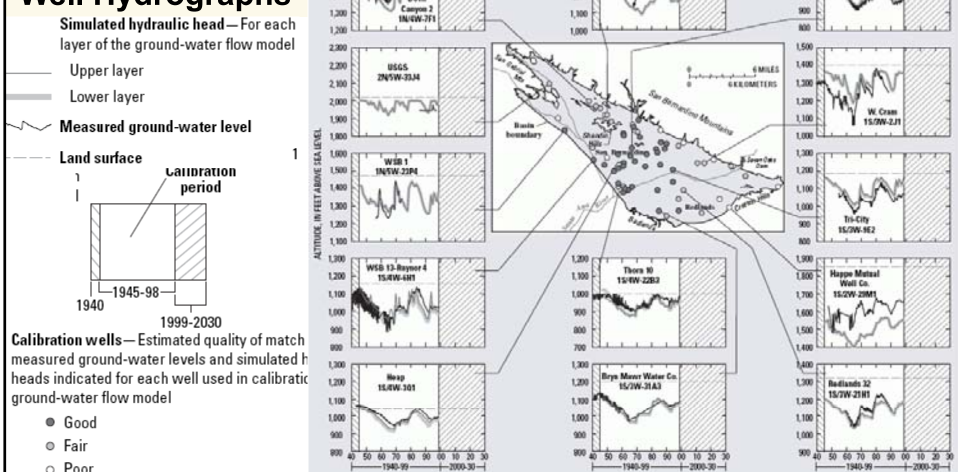
Dutcher & Garrett 1963



Danskin 2005

Think Transients as well

Well Hydrographs



Water levels were high in early years and good for recreation
Increased pumping led to problems with land subsidence
Urbanization resulted in less pumping & flooded foundations
Thus pumping was increased to lower water levels
An additional 15,000AFY is needed to keep levels in check
Projections is growth will require an additional 50,000AFY

DUE NEXT WEEEK **Assignment #1 Conceptual Model:**
Select a **SINGLE-PHASE, CONSTANT DENSITY, SATURATED, FLOW** modeling project with both a steady and transient aspect, and write a summary describing it to me. If you do not have a place to model, I can help you identify one. Your description should use illustrations and include:

Title
Objective
Problem Description
Geohydrologic Setting
FIGURES (at least one plan and one cross section) ARE REQUIRED TO ILLUSTRATE THE FOLLOWING ITEMS
location (show on map)
geometry (draw outline of modeled area on the maps and cross sections)
boundary conditions (head and flux boundaries and head dependent flux boundaries)
property value ranges (i.e. hydraulic conductivity, storage parameters, thicknesses)
stresses that will be applied for which you will predict the resulting conditions
special considerations (if any)
AT LEAST ONE FIGURE needs to show the outline of the area you will model with arrows indicating where water enters and leaves the system and a rough sketch of the pattern of flow through the area, hatched lines where there are no-flow boundaries and a few sketched lines indicating the pattern of flow in the area.
Calibration Data that are available (head and groundwater discharge to surface water features). Indicate location of stream flow gages and wells along with the frequency and period of record of flows and water levels)
A description of what you envision your final result will be
References

Submit a description and the drawings as hard copy OR as ASSGN1_LASTNAME.ZIP

ALL FILES IN ZIP FILE MUST EITHER INCLUDE YOUR LAST NAME OR BE IN A FOLDER THAT INCLUDES YOUR LAST NAME

2 WEEKS FROM NOW AN ANALYTICAL MODEL OF SOME ASPECT OF THIS NEEDS TO BE SUBMITTED

2 WEEKS FROM NOW but be thinking of it as you create your conceptual model * note typo in your pdf … 2 weeks from now not 3

Assignment #3 Analytical Model: Choose an analytical model to represent some aspect of your modeling project and implement it with your model conditions. Describe the problem set-up and solution in a concise and clear manner. If you use a spreadsheet, mathcad, or other code for calculation, provide at least one hand calculation to confirm that your results are correct. Your submission should use illustrations to describe the conceptual model and how it fits your problem. It should include the following items:

Title
Objective
Problem Description
Analytical Model Description
Simplification of System in order to use the analytical model
Parameter values used
Calculations
Results
References

submit the write-up as hard copy and if you have electronic files include it in your zip file labeled: ASSGN3_LASTNAME.ZIP