OPTIMIZING CONJUNCTIVE USE AND GROUNDWATER YIELD

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Abstract

Advances in computer power and mathematical optimization procedures can improve planning and developing sustainable irrigation systems. Simulation and optimization models can help plan groundwater and conjunctive use strategies to best achieve management goals while satisfying management and physical constraints. Simulation/optimization models that couple calibrated flow and transport simulation models with optimization algorithms can help design the best water management strategies. Managers can be relatively sure that the groundwater system will respond acceptably when appropriate procedures are employed to develop the water management strategies.

Presented case studies illustrate situations in which developed strategies simultaneously address conflicting management goals such as: maximizing sustainable groundwater extraction or conjunctive use versus: minimizing spread or degree of contamination, maintaining adequate artesian flow at springs, or maintaining adequate flow in rivers. Another case illustrates how time-varying future irrigation water needs can be best satisfied by combining groundwater and surface water resources--while assuring adequate saturated aquifer thickness for drought protection and maintaining sufficient river flow for navigation and commerce.

Abstrait

Les progrès dans les domaines de l'informatique et des procédures mathématiques d'optimisation peuvent contribuer à l'amélioration de la planification et favoriser le développement de systèmes d'irrigation pérennes. Au cours du processus d'établissement des stratégies d'exploitation d'eaux souterraines et de planification de systèmes d'irrigation avec les eaux de surface et souterraines combinées, les modèles de simulation/optimisation (S/O) peuvent faciliter l'accomplissement optimal des objectifs de gestion dans le cadre des constraintes physiques et gestionnelles existantes. Les gestionnaires peuvent être assurés que le système d'eaux souterraines répondra de façon satisfaisante quand les procédures appropriées sont mises en oeuvre dans le développement des stratégies de gestion de l'eau.

Les études presentées ci-dessous illustrent des stratégies qui englobent des objectifs de gestion conflictuels tels que: maximiser le pompage durable d'eaux souterraines, combiner l'utilisation d'eaux souterraines et de surface versus: minimiser la propagation d'un contaminant ou le degré de contamination, maintenir un débit adéquat aux sources artésiennes ou dans les cours d'eau. Une autre étude a démontré que les besoins futurs en eaux d'irrigation, variables dans le temps, peuvent être satisfaits de facon optimale à travers l'utilisation combinée d'eaux souterraines et de surface tout en maintenant dans la formation aquifère une profondeur saturée suffisante servant de securité contre la sécheresse et tout en maintenant dans les cours d'eau un dé bit suffisant pour la navigation et le commerce.

Introduction and Comparison Between Simulation/Optimization and Simulation Models

A groundwater pumping strategy is a spatially and possibly temporally distributed set of pumping values. A conjunctive use strategy involves using both pumped groundwater and diverted surface water. Conjunctive use strategies can involve situations in which groundwater and surface water systems are hydraulically connected or disconnected.

The spatial distribution of groundwater pumping is very important in maximizing sustained groundwater extraction. This results because the only ways to increase sustainable pumping over pre-development or current conditions are by reducing previous discharges or increasing previous recharges (such as boundary flows, river-aquifer or drain-aquifer interflows, evapotranspiration). For example, the more one draws down the water table near phreatophytes, the less they evapotranspire. Clearly, extracting groundwater from wells close to phreatophytes reduces the phreatophyte use of groundwater use more than pumping farther away. All other flows being equal, at aquifer equilibrium, minimizing discharge by phreatophytes increases water sustainably available for pumping.

Simulation/Optimization (S/O) models can greatly help determine the optimal spatial and temporal distribution of groundwater extraction. The S/O models improve strategy development: by forcing early clarification of management goals and criteria for strategy acceptability; by computing optimal strategies for posed management scenarios; and facilitating evaluation of trade-offs between conflicting objectives and constraints. Differences between groundwater flow S/O models and the simulation (S) models currently used by almost all modellers and pumping strategy developers are discussed below. Analagous differences exist for conjunctive use models.

Simulation/Optimization models contain both simulation equations and operations research style optimization algorithms. The simulation equations assure that the model appropriately reflects aquifer response to boundary conditions and system stresses. The optimization algorithms allow specifying the management objective as an equation, i.e., a function. The S/O model computes a pumping strategy that maximizes (or minimizes) the value of the objective function.

Total inputs and outputs of S/O and the common simulation (S) models differ although some elements are the same for both. The S models only compute aquifer heads and flows resulting from assumed (input) pumping values, and initial and boundary conditions. Developing acceptable pumping strategies using only experience and S models can be a tedious trial and error process. This is so because simulated head responses to an assumed pumping strategy might cause undesirable consequences. In that case, the modeller must assume another set of pumping values, again simulate system response and check whether unacceptable results occur. The process of assuming, computing and checking might have to be repeated many times. The more pumping locations and control locations (places where acceptability of system response must be reviewed) the more repetitions.

