RCP 170

CONSIDERING ECOLOGICAL CONSTRAINTS WHILE OPTIMIZING SUSTAINED GROUNDWATER YIELD: PAHVANT VALLEY, UTAH

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ABSTRACT: Concern for groundwater quality and availability is increasing in Pahvant Valley. Ground-water levels are declining due to intense groundwater extraction for irrigation; water having high total dissolved solids concentration is flowing from the southwest toward the pumping sites; and discharge from natural springs in a wildlife refuge is declining. Transient simulation of aquifer response to 20 years of the 1985 pumping rates (beginning with 1985 groundwater level) predicted that spring discharge would decrease by as much as 87% from 1985 rates. Presented are preliminary pumping strategies that maximize sustainable, steady-state groundwater extraction without unacceptably reducing discharge from the springs. A simulation/optimization (s/o) model is used to calculate optimized sustainable groundwater pumping rates that provide prespecified discharge rates from Clear Lake Springs. These optimal pumping strategies are sustainable unless significant changes occur in assumed system recharge and discharge rates. The usefulness of the s/o model for regional management is demonstrated by computing optimal strategies for four scenarios. Scenarios differ in the amount of discharge required from Clear Lake Springs or in the upper limit on pumping at individual locations. The optimal steady-state groundwater withdrawal and spring discharge rates obtained in this study are less than the 1985 rates. To provide sufficient sustainable discharge from Clear Lake Springs, pumping rates should be less than the 1985 rates.

KEY TERMS: Pahvant Valley, Utah; sustained ground water yield; simulation/optimization; modeling; ground water.

INTRODUCTION

Long term intense extraction of groundwater in Pahvant Valley has caused groundwater levels to decline. This decline will continue until a quasi steady state is attained or until recharge equals or exceeds discharge. Concerns associated with the declining water levels are (1) formation of a large cone of depression and increased pumping lift and pumping cost, (2) deterioration of the quality of pumped groundwater due to the migration towards the zone of depression of poor quality water having high total dissolved solids, and (3) the decrease in discharge from Clear Lake Springs.

This paper discusses preliminary optimal sustained groundwater yield pumping strategies for Pahvant Valley and adjacent areas. In this paper a strategy refers to a set of spatially distributed extraction rates that are temporally unchanging.

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The study area is situated in Millard County in west-central Utah (Figure 1). Located between 38° 45' N and 39° 15' N and 112° W and 113° W, it encompasses about 1500 square miles (960,000 ac.). Several ground water hydrology studies have addressed the Pahvant Valley area. Holmes (1984) discussed the groundwater system and the projected effects of groundwater withdrawal in the valley. The United States Geological Survey (U.S.G.S.) published selected hydrological data for Pahvant Valley and adjacent areas (1988). Burden (1989) summarized groundwater conditions for the spring of 1989, ground water level fluctuations and concerns of the concentrations of total dissolved solids. Holmes and Thiros (1990) described the groundwater hydrology of the valley and adjoining areas and discussed the effects of possible future changes in extraction and recharge.

