Chapter 11

Optimization-Based Approaches for Groundwater Management

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Introduction

Sustainable management of groundwater resources has gained increased attention in recent times, especially in the arid and semi-arid regions of Texas. The threat of large-scale unregulated pumping has spurred the creation of groundwater conservation districts in order to regulate the underlying aquifer resources in an efficient manner. Chapter 36 of the Texas Water Code and the more recent House Bill 1763 provide the legislative framework under which Groundwater Conservation Districts (GCDs) have to operate. In particular, GCDs have to develop a comprehensive management plan that addresses a variety of groundwater-related issues, including but not limited to: identifying efficient use of groundwater resources, addressing drought conditions, and characterizing surface water-groundwater interactions.

Obtaining reliable estimates for how much groundwater is available within a district is fundamental to its proper management. The available groundwater is a function of both aquifer hydrogeologic characteristics as well as the risk preferences of the decision makers' involved. While a significant quantity of water is held in the subsurface, it is not practical or advisable to remove all of it over a short duration. The concept of safe yield suggests that the total withdrawals from the aquifer in a given time period should not exceed the recharge occurring over the same time period. While this approach is conceptually appealing, it is increasingly being considered inadequate as it does not account for the ecological demands on groundwater. In certain other areas, the anthropogenic demands on groundwater are large and exceed the amounts being recharged. In such instances, the depletion of groundwater is taken for granted, and the rate of depletion is managed to ensure that sufficient quantities of groundwater are available until alternative supplies are identified or water use is shifted to reduce the demand.

Groundwater management is a multi-stakeholder process wherein competing objectives and differing sets of values and perceptions have to be effectively reconciled. From a practical standpoint, consensus-based water management strategies and solutions are likely to succeed and lead to efficient use of groundwater (Mace and others, 2001). The challenge is to adequately capture the subjective preferences and concerns of the stakeholders and characterize them in terms of aquifer stimulus-response behavior.

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The Texas Water Development Board (TWDB) has recently completed the development of groundwater availability models (GAMs) for major aquifers in Texas (for example, Chowdhury and others, 2004). These models utilize the conservation of mass and energy (Darcy's law) to predict the response of the aquifer to various natural and anthropogenic stimuli such as recharge, pumping, and evapotranspiration. The response of the aquifer is characterized as the total hydraulic head (well water levels measured from a pre-specified datum). As stated previously, the available groundwater within a GCD is a function of both hydrogeology and public policy. GAMs only address the hydrogeologic part of the water availability equation. Hence, an additional instrument that combines GAM with the policy preferences of the stakeholders within a GCD is required to derive scientifically-credible, risk-informed, and consensus-based groundwater availability estimates.

The overall goal of this paper is to demonstrate how optimization tools developed in the field of operations research can be integrated with simulation models (GAMs) to objectively estimate groundwater availability by incorporating appropriate stakeholder preferences. The basic concepts required to set up the management model (optimization model) is presented next and is followed by illustrative case studies that combine optimization modeling with GAMs to develop decision support tools for estimating groundwater availability.

Optimization-Based Groundwater Management Models

Optimization-based models for management are comprised of three parts: (1) the objectives that form the basis of management; (2) the constraints that limit the realization of the management objectives, and (3) the decision variables that control the management process. In optimization-based approaches, the decision variables are adjusted with the goal to maximize (or minimize) the objectives subject to meeting the constraints.

In the context of groundwater availability estimation, the objective functions could be maximizing the withdrawal of groundwater for economic gains and/or minimizing the withdrawal of groundwater to promote conservation. Multiple objectives such as maximizing pumping for economic gains and minimizing pumping for conservation or subsidence control can be simultaneously considered and such models are referred to as multiobjective optimization models. For groundwater availability estimation, constraints indicate the preferences and concerns of the stakeholders. Constraints could cover a gamut of issues, including: (1) ensuring that the pumping does not cause saltwater intrusion along the coast, (2) preventing subsidence from occurring, (3) protecting shallow wells from going dry, (4) making sure ecological requirements such as baseflows to streams and creeks are maintained, and (5) requiring that groundwater be equitably available to all stakeholders within the district. The decision variables could be point sources such as pumping at wells in different locations and areal sources/sinks like recharge rates indicating additional artificial recharge facilities or land use/land cover alterations that control evapotranspiration rates.

