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Optimization of Groundwater Use in the Goksu Delta at Silifke, Turkey

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ABSTRACT

An optimization model was developed to manage the supplemental use of groundwater in the coastal aquifer subject to saltwater intrusion in the Goksu Delta at Silifke, Turkey. The response of the aquifer system was linked to the optimization model using the response matrix method. A calibrated groundwater simulation model using the SUTRA (Saturated-Unsaturated Transport) code was run to generate aquifer response coefficients at specific well locations. It was assumed that pumping occurs from two wells, and a linear optimization model was constructed under steady-state conditions to maximize the total pumping rates from these two wells subject to water demands and chloride concentration and drawdown limitations. The model was solved for five levels of chloride concentration limits to develop an optimal pumping strategy for the different chloride concentration levels. To verify the optimization model, hydraulic heads and chloride concentrations estimated by the optimization model were compared with those computed by the simulation model. The GAMS (General Algebraic Modeling System) code was used to execute the optimization model. A trade-off curve was constructed at the conclusion of the study that shows the change in maximum pumping rate with respect to the different chloride concentration levels. After plotting the results of both the simulation and optimization models, the predicted hydraulic heads from the optimization model match those generated by the simulation model very closely. However, due to nonlinear effects, the correlation between the chloride concentrations predicted by the optimization model and those calculated by the simulation model is not as good.

INTRODUCTION

Optimization models have been widely used to help solve groundwater problems over the past two decades. These models have been used to identify optimal pumping strategies and cost effective development scenarios under the consideration of groundwater hydraulics and water-quality restrictions. In order to achieve this, groundwater simulation models are often combined with optimization models by means of various techniques.

Shamir et al. [1984] used a multi-objective linear optimization model to identify the optimal annual operation of a coastal aquifer in Israel. A coupled simulation-optimization model was developed by Yazicigil et al. [1987] to determine the optimal development and operating policies for a regional aquifer in Saudi Arabia. Willis and Finney [1988] presented a study describing the development of a planning model for the Yun Lin groundwater basin of southwestern Taiwan. The aim of the planning model was to control saltwater intrusion and maintain water-supply and recharge targets. Finney et al. [1992] developed a simulation-optimization model for the control of saltwater intrusion in a multi-layer aquifer system in Jakarta, Indonesia. The management model combines a quasi three-dimensional sharp interface model with a non-linear programming model. Hatfield et al. [1995] developed five optimization models for Volusia County, Florida, incorporating both water-quality and water-quantity aspects to identify groundwater allocation strategies and address the degradation in water quality due to saltwater intrusion and the protection of sensitive wetlands. GAMS was used in the solution process of the optimization model, and sensitivity analyses were performed to increase the efficiency of the management strategies.

Gorelick [1983] described two techniques, i.e., the embedding method and the response matrix approach. These two techniques, sometimes with a few modifications, have been widely used to couple simulation models with optimization models. The embedded model accurately simulates groundwater behavior in an aquifer. On the other hand, the entire aquifer is unnecessarily included in the optimization model since the goal of the management model is usually to address the drawdown change or concentration level only at specified points. This results in dimensionality and computational problems. Therefore, solving large-scale, particularly transient, problems by this method is not feasible. Consequently, this technique is restricted to the application of small scale and steady-state problems. Although the response matrix method does not simulate the aquifer system completely, by contrast, it can handle large-scale transient systems efficiently. The development of a response matrix requires repeated execution of a numerical simulation model. Since this procedure is done only for selected observation points, this method is generally more economical and needs less computational effort. One of the important disadvantages of this technique is the difficulty in estimating influence coefficients based on non-linear aquifer responses. Direct prediction of influence coefficients as is done for linear aquifer responses can lead to inaccurate results. To avoid this, these non-linear responses need to be corrected by creating a revised set of influence coefficients based on the previously estimated strategy.

