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ADVANCES IN GROUNDWATER MODELING AT OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

A groundwater flow and contaminant transport model validation study was performed to determine the applicability of verified and commonly used groundwater flow models for performance assessment of proposed waste disposal facilities at Oak Ridge, Tennessee. Standard practice site interpretation and groundwater modeling resulted in inaccurate predictions of contaminant transport at a proposed waste disposal site. The site's complex and heterogeneous geology, the presence of flow dominated by fractured and weathered zones, and the strongly transient character of shallow aquifer recharge and discharge combined to render assumptions of steady-state, homogeneous groundwater flow invalid in performance of high resolution modeling.

The study involved iterative phases of site field investigation and modeling. Prior to initial modeling, which involved conventional applications of a porous medium code, the site geology and hydrogeology were intensively characterized and a groundwater dye tracer test was performed to obtain data against which model results could be compared to test accuracy. The initial site groundwater model incorporated the assumptions of horizontally layered, homogeneous but anisotropic aquifer materials. Simulations using this approach failed to accurately simulate the dye tracer behavior because of poor resolution of the heterogeneous site conditions. Subsequent modeling activities focused on generation of a model grid incorporating the observed site geologic heterogeneity, and on establishing and using model boundary conditions based on site data.

This study demonstrates that in the Oak Ridge hydrogeologic setting, conventional porous medium modeling provides only low resolution results when compared to an aquifer tracer test. Site specific geologic factors which influence groundwater flow must be incorporated in the model to achieve high resolution model results.

Introduction

Modeling groundwater flow in the Appalachian orogenic belt presents numerous challenges in site characterization, data collection and interpretation, and model application. Reliable performance assessment of sites proposed for land disposal of solid waste depends on the combination of a properly implemented site characterization program, development of an accurate conceptual model of site hydrogeology, and use of a numerical model and grid combination which incorporate both the site data and conceptual model.

A groundwater flow and contaminant transport model validation study was performed to determine the applicability of commonly used groundwater flow models for performance assessment of proposed waste disposal facilities at Oak Ridge, Tennessee. Previous experience with standard practice site characterization methods, data interpretation, and groundwater modeling resulted in inaccurate prediction of contaminant transport at a proposed waste disposal site. The site's complex and heterogeneous geology, the presence of flow dominated by fractured and weathered zones, and the strongly transient character of shallow aquifer recharge and discharge combined to render assumptions of a horizontally layered, homogeneous but anisotropic aquifer and steady-state groundwater flow invalid.

Overview

This study was designed to integrate geologic and hydrogeologic concepts and data with setup and application of a numerical groundwater flow and contaminant transport model through an iterative feedback system. Site characterization investigations were guided by hypothesis testing which sometimes incorporated model simulation of alternative hypotheses. The hydrogeologic conceptual model evolved continually as site testing and modeling efforts progressed and hypotheses were either prove, modified, or abandoned. In addition to the battery of field tests and routine data collection, a groundwater tracer (Rhodamine-WT) was introduced to the upper 0.3 m of the water table surface, and its migration under ambient conditions (natural site gradient) was monitored for more than fifteen months. The tracer test was conducted in a quantitative mode with parts per billion resolution tracer analyses performed on groundwater samples from more than three dozen wells in and near the plume. Tracer migration behavior was documented and used as a bench mark against which model results were compared.

Site Characteristics

The study site encompasses about an acre of hillside terrain underlain by weathered interbedded calcareous siltstones, limestones, and shales of the uppermost Maryville Limestone and lowermost Nolichucky Shale of the Upper Cambrian Conasauga Group. Individual bed thicknesses range from about 1 to 50 cm and lithologic units (limestones, shales, and siltstones) range from less than 1 m to several meters in thickness. Bedrock dips southeast at about 45 degrees and strikes northeast-southwest consistent with regional structure. Weathered bedrock (saprolite) extends from just beneath the ground surface to depths ranging from about 3 to 10 m. The piezometric surface is generally coincident with the bedrock weathering interface. Depending on ground surface elevation, the water table exhibits seasonal fluctuations of approximately 0.3 to 1 m in respnse to the precipitation year.

The goal of site characterization was to obtain quantitative measurements of subsurface conditions which control groundwater flow. Detailed site characterization is an intrusive process which may significantly alter subsurface conditions, consequently altering groundwater flow characteristics. All drilling was performed either by augering or using water as the drilling fluid to reduce the artificial dilation of fractures which often occurs when high pressure air is used as the drilling fluid. Geologic and hydrogeologic characterization studies at the site included: rock core drilling, lithologic logging, and geophysical logging; core hole packer testing of hydraulic conductivity and static head; construction of individual and cluster wells; performance of two pump tests drawing water from different aquifer zones; single well hydraulic conductivity testing; and continuous and periodic water level monitoring in site wells. Detailed characterization tests at the study site extended to a depth of about 30 meters below ground surface.

Initial working hypotheses of geologic and hydrologic factors which may control groundwater flow at the site were developed on the basis of early core drilling and packer test results. These hypotheses are generalized into two categories: 1) geologic structures and differential weathering may control groundwater flow and are related to individual lithologies which vary at the meter scale, and 2) the variable tracer migration rate observed at the site was caused by a decrease in hydraulic gradient associated with seasonal water table decline.

