2004

Optimization modeling for groundwater and conjunctive use water policy development

R. C. Peralta
Utah State University

R. Shulstad

Recommended Citation

Peralta, R. C. and R. Shulstad. 2004. Optimization modeling for groundwater and conjunctive use water policy development. In Proceedings of FEM-MODFLOW International Conference. Presented by Peralta in Karlovy Vary, Czechoslovakia, 13-16 Sep, 2004.

Optimization Modeling for Groundwater and Conjunctive Use Water Policy Development

RICHARD C. PERALTA
Water Dynamics Laboratory, Utah State University Research Foundation, Utah State University, Logan, UT 84322-4105, USA
e-mail: richard.peralta@usurf.usu.edu

ROBERT N. SHULSTAD
College of Agric. & Environ. Sciences, Univ. of Georgia, Athens, GA 30602-7503, USA

Abstract
Planners must sometimes decide how to restrict or reduce groundwater use to prevent unacceptable future problems. Often there are several alternatives (policies). Comparing policies can involve formulating a sustained groundwater yield optimization problem and computing an optimal groundwater pumping strategy for each. This is easy via the SOMOS simulation/optimization (S/O) model. Subsequent analysis can include: flow simulation to predict transient water level response to pumping; and economic evaluation to estimate costs and returns. Two examples predict the best consequences of potential physical and legal management policies for alluvial and valley basin fill aquifers hydraulically linked to surface waters. Results show that: incorporating a physical sustainability requirement and legal water rights can help assure long term economic viability and ecosystems; and applying a pure socially egalitarian policy can be economically disastrous.
Key words management; groundwater; conjunctive; optimization; simulation/ optimization; S/O; planning; water law; water right; SOMOS

INTRODUCTION

Predicting policy decision consequences before decisions are finalized helps avoid costly mistakes. For a particular situation, an accurate simulation/optimization (S/O) model can determine how to maximize achievement of policy goals, subject to imposed restrictions. A S/O model couples: a simulation module that can predict the consequences of management; and an optimization module that can compute the mathematically best management strategy for a posed management optimization problem.

A S/O model computes an optimal management strategy for a management problem posed by the user. A pumping (groundwater management) strategy is a set of spatially and possibly temporally distributed rates of extracting water from an aquifer. An optimal pumping strategy is mathematically the best that can be developed for its posed mathematical problem. A pumping strategy that is optimal for one problem is often sub-optimal for a different problem.

A particular posed optimization problem can be referred to as a scenario or formulation. Either includes all the assumptions necessary for specifying the optimization problem and for applying an adequate simulation model.

Modelers must input management strategies into simulation models (here termed S models), such as MODFLOW and MT3DMS. S models predict how the modeled physical system will respond to a strategy input by the user.

S/O models differ from S models because S/O models produce an optimal management strategy for the user-specified management problem. A S/O model user must input data to describe the management problem, plus data describing the physical system, but does not need to input the strategy to be simulated.

S/O models are better than S models for developing management strategies and plans. Because S/O models must have a way to predict system response to management, they incorporate S models or surrogates.

Optimal groundwater pumping strategies are readily applied in the field for situations in which relevant pumping is controllable. Peralta et al (2003) list examples of groundwater contamination remediation, using the SOMOS code (SSOL, 2001; Peralta, 2003). There, a single entity might install dozens of extraction wells to remove contaminated water and then treat it to remove the contamination (pump and treat or PAT systems).

Optimal regional groundwater management strategies are applied less commonly in the field due to difficulty in controlling all pumping rates. On a regional or aquifer scale, S/O models are most suitable for determining the best that might be attainable, for a particular scenario.

This paper describes two S/O applications to regional or aquifer scales. The models simulate and optimize groundwater or conjunctive water management for coupled river-aquifer systems. In the first case, surface water is available for diversion to an area of severe groundwater over-mining. In the second case groundwater development is restricted because it would deplete river water flow.