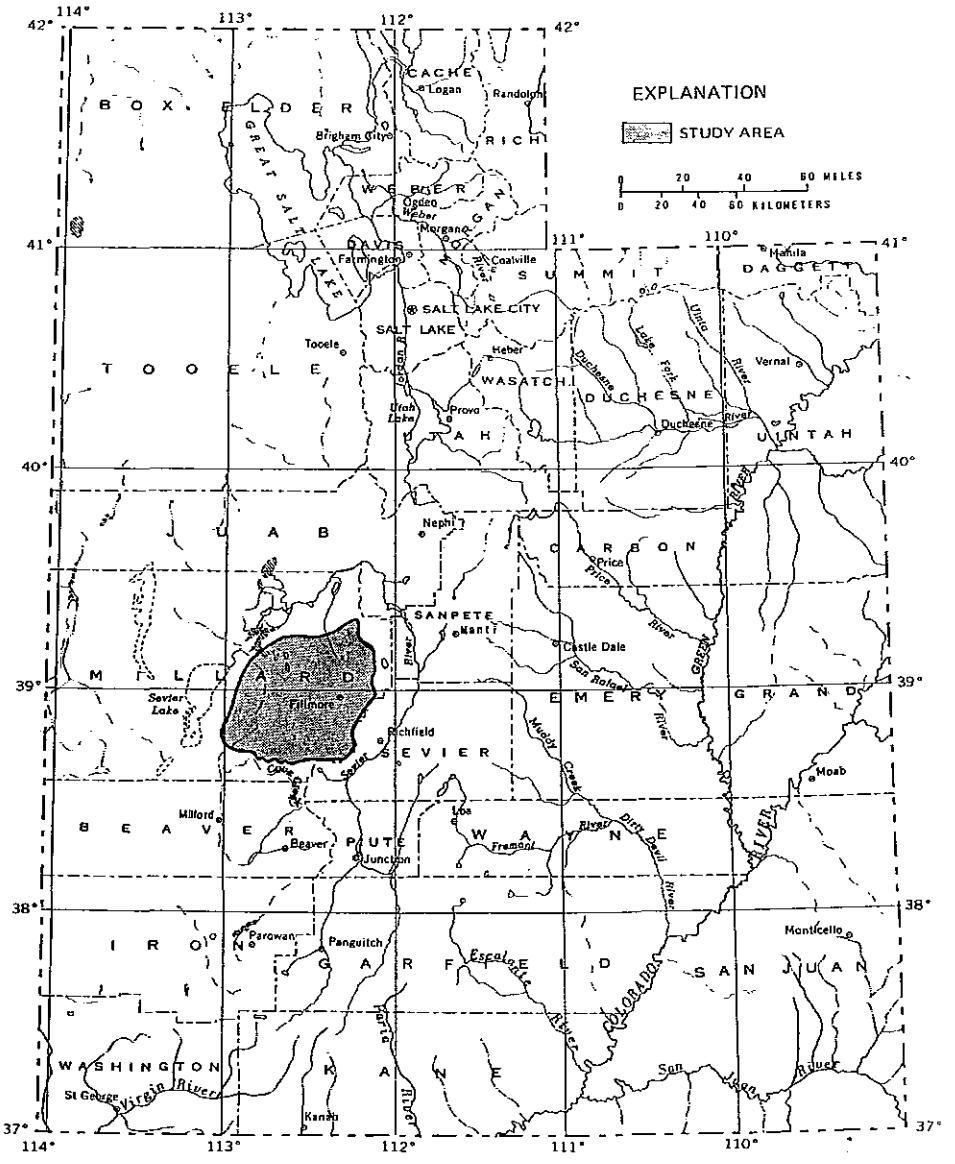

Figure 1. The study area (from Holmes, 1990).

Groundwater in the valley occurs in four layers. The top layer (layer one) is unconfined layers two, three, and four are leaky confined aquifers. Withdrawal for irrigation is primarily from layers two and three. Sources of recharge are seepage from streams, canals, excess irrigation water, precipitation, and subsurface inflow from an adjoining aquifer. Aquifer discharges include withdrawal for irrigation, evapotranspiration, flow from springs, and subsurface outflows.

The above concerns can be avoided or at least minimized by implementing appropriate groundwater management strategies. A basic goal in managing groundwater is to know where and how much to extract without causing unacceptable consequences by violating specified constraint.

Given physical system complexity, determining where and how much groundwater can be withdrawn with minimal or no unacceptable consequences can be difficult. A digital computer simulation/optimization (s/o) model can help by computing a set of long-term spatially distributed sustainable groundwater pumping rates that satisfy specified management constraints. A s/o model performs both simulation and mathematical optimization. The mathematical optimization component essentially has two parts, an objective function, and a set of constraints that are simultaneously satisfied. Here the objective function maximizes spatially distributed groundwater extraction, while the constraints assure that management specifications on the variables are not violated.

