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

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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

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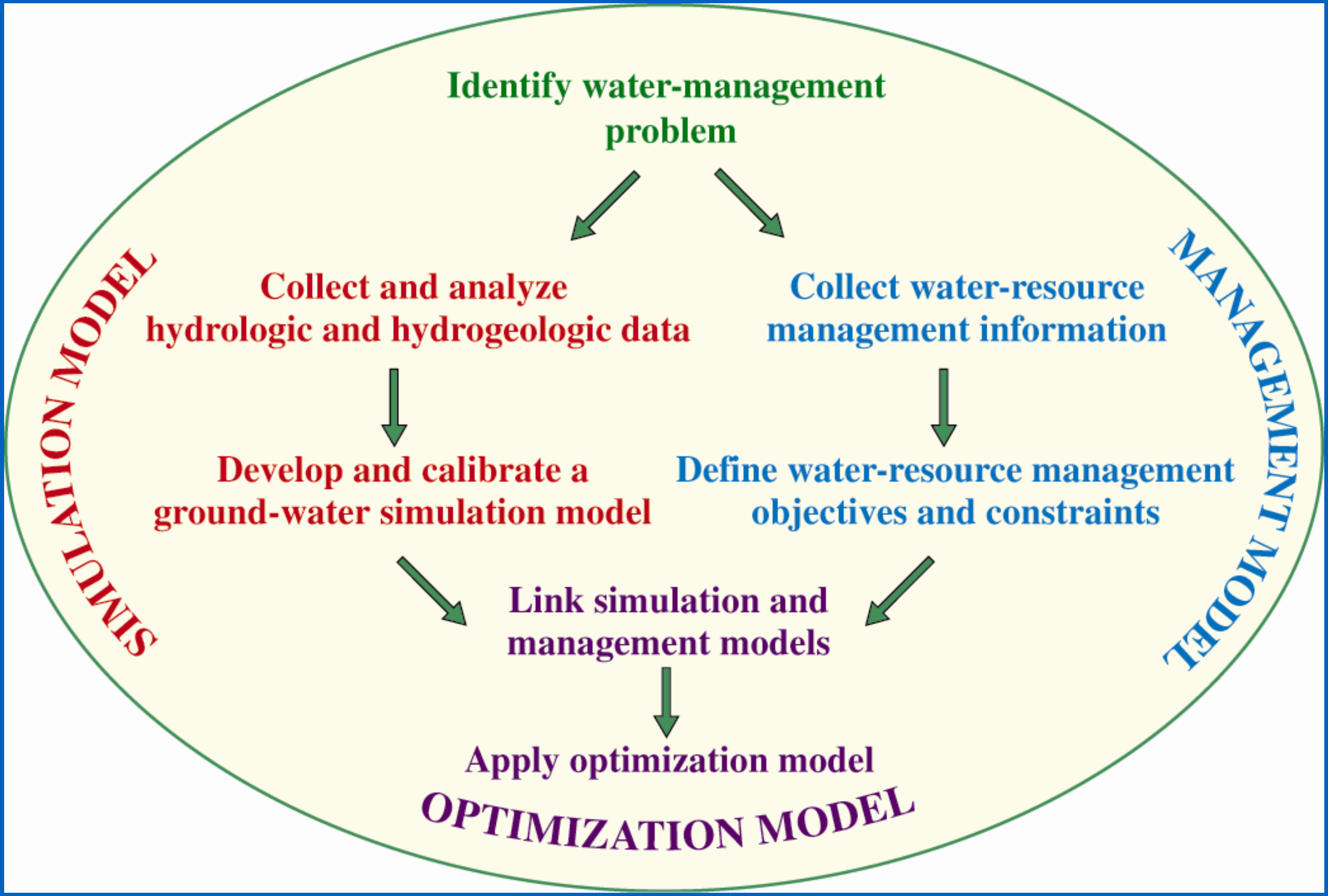
Alternative Approach

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



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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

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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

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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*

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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 ground-water resources
- Improves the understanding of the hydrogeologic system

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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.