Field tests performed to evaluate these hypotheses included: 1) falling head and straddle packer tests at the 0.6 to 1.1 m thickness scale in two nominal 20 m deep boreholes to test the relationship of hydraulic conductivity to lithology and structure, and 2) collection of tracer concentration (nominal monthly frequency) and water elevation data (biweekly frequency). Conductivity test intervals were selected by inspection of rock core to coincide with discrete lithologic and structured intervals.

Interpretation of the hydraulic conductivity test results revealed no consistent relationship between conductivity and lithology or with degree of rock weathering when stratigraphically correlative intervals were tested above and below the bedrock weathering interface. The apparent determinant of conductivity was degree of fracturing. Based on the discrete zone test, the hydraulic conductivity was found to range randomly from about 1 E-4 to 5 E-5 cm/s with the mean conductivity of 5.3 E-5 cm/s. This range of conductivity is generally consistent with results of the numerous other single well, pump test, and packer test results obtained at similar depths in the area. Aquifer conductivity anisotropy was determined on the basis of aquifer pump test behavior with maximum conductivity parallel to geologic strike.

Analysis of tracer migration and water table fluctuation data indicates that tracer migration rate and direction are strongly controlled by local geologic structural features. The direction of tracer migration (Fig. 1), parallel to geologic strike, is consistent with aquifer anisotropy and oblique to the overall site hydraulic gradient, indicative of the dominance of fractures in controlling local groundwater movement. Early time (the first month) tracer migration was quite rapid (5 m/d) with migration of a narrow (2-3 m wide), high concentration plume for about 15 m. Subsequent migration occurred at rates less than 0.02 m/d and measured migration velocity was observed to vary over one order of magnitude in relation to variations in precipitation. Fig. 2 illustrates the incremental velocity of tracer migration over a period of one year.

Water elevation contours indicate the pathway of maximum tracer concentration is coincident with a fracture-related water table anomaly (Fig. 3). The anomaly appears as a water table high under drought conditions and a trough under elevated water table conditions. Rather than migrating in a direction normal to the gradient, the center of mass of the tracer plume remains on the axis of a strike-parallel water table divide. The transient rate of tracer migration is unrelated to seasonal fluctuations in the hydraulic gradient.

Neither the long nor short-term rate of tracer migration is closely dependent on the overall site hydraulic gradient. The rapid migration rate early in the test is coincident with nearly the lowest and flattest measured hydraulic gradient (square symbol in Fig. 4). Short-term