THE MODEL

In this study, a s/o model is used to calculate optimal sustained yield groundwater management strategies which avoid unacceptable ecological effects for Pahvant Valley. Employed is the Utah State model for optimizing management of stream/aquifer systems using the REsponse MAtriX method, US/REMAX (Peralta and Aly, 1993). US/REMAX includes groundwater flow simulation and mathematical optimization algorithms. Input to the s/o model includes the hydraulic properties of the aquifer, and management specifications. Hydrogeological data for the study area and a MODFLOW model (McDonald and Harbaugh, 1988) calibrated for the area are obtained from the United States Geological Survey. The study area is located in Millard County in west central Utah (Figure 1). Management goals were defined by the State of Utah Department of Natural Resources.

The intent of using US/REMAX is to develop a preliminary optimal spatially distributed sustained groundwater yield withdrawal strategy for the study area (Figure 1). US/REMAX computations involve three major stages. The first stage involves simulating system response to utilized pumping rates to generate influence coefficients for selected control locations. A steady state influence coefficient describes head response at one location to a unit pumping at the same or other location.

The next stage involves formulating a set of equations to define the management problem. This set includes superposition equations which contain the influence coefficients and unknown pumping rate variables. Superposition is completely appropriate for a linear system, such as a confined aquifer. An unconfined aquifer can also be considered a linear system as long as change in hydraulic head does not significantly change transmissivity.

In the last stage, linear or nonlinear optimization algorithms calculate the optimal pumping strategy. Because of the incorporated constraint equations the s/o model adequately

represents aquifer response to pumping. The s/o model represents aquifer response to groundwater pumping, and other hydrologic stimuli.

In this study no-flow boundaries are used to the east and part of the southern periphery. Constant head boundaries are employed to the north and northwest. Clear Lake Springs are represented by a constant head cell. Recharges, including precipitation, deep percolation from unconsumed irrigation water, and discharge caused by evapotranspiration, are entered as known flux values. The objective function, (Equation 1) maximizes steady (sustainable) groundwater withdrawal ($p_{\hat{a}}$) from the prespecified potential pumping locations.

$$\text{max:} \quad z = \sum_{\hat{a}=1}^{M^p} C^p_{\hat{a}} p_{\hat{a}} \tag{1}$$

The empirical coefficient $C^p_{\hat{a}}$ is a weight which enables emphasizing or de-emphasizing a particular pumping location. All cells containing wells that were in operation in 1985 are used as potential pumping locations. The value of $C^p_{\hat{a}}$ is unity when all pumping locations are treated equally. Subscript â in Equation 1 represents the location of groundwater pumping extraction (row, column, and layer) within a finite difference grid.

The objective function value is maximized subject to constraints on discharge from Clear Lake Springs and bounds on groundwater pumping and hydraulic heads in selected locations. The constraint on the total rates of water discharging from Clear Lake Springs from the valley fill aquifer, Equation 2, assures that the optimal sustainable groundwater withdrawal in the Pahvant area will not cause a steady state spring discharge (φ_c) less than the minimum desired discharge (φ^L_c).

$$\varphi_c = f(h, r, et) \geq \varphi^L_c \tag{2}$$

In equation 2 the subscript c represents the constant head cell where the springs are located; h represents constant head of the free water surface at the springs, and the aquifer head in adjacent cells; r is recharge from precipitation; and et is discharge caused by evapotranspiration. f(h,r,et) represents the right-hand side of an aquifer volume balance for the constant head cell. The resulting constant head flux includes lateral and vertical flows. Each lateral flow is the product of harmonically averaged conductance and the difference in head between the constant head and the adjacent variable head cell. Vertical flow is a function of vertical leakance and head difference between the constant head and the head in the aquifer layer beneath the constant head cell.

Bounds are also imposed on groundwater pumping and the potentiometric surface elevation in pumping cells and selected locations in the unconfined layer. The lower bounds on the springs discharge and the potentiometric surface elevation are management-specified values.

APPLICATION AND RESULTS

Table 1 compares the simulated results of continuing 1985 pumping rates versus results of implementing four alternative optimal strategies. Values in row (a) include assumed 1985 pumping rates and resulting spring discharge based on MODFLOW simulated 1985 water levels. The spring discharge in row (b) is from transient MODFLOW model simulating through the year 2005. Row (c) contains computed optimal pumping rates and resulting simulated steady-state spring discharge.