APPLICATION OF OPTIMIZATION MODEL AT SELECTED SITE

The Goksu Delta (also known as the Silifke Plain), which is located in south-central Turkey on the Mediterranean Sea, was selected as the location for a case study (see Figure 1). An optimization model was created based on a vertical cross-section saltwater-intrusion model of the Goksu Delta by assuming pumping takes place at two existing well sites [Gordu, 2000]. The optimization model was developed using data generated using SUTRA [Voss, 1984] for steady-state conditions. It was assumed that pumping occurs from two wells that are located in two towns, i.e., Bahce and Kurtulus, in the delta (see Figure 1). The objective of the optimization model was to maximize the total pumping rate from these two wells, while meeting the demands of five municipal areas that were reduced to two demand areas in the optimization model. Since the purpose of these wells is to supply water for drinking and irrigation, their chloride concentrations must be maintained equal to or less than specified levels in the optimization models. A trade-off curve was constructed that shows the change in maximum pumping rate with respect to different chloride concentration limits.

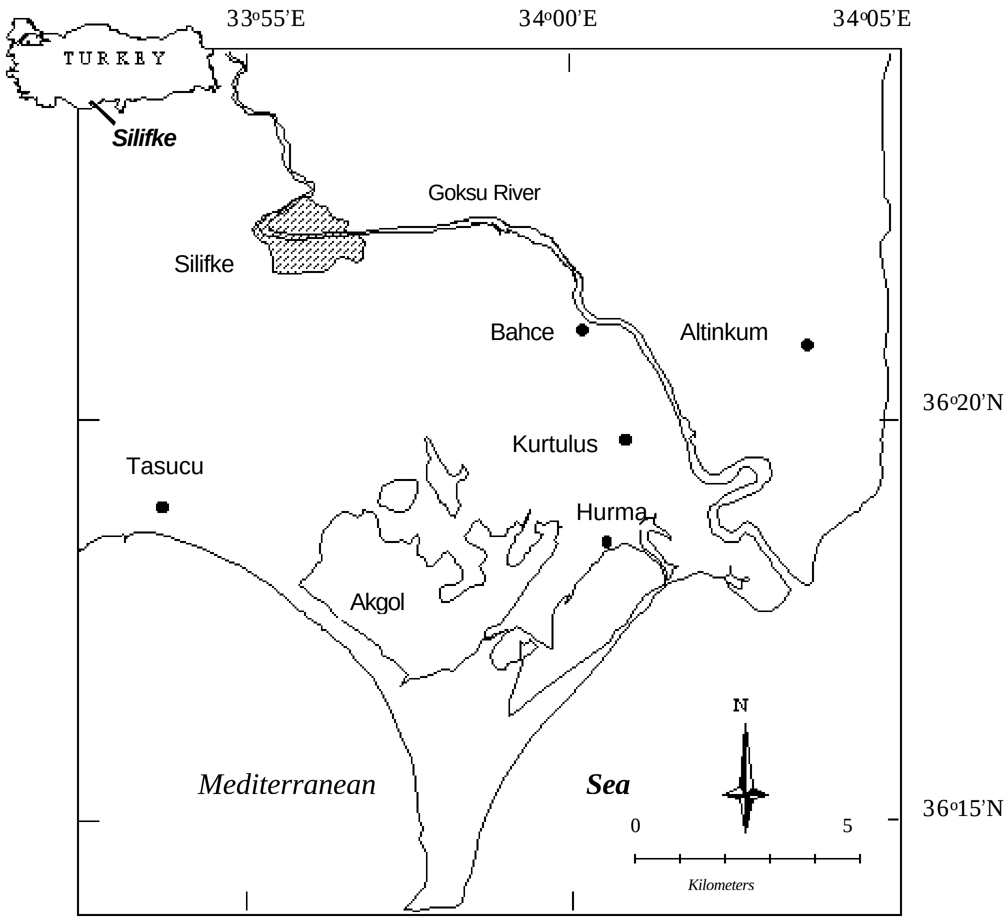

Figure 1: The Goksu Delta

Objective Function

The objective of the model was to maximize the total pumping rate, or:

$$Max \sum_j QT_j \tag{1}$$

where: QT_j = the pumping rate at well j (m^3/s).

Decision Variables

By taking the screen lengths of the wells into account, it was assumed that water pumped from well 1 was derived from three nodes, whereas water pumped from well 2 was derived from four nodes. Therefore, the decision variables were defined for each node and each well with s_i = drawdown at node i (m); H_i = hydraulic head at node i (m); CC_i = chloride concentration at node i (mg/L); QT_j = pumping rate at well j (m^3/s); Q_{jk} = pumping rate of well j that supplies water for demand area k (m^3/s); and QN_i = withdrawal rate from node i (m^3/s).

