Groundwater Hydraulics

Chapter 4 – Groundwater Modelling

CENG 6606

AAU

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Why model?

- The effective way:
  - To test effects of groundwater management strategies
  - To make predictions about a ground-water system's response to a stress
  - To understand the system
  - To design field studies
  - Use as a thinking tool
- Processes we might be interested to model:
  - Groundwater flow
    - *Calculate both heads and flow*
  - Solute transport – requires information on flow (velocities)
    - *Calculate concentrations*

Types of models

- CONCEPTUAL MODEL QUALITATIVE DESCRIPTION OF SYSTEM
  - "a cartoon of the system in your mind”
- MATHEMATICAL MODEL MATHEMATICAL DESCRIPTION OF SYSTEM
  - SIMPLE - ANALYTICAL (provides a continuous solution over the model domain)
  - COMPLEX - NUMERICAL (provides a discrete solution - i.e. values are calculated at only a few points)
- ANALOG MODEL e.g. ELECTRICAL CURRENT FLOW through a circuit board with resistors to represent hydraulic conductivity and capacitors to represent storage coefficient
- PHYSICAL MODEL e.g. SAND TANK which poses scaling problems

1. Why Model Groundwater?

- Can be used for three general purposes:
- To predict or forecast expected artificial or natural changes in the system. Predictive is more applied to deterministic models since it carries higher degree of certainty, while forecasting is used with probabilistic (stochastic) models.
- To describe the system in order to analyse various assumptions
- To generate a hypothetical system that will be used to study principles of groundwater flow associated with various general or specific problems.

Why model groundwater?

- A model is any device that represents an approximation of a field situation. Two types:
  - *Physical models* such as laboratory sand tanks simulate groundwater flow directly.
  - A *mathematical* model simulates groundwater flow indirectly by means of a governing equation, together with equations that describe boundary conditions and/or initial conditions.
- The set of commands used to solve a mathematical model on a computer forms the computer program or code. The code is generic, whereas a model includes a set of boundary and initial conditions as well as a site-specific nodal grid and site-specific parameter values and hydrologic stresses.

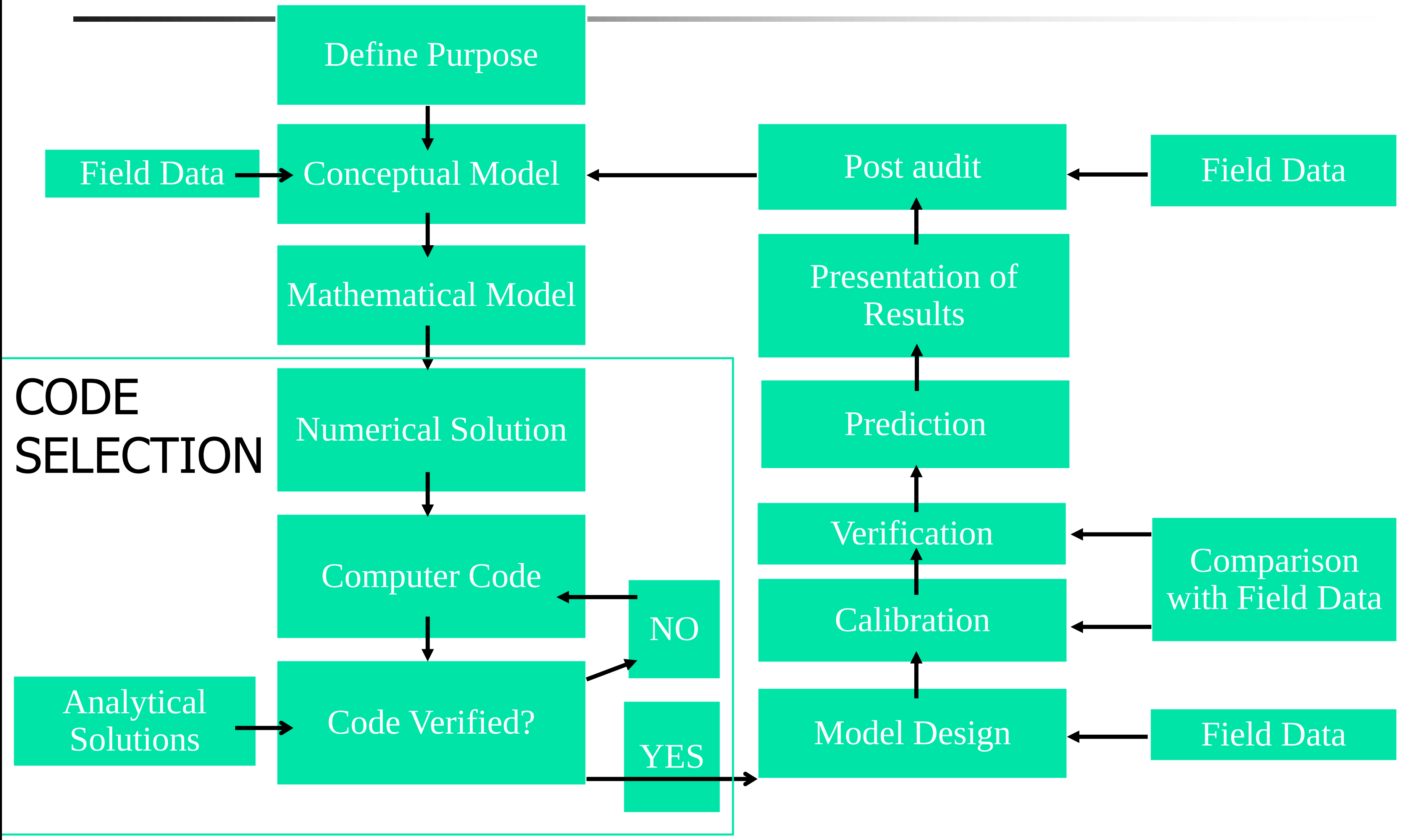
Why Model Groundwater?

