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REMEDIATION OF GROUNDWATER CONTAMINATION AT THE ROCKY MOUNTAIN ARSENAL: NUMERICAL AND GEOSTATISTICAL ANALYSIS

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ABSTRACT

Past activities at the Rocky Mountain Arsenal have resulted in contamination of the near surface shallow alluvial aquifer. Under orders to cease and desist off-site discharge of contaminated groundwater, the U.S. Army has constructed the north boundary barrier system (NBBS) to block critical migration pathways. This system involves arrays of pumping wells, recharge wells and trenches, and a bentonite slurry cut-off wall. Because of complex hydrogeologic conditions at the arsenal, this system has proven very difficult to manage. In response Colorado State University (CSU) and U.S. Army Corps of Engineers, have entered into cooperative research with the aims of evaluating the performance of the system and to investigate reconfiguration of the NBBS to improve operational flexibility and performance. In this study a very detailed model was developed to simulate the operation of the system using the CSU Finite Element Groundwater Modeling Package. To account for aquifer heterogeneities which can significantly affect the operational effectiveness of the system, geostatistical analysis were also performed. Kriging and Co-kriging were used to describe the spatial variability of several aquifer properties and the results incorporated in the numerical model. Several operational scenarios were simulated to asses system improvements and define optimal operational schemes that achieve a reverse gradient across the slurry wall. Scientific visualization techniques were implemented to illustrate modeling results. The experiences (difficulties and successes) learned in operating the north boundary barrier system at the Rocky mountain Arsenal should be valuable to others desiring to use similar barrier systems elsewhere.

INTRODUCTION

The Rocky Mountain Arsenal is located in Adams County, Colorado just nine miles northeast of Denver metropolitan area . It was established in 1942 for the production and storage of chemical and incendiary munitions. Since the mid-1940's to 1982 part of the arsenal was leased to private concerns, one of which was Shell Chemical Company, for the manufacture of various chemical compounds including pesticides. From 1943 to 1957 the wastes generated by government and private sources were discharged into unlined basins. These disposal practices resulted in groundwater contamination that extended from the arsenal to the South Platte River. In the early 1950's, farmers in the offpost vicinity of the arsenal complained of severe crop damage due to irrigation with waters pumped from the shallow alluvial aquifer.

In response to complaints, the Army constructed Basin F in 1956, an asphalt-lined impoundment of approximately 93 acres in size. At the time of its construction, Basin F represented the state-of-the-art in basin impoundment structures. In 1961 a 12,000 foot deep injection well was constructed for deep well disposal of the wastes. Deep well disposal ceased in the late 1960's after a series of small earthquakes in the Denver area were associated with disposal activities. In early 1975, Colorado Department of Health issued three administrative orders against the Army and Shell Chemical Company. The orders required that the Army and Shell cease unpermitted discharges of contaminated groundwater from the arsenal, develop source controls to intercept contaminated groundwater leaving the site, and implement a monitoring program.

Currently, there are no weapons produced or stored at this site and the production of pesticides ceased in 1982. The only official function of the arsenal is to plān and implement remedial activities for aquifer cleanup to comply with Federal and State environmental laws and regulations. An extensive system of groundwater monitoring has been implemented over the entire arsenal and in the offpost areas. This system will help to identify contamination sources and pathways of off-site migration of contaminated groundwater, as well as to better understand the complex hydrogeology of the site. Some remedial actions have been implemented to solve the immediate environmental problems. These include among others, the installation of groundwater barrier systems, closure of the deep injection well by pressure grouting in 1985 and closure of Basin F in 1988.

Three groundwater barrier systems have been installed at the boundaries of the arsenal which treat altogether approximately 1 billion gallons of water every year. The first of these systems was the North Boundary Barrier System (NBBS) which was constructed in the period of 1978-81. Subsequently Shell completed the Irondale Barrier System in 1981 and the U.S. Army constructed the Northwest Boundary Barrier System in 1984. These barrier systems were pioneering efforts in the use of groundwater barrier systems for the control of contaminant migration. Previous design and operational experience for such systems was unavailable. Because of the complex hydrogeologic conditions at the arsenal, these barrier systems have proved very difficult to manage and operate. Colorado State University and the U.S. Army Corps of Engineers have cooperated in developing several operational management models of these systems. This paper describes the groundwater model for the North Boundary Barrier System along with a geostatistical site characterization in the vicinity of the system.

THE STUDY AREA

The particular study area where the NBBS is located constitutes an alluvial water table aquifer that ranges from zero to about 30 feet in thickness, overlying a relative impervious bedrock shale of the Denver Formation. Bedrock highs create unsaturated alluvial conditions in certain zones that restrict groundwater flow in the north-northwest direction. This aquifer is directly influenced by an ephemeral stream (First Creek), man-made canals that transverse the area (Burlington Ditch and O'Brian Canal), carved paleochannels of the bedrock formation, as well as water impoundments. The aquifer is divided by the slurry soil-bentonite barrier of the system along the north boundary of the arsenal.

The alluvial aquifer is mainly composed of unconsolidated fine-grained eolian sand, silt and clay deposits which are underlaid by coarser sands and gravel. Typical hydraulic conductivities of sands and gravel at this site range from 118 to 970 ft/day (ESE,1988). Higher hydraulic conductivities may be found along paleochannels of the bedrock formation which occur both in the onpost and offpost areas. In the onpost area, a paleochannel trending in the northeast direction, encroaches in the NBBS vicinity upon the upgradient portion of an offpost paleochannel which trends north (ESE,1988). Another paleochannel extends along First Creek in the northwest direction. These paleochannels also act as preferential pathways for contaminant plumes.