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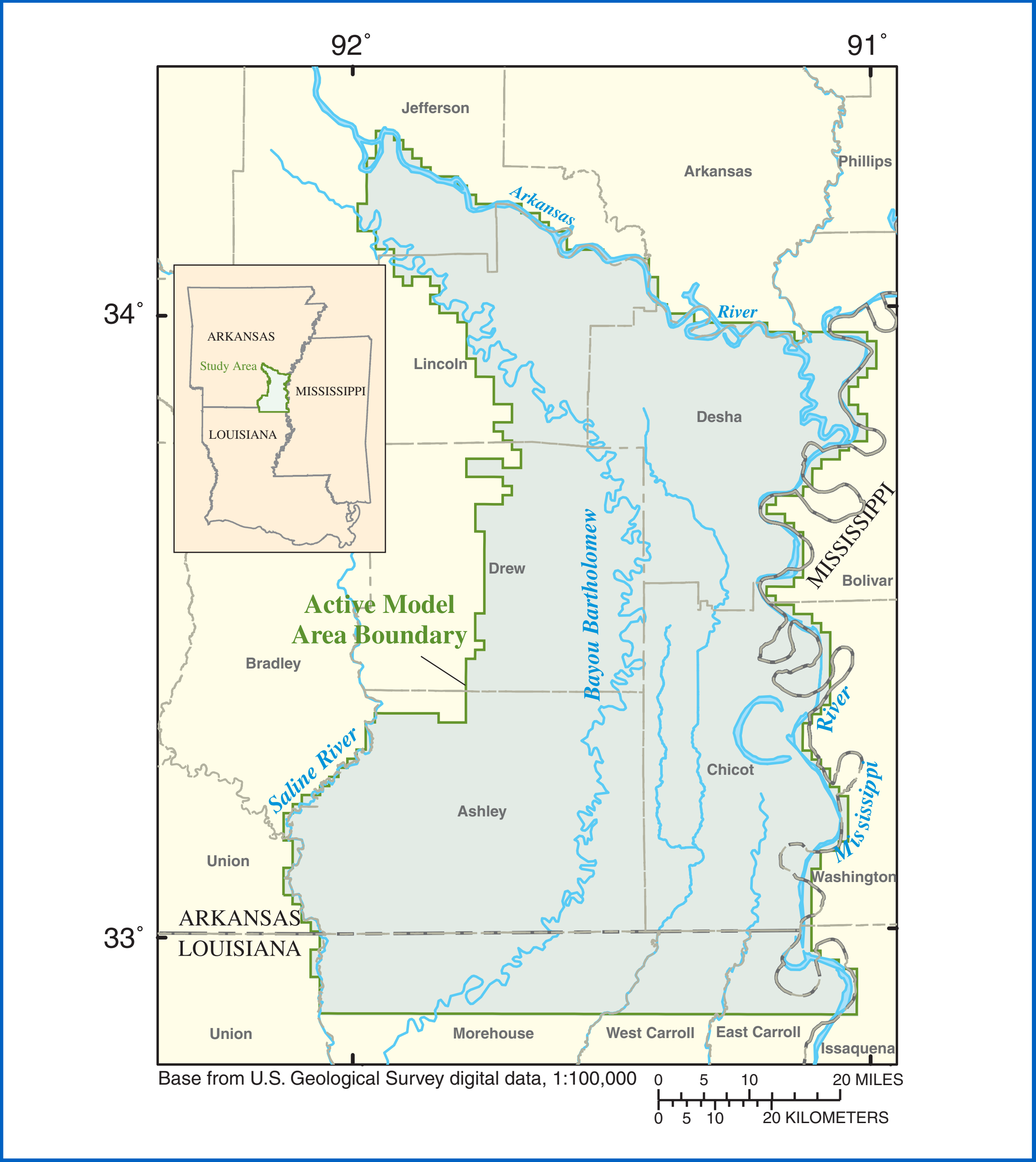
Czarnecki, J.B., Clark, B.R., and Stanton, G.P., 2003, Conjunctive-use optimization model of the Mississippi River Valley alluvial aquifer of southeastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 03-4233, 26 p.

