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OPTIMIZING LONG TERM GROUND WATER PLANNING AND MANAGEMENT

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Simulation/optimization (S/O) models can be used to speed the process of computing long term groundwater pumping strategies. These combined models can also greatly ease the planning tasks of water management agencies. They make the process of computing optimal perennial yield groundwater management strategies fairly straightforward. S/O models dramatically improve conjunctive water management and can help minimize the cost of groundwater contaminant clean-up. The differences between S/O models and the simulation (S) models currently used by over 98 % of practitioners are illustrated with recent applications of S/O models in regional planning.

Comparison Between S/O and the Commonly Used Simulation 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 and internal fluxes. The optimization algorithms allow specifying the management objective as an equation, i.e., a function. The model will then compute a pumping strategy that maximizes (or minimizes) the value of the objective function.

Figure 1 compares S/O model input requirements and how results differ from generally used simulation (S) models. The common S models only compute aquifer heads and flows which result from assumed (input) pumping values and boundary conditions. Using such models to develop desirable pumping strategies can be a tedious trial and error process. This is because simulated head responses to an assumed pumping strategy might cause undesirable consequences. In that case, the user has to assume another set of pumping values, reuse the model to compute aquifer system response and check again to see whether unacceptable results occur. This process of assuming, computing and checking might have to be repeated many times. The number of repetitions is affected by the number of pumping locations and control locations (places where acceptability of system response must be judged).

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 impractical or nearly impossible as problem complexity increases. There are simply too many different possible combinations of relative pumping values. Furthermore, even if the computation process is automated in a computer program, the act

of checking and assuring strategy acceptability becomes increasingly painful as the number of control locations becomes large. In essence, it becomes impossible to compute mathematically optimal strategies for complicated groundwater management problems using S models.

On the other hand, S/O models directly compute the best pumping strategies for the desired management objectives, while assuring that the resulting heads and flows do not lie outside of prespecified limits or bounds (Fig. 1). The upper or lower bounds reflect the range of values which are acceptable for pumping volume and head for each cell. The model automatically considers the limits in the course of computing optimal pumping strategies. Lower bounds on pumping might be used to assure that at least current pumping is permitted. Pumping may or may not be limited at the upper end of the range, or it might be limited to reflect the most water that can be practically used from a particular cell. Lower bounds on head might be set at a specific distance below current water levels to prevent pollutant intrusion, or above the base of the aquifer. Upper bounds might be the ground surface or a water table at 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, harmful consequences might result. Local drawdowns might also become excessive, causing unacceptable saturated thickness, reduced 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 unacceptable consequences. For example, assume that the objective is to maximize regional sustainable groundwater pumping. Assume also that the agency does not want future heads to be more than 10 m lower than current heads and, in addition, does not want to induce salt water intrusion from the ocean. The S/O model will directly calculate the maximum annual extraction possible in the basin and how much groundwater should be pumped from each cell. The potentiometric surface heads that will ultimately evolve from the optimal pumping will lie within the bounds specified initially (Fig. 1). In other words, future heads will not be more than 10 m below current heads and the gradient to the coast will be acceptable.

Of course, S/O models have some of the same limitations as standard simulation models. Inadequate data or poor system representation will cause error. It is not possible to truly optimize management of a system that cannot be correctly represented for simulation. Thus, useful simulation/optimization modeling presupposes that aquifer parameters are appropriate and actual boundary conditions are represented adequately within the model.

Utility and Limitations of Common S/O Models

Most S/O models use either an embedding or a response matrix approach for representing system (head) response to stimuli (pumping), (Gorelick, 1983). Embedding type models contain discretized finite difference or finite element equations embedded directly

as constraints. In a finite difference embedding model, head and pumping values (or other flows) are computed at each cell and for each time step. This is desirable for many agricultural situations in which: (1) pumping should be a decision variable at most cells, (2) head must be constrained in a high proportion of cells, and (3) an optimal perennially sustainable groundwater yield strategy is desired.

Steady-state embedding models are very useful for sustained yield planning (Knapp, 1985; Willis and Yeh, 1987). Implementation in the field of a computed optimal pumping strategy should result in the eventual evolution of an acceptable potentiometric surface. Actual short-term head variations will occur with time during the year and generally do not pose a difficulty. Heads at cells distant from rivers or other sources of rapid recharge will normally fluctuate around and return to their optimal quasi-steady-state values during a series of climatically 'average' years, once the optimal steady-state has been reached.

Response matrix S/O models use influence coefficients, superposition and linear systems theory (Heidari, 1982; Reichard, 1987; Morel-Seytoux, 1975; Illangasekare et al, 1984). These are called response matrix (RM) models and employ a two step process. First, a simulation model is used to calculate system response to unit stimuli. Then separate optimization is performed by an S/O model which includes summation equations (discretized forms of the convolution integral). RM models are superior for transient 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 S/O model, an external simulation model is applied after the optimization.

Both Embedding 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. Unconfined aquifers are nonlinear, but sometimes the change in transmissivity with time or during processing is insignificant. Most commonly, system nonlinearity is addressed by cycling. Cycling 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 inappropriate for the problem. This convergence process can frequently be completed within three computation cycles.

Recent Sample Applications of S/O Models in Regional Planning

Cantiller et al (1988) demonstrated use of the embedding 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 the areas of potential unsatisfied demand for the year 2030. The study (Figure 2) required cooperation between all agencies involved in large scale hydrologic planning (Mahon et al, 1989). They used the embedding approach because almost all cells contained pumping variables and drawdown needed to be constrained in most cells. Use of S/O models requires all the data

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Figure 5 shows a study area in Southwestern Florida for which a response matrix S/O model was used to minimize the 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. The optimization problem was posed by Mark Wilsnack (personal communication). Optimization was performed using the MACMAN module of the PLUMAN decision support software (Suguino, 1992). This is a precursor to the Utah State Response Matrix (US/REMAX) model.