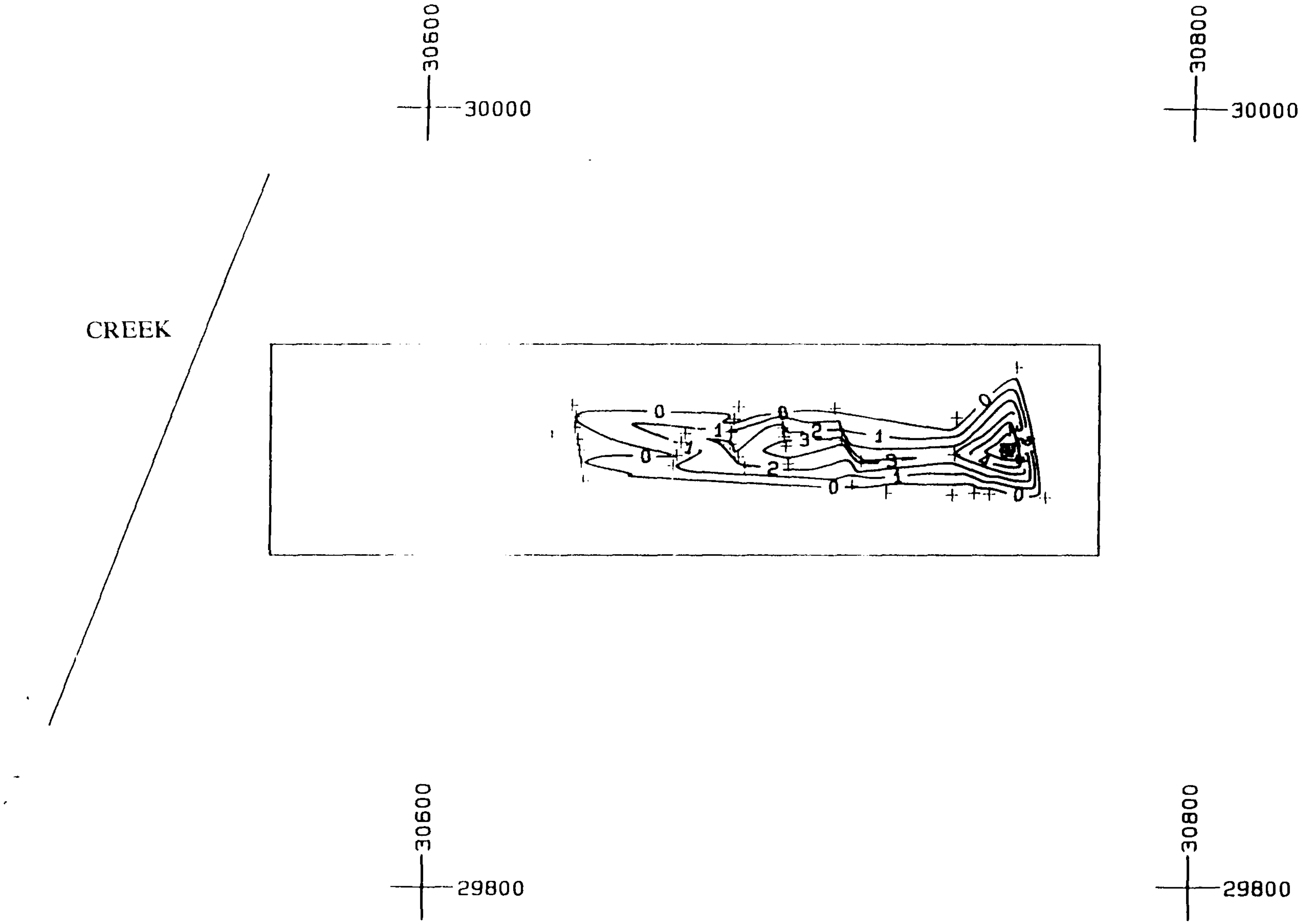

Fig. 1. Log tracer concentration (ppb) contour plot within model grid boundary rectangle. Crosses denote detection wells, square denotes tracer injection well at right, and slanted line at left represents creek. Scale: 1" = 40'.

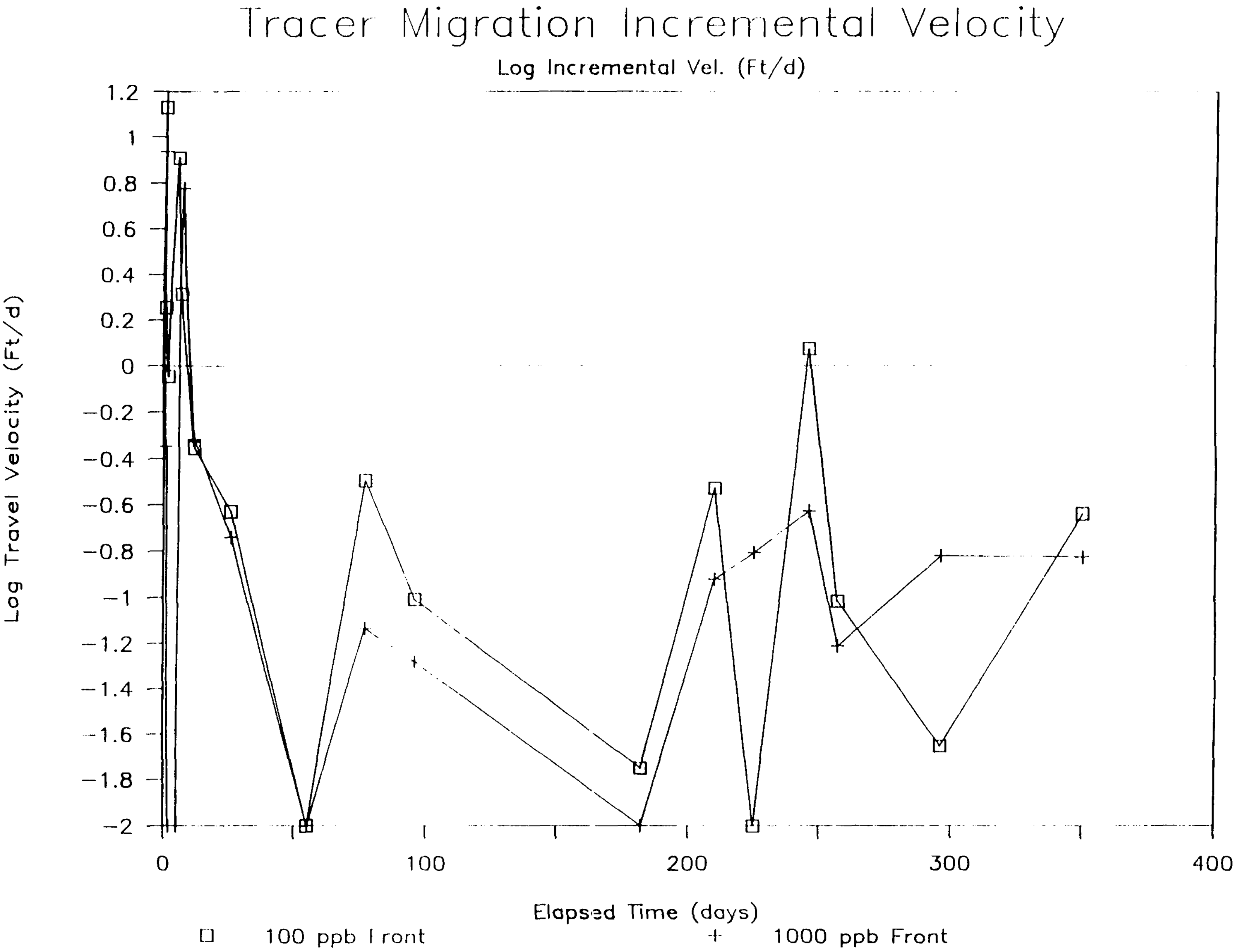

Fig. 2. Log tracer migration incremental velocity for 100 and 1000 ppb isopleths.