Both the objective and the constraints have to be the functions of the decision variable. If these functions are all linear, then the optimization model is called the linear programming model; otherwise, it is called a non-linear programming model. GAMs simulate the response of the aquifer to different imposed stresses. The state variable (total hydraulic head) at any location in the model domain is a function of imposed stresses—pumping or alterations to recharge and evapotranspiration. Hence, if the constraints are specified in terms of the state variable, the relationship provided by the GAM could be used to establish the relationship between the constraints and the objective function.

For example, the management goal—"Large-scale pumping projects should not cause shallow domestic and livestock wells to go dry"—could be quantified as "the drawdown at a monitoring well due to any proposed large-scale pumping should not cause the water levels to drop more than 20 feet from their long-term average values." The GAM can then be used to simulate the response of the aquifer when a new project is proposed and to establish a relationship between the pumping and the response at the monitoring well of interest. This relationship is then fed into the optimization model as a constraint to characterize the policy of GCD.

There are two approaches by which the responses from the simulation models such as GAMs can be incorporated into an optimization framework (Gorelick, 1983). In the embedded approach, the entire simulation model is included within the optimization framework. Alternatively, in the response function approach, the relationship between the stimulus (pumping at a well) and the response at a specified monitoring well is expressed as an algebraic relationship in the optimization model. GAM runs are carried out prior to the development of the management model to establish the necessary relationship between stimulus (pumping) and response (monitoring well heads). The embedded approach offers greater flexibility in terms of changing pumping and monitoring well locations during optimization exercises as the entire GAM is embedded within the optimization framework. However, development of such models requires considerable programming effort. In addition, the developed optimization models will be cumbersome and hard to interpret. As such, the response function approach is better suited for groundwater availability estimation and often employed in groundwater optimization studies (for example, Zhou and others, 2003).

The algebraic equation linking groundwater pumping to aquifer drawdown is noted to be linear for confined aquifers (Ahlfeld and Mulligan, 2000). As such, the total response at the monitoring well due to simultaneous pumping at different locations is equal to the sum of individual responses caused due to pumping at each well. Therefore, if the total number of new wells in a proposed project is N, a minimum of N+1 model runs will be required to obtain the necessary response at different monitoring wells for a given time-step. The stimulus-response relationship is nonlinear when the transmissivity of the aquifer changes with drawdown, as is the case in unconfined formations. However, if the pumping is not excessive, the assumption of linearity is noted to reasonably hold true in unconfined formations as well (Uddameri and Kuchanur, 2005). Suitable nonlinear formulations have been suggested in the literature (Maddock III, 1974) and can be employed when the assumption of linearity is not reasonable. While nonlinear optimization models are not difficult to conceptualize, certain computational complexities have to be dealt with in their implementation. Also, the number of GAM runs required to establish the nonlinear relationship can be substantial and adds to the modeling effort.

Groundwater practitioners and consultants often employ sensitivity studies to evaluate impacts of potential projects or altered situations on water levels in aquifers. At a mechanistic level, the optimization approach effectively automates this procedure and searches for all possible solutions (Ahlfeld and Mulligan, 2000). The optimization approach is also valuable from the policy standpoint, as it requires relevant stakeholders and decision makers to identify and characterize goals, objectives, and constraints. Using optimization models in an interactive mode is helpful to foster sustainability debate and reach consensus-based groundwater management policies as envisioned by the state legislature.

The literature is replete with applications of combined simulation optimization approaches to groundwater management (for example, Willis and Finney, 1988; Finney and others, 1992; Emch and Yeh., 1998; Zhou and others, 2003; Uddameri and Kuchanur, 2005). Additional information about this approach can be obtained in Gorelick (1983) and Ahlfeld and Mulligan (2000). Case studies illustrating the application of optimization schemes for groundwater management in the Gulf Coast aquifer of Texas are discussed next.

Case Study I: Coupling Optimization with Steady-State Central Gulf Coast GAM

The steady-state Central Gulf Coast aquifer Groundwater Availability Model (SS-CGC-GAM) described by Chowdhury and others (2004) was used to develop estimates for how much water is available for use in Refugio County, Texas. This county is predominantly rural and is experiencing very little growth. The water demands are estimated to be less than 3,000 acre-feet per year and projected to stay constant over the next several decades (TWDB, 2002). As such, the use of a steady-state model was deemed reasonable to obtain preliminary water availability estimates.