- **Predictive**: Used to predict the future (**predicting the consequences of a proposed action);** requires calibration.
- **Interpretive**: Used as a framework for studying system dynamics (**to gain insight into the controlling parameters in a site-specific setting)** and/or organizing field data (**to improve understanding of regional flow systems)**; does not necessarily require calibration.
- **Generic**: Used to analyze flow in hypothetical hydrogeologic systems; may be useful to help frame regulatory guidelines for a specific region **screening tools to identify regions suitable or unsuitable for some proposed action)**; does not necessarily require calibration.

Basic components for model development

- Geologic model - lithologic facies, expert knowledge on hydraulic properties of materials, etc.
- Hydrologic model - conceptualization of boundary conditions and initial conditions - what type of features are present?
  - Clear description of where the model is confined, unconfined, or leaky
  - Choose one the three basic boundary conditions for all boundaries of the groundwater system
  - Define recharge and ET processes and determine if simulating the unsaturated zone is necessary or not
- Construct the numerical model using standard software such as, MODFLOW.

Modelling protocol



Purpose - What questions do you want the model to answer?

- Prediction;
- System Interpretation: **Inverse Modeling: Sensitivity Analysis;**
- Generic Modeling: **Used in a hypothetical sense, not necessarily for a real site;**
- What do you want to learn from the model?
- Is a modeling exercise the best way to answer the question?
- Can an analytical model provide the answer?

Conceptual Model

"Everything should be made as simple as possible, but not simpler." Albert Einstein

- Pictorial representation of the groundwater flow system
- Will set the dimensions of the model and the design of the grid
- "Parsimony"….conceptual model has been simplified as much as possible yet retains enough complexity so that it adequately reproduces system behavior.

- **Select Computer Model**
- **Code Verification**
    - Comparison to Analytical Solutions; Other Numerical Models
- **Model Design**
    - Design of Grid, selecting time steps, boundary and initial conditions, parameter data set