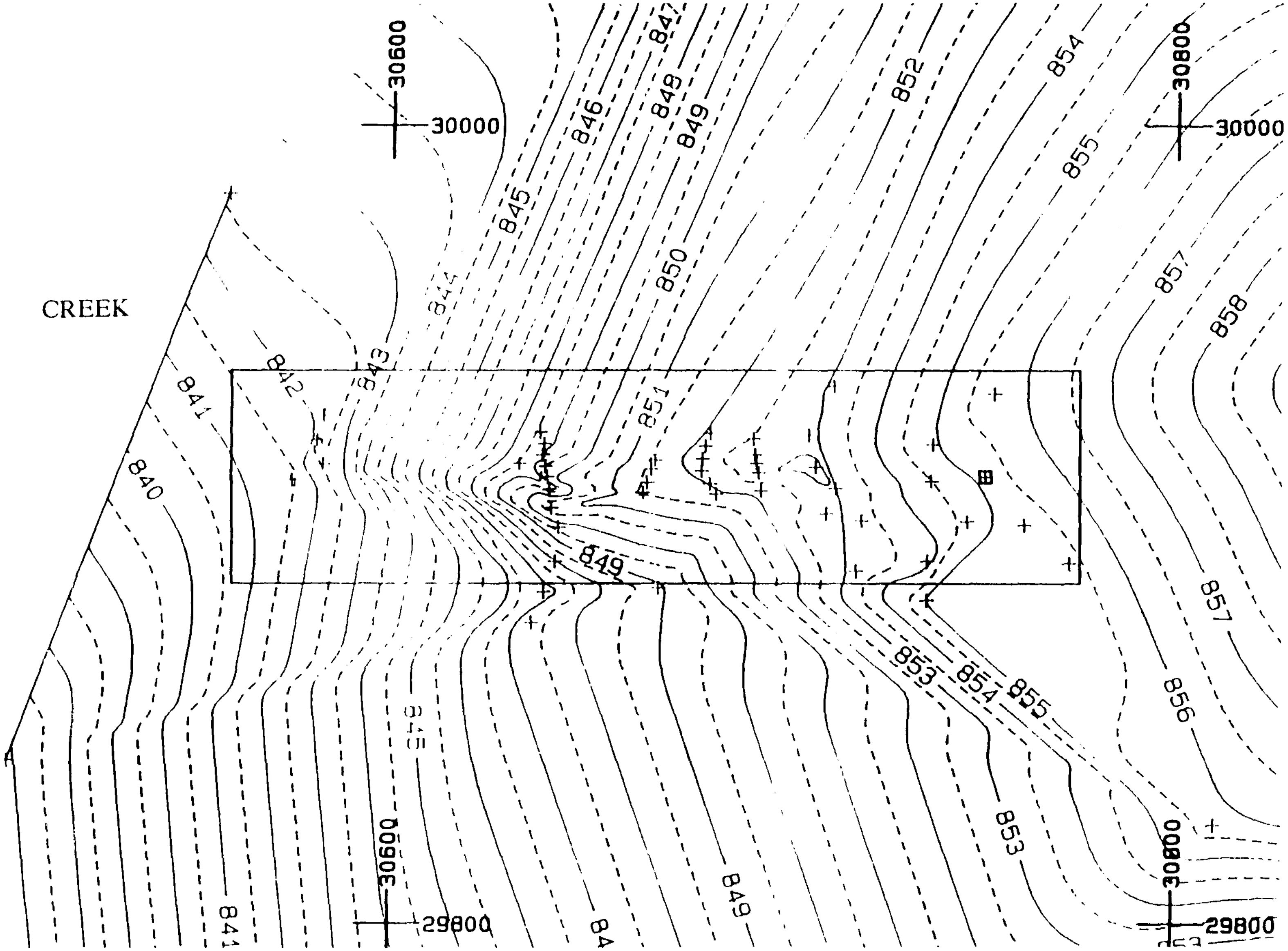

Fig. 3. Water table configuration at tracer site. Crosses denote detection wells, square denotes injection well, and slanted line at left represents creek. Contour interval 0.5 '. Scale: 1" = 40'.