The groundwater in Refugio County, Texas, is mostly extracted from the unconfined Chicot and semi-confined Evangeline aquifers of the Gulf Coast aquifer. Hydrogeologic studies carried out by Mason (1963) indicate that the Evangeline Formation is more prolific and consists of considerable sand thicknesses. Hence, it is likely that future large-scale development of groundwater resources are likely to occur in this formation. Being a coastal county, concerns with regards to potential saltwater intrusion under large-scale pumping were expressed by many stakeholders and decision makers. In addition, many ranchers and farmers use windmills to extract groundwater for their livestock, especially in remote ranch locations where electricity is not readily available. Hence, regional-scale drawdowns incurred due to any proposed large-scale project were to be kept at a minimum to avoid negative economic externalities. Refugio County has three perennial rivers: the Aransas River in the south, the Mission River in the central part, and the San Antonio River in the north. Surface water-groundwater interactions near these rivers were deemed important to sustain low summer flows and for aquifer recharge during precipitation events. In addition, as the aquifer is shared by other adjoining counties, the impacts of any groundwater withdrawals in Refugio County on water levels in adjacent counties were to be assessed as well.

Based on the above considerations, a management scenario consisting of several pumping and monitoring wells was developed and is depicted in Figures 11-1 and 11-2. The monitoring wells labeled B are used to monitor water levels in adjoining counties. Similarly, the monitoring wells labeled R, C, and M were used to monitor heads near the rivers, within the county (to maintain regional groundwater gradients), and along the coast to monitor for saltwater intrusion, respectively. The objective then was to identify how much surplus groundwater is available in

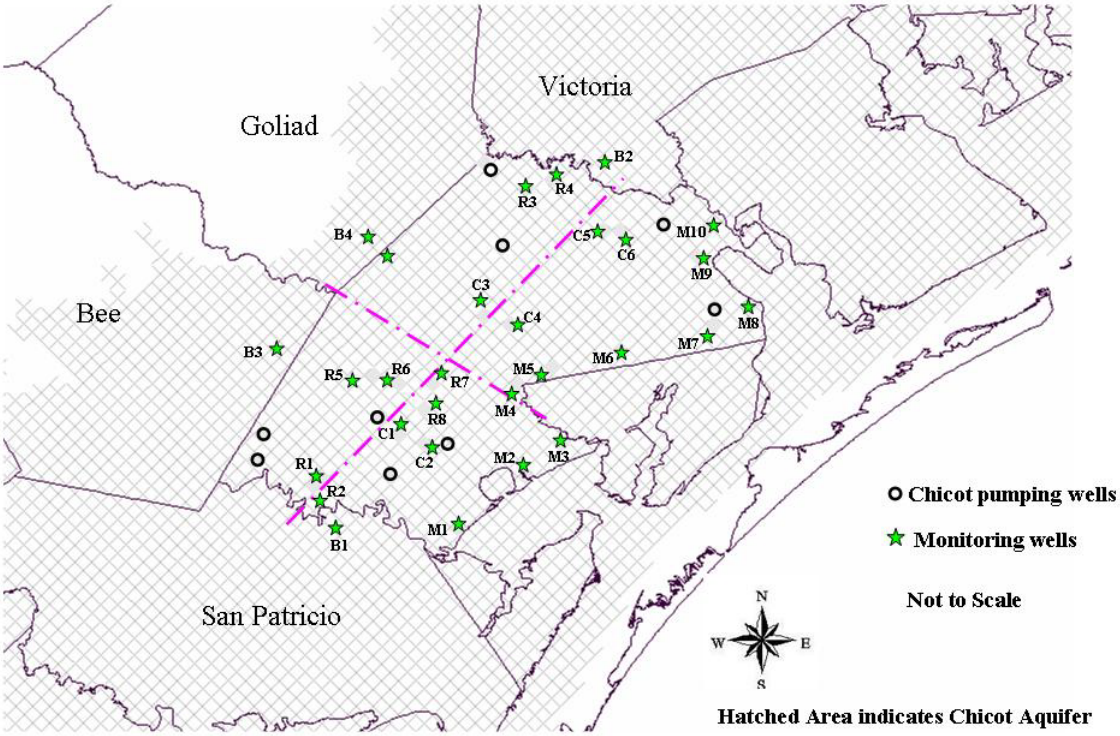

Figure 11-1. Pumping and monitoring wells in the Chicot aquifer—Case Study I.