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Summary

Simulation/Optimization models can greatly improve sustained groundwater yield and conjunctive water use planning. S/O modelling methods for flow management are well established and functional models are available. Increasing use of S/O models for planning and management purposes is expected, especially as ease-of-use and portability improves.

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Figure 1 Comparison between Simulation and Simulation/Optimization Models

Model Type	Input Values	Computed Values
Simulation (S)	Some boundary flows	Some boundary flows
	Some boundary heads	Heads at 'variable' head cells
	Pumping	
Simulation/ Optimization (S/O)	Some boundary flows	Optimal boundary flows
	Some boundary heads	Optimal heads at 'variable' head cells
	Bounds on pumping, heads, flows	Optimal Pumping

Figure 2. Volume of Anticipated Unsatisfied Demand in 2030, Based on Anticipated Demand (with Water Conservation Measures Implemented) and Optimal Conjunctive Water Use Strategy (Mahon et al, 1989)

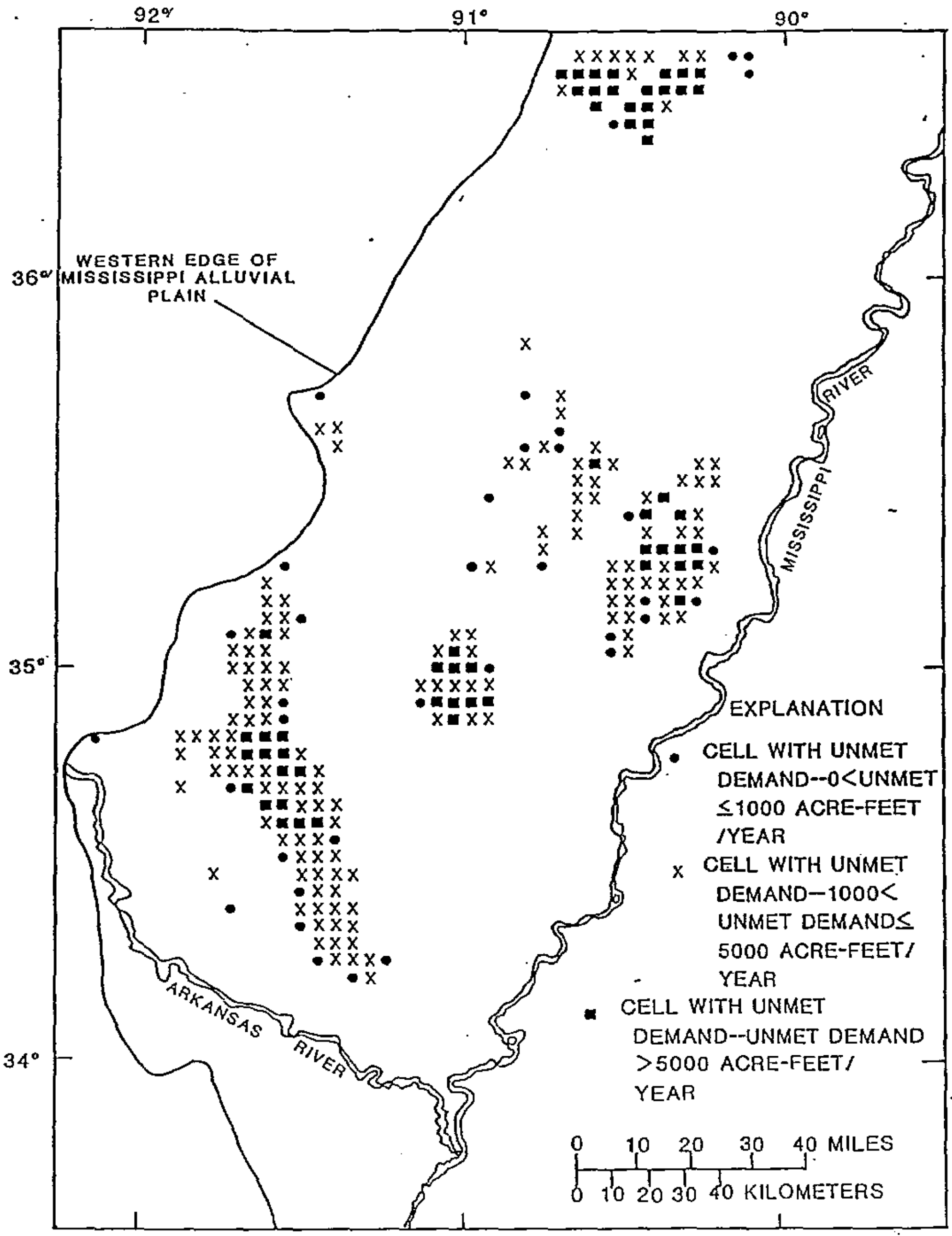


Figure 3. Optimal Sustainable Pumping Rates from Lower Layer of Salt Lake Valley Aquifer System (based on Gharbi, 1991)