Constraints

In this problem, there are seven observation nodes (at the two well locations) at which the aquifer drawdown and chloride concentrations were calculated and constrained. The response matrix technique was used to generate the drawdown and chloride concentration constraints. The following drawdown constraint for each observation node includes a linear superposition of aquifer responses to the wells:

$$s_i = \sum_j \alpha_{ij} QT_j \quad (2)$$

where: s_i = drawdown at observation node i (m); α_{ij} = aquifer influence coefficient describing the change of head at node i with respect to a change in pumping rate at well j; and QT_j = total pumping rate at well j (m^3/s).

Individual influence coefficients were multiplied by the changes in pumping rate, which produced the drawdown change at a specified node. Then the hydraulic heads at an observation node were estimated by subtracting the drawdown at node i from the initial hydraulic head:

$$H_i = (H_0)_i - s_i \quad (3)$$

where: H_i = hydraulic head at node i (m); and $(H_0)_i$ = initial hydraulic head at node i (m). The initial hydraulic head for each node was obtained from the saltwater intrusion simulation model.

Similar to the drawdown constraints, aquifer response matrices also were constructed for the chloride concentration constraints. These matrices include influence coefficients that constitute the aquifer response in terms of the change in chloride concentration with respect to a change in the pumping rate. The linear superposition of aquifer responses in terms of chloride concentration to the pumping wells gives the change in chloride concentration at each node as follows:

$$C_i = \sum_j \beta_{ij} QT_j \quad (4)$$

where: C_i = change in chloride concentration (mg/L); and β_{ij} = aquifer influence coefficients describing chloride concentration change at node i due to a change in the pumping rate at well j .

The final chloride concentration at a node was estimated by adding the change in chloride concentration to the initial concentration, which was obtained from the calibrated groundwater simulation model such that:

$$CC_i = (CC_0)_i + C_i \quad (5)$$

where: CC_i = chloride concentration at each node i (mg/L); and $(CC_0)_i$ = initial chloride concentration at node i (mg/L).

Since the water pumped in the field is used for drinking and irrigation purposes, the chloride concentrations must not exceed specified values. In the model, the chloride concentration was limited at each well by taking the average of the chloride concentrations of the nodes assigned to each well. Therefore, the following constraints were set:

$$CC_j \leq CL \qquad (6)$$

where: CC_j = chloride concentration at well j (mg/L); and CL = chloride concentration limit (mg/L); and:

Well 1

$$CC_1 = \frac{\sum_n CC_n}{3} \qquad n = 1,2,3 \qquad (7)$$

Well 2

$$CC_2 = \frac{\sum_m CC_m}{4} \qquad m = 4,5,6,7 \qquad (8)$$

where: n = the nodes assigned for well 1; and m = nodes assigned for well 2.

In addition to the drawdown and concentration constraints, the model was subject to the following constraints as well:

1. Water demand limitations:

$$\sum_j Q_{jk} \geq D_k \qquad (9)$$

where: Q_{jk} = pumping rate of well j supplying water for demand area k (m^3/s); and D_k = the amount of water required for demand area k (m^3/s).

2. Distribution of water from pumping wells to the demand areas:

$$QT_j = \sum_k Q_{jk} \qquad (10)$$

3. Well capacity limitations:

$$QT_j \leq CAPQ_j \qquad (11)$$

where: $CAPQ_j$ = maximum capacity of well j (m^3/s).

4. Avoidance of dewatering the well nodes:

$$H_i \geq B_i + 1.0 \qquad (12)$$

where: B_i = bottom elevation of the aquifer at node i below mean sea level (m).

The purpose of this constraint is to ensure that hydraulic heads do not decrease below a level of 1m above the bottom elevation of the aquifer at each node.