CASE I. CONJUNCTIVE USE ADDRESSES PROBLEM OF UNSUSTAINABLE GROUNDWATER MINING

The Arkansas Grand Prairie overlies part of the Mississippi Alluvial Aquifer (Figure 1). This is an important rice, soybean and aquaculture producing area. Historically, most of the region's water has come from a Quaternary aquifer that is part of the Mississippi Plain alluvial aquifer. Ground-water levels have been dropping in the Grand Prairie for many years, causing much potentiometric surface depression, and prompting groundwater modeling (Figure 2).

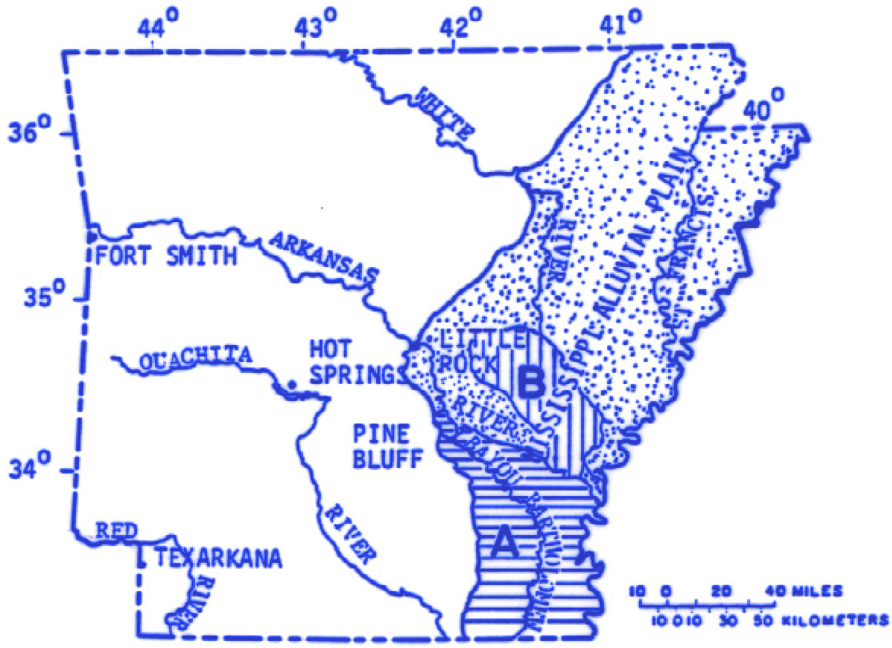

Fig. 1 Mississippi Alluvial Aquifer and groundwater study areas: (A) Bayou Bartholomew Basin, and (B) Grand Prairie.

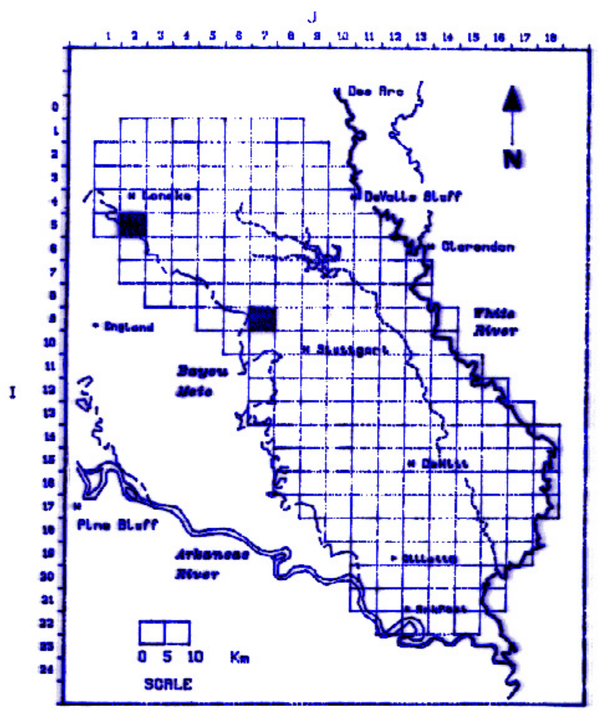

Fig. 2 Grand Prairie groundwater model grid.