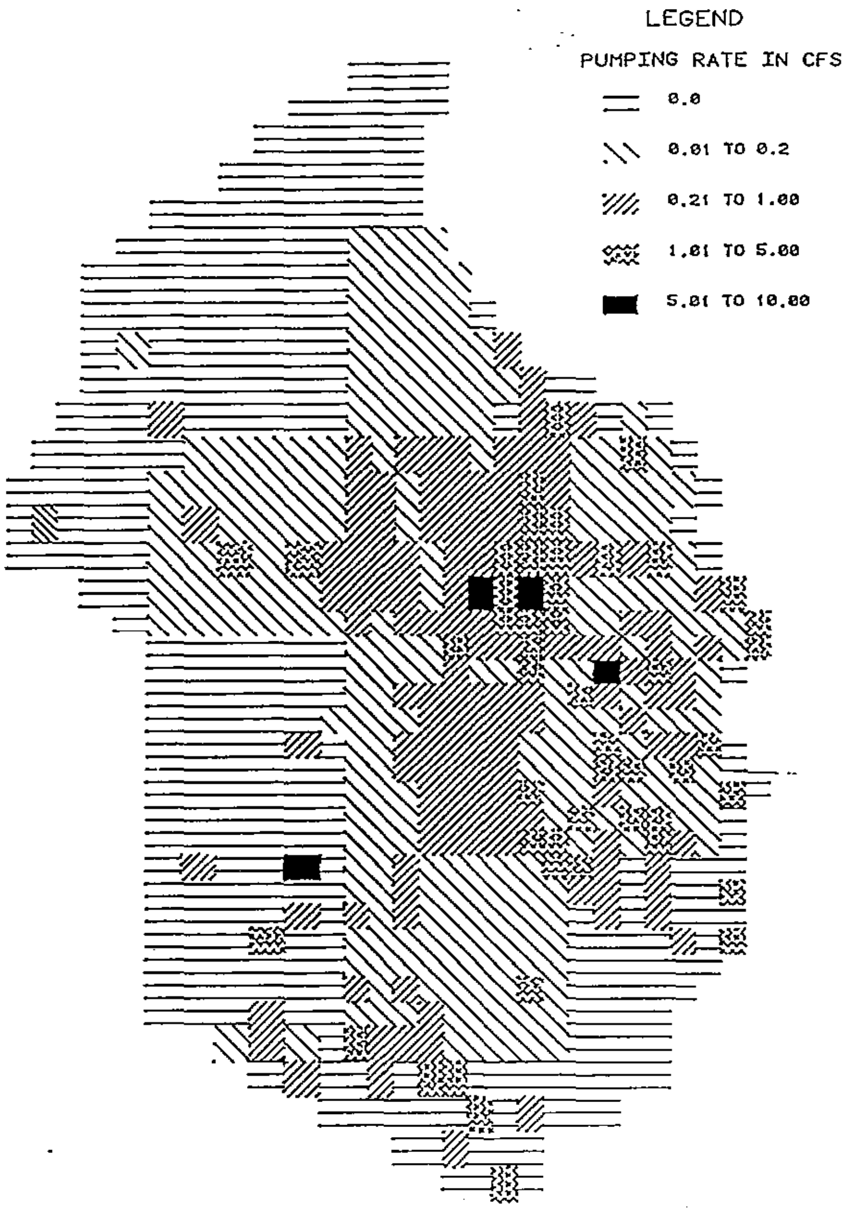
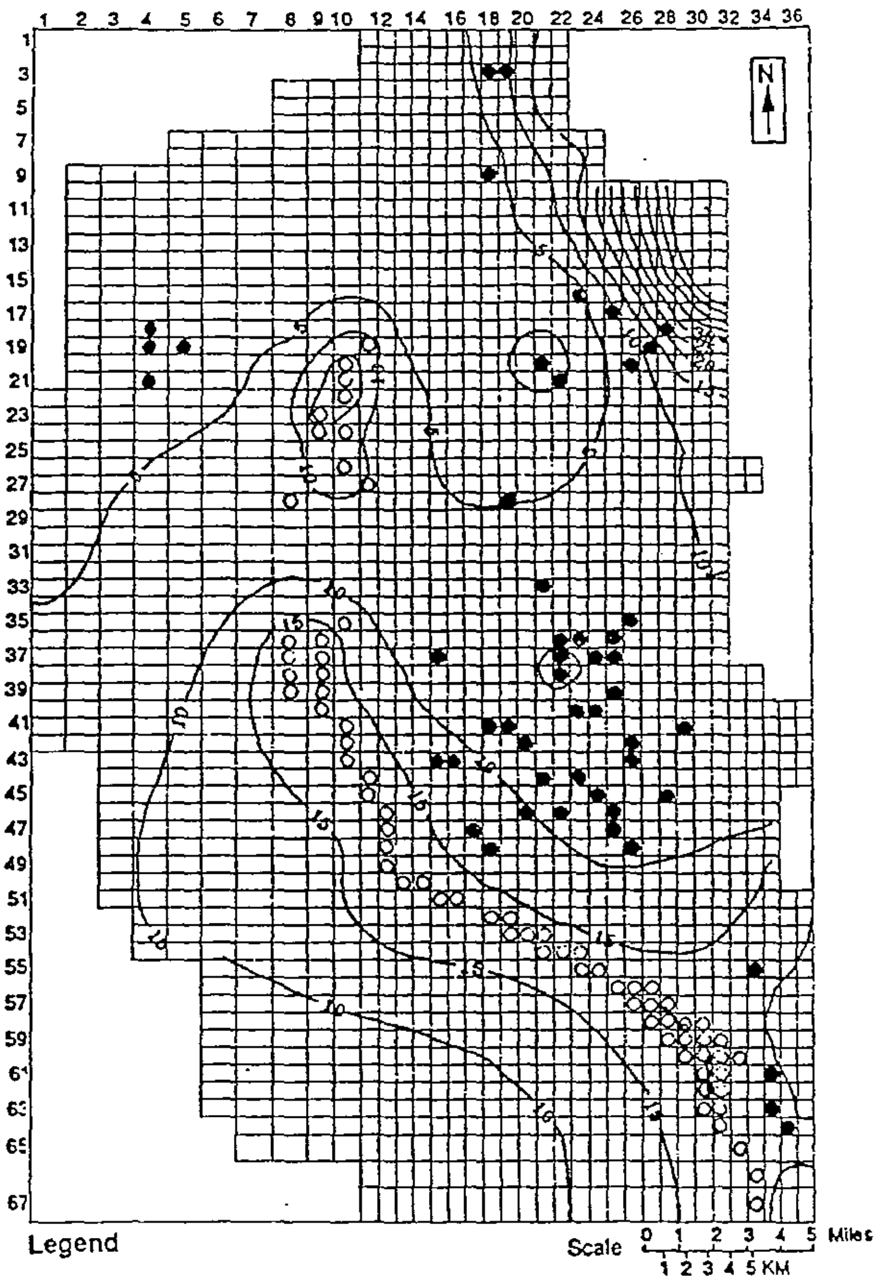