Location of Mississippi River Valley alluvial aquifer in southeastern Arkansas



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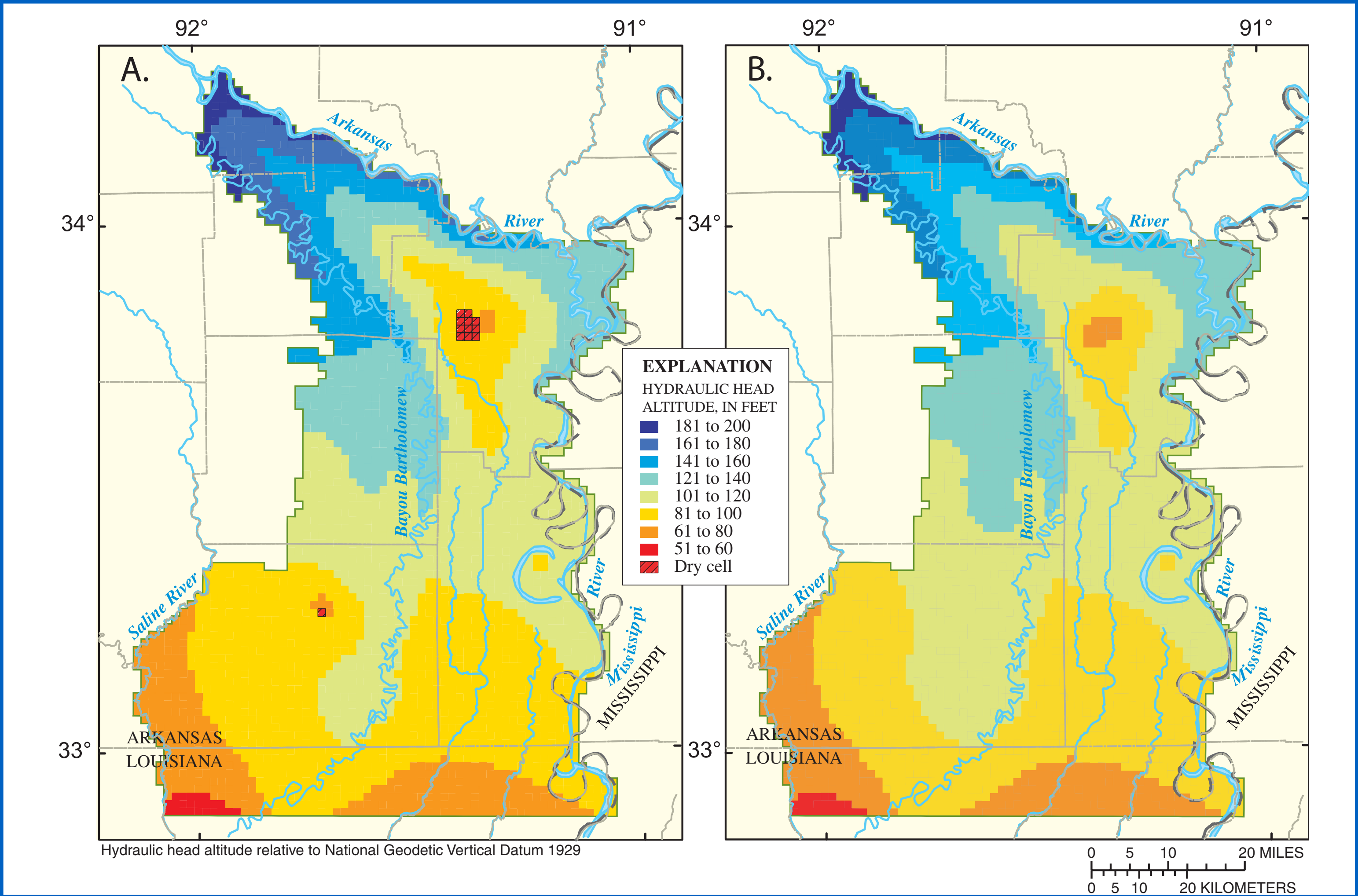
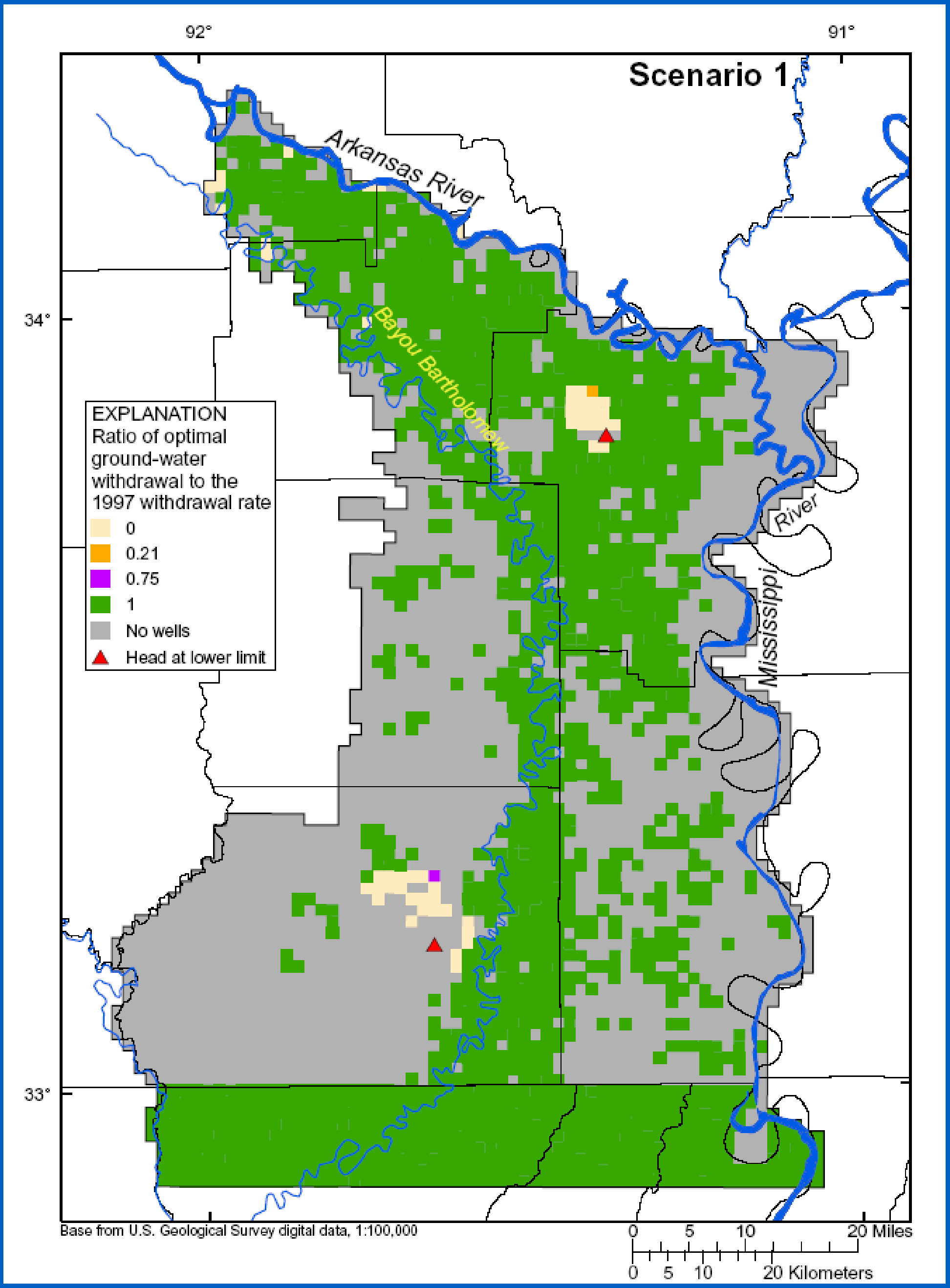
Simulated water levels in the Mississippi River Valley alluvial aquifer using (A) 1997 withdrawal rates and (B) sustainable-yield withdrawal rates calculated with the optimization model.