Table 1 contrasts water use and short-term results of five scenarios. The Historic Use scenario assumes continuing historic use for 10 years. Scenarios I-IV use SSTAR (Peralta, et al., 1989) for optimization to evaluate four possible policies. This uses steady-state ground-water optimization, transient flow simulation, and economic evaluation.

The Scenario I objective is to maximize the common proportion, χ, of current ground-water withdrawals that can be pumped from each cell in a sustained yield setting. (By this is meant the largest χ for which a solution to the set of steady state equations can be found without violating any bounds.) The percentage by which current withdrawals need to be reduced is obtained by subtracting χ from 1 and multiplying by 100. This socially egalitarian strategy is a mathematical representation of the correlative rights doctrine applied to Arkansas.

Constraints for all four optimization scenarios include: lower bounds on head in each cell sufficient to retain at least 20 feet of saturated thickness; bounds on recharge in each peripheral cell sufficient to prevent unacceptable dewatering of boundary rivers and adjacent aquifer material; and upper limits on groundwater pumping to prevent pumping more water than is needed in that cell in a particular scenario. Pumping upper bounds differ in some scenarios to reflect the use of conservation measures or availability of diverted surface water that reduce cell groundwater need.

The objective for Scenarios II-IV is to maximize total groundwater extraction. Optimal pumping is different for the scenarios because the upper bounds on pumping differs. Scenario II assumes no new use of water conservation measures and no availability of diverted surface water. Scenario III assumes water conservation but no diversion. Scenario IV assumes conservation and diversion.

Scenarios I and II demonstrate that historic groundwater pumping is not sustainable. Scenario I shows that the smallest across-the-board change in pumping needed to achieve sustainability is an 86 percent reduction. Scenario II is not egalitarian, reaping hydrologic and economic benefit, but would also require significant pumping reduction. Scenario III shows that the best that can be done without diverting surface water will cause about half of the water need to be unsatisfied.

Scenario IV provides the largest percentage of satisfied water need. It shows that even with conservation and diverted surface water, net return would reduce by 23 percent. Omitting either of these actions will cause at least a one third reduction in net return.

Table 1 Optimal strategies and short-term annual consequences of strategy implementation

	Historic groundwater use (base strategy)	Scenario I	II	III	IV
Water Need	286 (353)	286 (353)	286 (353)	253 (312)	253 (312)
Groundwater Use	286 (353)	38 (47)	118 (146)	115 (142)	62 (76)
Surface Water Use	0	0	0	0	160 (197)
Unmet Water Need	0	248 (306)	168 (207)	138 (170)	31 (39)
Change in Net Economic Return	NA	-6,985	-4,066	-2,634	-1,948

Water units are 1000 ac-ft and (10^6 m^3). Economic return units are 1000 dollars.

CASE II. STREAM DEPLETION RESTRICTS FUTURE GROUNDWATER PUMPING

Increasing population water need is causing water managers to look more closely at how much and where groundwater should be extracted from the Cache Valley aquifer of northeastern Utah and southeastern Idaho. Most of the 70 by 16 mile (113 x 26 km) valley's surface water, the primary source for irrigation, originates in snowpacks outside the valley. Its groundwater results from precipitation, percolation of unconsumed irrigation water, and seepage from canals and streams. Wells supply domestic, industrial, public supply and irrigation water.

Because groundwater pumping reduces surface waters, downstream user water rights and environmental concerns can affect how much groundwater can be extracted from the valley aquifer. Here, the SOMO1 simulation/optimization module of SOMOS (SSOL, 2001), which incorporates the MODFLOW simulation model, estimates how groundwater should be extracted to achieve the best mix of sustainable population support, water rights, and ecosystem preservation for posed scenarios. Strategies are evaluated with respect to the heads and flows that would result from continuing 1990 pumping (termed the “background pumping rates”) to steady-state. According to the simulation model, the 52 cubic feet per second (cfs; 1.5 cubic meters per second, m^3s^{-1}) of background pumping would ultimately cause 115 cfs (3.3 m^3s^{-1}) of net water flow to rivers from the aquifer and 80 cfs (2.3 m^3s^{-1}) aquifer discharge to springs (drains). Continuing 1990 pumping to steady-state is the ‘unmanaged scenario’.