5. Non-negativity constraints:

$$QT_j, \quad Q_{jk}, \quad CC_i \geq 0 \tag{13}$$

Generation Of Response Matrices

Two different sets of influence coefficients were developed under steady-state conditions. The first set is for the estimation of drawdown, and the other is for the estimation of chloride concentration at each observation node. In order to determine the influence coefficients, the simulation model was executed a number of times for different pumping rates. Then, for each pumping rate, hydraulic heads and chloride concentration were correlated. A linear relationship between hydraulic head and pumping rate was obtained as expected. Therefore, the slope of the hydraulic head versus pumping rate plot gives the influence coefficient for drawdown constraint, a_{ij}, which represents the hydraulic head change at node i due to a change in the pumping rate at well k. This step was repeated for each of the seven observation nodes, using Equation 2 to write the drawdown response function in discrete form.

In contrast to drawdown, a nonlinear relationship between chloride concentration and pumping rate was observed. In order to avoid non-linearity in the optimization model, the non-linear curves were linearized by dividing them into two or three parts when necessary, and different influence coefficients were calculated for each part (see Figure 2).

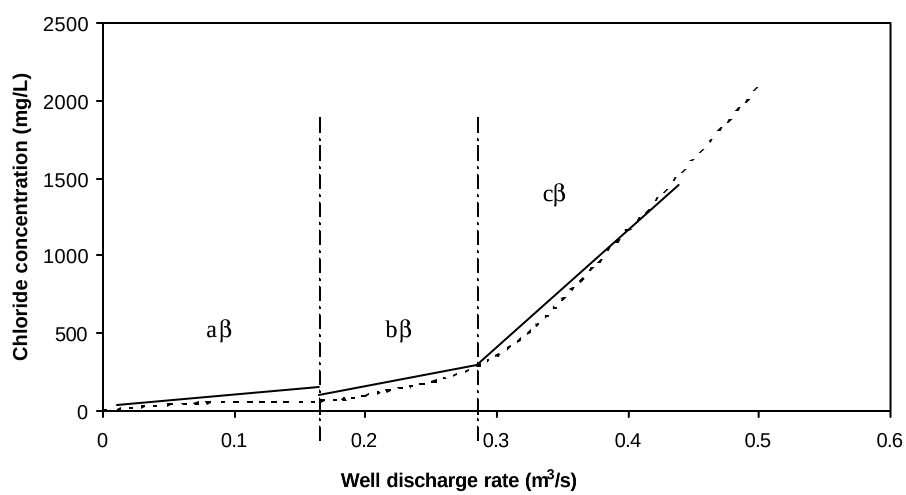

Figure 2: Chloride concentration versus discharge and estimation of chloride concentration influence coefficients.

Due to the non-linearity in the pumping-chloride relation, the initial estimation of the influence coefficients for this relation might not have been accurate. The following steps were followed in order to correct the influence coefficients. First, the optimization model was solved by using the initially predicted coefficients. Then, by using the optimum pumping strategy obtained from the optimization model, the simulation model was executed. The results from the simulation model were compared with those from the optimization model. If they were not in agreement, a revised set of influence coefficient would be calculated based on the results of the simulation model obtained under the previously predicted optimum strategy. Then, the optimization model was re-solved with the revised influence coefficients, and the simulation model was executed with the predicted pumping strategy. The procedure was repeated until the optimization model results matched the simulation model computations. Consequently, the following constraints were included in the optimization model:

$$C_i = \sum_j \left(a\boldsymbol{b}_{ij} AQ_{ij} + b\boldsymbol{b}_{ij} BQ_{ij} + c\boldsymbol{b}_{ij} CQ_{ij} \right) \tag{14}$$

$$QT_j = \sum_i \left(AQ_{ij} + BQ_{ij} + CQ_{ij} \right) \tag{15}$$

i = n = 1,2,3 for Well 1
i = m = 4,5,6,7 for Well 2

where:

$a\boldsymbol{b}_{ij}$ = first set of influence coefficient for chloride concentration;
$b\boldsymbol{b}_{ij}$ = second set of influence coeffic ient for chloride concentration;
$c\boldsymbol{b}_{ij}$ = third set of influence coefficient for chloride concentration;
AQ_{ij} = first set of pumping rates where $a\boldsymbol{b}_{ij}$ is valid;
BQ_{ij} = second set of pumping rates where $b\boldsymbol{b}_{ij}$ is valid; and
CQ_{ij} = third set of pumping rates where $c\boldsymbol{b}_{ij}$ is valid.