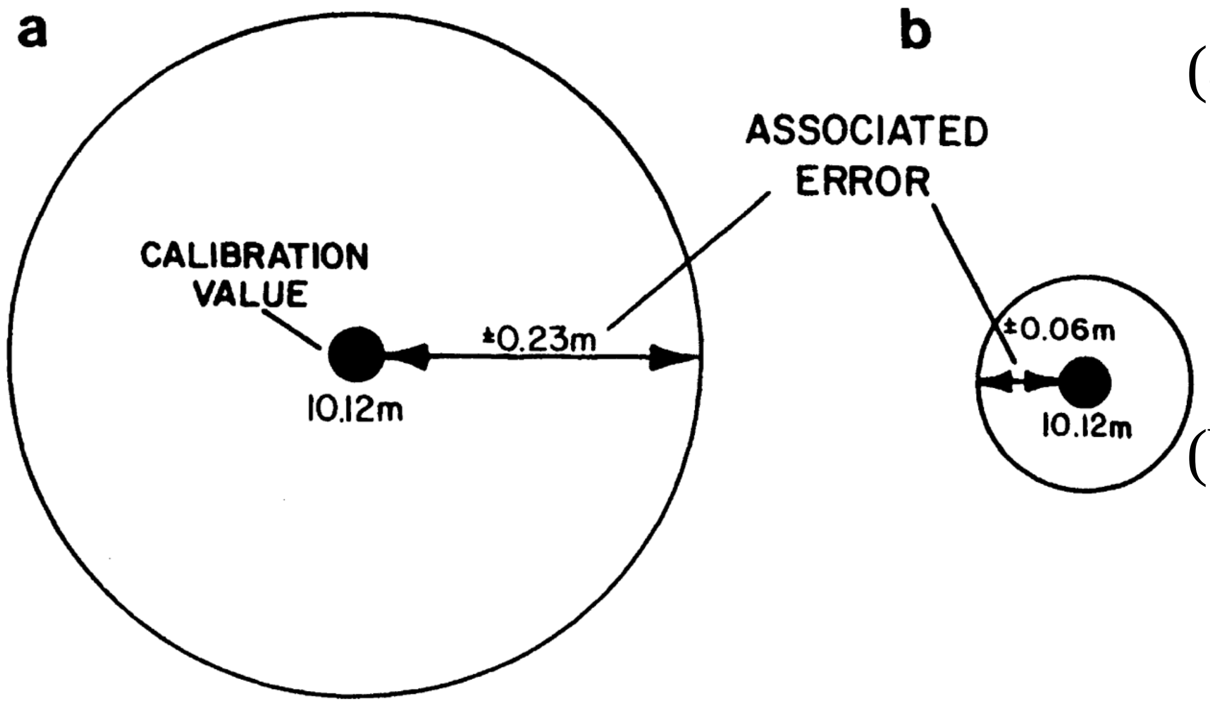
Steady/Unsteady..1, 2, or 3-D;
…Heterogeneous/Isotropic…..Instantaneous/Continuous

- **Calibration**:
  - Show that Model can reproduce field-measured heads and flow
  - Results in parameter data set that best represents field-measured conditions.
- **Calibration Sensitivity Analysis**
  - Uncertainty in Input Conditions
  - Determine Effect of Uncertainty on Calibrated Model
- **Model Verification**
  - Use Model to Reproduce a Second Set of Field Data
- **Prediction**
  - Desired Set of Conditions
  - Sensitivity Analysis: Effect of uncertainty in parameter values and future stresses on the predicted solution

- **Presentation of Modeling Design and Results**:
  - Effective Communication of Modeling Effort
    - Graphs, Tables, Text etc.
- **Post audit**:
  - New field data collected to determine if prediction was correct
  - Site-specific data needed to validate model for specific site application
- **Model Redesign**
  - Include new insights into system behavior

Inverse Modelling

- Calibration is accomplished by finding a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field-measured values within a preestablished range of error