Transient pumping and MODFLOW simulated spring discharge values shown in Table 1 (rows a or b) are not actually sustainable. Continuing withdrawal of groundwater at the 1985 pumping rate will result in spring discharge decreasing from 57,800 to 7,426 ac-ft per year within twenty years. Also, the uppermost aquifer layer will become dewatered in some peripheral cells. Continuing that pumping rate longer will cause more severe problems

Table 1. Optimal steady state and projected values obtained in this study and reported 1985 pumping and Clear Lake Spring discharge values .

	Groundwater pumping ac-ft per year (cfs)	Clear Lake Springs discharge ac-ft per year (cfs)
(a) Transient (1985) values reported by Holmes and Thiros (1990)	61,500 (84.95)	57,800 (79.84)
(b) Computed value obtained using the 1985 pumping rate for 20 years (1985-2005)	61,500 (84.95)	7,426 (10.26)
(c) Optimal steady state values obtained in this study		
Scenario 1	33,722 (46.58)	10,860 (15.00)
Scenario 2	23,905 (33.02)	14,480 (20.00)
Scenario 3	20,792 (28.72)	15,203 (21.00)
Scenario 4	27,386 (37.83)	13,511 (18.66)

The computed optimal steady-state strategies shown in row c are sustainable as long as assumed boundary conditions and/or the recharge-discharge rates are maintained. The four scenarios differ via the bounds imposed on the discharge from Clear Lake Springs and the upper bound on groundwater pumping in potential pumping cells. For scenarios 1-3 the upper bound on groundwater pumpings, is the 1985 pumping rates in the valley. Scenario 4 differs from

Scenario 3 in that the upper bound on groundwater pumping is twice the 1985 pumping rates. For all scenarios the lower bound on head in the confined aquifer assures that it remains confined. The lower bound on head in the unconfined aquifer is slightly lower than the head resulting from the 1985 pumping. Potentiometric surfaces elevation are controlled only at pumping cells and in cells adjacent to the constant head cells.

Total optimal groundwater pumping computed for scenario one is 46.58 cfs or 33,722 ac-ft per year (Table 1). For this pumping strategy optimal pumping values are at their upper bounds in some potential wells and at lower bounds in other cells. Steady-state spring discharge computed for this scenario is at its lower bound 15.00 cfs (10,860 ac-ft per year).

Raising the lower bound on spring discharge by 33% in scenario 2 reduces groundwater pumping by 30% relative to scenario 1. Relaxing the upper bound in groundwater pumping in Scenario 4 permitted increased total groundwater withdrawal. However, more pumping cells are tight at their lower bound (0.00 cfs), reducing the number of optimal pumping cells in the study area. Generally, the greater the effect of pumping at a location on spring discharge, the less the model will state should be pumped at that location.

Simulated head responses to the optimal pumping strategies in layers 2 and 3 are presented in Figures 2 and 3, respectively. A cone of depression forms in layer 2 in locations of intense groundwater extraction. Figure 4 shows the 5,000 mg/l concentration contour overlaid on the water levels of Figure 2. This salinity threatens crops irrigated with the groundwater. Arrows in Figure 4 show directions we would prefer for the hydraulic gradient. The gradient change can be achieved in several ways. Figure 4 shows an approach requiring installing additional extraction wells northwest of the illustrated cone of depression. The extracted water can be used for irrigation after treatment to lower the concentration of TDS to an acceptable level. The s/o model can be used to determine the optimal distribution of the wells and rates of extraction for attaining the desired gradients.

CONCLUSIONS

A s/o model can aid decision makers in identifying optimal groundwater withdrawal rates and locations, subject to acceptable hydrologic system responses. The utilized s/o model computes optimal sustainable pumping strategies for Pahvant Valley, Utah. The more spring discharge we want, the less total sustainable groundwater pumping is possible. The s/o model is more powerful than a normal simulation model because it can directly compute the most pumping possible for a specified spring discharge. The s/o model readily depict the tradeoff between pumping and spring discharge.