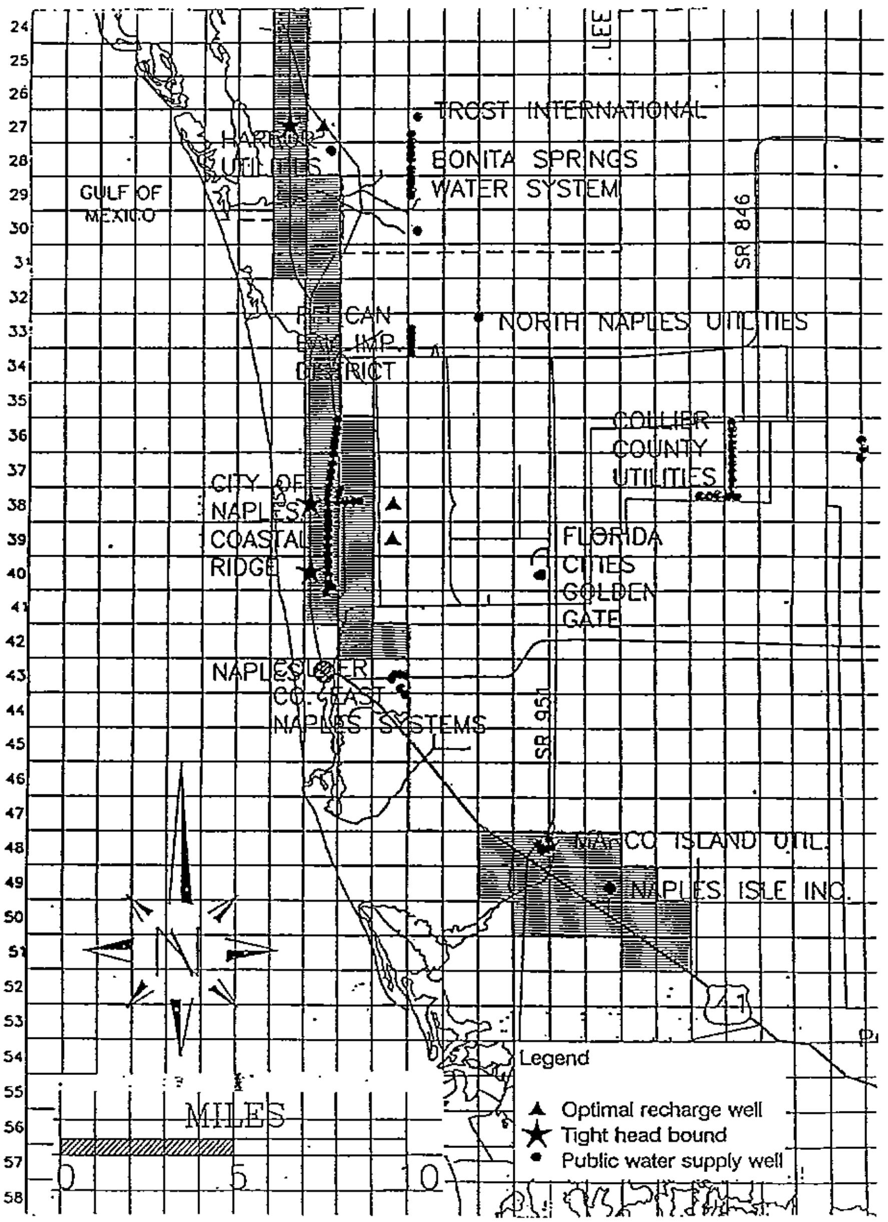