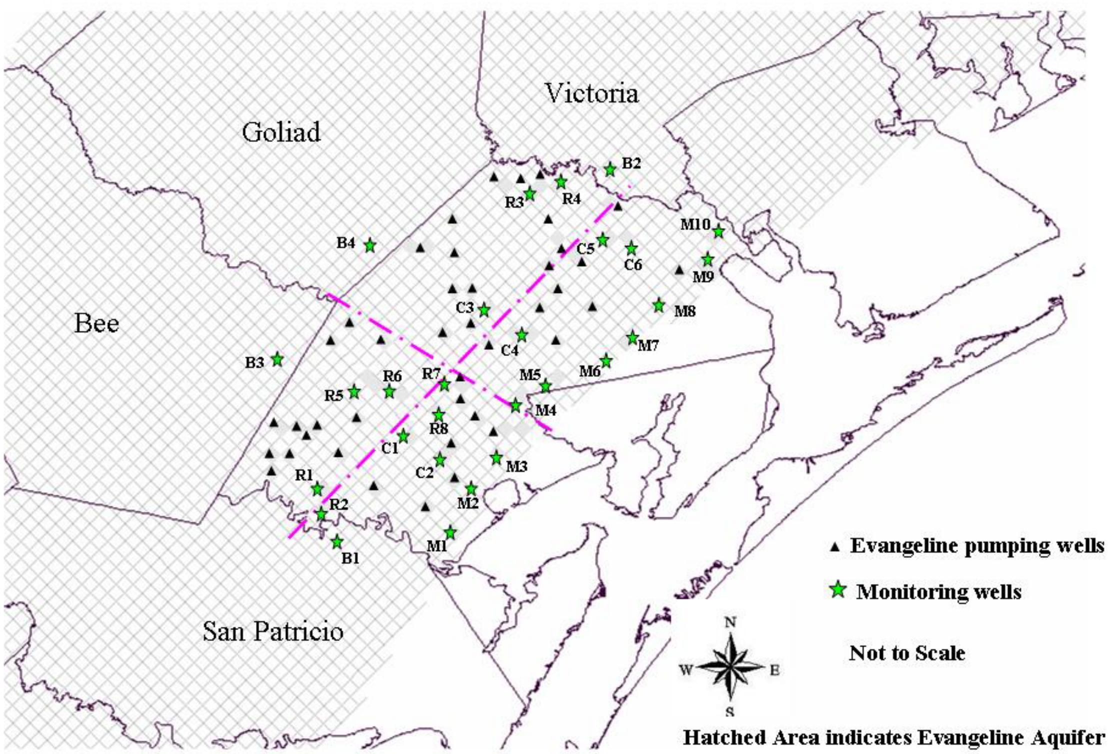

Figure 11-2. Pumping and monitoring wells in Evangeline aquifer—Case Study I.

the district, subject to constraints on saltwater intrusion, sustaining baseflows, and maintaining regional gradients. Mathematically, these constraints can be stated as (Uddameri and Kuchanur, 2005):

$$Max : \sum_{i=1}^{i=50} Q_i \tag{1}$$

Subject to:

$$H_{MW,j,k} \geq (MSL - \Delta) \; \forall \; j = 1, 2 \; and \; k = 1,...,10 \tag{2}$$

$$H_{C,i,j} - H_{C,i,k} \geq 0 \; \forall \; i = 1, 2 \; and \; \{j, k\} = \{1, 2\}; \{3, 4\}; \{5, 6\} \tag{3}$$

$$H_{R,i,j} - H_{R,i,k} \geq 0 \; \forall \; i = 1, 2 \; and \; \{j, k\} = \{1, 2\}; \{3, 4\}; \{5, 6\}; \{7, 8\} \tag{4}$$

$$H_{BW,j,k} \geq (H_{BW0,j,k} - \phi) \forall j = 1,2, k = 1,2,3,4 \tag{5}$$

$$Q_i \geq Q_{\min,i} \quad \forall \; i = 1,...,50 \tag{6}$$

Equation (1) represents the objective of maximizing the amount of groundwater that can be safely pumped (Q) from the aquifer. The prevention of saltwater intrusion is captured in Equation (2) where hydraulic heads (H) monitored at ten locations along the coast (MW1, … , MW10) in both Chicot and Evangeline aquifers (j = 1, 2) are assumed to be below specified head (MSL - Δ). Where MSL is the height of the mean sea level from a pre-specified datum (equal to zero when mean sea level is used as the datum) and Δ is the magnitude of the depth below the sea level that can be tolerated. The value of Δ was taken to be equal to zero in the baseline case.