Unless additional management constraint are used with problem formulation, poor-quality groundwater will continue to threaten pumping wells. Fortunately, the s/o model can compute pumping strategies that optimally address such goals.

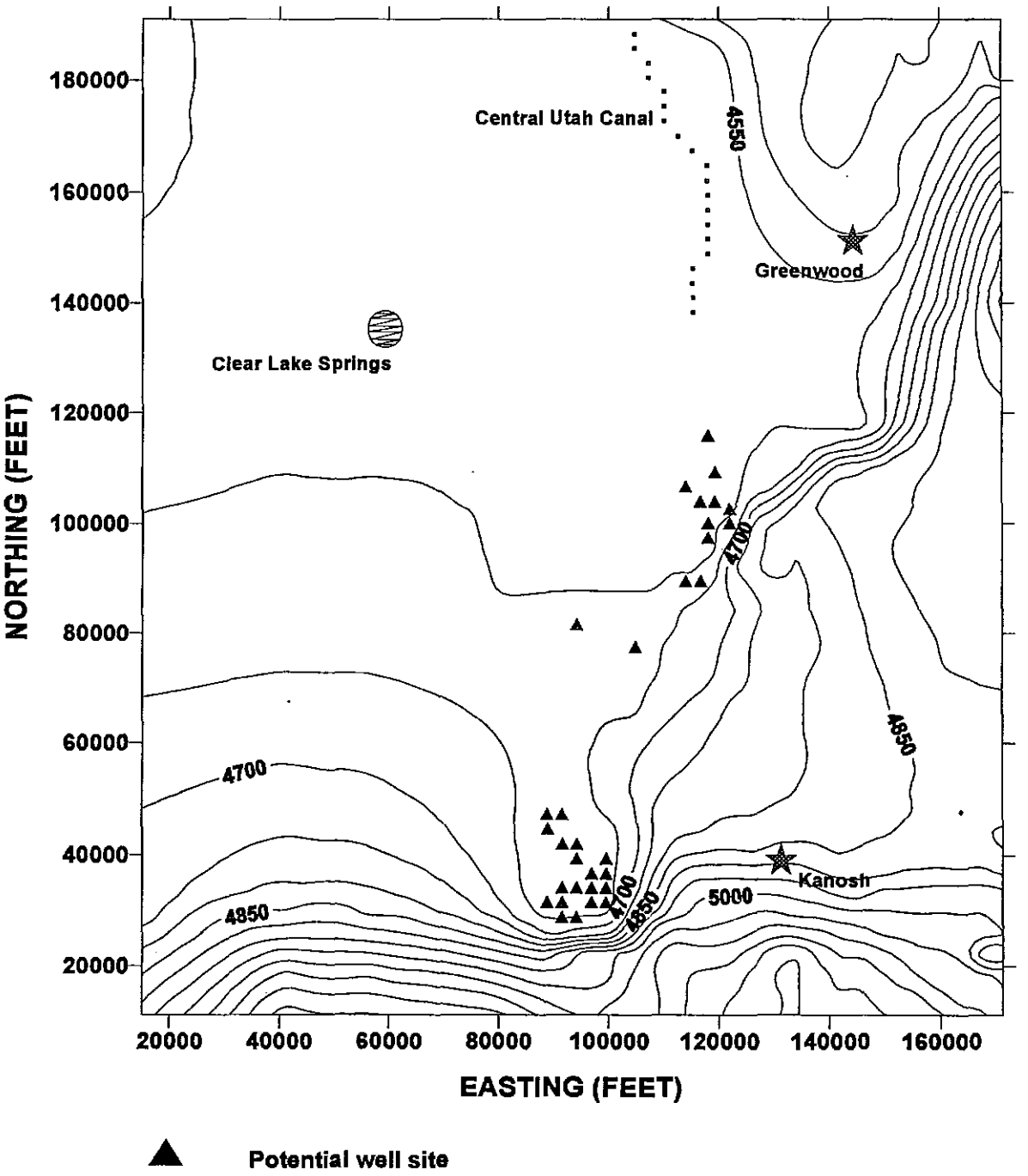

Figure 2. Potential groundwater pumping well sites and equi-potentiometric surface elevation in layer 2 obtained using optimal strategy for Scenario 1.

