GROUND WATER IN THE PACIFIC RIM COUNTRIES

Proceedings of the Symposium
Sponsored by the Irrigation and Drainage
Division of the American Society of Civil Engineers

Edited by Helen J. Peters

Honolulu, Hawaii
July 23-25, 1991

Published by the
American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398

Optimal Aquifer Planning with Salt Water Boundary

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Abstract

Optimal sustained-yield pumping strategies were developed for the irrigated and industrialized eastern shore of the Great Salt Lake. The combined optimization and simulation model, in which steady-state, finite-difference, quasi-three-dimensional ground water flow equations were embedded as constraints, computes the optimal distribution for sustainable annual ground water pumping rates for alternative scenarios.

1. The model deals with management of a large, multilayer, confined/unconfined (linear/nonlinear) aquifer system.
2. The research can help manage water in the study area where the demand for water of sufficient quality and quantity is increasing due to urbanization.

Introduction

The East Shore Area is bounded by the Great Salt Lake on the West and the Wasatch Front mountains on the East. It extends from Willard on the north to Farmington on the south. The population of the East Shore Area has tripled with the growth of agriculture, industry, and business during the last 40 years (Price, 1985).

Potentiometric heads in the East Shore Area have declined for more than 40 years. The decline ranges from 20 feet on agricultural lands along the shore of the Great Salt Lake to 50 feet in the vicinity of Hill Air Force Base, where large pumping wells are installed. The decline is caused by increasing pumping for M&I use and decreasing

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subsurface recharge from lower precipitation along the Wasatch Front. Near the shore of the Great Salt Lake, the potentiometric heads of the aquifer are above the ground surface. On agricultural lands, small-diameter flowing wells installed at relatively shallow depths are used for irrigation, stock, and domestic use. In the urban area along the Wasatch Front, large-diameter pumping wells are installed at greater depths for M&I use (Bolke and Waddle, 1972).

The ground water reservoir, consisting of one unconfined and two partially confined aquifers, is expected to be able to meet the increasing demand for water in the East Shore Area (Fig. 1). However, if the ground water is not managed properly, the following problems may result from the declines in potentiometric heads:

1. Pumping costs may increase.
2. Many flowing wells on agricultural lands may not produce the required discharge.
3. Salt or brackish water may intrude from the Great Salt Lake.

In this study, an optimization model that simulates the ground water flow was used to develop sustained-yield, ground water management strategies for the area.

Model Formulation

This modified version of the USU ground water management model (Gharbi et.al, 1990) consists of:

1. Objective function which maximizes total ground water extraction.

$$\text{maximize } Z = \sum_{i=1}^{N} g_i \quad (1)$$

where, g_i = ground-water pumping in a cell i, (L^3/T);
N = total number of cells with pumped wells;

In the model, discharge, i.e. ground water pumping, is a negative value, and recharge is a positive value.

2. Constraints and bounds to describe the physical system and management desires.

The steady-state finite-difference form of the quasi-three-dimensional ground-water flow equation (McDonald and Harbaugh, 1984) is involved in the model as a constraint.

$$\begin{aligned} & CR_{l,i,j+1/2}(h_{l,i,j+1}-h_{l,i,j})+CR_{l,i,j-1/2}(h_{l,i,j-1}-h_{l,i,j}) \\ & +CC_{l,i+1/2,j}(h_{l,i+1,j}-h_{l,i,j})+CC_{l,i-1/2,j}(h_{l,i-1,j}-h_{l,i,j}) \\ & +CV_{l+1/2,i,j}(h_{l+1,i,j}-h_{l,i,j})+CV_{l-1/2,i,j}(h_{l-1,i,j}-h_{l,i,j}) \\ & =g_{l,i,j}+q^f_{l,i,j}+q^r_{l,i,j}+q^g_{l,i,j}+q^d_{l,i,j}+q^e_{l,i,j}+q^{rd}_{l,i,j} \quad (2) \end{aligned}$$

where,

$$CR_{l,i,j+1/2} = 2dx_j(T^j_{l,i,j}T^j_{l,i,j+1})/(T^j_{l,i,j}dy_{i+1}+T^j_{l,i,j+1}dy_i)$$

$$CC_{l,i+1/2,j} = 2dy_i(T^i_{l,i,j}T^i_{l,i+1,j})/(T^i_{l,i,j}dx_{j+1}+T^i_{l,i+1,j}dx_j)$$

$$CV_{l+1/2,i,j}=dx_jdy_i/\{(dz_l/2Kz_{l,i,j})+(dz_{l+1}/2Kz_{l+1,i,j})\}$$

l,i,j = layer, row, and column indices of a finite-difference cell;

