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OPTIMIZING SHORT-TERM PLUME CONTAINMENT: COMPARISON OF WELL ARRANGEMENTS

HERMINIO H. SUGUINO[1] AND RICHARD C. PERALTA[1]

ABSTRACT

Three well configurations were compared in terms of short-term ground-water contaminant plume containment. These include parallel, octagonal and combination systems. Each system had three extraction wells upgradient and three injection wells downgradient of the contaminant plume.

For each system, optimal pumping values and resulting potentiometric surface smoothness were computed for a hypothetical plume. Tested models utilized linear programming optimization and simulation via the response matrix method.

The octagonal well configuration required less pumping for a pumping period of 8 days, than did the parallel or combination systems. The octagonal configuration resulted in the smoothest potentiometric surface, in terms of difference in final head at observation wells compared with those at the contaminant source.

INTRODUCTION

The control of plume migration is sometimes the first step in a remedial action. This can be achieved by injecting water into and/or withdrawing ground-water from the aquifer to alter the hydraulic gradient. Halting the movement of a contaminant plume can be accomplished by a number of different well configurations.

Many studies have utilized both optimization and simulation in ground-water contamination cleanup or extraction. Sometimes, an emergency situation arises that requires a temporary solution. This is the case when contamination should be prevented from reaching a downgradient well or when it should be kept within the boundaries of a company property, but comprehensive clean-up is not practical within available time.

In this paper, parallel, regular octagonal, and combination well configurations were compared for the purpose of optimizing the short-term containment of a contaminant plume.

For all well configurations, three extraction wells were placed upgradient and three injection wells were placed downgradient of the contaminant source. These directions refer to the potentiometric surface that exists before pumping begins. The utilized management model combines simulation and optimization to compute the pumping strategy that requires the least total pumping volume, while halting plume movement within a specific planning horizon. For the assumed emergency situation, total extraction is forced to equal total injection, avoiding the need for import or export of water. Since no contaminated water is pumped, permits for pumping might be more easily obtained than they would be otherwise.

[1] Utah State University, Department of Agricultural and Irrigation Engineering, Logan (Utah) 84322-4105

LITERATURE REVIEW

The following citations describe studies using operations research type of optimization to develop permanent solutions. In these papers, extraction, cleaning and reuse of contaminated water is a legally feasible option. No studies have been found examining well placement for short-term scenarios in which only uncontaminated water is extracted and injected.

Gorelick and others (1986), used linear programming optimization techniques and a response matrix method combined with preliminary aquifer simulation. They optimized hydraulic management in a hypothetical system in order to isolate and remove contaminated ground water. Their simulation-management model determined which wells should be used and the optimal pumping or recharge rate needed to prevent plume migration.

Atwood and others (1985) used the Rocky Mountain Arsenal near Denver, Colorado, as a realistic setting for a hypothetical test. Their procedure planned the hydraulic stabilization and removal of a contaminated ground-water plume. In the first stage, contaminant transport was simulated so that well-site options could be based on the expected geometry of the contaminant plume. In the second stage, linear programming selected best wells from predetermined options and computed optimal pumping/recharge schedules by minimizing total pumping and recharge. By using response matrix simulation, they assumed the applicability of linear systems theory and superposition.

