Optimal Aquifer Management for Controlling Land Subsidence

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Introduction

Land subsidence due to groundwater withdrawals affects many regions world wide. Subsidence in the Houston-Galveston Region led to a plan to convert from groundwater to surface water over the course of several decades. Unfortunately, the easily available surface water rights are nearly exhausted and this situation has led to renewed interest in aquifer management methods to meet water demands while controlling subsidence.

Interestingly, in the Houston-Galveston Region, several groundwater models for predicting drawdown and subsidence have been constructed in the last three decades, yet no formal modeling attempts at determining optimal policies to control subsidence have been reported despite the rich literature in modeling techniques for groundwater management. Most likely this situation occured because of the early decision to abandon the groundwater resource for surface water, so optimal policies were not a priority.

This paper discusses on-going research in optimal regional aquifer management that has a multiplicity of goals: water supply, subsidence control, and energy management. Current research is directed at simulation and optimization of the aquifer system using a variety of methods. The goal of the research is to identify pumping policies that control subsidence, yet meet current and projected groundwater demands and require minimal lift (a surrogate for energy). Two fundamentally different operational strategies will be studied: (1) pumping (extraction) only; and (2) pumping combined with injection where net extraction meets demand.

The simulation model uses the U.S.G.S. modular three-dimensional finite difference groundwater flow code (McDonald and Harbaugh, 1988) with the interbed storage package (Leake and Prudic, 1991) for modeling flow and subsidence. The current model is a four layer model with spatial resolution of 2.5 miles in the horizontal dimensions and 0.1 miles in the vertical dimension. The flow model parameters were estimated from the literature and the subsidence model parameters were estimated by analysis of borehole extensometer records. Qualitative regional geologic data were imbedded in the model using scoring techniques and empirical conditional probability functions.

Current status of the research is the implementation and preliminary calibration of the simulation model. The conceptual optimization model is described but is not implemented in this research.

Background

The Houston-Galveston area is located in southeast Texas along the Gulf of Mexico.

Drilling logs and interpretation of geophysical logs indicate alternating sand and clay layers (Williams and Ranzau, 1987; Bebout, et al., 1976). The major water bearing units are the Chicot aquifer that overlies the Evangeline aquifer.

Land subsidence has long been a serious problem near Houston. In 1926, a meter of subsidence (due to petroleum extraction) was reported at the Goose Creek Oil field at the North end of Galveston Bay. Since that time, the area has experienced dramatic growth in population that was supported exclusively by withdrawal of ground water from the Chicot and Evangeline aquifers. These withdrawals have lowered water pressures in the aquifers allowing the clay layers to compress causing land subsidence up to 3 meters in some areas. Many acres of valuable land have been submerged due to subsidence, and larger areas are now subject to flooding. The areas most impacted are Baytown, Pasadena, Southwest Houston, and Texas City.

This subsidence led to the plan several decades ago to abandon the groundwater resource for surface water resources. The aquifer simulation and management model described described in this paper will be applied to the Houston region to explore the possibility of meeting demands while controlling land surface movement, in order to develop alternatives to abandonment of the groundwater resource.

Groundwater Flow and Land Subsidence Simulation Model

The groundwater system in the Houston-Galveston region is conceptualized as a multi-layered aquifer system with interbedded compressible layers. Figure 1 is a schematic of an aquifer unit with interbedded compressible layers. The aquifer material is assumed to be incompressible, while the interbedded layers are compressible. The governing equation of horizontal groundwater flow in any of the isotropic aquifer layers is (Marsily, 1986)

$$\mathrm{div}(\mathbf{T}\ \mathrm{grad}(h_i)) - W_i = (S_i + S_i)\frac{\partial h_i}{\partial t} \qquad (1)$$

where h_i is the hydraulic head in the i-th aquifer, $\mathbf{T}_i$ is the transmissivity tensor in the i-th aquifer, S_i is the aquifer storativity in the i-th aquifer, S_i is the interbed storage coefficient, W_i is the volumetric flux per unit volume of aquifer of sources or sinks of water. The interbed storage coefficient is a function of the mechanical properties of the compressible material and the aggregate thickness of the beds. The model is subjected to appropriate boundary conditions, which include specified head and groundwater fluxes at the model boundaries.

