Simulation-Optimization Modeling for Management of Groundwater Resources: Overview and Selected Applications of GWM-2005, the Groundwater Management Process for MODFLOW-2005

USGS Texas Water Science Center

San Antonio, March 18, 2015

Many types of groundwater-management problems

- Maximize groundwater yields from a basin
- Control water-level declines
- Control saltwater intrusion
- Conjunctively use groundwater and surface-water resources

Flood irrigation of rice, Mississippi Delta
(photo by David Burt, USGS)

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Modeling Tools for Management

- Simulation models
  - Predict heads, concentrations, saturation, etc.
  - Predict system responses to stress
- Management models (simulation-optimization modeling)
  - Specify desired system-state outcomes
  - Management model determines stresses needed to achieve desired state

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Simulation-Optimization Approach

Construct Simulation Model

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Define Management Goals and Constraints

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Mathematically Formulate Optimization Problem

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Solve Combined Simulation-Optimization Model

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Building a Management Formulation—Components of an Optimization Model

- Objective Function
  - Maximize withdrawals
  - Minimize drawdowns
- Constraints
  - Upper and lower bounds on pumping rates
  - Maximum drawdowns; maximum rates of streamflow depletion
  - Minimum water-supply demands
- Decision Variables
  - Quantifiable controls (decisions) whose values are determined by solution of the model

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Outputs of an Optimization Model: Values for the Decision Variables

- 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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GWM Process for MODFLOW

- A MODFLOW Process that links optimization techniques with the MODFLOW groundwater simulator.
- Developed for both MODFLOW-2000 (GWM-2000) and MODFLOW-2005 (GWM-2005)
- Available on USGS GW Software Page: http://water.usgs.gov/software/lists/groundwater/
- Documentation:
  - Available on the distribution webpage
  - Also recommend: Ahlfeld and Mulligan, 2000, *Optimal management of groundwater flow*: Academic Press

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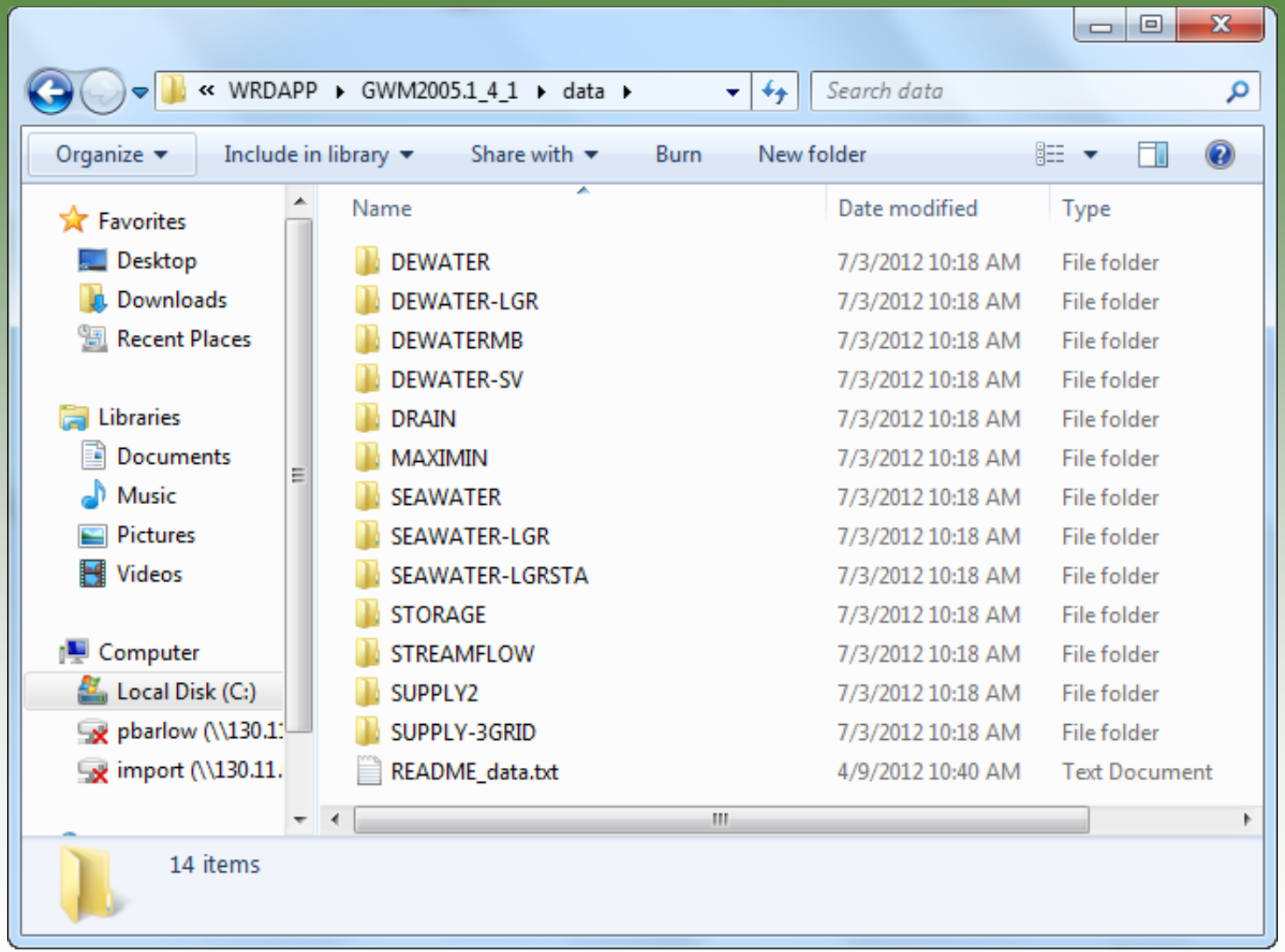
Sample Problems



