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USING LINEAR PROGRAMMING**

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Optimized Groundwater Containment Using Linear Programming¹

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ABSTRACT

Groundwater extraction systems are typically installed to contain contaminant plumes. These systems are expensive to install and maintain. A traditional approach to designing such a wellfield is to use a series of trial-and-error simulations to test the effects of various well locations and pump rates. However, optimal locations and pump rates of extraction wells are difficult to determine when the objectives of the potential pumping scheme and the site hydrogeology are considered.

This paper describes a case study of an application of linear programming theory to determine optimal well placement and pump rates. Calculations were conducted by using ModMan to link a calibrated MODFLOW flow model with LINDO, a linear programming package. Past activities at the site under study included disposal of contaminants in pits. Several groundwater plumes have been identified, and others may be present. The area of concern is bordered on three sides by a wetland, which receives a portion of its input water budget as groundwater discharge from the disposal area.

The objective function of the optimization was to minimize the rate of groundwater extraction while preventing discharge to the marsh across a user-specified boundary. In this manner, the optimization routine selects well locations and pump rates to produce a groundwater divide along this boundary. Well yields were constrained to a field-determined maximum. Optimization of the containment pumping scheme achieves the following three goals: (1) preventing discharge of contaminated groundwater to the wetland (ecological benefit), (2) minimizing the total water pumped and treated (cost benefit), and (3) avoiding dewatering of the wetland (cost and ecological benefits).

The code identified optimal well locations, with varying individual flow rates, that successfully produced a flow divide between the pits and the wetland along the constraint boundary. Limiting the maximum number of wells provided a means of exploring the cost-related trade-off between the number of wells to be installed and the rate of pumping and treatment.

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PURPOSE AND APPROACH

This case study is presented to demonstrate the use of linear programming techniques to optimize a proposed groundwater extraction system. Initially, the flow field in the site vicinity is characterized with a three-dimensional model that makes use of existing data and several numerical techniques. A user-specified border is set near the wetland and used as a constraint boundary in a containment area. The extraction system is designed to consist of the smallest number of wells necessary to meet the objective, while striving to pump no water from the wetland. This optimization approach minimizes the initial and on-going costs and is protective of the marsh ecology.

SITE DESCRIPTION

The focus of the study is a former disposal pit area bordered on three sides by a wetland (Figure 1). Local stratigraphy consists of Pleistocene units with varying contact surfaces and widely differing hydraulic conductivities. The surficial 11-m (35-ft) alluvial sequence of medium- to fine-grained sand with interbedded clay is the aquifer of concern.

A pump test well was constructed in the pit area in a 35-cm (14-inch) diameter hole. Aquifer parameters calculated from the test include a horizontal hydraulic conductivity of 1.5×10^{-3} to 2.2×10^{-3} cm/s (4.3 to 6.3 ft/d) during the recovery phase (Quinn 1995). Perhaps the most important knowledge gained during step drawdown testing of the well is that despite the well's large diameter, it could not achieve a yield of 0.12 L/s (2 gpm). A yield of 0.06 L/s (1 gpm) was sustained during the constant rate test.

Field measurements of heads at the site indicated that groundwater flow is generally from topographic highs in the pit area to the wetland discharge area.

GROUNDWATER FLOW MODEL

A computer code capable of three-dimensional modeling was required to investigate the flow system. MODFLOW (McDonald and Harbaugh 1988) allows three-dimensional modeling of hydrogeologic flow systems, and the program's versatility includes the ability to model aquifer recharge, drains, heterogeneities, pumping wells, varying surfaces of hydrostratigraphic units, and different types of boundary conditions.

Details of the model setup and results are provided in Quinn et al. (1996). A rectangular, variably spaced grid was designed for a modeling domain of 8 km² (3 mi²). The grid extended to distant hydrologic boundaries and was focused on the pit area. In the vicinity of the pit area, the grid is the finest, with cells 7.6 m by 7.6 m (25 ft by 25 ft).

Wetlands in the surficial aquifer layer were modeled with the drain package of MODFLOW. Input parameters include an elevation below which the effect of the drain is inactive and a drain conductance, which is normally determined through calibration exercises (McDonald and Harbaugh 1988).

The spatially varying upper and lower surfaces of the hydrostratigraphic units affect the local saturated thickness of each unit. To include these variable thicknesses in the flow model, the contact

FIGURE 1 Pits Area and Steady-State Water-Table Surface

elevations between the units were determined with geostatistical techniques (Isaaks and Srivastava 1989). With site stratigraphic contact data as input, variogram modeling and kriging were performed with the Geo-EAS program (Englund and Sparks 1991).

The horizontal hydraulic conductivity of the surficial aquifer was set to 1.2×10^{-3} cm/s (5.3 ft/d) on the basis of the pump test results. The recharge determined during calibration was 27 cm/yr (10.5 in/yr). The calibrated surficial aquifer heads in the pit area are shown in Figure 1. In a sensitivity analysis, the model output was found to be strongly affected by changes in hydraulic conductivity of the surficial aquifer and recharge, and somewhat affected by drain parameters (Quinn et al. 1996).