The groundwater flow in the aquifers is from west to east. One important management objective was to ensure that any future groundwater development should not cause an alteration to this regional flow direction. Three well couplets each in Chicot and Evangeline formations (i = 1, 2) were selected at different locations, (C1, C2, C3, C4, C5, C6) as depicted in Figures 11-1 and 11-2, in order to enforce the constraint that the heads in the western section (at C1, C3, C5) were greater than the corresponding wells on the eastern side (at C2, C3, C5) as mathematically stated in Equation (3). Along the same lines, another management objective was to maintain groundwater flows towards streams to sustain baseflows during dry periods. A set of four well couplets each in Chicot and Evangeline aquifers (R1-R2, R3-R4, R5-R6, R7-R8) were used for this purpose and the management objective was mathematically stated using Equation (4).

The hydraulic heads in the adjoining counties could not fall below a pre-specified level (Δ). This constraint is mathematically captured using Equation (5). Equation (6) implies that the flow rate (Q) in any management well should not be less than a pre-specified flow rate (Q_{min}) specific to that well. A nominal minimum flow rate of 100 acre-feet per year was assigned to ensure at least a certain degree of pumping at each well without rendering the linear programming result infeasible. The necessary response coefficients were generated by carrying out appropriate GAM runs and the management model was coded in an MS-EXCEL spreadsheet and solved using the WHATSBEST add-in (Lindo Systems Inc., 2005).

The results of the optimization model are summarized in Table 11-1. The illustrative results indicate that how much groundwater is available in Refugio County depends upon how much drawdown is deemed acceptable in adjoining districts, suggesting the need for cooperation and joint planning among neighboring districts.

Table 11-1. Estimated groundwater availability under various drawdown conditions at the Refugio County boundaries.

No.	Saltwater intrusion constraint (feet)	Boundary drawdown constraint (feet)	Available groundwater (acre-feet per year)
1	0	5	12409
2	0	25	30481
3	0	50	37247
4	0	100	39630
5	0	150	39650

Case Study II: Coupling Optimization with Transient Central Gulf Coast GAM

The transient version of the Central Gulf Coast aquifer GAM (T-CGC-GAM) was coupled with optimization routines to evaluate the impacts of proposed large-scale pumping projects along the western sections of the Refugio County. Two potential well fields, one in the southwestern section and the other in the northwestern section, were simulated by placing ten production wells in the Evangeline Formation. A suite of monitoring wells similar to the ones used in the previous study was also employed in this scenario evaluation. The locations of the monitoring and pumping wells are schematically depicted in Figure 11-3. The management model can be mathematically stated as follows:

$$Max : \sum_{t=2000}^{t=2009} \sum_{i=1}^{i=10} Q_{i,t} \tag{7}$$

Subject to:

$$H_{MW,j,k,t} \geq (MSL - \Delta) \forall j = 1,2, k = 1,.....,10 \; and \; t = 2000,.....,2009 \tag{8}$$

$$H_{c,i,j,t} - H_{c,i,k,t} \geq 0 \forall i = 1,2, \{j,k\} = \{1,2\}; \{3,4\}; \{5,6\} \; and \; t = 2000,.....,2009 \tag{9}$$

$$H_{R,i,j,t} - H_{r,i,k,t} \geq 0 \forall i = 1,2, \{j,k\} = \{1,2\}; \{3,4\}; \{5,6\}; \{7,8\} \; and \; t = 2000,.....,2009 \tag{10}$$

$$H_{BW,j,k,t} \geq (H_{BW,j,k,2000} - \phi) \forall j = 1,2, k = 1,2,3,4 \; and \; t = 2000,.....,2009 \tag{11}$$

$$Q_{i,t} \geq Q_{\min} \quad where \; i = 1,...,10 \forall \; t = 2000 \; to \cdots 2009 \tag{12}$$