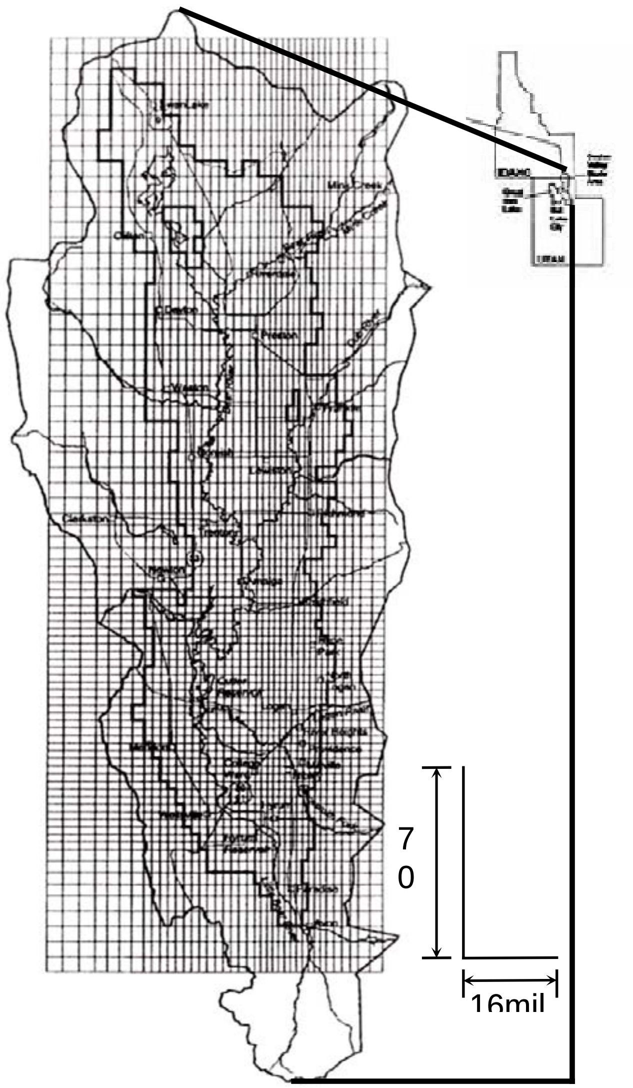

Fig 3 Cache Valley location in Utah and Idaho, and groundwater model grid (from Kariya, et al., 1994).

SOMO1 computed maximum sustainable (steady) groundwater pumping strategies for scenarios, and groups of scenarios, that differ in utilized constraints. Group A scenarios evaluates the feasibility of supplying water to 18 towns using one candidate new well site for each, subject to: (1) head at new pumping cells cannot decline more than 30 feet (9 m) in layers 1-4; (2) springs continue to flow where they flow in 1990 and the unmanaged scenario; (3) saturated aquifer-river seepage continues where it occurs in 1990 and the unmanaged scenario; and (4) total aquifer seepage to river cannot decrease by more than 10%.

Scenario Group A results show that sustainable pumping can increase 4-20 cfs above background rates. Other scenarios showed sustainable groundwater pumping could increase even with more restrictive river depletion constraints. Results encouraged the office of the state engineer to relax a moratorium that had been placed on further groundwater development. Plans include improving the simulation model to enhance predictive accuracy and optimization utility.