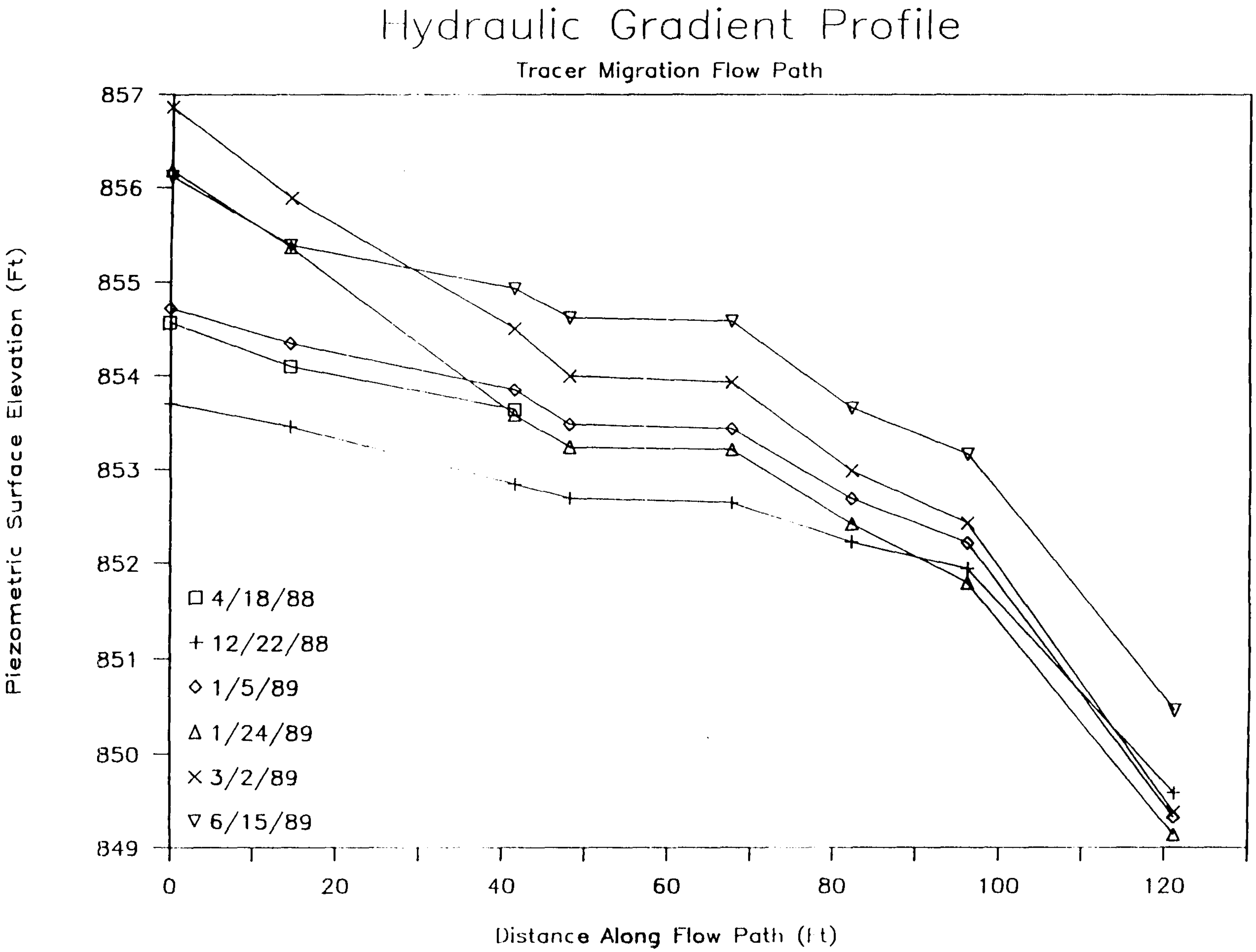

Fig. 4. Representative hydraulic gradient profiles at tracer site. Tracer injected on 4/20/88.

perturbations in tracer concentration are apparently closely related to a threshold precipitation accumulation of 1 to 3 cm over periods of several days. In combination, the tracer migration and water table configuration and fluctuation data indicate the presence of a fracture-related conduit through which initial flow occurred. Later time tracer migration data show fingering and lateral spreading of tracer within the aquifer. Other conduits are inferred from tracer and water table data.

Modeling Method

The site was modeled using standard concepts of groundwater flow through porous media. The underlying assumptions in this approach are that the velocity field is determined by Darcy's Law and contaminant transport is controlled by advection and dispersion processes. The numerical model used for site simulation was driven by shallow aquifer hydraulic data and tracer migration data collected from April 1988 through June 1989.

Modeling proceeded in the following steps.

1. A detailed two-dimensional grid was constructed based on the heterogeneous site geology. This grid incorporated elements representing the 1 m variations in lithology. Grid elements were aligned parallel to geologic strike and flow was assumed to occur in a horizontal aquifer 3 m thick.

2. An initial boundary value problem was formulated and solved for this grid configuration to simulate a steady-state theoretical head distribution and time dependent concentration distribution. Grid boundary hydraulic head data (Dirichlet data) were developed using the fit of a quintic spline to measured water table elevations at wells within the test area.

3. The hydraulic conductivity field assigned to the grid was based on conductivity measurements previously discussed. Conductivity was randomly assigned for each grid node with the overall conductivity distribution in the model grid consistent with the measured conductivity distribution from field data. Flow and transport simulations using the purely randomized grid showed transport behavior similar to the tracer behavior but underestimated early time migration velocity. To enable the model to simulate the early rapid migration, a line of elevated conductivity (1 E-4 cm/s) nodes, equivalent to the observed rapid flow conduit, was superimposed on the grid.

