In cooperation with

U.S. Army Garrison, Aberdeen Proving Ground
Environmental Conservation And Restoration Division
Aberdeen Proving Ground, Maryland

Optimization of Ground-Water Withdrawal at the Old O-Field Area, Aberdeen Proving Ground, Maryland

Water-Resources Investigations Report 00-4283

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Baltimore, Maryland
2001

U.S. DEPARTMENT OF THE INTERIOR
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Conversion Factors and Vertical Datum

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inch per year (in/yr)	2.54	centimeter per year
gallon (gal)	3.785	liter
gallon per minute (gal/min)	3.785	liter per minute
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
square foot (ft^2)	0.09290	square meter
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
mile (mi)	1.609	kilometer
acre	4,047	square meter

Vertical datum: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Chemical concentration in water is expressed in milligrams per liter (mg/L), or micrograms per liter (µg/L).

Optimization of Ground-Water Withdrawal at the Old O-Field Area, Aberdeen Proving Ground, Maryland

By **William S.L. Banks** *and* **Jonathan J.A. Dillow**

Abstract

The U.S. Army disposed of chemical agents, laboratory materials, and unexploded ordnance at the Old O-Field landfill at Aberdeen Proving Ground, Maryland, beginning prior to World War II and continuing until at least the 1950's. Soil, ground water, surface water, and wetland sediments in the Old O-Field area were contaminated by the disposal of these materials. The site is in the Atlantic Coastal Plain, and is characterized by a complex series of Pleistocene and Holocene sediments formed in various fluvial, estuarine, and marine-marginal hydrogeologic environments. A previously constructed transient finite-difference ground-water-flow model was used to simulate ground-water flow and the effects of a pump-and-treat remediation system designed to prevent contaminated ground water from flowing into Watson Creek (a tidal estuary and a tributary to the Gunpowder River). The remediation system consists of 14 extraction wells located between the Old O-Field landfill and Watson Creek.

Linear programming techniques were applied to the results of the flow-model simulations to identify optimal pumping strategies for the remediation system. The optimal management objective is to minimize total withdrawal from the water-table aquifer, while adhering to the following constraints: (1) ground-water flow from the landfill should be prevented from reaching Watson Creek, (2) no extraction pump should be operated at a rate that exceeds its capacity, and (3) no extraction pump should be operated at a rate below its minimum capacity, the minimum rate at which an Old O-Field pump can function. Water withdrawal is minimized by varying the rate and frequency of pumping at each of the 14 extraction wells over time. This minimizes the costs of both pumping and water treatment, thus providing the least-cost remediation alternative while simultaneously meeting all operating constraints.

The optimal strategy identified using this objective and constraint set involved operating 13 of the 14 extraction wells at rates ranging from 0.4 to 4.9 gallons per minute.

Introduction

The U.S. Army disposed of chemical agents, laboratory materials, and unexploded ordnance at the Old O-Field landfill at Aberdeen Proving Ground (APG), Md., from before World War II until at least the 1950's. As a consequence of these activities, shallow ground water is contaminated with a variety of organic and inorganic constituents. These contaminants are migrating toward and into Watson Creek, an estuary adjacent to the Old O-Field area. In an effort to prevent contaminated ground water from reaching Watson Creek, the Army has installed a network of extraction wells designed to intercept shallow ground water and direct it toward a wastewater-treatment facility.

A Federal regulatory presence was established in 1990 when the entire Edgewood Area of APG was added to the National Priority List and came under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) of 1980. In 1995, as part of the effort by the U.S. Army to remediate existing contamination and prevent further migration of contaminated ground water from Old O-Field into Watson Creek (a tidal estuary and a tributary to the Gunpowder River), a remediation system consisting of an extraction-well network and wastewater-treatment plant was installed at Old O-Field. This remediation system is part of a remedial action plan designed to prevent contaminated ground water from migrating off site. The extraction-well network is designed to intercept contaminated ground water before it reaches Watson Creek, and direct it to the wastewater-treatment plant for decontamination. In addition, a permeable infiltration unit (PIU) consisting of sand and coarse gravel was placed on top of the Old O-Field area in 1997 as part of the remedial action plan. The PIU was designed to cover the landfill and stabilize and contain its contents in the event of an explosion. A complete history of disposal activities at the site can be found in Nemeth (1989). A comprehensive list of regulatory actions at APG for the O-Field area can be found in IT Corporation (1999).

Purpose and Scope

In 1998, the U.S. Army asked the U.S. Geological Survey (USGS) to develop an optimal pumping strategy at the Old O-Field area to prevent contaminated shallow ground water from reaching Watson Creek, and minimize the amount of ground water extracted, thereby reducing the operating costs of the remediation system. The purpose of this report is to describe an optimal pumping strategy and the methods used to develop it. The report also briefly describes the ground-water-flow model used in the optimization, including boundary conditions, model stresses, and calibration. The report describes pumping rates that can be applied at existing extraction wells at the Old O-Field area under certain constraints applied to the system. The management goals that will be achieved by applying this strategy include: (1) preventing contaminated ground water from Old O-Field from reaching Watson Creek; and (2) controlling ground-water withdrawal so that institutional constraints such as plant treatment and storage capacity, and individual pump capacity are not exceeded.

The methods used to develop the optimal pumping strategy include several steps, as follows: (1) define the water-table-aquifer response to operation of the extraction wells using the transient ground-water-flow model developed by ICF Kaiser Engineers (1999); (2) use the data management software package MODMAN (Greenwald, 1998) to develop a linear program to represent the objective and constraints that define and limit the optimal pumping strategy; (3) apply **L**inear **IN**teractive and **D**iscrete **O**ptimizer (LINDO) (HyperLINDO/PC, 1998), a linear programming software package, to solve the linear program and identify the optimal pumping strategy; and (4) use the transient ground-water-flow model developed by ICF Kaiser Engineers (1999) to verify that the optimal pumping strategy meets pertinent physical and institutional constraints. Precipitation data recorded between March 1996 and February 1997 were used to calibrate the ground-water-flow model for a 2-year period.

Location of Study Area

APG is a 72,516-acre military facility in Harford and Baltimore Counties, Md. The facility is bordered by the Chesapeake Bay to the south, the Bush River to the east, and the Gunpowder River to the west (fig. 1).

The Bush River divides the facility into two areas, the Aberdeen Area to the northeast and the Edgewood Area to the southwest. Since its commissioning in 1919, the primary mission of the facility has been to develop and test weapons systems for the U.S. Army.

O-Field is in the Edgewood Area on the western side of the Gunpowder Neck, and is bordered on the north by Watson Creek, on the west by the Gunpowder River, and on the south by H-Field. Between the 1930's and the 1970's, the O-Field site was used as a disposal and handling area for chemical and conventional ordnance, chemical warfare materials, decontaminating chemicals, laboratory waste, and contaminated equipment. O-Field is divided into two areas where known disposal activities have taken place. The northern 4.5 acres comprise Old O-Field. The remaining area to the south is designated as New O-Field (fig. 2).

Hydrogeologic Setting

Old O-Field is located on the unconsolidated sediments of the Atlantic Coastal Plain. In a description of a 961-ft (feet) core hole to bedrock drilled 2.5 mi (miles) south of Old O-Field, Powars (1997) identified the upper 177 ft as Quaternary deposits of unconsolidated clayey silt, sand, clay, and gravel consisting of numerous fining-upward sequences. The geology of the Coastal Plain sediments in Harford County, including Old O-Field, was described by Owens (1969) and Drummond and Blomquist (1993).

The hydrogeologic framework of Old O-Field was described by Vroblesky and others (1995). They divided the uppermost 120 ft of sediment into a water-table aquifer, an upper confined aquifer, and a lower confined aquifer. The water-table aquifer is considered to be hydrologically separated from the confined aquifers by a clay confining unit ranging from 1 to 4 ft thick near Old O-Field. Additional information on the confined aquifers is provided in ICF Kaiser Engineers (1994), Vroblesky and others (1995), and Banks and others (1995).

The water-table aquifer consists of a sequence of saturated sediment comprised mostly of quartz sand interbedded with silt and clay, and extends throughout the Gunpowder Neck. In the Old O-Field area, this sequence ranges in thickness from about 13 to 23 ft. Studies at Old O-Field and surrounding areas have described the sediments as having been deposited or reworked in fluvial, marine, and estuarine environments (Mixon, 1985; Hughes, 1995; Vroblesky and others, 1995; and Banks and others, 1995). During the Holocene epoch, some of the sediments were eroded and redeposited along the banks of and beneath the present tidal rivers, wetlands, and estuaries.

The sand of the water-table aquifer ranges in size from fine-grained to coarse. Gravel is mixed with the sand in some places as indicated by lithologic logs from boreholes (ICF Kaiser Engineers, 1991). Sieve analyses of several samples from the aquifer show an average of 80 percent sand, 19 percent silt, and 0.09 percent gravel (ICF Kaiser Engineers, 1994).

The water-table aquifer is recharged primarily by precipitation on Gunpowder Neck. A small amount of rainfall and snowmelt is carried in runoff to the Gunpowder River and Watson Creek. A larger part of the precipitation is evaporated at land surface or is taken up by plants and transpired. The remaining precipitation infiltrates through the unsaturated zone to recharge the water table.