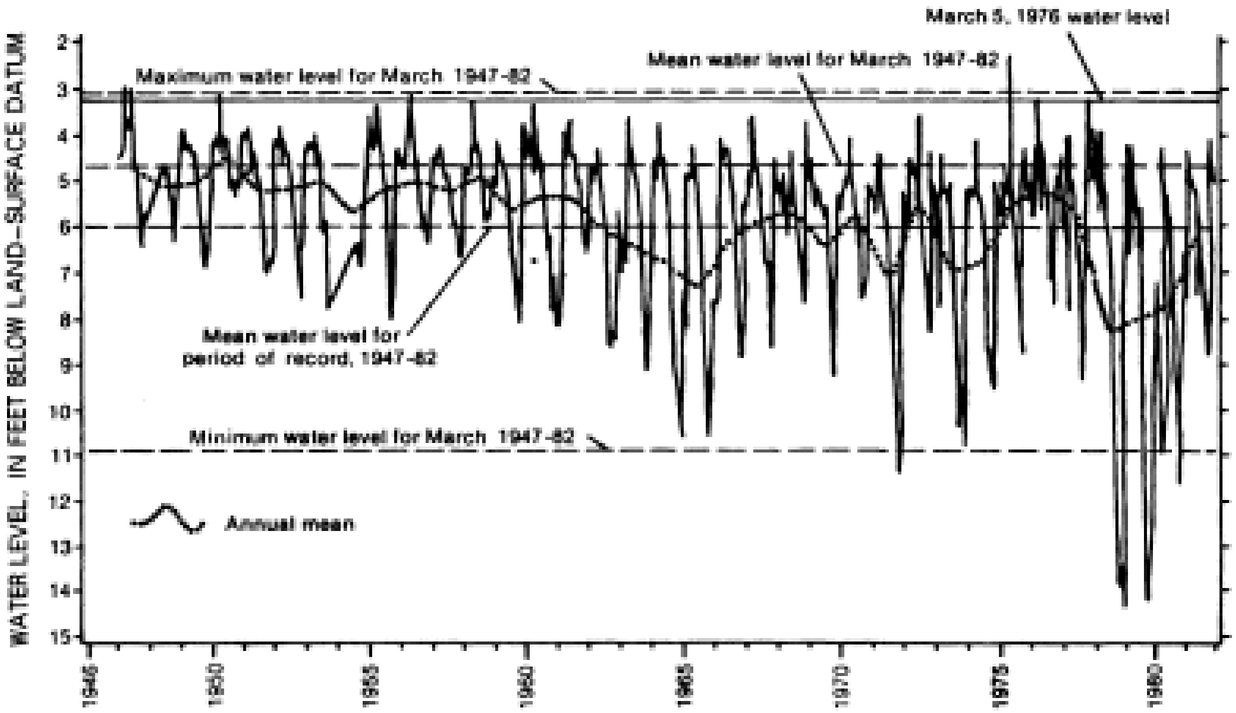


(a) A target for head with a large associated error, 10.12 m ± 0.23 m.
(b) A target for head with a small associated error, 10.12 m ± 0.06