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GWM Capabilities

- Decision Variables
- Objective Function
- Constraints
- Solution Procedures

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Decision Variable Types

- Flow-rate variables (Qw_n):
  - Withdrawal (discharge) or injection (recharge) flow rate at a managed well site
  - Can represent wells or artificial recharge basins
- External variables (Ex_m):
  - External sources or sinks of water that do not directly affect the flow system
- Binary variables (I_l; 0 or 1):
  - Define the status of each flow-rate or external variable

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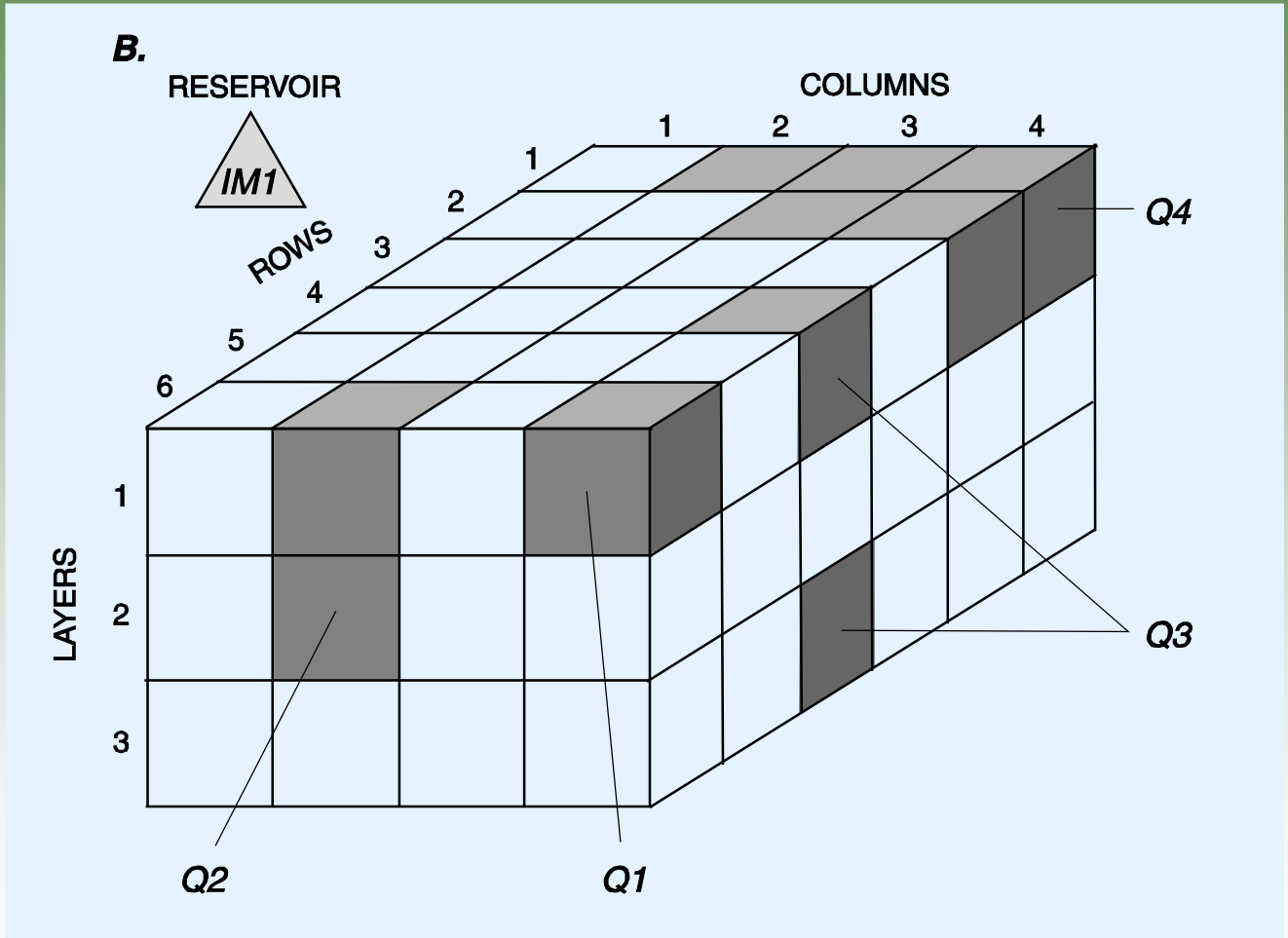
Examples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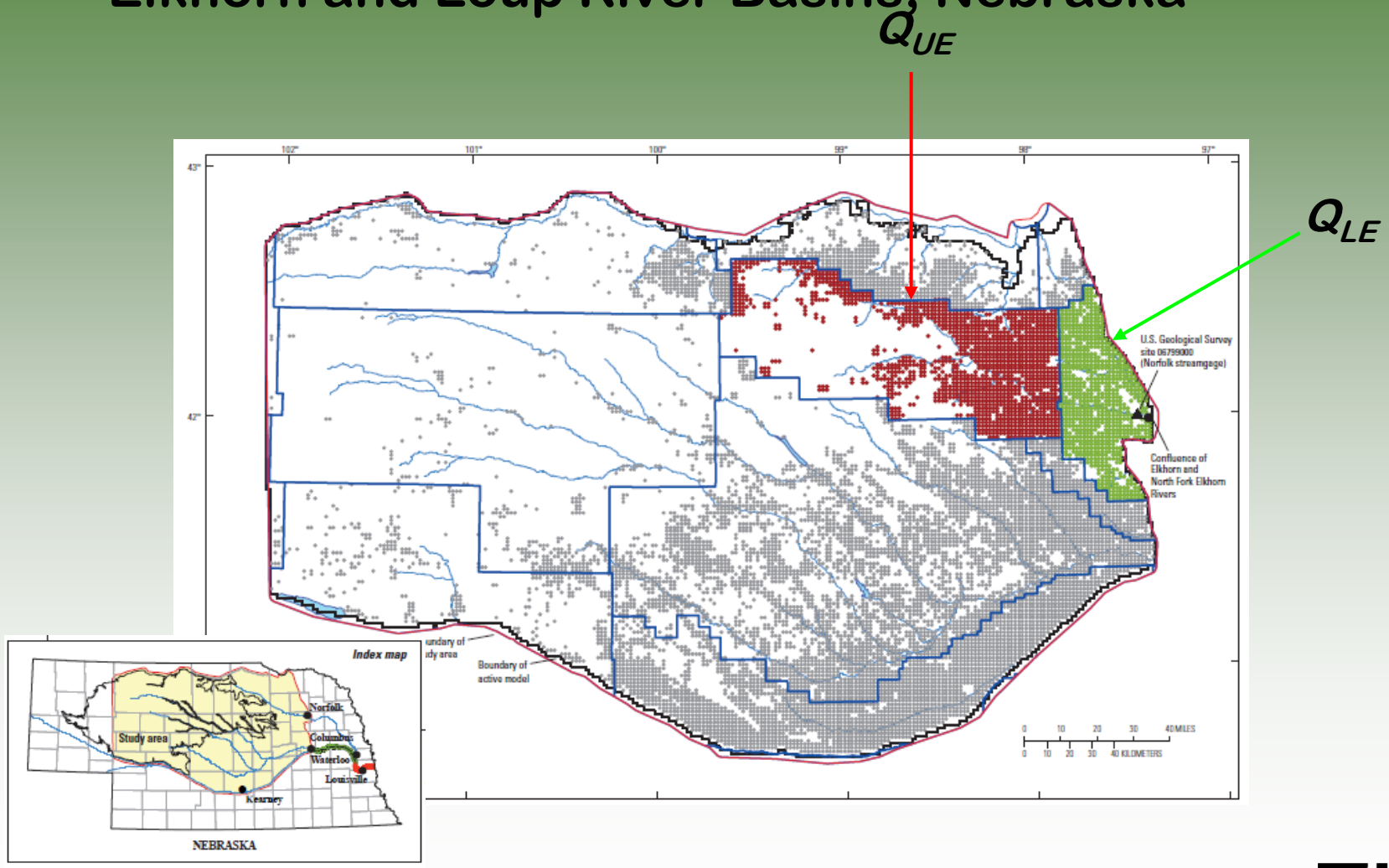
Q4