THE NORTH BOUNDARY SYSTEM

A pilot boundary system was installed at the north boundary in 1978. This pilot system consisted of a 1,500 foot long bentonite slurry wall, 6 dewatering wells and 12 recharge wells. In 1981 the barrier system was extended to a total length of 6,470 feet *(Figure 1)*. This original barrier system consisted of 35 dewatering wells, 38 recharge wells, separated by a bentonite slurry wall. In 1989 and 1990 the barrier system was modified to its current configuration which included the addition of 15 recharge trenches. Contaminated groundwater is pumped from the upgradient side of the slurry wall, treated by granular activated carbon adsorption, and the treated water is recharged downgradient of the wall. The dewatering wells are divided into three collection manifolds (A, B and C). Flow from each manifold has historically been treated by separate adsorber units. Manifold A (wells 330-335, and 301-306) intercepts a plume of Diisopropylmethylphosphonate (DIMP) flowing from the Basin F area. Manifold B (wells 307-318) intercepts Dibromochloropropane (DBCP), chlorinated pesticides, Aldrin, Dieldrin, and Endrin, and several organosulfur compounds. Inorganic contaminants include chloride and fluoride. Manifold C (wells 319-329) intercepts groundwater of relatively low concentration. In 1990, the treatment process was reconfigured to treat the combined inflow from the separate manifolds as a single inflow stream.

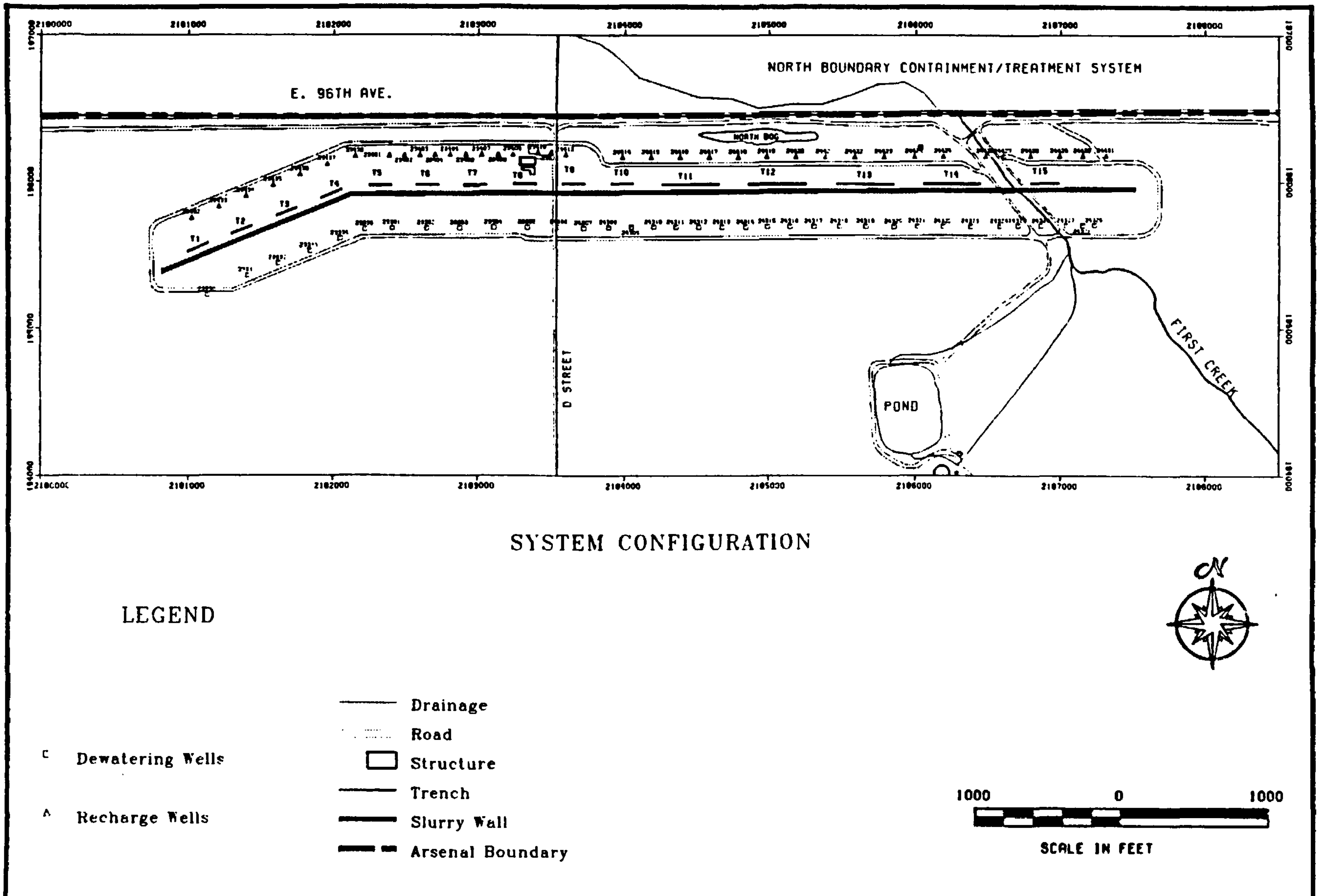

Figure 1. North Boundary Barrier System Layout

OPERATIONAL CONCERNS

Since the bentonite slurry wall extends across the entire shallow alluvial aquifer and it is keyed at its ends into relatively impermeable bedrock highs, the barrier system, regardless of how it is operated, should intercept all of the contaminated groundwater in this aquifer reaching the north boundary. However, concerns have been expressed about the integrity of the bentonite slurry wall and about the potential underflow past the barrier system of contaminated groundwater in the underlying Denver Formation. The prevailing thought is that this potential underflow is best controlled by maintaining a reverse gradient (a gradient inward towards the arsenal) across the bentonite slurry wall. Management of the contaminant plumes approaching the barrier system is also desired. Questions about the operation of the barrier system concern: 1) what is the total barrier system flow rate, 2) what is the distribution of manifold flow rates, 3) what is the best distribution of the treated recharge water, 4) in case of system failure, time and location of groundwater overtopping of the bentonite slurry wall, 5) feasibility of achieving a gradient reversal and 6) system modifications to improve barrier operation.