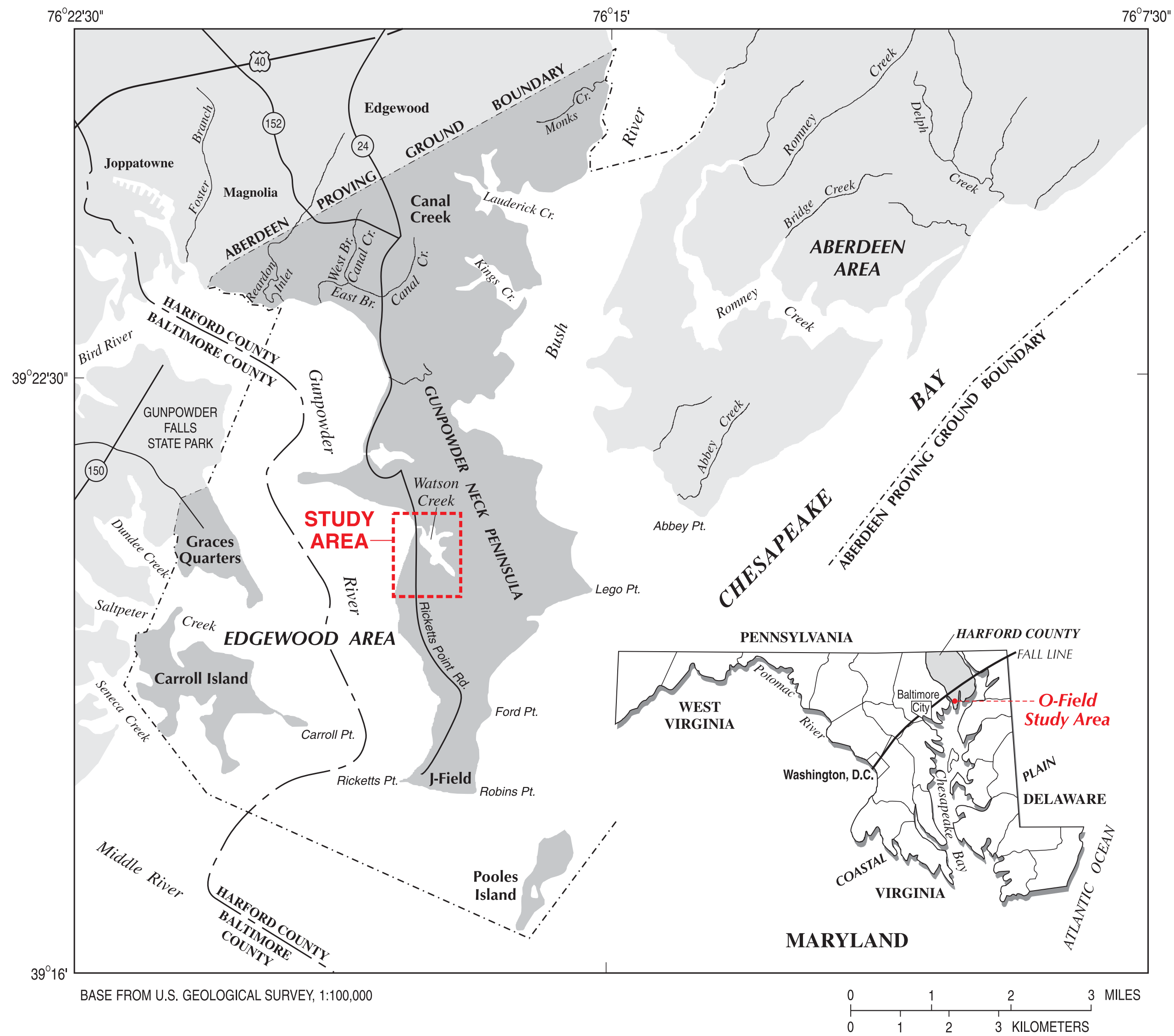

Figure 1. Location of the O-Field study area, Aberdeen Proving Ground, Maryland.

Water levels in wells screened in the water-table aquifer tend to rise in the winter and early spring, indicating seasonal ground-water recharge when plants are dormant and effective ground-water recharge is relatively high. Water levels tend to decline in the late spring and throughout the growing season from summer to early autumn when there is little or no effective recharge. The seasonal fluctuations in the water table are observed consistently from year to year (Banks and others, 1995).

Previous Investigations

Banks and others (1995) described the hydrogeology of the area and used MODFLOW (McDonald and Harbaugh, 1988) to simulate steady-state ground-water flow. ICF Kaiser Engineers (1999) defined the extent of shallow ground-water contamination and incorporated new hydrogeologic information and water-table gradients in order to simulate transient flow that accounts for the effects of the extraction-well network. Contaminants detected in the water-table aquifer east of Old O-Field and west of Watson Creek include 1,1,2,2-tetrachloroethane, trichloroethene, and various volatile organic compounds, chemical warfare material degradation products, and arsenic and mercury (ICF Kaiser Engineers, 1991; Vroblesky and others, 1995; and Roy F. Weston, 1993). The approximate extent of volatile organic contamination in the water-table aquifer in May 1997 is shown in figure 3 (ICF Kaiser Engineers, 1999).

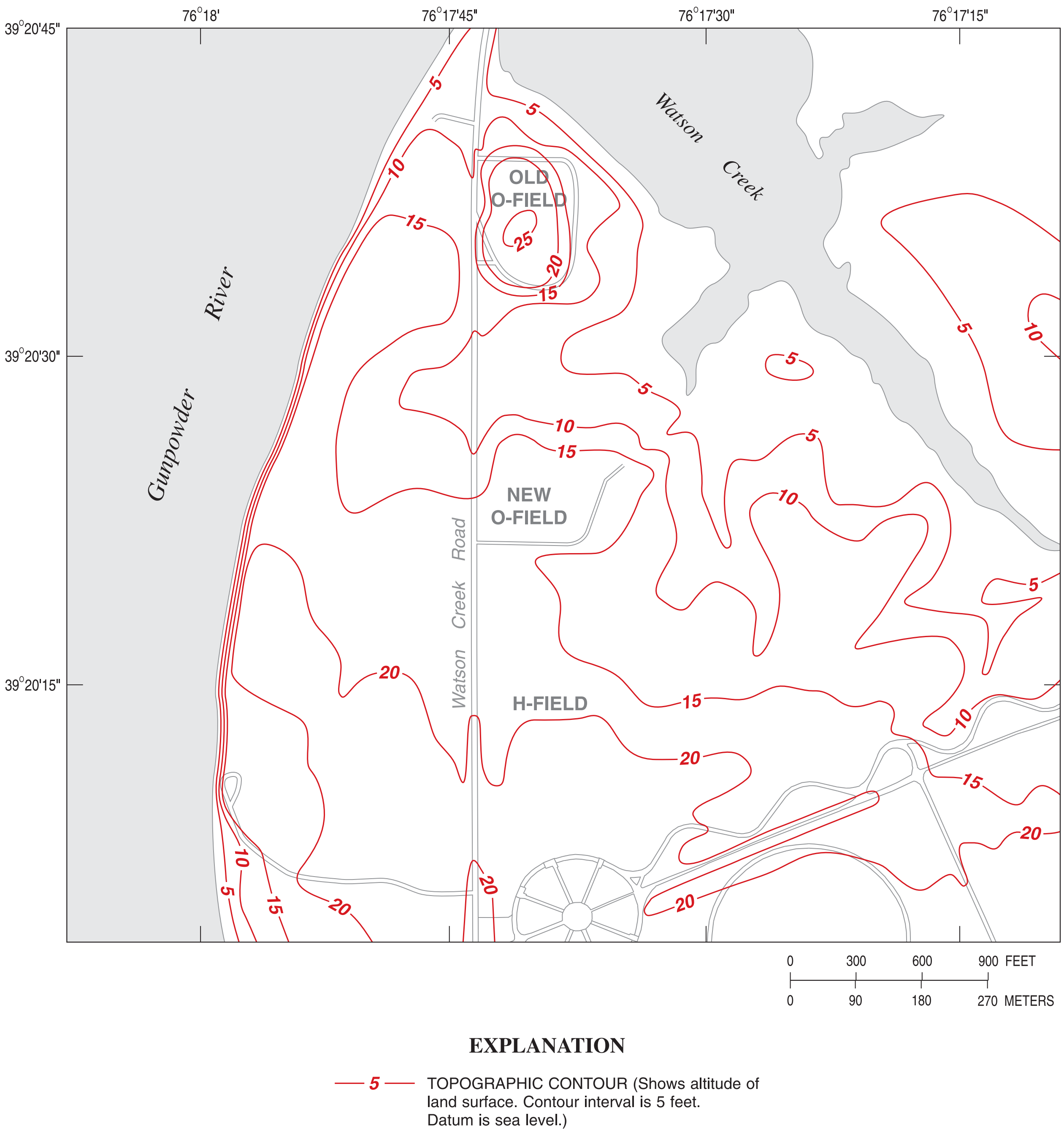

Figure 2. Location of Old O-Field and New O-Field and topography of the study area, Aberdeen Proving Ground, Maryland (modified from Banks and others, 1995).

