Tracer study in a complex three-dimensional flow system. 1994

Meigs, Lucy Chambers; Bahr, Jean Marie
Madison, Wisconsin: University of Wisconsin, Water Resources Center, 1994

Water Resources Center • University of Wisconsin-Madison

Groundwater Research Report
WRC GRR 94-02

TRACER STUDY IN A COMPLEX THREE-DIMENSIONAL FLOW SYSTEM

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Groundwater Research Report
WRC GRR 94-02
University of Wisconsin System
Groundwater Research Program

Water Resources Center
University of Wisconsin-Madison
1975 Willow Drive
Madison, Wisconsin

1994

This project was supported, in part, by General Purpose Revenue funds of the State of Wisconsin to the University of Wisconsin System for the performance of research on groundwater quality and quantity. Selection of projects was conducted on a competitive basis through a joint solicitation from the University and the Wisconsin Departments of Natural Resources; Agriculture, Trade and Consumer Protection; Industry, Labor and Human Relations; and with the concurrence of the Wisconsin Groundwater Coordinating Council.

ABSTRACT

An ongoing series of natural gradient tracer tests are being conducted in Wisconsin's central sand plain, a region of thick sandy glacial outwash. The initial motivation for the tracer tests was to determine the flow path around a drainage ditch in order to evaluate the role of ditches in limiting the spread of agricultural contamination. The tests were also designed to permit a detailed evaluation of the tracer movement within the aquifer. These tracer tests involve the simultaneous introduction of bromide and iodide tracers, each at a different depth, up-gradient of the ditch. The path of the tracer is monitored by frequent synoptic sampling from a dense three-dimensional array of multilevel sampling wells.

The overall movement of the tracer plume suggests that the drainage ditch acts as a barrier to the shallow flow within the aquifer. A more detailed examination of the groundwater flow pattern reveals that it is quite complex. The direction and velocity of the flow varies spatially and includes a significant component of vertical flow across aquifer stratification. A variation in groundwater velocity, from an average rate of 0.4 feet/day at a depth of 20 feet to more than 1 foot/day near the water table, clearly affected the movement of the tracer plume. The transient nature of the flow system and small scale aquifer heterogeneities also appear to have affected the shape and path of the tracer plume. A detailed examination of breakthrough curves along with plume and water table maps calculated for more than 40 days during the test were used to assess the combined effects of aquifer heterogeneity, flow across stratification, and fluctuating gradients on macroscale dispersion. Additional tracer tests are being conducted in order to refine our interpretations.

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INTRODUCTION

The central sand plain of Wisconsin is a region of thick sandy sediment of glaciofluvial and glaciolacustrine origin. The glacial sands form the principal aquifer for municipal use and irrigation in this important agricultural region. High nitrate concentrations and pesticide contamination have resulted in the closing of a municipal well (Born et al., 1988) and a number of domestic wells (Lulloff, 1987). A number of recent research and monitoring efforts have been designed to determine the extent of contamination and characterize the processes that control contamination migration in the unsaturated zone and groundwater of the central sand plain (Brasino, 1986; Chesters et al., 1982; Harkin et al., 1986; Jones, 1987; Manser, 1983; Kung, 1990a, b; Rothschild et al., 1982; Stoertz, 1985).

The results of these studies have highlighted the need for effective measures to control shallow contaminant migration. Interceptor ditches have been used with success to remove shallow contamination at waste management sites (Cantor and Knox, 1986; Gilbert and Gress, 1987). In the sand plain an existing network of drainage ditches serves to lower the water table and may act as passive controls on contamination. Zheng et al., (1988a, b) developed an analytical and a numerical model to evaluate the effectiveness of existing ditches by identifying the "capture zone" of a ditch (Figure 1). The capture zone is the region above the dividing stream line from which all water flows into the ditch.

The objectives of the field experiment were to verify the existence of a capture zone in the vicinity of a drainage ditch in the central sand plain and to generate a data set that could be used to conduct a detailed evaluation of tracer movements in a complex flow system. An ongoing series of natural gradient tracer tests is being used to evaluate the flow system and to assess the combined effects of aquifer heterogeneity, flow across aquifer stratification, and fluctuating gradients on macroscale dispersion.

The field site for this study is located about 100 miles north of Madison, Wisconsin within the region known as the central sand plain (Figure 2). The sand plain is a region of sandy glacial outwash just west of the maximum extent of Pleistocene glaciation delimited by a terminal moraine. The sandy glaciolacustrine and glaciofluvial sediments, primarily derived from the poorly lithified Cambrian sandstone bedrock, were deposited in this area during several episodes of filling and draining of Glacial Lake Wisconsin. A relatively extensive silt and clay bed, known as the New Rome Member, was probably deposited during the last filling of Glacial Lake Wisconsin (Clayton and Attig, 1989). A meter or more of windblown sediment covers the outwash in some portions of the sand plain (Clayton, 1986; 1987). The total thickness of sediments above the bedrock ranges from 0 to more than 150 feet (Faustini, 1985; Weeks and Stangland, 1971).