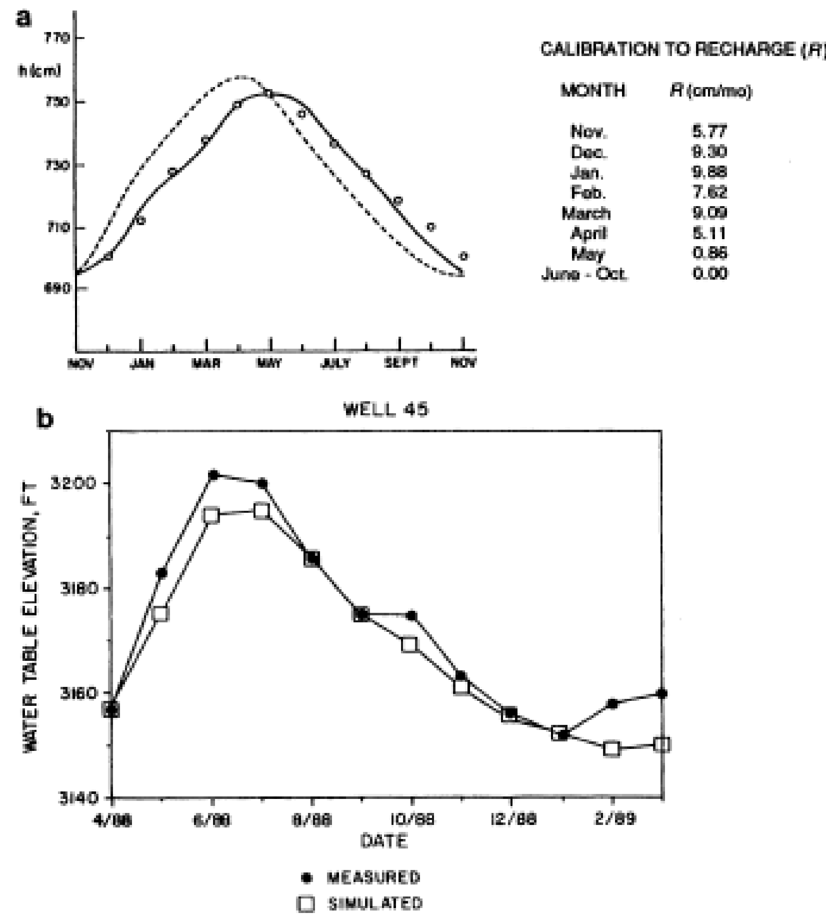
Inverse Modelling

- Finding set of parameter values amounts to solving what is known as the inverse problem.
- In an inverse problem the objective is to determine values of the parameters and hydrologic stresses from information about heads,
- whereas in the forward problem system parameters such as hydraulic conductivity, specific storage, and hydrologic stresses such as recharge rate are specified and the model calculates heads.
- Thus steady state models can be used to compute hydraulic conductivities while transient models must be used to estimate both specific storage and hydraulic conductivity values.
- Both models can be used to estimate recharge

- Definition of possible steady-state calibration values based on the mean water level for the period of record, the mean water level for a month for the period of record, and the mean water level for a year.



- Transient calibration.
- (a) Calibration to dynamic cyclic conditions as defined by a well hydrograph. Calibration is achieved by adjusting monthly recharge rates. The solid line (observed) against the Brocken line (simulated)
- (b) Transient calibration to a well hydrograph for an unconfined aquifer receiving recharge from adjacent highlands and leaking streams and irrigation ditches.



Calibration techniques

- Parameter estimation is essentially synonymous with model calibration, which is synonymous with solving the inverse problem.
- Kriging is a method of estimating the spatial distribution of parameters (or heads), but it is generally recognized that kriging should be combined with an inverse solution because the uncertainty associated with estimates of transmissivity can be greatly reduced when information about the head distribution is used to help estimate transmissivities.
- In other words, better estimates of aquifer parameters can be obtained when both prior information and sample information are used in the analysis.