92°
91°
Scenario 1
34°
33°
Arkansas River
Bayou Bartholomew
River
Mississippi
EXPLANATION
Ratio of optimal ground-water withdrawal to the 1997 withdrawal rate
0
0.21
0.75
1
No wells
Head at lower limit
Base from U.S. Geological Survey digital data, 1:100,000
0 5 10 20 Miles
0 5 10 20 Kilometers

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)

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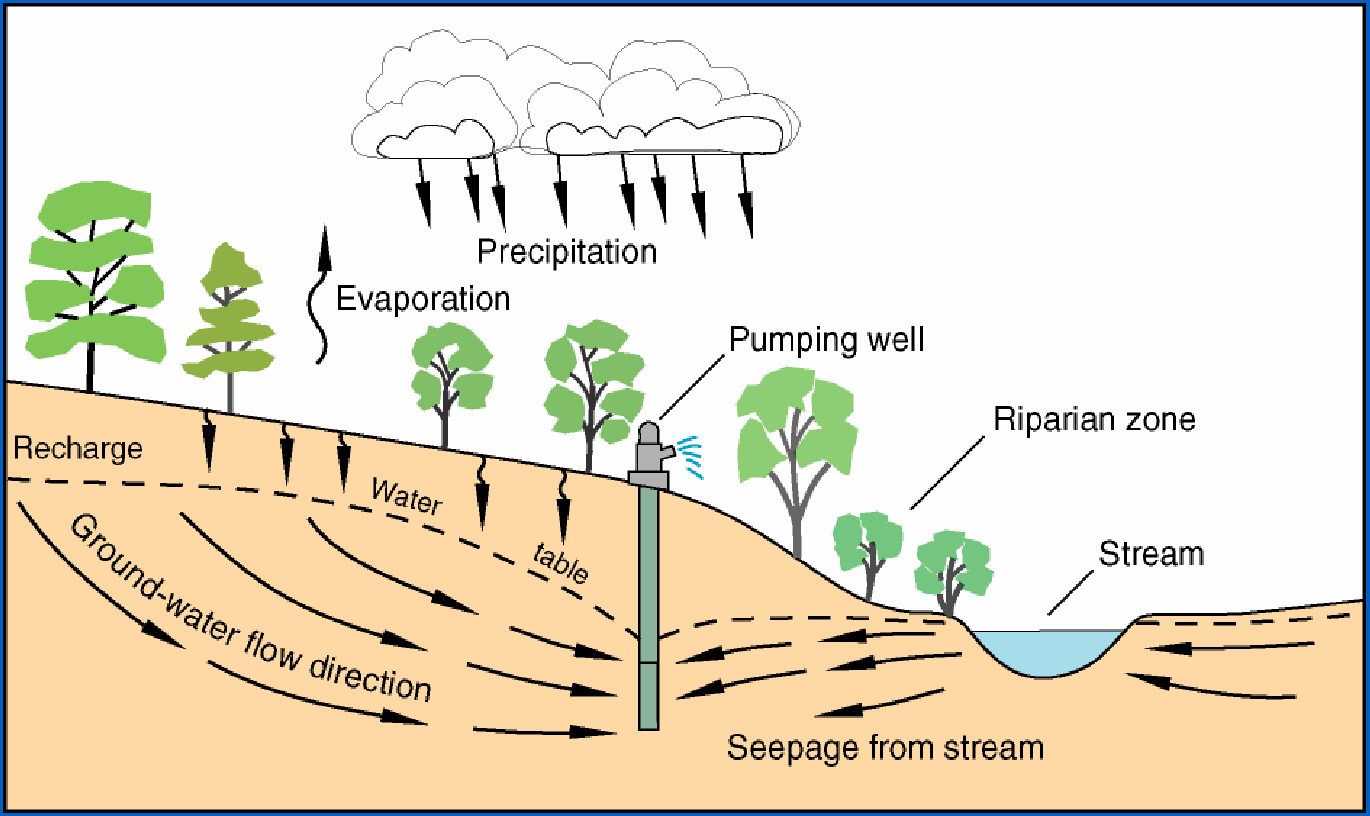