The regional groundwater flow within the eastern portion of the central sand plain is towards the Wisconsin River. The mean hydraulic conductivity in this region, as computed by Stoertz and Bradbury (1989) from results of 11 pumping tests, is 250 feet/day. The vertical

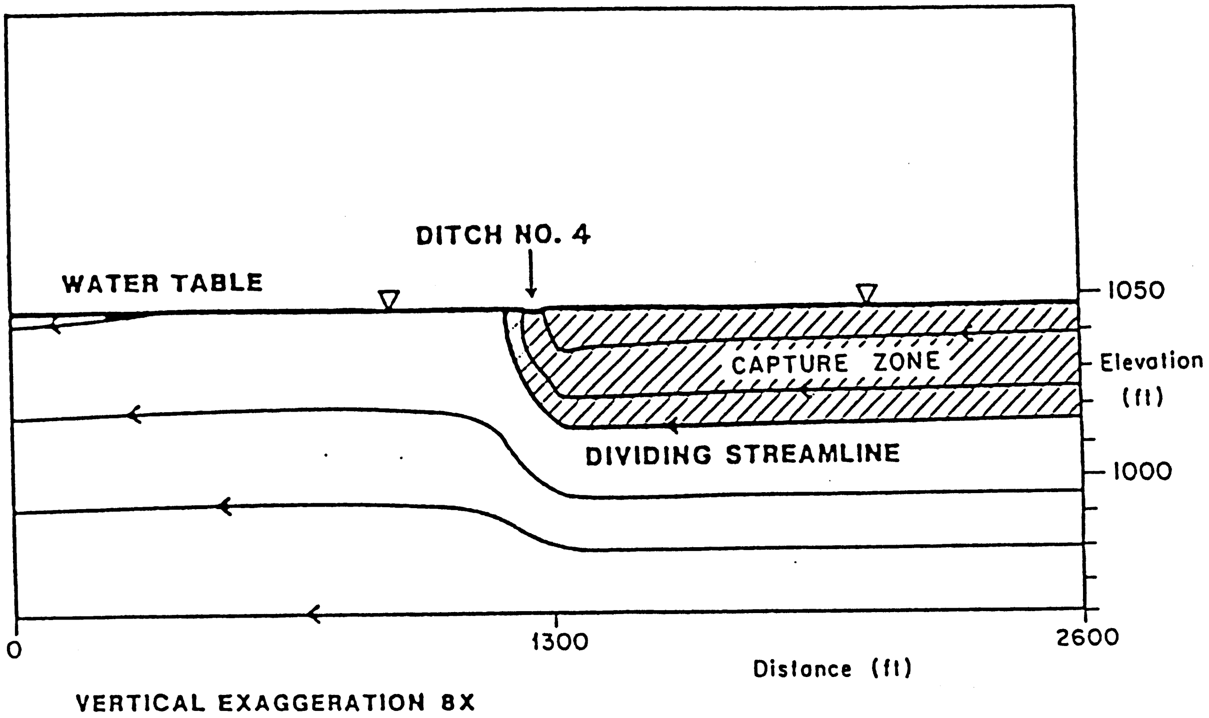

Figure 1. The capture zone of ditch no. 4 in the Central Sand Plain on August 22, 1984 (modified from Zheng et al. (1988a)).

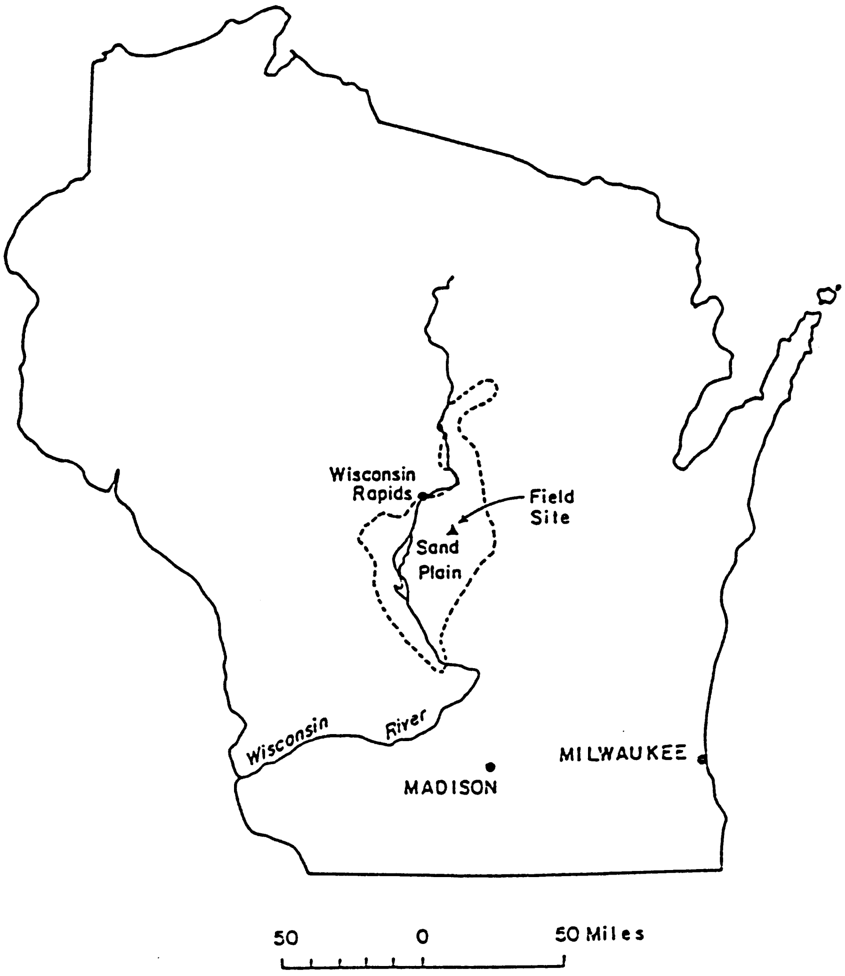

Figure 2. The location of the field site within the Central Sand Plain of Wisconsin (modified from Anderson (1986)).

hydraulic conductivity appears to be somewhat lower due to horizontal layering within the aquifer. Weeks and Stangland (1971) evaluated five pumping tests and concluded that the probable anisotropy ratio for the central sand plain is between 1 and 7.

According to the maps of Clayton and Attig (1989), the field site for this study is located near the edge of the maximum extent of Glacial Lake Wisconsin. Drilling at the site revealed the presence of a silt and clay layer, presumably the New Rome Member, at a depth of approximately 30 feet. The sediment above the silt and clay layer is predominantly well sorted fine sand, based on the Folk (1989) classification. A vibracore of the relatively shallow sediment at the site revealed distinct narrow zones of coarser and finer sediment. A number of slug tests and grain size analyses are currently being conducted in order to evaluate variations in hydraulic conductivity at the site.