RESULTS AND DISCUSSION

A management model was developed under steady-state conditions. The objective of the management model was to maximize the total pumping rate at the two wells that supply water for the two demand areas, while constraining chloride concentrations. GAMS (General Algebraic Modeling System) [Brooke, 1996] was employed to execute the optimization model.

The model was solved for five levels of chloride concentrations. Each solution sought an optimal pumping strategy for the different chloride concentration limits. Well 1 was represented by three nodes, whereas well 2 in was represented by four nodes based on their screen lengths. In the model, the chloride concentration was constrained for each well by taking the average of the chloride concentrations of the nodes assigned for each well. The optimal pumping strategies determined by the optimization model were incorporated into the groundwater simulation model to verify the optimization model. Each time, the optimum pumping rates were used as input to the simulation model to compute the hydraulic head and chloride concentration for each node so as to compare them with those estimated from the optimization model.

To display the correlation of aquifer responses between the simulation model estimates and the optimization model results, hydraulic heads and chloride concentrations estimated from the optimization model were plotted versus those of the simulation model (see Figures 3-4). The predicted hydraulic heads from the optimization model match those generated with the simulation model very closely (Figure 3). However, due to the nonlinear effects previously discussed, the correlation between the chloride concentrations predicted from the optimization model and those estimated from the simulation model is not as good as the correlation between the hydraulic head estimations (Figure 4).

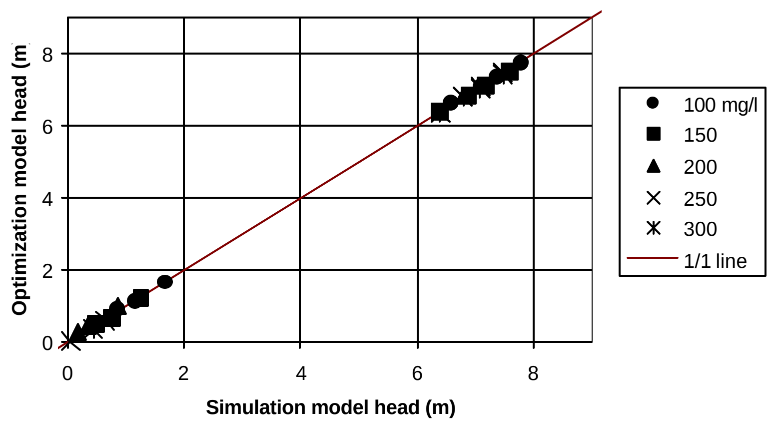

Figure 3: Correlation between simulation model results and optimization model results for hydraulic heads.

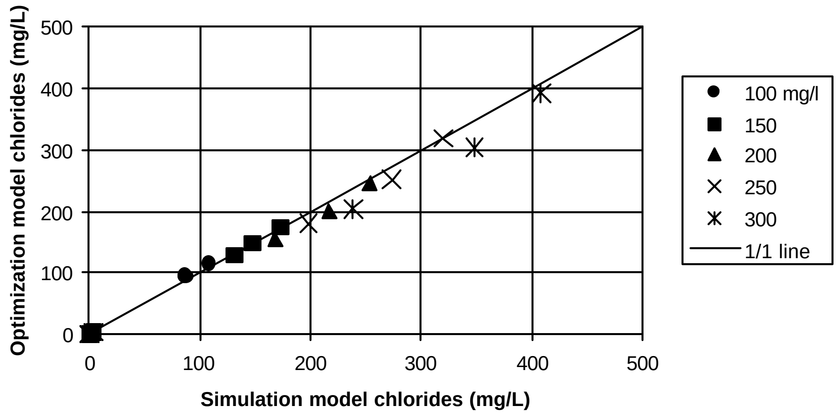

Figure 4: Correlation between simulation model results and optimization model results for chloride concentrations.