MODELING PROCEDURE

A finite element groundwater model (CSU/GWFLOW) was applied to the North Boundary Barrier System to study these concerns. For the 2.4 square miles study area, a very detailed mesh was used for the model grid which consisted of 13,156 nodes and 25,524 elements (*Figure 2*). The resolution of this mesh in the immediate vicinity of the NBBS was in the order of about 25 ft between adjacent nodes. Each of the 35 dewatering wells and the 38 recharge wells were represented in the mesh by separate nodal points so as to allow specification of individual well pumping rates. Each of the 15 recharge trenches were represented by 3 to 6 nodes in the model grid. Similarly, 409 monitoring wells at the arsenal in the vicinity of the barrier system were represented in the mesh by separate nodal points so as to allow direct observation of model results with field observations. In the mesh the bentonite slurry wall was simulated as an interior no-flow boundary.

Three different boundary conditions were assigned to the model. No-flow boundaries were assigned at the limits of unsaturated alluvial areas and in areas where groundwater flow lines are parallel to the boundaries. Specified flux and/or constant head boundaries were also used in the model, and their values adjusted for different calibration time periods according to the observed data.

MODEL INPUT DATA

Input data requirements for the model consisted of alluvial aquifer characteristics such as hydraulic conductivity, saturated thickness, transmissivity, and specific yield. To account for aquifer heterogeneities in the vicinity of the NBBS, a geostatistical analysis was performed. As part of this modeling effort, Kriging and Co-Kriging techniques were applied for selected aquifer properties such as hydraulic conductivity to estimate model