4. Transport was assumed to be primarily advection driven based on observed concentration/time tracer behavior, and consequently dispersivity parameters in the model were held at moderate values. It was assumed that the tracer was non-reacting and not subject to retardation.

5. Flow and transport computations were made using the USGS Method of Characteristics computer program. The problem was solved repeatedly with variation in input parameter values to optimize parameter input and arrive at a combination of parameters which allowed the code to most closely simulate the observed tracer migration behavior. The range within which input parameters were allowed to vary was constrained to that defined by field data.

Performance of the computer simulations established the following points:

1. When isotropic porous medium conditions with randomly distributed conductivity are assumed, the simulations show migration of tracer directly down hydraulic gradient at a rate of about 0.1 m/d.

2. When randomly distributed conductivity conditions with conductivity parallel to strike 10+ times that perpendicular to strike are assumed, the simulated tracer migration is essentially parallel to strike. The actual plume migration velocity is best simulated when an anisotropy of 30+ is used and a line of elevated conductivity nodes is superimposed on the grid to simulate the rapid migration zone observed in the tracer test (Figs. 5, 6, and 7). Aquifer anisotropy values as high as 30 have been measured by pump testing in the Conasauga Group at Oak Ridge. Use of a permeable conduit in simulation is indicated based on water table and tracer migration behavior measured at the site.

3. For the purpose of simulating the effects of a larger scale source, a solute line source was input at the North/South grid row equivalent to the tracer injection well location. Several simulations were performed including no discontinuous high conductivity conduits and one conduit. Simulation results suggest that flow in these cases results in local fingering of solute with little effect on the long term (12 month), long distance (50+ m) transport rate. Multiple closely spaced but discontinuous conduits act as continuous preferential conductors of solute which can greatly affect transport rate.

Discussion

A hydrogeologic conceptual model for the shallow aquifer evolved from analysis and interpretations of site data combined with numerical simulations of groundwater flow and transport. Hydraulic conductivity values vary randomly within approximately 1.5 orders of magnitude, and apparently discontinuous, narrow conduits of comparatively high hydraulic conductivity provide preferred pathways for tracer migration. The rate of local tracer migration is dependent upon the presence of conduits and independent of the overall site hydraulic gradient. The pathway of maximum tracer concentration is coincident with the axis of a strike-parallel water table divide. This water table anomaly is considered to represent a fracture-controlled zone of preferred aquifer discharge (and presumably recharge at higher elevations).

Conclusions

This study demonstrates the fundamental influence of local geologic conditions on groundwater flow. By incorporating a systematic approach to site characterization and conceptual model formulation and testing with development of a groundwater flow simulation model, it was possible to numerically simulate a field tracer test using rational model input parameters derived from the interpretation of site data. While mathematical simulation of aquifer behavior using the concept of porous medium flow can provide an approximation of observed groundwater flow and contaminant transport, interpretation of field test results suggests that much of the significant transport activity occurs through mechanisms of fracture-related flow. This study contributes significantly to the general understanding of mechanisms which control groundwater flow in the Oak Ridge area. Based on the advanced understanding of local groundwater flow, the study successfully simulated an aquifer dye test using the porous medium equivalent concept to approximate the apparently fracture dominated aquifer.