The land subsidence model is based on Terzaghi's effective stress principle. A change in head by pumping in the aquifer causes a change in effective stress, which in turn causes the compressible materials to expand or compact depending on the magnitude and sign of the effective stress change. When changes in effective stress are small and less than a previous maximum stress, the material behaves elastically. The elastic change in thickness of an aquifer unit containing compressible interbeds is (Leake and Prudic, 1991)

$$\Delta b = -\Delta h S_{ke} \qquad (2)$$

where Δb is the change in aquifer thickness, S_{ke} is the elastic storage coefficient for the interbeds, and Δh is the change in head in the aquifer unit.

When the change in stress exceeds a previous maximum stress, the material deforms inelastically (a good portion of this deformation is permanent). The inelastic change in thickness of an aquifer unit containing compressible interbeds is (Leake and Prudic, 1991)

$$\Delta b = -\Delta h S_{kv} \qquad (3)$$

where Δb is the change in aquifer thickness, S_{kv} is the inelastic storage coefficient for the interbeds, and Δh is the change in head in the aquifer unit. The subsidence model is coupled to the flow model through the interbed storage coefficient ;

$$S_i = S_{ke} \quad \text{for elastic compression in i-th layer} \qquad (4a)$$

$$S_i = S_{kv} \quad \text{for inelastic compression in i-th layer} \qquad (4b)$$

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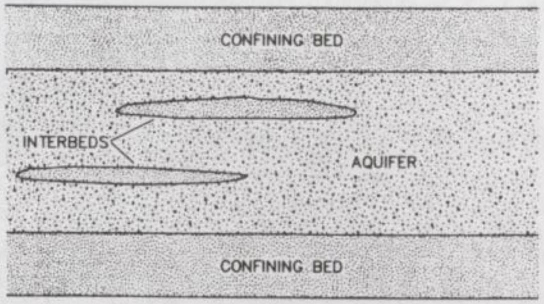

Figure 1 . Aquifer Unit Schematic Diagram (from Leake and Prudic, 1991)

The numerical implementation of the models is accomplished using the Interbed Storage Module (Leake and Prudic, 1991) that is attached to the U.S.G.S. Modular Three-dimensional Finite Difference Ground-Water Flow Model (McDonald and Harbaugh, 1988).

Aquifer System Optimization Model

Ideally the objective function of the planning model should reflect benefits derived from groundwater production, costs associated with increased subsidence, costs associated with groundwater production and reinjection, and the costs of alternative supply. For this preliminary research the maximum net subsidence is used as a surrogate for these benefits and costs. The overall objective function is expressed as

$$Z = \max_{i \varepsilon I}(\text{subsidence}_i)$$

where I is an index set that locates all locations of subsidence in the region. The net subsidence is defined as the cumulative subsidence over the entire simulation period that may include several decision periods. The positive effect of rebound is included in this objective so that the dynamics of the aquifer system are considered.

The planning model determines optimal pumping schedules and distributions to minimize the objective function. The decision variables are pumping locations and rates. These decision variables are constrained by maximum values determined from well field hydraulic limitations (NPSHa > NPSHr for each well, etc.) and minimum values determined from institutional limitations. These constraints are represented as

$$Q_{i\,MIN} < Q_i < Q_{i\,MAX} \qquad i \varepsilon I$$

The decision variables are also constrained in that the net groundwater supplied must meet some demand, either regionally of locally (i.e. for a particular water plant). Because the water distribution network is not intended to wheel large volumes of water across the system, sub-regional demand constraints are used in the planning model. These localized demands are represented as

$$\left(\sum_{i=1}^{NL} Q_i\right)_j < \text{Demand}_j \qquad j \varepsilon J\,;\; i \varepsilon I \cap j$$

where J is an index set that locates each subregion and the notation, $i \varepsilon I \cap j$, means all wells in the index set I that contribute to satisfying demand in subregion j.

Combining the objective function and the decision variable constraints the formal management problem can be stated as

$$\min Z = \max_{i \varepsilon I}(\text{subsidence}_i)$$

subject to:

$$Q_{i\,MIN} < Q_i < Q_{i\,MAX} \qquad i \varepsilon I$$

$$\left(\sum_{i=1}^{NL} Q_i\right)_j < \text{Demand}_j \qquad j \varepsilon J\,;\; i \varepsilon I \cap j$$

The optimization problem is a nonlinear non-convex programming problem, the nonconvexity arising from the dynamic response of the system to pumping decisions.