When using an S model, as the number of possible pumping sites increases, the likelihood that the user has assumed an 'optimal' strategy decreases. Assuming a truly optimal strategy becomes impossible as problem complexity increases. There are too many possible combinations of pumping values. Even if the iterative process is automated, the act of checking and assuring strategy acceptability becomes increasingly painful as the number of control locations becomes large. It becomes impossible to calculate mathematically optimal strategies for complex groundwater problems using S models.

By comparison, S/O models directly determine the best pumping strategies for the posed management goals, while assuring that resulting flows and heads do not violate pre-specified limits or bounds. These upper or lower bounds reflect the ranges of pumping rate and head considered acceptable for model cells. The model automatically considers the limits while calculating an optimal pumping strategy. For example, a pumping lower bound might be used to assure that at least current pumping is permitted in a particular model cell. Pumping might or might not be limited at the upper end of the range. It might be restricted to reflect the most water that can be practically used from that particular cell. Lower bounds on head might be set to limit pollutant movement, or to assure adequate saturated thickness for good well performance. Upper bounds on head might be at the ground surface or a specified distance below the ground surface.

Assume, for example, a situation in which a planning agency is attempting to determine how much groundwater they should permit to be pumped from an aquifer and the locations where it should be pumped, i.e., the spatial distribution of the withdrawals. If current pumping rates continue, drawdowns might cause unacceptable pumping costs, well yields, salt water intrusion or stream dewatering. A finite difference S/O model can be used to directly calculate an optimal pumping strategy for any of several management objectives, without causing any of the listed unacceptable consequences. Assume the objective is to maximize sustainable regional groundwater withdrawal. Assume future heads should be no more than 10 m lower than current heads and that salt water intrusion from the ocean should not increase. The S/O model will directly calculate the maximum annual extraction possible from the aquifer and the rate of groundwater extraction from each cell. The groundwater heads that will evolve from the optimal pumping will lie within the initially specified bounds. In other words, future heads will be no more than 10 m below current heads and the gradient to the coast will be acceptable.

One cannot optimize management of a system that one cannot adequately simulate. Predicted system response to a strategy developed by an S/O model cannot be more accurate than the utilized simulation equations. Aquifer parameters assumed by the S/O model must be reasonably accurate. Therefore, an S model must be calibrated for an area before an S/O model should be used to develop a pumping strategy for that area.

Standard S/O Model Approaches to Representing System Response to Pumping

Groundwater S/O models generally use what can broadly be termed as either embedding (EM) or response surface (RS) approaches to represent system (head) response to stimuli (pumping). Most EM-based models contain discretized finite difference or finite element equations embedded directly as constraints. In a finite difference EM-based model, head and pumping values (or other flows) are computed at each cell and for each time step. This is commonly desirable when computing an optimal sustained groundwater yield strategy if: (1) pumping should be a decision variable at most cells, and (2) head should be constrained in a high proportion of the cells.

Steady-state EM-based models are very useful for sustained yield planning (Knapp, 1985; Willis and Yeh, 1987). Implementing a computed optimal pumping strategy in the field should cause an acceptable potentiometric surface to evolve. Even after evolution is considered complete, short-term head variations will occur during the year. Heads at cells distant from rapid recharge sources are expected to fluctuate around and return to their optimal quasi-steady-state values after a series of climatically 'average' years.

The Response Surface (RS) approach uses other linear or nonlinear surrogate expressions to describe system response to stimuli. The simplest RS-based models assume system linearity and employ what is commonly termed the response matrix (RM) approach. RM S/O models describe head or flow response using influence coefficients, superposition and linear systems theory (Heidari, 1982; Gorelick, 1983; Reichard, 1987; Morel-Seytoux, 1975; Illangasekare et al, 1984). Applying a RM approach requires a two-step process. First, a simulation model is used to calculate system response to unit stimuli. Then, a S/O model (containing summation equations--discretized forms of the convolution integral) performs optimization. RM S/O models are generally superior to EM S/O models for transient flow management situations. They require constraint equations for only those specific cells and time steps at which head or flows (other than pumping) need restriction during the optimization. To predict system response to the optimal strategy at locations and times other than those constrained in the RM S/O model, one applies an external simulation model after the optimization.