A ditch approximately 9 feet wide runs north-south across the field site. Mini-piezometers installed in the ditch indicate that head in the aquifer exceeds ditch stage by 0.1 to 0.2 feet. Based on a water table map of Adams County, regional flow is to the west-southwest, roughly perpendicular to the ditch, and the gradient is about 0.0015. Water table measurements at the site indicate that the local water table gradient near the east side of the ditch ranges from >0.007 to $\simeq 0.003$. The local groundwater gradient on the west side of the ditch varies from $\simeq 0.004$ to being undetectable. Figure 3 shows the water table configuration in the vicinity of the ditch as water levels dropped from mid-July (when the tracer test was begun) until late September when the fall recharge caused water levels to rise.

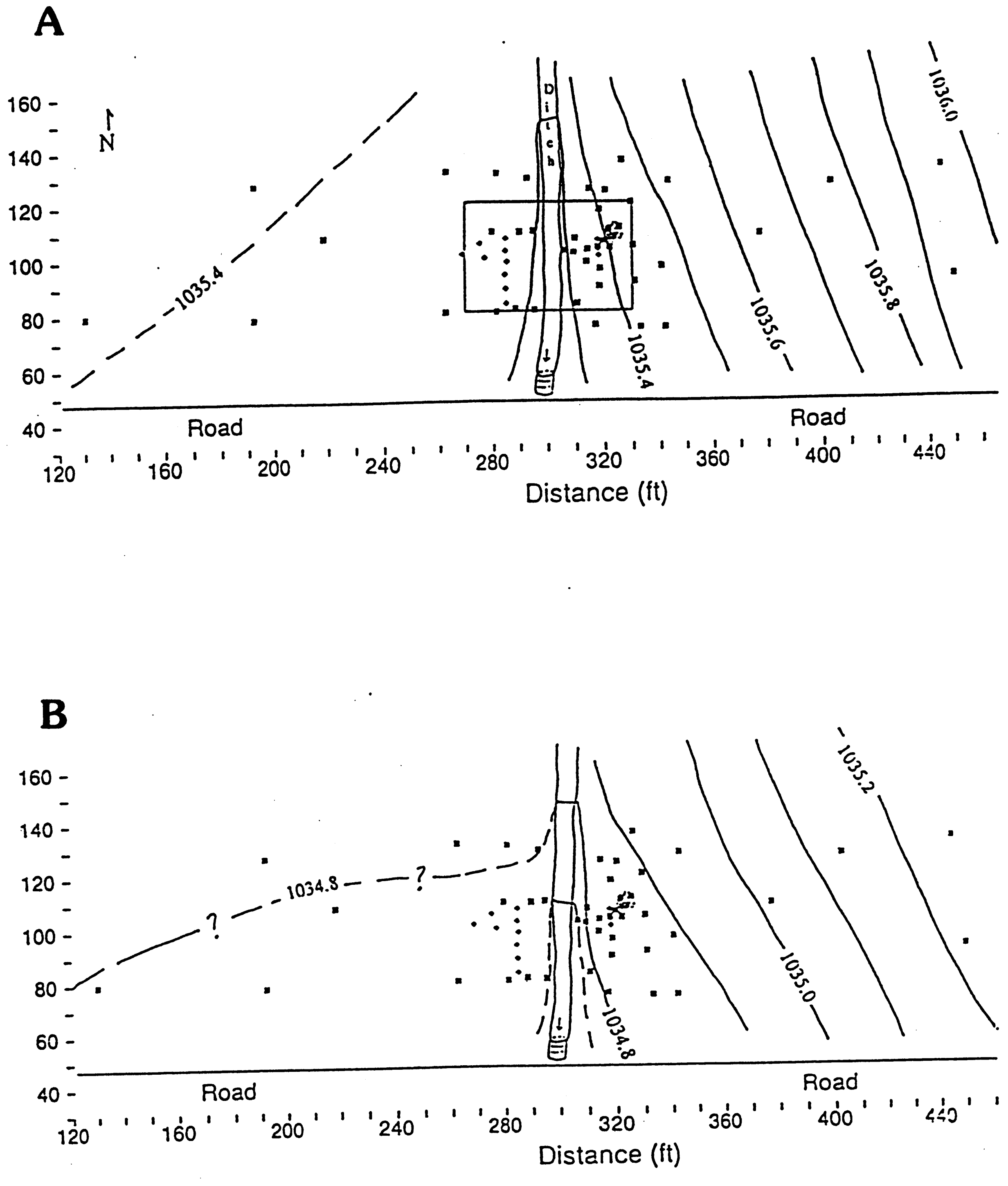

Figure 3. Water table maps for the field site on (A) July 16, 1989 and (B) September 23, 1989. Squares represent water table wells, diamonds represent multilevel wells, and upside down triangles represent injection wells. The rectangle on Figure 3A delineates the area instrumented for the tracer test shown in Figure 5A.

TRACER TEST METHODOLOGY

CONCEPTUAL DESIGN

Figure 4 is a schematic of a tracer test designed to identify the capture zone of a ditch. Distinct tracers are introduced and different depths and tracer paths are monitored by sampling from multilevel sampling wells located on both sides of the ditch. Based on preliminary estimates using the analytic solution by Zheng et al. (1988a), the capture depth at the field site was predicted to be above the silt and clay layer. Bromide and iodide were selected as tracers because they were expected to behave conservatively in the sandy sediments at the site. Background concentrations of these anions were below the limit of detection for specific ion electrodes, permitting introduction of tracers at relatively low concentrations.