Figure 4. Locations of Optimal Pumping from Delta Formation, and Resulting Potentiometric Surface Elevations, East Shore Area, Utah (Takahashi, Unpublished PhD dissertation, Utah State Univ., 1992)



Active cell with existing pumping wells
Active cell with new pumping wells
Active cell

Figure 5. Optimal Well Locations for Minimizing Injection Needed to Prevent Salt Water Intrusion (adapted from Bennett, 1992)



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by Richard C. Peralta and Lyman S. Willardson, Professors, Utah State University

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On the other hand, S/O models directly compute the best pumping strategies for the desired management objectives, while assuring that the resulting heads and flows do not lie outside of prespecified limits or bounds (Fig. 1). The upper or lower bounds reflect the range of values which are acceptable for pumping volume and head for each cell. The model automatically considers the limits in the course of computing optimal pumping strategies. Lower bounds on pumping might be used to assure that at least current pumping is permitted. Pumping may or may not be limited at the upper end of the range, or it might be limited to reflect the most water that can be practically used from a particular cell. Lower bounds on head might be set at a specific distance below current water levels to prevent pollutant intrusion, or above the base of the aquifer. Upper bounds might be the ground surface or a water table at a specified distance below the ground surface.

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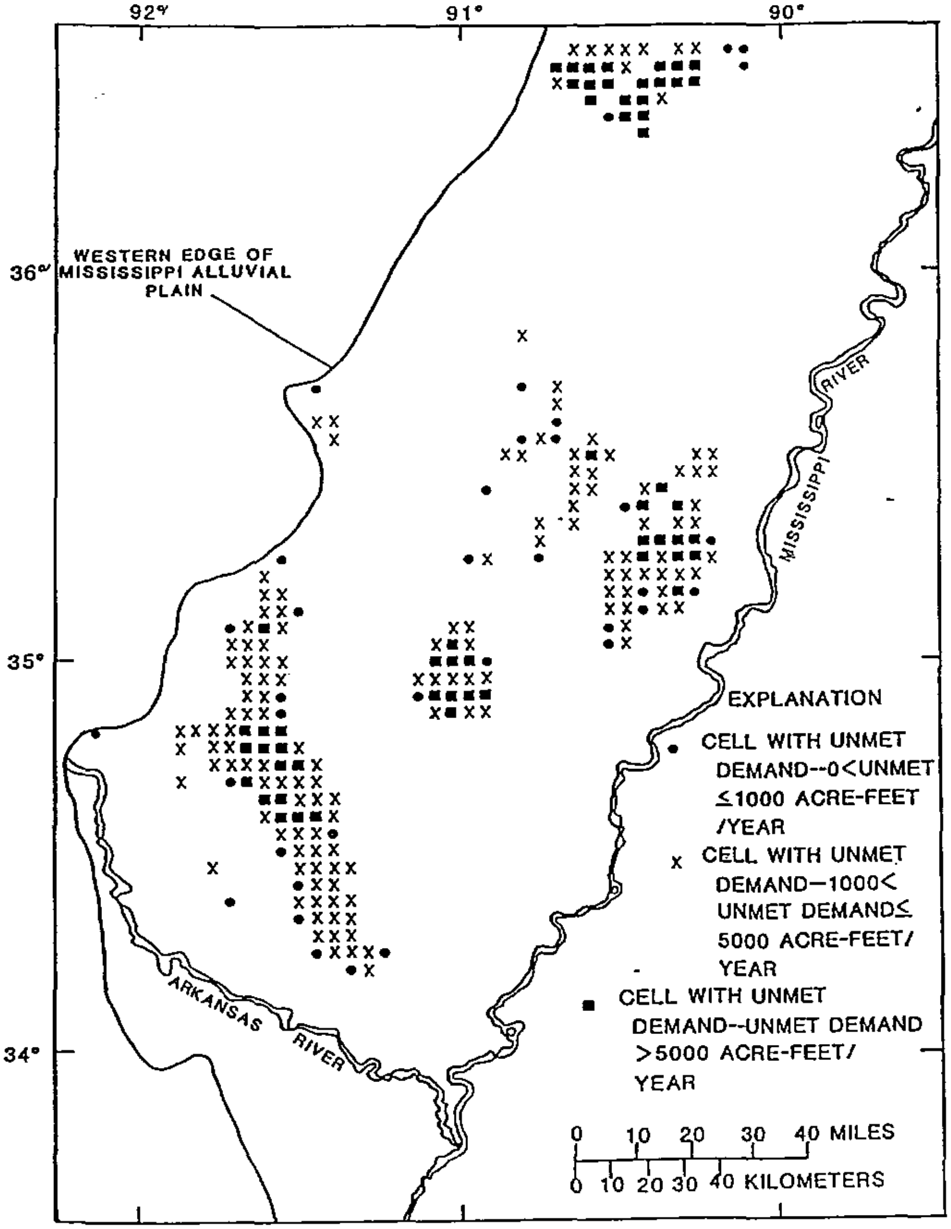

Figure 2. Volume of anticipated unsatisfied demand in 2030, based on anticipated demand (with water conservation measures implemented) and optimal conjunctive water use strategy (Mahon et al., 1989).