A steady-state and a 2-year, transient particle-tracking simulation were used by ICF Kaiser Engineers (1999) to determine the effects of selected pumping strategies on the flow system and to evaluate the capture of ground water from the zone of contamination. The results of that analysis indicated that ground-water pumping by the extraction-well network could effectively capture particles originating from the contaminated part of the Old O-Field area during a 2-year particle-tracking simulation (ICF Kaiser Engineers, 1999).

Acknowledgments

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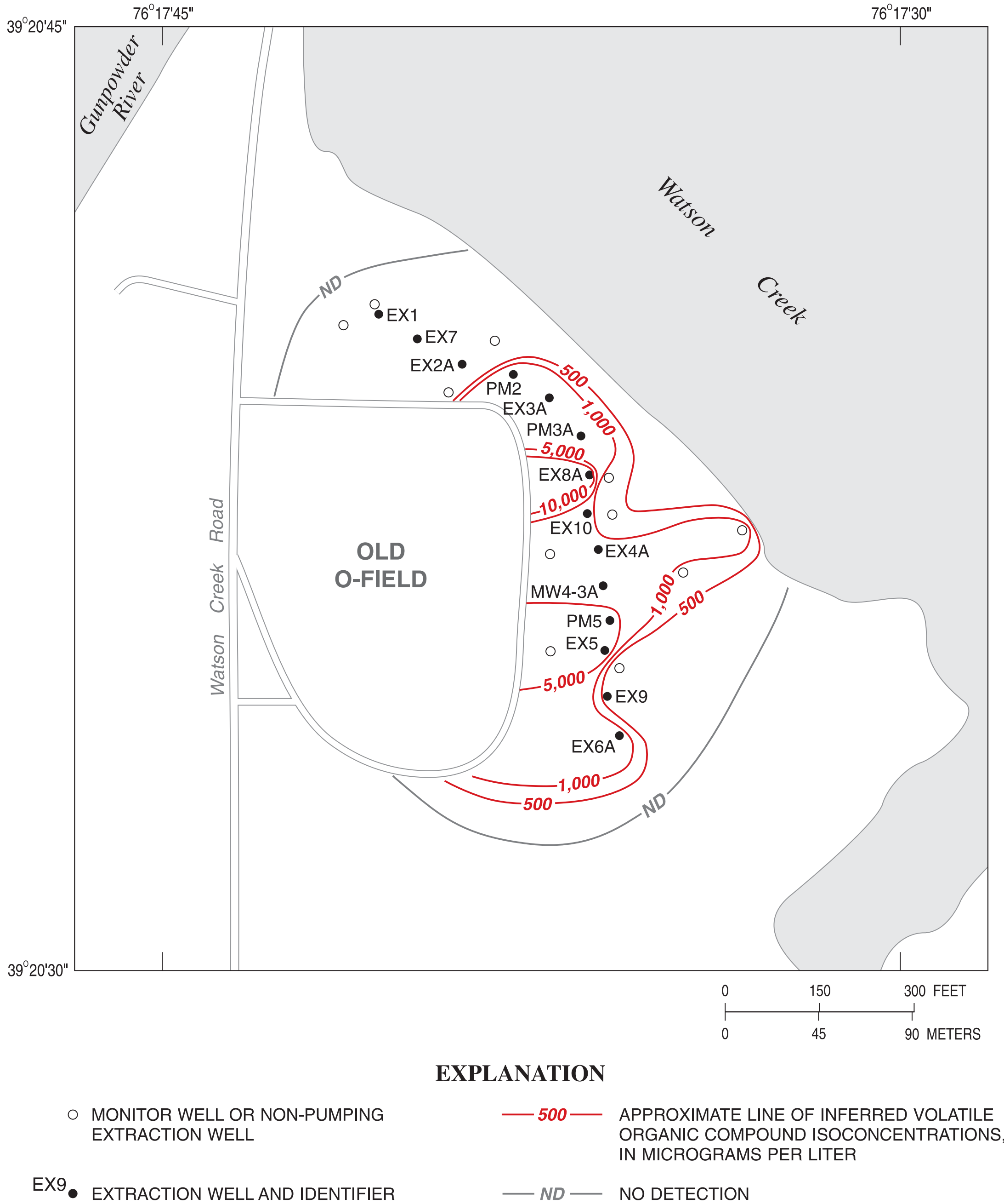


Figure 3. Location of extraction wells and volatile organic compound distribution in the water-table aquifer, May 1997, at Old O-Field, Aberdeen Proving Ground, Maryland (modified from ICF Kaiser Engineers, 1999).

Ground-Water-Flow Simulation Model

ICF Kaiser Engineers (1999) used the modular finite-difference ground-water-flow model (MODFLOW) by McDonald and Harbaugh (1988) to build a 2-year, transient ground-water-flow simulation model to represent ground-water flow. The transient model significantly modifies a steady-state model created by the USGS (Banks and others, 1995) by changing model boundaries, accounting for stresses induced by extraction wells, and by using a more rigorous approach to define areal ground-water recharge. The transient model is fully documented in ICF Kaiser Engineers (1999); a summary of the model's parameters, geometry, boundary conditions, and calibration is presented to better aid in the understanding of limitations of the optimization.

The transient model was used to predict responses in the ground-water-flow system during and after a simulation of a 2-month well-field shutdown. The transient model uses average pumping rates collected between March 1996 and

February 1997 to simulate monthly fluctuations in hydrologic and pumping conditions resulting from the operation of the 12-extraction-well network. The model also represents the water-table aquifers' response to the PIU described in ICF Kaiser Engineers (1999). ICF Kaiser Engineers (1999) also used MODPATH/MODPLOT (Pollock, 1994) to perform particle tracking. The use of particle tracking allowed visual examination of capture efficiency under different pumping scenarios.

Model Geometry

The active model grid for the transient model (ICF Kaiser Engineers, 1999) includes both the New and Old O-Field areas, and the surface-water and wetland areas to the north, northeast, northwest, and southeast of O-Field, as well as significant parts of the Gunpowder Neck to the south. The finite-difference grid is defined by 88 rows and 99 columns that represent distances ranging from 25 ft on a side in the area around the well field and PIU at Old O-Field to 900 ft on a side south of the study area. The model simulates ground-water flow over 1,085 acres and has 17,424 active cells in each of two layers (fig. 4). The previous steady-state model by Banks and others (1995) covered about 2,050 acres and had 18,480 active cells arranged in 88 rows, 105 columns, and 2 layers.

A vertical representation of the subsurface of Old O-Field designates the uppermost layer as the water-table aquifer, and the second layer as the upper confined aquifer. Each layer is continuous within the active area of the model. The confining unit between layers 1 and 2 is not explicitly represented in the model. Instead, it is implicitly included using a quasi-three-dimensional representation employing an array of the quotient of the vertical hydraulic conductivity and the thickness of the confining unit of each cell to account for the effects of the confining unit in the model.

Model Boundaries and Initial Conditions

The locations of the general-head, constant-head, and no-flow boundaries of the transient flow model are shown in figure 5. Two constant-head cells in the southeast corner of the model represent equilibrium between shallow ground water and Boon Creek. The remainder of the southern model boundary and all other boundaries not identified as general-head or constant-head are no-flow boundaries—areas in which no water flows into or out of the model. These boundaries are either coincidental with ground-water flow that is tangential to the boundary or are sufficiently distant from the area of interest so that they do not influence the simulation results. Parts of the model domain, including Watson Creek, the Gunpowder River, and the wetlands surrounding Old O-Field, are subject to a tidal flux and are designated as general-head boundaries. General-head boundaries allow water to flow into or out of a cell based on differences in head and hydraulic conductivity between the cell and an external source of water.

From March 1996 through February 1997, tide-elevation data for Watson Creek were collected every 15 minutes at a gage on the culvert between Watson Creek and the Gunpowder River. Additional tide-elevation data for Watson Creek were collected weekly. From these two data sources, high and low average-monthly stage-elevation values were calculated and used for all general-head boundary cells (ICF Kaiser Engineers, 1999). Average-monthly tide elevation values ranged from 1.92 to 1.21 ft above msl (mean sea level). Conductance values for the general-head boundary cells are based on a ratio of river or creek bed thickness to vertical hydraulic conductivity (McDonald and Harbaugh, 1988). Calibrated conductance values for the wetlands, Watson Creek, and the Gunpowder River were 0.0033, 0.02, and 0.025 ft/d (feet per day), respectively (fig. 5). The steady-state model by Banks and others (1995) used constant-head boundaries for the Gunpowder River and Watson Creek, and had a sufficiently large domain so that the model boundaries extended well beyond the area of interest and did not affect simulated flow near the Old O-Field area.

Hydraulic properties and starting heads for the transient model are based, in part, on values derived from field tests and those described in Banks and others (1995) and Vroblesky and others (1995). Horizontal hydraulic conductivities for layer 1 range from 15 to 100 ft/d and transmissivities for layer 2 range from 150 to 600 ft^2/d (feet squared per day). The vertical conductance of the confining layer is between 0.00017 and 0.036 ft/d. Specific yield for the water-table aquifer and storage for the upper confined aquifer are set at 0.2 and 0.0001, respectively.