OPTIMIZATION OF PUMPING STRESSES

The primary goal of this study was to determine an optimum wellfield for containment of contaminated groundwater at the pit area, while extracting water at the lowest possible rate. The extraction system was to prevent any groundwater discharge to the wetland and to avoid pumping water from the wetland.

To determine the number of wells needed, their locations, and their individual pump rates, linear programming was used to evaluate the effect of numerous possible well locations and to indicate optimal pumping arrangements for two scenarios.

The optimization of stresses imposed by the groundwater extraction system was performed with ModMan (GeoTrans, Inc. 1992). ModMan serves as the communication link between a calibrated MODFLOW model and a linear optimization program, LINDO (Schrage 1991). ModMan requires input on the objective and constraints of the optimization problem. These constraints may relate to hydrogeologic aspects of the situation (e.g., head or drawdown values, head differences) and pumping system design (e.g., number of wells, maximum pump rates of each). The fundamental questions that ModMan addresses are (1) the optimal locations of pumping wells, and (2) the optimal pump rate of each well.

A decision was made to restrict potential well locations to known or suspected source areas. In this manner, containment would be achieved with an emphasis on extraction of the most contaminated groundwater. Candidate wells were located at 45 model cells located at the known source areas (Figure 2).

To provide containment, the head difference constraint was applied to a user-specified boundary approximately 30 m (100 ft) from the wetland boundary (Figure 2). With this approach, ModMan was instructed to determine well pumping rates such that the head at the outer constraint node is equal to or greater than the head at the inner constraint node. Because the optimization code strives to extract groundwater from the system at the lowest possible rate, the model tries to achieve equality between each pair of head difference nodes. In this manner, a groundwater divide would ideally be created along the constraint boundary. Otherwise, the routine would allow an inward gradient, which would cause some water from the wetland to be pumped, but would achieve the primary goal of preventing any groundwater discharge to the wetland. Because of the yield information obtained from the pump test, the maximum allowed pump rate of an individual well is

FIGURE 2 Constraint Setup and Candidate Well Locations for Optimization Model

0.063 L/s (1 gpm). Although higher or lower sustainable pump rates may be possible at other pit area locations, this pump rate is assumed to be a best estimate of the maximum possible value.

ModMan was initially instructed to choose 20 or fewer wells. The code selected nine of the candidate well locations, with a combined pumping rate of 39.13 m³/d (1,381.9 ft³/d). A second optimization run was performed with the maximum number of wells set to eight or fewer. Eight wells were selected with a very similar combined rate of 39.15 m³/d (1,382.4 ft³/d). The resulting steady-state heads from this run are shown in Figure 3. Another optimization run executed for seven or fewer possible wells. No feasible solution could be determined by LINDO.

SUMMARY OF OPTIMIZATION RESULTS

A goal of the optimization modeling was to provide containment of groundwater within the pit area to protect the ecology of the wetland from the discharge of contaminated groundwater. An inspection of Figure 3 indicates that this goal has been attained, because each case shows a flow divide along most of the constraint boundary.

In both cases, an inward gradient occurs along only a small portion of the wetland boundary. These results suggest that a second objective, namely minimally affecting the wetland hydrology, has also been achieved. Although the pumping scheme does draw some water from the wetland, the amount is minimal compared with the groundwater input across the rest of the wetland border, and the discharge of contaminated groundwater is effectively negated.

The results are believed to provide the best design for an efficient groundwater extraction system at the pit area. An important factor incorporated by the optimization modeling was the limited yield of the candidate wells. The result is a larger number of required wells than would be necessary in a case of unlimited yield for modeled wells.

The optimization modeling is based on application of linear programming to a system that includes non-linear elements (e.g., unconfined flow and flow to drains). Any error associated with this application is assumed to be negligible, especially in comparison with errors resulting from the calibration of the flow model. While a great deal of data have been collected at the site, data gaps are present. These data gaps include aquifer parameters identified as sensitive, namely the hydraulic conductivity of the surficial aquifer and recharge rate. While recharge is typically difficult to measure, additional estimates of hydraulic conductivity could be obtained through pump tests at any fully screened pumping wells installed in a remediation effort. This information would provide greater confidence in the value or define the degree of variability of the bulk horizontal hydraulic conductivity of the aquifer.

The optimization code allows the user to specify a maximum number of wells to allow per simulation. In this study, the number of pumping wells is inversely proportional to the overall pump rate of the system. By sequentially decreasing the number of wells allowed, the user can explore the tradeoff between the number of pumping wells versus the total rate of groundwater extraction. The minimum number of wells providing a feasible solution is also determined. In this study, a negligible difference was demonstrated in the total pump rates in the simulations using nine and

FIGURE 3 Optimized Steady-State Water-Table and Selected Candidate Well Locations

eight pumping wells. This type of analysis is useful in determining the relationship between initial costs (well installations) and on-going costs (rate of water requiring treatment).

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