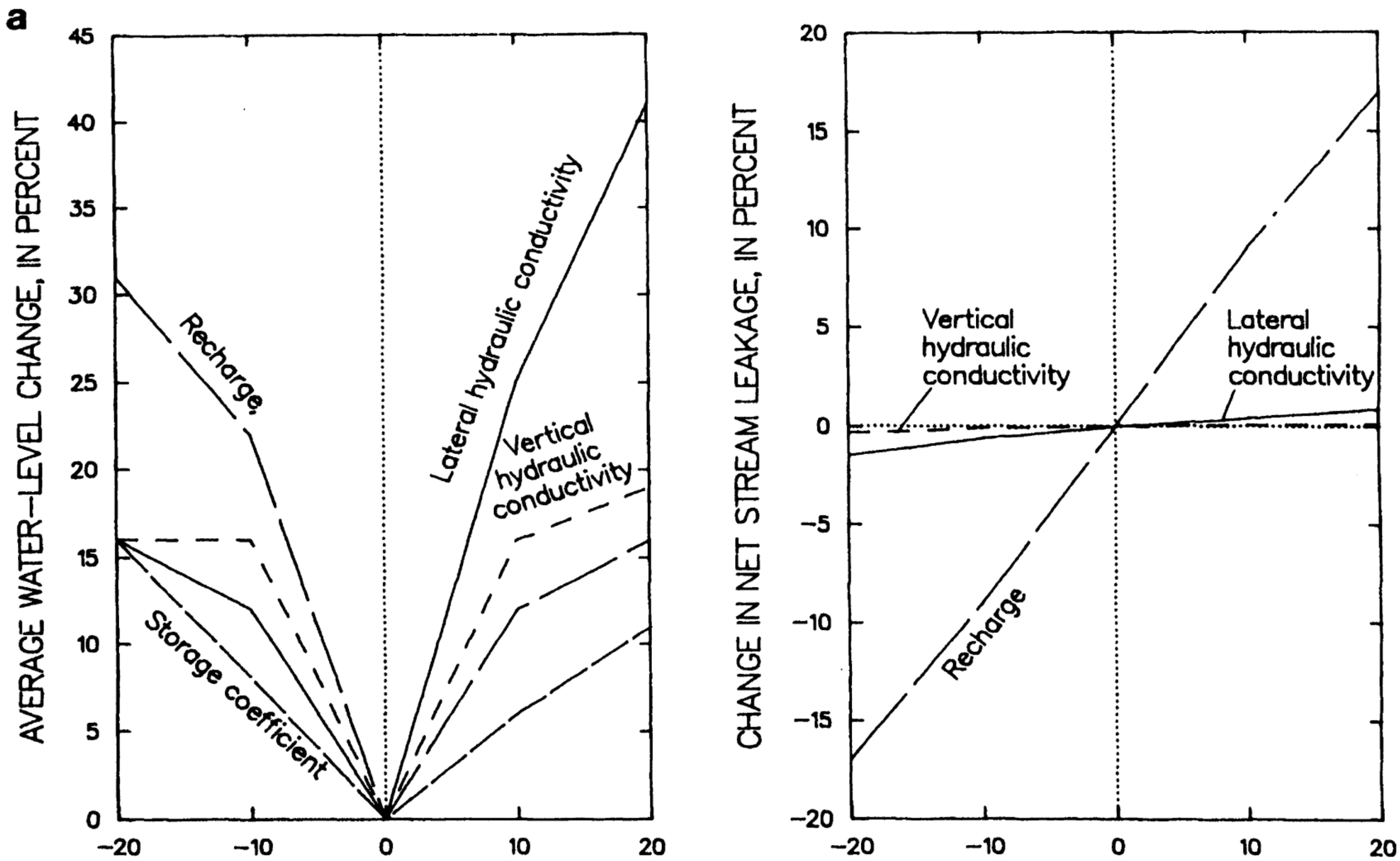
Two approaches

- Manual trial-and-error adjustment of parameters:
  - Does not give information on the degree of uncertainty in the final parameter selection, nor does it guarantee the statistically best solution.
- Automated statistically based solution
  - Quantifies the uncertainty in parameter estimates and gives the statistically most appropriate solution for the given input parameters provided it is based on an appropriate statistical model of errors.

Sensitivity Analysis

- The purpose is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions.
- Other uncertainty about the very geometry of the model area include: uncertainties of lithology, stratigraphy, and structure
- During a sensitivity analysis, calibrated values for hydraulic conductivity, storage parameters, recharge, and boundary conditions are systematically changed within the previously established plausible range. The magnitude of change in heads from the calibrated solution is a measure of the sensitivity of the solution to that particular parameter.
- The results of the sensitivity analysis are reported as the effects of the parameter change on the average measure of error selected as the calibration criterion.

- Sensitivity analysis is typically performed by changing one parameter value at a time.
- The effects of changing two or more parameters also might be examined to determine the widest range of plausible solutions.
- For example, hydraulic conductivity and recharge rate might be changed together so that low hydraulic conductivities are used with a high recharge rate and high hydraulic conductivities are used with a low recharge rate.
- The left-hand-side figure (next slide) shows the effect of varying the storage coefficient on the average water level change, plotted with other sensitivity analyses. The right-hand side figure shows the effect on stream leakage.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AVERAGE WATER–LEVEL CHANGE, IN PERCENT
45
40
35
30
25
20
15
10
5
0
–20
–10
0
10
20
Recharge,
Storage coefficient
Lateral hydraulic conductivity
Vertical hydraulic conductivity
CHANGE IN NET STREAM LEAKAGE, IN PERCENT
20
15
10
5
0
–5
–10
–15
–20
Vertical hydraulic conductivity
Lateral hydraulic conductivity
Recharge

Tutorial Handout

- Your First Groundwater model using PMWIN (30 Page Reading Assignment)

PMWIN Exercise

- Fig. below shows a part of an unconfined aquifer. The extent of the aquifer to the North and South is assumed to be unlimited. The aquifer is homogeneous and isotropic with a measured horizontal hydraulic conductivity of 0.0005 *m/s* and an effective porosity of 0.1. The elevations of the aquifer top and bottom are 15 *m* and 0 *m*, respectively.
- The aquifer is bounded by a no-flow zone to the west. To the east exists a river, which is in direct hydraulic connection with the aquifer and can be treated as fixed-head boundary. The river width is 50 *m* and stage is 10 *m*. The mean groundwater recharge rate is 8×10^{-9} *m/s*. A pumping well is located at a distance of 1000 *m* from the river.
- The task is to calculate the catchment area of the well and the 365-days-capture zone under steady-state flow conditions.