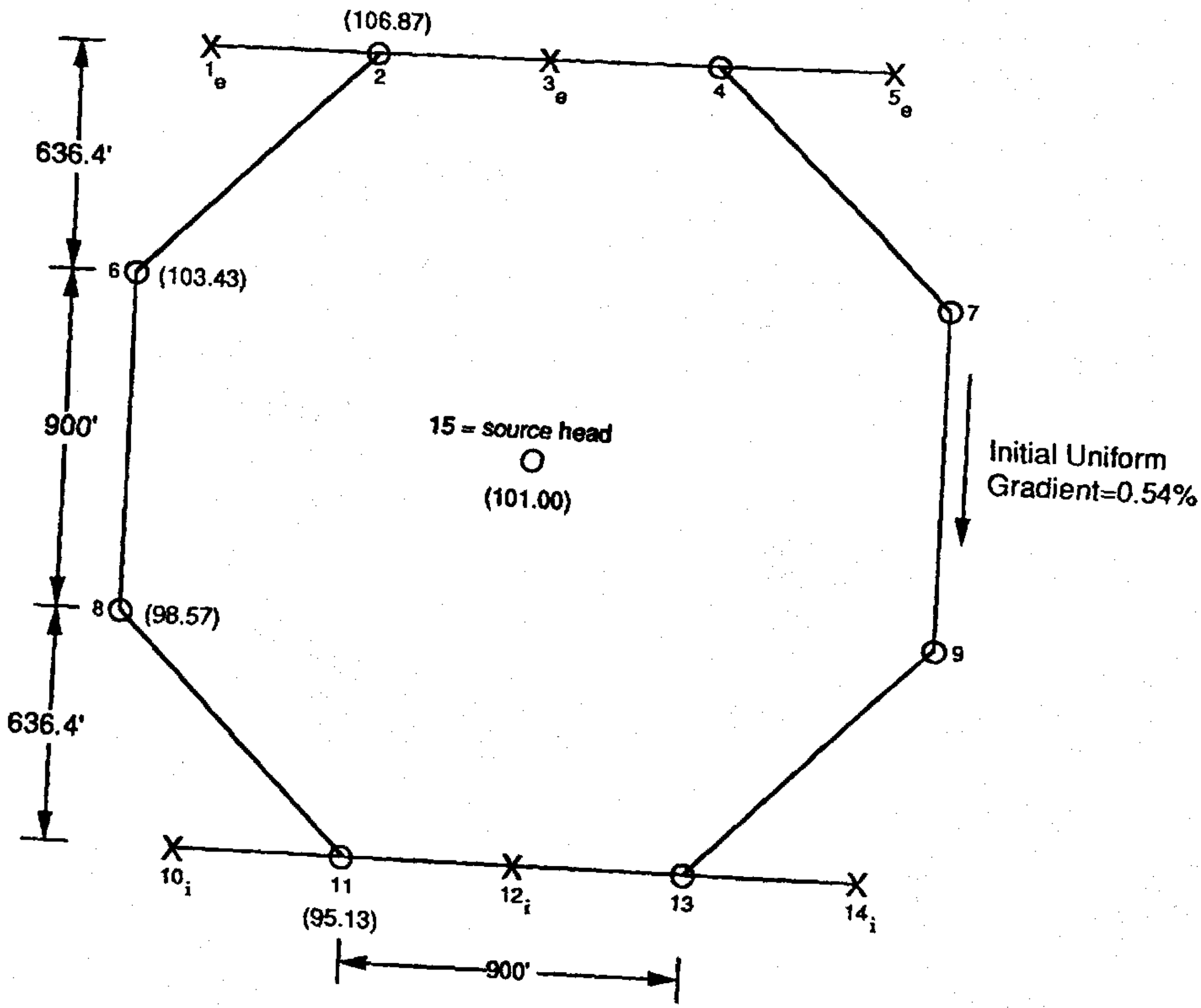
Lefkoff and others (1986) combined quadratic and linear programming to evaluate design alternatives for rapid aquifer restoration. The design model ensures that a contaminant plume is removed and treated within four years at minimum cost. They concluded that treatment and pumping costs depend dynamically on the t[illegible] of treatment process, the capac[illegible] of extraction and injection wells, and the number of wells.

Heidari and others (1987) developed a linear ground-water management model to investigate the best management options for diverting an oil-field-brine plume in the Equus Beds aquifer in south-central Kansas. The main purpose of the management model was to find the optimal locations and minimum rates of pumping of a set of plume-interception wells. The objective was to reverse the velocity vectors at observation wells located along the plume front and to satisfy fresh-water demands from a supply well. A solute transport model was used to evaluate contaminant movement resulting from the optimal pumping strategies.

Ward and Peralta (1988) developed deterministic and stochastic models for optimizing plume containme[illegible] but did not report comparisons [illegible] their well arrangement with [illegible] common parallel arrangement.