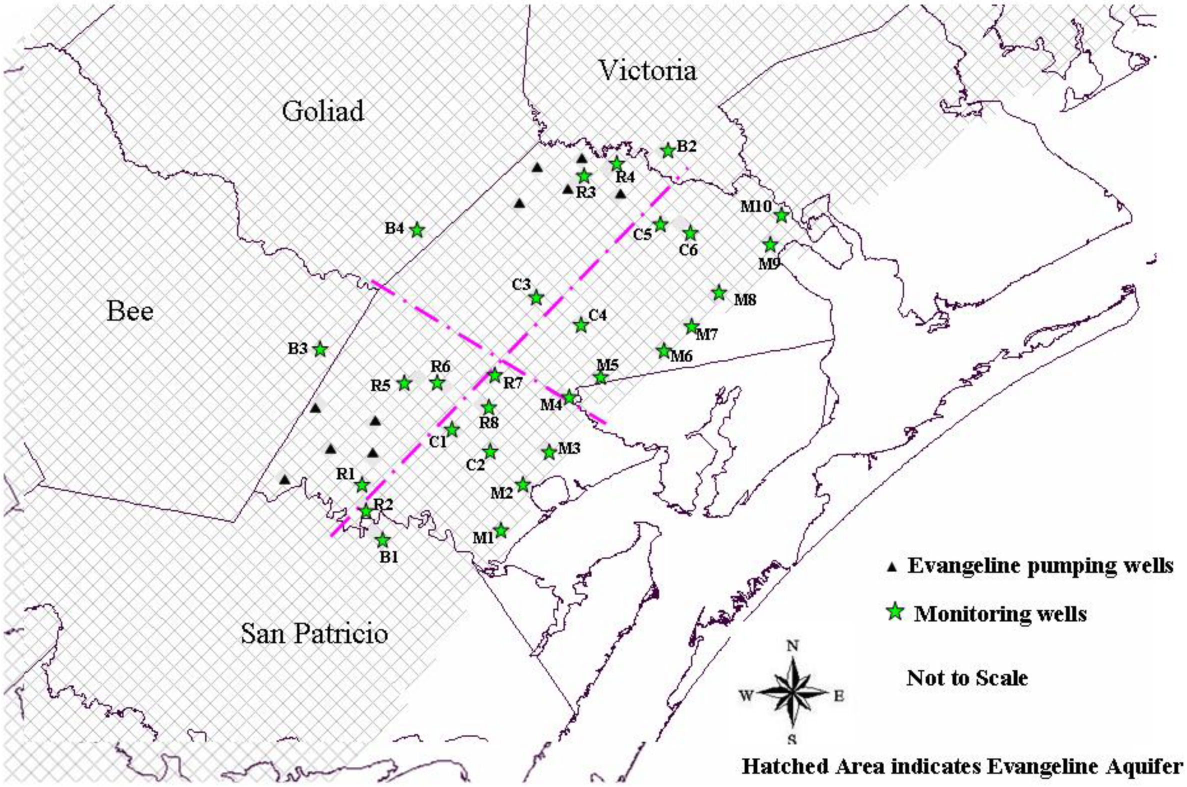

Figure 11-3. Pumping and monitoring wells in Evangeline aquifer—Case Study II.

The objective function and constraint set (Equations 7–12) for the transient model is very similar to their steady-state counterparts. However, an additional indexing variable (t = 2000, …, 2009) is used to depict predicted annual pumpage rates between the years 2000 and 2009. Quasi steady-state conditions were assumed with respect to recharge, evapotranspiration, and other groundwater users, and the inputs and withdrawals during the period 2000–2009 were assumed to be the same as that occurring between the years 1990–1999. The value of Δ in Equation (2) was set to zero and the heads in the coastal monitoring wells were required to be above mean sea level (MSL). Similarly, the allowable drawdown in boundary monitoring wells (Equation 11) was assumed to be 25 feet in this illustrative application.

The transient simulation-optimization model provides a schedule of how much water can be safely extracted while meeting the prescribed constraints. This schedule is the most optimal of many possible combinations in that the total pumpage over the ten-year horizon is maximized and the constraints are satisfied over the entire planning period. In addition to depicting the pumping schedules, Figures 11-4 and 11-5 also depict the average heads in all the monitoring wells in Evangeline and Chicot aquifer, respectively. The hydraulic heads in the year 1999 serve as the baseline for calculating the drawdown in the year 2000 and heads calculated by the GAM are used to compute drawdowns in subsequent years. The results (Figures 11-4 and 11-5) indicate that large amounts of water cannot be withdrawn on a steady basis for the conditions assumed in this study. The results in Figure 11-4 also indicate that there is on average a 20 foot drop in heads in the monitoring wells tapping into the Evangeline Formation. On the other hand,