Monitoring Network. A dense array of monitoring points has been installed at the field site. More than 50 water table wells have been installed by hand auguring or using a trailer-mounted auger. Mini-piezometers of the type described by Lee and Cherry (1978) were installed in the ditch to depths of 2 to 7 feet below the sediment surface. Seven 2-inch diameter injection wells, installed using a truck-mounted auger, were used for the test described: one well screened 0.6 to 2.0 feet below the water table, a set of three wells screened from 6.4 to 11.1 feet below the water table, and another set of three wells screened from 16.4 to 21.1 feet below the water table. Twelve bundle-type multilevel sampling wells of the type described by Jackson et al. (1985) were installed in borings completed using a hollow stem auger. Each multilevel consists of approximately twenty 0.25-inch polyethylene tubes attached to a PVC backbone. Nylon mesh at the end of each tube forms the sampling point. Sampling points were spaced at intervals of 1.5 to 3 feet. Miniature multilevels, consisting of three 0.25-inch tubes with nylon mesh points, were installed using the method described by Stites and Chambers (1991). Most of these were added during the tracer test in order to obtain improved definition of tracer paths. A number of these were installed through the base of the ditch, permitting monitoring of the tracer within the capture zone prior to discharge into the ditch. Figure 5 shows the location of multilevels, miniature multilevels, and injection wells employed during the tracer test.

TRACER INJECTION

A number of preliminary tests were conducted at the site between August 1988 and June 1989 (Chambers, 1990). Only the results of the multiple tracer test initiated in July 1989 will be described here. Another multiple tracer test begun in the summer of 1990 is currently in progress. For the test begun in mid-July 1989 two different tracer solutions were injected into three different levels within the aquifer: iodide solution at a concentration of 0.5 g/liter in the shallowest injection well; bromide solution at a concentration of 1 g/liter in the three intermediate injection wells; and iodide at a concentration of 1 g/liter in the three deep injection wells. Each tracer solution was mixed in carboys by combining a measured amount of crystalline potassium bromide or potassium iodide with approximately 20 liters of water from the aquifer. Injection was accomplished by draining the solution through the carboy spigot into

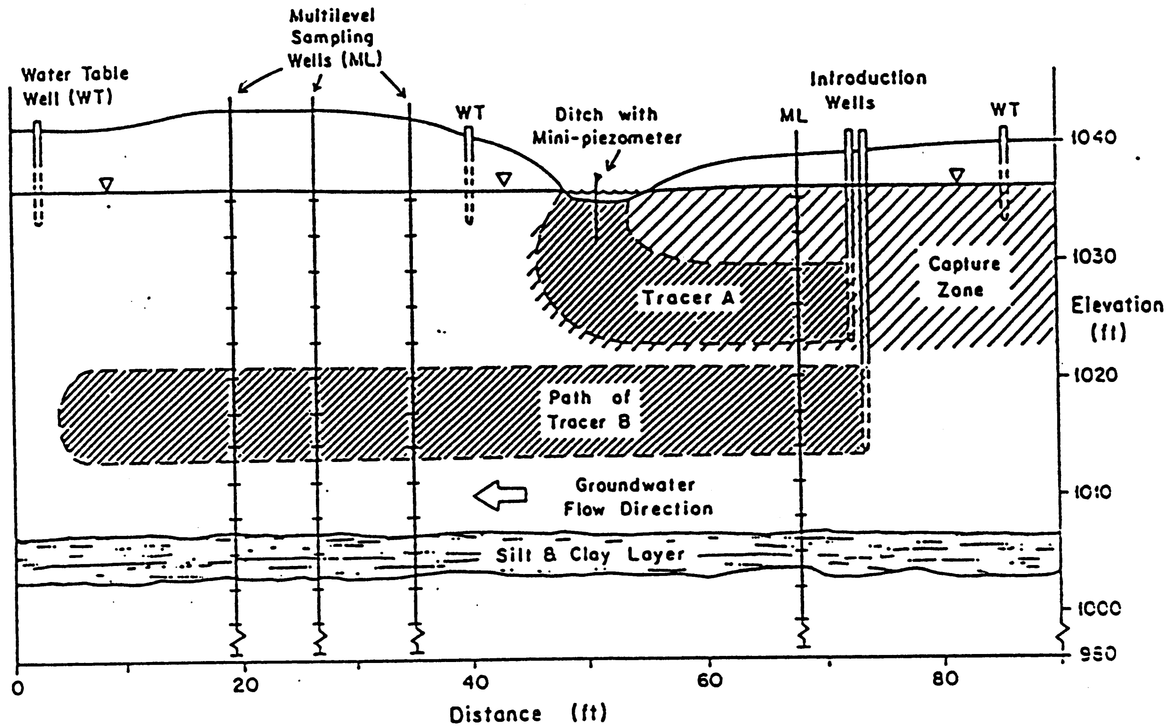

Figure 4. A schematic of the tracer test designed to identify the capture zone.