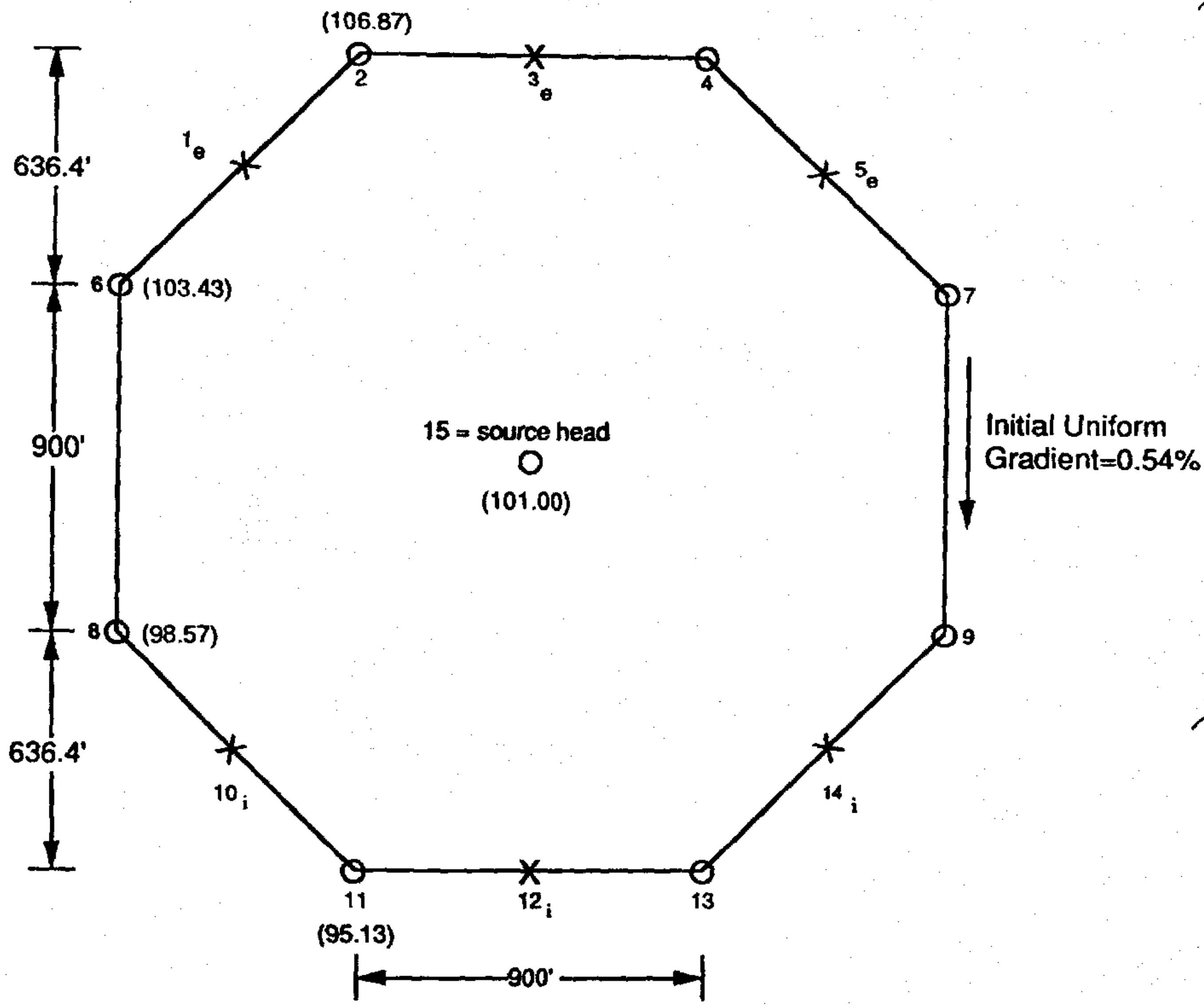
METHODS

A hypothetical aquifer was considered, with an initial potentiometric surface gradient of 0.54 percent, transmissivity of 13,500 (feet squared per day), and a specific yield of 0.01. A pumping period of 8 days was tested. Octagonal, parallel and combination arrangements of pumping wells were compared (fig. 1 and 2). A 900-foot length was chosen for each octagon side. Three pumping wells were placed upgradient and 3 recharge wells were placed downgradient. The intent was to minimize the pumping needed to prevent the plume from migrating beyond the wells. A secondary consideration, not explicitly included in the objective functi[illegible] was to cause as smooth a



Legend:
(101.00) = initial water-table elev. (ft.)
x = extraction/injection well
O = observation well
(e) = pumping well
(i) = recharge well

Figure 1.-Parallel well configuration



Legend:

(101.00) = initial water-table elev. (ft.)

x = extraction/injection well

O = observation well

(e) = pumping well

(i) = recharge well

Figure 2.-Octagonal well configuration

potentiometric surface as possible. Observation wells encircled the plume. Those used for hydraulic-gradient constraints were downgradient of the plume. All wells were outside of the zone of contaminated ground water.