Areal recharge to the model is from precipitation and is applied to the uppermost model layer. The amount of recharge was determined on the basis of techniques developed by Thornthwaite and Mather (1955). The model is divided into two zones for the purpose of areal recharge based on the assumption that the PIU has less evapotranspiration and runoff than the remainder of the model domain. The PIU zone has recharge rates that vary monthly between 0.0 and 0.019 ft/d. The non-PIU zone is recharged at rates that vary monthly between 0.0 and 0.0072 ft/d. It is important to note that precipitation (and thus recharge) for the period of calibration (March 1996 through February 1997) was higher than normal.

The location of a small ephemeral stream flowing west to east in the wetlands between New and Old O-Fields is shown in figure 5. The stream has a minimally incised bed and flows only for short durations during and after heavy precipitation. The stream is simulated as a drain in the uppermost layer of the model. When the water table rises due to recharge, the streambed intercepts the shallow ground water causing the stream to flow. Each cell of the drain has a hydraulic conductivity of 30 ft/d. Drain cell elevations range from 7 to 1.15 ft above msl.

Temporal Conditions

Month-long stress periods were chosen based on an analysis which showed that water-level and tide data averaged over a 1-month period produce results consistent with weekly values (ICF Kaiser Engineers, 1999). The ground-water-flow model uses twelve 1-month time periods.

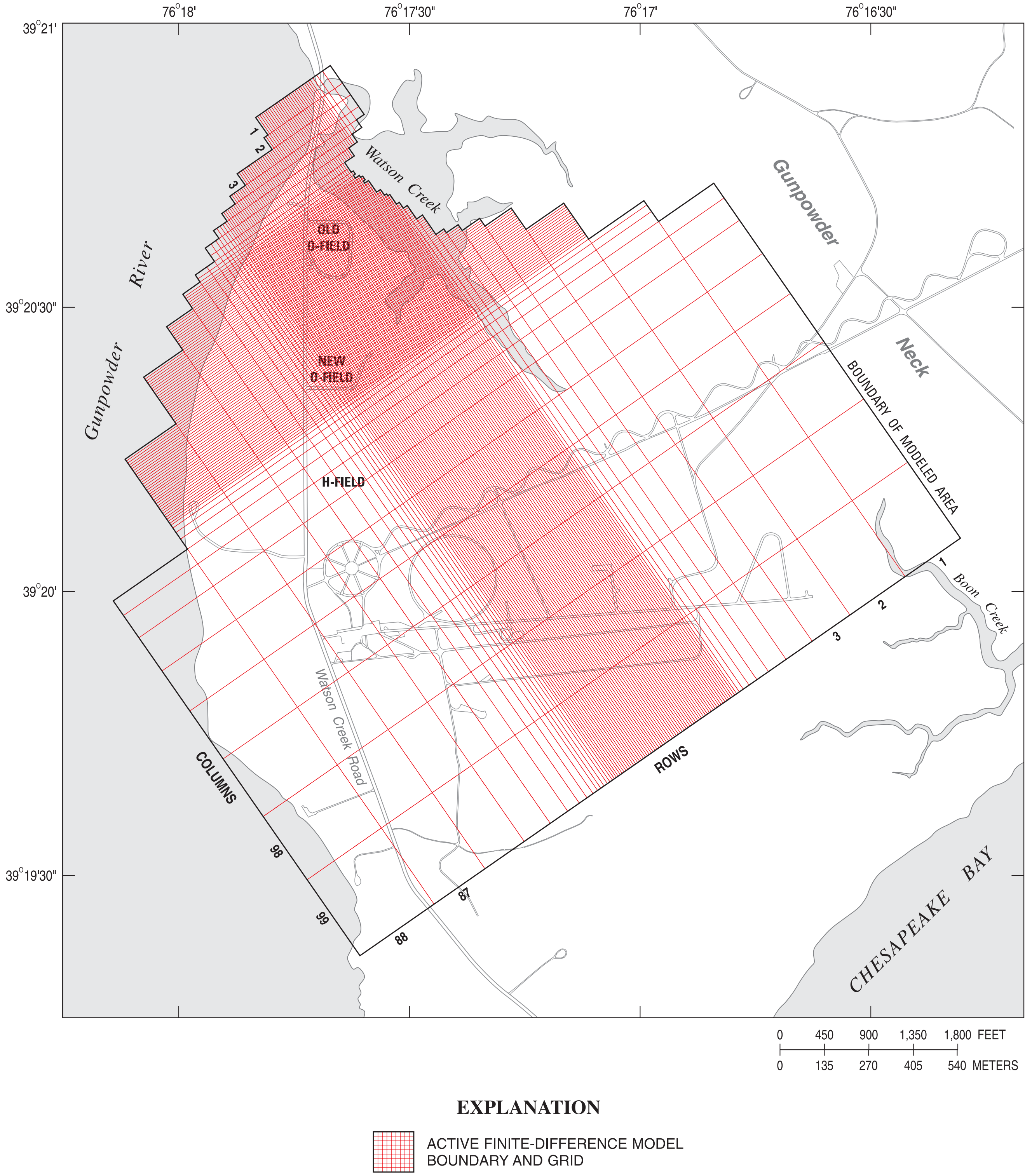
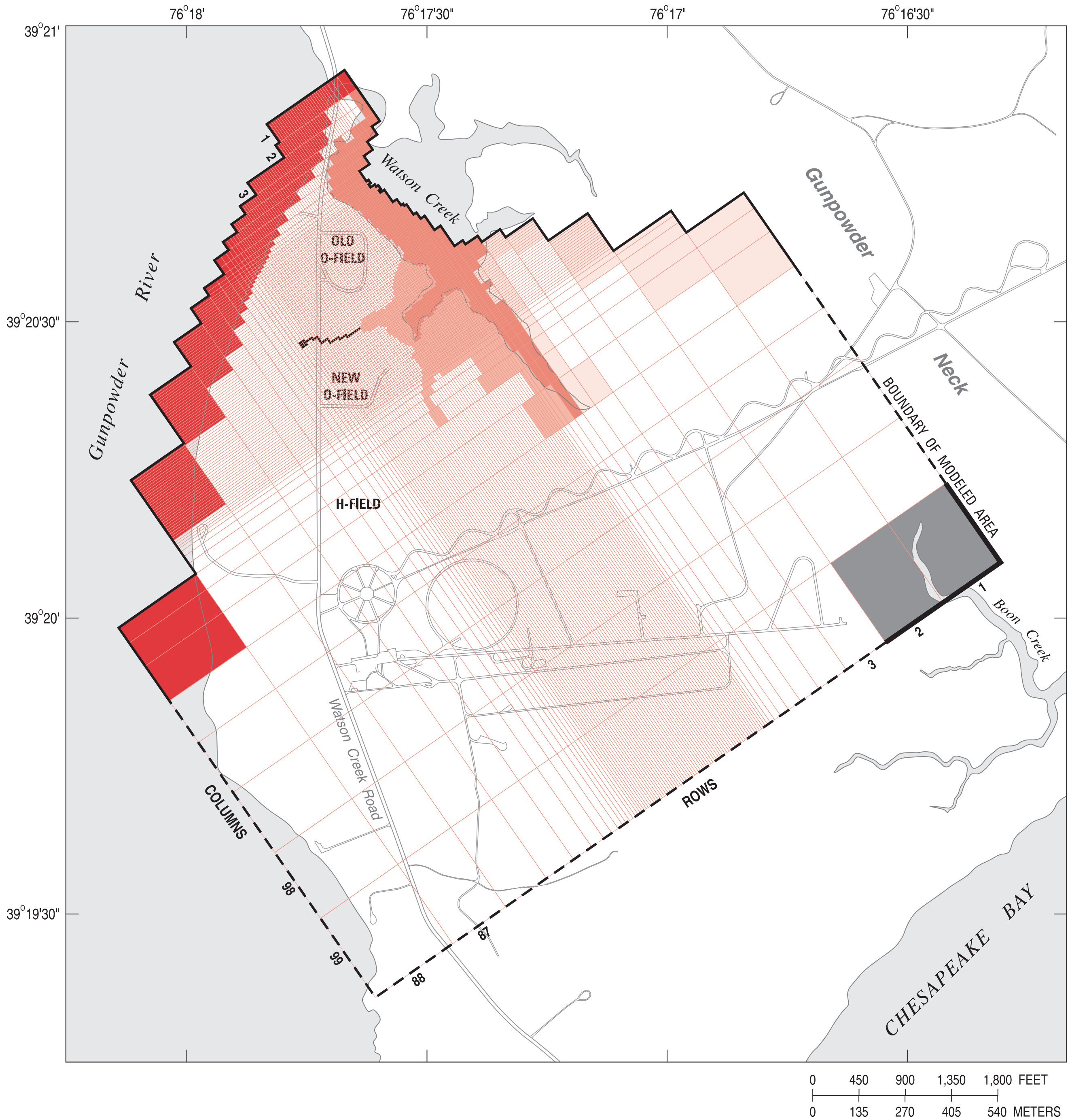


Figure 4. Active finite-difference model grid for the O-Field area (modified from ICF Kaiser Engineers, 1999).

During these time periods, model inputs, stresses, and boundary conditions are kept constant to simulate head as a time-dependent variable. Measured water levels in some wells did change diurnally in response to the tidal influence of Watson Creek. These responses were small (typically less than 0.1 ft), however, when compared to seasonal water-level variation (typically greater than 2.5 ft).