- **Example application illustrating flow-rate variables Q_{UE} and Q_{LE} extending over many cells (wells), Elkhorn and Loup River Basins, Nebraska**



From Stanton, Peterson, and Fienen, SIR 2010-5149.

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Decision Variable Types

- State variables (S_r):
  - Any simulated condition that defines the state of a gw flow system or coupled gw/sw system
  - State variables currently supported in GWM: heads, streamflows, drainflow to a set of drain cells, changes in aquifer storage

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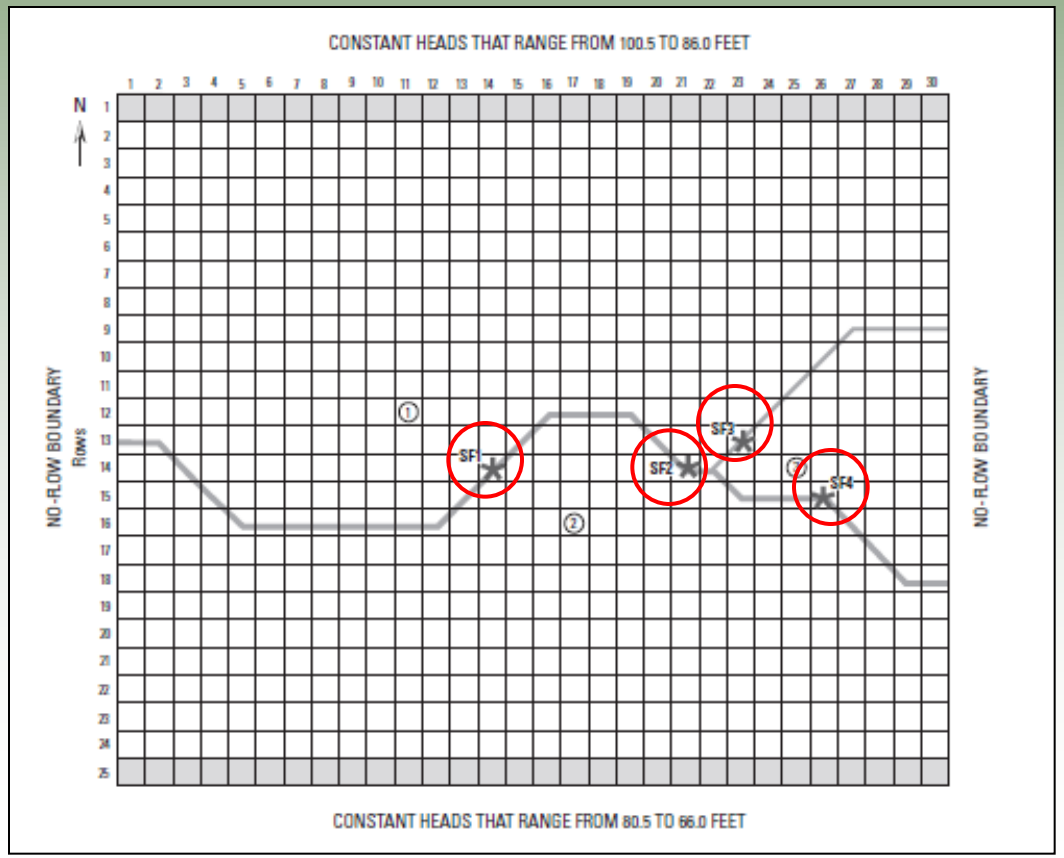
Uses of State Variables in a Management Formulation