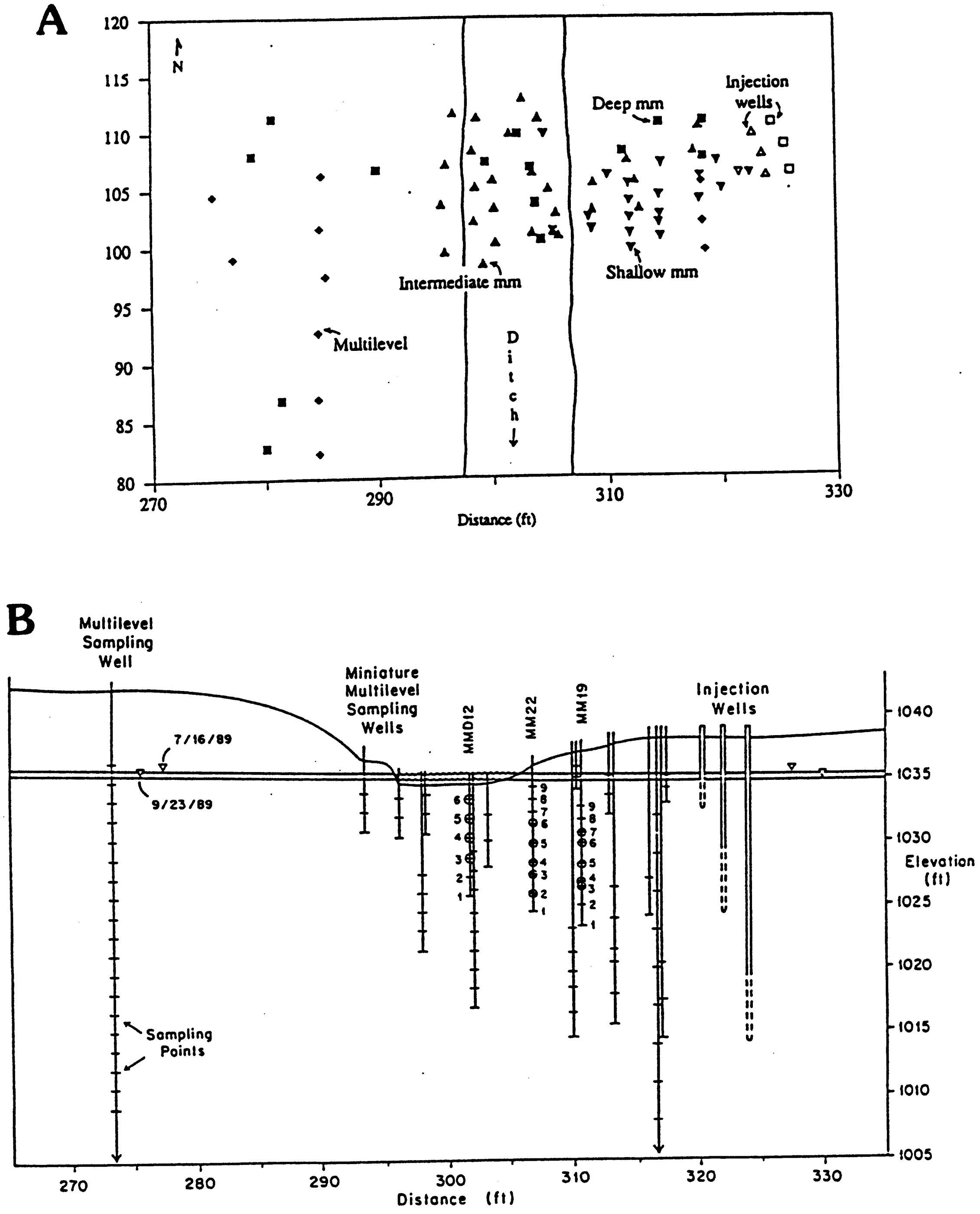

Figure 5. A) Location of all multilevel and miniature multilevel wells at the field site. Open triangles and squares represent miniature multilevel wells (mm). Squares represent the deeper miniature multilevels of the depth for monitoring the tracer injected into the deeper injection wells. Triangles represent monitoring at an intermediate depth and the upside down triangles are very shallow miniature multilevels. Diamonds represent the multilevel wells. B) A cross-section of the wells along the axis of the plumes. (Breakthrough curves for some of the circled points are shown in Figure 8.)

the well while carefully monitoring the flow rate. At the intermediate and deep levels three injection wells were used to ensure that the resulting tracer plume would be sufficiently wide to be detected should the tracer travel beyond the ditch. Because the shallow iodide plume was expected to have a much shorter flow path, a single injection well was judged to be sufficient to generate a plume that could be traced to the ditch. Additional injection well characteristics are summarized in Table 1.

Table 1. Characteristics of the injection well.

	Shallow	Intermediate	Deep
Elevation of screen (feet)	1033.5-1034.9	1024.4-1029.1	1014.4-1019.1
Tracer	Iodide	Bromide	Iodide
Concentration (g/liter)	0.5	1.0	1.0
Injection rate (liter/hour)	45	235	235
Duration of injection (hours)	2.3	3.0	3.0
Volume (liters)	102	705	800

SAMPLING AND ANALYSIS

Samples were collected from multilevel and miniature multilevel points using a peristaltic pump. A volume of 150 to 500 ml, corresponding to two or three tube volumes, was removed from each multilevel point prior to sampling. Field measurements of electrical conductance provided a preliminary estimate of tracer concentration. Samples for laboratory analysis were stored in 120 ml polypropylene cups. Sampling frequency for points at which tracer arrival was expected ranged from at least once a day during the first 11 days of the test and gradually decreased to at least once a week after the first 2 months of monitoring. More than 2,500 samples were analyzed during the course of the test.

Laboratory analyses were performed using Orion specific ion electrodes and a Chemcadet electrode meter. Ionic strength adjuster (ISA, 5 *M* sodium nitrate) was added to samples prior to analysis using 2 ml of ISA per 100 ml of sample. Electrodes were standardized before and after each set of analyses using solutions with concentrations in the range anticipated for the samples. When periods of analysis extended over several hours electrodes were restandardized to check for drift at least every 2 hours.

RESULTS AND DISCUSSION

TRACER PATHS

Figure 6a illustrates the total horizontal movement of the deep iodide and intermediate bromide plumes between the time of injection on July 17, 1989 and the last sampling round on December 5, 1989. The shallow iodide plume followed a horizontal path similar to that of the bromide and is not shown. The total movement of the tracer plumes and the range of average velocities for each plume are shown in cross section (Figure 6b). The flow paths of the bromide and deep iodide plumes appear to bracket the dividing stream line of the capture zone for the summer and fall of 1989. At a lateral distance of 25 feet from the ditch the dividing stream line lies between 11.3 and 15.7 feet below the average water table position for the test. Given that the deep iodide plume showed an upward component of flow even at this distance, it is likely that the depth to the dividing stream line is even greater as distance from the ditch increases. The capture depth falls within the range predicted using the analytic model by Zheng et al. (1988). Preliminary evaluations of the tracer test begun in the summer of 1990 indicate that there may be significant transient variations in the depth of the capture zone.