Granato, G.E., and Barlow, P.M., 2005, Effects of alternative instream-flow criteria and water-supply demands on ground-water development options in the Big River area, Rhode Island: U.S. Geological Survey Scientific Investigations Report 2004-5301, 110 p.

General Water-Resource Issue: Ground-Water Withdrawals Reduce Streamflow



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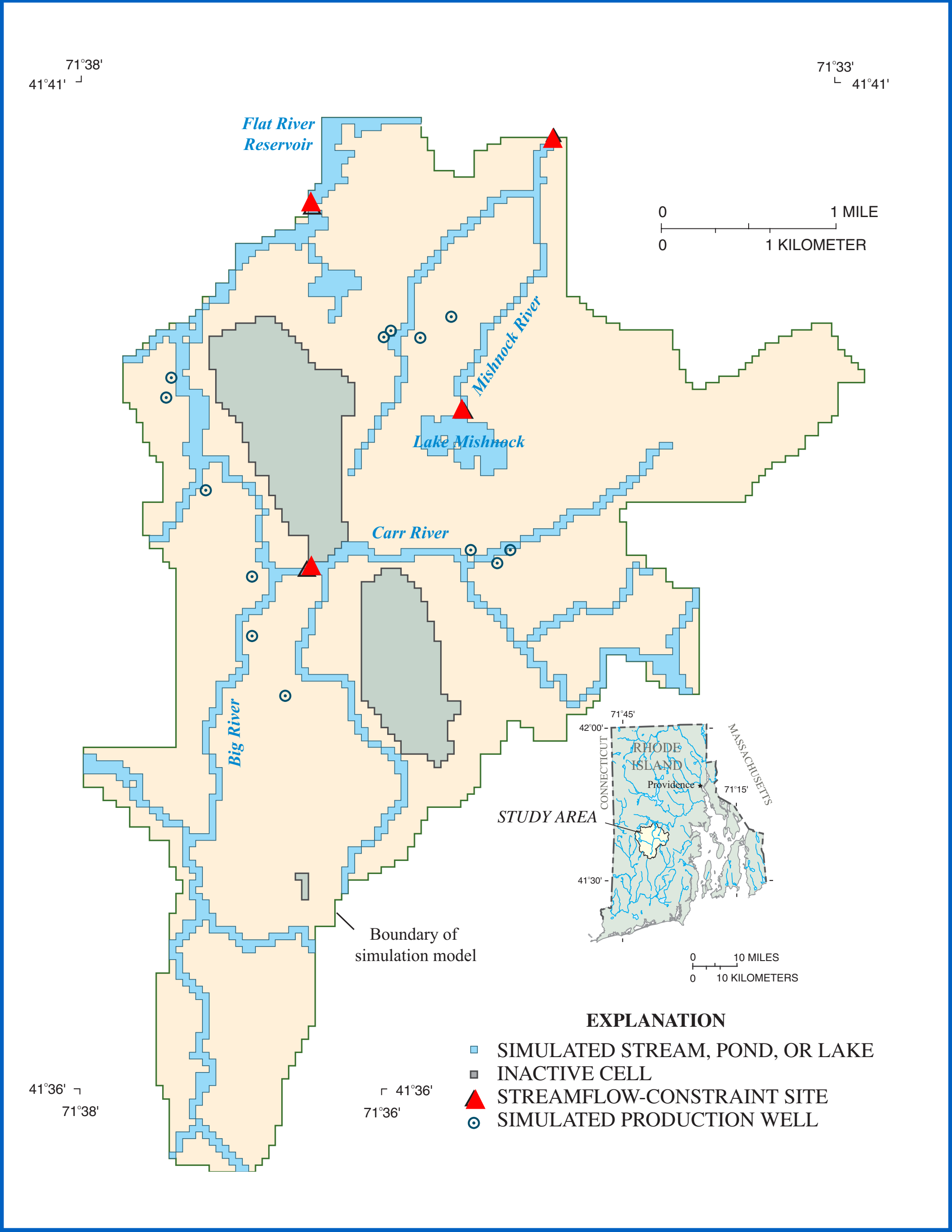
Well Sites and Streamflow-Constraint Locations, Big River Basin