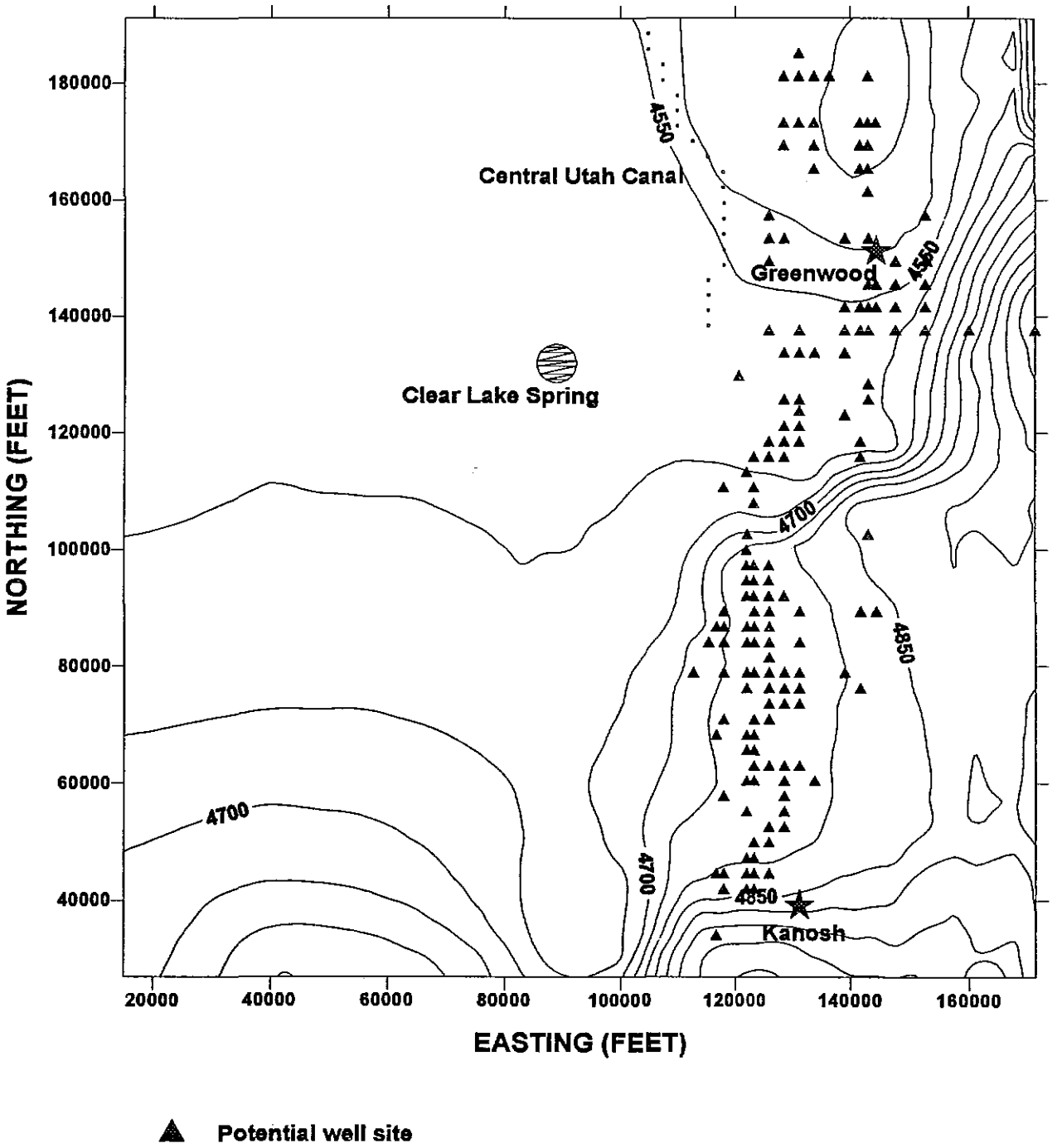

Figure 3. Potential groundwater pumping well sites and equi-potentiometric surface elevation in layer 3 obtained using optimal strategy from Scenario 1.