The procedure consisted of 3 stages. In the first stage, the influence coefficients were developed using the Theis equation,

$$R_{i,j} = W(u)/4T\pi \qquad (1)$$

$$u = r^2S/4Tt \qquad (2)$$

$R_{i,j}$ = influence on head at well i due to a unit pumping stimulus at well j [T/L^2]

T = transmissivity [L^2/T]

S = storage coefficient [dimensionless]

$$W(u) = -0.5772 - \ln(u) + u - u^2/(2*2!) + u^3/(3*3!) - \ldots$$

r = distance between stimulus point and point at which head must be computed [L]

In the second stage, the optimal extraction/injection rate was computed using MINOS (Gill and others, 1988), an optimization package suitable for linear and nonlinear problems. The objective function tried to minimize pumping. Constraints utilized include the following: (a) At each extraction well i, drawdown must be less than 20 percent of the initial saturated thickness. (This constraint did not increase required pumping in any of the performed optimizations).

$$0.2H_{sat} - \Sigma R_{i,j}q_{jext} + \Sigma R_{i,j}q_{jinj} \geq 0 \qquad (3)$$

Σ = summation over total number of pumping wells

(b) At each injection well i, the injection cone must not rise above the ground surface.

$$H_{dif} + \Sigma R_{i,j}q_{jext} - \Sigma R_{i,j}q_{jinj} \geq 0 \qquad (4)$$

(c) In order to guarantee that the plume does not migrate, the hydraulic head at each observation well on the downgradient system boundary was forced to be greater than or equal to the contaminant-source head. The contaminant source was located in the center of the well configuration.

$$H_{surf} - \Sigma R_{i,j}q_{jext} + \Sigma R_{i,j}q_{jinj} - (H_{cont} - \Sigma R_{c,j}q_{jext} + \Sigma R_{c,j}q_{jinj}) \geq 0 \qquad (5)$$

In these equations:

q_{jext} = withdrawal from the aquifer at well j [L^3/T]

q_{jint} = injection to the aquifer at well j [L^3/T]

H_{sat} = initial saturated thickness at well i [L]

H_{dif} = difference between the ground-surface elevation and the initial water-table elevation at well i [L]

H_{surf} = initial potentiometric-surface elevation at the observation well i [L]

H_{cont} = potentiometric-surface elevation at the contaminant source [L]

$R_{c,j}$ = influence on head at contaminant source due to pumping at well j [T/L^2]

In the third stage, a method of characteristics solute transport model (MOC), (Konikow and Bredehoeft, 1984), was used to determine the concentration that would result from implementing the optimal strategy. Contaminant transport was simulated for pumping periods of 8 days.

RESULTS

The octagonal well configuration required less pumping than did the parallel and the combination arrangements, when tested using a pumping period of 8 days (table 1).

The maximum final difference between the observation well heads and the source head was also the lowest for the octagonal well configuration. Thus, when comparing the head at the source with that at the observation wells, the potentiometric surface was smoothest for the octagonal well configuration. The head distribution computed by the MOC model also showed that the potentiometric surface achieved by the octagonal system was smoother than that obtained by the other systems. The MOC solute transport model showed that the octagonal configuration spread the plume less than did the parallel configuration during the first 8 days of pumping. If steady pumping continued, this trend continued for the first 31 days. However, after 40 days, the octagonal system spread the contaminant more than did the parallel system. This final spreading occurred because contaminant reached the upgradient wells (1,3 and 5) more rapidly than in the parallel arrangement. In this regard, care should be exercised in using either well configuration. Pumping rates should be designed to prevent extraction of contaminated water. This can be assured by direct simulation or by including constraints on pore velocities toward extraction wells in the optimization model. If the head at the source were higher (due to leakage from a contaminant-containing tank or other cause), the octagonal well arrangement would still require slightly less pumping than the parallel system. In addition, when considering heads the observation wells, t potentiometric surface would be slightly smoother.