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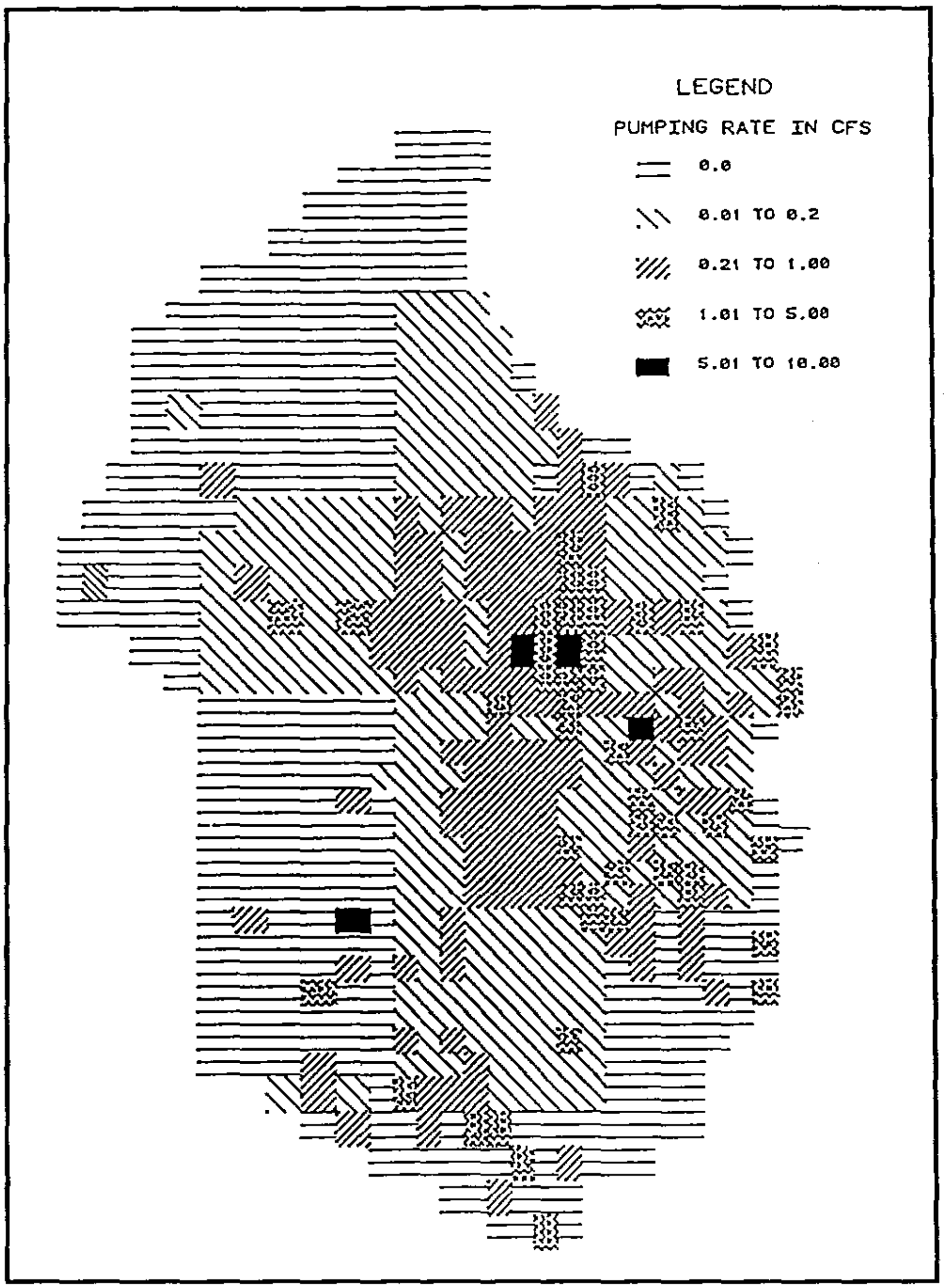

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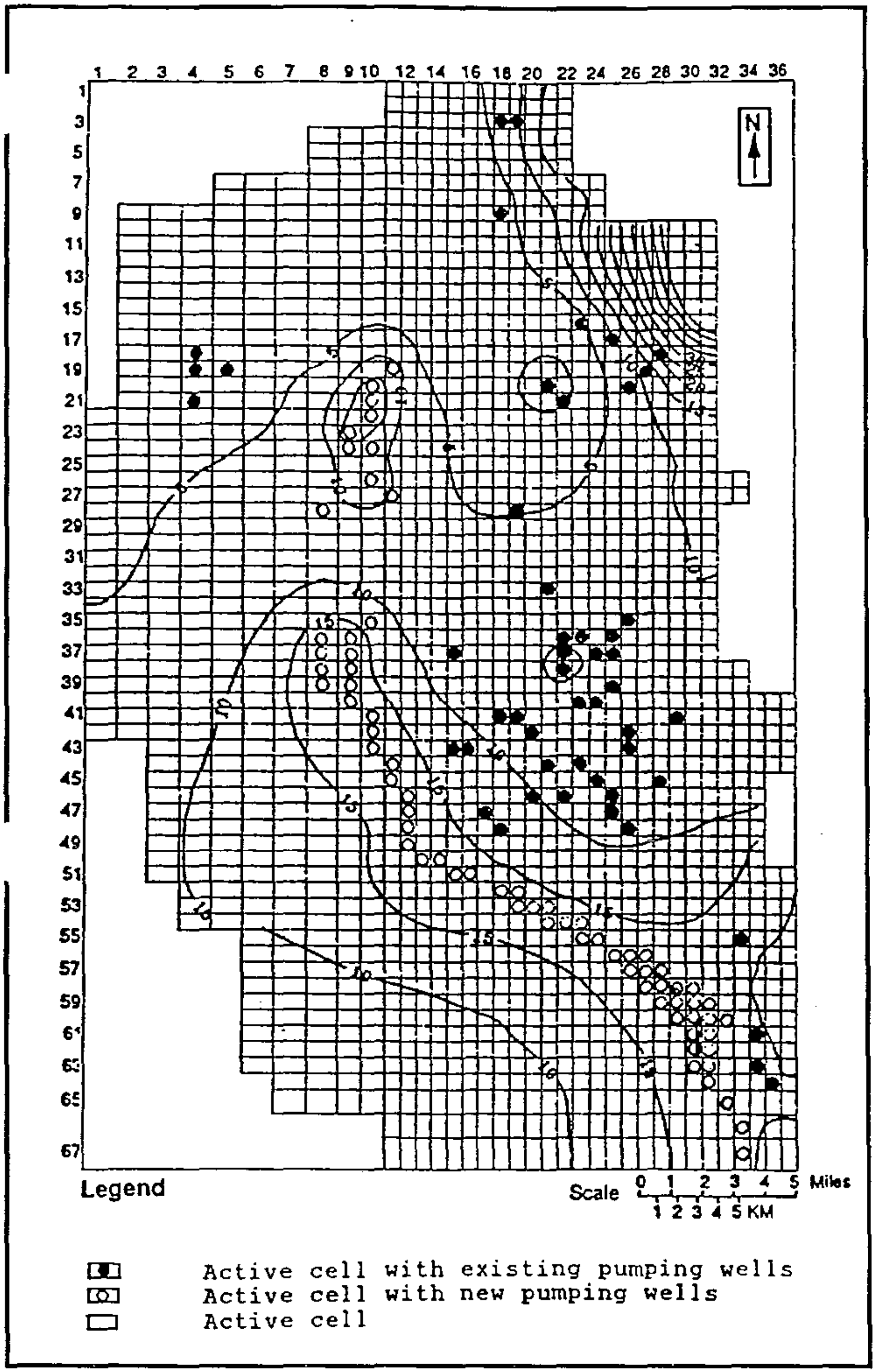