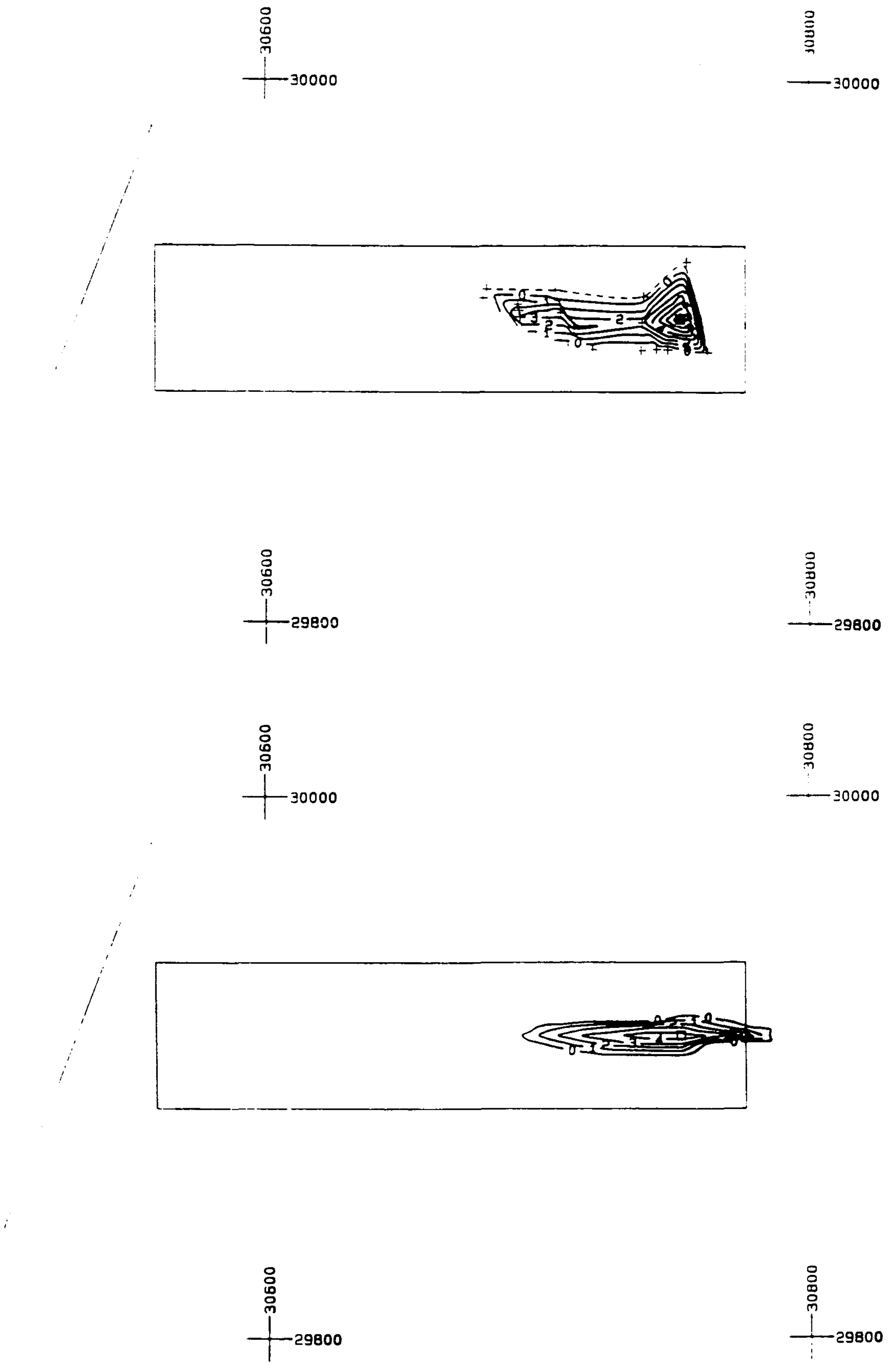

Fig. 5. Comparative plots (log ppb) of measured tracer concentration (top) and model generated plume (bottom) 1 month after tracer injection.