- In the Objective Function
  - Example: Maximize sum of streamflows at locations of interest within a basin



Uses of State Variables in a Management Formulation

- As part of the Constraint Set (Linear Summation Constraints)
  - Head at observation well ≥ 10 ft
  - Control aquifer-storage depletions over time

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Objective Function

- Minimize or maximize the weighted sum of the four types of decision variables:

$$\sum_{n=1}^{N} \beta_n Qw_n T_{Qw_n} + \sum_{m=1}^{M} \gamma_m Ex_m T_{Ex_m} + \sum_{l=l}^{L} \kappa_l I_l + \sum_{r=1}^{R} \xi_r S_r T_{S_r}$$

- Examples
  - Maximize withdrawals
  - Minimize interbasin transfers of surface water
  - Minimize cost of number of supply wells built
  - Minimize drawdowns

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Constraint Types

- Upper/Lower Bounds on Decision Variables
- Linear Summations of the Decision Variables or State Variables:
  - Sum of withdrawals at managed wells must be $\geq$ demands. Example: $Q_1 + Q_2 + Q_3 + Q_4 \geq D$
  - Total number of pumping wells $\leq$ specified #
- Hydraulic heads, drawdowns, gradients
- Streamflows and streamflow depletions (using the STR or SFR Packages)

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Solution Procedures

- Based on the Response Matrix technique:
  - Linear formulation solved using linear programming (simplex algorithm)
  - Nonlinear-formulations solved using sequential linear programming
  - Mixed binary (integer) formulations solved using branch-and-bound algorithm

- All solution techniques are incorporated directly into GWM

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Applications of GWM

- Several have been published or are in progress for a wide range of management issues:
  - East-Central New Jersey (USGS SIR 2007-5193)
  - Elkhorn and Loup River Basins, Nebraska (USGS SIR 2010-5149)
  - Central Michigan (USGS SIR 2009-5244)
  - Other research-oriented applications published in journals (Rhode Island, California, Spain)
  - Western Nebraska
  - Denver Basin, Colorado
  - Yuma area, Arizona
  - Private-sector applications

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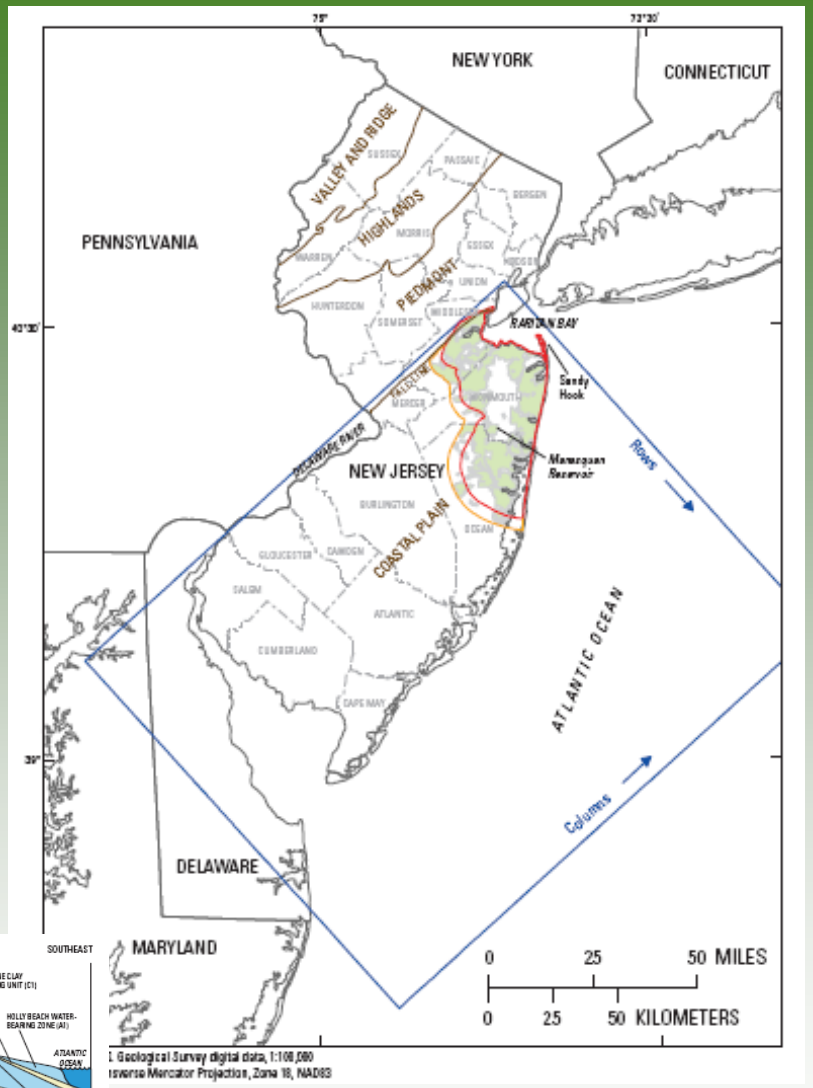
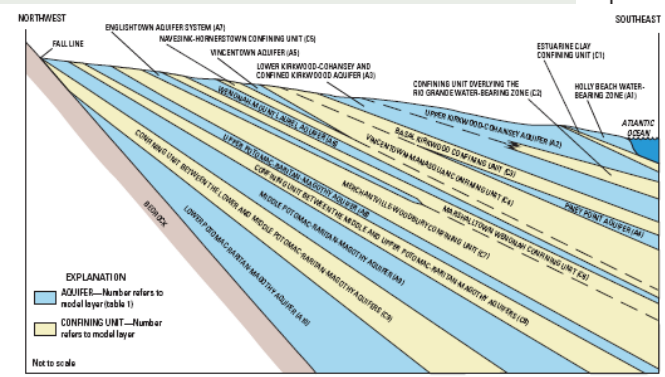
- Maximize additional groundwater withdrawals while maintaining
  - acceptable drawdowns
  - movement of the freshwater-saltwater interface
  - streamflow depletions
- Coastal plain of NJ
- Spitz and others, 2008, USGS SIR 2007-5193