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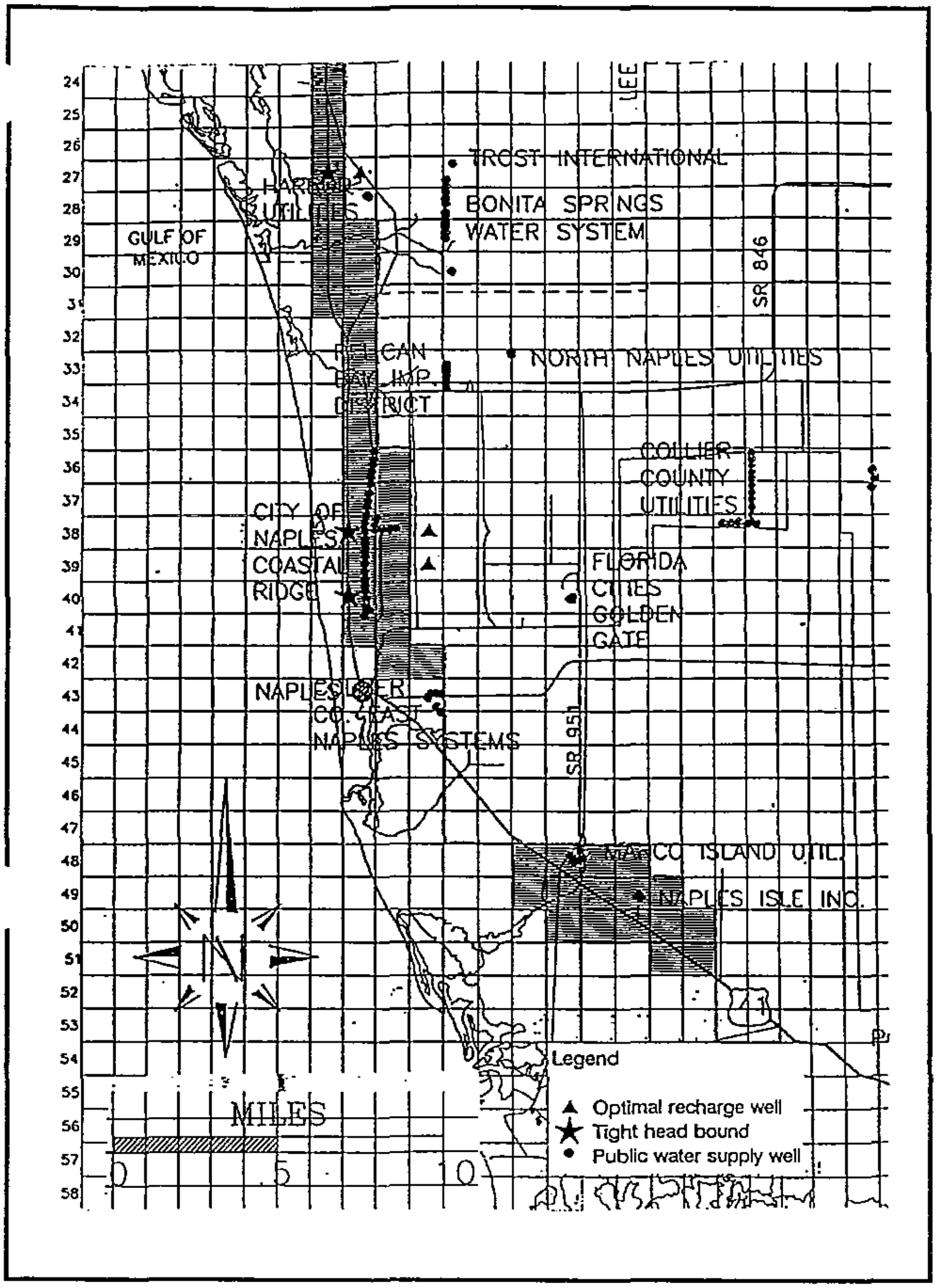

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Summary

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TO: SUE ANDERSON
USCID
DENVER

FAX NO.: 303-628-5431

FROM: L.S. WILLARDSON
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REMARKS: Attached are 4 pages of the Report Text. There were minor corrections on page 2. The main change is the last paragraph on page 4.

BIOLOGICAL AND IRRIGATION ENGINEERING DEPARTMENT

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FACSIMILE NUMBER: (801) 750-1248

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TO: United States Committee on Irrigation and Drainage

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REMARKS: Corrections made on pages 2 & 4.