In order to provide water-resource managers with complete and useful information and assist them in evaluating different management scenarios, the results of the optimization model were expressed in the form of a trade-off curve relating the chloride concentration to the maximum pumping rate for each well (see Figure 5). These curves enhance the ability of a water-resource manager to select the optimum strategy with respect to chloride concentration limits. The optimization model tends to maximize the pumping rate at well 2, which is farther from the saltwater-freshwater interface, as much as possible until the chloride concentrations reach a specific level, which is 100 mg/L. After this point, the influence that pumping from well 2 has on the well 1 becomes significant, and then the optimization model begins to maximize the pumping rates for both wells. The results from the optimization model showed that the chloride concentration constraint was the most important component that determined the optimum pumping strategies. Similar to the conclusion reached by Hallaji and Yazicigil [1996] for wells in the Erzin Plain, which also is in south-central Turkey, it can be concluded that the overland transportation of water pumped from wells far from the interface to meet the local demands in place of the wells closer to the interface might be more feasible at certain concentration levels. However, the economics of this option would have to be evaluated.

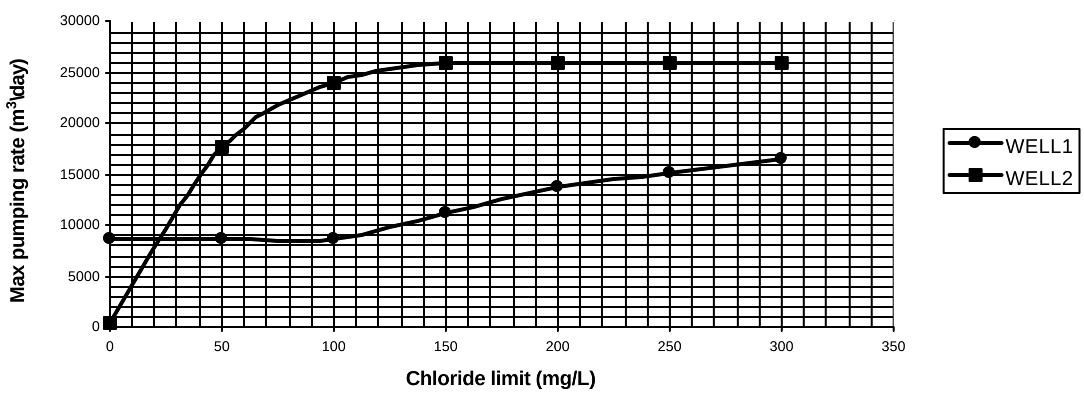

Figure 5: Trade-off curves between maximum pumping rate and chloride concentration limit

References

Brooke, A., Kendrick, D., Meeraus, A., and Raman, R., GAMS: A User's Guide, GAMS Development Corporation, Washington, DC, 262 p., 1996.

Finney, B. A., Samsuhadi, And Willis, R., "Quasi-three dimensional optimization model of Jakarta Basin," *Journal of Water Resources Planning and Managemnt*, **118** (1), 18-31, 1992.

Gordu, F., Simulation of seawater intrusion and optimization of groundwater use in the Goksu Delta, Turkey, M.E. Thesis, University of Florida, Gainesville, Florida, 105 p., 2000.

Gorelick, S. M., "A review of distributed parameter groundwater management modeling methods," *Water Resources Research*, **19** (2), 305-319,1983.

Hallaji, K., and Yazicigil, H., "Optimal management of a coastal aquifer in southern Turkey," *Journal of Water Resources Planning And Management*, **122** (4), 233-244, 1996.

Hatfield, K., Hearn, D. W., Graham W., Burger P. C., and Holland M. E., Water resource allocation and quality optimization modeling, St. John River Water Management District Special Publication SJ96-SP5, 217 p., 1995.

Shamir, U., Bear J., and Gamliel, A., "Optimal annual operation of a coastal aquifer," *Water Resources Research*, **20** (4), 435-444, 1984.

Voss, C. I., SUTRA (Saturated-Unsaturated Transport): A finite-element simulation model for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically reactive single-species solute transport, USGS National Center, Reston, Virginia, 409 p., 1984.

Willis, R., and Finney, B. A., "Planning model for optimal control of saltwater intrusion," *Journal of Water Resources Planning and Management*, **114** (2), 163-178, 1988.

Yazicigil, H., Al-Layla, R.I., and De Jong, R.L, "Optimal management of a regional aquifer in eastern Saudi Arabia," *Water Resources Bulletin*, **23** (3), 423-434. 1987.

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