$h_{l,i,j}$ = potentiometric head, (L);

$T_{l,i,j}$ = transmissivity of a cell, (L^2/T); The transmissivity of unconfined layer 1 is a function of head. Transmissivities of layers 2 and 3 are assumed constant.

dz, dy, dx = cell sizes in layer l, row i, and column j, (L);

$Kz_{l,i,j}$ = vertical hydraulic conductivity, (L^2/T);

$g_{l,i,j}$ = pumping rate in a cell, (L^3/T);

$q^f_{l,i,j}$ = discharge from flowing wells in a cell, (L^3/T);

$= -\Pi^f_{l,i,j}(h_{l,i,j}-h^{gs}_{l,i,j})$ for $h_{l,i,j} \geq h^{gs}_{l,i,j}$

$= 0$ for $h_{l,i,j} < h^{gs}_{l,i,j}$

where, Π^f = coefficient describing reduction in discharge rate of the flowing wells per 1 foot head decline, (L^2/T);

h^{gs} = ground surface, (L);

$q^r_{l,i,j}$ = known recharge in a cell in the recharge area along the Wasatch Front, including bedrock recharge, unsaturated seepage from the Weber River and Ogden River, canal seepage, precipitation and irrigation seepage, (L^3/T);

$q^g_{l,i,j}$ = saturated flow between the aquifer and general boundary head cells, that is used for estimating diffuse seepage from the aquifer to the Great Salt Lake, (L^3/T);

$= \Pi^g_{l,i,j}(h_{l,i,j}-h^{gb}_{l,i,j})$

where, Π^g = hydraulic conductance between the aquifer and the general boundary head cell, (L^2/T);

h^{gb} = water level of the Great Salt Lake, (L);

$q^d_{l,i,j}$ = saturated flow leaving the aquifer in a cell with drains, (L^3/T);

$= \Pi^d_{l,i,j}(h_{l,i,j}-B^d_{l,i,j})$ for $h_{l,i,j} \geq h^d_{l,i,j}$

$= 0$ for $h_{l,i,j} < h^d_{l,i,j}$

where, Π^d = hydraulic conductance between the aquifer and drains, (L^2/T);

B^d = Bottom elevation of the drains, (L);

$q^e_{l,i,j}$ = distributed discharge from evapotranspiration in a cell, (L^3/T);

$= E_0\, dx_jdy_i$ for $h_{l,i,j} \geq h^s_{l,i,j}$

$= E_0\, dx_jdy_i\{h_{l,i,j}-(h^s_{l,i,j}-d^e_{l,i,j})\}/d^e_{l,i,j}$ for $h^s_{l,i,j}-d_{l,i,j} \leq h_{l,i,j} < h^s_{l,i,j}$

$=0$ for $h_{l,i,j} < h^s_{l,i,j}-d_{l,i,j}$

where, E_0 = potential evapotranspiration, (L/T);

h^s = potentiometric surface elevation below which evapotranspiration decreases, (L);

d^e = extinction depth, (L);

$q^{rd}_{l,i,j}$ = reduction of vertical flow between layer 2 and layer 3 due to partial desaturation of the cell in layer 3, (L^3/T);

$=CV_{2,i,j}(E^{top}_{3,i,j}-h_{3,i,j})$ for $h_{3,i,j} \leq E^{top}_{3,i,j}$

$=0$ for $h_{3,i,j} > E^{top}_{3,i,j}$

$(q^{rd}_{2,i,j}=-q^{rd}_{3,i,j})$

where, E^{top}_3 = elevation of the top of layer 3, (L);

Bounds on pumping and head are:

$g^L_{l,i,j} \leq g_{l,i,j} \leq g^U_{l,i,j}$ and $h^L_{l,i,j} \leq h_{l,i,j}$

where, L,U = notations of upper and lower bounds

$h^L_{l,i,j}$ = bottom elevation of layer 1

For the confined/unconfined aquifer (linear/nonlinear system), the model has to be rerun (cycled) until variables (heads) do not change with cycle (Gharbi et.al, 1990).