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OPTIMIZING LONG TERM GROUND WATER PLANNING AND MANAGEMENT

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Simulation/optimization (S/O) models can be used to speed the process of computing long term groundwater pumping strategies. These combined models can also greatly ease the planning tasks of water management agencies. They make the process of computing optimal perennial yield groundwater management strategies fairly straightforward. S/O models dramatically improve conjunctive water management and can help minimize the cost of groundwater contaminant clean-up. The differences between S/O models and the simulation (S) models currently used by over 98 % of practitioners are illustrated with recent applications of S/O models in regional planning.

Comparison Between S/O and the Commonly Used Simulation 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 and internal fluxes. The optimization algorithms allow specifying the management objective as an equation, i.e., a function. The model will then compute a pumping strategy that maximizes (or minimizes) the value of the objective function.

Figure 1 compares S/O model input requirements and how results differ from generally used simulation (S) models. The common S models only compute aquifer heads and flows which result from assumed (input) pumping values and boundary conditions. Using such models to develop desirable pumping strategies can be a tedious trial and error process. This is because simulated head responses to an assumed pumping strategy might cause undesirable consequences. In that case, the user has to assume another set of pumping values, reuse the model to compute aquifer system response and check again to see whether unacceptable results occur. This process of assuming, computing and checking might have to be repeated many times. The number of repetitions is affected by the number of pumping locations and control locations (places where acceptability of system response must be judged).

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 impractical or nearly impossible as problem complexity increases. There are simply too many different possible combinations of relative pumping values. Furthermore, even if the computation process is automated in a computer program, the act

of checking and assuring strategy acceptability becomes increasingly painful as the number of control locations becomes large. In essence, it becomes impossible to compute mathematically optimal strategies for complicated groundwater management problems using S models.

On the other hand, S/O models directly compute the best pumping strategies for the desired management objectives, while assuring that the resulting heads and flows do not lie outside of prespecified limits or bounds (Fig. 1). The upper or lower bounds reflect the range of values which are acceptable for pumping volume and head for each cell. The model automatically considers the limits in the course of computing optimal pumping strategies. Lower bounds on pumping might be used to assure that at least current pumping is permitted. Pumping may or may not be limited at the upper end of the range, or it might be limited to reflect the most water that can be practically used from a particular cell. Lower bounds on head might be set at a specific distance below current water levels to prevent pollutant intrusion, or above the base of the aquifer. Upper bounds might be the ground surface or a water table at 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, harmful consequences might result. Local drawdowns might also become excessive, causing unacceptable saturated thickness, reduced 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 unacceptable consequences. For example, assume that the objective is to maximize regional sustainable groundwater pumping. Assume also that the agency does not want future heads to be more than 10 m lower than current heads and, in addition, does not want to induce salt water intrusion from the ocean. The S/O model will directly calculate the maximum annual extraction possible in the basin and how much groundwater would be pumped from each cell. The potentiometric surface heads that will ultimately evolve from the optimal pumping will lie within the bounds specified initially (Fig. 1). In other words, future heads will not be more than 10 m below current heads and the gradient to the coast will be acceptable.

Of course, S/O models have some of the same limitations as standard simulation models. Inadequate data or poor system representation will cause error. It is not possible to truly optimize management of a system that cannot be correctly represented simulation. Thus, useful simulation/optimization modeling presupposes that aquifer parameters are appropriate and actual boundary conditions are represented adequately within the model.

Utility and Limitations of Common S/O Models

Most S/O models use either an embedding or a response matrix approach for representing system (head) response to stimuli (pumping), (Gorelick, 1983). Embedding type models contain discretized finite difference or finite element equations embedded directly

as constraints. In a finite difference embedding model, head and pumping values (or other flows) are computed at each cell and for each time step. This is desirable for many agricultural situations in which: (1) pumping should be a decision variable at most cells, (2) head must be constrained in a high proportion of cells, and (3) an optimal perennially sustainable groundwater yield strategy is desired.

Steady-state embedding models are very useful for sustained yield planning (Knapp, 1985; Willis and Yeh, 1987). Implementation in the field of a computed optimal pumping strategy should result in the eventual evolution of an acceptable potentiometric surface. Actual short-term head variations will occur with time during the year and generally do not pose a difficulty. Heads at cells distant from rivers or other sources of rapid recharge will normally fluctuate around and return to their optimal quasi-steady-state values during a series of climatically 'average' years, once the optimal steady-state has been reached.

Response matrix S/O models use influence coefficients, superposition and linear systems theory (Heidari, 1982; Reichard, 1987; Morel-Seytoux, 1975; Illangasekare et al, 1984). These are called response matrix (RM) models and employ a two step process. First, a simulation model is used to calculate system response to unit stimuli. Then separate optimization is performed by an S/O model which includes summation equations (discretized forms of the convolution integral). RM models are superior for transient 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 S/O model, an external simulation model is applied after the optimization.

Both Embedding 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. Unconfined aquifers are nonlinear, but sometimes the change in transmissivity with time or during processing is insignificant. Most commonly, system nonlinearity is addressed by cycling. Cycling 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 inappropriate for the problem. This convergence process can frequently be completed within three computation cycles.

Recent Sample Applications of S/O Models in Regional Planning

Cantiller et al (1988) demonstrated use of the embedding 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 the areas of potential unsatisfied demand for the year 2030. The study (Figure 2) required cooperation between all agencies involved in large scale hydrologic planning (Mahon et al, 1989). They used the embedding approach because almost all cells contained pumping variables and drawdown needed to be constrained in most cells. Use of S/O models requires all the data

needed by simulation models, plus information on lower and upper bounds on the variables.

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