RS S/O models also employ a multi-step process to address nonlinear systems or processes. First a S model is used to simulate system response to an array of stimuli and stimuli combinations. Stimuli combinations and magnitudes are selected to represent the range of situations that might occur within management scenarios. This is necessary because control (dependent) variable response to stimulus is nonlinear. Next, a functional expression is developed to describe control variable response to stimulus combinations. Finally a S/O model including the functional expression calculates an optimal water management strategy.

The nonlinear expression used in RS models can have many forms, depending on the situation. Ejaz and Peralta (1995a) applied one form to constrain surface water quality while optimizing conjunctive water management. Peralta and Aly (1995) and Cooper et al (1997) used other varients to constrain dissolved contamination and nonaqueous phase contaminant volumes, respectively, while optimizing aquifer cleanup. Aly (1997) employed a polynomial function having second-order interaction terms to optimize groundwater cleanup and treatment facility size.

Both EM and RM S/O models generally assume system linearity during at least some part of their processing operation. Confined aquifers are linear systems, unless they become unconfined during computation. Although unconfined aquifers are nonlinear, transmissivity changes with time or during processing might be insignificant. Most commonly, system nonlinearity is addressed by cycling. Cycling for EM and RM S/O models involves: (1) assuming system parameters, (2) computing an optimal strategy, (3) recomputing system parameters, (4) comparing assumed and newly computed parameter values, and (5) either stopping or returning to step (2) and repeating the process if the assumed values are still unacceptably inaccurate.

The number of cycles required depends on the problem and the required accuracy. Gharbi and Peralta (1994), Takahashi and Peralta (1995), Daza (1993) and Kumar et al (1994) applied automated cycling in the EM S/O models they used for sustained yield planning. Peralta et al (1995) used cycling to constrain groundwater salinity concentrations within regional sustained yield planning optimization. Suguino (1992) used cycling in his RM S/O groundwater model. Peralta and Aly (1996) automated cycling within a general purpose RM S/O model for transient and steady state groundwater and conjunctive water management. Belaineh (1995) employed cycling to optimize conjunctive management in a dynamic system including reservoirs, stream channels, conveyance systems, water-use command areas, and the groundwater system. RS models using nonlinear expressions can also employ cycling (Ejaz and Peralta, 1995b: Cooper et al, 1997).

S/O Model Applications to Groundwater and Conjunctive Water Supply Planning

Cantiller et al (1995) used the EM approach for a 50-year conjunctive water use planning study. They maximized the combined use of groundwater and surface water for a 30,000 km^2 portion of eastern Arkansas and predicted areas of potential unsatisfied demand for the year 2030. The project required cooperation between all agencies involved in large scale hydrologic planning (Mahon et al, 1989). They used the EM method because almost all cells had pumping variables and drawdown needed to be constrained in most cells.

Gharbi (1994) applied the EM method for optimizing 20-year transient pumping, flow and transport in the Salt Lake Valley. The many nonlinear or piecewise-linear processes addressed included solute transport in an unknown flow field, evapotranspiration extraction of groundwater, stream-aquifer interflow, and flow between layers when a confined layer becomes unconfined. Results included the sustainable pumping rate for each cell, and areas where increased pumping should not be allowed.

Takahashi and Peralta (1995) also employed embedding when developing a maximum sustained yield pumping strategy for an area bordering the Great Salt Lake. Their three-layer study area included piecewise expression of flow from drains and artesian flow that would cease when the potentiometric surface dropped below the ground surface.

A RM S/O model (Suguino, 1992) was applied to an area in Southwestern Florida to determine the minimum amount of fresh water injection needed to prevent salt water intrusion into layer 2 of a 5 layer system. Public supply wells are withdrawing water from layers 1 and 2. In the optimization problem (posed by Mark Wilsnack), the hydraulic gradient in one area is constrained to be towards the coast. In another area, freshwater heads are constrained to be at least one foot above sea level. Heads in injection cells were constrained not to rise above the ground surface.

Belaineh and Peralta (1995) and Johnson and Peralta employed the REMAX RM model of Peralta and Aly (1996) in their case studies. This powerful model can address a wide range of management problems and physical systems. Belaineh and Peralta (1995) addressed maximizing sustained groundwater pumping for Pahvant Valley, Utah. They developed trade-off curves for sustainable pumping versus discharge from springs supplying water to a wildlife refuge. Johnson and Peralta (1997) maximized sustained yield pumping for Cache Valley, Utah. They tried to satisfy projected water needs without unacceptably reducing flow in surface water bodies.

Summary

Simulation/Optimization model use can greatly improve sustained groundwater yield and conjunctive water use planning. S/O modelling methods are well established and a very powerful transferable response matrix S/O model (REMAX) is available. Increasing S/O model use for planning and management is inevitable.

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