Each of the 12 stress periods were divided into 2 equal-length time steps. For the purposes of optimization, the 12-month (365-day) simulation was shortened to a 360-day



EXPLANATION

- GENERAL-HEAD BOUNDARY
- CONSTANT-HEAD BOUNDARY
- NO-FLOW BOUNDARY
- DRAIN CELLS
- CONSTANT-HEAD CELL
- GUNPOWDER RIVER GENERAL-HEAD BOUNDARY (Calibrated conductance value = 0.025 feet per day.)
- WATSON CREEK GENERAL-HEAD BOUNDARY (Calibrated conductance value = 0.02 feet per day.)
- WEST WETLAND GENERAL-HEAD BOUNDARY (Calibrated conductance value = 0.0033 feet per day.)
- EAST WETLAND GENERAL-HEAD BOUNDARY (Calibrated conductance value = 0.0033 feet per day.)

Figure 5. Finite-difference model grid boundary conditions and conductance values for the O-Field area (modified from ICF Kaiser Engineers, 1999).

simulation using twelve 30-day stress periods. This was necessary to accommodate an equal-time-length requirement of the response matrix.

Model Stresses

Between 1990 and 1997, 12 extraction wells were either installed or converted from water-level-monitoring wells to intercept contaminated ground-water flow between the PIU and Watson Creek.

Average pumping rates for this network ranged from 0 ft^3/d (cubic feet per day) for several wells during several months to 1,053 ft^3/d for well EX8A in August 1996 (ICF Kaiser Engineers, 1999). In 1998, during the development of the optimization model, two additional wells were installed. Wells EX10 and PM5 were drilled between wells EX8A and EX4A, and wells MW4-3A and EX5, respectively. These two wells are included in the optimal solution (fig. 6).

Model Calibration

ICF Kaiser Engineers (1999) used the proprietary parameter estimation software package PEST (Watermark Computing, 1997) to calibrate the model. Software such as PEST allows the user to vary the relative magnitude of one or more model parameters and employs a nonlinear estimation procedure that iteratively compares calculated heads to measured heads until, through a process of comparative reduction of the absolute value of the squared residual of heads, an acceptable solution is reached. Selected hydrologic parameters were allowed to change within the ranges discussed previously. The selected variables include the specific yield and horizontal hydraulic conductivity of layer 1, the storage capacity and transmissivity of layer 2, the vertical conductance between layers 1 and 2, and the conductance of the general-head boundary cells in layer 1. ICF Kaiser Engineers (1999) documents and describes the calibration process. Final analysis of residuals between measured and simulated heads at 37 wells for 12 months resulted in an absolute mean residual of 0.34 ft, with a 0.46-ft standard deviation. A water-budget analysis indicated that virtually all water enters the model as recharge. Almost half (48.3 percent) of the water leaves the model domain at the Gunpowder River boundary. About 38.5 percent leaves through Watson Creek and the surrounding wetlands. About 10.7 percent of the water leaves through the constant-head boundaries, and about 0.6 percent leaves through the drain. Only 1.8 percent of the water leaving the model domain is removed by pumping (ICF Kaiser Engineers, 1999). Additional refinement of the calibrated flow model by ICF Kaiser Engineers (1999) resulted in a 10-percent increase in recharge, and decreases in the hydraulic conductivities of the water-table aquifer and general-head boundary.

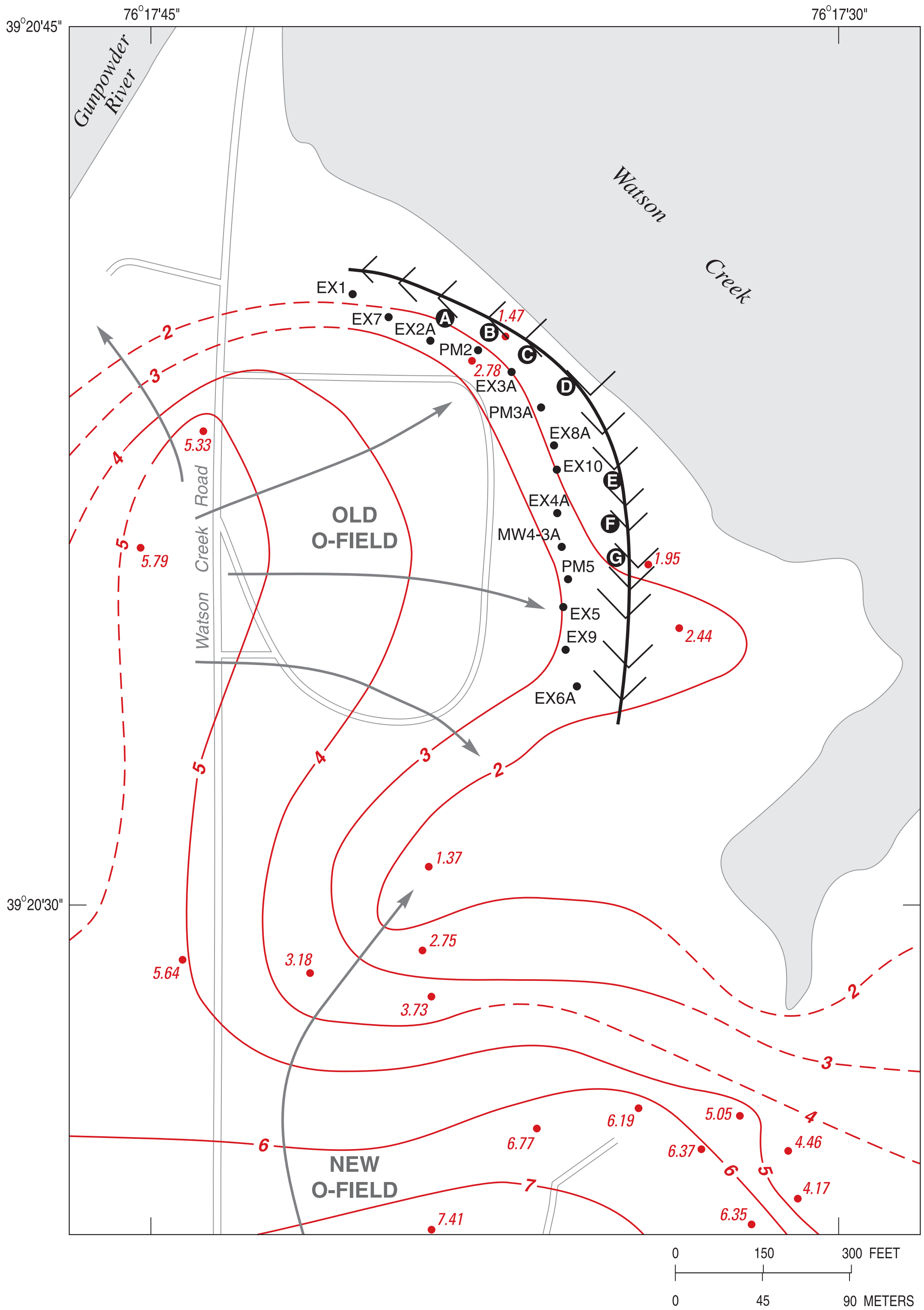
Optimization of the Model

In this report, optimization of the model represents the most efficient pumping strategy developed from the group of all possible pumping strategies that can be applied within the operational constraints of the remediation system. The strategies defining the extreme solutions are (1) do not operate any pumps, and (2) operate all pumps at maximum capacity all of the time. Neither of these strategies can meet the constraints that apply to the problem considered, but both, and all possible combinations of pump operation and pumping rates were considered in selecting the optimal solution using linear programming techniques. In this section, a description of the objectives and constraints placed on the modeled system will be discussed. The results will be presented as the minimum water volume that must be extracted from the shallow ground-water system to prevent ground-water flow downgradient from the well field. Verification will be performed using MODPATH (Pollock, 1994). For this report, the ICF Kaiser Engineers (1999) ground-water-flow simulation model was used in conjunction with MODMAN (Greenwald, 1998) and LINDO (HyperLINDO/PC, 1998) to identify the optimal pumping strategy to meet the ground-water management goals of the U.S. Army for APG’s Old O-Field area.

Approach

The configuration of the extraction wells and the direction of the natural flow gradient in the water-table aquifer are shown in figure 6. The primary operational objective is to prevent contaminated ground water from Old O-Field from reaching Watson Creek by pumping the wells in a way that creates a hydrologic flow boundary along a curved envelope related to the well configuration (fig. 6). Locating this capture curve east of, and close to, the extraction wells will allow establishment of a flow boundary that will prevent the flow of contaminated ground water from reaching the creek, while drawing little or no water from Watson Creek.

Applications of linear programming to aid in the design of ground-water remediation systems have been extensively documented. Gorelick and others (1984), Ahlfeld and others (1988), Gailey and Gorelick (1993), and Zheng and Wang (1999) provide case histories of contamination and potential remediation schemes. An optimal pumping strategy for the remediation system being operated at Old O-Field can be identified by developing and solving a linear program representing the objective and constraints that define and limit this strategy. The program is developed by first stating the objective and constraints, and then converting the statements into a set of mathematical expressions. The linear program can then be solved using the simplex method (Bradley and others, 1977), which proceeds from one feasible pumping strategy to another, improving the solution at each step with respect to the stated objective, and stopping when no further improvement to the solution is possible. The application of this method requires that each



EXPLANATION

GRAD (I) GRAD (II) — CAPTURE-CURVE BOUNDARY AND ABSOLUTE-GRADIENT CONTROL PAIRS

F — BINDING ABSOLUTE-HEAD-GRADIENT CONSTRAINT

EX9 — EXTRACTION WELL AND IDENTIFIER

5 — POTENTIOMETRIC-SURFACE CONTOUR (Shows altitude of the water table. Dashed where approximately located. Contour interval is 1 foot. Datum is sea level.)