The predictive simulation of the USGS (Clark, et al., 1990) used the 1970-1984 average annual recharge rate of 10,700 acre-ft (normal climatic condition) and the 1980-1984 average annual pumping rate of 23,400 acre-ft. Those geohydrologic and pumping data were included in the combined model.

Description of scenarios

The results of alternative future scenarios were compared. Due to the rapid urbanization in the area over the last 20 years, the demand for M&I water has increased markedly, but demand for irrigation water, which is mainly obtained from the Weber River, has not increased as much as expected. Those trends are expected to continue. For all scenarios, it was assumed to be more important to extract water for M&I than to have flowing wells for agricultural use. Scenario 1 is the no-management option. Optimal sustainable annual ground water pumping rates were computed using the modified USU model for scenarios 2, 3, and 4. Those scenarios were developed using different sets of bounds on withdrawal rate from existing pumping wells.

Scenario 1: A steady-state predictive simulation estimated the additional water-level declines that would ultimately result from continuing current withdrawals from flowing wells and pumping wells.

Scenario 2: The lower bound on pumping was the current withdrawal rate for all existing pumping wells. For most cells, the upper bound on pumping was twice the current withdrawal rate for existing pumping wells in those cells. In the nine cells that contained U.S. Bureau of Reclamation (USBR) wells, well capacity was the upper bound on pumping.

Scenario 3: The upper bound on pumping was twice that of scenario 2, except for cells with USBR wells. Other bounds were the same as scenario 2.

Scenario 4: The lower bound on pumping was the current withdrawal rate for all existing pumping wells. For most cells, the upper bound on pumping was 1.114 cfs (500 gpm) larger than in scenarios 2 and 3. In the 13 cells that contained USBR and Hill Air Force Base wells, well capacity was the upper bound on pumping.

Results and Discussion

Computed steady-state water budgets of the aquifer are summarized in Table 1. For scenarios 2, 3, and 4, optimal sustainable ground water pumping rates were 126%, 137%, and 193% of the current pumping rate, respectively. Discharges of the flowing wells are 75%, 71%, and 50% of the unmanaged discharge rate. Clearly, an increase in pumping in the urban area along the Wasatch Front decreases water from flowing wells that is available for agriculture.

Table 1 Computed steady-state water budgets of the aquifer

Items	Scenario 1 (cfs)	Scenario 2 (cfs)	Scenario 3 (cfs)	Scenario 4 (cfs)
A. Recharge to the aquifer	148	148	148	148
B. Discharge from the aquifer				
Pumped wells	32	40	44	62
Flowing wells	42	31	30	21
Evapotranspiration	8	8	8	8
Drain discharge	46	48	46	40
Diffused seepage	20	21	20	18
Total	148	148	148	148