Simulation Model Application to Houston-Galveston Region, Texas

The aquifer system was modeled as a four layer system with vertical leakage between layers, and interbedded compressible aquitards within layers. The system was discritized into 30 rows by 30 columns (Fig. 3) with a uniform grid spacing of 2.5 miles. The depth of the aquifer system ranges from 1,200 ft (400m) at the Harris-Montgomery county line to 3,600 ft (1200m) at the Gulf of Mexico. The aquifer transmissivity and storage coefficients were based on studies done by Bravo (1991) and others (Jorgensen, 1975; Meyer and Carr, 1979; Gabrysch, 1984).

The compressible properties of the aquitards were determined by regression analysis that correlated sand fraction maps with compressible properties determined from borehole extensometer and piezometer data (Cleveland et al. 1992).

Flow into the system is by recharge through infiltration from precipitation. The recharge area for the aquifer system is beyond the model boundaries so a constant flux boundary condition was used based on a hueristic model of flux developed by Cleveland et al. (1991). Flow out of the system is through discharge from pumping, and groundwater discharge to Galveston bay and the Gulf of Mexico. The effects of regional fault systems was ignored in this study, although our interpretation of existing geochemical data suggests that there is a hydraulic barrier to flow in the southern part of the modeled region

Discharge through pumping currently occurs in nearly every cell of the modeled region. Specific capacites for each cell will be estimated and used as bounds on pumping policies for the planning model.

The model was calibrated using historical conditions for the year 1983, and the best calibration results were obtained by allowing the degree of anisotropy in the system vary. The principal directions of anisotropy are more aligned with Galveston Bay than we expected, we have not yet developed an interpretation for this observation.

Management Model Application

The complexity of the management model is dependent on the number of decision periods and simulation time steps used within each period. We tentatively will investigate a decision period of one month, which is roughly the sampling frequency that the borehole extensometers are monitored, and a planning horizon of five years, which is roughly the scheduled re-leveling frequency for the region. The simulation time step is currently one month.

To summarize the model(s); the simulation runs monthly with the possibility of changing pumping schedules each month to control subsidence. The planning horizon is five years so that the optimal schedule of pumping (60 decision periods with around 400 decisions per period) will minimize the maximum subsidence over the region. The management objective is to minimize the maximum subsidence. The constraint set is to supply a minimum amount of water in a subregion with additional constraints imposed by the well hydraulics and administrative limitations. Locally optimal solutions to the management model will be generated by the Large Scale Generalized Reduced Gradient (LSGRG2) code (Lasdon and Warren, 1989).

Results

To date, the simulation model has been created and is being calibrated. Some initial simulation results are shown on Figure 2 which is a map of simulated subsidence over the region for the pumping rates that were in effect in 1983. In general, the simulation predicts subsidence that is geographically consistent with the pumping data and the sand fraction data that were used to create the dataset that represents the mechanical properties of the aquifer.

The remaining steps in this preliminary effort are to incorporate the simulation model into the management model and explore different pumping policies. The full parametric study will be to explore the tradeoffs associated with different demand scenarios based on population and other economic projections.

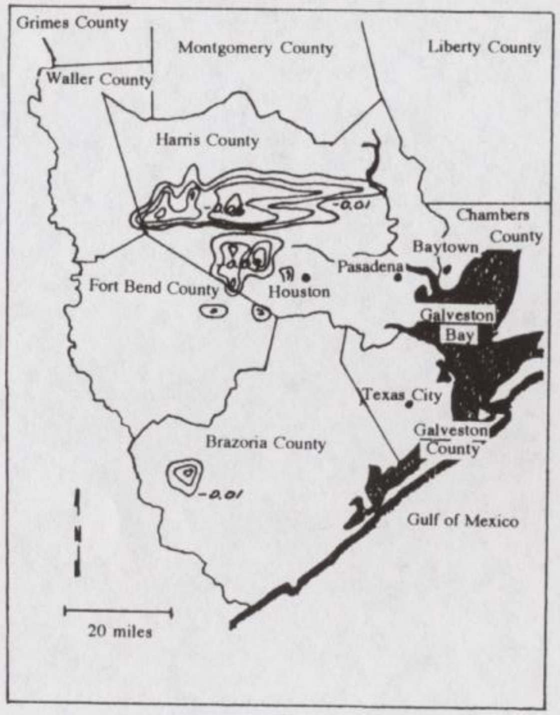

Figure 2. Land Surface Elevation Changes (in feet) from Simulation Model

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