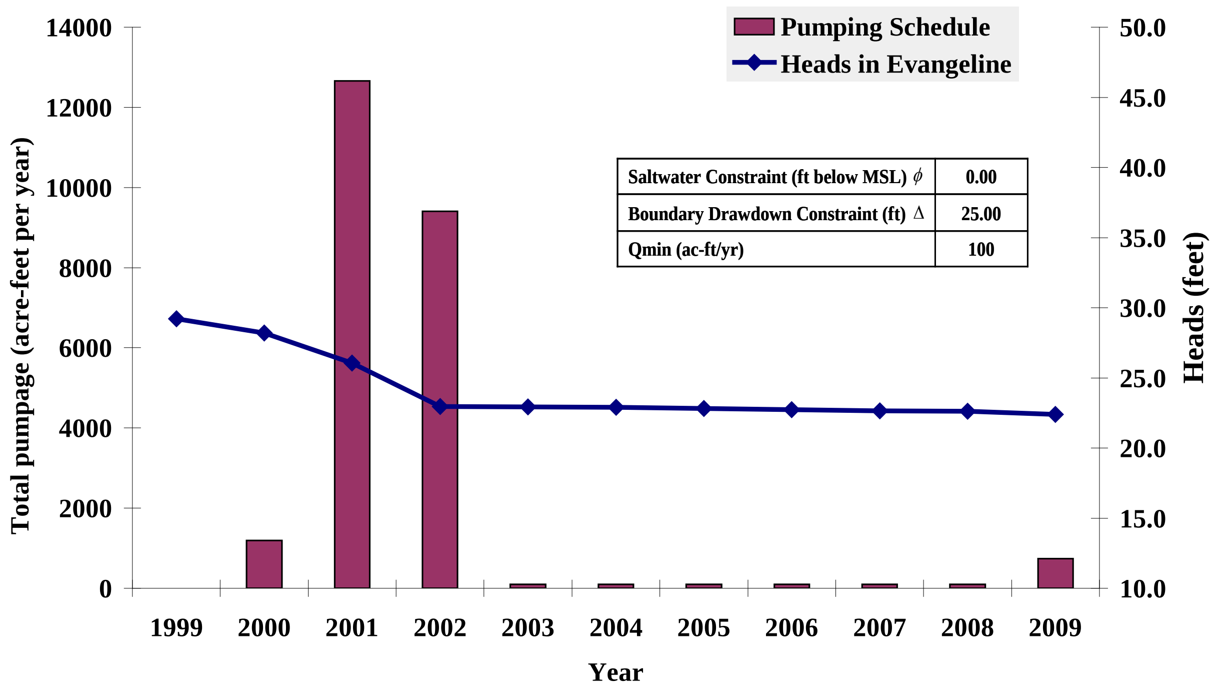

Figure 11-4. Total pumpage versus average heads in the Evangeline aquifer for Case Study II.