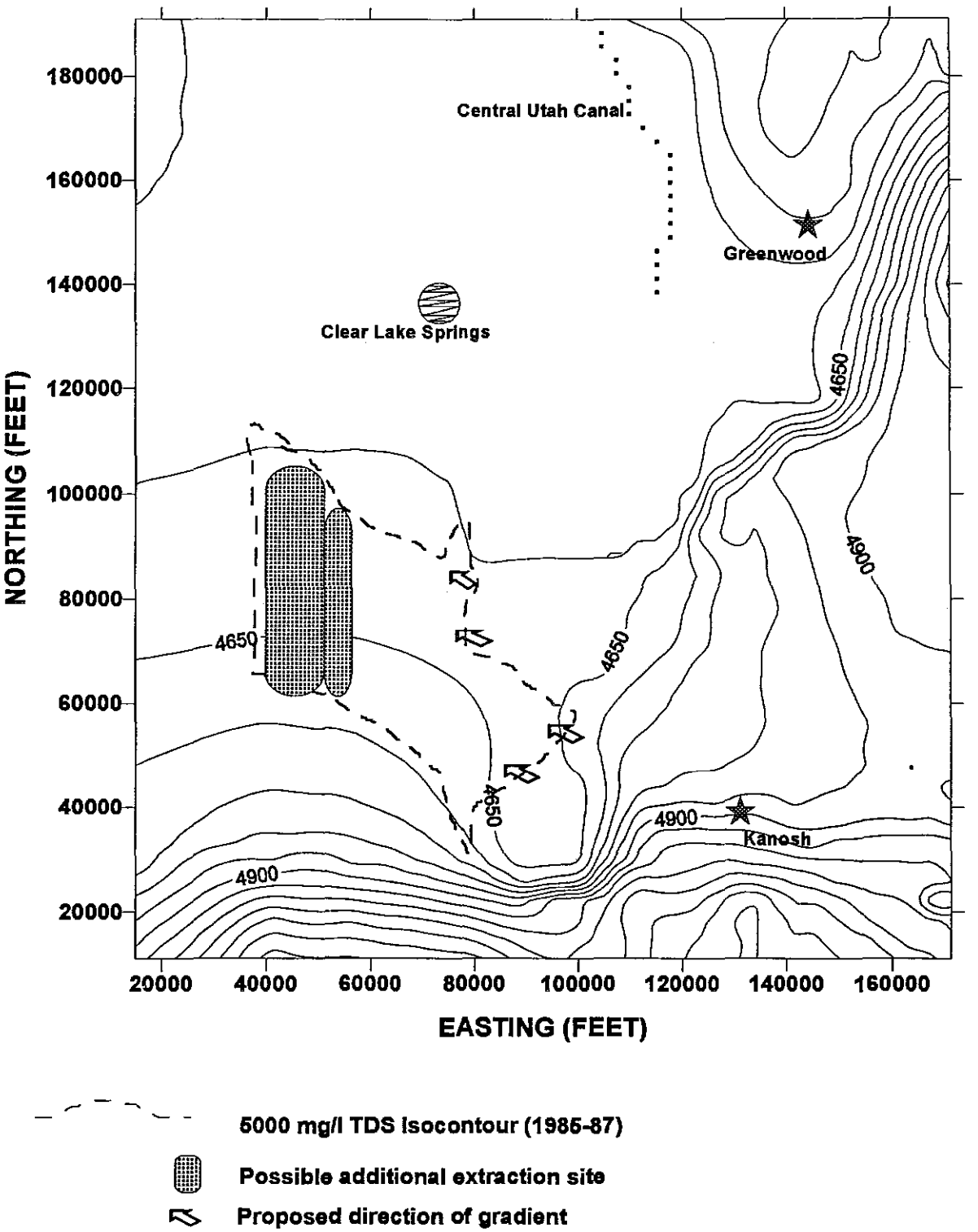

Figure 4. Map showing proposed strategy for controlling migrating high TDS in layer 2.

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