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Formulation

- Decision Variables: Long-term (steady state) withdrawal rates at ~100 wells

- Objective Function: Maximize total additional withdrawals (above 2003 rates) from four aquifers of interest

- Constraints
  - Maximum allowable drawdowns to prevent excessive withdrawals from two of the aquifers
  - Minimum allowable heads near northern boundaries of the PRM aquifers to limit sw intrusion and streamflow depletion
  - Maximum allowable drawdowns along southern boundaries of the PRM aquifers to limit sw migration
  - Maximum withdrawal rates at wells

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Example Results: Alternative Well Networks

- Current well network:
  - 7.0 Mgal/d of additional withdrawals
- "Clean slate" network: regularly spaced well network with all wells managed:
  - 11.9 Mgal/d of additional withdrawals

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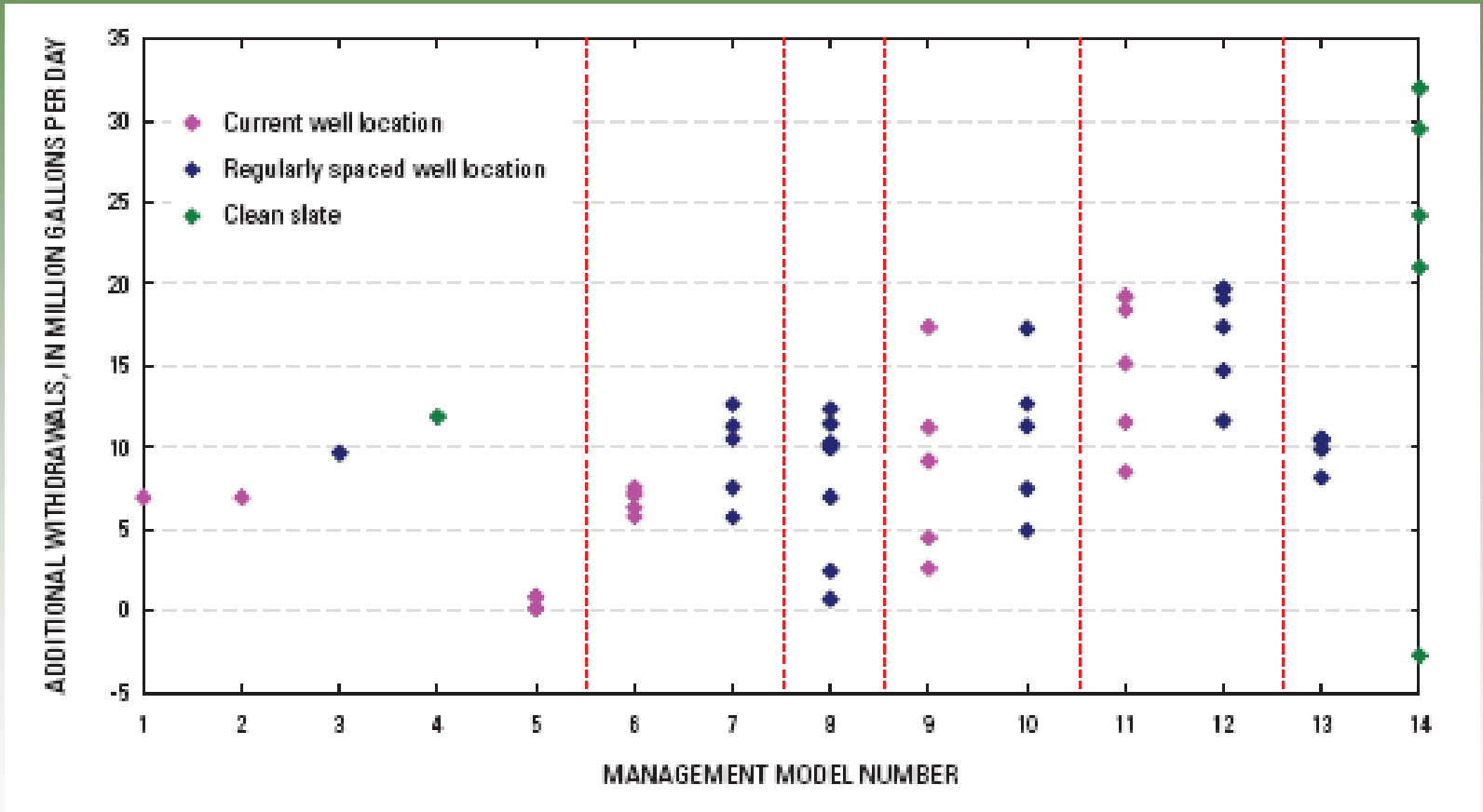
- **Many alternative formulations evaluated to determine tradeoffs between constraint values and optimal pumping strategies**