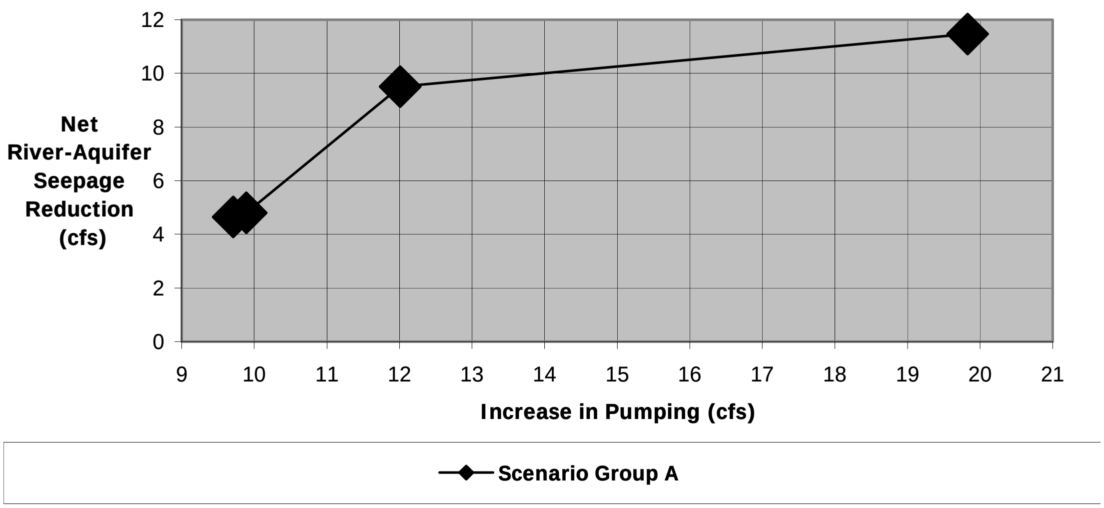

Fig 4 Trade-off curve of groundwater pumping increase versus net river-aquifer seepage decrease. (To convert cfs to m^3s^{-1} multiply by 0.0283.)

SUMMARY

Water policy decisions can significantly affect regional well-being. Evaluating potential policies via S/O models before finalization is important for systematically designing policies and regulations. Linear programming S/O models are valuable for sustainable groundwater policy situations.

To achieve sustainable agricultural production in the Grand Prairie without severe economic hardship, diversion of surface water is needed. A policy combining water conservation and importation would cause the least economic hardship. Severe economic dislocation would result from rigid adherence to a correlative rights doctrine without importation and conservation. In Cache Valley, increased groundwater pumping is sustainable without unacceptably harming ecosystems and water rights. For both study areas, S/O results can help guide the planning and policy development process. Computed strategies are not proposed for implementation. Improved knowledge of system parameters, such as conductances or maximum feasible boundary recharge rates can yield improved strategies (unlikely to change Grand Prairie strategy relative ranking).

Acknowledgements We are grateful for aid by K. Asghari, A. M. Bennet III, R. Das, I. Kalwij, P. Killian, B. Timani, Ark. & Utah Ag.. Exp. Stns., Ark. Soil & Water Cons. Comm., Hartz Seed Co. and Winthrop Rockefeller Foundation.

REFERENCES

Das, R. (2002) *Planning sustainable optimal groundwater yield for the Utah part of Cache Valley*. Irrigation Eng. MS thesis. Utah St. Univ., Logan, UT. 115 p.

Kariya, K.A., M.D. Roark and K.M. Hanson. 1994. "Hydrology of Cache Valley, Cache County, Utah and adjacent part of Idaho, with emphasis on simulation of ground-water flow," *Tech.Pub., 108*, Utah Dept. of Natural Rsrcs. 120p.

Peralta, R. C. (2003) SOMOS Simulation/Optimization Modeling System. In Proc., *MODFLOW and More 2003: Understanding through Modeling*, IGWMC, Golden, CO. p 819-823.

Peralta, R. C., Kalwij, I. M. and S. Wu. (2003) Practical simulation /optimization modeling for groundwater quality and quantity man. In *MODFLOW & More 2003: Understanding through Modeling*, IGWMC, Golden, CO., p 784-788.

Peralta, R.C., Killian, P.J., Yazdanian, A. and V. Kumar. 1989. SSTAR Users Manual. International Irrigation Center Report, IIC-89/3. 40 p.

Systems Simulation/Optimization Lab. and HydroGeoSystems Group. (2001) *Simulation/Optimization MOdeling System (SOMOS) users manual*. SS/OL, Biological and Irrigation Eng. Dept., Utah State Univ., Logan, Utah. 457 p.