PLUME DISPERSION

The areal distributions of the deep and intermediate tracer plumes are illustrated by a series of plan views (Figure 7a) for days 15, 45, and 131 following injection. Maximum concentrations measured within each multilevel were used to contour the plumes in order to define the edges of the plumes. Evaluation of frequent synoptic sampling suggests that there was little horizontal transverse dispersion in the intermediate bromide plume, plume width appeared relatively constant until the plume began discharging to the ditch. The width of the deep iodide plume appears to increase once the plume is beneath the ditch. This increase in plume width is probably due to the change in flow path of the plume as it curved off toward the southwest.

The cross sections in Figure 7b show the vertical distributions of the three plumes on days 15, 45, and 131, projected from the approximate longitudinal axis of each plume. There appears to be little vertical transverse dispersion based on the examination of numerous synoptic sampling rounds. Examination of the plumes, for example the bromide plume on day 15, shows that there are clearly zones of higher and lower velocity within the aquifer, presumably due to variations in the hydraulic conductivity of the sediment. On day 15 bromide was found at points 2 and 5 in miniature multilevel (mm) 22 (locations on Figure 5) and not at the points in between. Near the center of the plume, concentrations of >300 mg/liter were found in points 3, 4, and 7 in mm19, and concentrations of <100 mg/liter were found at points 5 and 6 in between. A peak concentration of 700 mg/liter was measured on day 11 in point 6 in mm19; point 5 reached its peak of just over 200 mg/liter on about day 20 of the test. The dramatic variations in velocity seen in mm19 appeared to have decreased by the time the center of mass of the plume reached mm22. It appears that as the plume moved upward toward the ditch, the portion of the plume that had been flowing in a higher hydraulic conductivity zone reached a zone of slightly

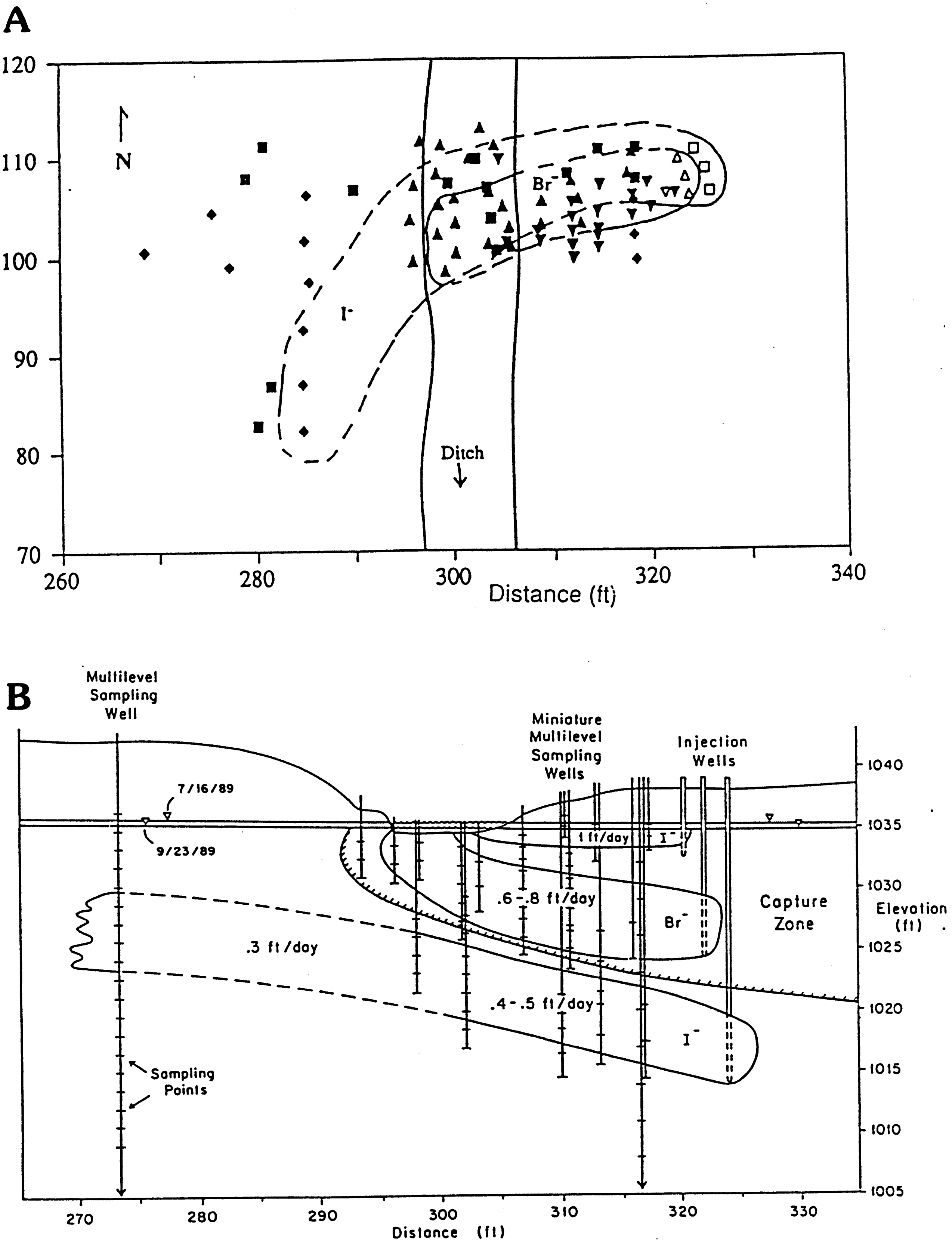

Figure 6. A) Total horizontal movemement of the intermediate bromide plume and the deep iodide plume. B) Cross section of the total movement of the tracer and the capture zone.