Optimal pumping caused a maximum drawdown of about 9 ft at the location of extraction wells. This represents almost a 20 percent decrease in the saturated thickness and transmissivity at the extraction well. If global transmissivity is reduced by 20 percent, and the influence coefficients and optimal strategies are recomputed, the octagonal system still performs the best. The error caused by using the Theis equation for this unconfined system is relatively small. For this example, using linear systems theory and superposition is justifiable.

Sensitivity to assumed specific yield was analyzed by performing new optimizations using a value of 0.25 (transmissivity was unchanged). Because the change in head caused a unit pumping becomes smaller, mo pumping is needed to achieve th gradient constraint. In addition, the injection cone becomes higher. In these tests, the octagonal arrangement required only 79 percent of the pumping and caused only 22 percent of the maximum head difference resulting from the parallel system. Its highest injection cone was also only 80 percent as tall as that produced by the parallel arrangement.

Table 1. Results of optimal pumping strategies for parallel, octagonal and combination well configurations for a pumping period of 8 days.

Well Configuration	Discharge indiv.well (ft^3/sec)	Total pumping (inj.+ext.) (ft^3/sec)	Source[3] head (ft)	Maximum head[4] difference (ft)
Parallel	1.736	10.416	101.000	0.604
Octagonal	1.663	9.978	101.000	0.181
Combination[1]	1.790	0.740	101.931	-1.253
Combination[2]	(2.212(ext.) 1.352(inj.))	0.692	98.126	-1.282

\1: Combination system using parallel extraction-well configuration placed upgradient and octagonal injection-well configuration placed downgradient. All discharge rates are forced to be equal.
\2: Same as \1, except injection pumping rates are not forced to be equal to extraction discharge rates.
\3: Final potentiometric-surface elevation of the contaminant source located in the center of the configuration system.
\4: Greatest difference between final heads at observation wells and the source of contamination ($H_{obs} - H_{cont}$).

SUMMARY AND CONCLUSIONS

Short-term ground-water contaminant plume containment is optimized for a hypothetical emergency situation. The approach is applicable for cases in which contamination should be prevented from reaching a downgradient well or should be kept within the boundaries of a company property. Parallel, octagonal, and combination well configurations were compared. In these systems there were 3 extraction wells initially upgradient and 3 injection wells downgradient of the contaminant plume. The utilized model combines linear programming optimization and simulation via the response matrix method.

In the first stage, influence coefficients were developed for all injection, extraction, and observation wells. In the second stage, the optimal pumping (minimum rate) was obtained for each well configuration using operations research type of linear programming. In the third stage, contaminant migration resulting from optimal pumping was computed using a solute transport model.

The octagonal well configuration required less pumping for a pumping period of 8 days than did the parallel or combination systems. The octagonal configuration caused the smoothest potentiometric surface, when heads at observation wells are compared with those at the contaminant source.

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REFERENCES CITED

Atwood, D.F. and Gorelick, S.M., 1985, Hydraulic gradient control for groundwater contaminant removal: Journal of Hydrology, v.76, P. 85-106.

Brooks, A., Kendrick, D. and Meeraus, A., 1988, GAMS - A user's guide. The International Bank for Reconstruction and Development/The World Bank, 289 p.

Gill, P.E., Murray, W., Saunders, M.A. and Wright, M.H., 1988, GAMS/MINOS in: GAMS - a user's guide. The International Bank for Reconstruction and Development/The World Bank, 289 p.

Gorelick, S.M. and Wagner, B.J., 1986, Evaluating strategies for groundwater contaminant plume stabilization and removal. Selected Papers in the Hydrologic Sciences. USGS Water-Supply Paper 2290, P. 81-89.

Heidari, M., Sadeghipour, J. and Drici, O. 1987, Velocity control as a tool for optimal plume containment in the Equus Beds aquifer, Kansas. Water Resources Bulletin, vol.23, no.2, P. 325-335.

Konikow, L.F. and Bredehoeft, J.D., 1984, Computer Model of two-dimensional solute transport and dispersion in ground water. Techniques of water resources investigations of USGS. US Department of Interior. Book 7, Chapter C2, 90 p.

Lefkoff, L.J. and Gorelick, S.M. 1986, Design and cost analysis of rapid restoration systems using flow simulation ar quadratic programmin Groundwater v. 24, no.6, P. 777-790.

Ward, R. and Peralta, R.C. 1988, Expert potentiometric surface modification for groundwater contaminant containment. Draft project completion report, 250 p.