“Facts are stubborn things, but statistics are pliable.”

Mark Twain

Hydrologic Modeling

ADEQ SW Short Course

June 13, 2013

Phoenix, AZ

Outline

• Model basics
• Conceptual models (WoW)
• Modeling continuum
• Examples of models
• Model shortcomings
• On-line modeling tools
• Parameter estimation (Gupta)

Bottom line: one page summary

• A Model is a simplified representation of a system
• Models are made up of various components – defined in terms of parameters and states/processes
• Most hydrologic models include many submodels
• Computational effort and Convergence are two important model characteristics
• Empirical models are questionable in new settings
• Physical models have sign. computational and data requirements.

What is a Model?

A Model is a simplified representation of a system.

Its purposes are:
   a) to enable reasoning within an idealized framework, and
   b) to enable testable predictions of what might happen under new circumstances.

The representation is based on explicit simplifying assumptions (known to be false, or perhaps poorly-known, in some detail) that allow acceptably accurate simulations of the real system.

Purpose of Model

• Critical part of science – to test our understanding of complex behavior

• Forward – Goal: basic parameters known
  – Estimation
  – Prediction / Planning

• Inverse/Inversion – Goal: learn from model
  – Data interpretation

Systems Models

Process, State or Reservoir

Input

Flows or Flux

Output
Feedback Model

Process or Reservoir

Input ➔ Output

Flows or Flux

Inversion Model

Model

parameters ➔ Compare

RMSE?

Effective Parameters and States

time invariant vs. time varying

real world

homog. (x_eff, θ_eff)

measurement

identical?

Conceptual Models

- What are they?
  - Qualitative
  - Might be based on graphs
  - Represent important system:
    - components
    - processes
    - linkages
    - interactions

- When should they be used?
  - As an initial step –
  - For hypothesis testing
  - For mathematical model development
  - As a framework –
  - For future monitoring, research, and management actions at a site

- How can they be used?
  - Design field sampling and monitoring programs
  - Guide selection of measurement
  - Suggest likely causes of environmental problems
  - Identify system linkages and possible cause and effect relationships
  - Identify potential conflicts among management objectives
  - Anticipate the range of possible system responses to management actions
  - Including potential negative effects

After Grayson and Blöschl, 2000, 
Cambridge Univ. Press

www.waterontheweb.org/curricula/ws/unit_05/index.html
Conceptual Model Example - Ecologic

Mathematical Models

- **What are they?**
  - Mathematical equations that translate a conceptual understanding of a system or process into quantitative terms

- **How are they used?**
  - Diagnosis
    - E.g., What is the cause of reduced water clarity in a lake?
  - Prediction
    - E.g., How long will it take for lake water quality to improve, once controls are in place?

Categories of Mathematical Models

<table>
<thead>
<tr>
<th>Type</th>
<th>Time Factor</th>
<th>Treatment of Data Uncertainty and Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical</td>
<td>Static or steady-state</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Based on data analysis</td>
<td>Dynamic</td>
<td>Address variability/uncertainty</td>
</tr>
<tr>
<td>Mechanistic</td>
<td>Dynamic</td>
<td>Stochastic</td>
</tr>
<tr>
<td>Based on theory</td>
<td>Changes with time</td>
<td></td>
</tr>
</tbody>
</table>

Mathematical Models

- **When should models not be used?**
  - If you do not understand the problem or system well enough to express it in concise, quantitative terms
  - If the model has not been tested and verified for situations and conditions similar to your resource

  - It is important to understand model:
    - Structure (processes, variables, numerics)
    - Assumptions
    - Limitations

Remember!

- Models do not substitute for:
  - logical thinking
  - problem expertise
  - direct observation / data collection
  - in-depth analysis

- Models should be no more complicated than is necessary for the task at hand

Selecting or Developing a Model

- **Important first steps**
  - Define the question or problem to be addressed with the model
  - Determine appropriate spatial and temporal scales
  - Identify important ecosystem components and processes that must be considered to answer the management questions
Selecting or Developing a Model

- Some specific questions to ask
  - Temporal scale
    - Do I need to predict changes over time or are steady-state conditions adequate?
    - If time is important, do I need to look at
      - Short-term change (e.g., daily, seasonal) or
      - Long-term change (e.g., trends over years)?
  - Spatial scale
    - Is my question best addressed:
      - On a regional scale (e.g., compare streams in a region) or
      - By modeling specific processes within an individual system?