2.44 — WELL LOCATION (Used to determine altitude of the potentiometric surface. Number is altitude, in feet above sea level.)

→ GENERAL DIRECTION OF GROUND-WATER FLOW

Figure 6. Location of extraction wells, capture-curve boundary, and potentiometric-surface contours of the water-table aquifer at Old O-Field, Aberdeen Proving Ground, Maryland (modified from Banks and others, 1995, and ICF Kaiser Engineers, 1999).

mathematical expression in the program be in linear form so that the principle of linear superposition to water-table drawdowns may be applied in response to pumping in the study area.

In a ground-water-flow system, the principle of linear superposition states that multiplication of a well rate by a factor increases drawdown induced by that well by the same factor at all points within the zone of influence of that well. Similarly, drawdown at a point induced by more than one well is equal to the sum of drawdowns induced by each individual well (Greenwald, 1998). Given the initial head field and the head-field response to a known pumping rate at each well, this principle can be used to predict ground-water heads and flow in the study area as a result of any pumping strategy. Some hydrologic systems, including water-table aquifers, respond to stress in a nonlinear manner. The nonlinearities of the ground-water-flow system response to well pumping at Old O-Field do not have a significant effect on the solution to the linear program because drawdown in the water-table aquifer is small (less than 1 ft) relative to the thickness of the aquifer (13 to 23 ft). Similarly, the drains in the water-table aquifer do not significantly affect the solution as they account for only about 0.6 percent of the total water outflow. Therefore, it is valid to formulate the optimization problem as a linear program.

Model Objective

The primary objective of the U.S. Army is to minimize costs for the operation of the remediation system at Old O-Field. Because there is a direct relation between pumpage and remediation cost, pumpage can be considered a surrogate for cost. And because pumpage is a variable that can be controlled in the ground-water-flow simulation, it can be manipulated to solve the linear program. Therefore, the objective of the optimization model is to minimize the total annual pumpage being performed by the remediation system at Old O-Field.

Operational Constraints

The operational constraints on the remediation system are as follows:

(1) do not allow contaminated water to flow from Old O-Field into Watson Creek,

(2) do not allow any of the 14 wells to inject water into the water-table aquifer at any time,

(3) do not allow the combined pumping rate of all 14 extraction wells to exceed 32 gal/min (gallons per minute) or 6,160 ft^3/d, the maximum capacity of the treatment facility,

(4) do not require any of the 14 pumps to operate at a rate that exceeds its individual capacity of about 7.7 gal/min (1,500 ft^3/d),

(5) do not allow any of the 14 pumps to operate at a rate of less than 0.4 gal/min (77 ft^3/d), the minimum rate at which an Old O-Field pump can function, and

(6) do not allow the water level in any of the 14 wells to fall below the midpoint of the screened well interval.

Constraints 2, 3, and 6 were not included in the problem formulation. Constraint 2 was not binding (and thus not needed) as long as constraint 5 was applied. In order to reduce the numerical complexity of the program, constraints 3 and 6 were not included in the problem formulation because it was considered unlikely that they would be binding on the solution based on the operational history of the remediation system. The optimal pumping strategy that was subsequently identified indicates that these assumptions were correct.

To ensure that no well would be artificially pumped unnecessarily, a formulation allowing a 0.0 gal/min minimum pumping rate was solved. This formulation determined that one well, EX8A, would not contribute to the solution of the final problem formulation. On the basis of this information, the remaining 13 wells were used in the final formulation. Constraints 1, 4, and 5 were applied to the optimization formulation.

Mathematical Formulation

The management objective and constraints 1, 4, and 5 must be defined in terms that relate to the pumpage rates of each well in the remediation system and their effect on the water-table altitudes in the vicinity of Old O-Field in order to allow the linear program to be solved. If the problem has a feasible solution, all of the constraints can be met by controlling the response of the water-table altitudes to the location and amount of pumping conducted over time. The objective and constraints can be written as follows:

$$\text{Minimize Total Cost} = \text{Minimize } \Sigma_i \Sigma_j Q_{ij} ,$$

subject to:

Constraint 4	$Q_{ij} <= 1{,}500$;
Constraint 5	$Q_{ij} >= 77$,
	$G_{ik} >= X$, and
	$G_{ik} <= Y$;
Constraint 1	$RG_h >= (G_{ik})/(G_{in})$;

where

Q_{ij} = pumping rate at managed well location i during stress period j, in ft^3/d,

G_{ik} = head gradient between control location i and control location k, dimensionless,

X = minimum head-gradient limit, dimensionless,

Y = maximum head-gradient limit, dimensionless,

RG_h = relative gradient coefficient for gradient pair h, dimensionless,

G_{in} = head gradient between control location i and control location n, orthogonal to G_{ik} , dimensionless, and

$(G_{ik})/(G_{in})$ = tangent of the angle limiting flow direction at gradient pair h on the capture-curve boundary.

To prevent contaminated ground water from reaching Watson Creek, a boundary must be created so that hydraulic heads outside the boundary are greater than or equal to those inside the boundary. The placement of this capture-curve boundary is somewhat arbitrary, but it must be downgradient of the well field and upgradient of Watson Creek (fig. 6). Contaminated ground-water flow is controlled by defining hydraulic head and computing gradients at 15 gradient control pairs oriented 90 degrees apart that share the same initial location along the capture-curve boundary. Gradient controls placed on the convex side of the capture envelope (GRAD (II) in fig. 6) are constrained to have a maximum gradient of plus infinity and a minimum gradient of minus infinity. Gradient controls located on the concave side of the capture envelope (GRAD (I) in fig. 6) are constrained to have a maximum gradient of plus infinity and a minimum gradient of 0.00001. A non-zero minimum number was used so as not to force unnecessary pumpage or to cause a competition for water with a neighboring well. Flow directions are limited according to the resultant of the two gradients, and thus the ratio of the two gradients can be related to the optimal flow direction assuming there is no anisotropy and heterogeneity between the control points. In the area near Old O-Field, the effects of anisotropic flow are assumed to be negligible.

For the stated problem, ground-water flow in the water-table aquifer cannot cross the capture envelope. In this formulation, G_{ik} and RG_h are related to Q_{ij} in the following manner:

$$D \bullet G_{ik} + \Sigma(R_{im} - R_{km})Q_m = (U_i - U_k), \text{ and}$$

$$RG_h >= (G_{ik})/(G_{in}),$$

where

D	=	distance between control locations in ft,
R_{im} , R_{km}	=	drawdown response at control locations i and k to a unit pumping rate at managed well location m, in ft/ft^3/d,
Q_m	=	pumping rate at managed well location m, in ft^3/d, and
U_i ,U_k	=	unmanaged heads at control locations i and k in ft.

The preceding formulation was successfully solved for 14 managed well locations, 229 control locations, 30 absolute head gradients, and 15 relative gradient pairs over 12 stress periods. The optimal feasible solution involves operating 13 of the 14 managed wells during all 12 stress periods.

Simulation Results

The optimal feasible solution to the linear program consists of pumping extraction wells at rates shown in table 1. The annual total pumped volume of 9.5 million gallons per year from the well field is also shown in table 1. This represents a 39-percent reduction from the average operational rate of 15.8 million gallons per year computed from 1997 pumping data (Joseph Ambrozwitz, Maryland Environmental Service, oral commun.,1999). In addition, well EX8A was excluded from the optimal solution since wells PM3A and EX10 were more efficient in capturing ground water near the center of the capture-curve boundary.

These results are dependent on the accuracy of the ground-water-flow model in simulating changes of the water-table elevation in response to pumping, and on the appropriateness of the objective and constraints used in the linear program. The ground-water-flow model was re-run using this set of optimal pumping rates to verify that none of the operational constraints on the remediation system were violated by implementing the optimal solution. Part of the verification process included the use of the particle-tracking program MODPATH (Pollock, 1994). Results from MODPATH were used to graphically demonstrate that flow from Old O-Field did not reach Watson Creek. The MODPATH simulation was run for 10 years to ensure that no operational constraints would be violated by long-term operation of the remediation system. The results of this step in the verification process are shown in figure 7. On the basis of the graphical representation of ground-water capture shown in figure 7, virtually all flow originating from the PIU in the water-table aquifer south of well EX1 and north of well EX6A is captured by the well network. Further, ground water contaminated by volatile organic compounds east of the extraction well network (as measured in May 1997) is contained.