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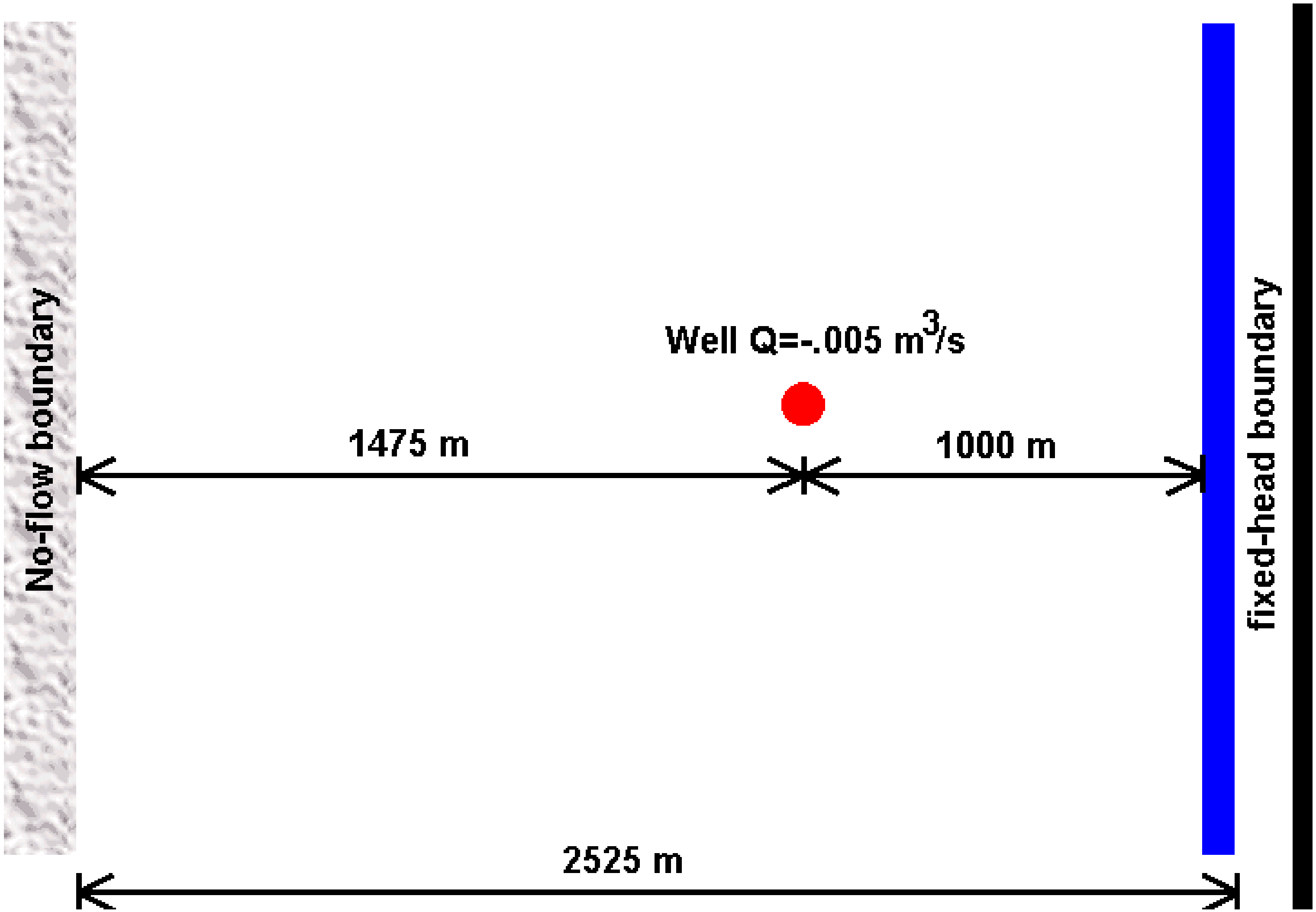

No-flow boundary
Well Q=-.005 m3/s
1475 m
1000 m
fixed-head boundary
2525 m