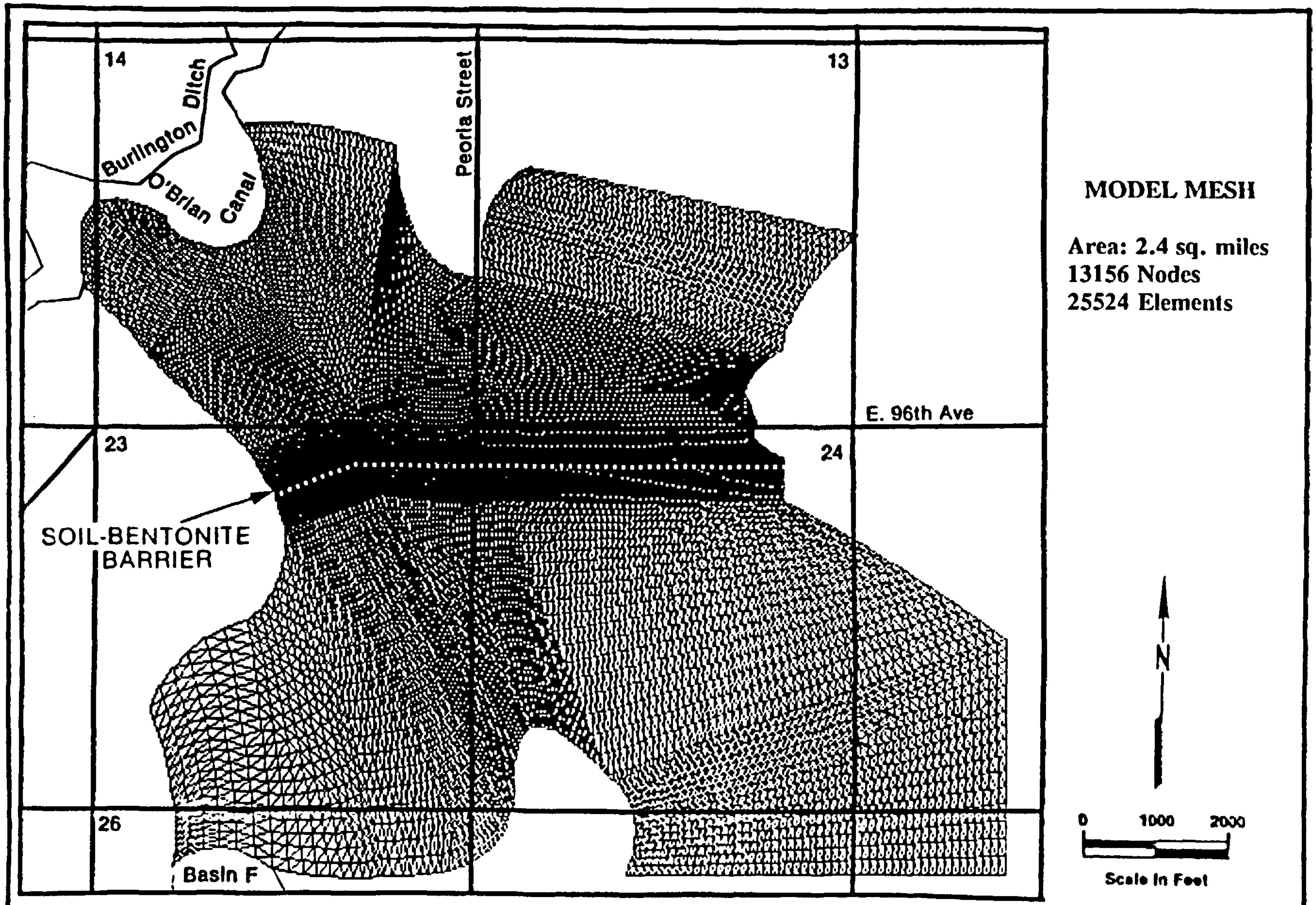

Figure 2. The Finite Element Mesh

input data. These geostatistical techniques also account for the uncertainty in the estimated values of aquifer parameters and the precision of the results. Details of the theory of Kriging and Co-Kriging are thoroughly documented in the works of Marsily (1986) and Myers (1982), respectively. Operational flow rates from pumping and recharge wells, recharge trenches, manifolds and system adsorbers were also used as a model input data. Average rates were used for different time periods.

Different discharge and recharge sources and stresses to the system were thoroughly evaluated in the study area and incorporated in the model. Recharge from precipitation was taken into account in the entire model area. The offpost impoundment (Mul reservoir) located along First Creek and the north bog were represented as constant head which resulted in a net recharge to the aquifer. Later the bog was discontinued as a source of water as the recharge trenches were installed. Upgradient of the NBBS, First Creek gains water from the aquifer (net discharge) in a small wetland area.

GEOSTATISTICAL SITE CHARACTERIZATION

Description of the spatial variability of aquifer properties, regarded as regionalized variables, is being approached by geostatistics (Marsily,1986). Kriging is a geostatistical technique that estimates the best, linear, unbiased values of regionalized variables at unsampled locations based on the available measurements of these variables. Co-kriging is an extension of kriging to situations where two or more variables are correlated in such a manner that the spatial variability of one of the variables improves the estimation process. This is the case of the under-sampled variable such as transmissivity data from pumping test results and the better sampled saturated thickness. Before these techniques are applied a structural analysis of the data must be conducted. That includes the determination of frequency distribution functions, experimental semivariograms and cross-semivariograms as well as model fitting and cross validation.

At the arsenal a total of 18 hydraulic conductivity (K) values derived from pumping tests performed in the vicinity of the NBBS were available for analysis. Seventy one wells were used to estimate the spatial variability of aquifer transmissivity and 273 wells for saturated thickness.

As recommended by Delhomme (1978) a natural log (Ln) transformation was performed for hydraulic conductivity (K), transmissivity (T), and saturated thickness (b) values and the resulting distributions checked for normality. From the histograms and statistical analysis the Ln(K) and Ln (T) approximated a normal distribution. The cumulative distribution function for saturated thickness also plotted as a straight line on normal probability paper indicated normality conditions.

To use Kriging an experimental semivariogram which describes the spatial correlation structure of the regionalized variables is required. The semivariogram depends on the distance separating two known data points. The procedure to obtain an experimental semivariogram is given in Istok et al., (1988). To use co-kriging the calculation of a cross-semivariogram is required for two or more variables of interest.

The experimental semivariograms and cross-semivariograms were fitted with different mathematical models based on a least square minimization procedure. These fitted models must be positive definite to ensure positive estimation variances (Journel and Huibregts, 1978). The experimental semivariogram for Ln (K) was best fitted with an exponential model with no nugget-effect, a sill of 0.55 and a range of 9,549 feet. The experimental semivariogram of Ln (T) was best fitted by a spherical model with a nugget of 0.023, sill of 0.152 and a range of 3,860 ft. For the Ln (b), a spherical model with nugget, sill, and range of 0.053, 0.119, and 10,700 feet, respectively was obtained. The cross-semivariogram between Ln (T) and Ln (b) was also calculated. A spherical model was fitted to this experimental cross-semivariogram with the following parameters: nugget of 0.04, sill of 0.13 and range of 8,000 feet. These models are shown in *Figure 3*.

All of the fitted models were cross-validated by the jackknifing procedure (Vauclin et al., 1983). This method is used to evaluate whether the fitted models are appropriate for the experimental data. It estimates the value of the variable of interest at every known sampling location, but excluding the known measured value from the estimation process. A comparison between the actual and estimated value was performed. The mean kriging (or co-kriging) error along with the mean squared (variance) error were calculated to measure the goodness of the model fit. To be unbiased the former must be close to zero and the latter should be close enough to one. The reduced mean for Ln (K) was 0.0381 and the reduced variance 0.9937. The mean kriging error and mean squared error for Ln (T) and Ln (b) were (-0.0515,0.9949) and (-0.036,1.002), respectively. The overall reduced mean and variance for the set of semivariograms used in the co-kriging calculations were -0.0446 and 1.004, respectively. Based on these results, the fitted models were considered appropriate for this study.

KRIGING AND CO-KRIGING ESTIMATION

Based on the spatial structure of the aquifer regionalized variables, Kriging and Co-kriging estimates and variances of hydraulic conductivity, transmissivity, and saturated thickness were computed for a 2 x 2 miles grid that represents the study area. The estimated data was then transposed to each node of the finite element mesh for model data input.

To aid in the calibration process, Kriged estimates and variance maps were made for hydraulic conductivity transmissivity and saturated thickness. An excellent reproduction of mapped unsaturated areas was achieved with the kriging interpolator. Maps of 95 percent confidence level were also made for the estimated values. These maps were considered to appropriately describe the spatial variability of these parameters except for transmissivity. Kriged estimates of transmissivity showed some discontinuities in areas where the flow is known to be continuous due to a lack of enough data points used in the estimation process. As expected high estimation errors were found in these discontinuous areas.