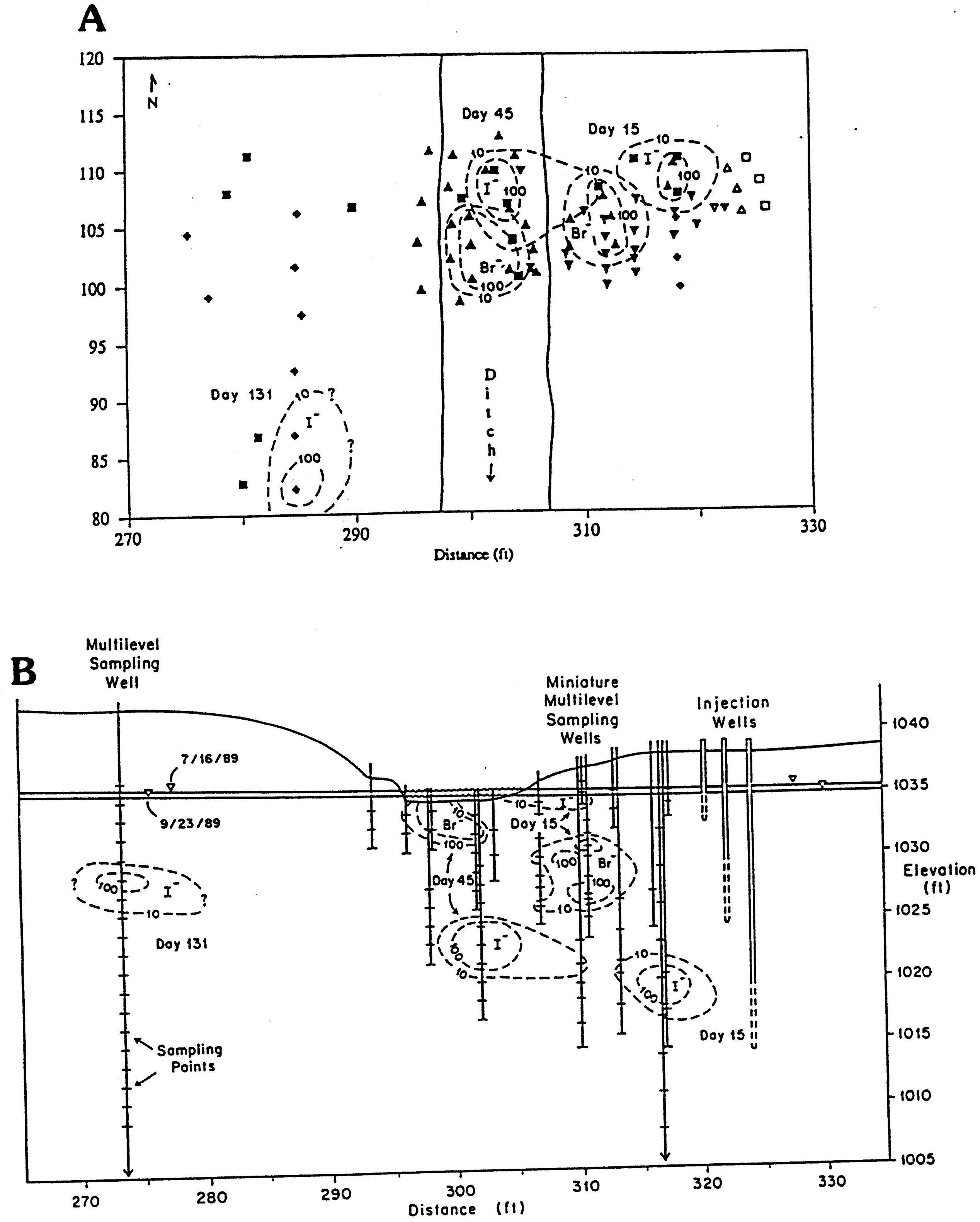

Figure 7. A) Plan view of tracer plumes on days 15, 45, and 131 of the test. B) A cross sectional view of plume movement. Contours represent concentrations of 10 and 100 mg/liter.

lower conductivity.

All three plumes clearly lengthened along the axis of flow as they migrated through the aquifer. The longitudinal dispersion of the plumes appears to be predominantly due to velocity variations caused by aquifer heterogeneity and intensified by flow across aquifer stratification. Fluctuating gradients within this shallow flow system also appear to have contributed to plume dispersion.

APPARENT DISPERSIVITIES

In order to evaluate the apparent dispersivity, breakthrough curves from the bromide plume were modeled. The one-dimensional analytic solution used by Moltyaner and Killey (1988) to model two tracer tests at the Twin Lake site was used to evaluate a series of breakthrough curves. The model, Eq. 6 in Moltyaner and Killey (1988), assumes that the tracer is instantaneously added to the aquifer at time t = 0. At the moment the tracer is added to the system the plume has a width of x_0 and a concentration of c_0. DL is the coefficient of longitudinal dispersivity, v is the plume velocity, and x is the distance from the source. A one-dimensional model should be a good initial approximation with which to evaluate the longitudinal dispersion of the bromide plume because there appears to be little transverse dispersion.

$$c(x,t) = 0.5c_o \left[erf\left(\frac{x + x_o / 2 - vt}{2\alpha_L Vt}\right) - erf\left(\frac{x - x_o / 2\ vt}{2\alpha_L Vt}\right)\right]$$

Figure 8 shows the observed and calculated breakthrough curves for three miniature multilevel wells along the apparent axis of the plume. (See Figure 5b for the location of each sampling point.) The breakthrough curves for points 5 and 6 in mm19 show the extremes in velocity variation which were discussed earlier. Between the injection of the plume and breakthrough at mm19 the flow of the tracer had been predominantly horizontal, thus extremes of velocity variations due to layers of higher and lower hydraulic conductivity may have developed. During transport between mm19 and mmd12 the vertical component of flow becomes more important. Flow across aquifer stratification is likely to cause a dampening in the extremes of flow rates as a portion of the tracer flowing in a low hydraulic conductivity zone reaches a higher hydraulic conductivity zone. A decrease of velocity variations is visible in the breakthrough curves for mm22 and mmd12.