End-to-End Modeling of Land-Surface Hydrology

Continuum of Model Approaches

Examples follow:

- Physical/Mathematical– most quantitative
  - Distributed: grid/GIS-based model
  - Aggregated or classified
- Conceptual – more qualitative
  - Lumped parameter/process
  - Empirical
- Decision Support Simulations (DSS)
- Scenario Models

Sacramento Soil Moisture Accounting (SMA) Model

Flows
- Arrows
- Reservoirs
- Boxes

Physical Processes

- Arrows
- Boxes

Evolution of Hydrologic Models
Distributed vs. Lumped

SCS Curve Number Model

Decision Support Models

DSS Submodels

Scenarios - Context

Scenarios - Development Process

Decision Support Models

DSS Submodels

Scenarios - Development Process
Scenario - Themes

Scenario Development for Water Resources, Mohammed Mahmoud, 2008
also, Environmental Modelling & Software 24 (2009) 798–808

EXAMPLES OF MODELS

HEC-HMS

Components
- Watershed Physical Description
- Meteorology Description
- Hydrologic Simulation
- Parameter Estimation
- Analyzing Simulations
- GIS Connection

www.hydro.washington.edu/Lettenmaier/Models/VIC/

HMS, Yu, www.essc.psu.edu/hms/hms/
Estimating Floods

Based on:
- Regional regression eqs.
  - \( RQ = aX^bY^cZ^d \)
- Dimensionless hydrograph
- Flood frequency graphs

Requires data like:
- Topo
- Soils
- Slope
- Storm
- Rural/urban
- Land cover
- Impoundments

Model Shortcomings

The modeler’s dilemma:
Know everything \( \Leftarrow \) or \( \Rightarrow \) Make lots of approximations

- Too simplistic
- Numerical errors
- Improper application
- Poor calibration
- Edge effects
- Non-unique solutions

Discretization

Challenge: How to represent something digitally

Calibration & Validation

Challenge: Assessing model reliability

Model Mesh or Grids

Challenge: Min. nodes, Max. resolution
Nested Models
Challenge: avoid edge effects

Parameter Estimation
Challenge: avoiding non-unique solutions

ON-LINE STUDY MATERIALS

https://www.meted.ucar.edu/index.php

https://wikiwatershed.org/model.php
The Problem of Parameter Estimation:

All RR models are (to some degree) lumped, so that the equations and parameters are “effective” conceptual representations of hydrologic processes aggregated in space & time.

The “effective” nature of model parameters means they are usually not directly measurable (at the model scale) and must therefore be specified by some indirect process, such as:

- Theoretical considerations
- Lookup tables (previous studies)
- “Calibration” of model to input-output data

Stages in Parameter Estimation

**LEVEL ZERO — (Qualitative Analysis)**
- Specify feasible ranges and nominal values based on:
  - Theoretical considerations
  - Regional estimates
  - Lookup tables
  - Maps & Databases

**LEVEL ONE — (Behavioral Analysis)**
- Estimate Parameter (ranges) by isolating & examining particular segments of the input-state-output response
- Ignores parameter interactions

**LEVEL TWO — (Regression)**
- Estimate Parameter (ranges) by matching model output response to observed data for some calibration period of interest
- Considers parameter interactions

Level Zero Parameter Estimation

Define initial parameter uncertainty by specifying feasible ranges for each parameter, using estimates from similar watersheds, look-up tables, maps & databases.

**LEVEL ONE**
- Define initial parameter uncertainty by specifying feasible ranges for each parameter, using estimates from similar watersheds, look-up tables, maps & databases.

**LEVEL TWO**
- Parameters are further adjusted while examining the entire hydrograph, taking into account parameter interactions:
  a. Strategy to measure closeness between model simulations and observed watershed input-output response
  b. Strategy to reduce the size of the feasible parameter space

Level One Parameter Estimation

Reduce the size of the initial uncertainty by adjusting one-parameter-at-a-time to try and match particular segments of the input-output response. Parameter interaction is generally ignored.
Problems with Level Two Parameter Estimation

1. **Dimensionality** - Usually large number of parameters that can be adjusted (e.g. SAC-SMA has 15).
2. **Interdependence** - Parameters have similar or compensating (interacting) effects on different portions of the output.
3. **Ambiguity** - Exists no unique or un-ambiguous way to evaluate the "closeness" of the simulated and observed output time-series.
4. **Uncertainty** - Exists errors & uncertainties in input-output data, model initialization, and model conceptualization (structure).

Parameter Estimation as Optimization Problem

Classical parameter estimation methods are rooted in a philosophy of searching for the "best" parameter values (best = gives the "closest" match to the data).

The underlying premise is that there is an "correct" values for the parameters -- the problem was only how to find them -- the solution was an optimization approach based in regression theory -- fitting the model to the data.

Causes of Difficulty in Finding Optimal Parameter Set

**Working Hypothesis:**
Poor model performance caused by inability to find the optimal parameters.

**Possible Causes**
1. Wrong Measure of Closeness
2. Model Structural Parameterization
3. Poorly Informative Data
4. Weak Optimization Method

FROM -- Parameter Estimation as Optimization Problem

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TO -- Parameter Estimation as Progressive Uncertainty Reduction

Modern parameter estimation methods are based in a philosophy of progressive parameter uncertainty reduction.

The understanding is that:
Model identification consists of an infinite series of steps in which the initial (large) uncertainty is progressively reduced by bringing more understanding and information to bear on the problem.

The final estimated model will always have some remaining uncertainty.

Parameter Est. as a Process of Progressive Uncertainty Reduction

Impossible to reduce model uncertainty (structure & parameters) to zero, even if we have perfect (noise free) input-output data.

The best we can achieve is some minimal (representative) set of models that closely and consistently approximates (in an uncertain way) the observed behavior of the system.