To enhance the understanding of the spatial distribution of transmissivity, saturated thickness was used as an auxiliary variable in co-kriging. The accuracy of the

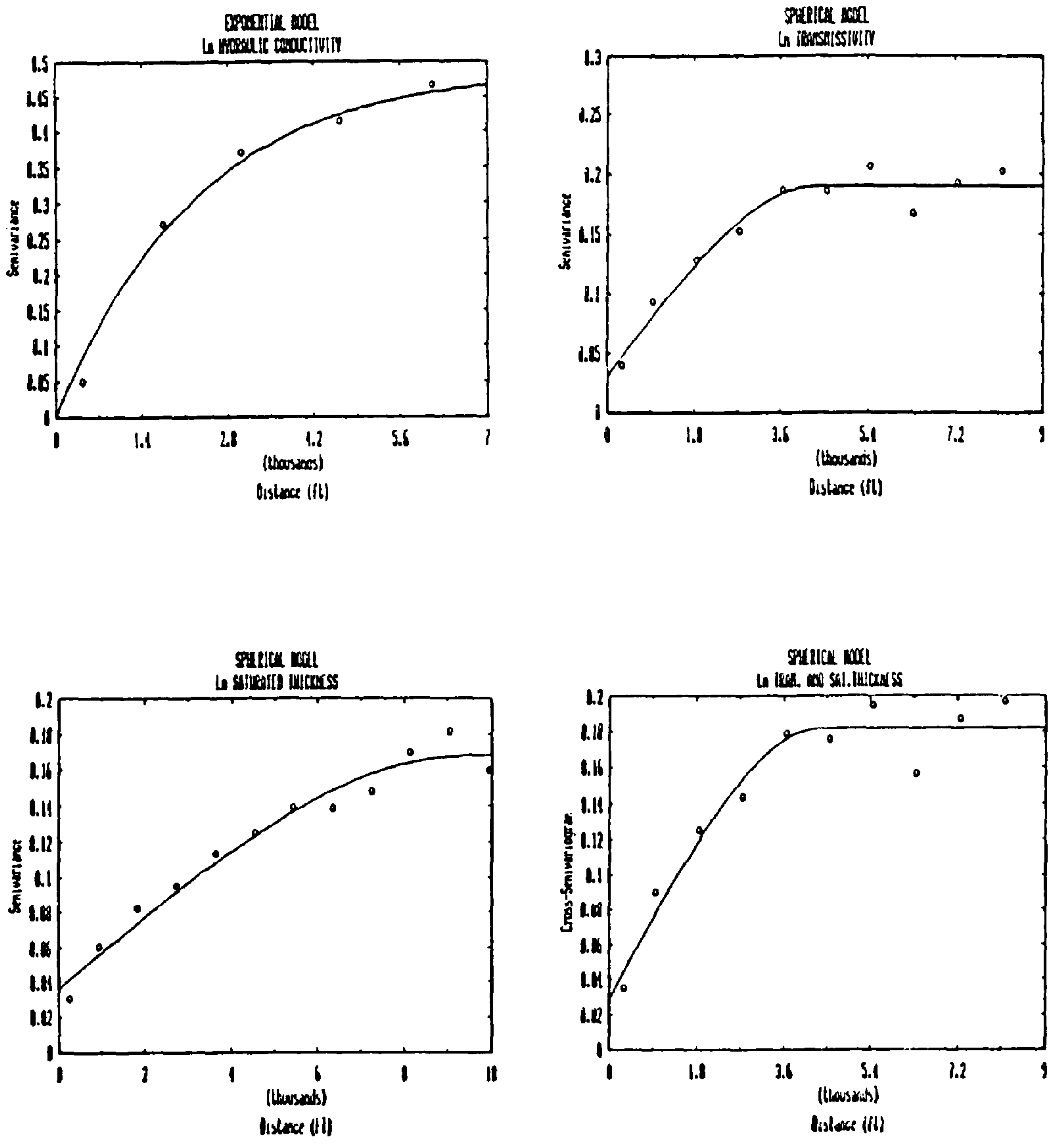

Figure 3. Semivariogram and cross-semivariogram models of aquifer parameters

estimation of transmissivity was thought to be greatly improved and the estimation of variances significantly reduced due to the high correlation that exist between transmissivity and saturated thickness of the aquifer. These transmissivity values were used as initial estimates for model calibration.

Based on these geostatistical results, the best unbiased estimates of aquifer parameters were used as data input in the model. This data along with the average operational flow rates of the system at different time periods were used for model calibration.

MODEL CALIBRATION

A steady-state calibration of the model was initially performed to the pre-barrier conditions (Feb-March 1978). The steady state model calibration was then further refined by a series of transient calibrations. This calibration consisted of simulating actual barrier system operation beginning with the pilot system (July 78 to Nov 81) to full barrier system operation (Nov 1981 to January 1991). Thirteen separate transient calibrations were performed at selected time periods. The model results were compared with field observations at the monitoring wells and average manifold flow rates. One of the difficulties with the transient calibration is that poor records were often kept about barrier system operation. Metering problems for the distribution of total barrier flow rate by individual wells was frequently encountered. The model calibration was considered to be excellent with an average model calibration error of less than 0.5 foot.

Model calibration also accounted for all changes in the NBBS and aquifer stresses that occur during the period of calibration. For example, the closure of Basin F, the use of the north bog for recharge, the addition of recharge trenches, etc. The ability to recreate the history of NBBS operation and aquifer response was somewhat limited due to poor operational records during some time periods. Despite this limitations, favorable results were obtained during the calibration procedure. The latest model calibration period was from spring, 1990 to February, 1991.