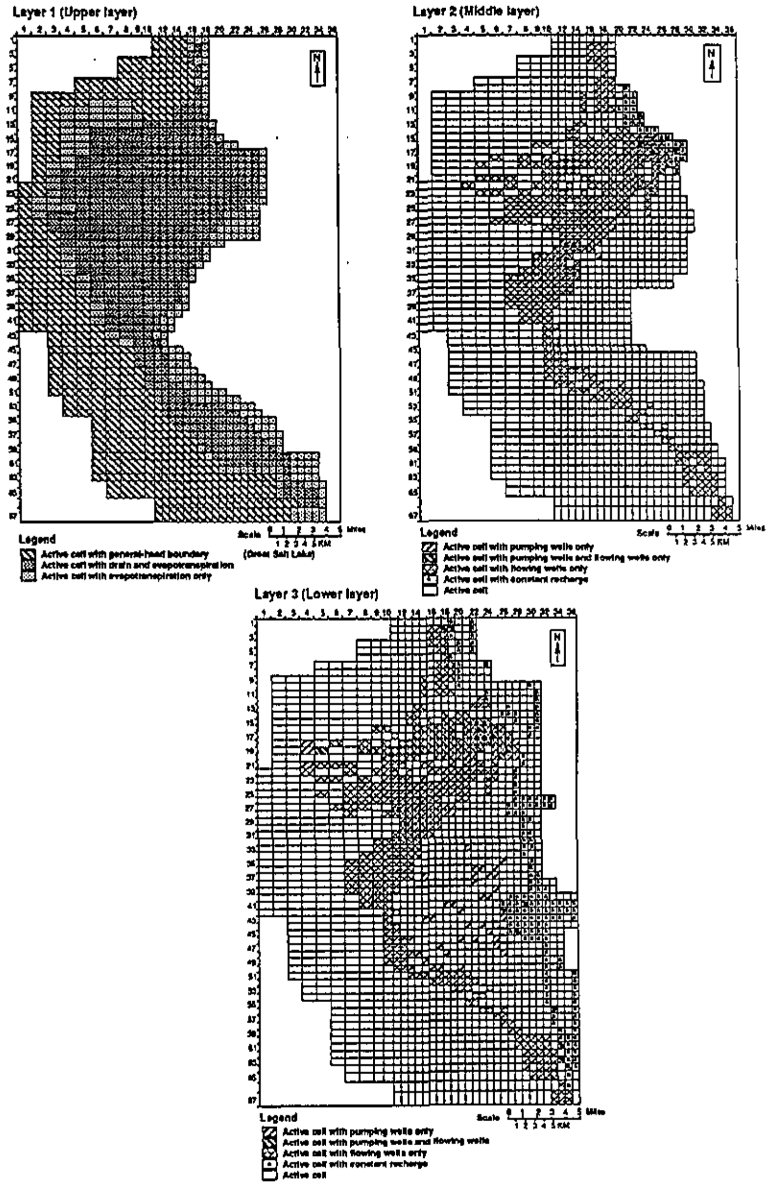

Figure 1. Discretization of the East Shore Area

Summary

This paper illustrates the utility of the embedding method in optimizing sustained-yield planning. Using a modified version of the USU management model, optimal sustained-yield strategies were computed for a large, three-layer aquifer system. Solved problems have about 12,000 single equations & single variables, and about 47,000 non-zero elements.

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Acknowledgement

The authors are grateful to Ali Gharbi for his support and to Andrea Wilson for graphical support. We appreciate the financial support of the Dept. of Agricultural and Irrigation Engineering and Agricultural Experiment Station (approved as paper no. 4125), Utah State University, Logan, UT 84322-4810 and of Nippon Koei, Co.,Ltd.

Conversion table

1 cfs = 724.0 acre-ft/yr = 0.02832 m^3/s
1 acre-ft/yr = 1233.4 m^3

Chloride Sources in a California Coastal Aquifer

by John A. Izbicki[1]

Abstract

The Oxnard Plain, about 60 miles northwest of Los Angeles, is underlain by a complex system of five aquifers that are used for water supply. These aquifers have a total thickness of more than 1,000 feet. On the basis of previous studies, it had been estimated that more than 23 square miles of the Oxnard aquifer (shallowest of the five major aquifers) is intruded by seawater that entered primarily through outcrop areas in submarine canyons near the coast. Water-quality data, including stable-isotope analyses, from more than 40 wells installed as part of this study show that the area affected by seawater intrusion is less than originally believed. The source of elevated chloride concentration, in at least some wells, is leakage of seawater through failed well casings or through abandoned irrigation wells perforated in more than one aquifer. In other wells, irrigation return may be the cause of elevated chloride concentrations. In addition, seawater has intruded deeper aquifers near Hueneme submarine canyon and a brine other than seawater may have invaded deeper aquifers near Point Mugu.

Introduction

Agencies responsible for management of seawater intrusion on the Oxnard Plain presently use 100 mg/L (milligrams per liter) chloride as the criterion to determine the position of the seawater front. (Chloride concentration in native ground water typically is about 40 mg/L.) On the basis of this criterion, it had been estimated that in 1989 more than 23 square miles of the Oxnard aquifer was intruded by seawater (County of Ventura Public Works Agency, 1990). However, several sources of poor-quality (high chloride concentration) water, other than lateral movement of seawater, contribute chloride at concentrations greater than 100 mg/L to wells. These sources include: irrigation-return water, seawater in overlying contaminated aquifers, and poor-quality water from deposits that surround and underlie much of the ground-water basin.

This paper identifies potential sources of chloride in aquifers of the Oxnard Plain. It is based on preliminary work that is part of the U.S. Geological Survey's Southern California Regional Aquifer-Systems Analysis.

Hydrogeology

The Oxnard Plain is about 60 miles northwest of Los Angeles. The 130-square-mile area contains a complex system of five aquifers that are used for water supply. These aquifers have a total thickness of more than 1,000 feet. The aquifer system is underlain by consolidated marine sediments and volcanic rocks similar to those exposed along the south-east margin of the Oxnard Plain. A shallow unconfined aquifer, which contains relatively

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