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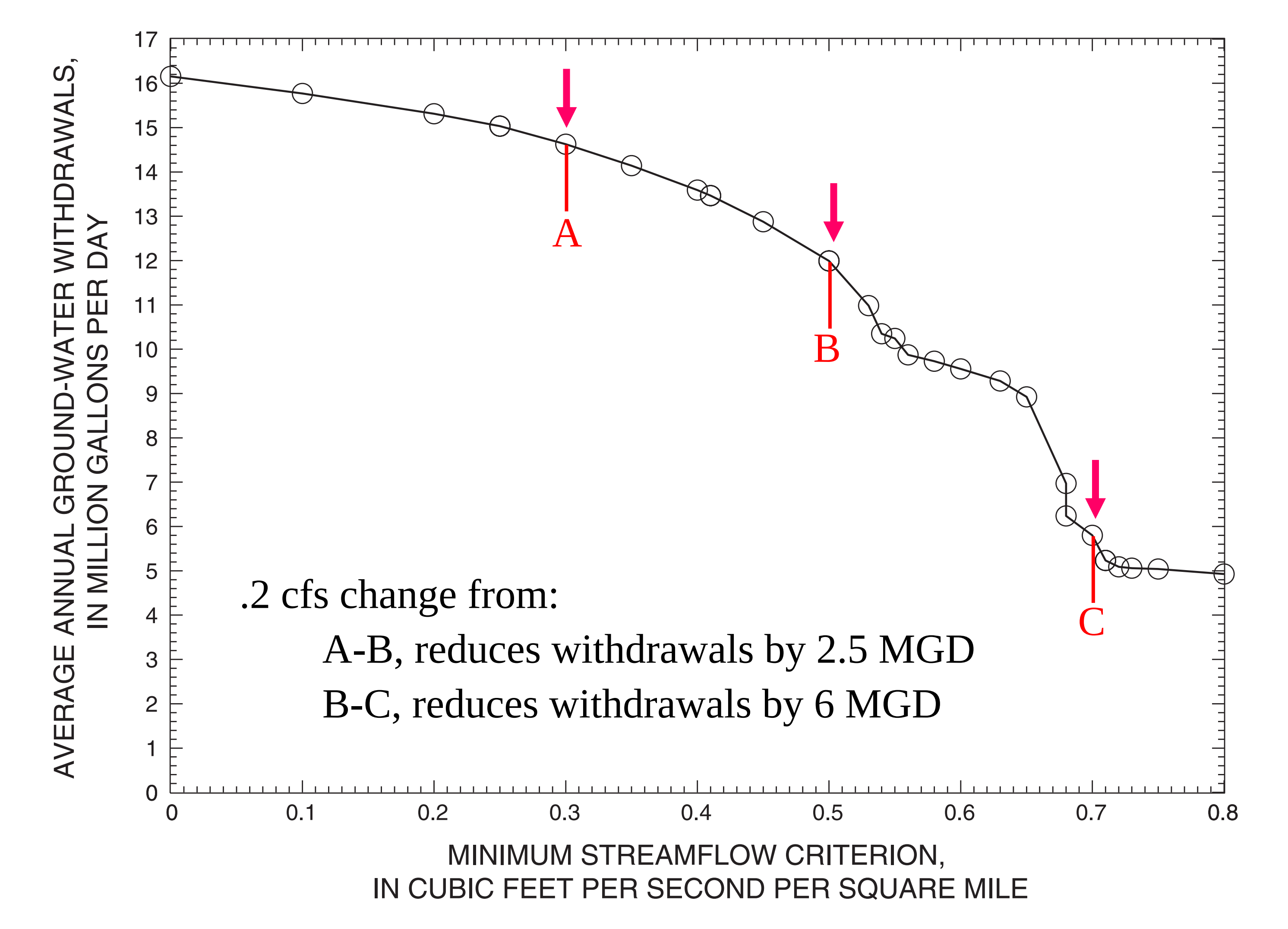
Ground-Water Withdrawals Calculated for Alternative Definitions of Minimum Instream-Flow Criteria