Figure 4 shows the calibrated Groundwater Mass Balance for February 1991, which agrees with the observed flow rates and the system current operation. The model estimated 218 gpm as the total flow currently approaching the NBBS. This mass balance also shows a decrease of inflow from Basin F area of about 45 gpm compared to the inflow occurred in spring 1987. This decrease has been mainly attributed to the closure of Basin F. In addition, a net recharge of 54 gpm from the Mul reservoir was calculated from the model which indicates an approximate leakage rate of 0.56 inches/day. The aquifer discharges 55 gpm to First Creek and receives a total of 108 gpm of distributed recharge from precipitation. Inflows and outflows at the boundary limits are also shown in *Figure 4*.

Transient calibration runs were performed on the supercomputer CRAY Y-MP. An average CPU time for a transient run (20 Pumping Periods) was 20 minutes on the CRAY Y-MP. Steady state calibrations and simulations were performed on a Silicon

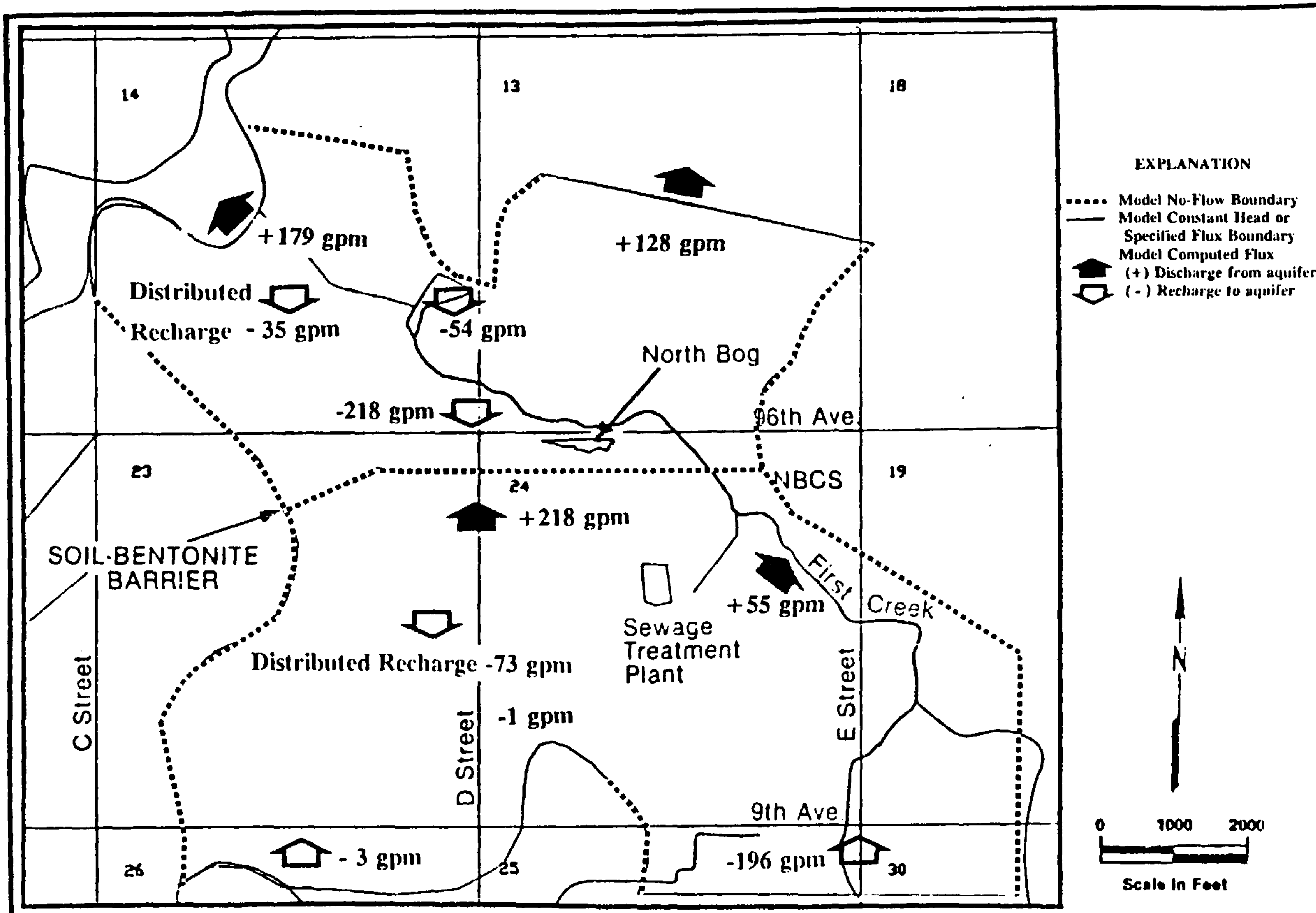

Figure 4. Model computed Water Mass Balance

Graphics Personal IRIS (SGI,4D35TG) computer, with 16 MB virtual memory. An average CPU time for steady state simulation was 3.5 minutes on the SGI workstation. Also most transient calibrations for the period of May,1987 to Feb.,1991 (3 pumping periods) were run on the SGI for 3.5 hours of CPU time.