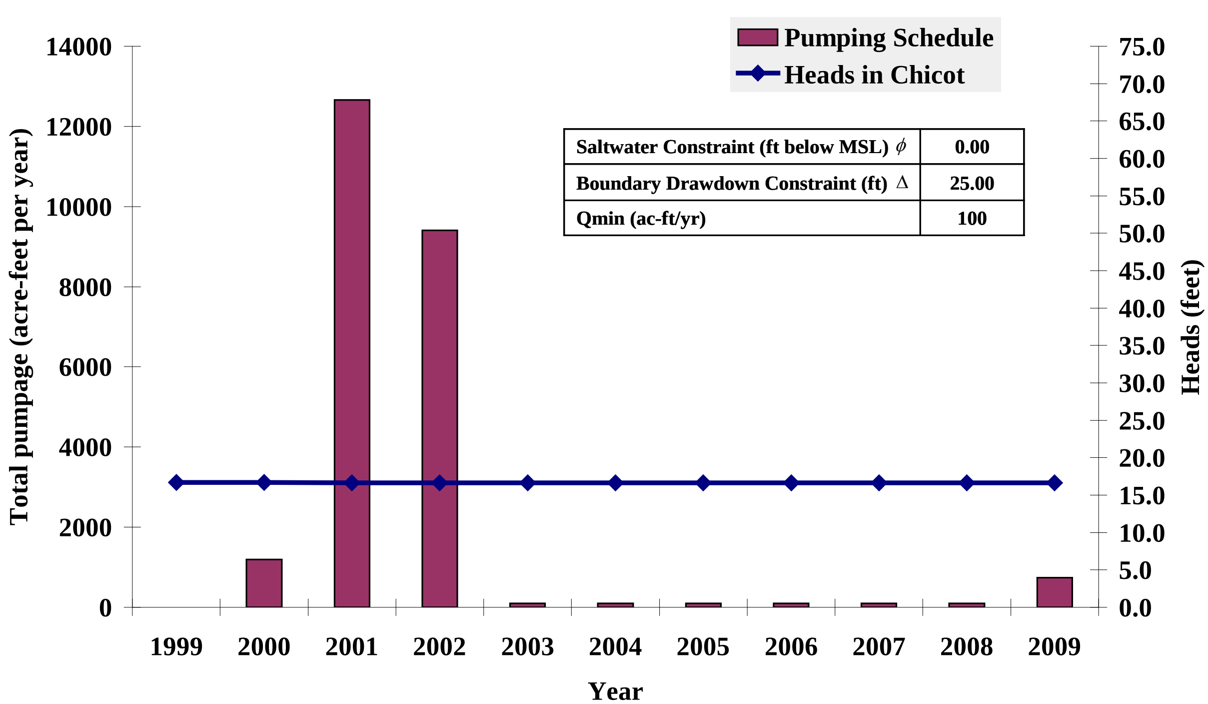

Figure 11-5. Total pumpage versus average heads in the Chicot aquifer for Case Study II.

the hydraulic heads in the Chicot Formation are not affected by pumping in the Evangeline Formation, suggesting that the cross-formational flow in the TWDB GAM is not significant between the Chicot and Evangeline formations at the optimally derived pumping rates.

Sensitivity of the estimated water availability to the drawdown constraint at the county boundaries is schematically depicted in Figure 11-6. The results indicate that the specified drawdown at the boundary wells is significant if the acceptable drawdown is less than ten feet. Other constraints, notably the need to preserve regional groundwater gradients (Equation 9), affected the estimated water availability when the acceptable drawdown at the county boundaries was greater than ten feet.

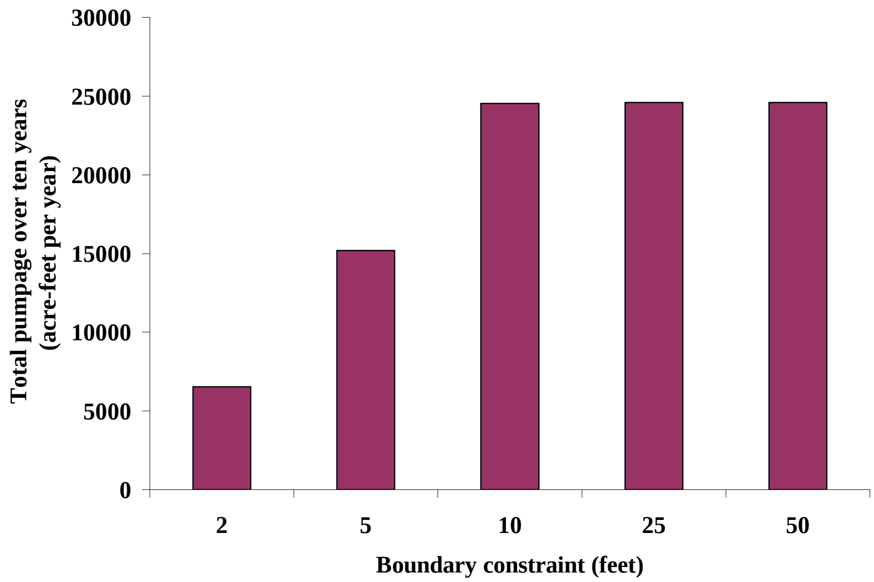

Figure 11-6. Sensitivity of the estimated water availability to the boundary drawdown constraint.

Summary and Conclusions

Obtaining reliable estimates for groundwater availability is vital for efficient management of groundwater resources. The managed available groundwater in an aquifer is a function of both aquifer characteristics and public policy. GAMs developed by the Texas Water Development Board utilize conservation laws of physics to simulate the aquifer response characterized as hydraulic heads to various stresses (pumping, recharge, evapotranspiration, and other energy gradients). Optimization models can be established with specific management objectives (such as maximize groundwater extraction for economic gains) subject to environmental, ecological, and social constraints. The response from the GAMs can be used to characterize these constraints, and the combined simulation optimization models can be used to estimate groundwater availability and evaluate other policies.

The general simulation optimization approach has been discussed in this paper and two case studies demonstrating the utility of integrating GAMs with optimization schemes have been illustrated. These real-world case studies demonstrate the utility of optimization schemes in groundwater management. The optimization approach effectively automates this procedure and searches for all possible solutions and as such is superior to conventional sensitivity analysis. The optimization approach is also valuable from the policy standpoint, as it requires relevant stakeholders and decision makers to identify and characterize goals, objectives, and constraints. Optimization models abstract the essential features of GAMs that are pertinent to the specific problems and therefore are more intuitive to understand. Application of these models in an interactive mode could help stakeholders understand the economic, environmental and ecological implications of proposed policies and help reach consensus-based groundwater management objectives as envisioned by the state legislature.

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