Optimization in Ground-Water Modeling

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General Issue

• Numerical ground-water models are powerful tools for simulating hydrogeologic systems and water-resource development and management strategies.

• Trial-and-error use of numerical models to determine ‘best’ operating policies is difficult because of the complex nature of ground-water systems and the large number of engineering, legal, and economic facts that can affect water-resource development and management.
Example Ground-Water Management Problems

- Evaluate effects of various withdrawal scenarios on GW system
  - Simulated water-level declines
  - Simulated effect on saltwater intrusion
  - Simulated streamflow
- Simulate conjunctive use of ground-water and surface-water resources
- Simulate ground-water withdrawals from multiple aquifers

*Water-supply well house near a stream, Rhode Island*
Alternative Approach

Use simulation-optimization modeling—
Combines ground-water modeling with mathematical management-modeling techniques* to determine optimal ground-water management strategies given a specific management objective and set of management constraints

*such as linear and nonlinear programming
General Approach for Optimization Modeling

1. Identify water-management problem
2. Collect water-resource management information
3. Collect and analyze hydrologic and hydrogeologic data
4. Define water-resource management objectives and constraints
5. Develop and calibrate a ground-water simulation model
6. Link simulation and management models
7. Apply optimization model

USGS
What Are the inputs needed for an Optimization Model?

- **Objective**
  - The objective function is used to identify the best solution among many possible solutions. The function is written in terms of one of the model decision variables (heads, withdrawals, or streamflow for example). This function may be maximized or minimized.
    - Ex) maximize withdrawals

- **Constraints**
  - Limits on physical system that must be satisfied
    - Ex) specified minimum water levels

- **Locations of potential withdrawal sites**
Example Objectives

- Maximize ground-water withdrawals from a set of available wells
- Minimize water-level declines under a wetland
- Minimize streamflow depletions to protect aquatic ecosystems
- Minimize costs:
  - To pump wells
  - To capture and contain a plume
Example Constraints

- Meet minimum water-supply demands
- Limit water-level declines (drawdowns) to specified maximum values
- Maintain absolute minimum water levels
- Maintain minimum streamflow
- Limit streamflow reductions to specified maximum values
- Upper and lower bounds on pumping rates at wells
What Are the Outputs of an Optimization Model?

- Timing, rates, and locations of withdrawals at wells
- Timing, rates, and locations of injection at wells or discharge to artificial-recharge basins
- Timing, rates, and locations of interbasin transfers

- In simulation modeling alone, these variables are specified
Why is Optimization Modeling Useful?

- Explicitly accounts for management objectives and constraints within the modeling process
- Avoids trial-and-error process of testing alternative management strategies
- Provides a means to understand tradeoffs between various constraints and possible uses of groundwater resources
- Improves the understanding of the hydrogeologic system
Example Application: Estimation of sustainable yield from the Mississippi River Valley alluvial aquifer, Southeastern Arkansas

- **Objective:**
  - Maximize ground-water production from the alluvial valley and two stream withdrawal locations

- **Constraints:**
  - Water levels must remain greater than half the predevelopment saturated thickness of the aquifer
  - Simulated streamflow is required to remain above minimum levels regulated by the Arkansas Soil and Water Conservation Commission
  - Minimum and maximum pumping rates at wells

- **Output (Decision Variables):**
  - Long-term average pumping rates from 1,841 simulated well locations.

Location of Mississippi River Valley alluvial aquifer in southeastern Arkansas
Simulated water levels in the Mississippi River Valley alluvial aquifer using (A) 1997 withdrawal rates and (B) sustainable-yield withdrawal rates calculated with the optimization model.
Example Application: Effects of Minimum Instream-Flow Criteria on Ground-Water Development, Big River Basin, RI

• Objectives:
  • Determine maximum withdrawal rates
  • Evaluate tradeoffs between potential instream-flow criteria and maximum withdrawals rates

• Constraints:
  • Minimum instream-flow criteria defined by State
  • Water-supply demands
  • Maximum pumping rates at wells

• Output (Decision Variables):
  • Monthly pumping rates at the 13 wells (156 variables determined by the model)

General Water-Resource Issue: Ground-Water Withdrawals Reduce Streamflow
Well Sites and Streamflow-Constraint Locations, Big River Basin
Ground-Water Withdrawals Calculated for Alternative Definitions of Minimum Instream-Flow Criteria

MINIMUM STREAMFLOW CRITERION, IN CUBIC FEET PER SECOND PER SQUARE MILE

AVERAGE ANNUAL GROUND-WATER WITHDRAWALS, IN MILLION GALLONS PER DAY

.2 cfs change from:
A-B, reduces withdrawals by 2.5 MGD
B-C, reduces withdrawals by 6 MGD
Optimization-Modeling Tools

• **GWM:** a new process for MODFLOW-2000:
  o Available through USGS Ground-Water Software site: [http://water.usgs.gov/software/ground_water.html](http://water.usgs.gov/software/ground_water.html)
  o GWM can handle many, though not all, of the example management problems, objectives, and constraints described here
    o Can maximize/minimize withdrawals
    o Cannot maximize/minimize heads/drawdowns/streamflow at this time

• **Others:** MODMAN, MODOFC, MGO, SOMOS
Example Instream-Flow Criteria

- Median of Average Monthly Streamflow
- USFWS Seasonal ABF
- Modified ABF

 ESTIMATED STREAMFLOW, IN CUBIC FEET PER SECOND

Ground-Water Withdrawals Calculated for Alternative Definitions of Minimum Instream-Flow Criteria

Point referred to in text:
A. MM01A Hydrologic limit (0 CFSM; 16 Mgal/d)
B. MM01B Connecticut minimum flow standard (0.25 CFSM; 15 Mgal/d)
C. MM01C Wetted-perimeter method (0.41 CFSM; 13.5 Mgal/d)
D. MM01D Modified USFWS aquatic baseflow (0.5 CFSM; 12 Mgal/d)
E. MM01E R2Cross method (0.72 CFSM; 5.1 Mgal/d)