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Optimization-Modeling Tools

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

- Others: MODMAN, MODOFC, MGO, SOMOS

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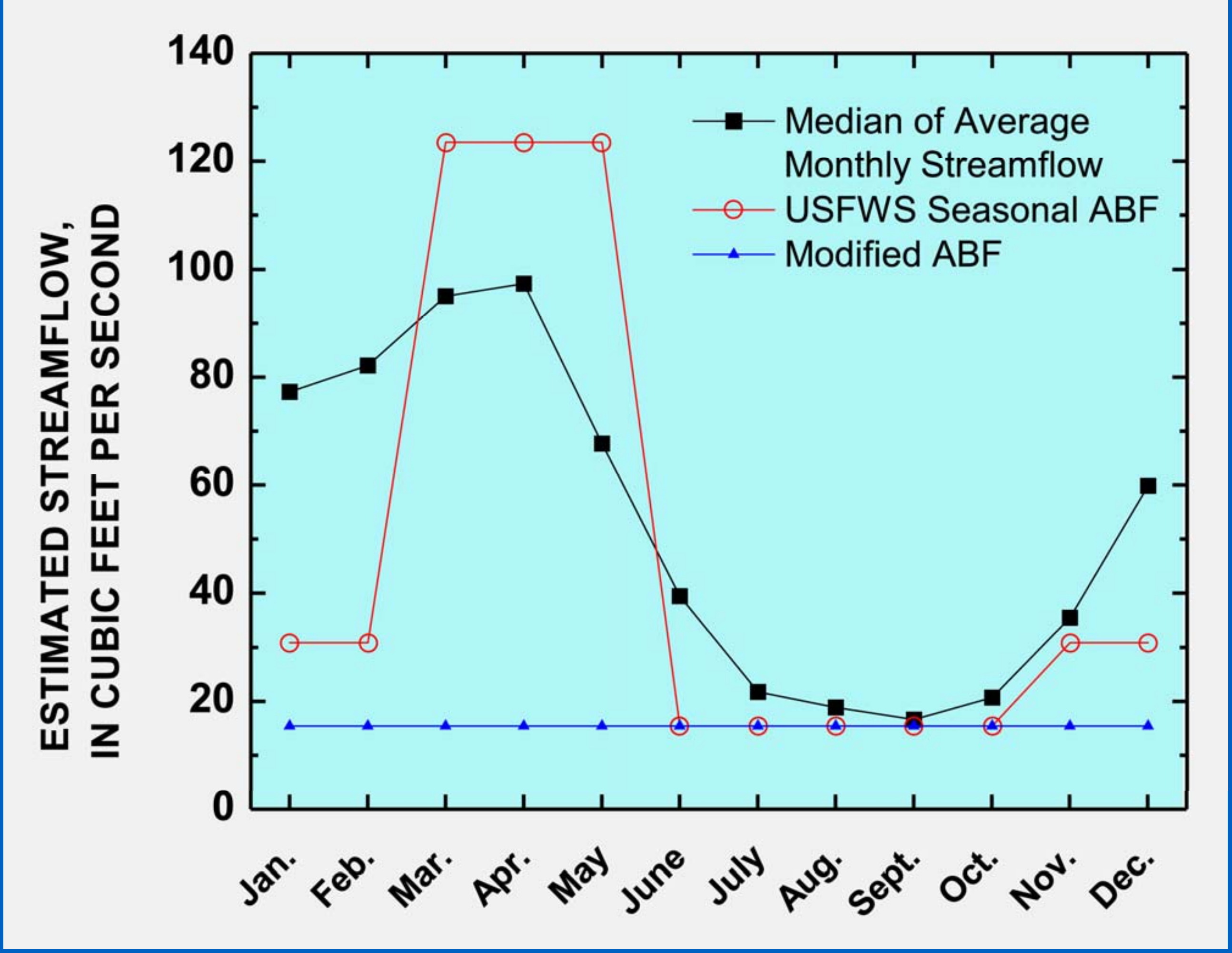
Example Instream-Flow Criteria