MODELING SIMULATIONS

Utilizing the calibrated model, various operational, breakdown and barrier reconfiguration simulations were performed. One of the major questions asked by arsenal personnel was whether a gradient reversal could be achieved for the barrier system without using the recharge trenches (ie. using only the recharge wells). The line of recharge wells are located 250 feet downgradient of the slurry wall and the line of dewatering wells are located 250 upgradient of the slurry wall. The rate of groundwater flow to the North Boundary Barrier System has varied with time but in recent years has been about 220 to 230 gpm. Under this natural interception rate the average head difference between the two lines of wells is 3.5 feet over Manifold A, and 4 feet over Manifolds B and C. Model results indicated that the best that could be achieved by the barrier system in the long term was the natural interception conditions. A gradient reversal over the entire length of the barrier system was not possible without increasing the amount of recharged water relative to the total dewatering pumping rate (in the long term it is impossible to pump more than the natural interception rate but it is possible to increase the amount of recharge water). One possibility is to retain First Creek flows for recharge downgradient of the barrier. At present time this option has not been pursued by the Army.

The recharge capacity of the injection wells has considerably decreased since the wells were first installed. This loss of recharge capacity is thought to be due to deposition of carbon fines from the adsorber units and from microbial growth in the wells. These problems are currently being studied in a separate project between Colorado State University and the U.S. Army Corp of Engineers. Because of this loss of recharge capacity of the wells, much of the treated recharge water was for a period of time disposed of in a bog at the east end of the barrier system (this occurred before the installation of the trenches). Additionally Manifold C was over pumped relative to Manifolds A and B because of concerns about overtopping of the slurry wall in that section if the barrier system were to breakdown for an extended period of time. As a result the actual head differential across the slurry wall for 1987 operating conditions was considerably different than that for natural interception rates. For this operating condition the head differential across the slurry wall in the Manifold A section was about 7 feet, in the Manifold B section was about 2.5 feet and in the Manifold C section was about zero.

Since Manifolds A and B intercept contaminated groundwater of high concentrations and Manifold C intercepts low concentration groundwater, it is desirable to maintain a reverse gradient over at least Manifolds A and B. In order to accomplish this, the model was used to simulate and evaluate various system reconfigurations such as installation of additional dewatering and recharge wells, trenches, recharge ponds, etc.

at different locations and operating conditions. Results of these simulations predicted that a series of recharge trenches located 45 feet downgradient from the slurry wall was needed to achieve reverse gradients. Treated water previously discharged to the bog near the east end of the barrier system would be then discharged through trenches located in the western half of the barrier system to cause a gradient reversal in this region. Model simulations indicated that under this operating condition a gradient reversal was to be achieved over the entire section for Manifold A and about half of the section for Manifold B. In the section of the barrier system with a calculated gradient reversal the average head differential was about -2 feet and over the remainder of the barrier system it was about 5 feet.

The simulated recharge trenches were implemented by the Army in 1989 and 1990. They have performed excellently, achieving the desired gradient reversal over the critical sections of the North Boundary Barrier System. In actuality the Army has thus far been able to maintain a gradient reversal over a somewhat longer length of the barrier system than that indicated by model results. This has been achieved by slightly overpumping the dewatering wells. Current withdrawal rates for the barrier system are about 250 gpm. The natural interception rate of groundwater flow to the barrier system has dropped slightly over the past several years and is now estimated to be less than 220 gpm. Consequently, parts of the alluvial aquifer on the upgradient side of the barrier system have been desaturated due to overpumping.

Several other NBBS operational simulations were also performed. First, the system was overpumped by up to 100 gpm above the equilibrium barrier flow of 220 gpm. Second, different simulations were performed to determine the aquifer response and effects of permeability reduction by potential clogging of the pores within recharge trenches by carbon fines. This was accomplished by decreasing transmissivity values by up to 75 percent across the line of nodes representing the trenches. Third, simulations were performed to obtain an estimate of the maximum recharge capacity of the trenches and their predicted reverse gradients. This estimate was determined by setting constant heads values (at the nodes corresponding to the trenches) to 4 ft below trench ground surface elevations which is the maximum head that can be physically accommodated in each trench. A total recharge of 400 gpm was predicted in this simulation with a calculated average head differential of about -3.5 feet over the length of manifold A and half of manifold B. This simulation was carried out under current dewatering flow rates.

A particle tracking capability was incorporated to the finite element model CSU/GWFLOW using the area coordinate system as a new interpolation scheme of particle velocities. The area coordinate system interpolation scheme has the same properties as those for the local shape functions of the triangular elements used in the finite element method (Warner, 1981). The particle tracker in the model allowed the delineation of particle pathlines and identification of particle travel times. This capability was extremely useful for the evaluation of various operational alternatives of the NBBS by particle capture. *Figure 5* shows a particle velocity contour map for January 1991, and the display of particle pathlines after five years of system operation under current