The distribution of average operational pumping rates is related to the distribution of the horizontal hydraulic conductivity in the water-table aquifer near Old O-Field. If the effectiveness of capturing shallow ground water is based on creating uniform and intersecting cones of depression at each well in the extraction-well network, then more water must be pumped from wells screened in high rather than low zones of horizontal hydraulic conductivity to achieve uniform drawdowns. Vroblesky and others (1995) and Roy F. Weston (1993) performed numerous slug tests, step drawdown, and drawdown and recovery tests designed to determine hydraulic conductivity in the water-table aquifer. Values as high as 184 ft/d have been measured south and east of well EX8A—near the center of the well field. Specific capacity data for wells EX1 (the northernmost well) and EX6A (the southernmost well) indicate estimated horizontal hydraulic conductivity values of 3.7 ft/d and 8.8 ft/d, respectively. Similarly, on the basis of 1997 operational pumping rate data, the four wells near the center of the field (EX8A, EX10, MW4-3A, and PM5) pumped at rates that accounted for about 60 percent of the total water extracted

Table 1. *Optimal pumping rates by well and stress period*

[Stress period (SP) totals in gallons per month. Well totals in gallons per minute (gal/min). Grand total in gallons. Total volume in gallons per stress period based on 30 days per stress period and 1440 minutes per day]

	STRESS PERIOD TOTALS												
Well name	SP #1 March	SP #2 April	SP #3 May	SP #4 June	SP #5 July	SP #6 August	SP #7 September	SP #8 October	SP #9 November	SP #10 December	SP #11 January	SP #12 February	Average pumping rate (gal/min)
EX1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
EX7	2.3	2.6	2.6	1.9	2.1	1.6	0.7	1.3	2.0	2.9	3.4	3.1	2.2
EX2A	2.1	2.2	2.2	1.6	1.9	1.4	0.7	1.3	1.8	2.6	2.9	2.6	1.9
PM2	0.9	1.0	1.1	0.8	1.0	0.7	0.4	0.7	0.9	1.2	1.3	1.2	0.9
EX3A	1.0	1.2	1.3	1.0	1.2	0.9	0.5	0.8	1.0	1.4	1.5	1.4	1.1
PM3A	2.3	3.1	3.3	2.9	3.2	2.6	1.4	2.3	2.5	3.0	3.5	3.6	2.8
EX8A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EX10	3.3	3.2	3.1	1.7	2.4	1.3	1.4	1.6	3.1	4.6	4.9	3.8	2.9
EX4A	1.6	1.6	1.6	1.0	1.2	0.8	0.5	0.8	1.5	2.2	2.3	1.9	1.4
MW4-3A	1.0	1.2	1.2	0.9	0.9	0.7	0.6	0.5	1.0	1.4	1.6	1.5	1.0
PM5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.6	0.5	0.4
EX5	0.6	0.7	0.7	0.6	0.6	0.5	0.4	0.4	0.6	0.8	0.9	0.9	0.6
EX9	1.1	1.4	1.4	1.2	1.3	1.1	0.7	0.8	1.1	1.5	1.7	1.7	1.2
EX6A	1.4	1.6	1.6	1.4	1.3	1.1	0.7	0.9	1.2	1.7	2.0	1.9	1.4
TOTAL VOLUME IN GALLONS PER STRESS PERIOD [A]	**795,000**	**891,000**	**900,000**	**677,000**	**771,000**	**579,000**	**384,000**	**524,000**	**753,000**	**1,040,000**	**1,170,000**	**1,050,000**	**9,534,000**

[A] Totals different due to rounding.

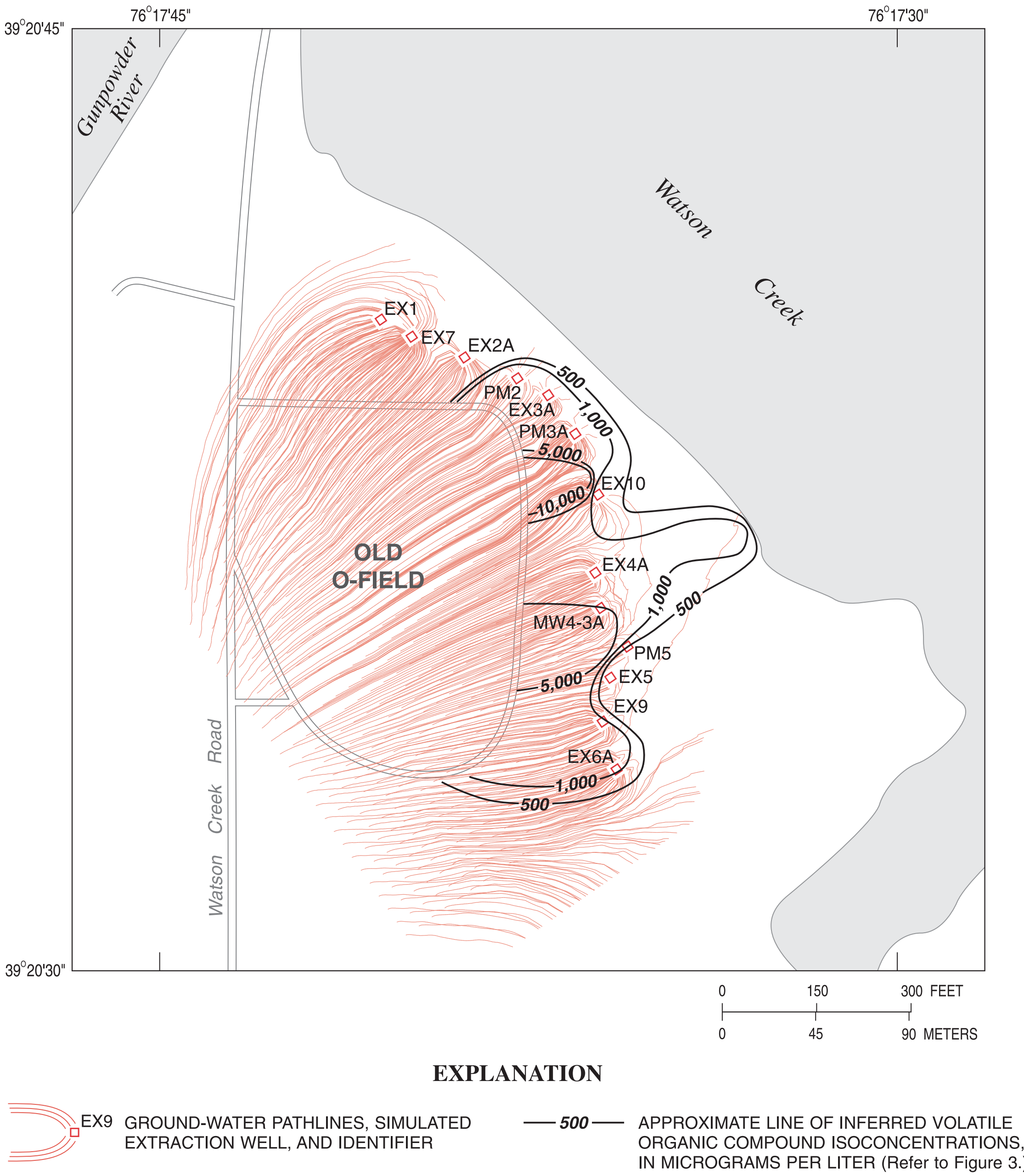


Figure 7. Graphical representation of ground-water capture based on the optimal feasible solution to the linear program.

(figure 8) (Joseph Ambrozwitz, Maryland Environmental Service, oral commun., 1999). This distribution of horizontal hydraulic conductivity values coupled with the current operation of the extraction-well network probably indicates that wells located in zones of high horizontal hydraulic conductivity are being pumped in excess of what is necessary to achieve ground-water capture.

In order to determine the significance of assuming a linear drawdown response to pumping in a water-table aquifer, the pumping rates obtained from the optimal solution to the linear program were applied to the ground-water-flow simulation. The resulting head field and its associated gradients were compared to the heads and gradients specified in the formulation of the constraints of the linear program.

MODMAN, the data-management software package, allows the user to define a minimum tolerance level for the absolute difference between simulated heads and specified optimal heads (Greenwald, 1998). Generally, a difference of less than 10 percent of the saturated thickness of the aquifer is acceptable in order to assume a linear response (Reilly and others, 1987). The absolute difference between