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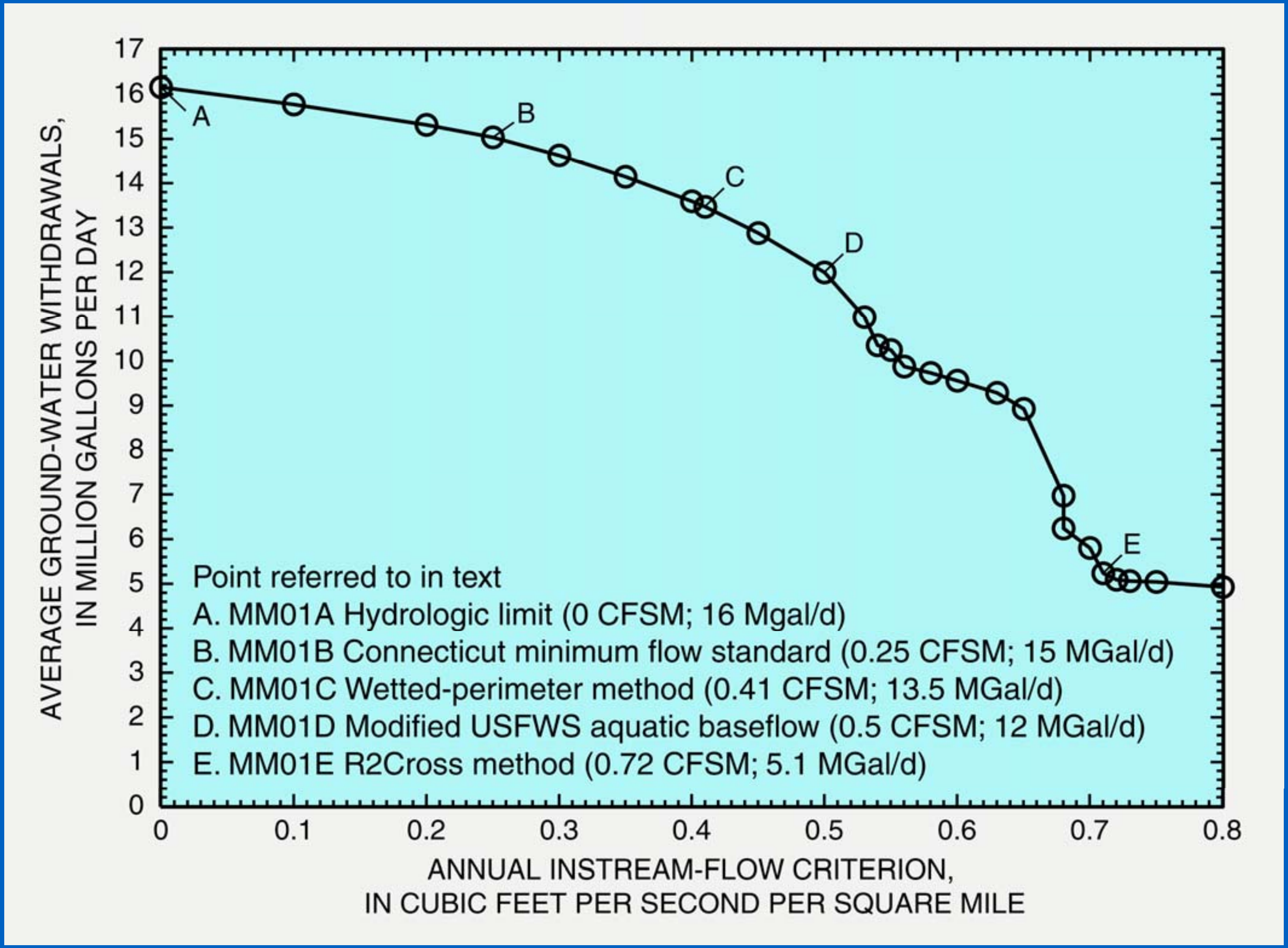

Ground-Water Withdrawals Calculated for Alternative Definitions of Minimum Instream-Flow Criteria

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