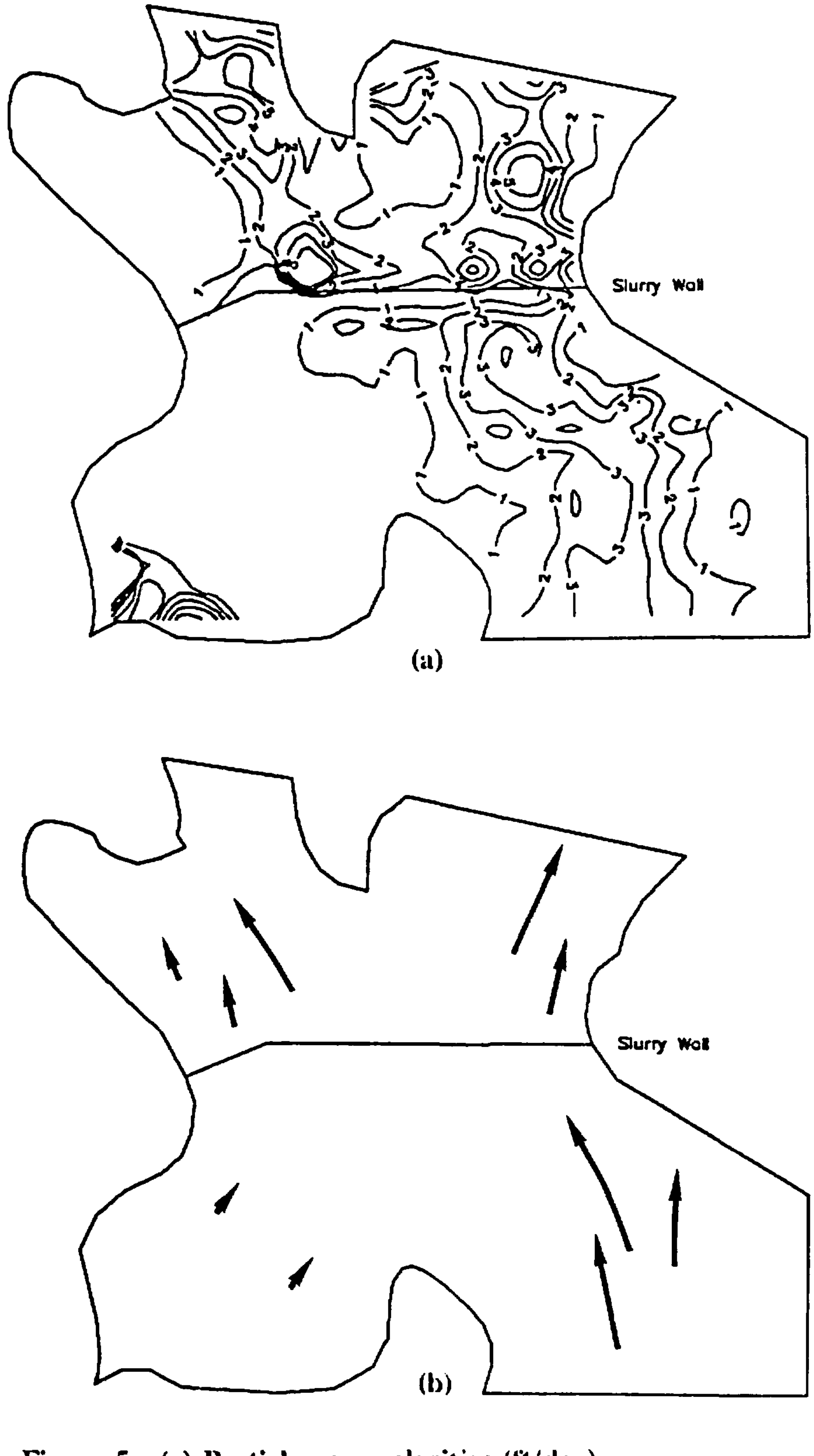

Figure 5. (a) Particle pore velocities (ft/day)
(b) Particle pathways after 5 years travel time

conditions. Notice the differences of the distance traveled by some particles in certain areas for the same travel time.

SCIENTIFIC VISUALIZATION

Visualization techniques is a new technology for capturing, processing and enhance information. Scientific visualization has become an integral part of any large scale modeling effort, and it is especially useful in allowing modelers to interrogate the huge volume of input or output of their data sets produced by their models. Scientific visualization assists the modeler, easily and effectively, to ensure that his computational results are correct before undertaking the expensive task of recomputing.

Scientific visualization was in modeling the NBBS at different stages: data set preparation, model calibration and exploration of final results. Scientific visualization, as an example, coupled with numerical interpolation routines (kriging and co-kriging) were used to describe the spatial variability of several aquifer properties in the study area. Color raster maps of one or many slices along a plane through a 3-D field of transmissivities, saturated thickness, etc., were displayed and generated at time spans using the Silicon Graphics Personal IRIS Workstation. Cutting planes, hidden surface removal and color shading techniques were also used to generate different images. This practice enhanced the understanding of aquifer hydrogeological conditions which helped in achieving the objectives for modeling this complex problem.

CONCLUSIONS

The experiences gained at the Rocky Mountain Arsenal through the 13-year operation of the NBBS are that groundwater barrier systems are commonly complex and difficult to operate and manage. The operational management model developed jointly by Colorado State University and the Army Corps of Engineers has proven to be a very useful and practical tool in the management of these systems.

Different questions regarding the overall effectiveness and efficiency of the system posed by the U.S. Army were evaluated using this finite element operational model. A steady state calibration for pre-system conditions and 13 separate transient calibrations were carried out from 1978 to 1991. The use of a refined model mesh allowed a better calibration in the NBBS area, particularly close to the system where the effects of pumping and recharge are the highest. Also, it increased the model capability for representing different system reconfiguration to achieve desired conditions such as reverse gradients along the entire length of the system.

The model predicted among other simulated scenarios that the implementation of recharge trenches located 45 ft downgradient of the slurry wall would achieve reverse gradients across the slurry wall. This condition has already been achieved since the implementation of the trenches in 1989-1990. In addition to this, the model simulated different operational scenarios to improve system performance and define guidelines for optimal operational rates.

Geostatistics was also successfully applied in this study as a tool to improve data input in the model by accounting for spatial variability of aquifer parameters. Kriging and Co-kriging techniques were used to estimate values of hydraulic conductivity, transmissivity and saturated thickness at unsampled locations. In addition, the uncertainty associated with these estimates and the precision of the kriging interpolation were also obtained through variance error calculations. Scientific visualization techniques were very beneficial as a tool to enhance hydrogeological understanding of the modeled area, along with helping display large amount of input and output data in a more efficient and accurate way.

ACKNOWLEDGEMENTS

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