Wide range of additional withdrawals possible depending on constraint values specified and locations of withdrawals

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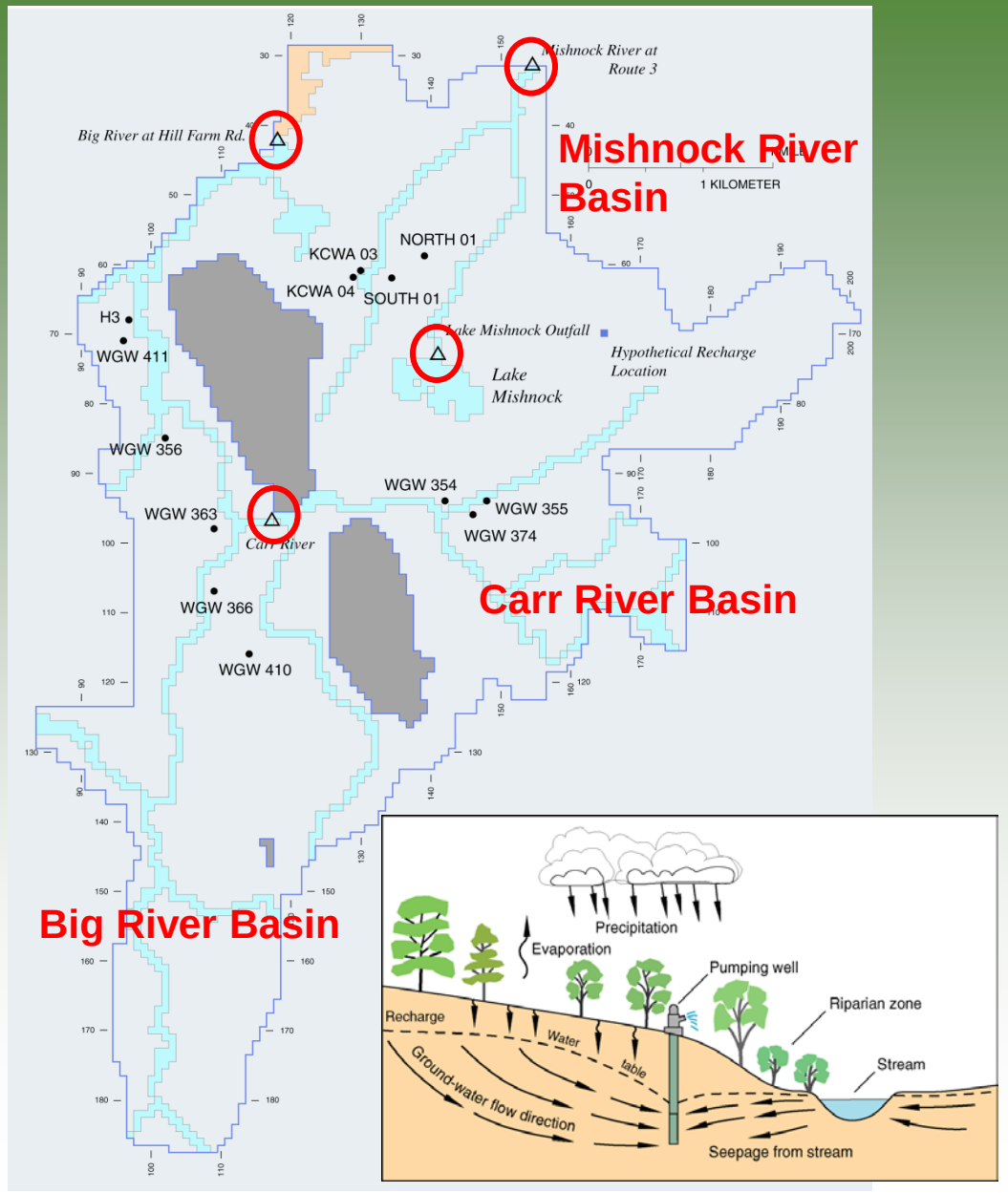
- Maximize groundwater development with constraints on streamflow depletion to protect aquatic habitat

- Stream-aquifer system of Rhode Island

- Ahlfeld and Hoque, GW, 2008, v. 46, no. 5



Formulation

- Decision Variables: Monthly withdrawal rates at wells (13 wells x 12 months = 156 variables)
- Objective Function: Maximize total annual withdrawals
- Constraints
  - Specified streamflow requirements during some or all months of the year
  - Water-supply demands, which vary by month
  - Maximum/minimum withdrawal rates at wells