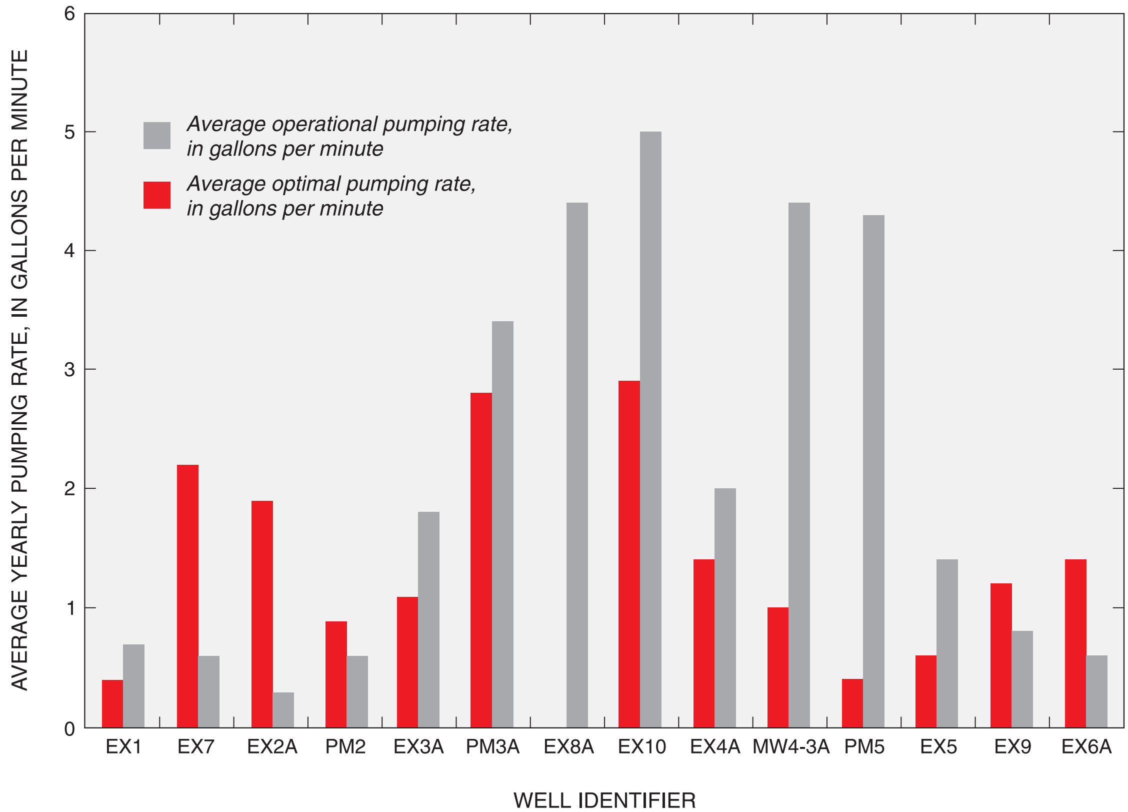


Figure 8. Average operational and average optimal pumping rates at the Old O-Field extraction-well network, Aberdeen Proving Ground, Maryland.

a simulated head and a specified optimal head for each well at any time step did not exceed 0.01 ft. This is significantly below the 1.3-ft value representing 10 percent of the minimum saturated thickness of the water-table aquifer.

The precision to which gradients can be calculated at Old O-Field is dependent on the precision of measured water levels and the distance between measuring points. Water levels at Old O-Field are typically measured with a precision of 0.01 ft. In the flow-simulation-model grid, the minimum distance between measuring points is 25 ft. Therefore, the minimum threshold for errors in gradients due to a nonlinear drawdown response can be obtained by doubling water-level measurement precision (0.01 ft) and dividing by the cell length (25 ft). As a result, a value of 0.0008 was used as a threshold for a nonlinear gradient response.

The pumping rates identified in the optimal solution were used to calculate the absolute differences between the gradients specified in the formulation of the linear program and the corresponding head field gradients resulting from the flow simulation. These differences, calculated for each stress period, were then compared to the minimum threshold value. Residuals with absolute values less than this threshold indicate that there is no measurable nonlinear response; values that exceed this threshold indicate that when the optimal pump rate is simulated, a nonlinear response in the aquifer may be produced. No residual had a value higher than 0.0008.

An analysis of dual prices (Schrage, 1997) was performed to determine the benefit of changing the constraints applied to the optimization problem. The dual price can be used as a measure of the sensitivity the optimization model has to changes in formulation. The dual price of a constraint is the amount by which pumping will be reduced if that constraint is relaxed. Conventions in LINDO state that a positive dual price means that decreasing the gradient will improve the final solution. A dual price of zero indicates that changing the gradient will have no effect on the final solution—the constraint is not binding. Constraints 4 and 5 were not binding and therefore had a dual price of 0. Constraint 1 was formulated so that each relative head gradient was evaluated for each stress period—as discussed previously, gradients at Old O-Field are resolved to 0.0008. The two absolute head gradients that make up each relative gradient pair had associated dual prices. The absolute head gradients labeled GRAD (II) in figure 6 were not binding and had a dual price of zero. Six of the absolute head gradients, labeled A, B, D, E, F, and G on figure 6, had positive dual prices for each of the 12 stress periods. Absolute head gradient C had positive dual prices for stress periods 2 through 12, and a 0 dual price for stress period 1. Thus, by relaxing any of these seven binding constraints, a net improvement in the optimal solution could be achieved. Because the maximum gradient that can be resolved at Old O-Field is 0.0008, however, reducing any of the binding absolute head gradients below that value may allow contaminated ground water to reach Watson Creek, thus failing to meet the operational objective of ground-water capture.

Summary and Conclusions

In 1998, the U.S. Army asked the U.S. Geological Survey to develop an optimal pumping strategy at the Old O-Field area at Aberdeen Proving Ground, Maryland, to prevent contaminated shallow ground water from reaching Watson Creek, and minimize the amount of ground water extracted, thereby reducing the operating costs of the remediation system. An optimization model was created from a calibrated transient ground-water-flow simulation of the O-Field area.

Linear optimization strategies that explore possible combinations of pump operation and pumping rates were used to select a solution that prevents contaminated ground water from entering Watson Creek, while minimizing pumpage at the pump-and-treat remediation system. This approach builds on and refines the conclusions of previous investigators who identified ground-water pumping as an effective strategy for controlling contaminant movement in shallow ground water.

The simulation-optimization model developed for the Old O-Field area provided an optimal solution in which 9.5 million gallons per year were pumped from the well field, a 39-percent reduction from the average operational rate of 15.8 million gallons per year computed from 1997 pump data. In addition, the optimal simulation showed that well EX8A was not needed to maintain ground-water capture along the capture-curve boundary. On the basis of a graphical representation of ground-water capture, virtually all flow originating from the permeable infiltration unit in the water-table aquifer south of well EX1 and north of well EX6A is captured by the well network.

The simulation-optimization approach provides an improved understanding of how the shallow ground-water system responds to stresses induced by pumping. The strategies evaluated do not include the possibility of injecting water to control shallow ground-water flow to Watson Creek. Further, the optimal solution reflects model parameter uncertainty only to the extent discussed in the documented flow model. These issues have a direct impact on the volume of water that must be pumped in order to maintain capture. Any further optimization would benefit from addressing both of these issues as well as the effect of pumping on the upper confined aquifer. As these issues are addressed, the simulation-optimization model will provide a more complete understanding of the flow system and a more accurate accounting of the amount of water needed to maintain capture.

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Addendum: Comments from the U.S. Army Garrison, Aberdeen Proving Ground, Environmental Conservation and Restoration Division, concerning U.S. Geological Survey Water-Resources Investigations Report 00-4283.

The text below are comments that the U.S. Army Garrison, Aberdeen Proving Ground (APG), requested be added to the back of the U.S. Geological Survey Water-Resources Investigations Report 00-4283 “Optimization of ground-water withdrawal at the Old O-Field area, Aberdeen Proving Ground, Maryland” by William S.L. Banks and Jonathan J.A. Dillow. The comments were written primarily by Grant A. Anderson of the U.S. Army Corps of Engineers, Baltimore District, Gerald Garcia of the U.S. Army Aberdeen Test Center and Cindy Powels of the U.S. Army Garrison, APG and reflect the opinions of APG.

During the course of this project it became apparent that the optimal pumping strategy described in this report could not be implemented. Specifically, there are wells whose suggested pumpage exceeds the well’s capacity. Also, the report suggests eliminating the pumpage from well EX8A. This well is one of the largest producers and lies in an area where containment is often challenged during periods of significant precipitation. Subsequent to the development of the MODFLOW model, geologic investigations identified the presence of a high-conductivity channel which runs across the well field in the area of wells EX8A and EX10. Although the flow model was calibrated and verified, it appears the hydraulic conductivity in parts of the model area was not simulated well enough for the purpose of optimizing pumping.

Grid refinement posed another challenge for optimization. Because the MODFLOW grid was coarse (25 feet in the area of the pumping wells), the flow model could not accurately calculate the cones of depression in close proximity to the pumping wells—a sensitive variable for optimization. In addition, the well locations in the MODFLOW model sometimes differed as much as 60 feet from the actual location of the pumping well. This difference occurs because MODFLOW cannot place more than one well per grid cell. For example, well EX10 is located about 60 feet south of well EX8A in MODFLOW model space. In reality, EX10 is located about 20 feet east of EX8A. These effects probably contributed to the nonrealistic optimization results.

Because optimization is based on superposition of conditions within the whole system, it is not feasible to simply “ignore” the part that doesn’t work and implement the rest of the optimal strategy. For this reason, the suggestions made in the optimization report were not implemented in toto. Instead, certain suggestions can be field-tested. For example, pumpage from well EX8A can be suspended for a short time (for example, 2 weeks) during differing seasons to assess the effect on well field containment. If containment can be maintained with lower pumpage, then some of the goals of the optimization can be realized.

Another solution would be to rediscretize and recalibrate the ground-water flow model based on the new information, and reoptimize the pumping strategy. For several reasons, this does not appear to be a cost-effective approach at this site. For example, well pumpage rates are always changing. Wells plug due to fouling, so they are constantly being rehabilitated or replaced. This result makes the application of constraints to the optimization difficult to estimate. In addition, operation of the well field is being converted to an automated system (Supervisory Control And Data Acquisition) that will automatically monitor performance of the well field and allow pumping rates to be changed in real time.

Because the optimization methods that were used are valid and could be a benefit to other sites with multi-well ground-water extraction systems, this report was released. Information gained during this project can benefit others who attempt to use optimization methods at other sites.

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