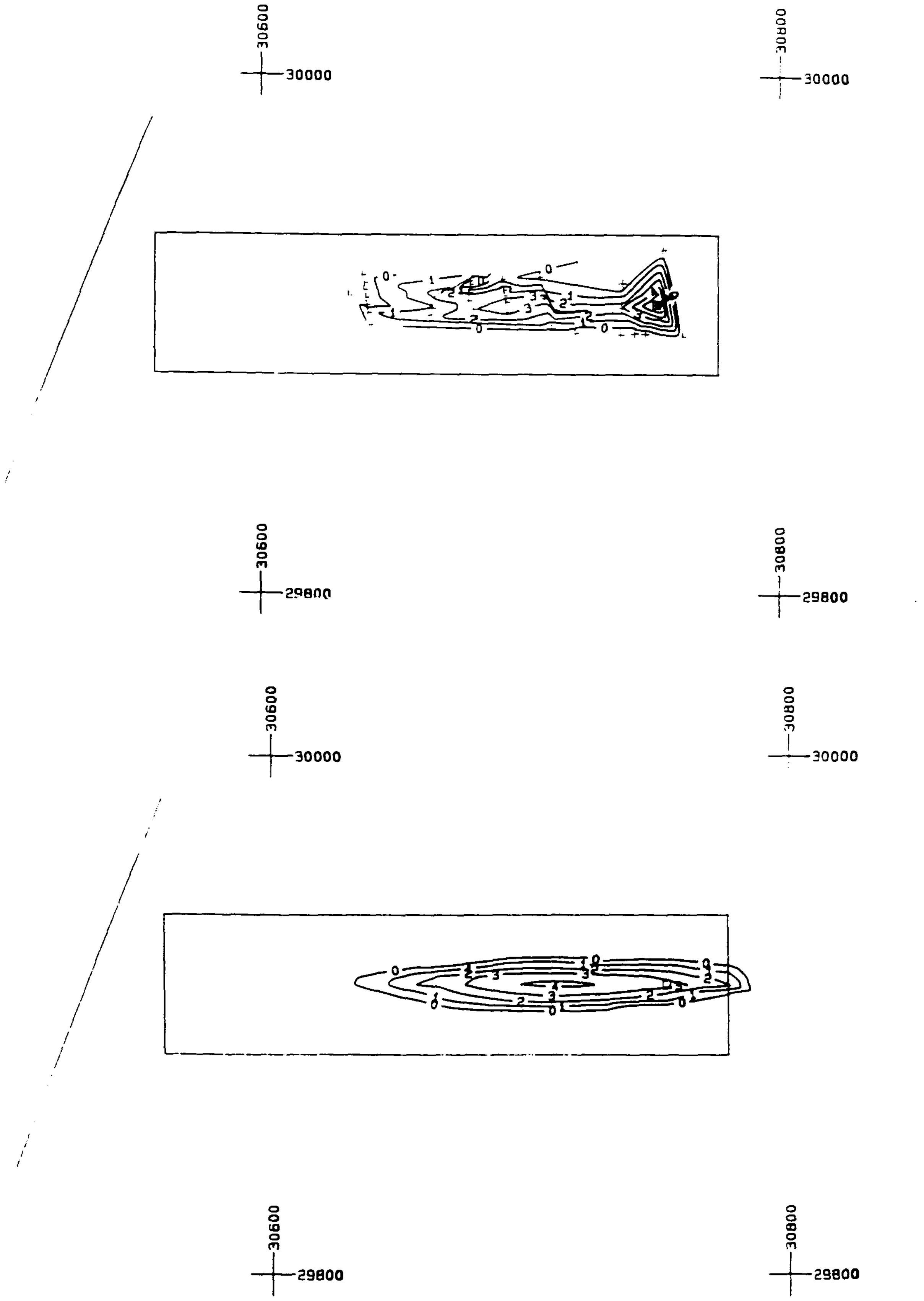

Fig. 6. Comparative plots (log ppb) of measured tracer concentration (top) and model generated plume (bottom) 6 months after tracer injection.

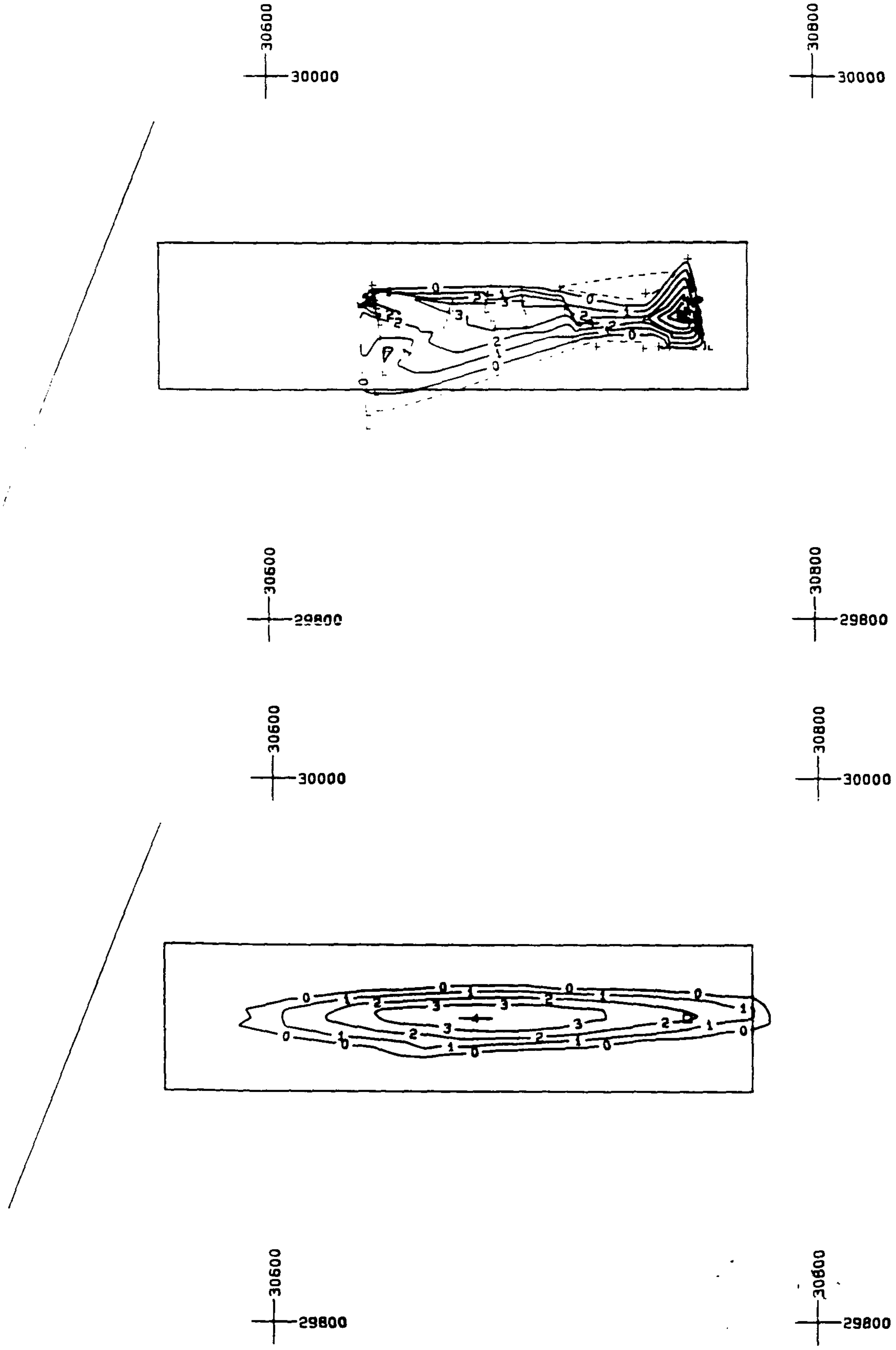

Fig. 7. Comparative plots (log ppb) of measured tracer concentration (top) and model generated plume (bottom) 12 months after tracer injection.