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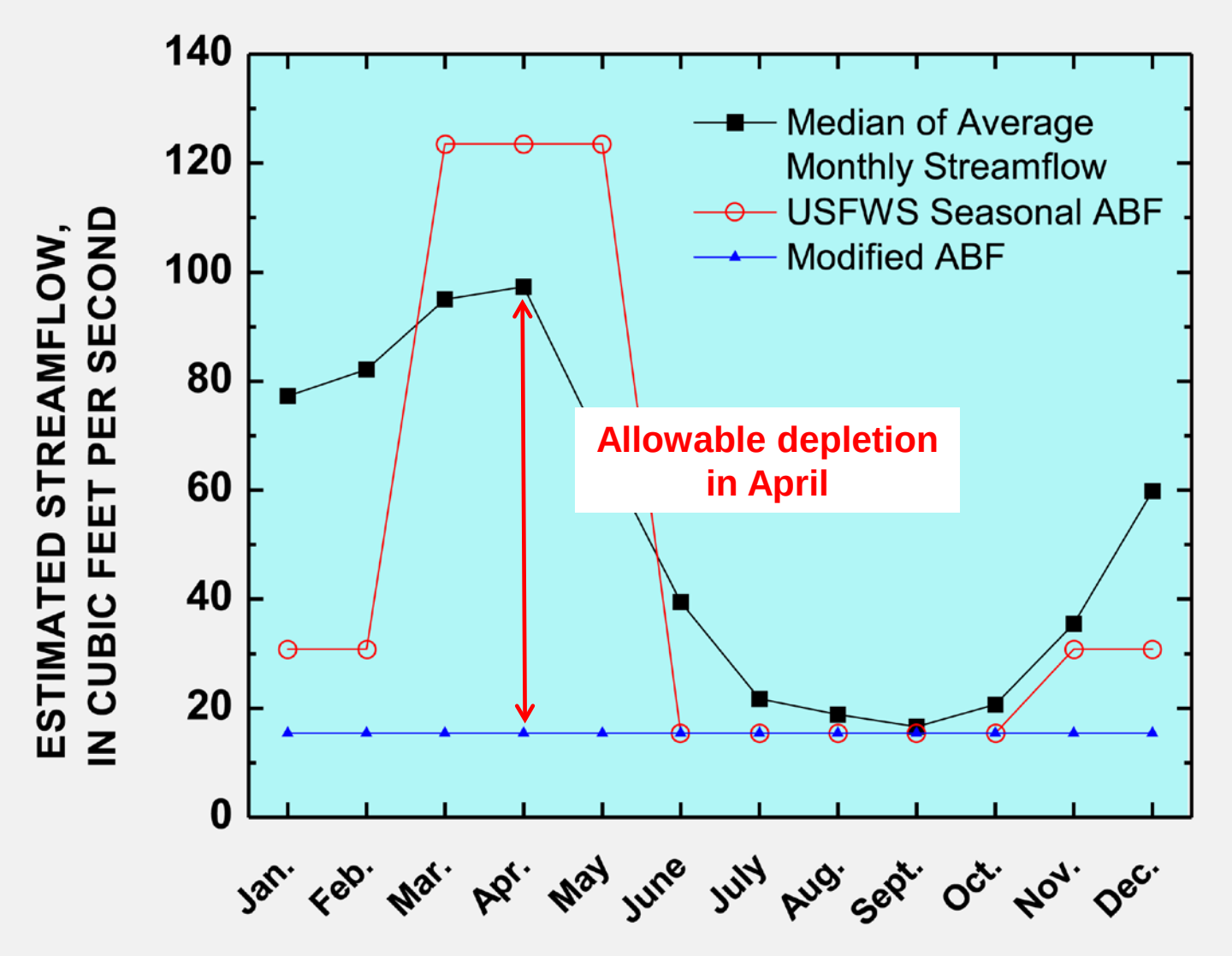
Example Streamflow and Instream-Flow Criteria for Big River at its Outflow



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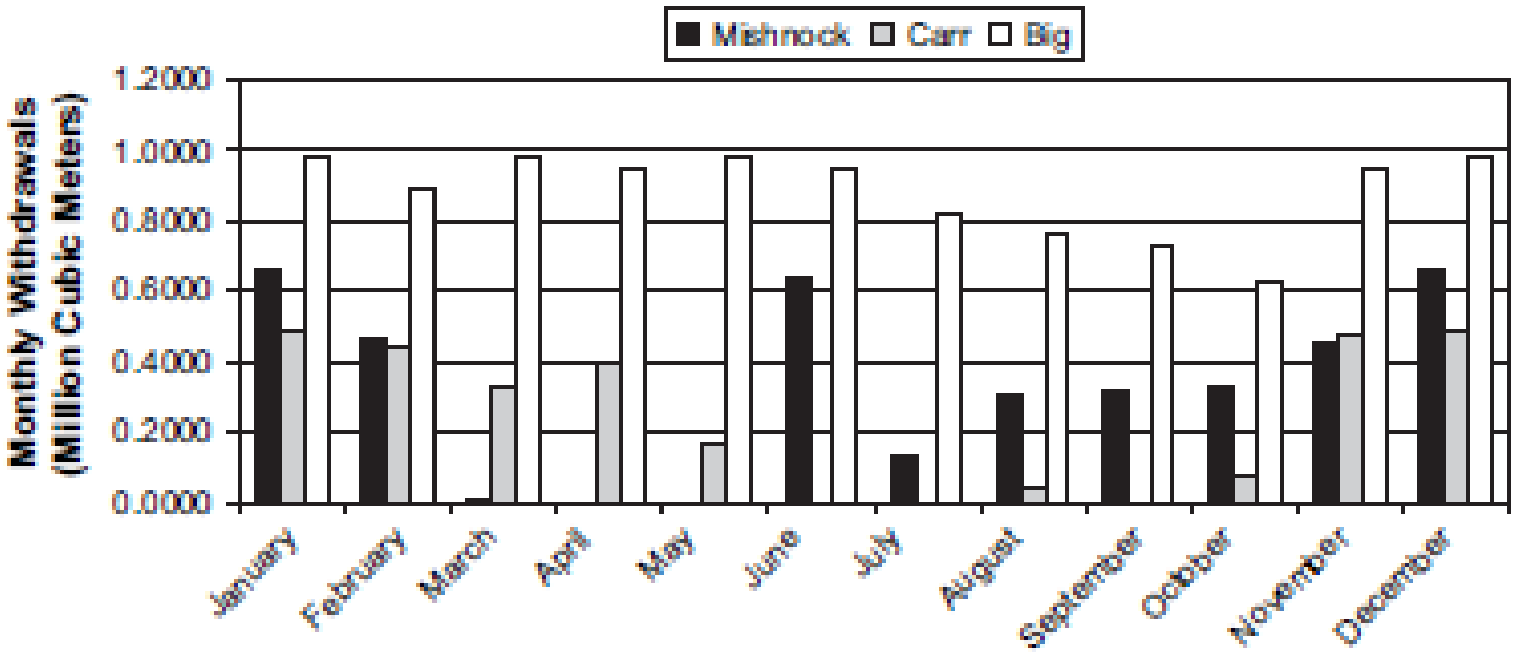
Optimal monthly withdrawal patterns for wells within each subbasin



Source: Ahlfeld and Hoque, 2008

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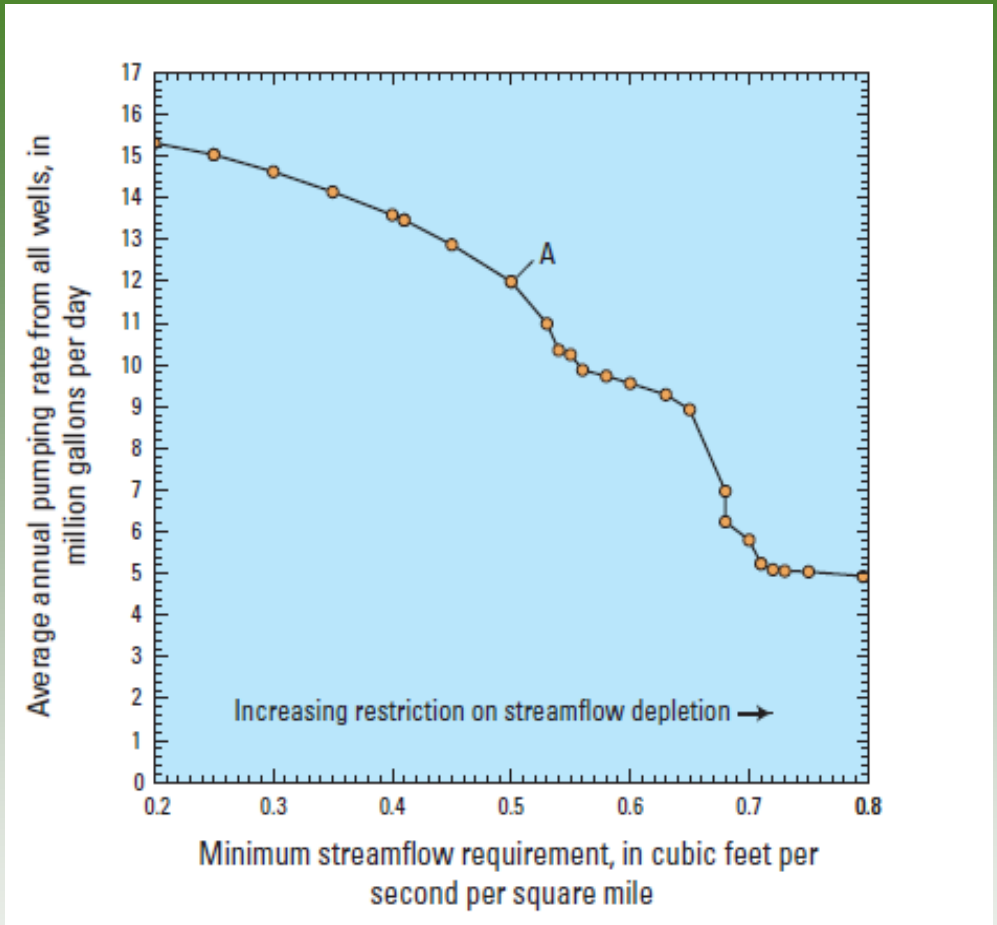
- Tradeoff analysis between instream-flow criteria and resulting optimal groundwater pumping rates

- Each point on the graph represents a single model run; each run uses a different minimum streamflow requirement (constraint): Point A is for the Modified ABF criterion



Granato and Barlow, SIR 2004-5301

(Also see SIR 2010-5149, for GWM example of streamflow/pumping tradeoff analysis, High Plains aquifer)

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Questions?

- GWM available on USGS Webpages: http://water.usgs.gov/ogw/gwm/
- pbarlow@usgs.gov

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