It is not possible to match the model to point 5 in mmd12 because the dispersion is large given the peak concentration. The large apparent dispersivity observed at point 5 was probably due to the fact that the point is only 1.5 feet below the base of the ditch. The long period of tracer breakthrough may reflect a combination of different portions of the bromide plume as the plume rose up into the ditch. The large apparent dispersivity is also likely to have been partially caused by transient variations in gradients directly beneath the ditch.

Table 2 shows the parameter values which were used in the model in order to match the

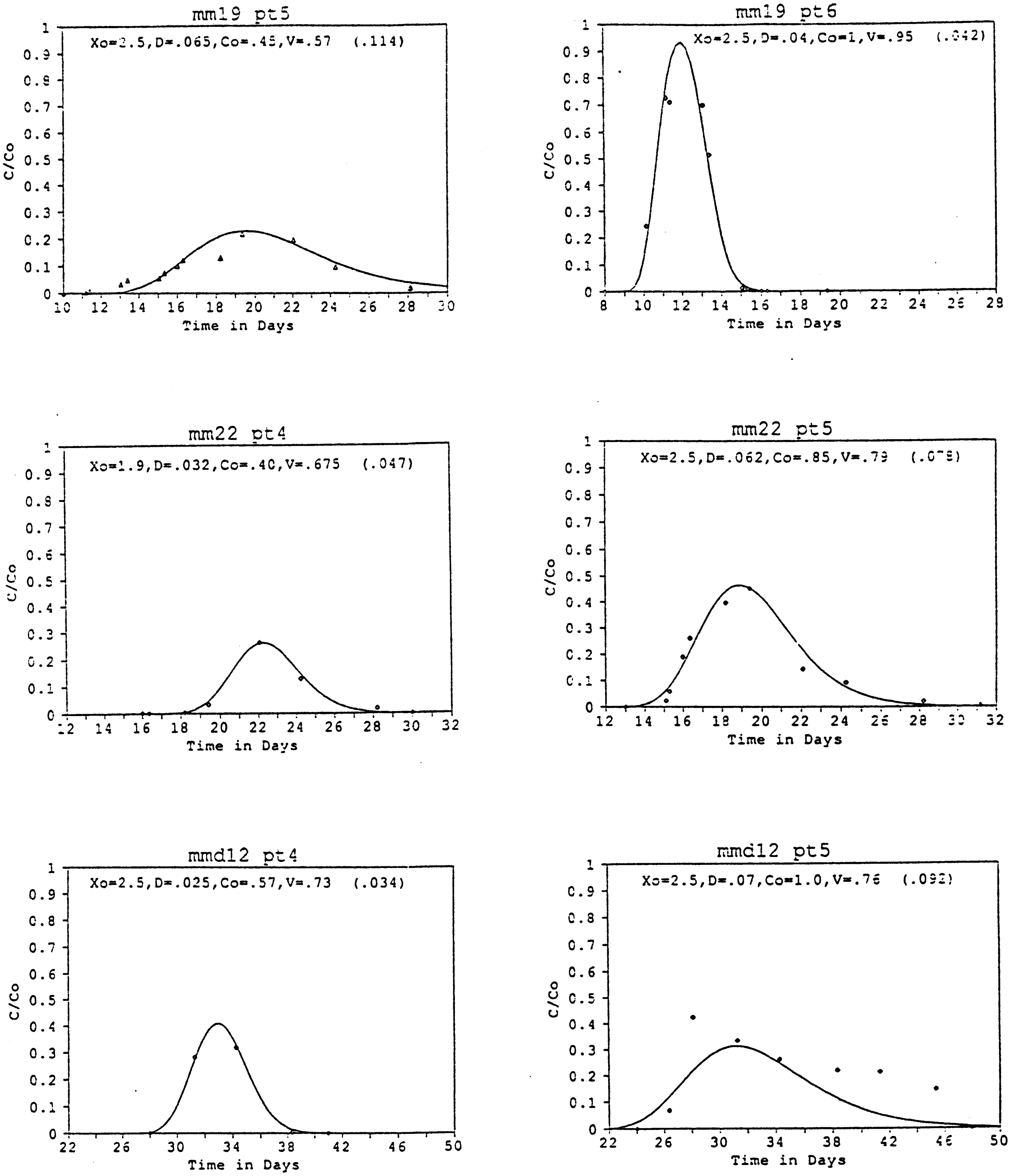

Figure 8. Observed (diamonds) and calculated (solid curves) breakthrough curves. The locations of the points can be found in Figure 5B.

model to the actual breakthrough curve data. At times, it was necessary to adjust the value of the initial plume width or initial concentration value in order to obtain a good fit. The need to adjust the parameters may be partially due to the fact that the initial plume was not perfectly homogeneous. With the exception of the slow moving region of tracer at point 5 in mm19, the apparent dispersivity values show a general trend of increasing as the upward component of flow increases. The increase in apparent dispersivity probably reflects the plume flowing across rather than parallel to aquifer stratification.

Table 2. Breakthrough curve information.

Sampling point	Elevation (ft)	v (ft/day)	x_0 (ft)	c_0 (%)	α_L (ft)
mm19 pt7	1030.65	0.73	1.6	0.70	0.027
mm19 pt6	1029.89	0.95	2.5	1.0	0.042
mm19 pt5	1028.14	0.57	2.5	0.45	0.11
mm19 pt4	1026.39	0.72	1.6	0.63	0.027
mm22 pt6	1031.50	0.76	1.8	0.38	0.039
mm22 pt5	1030.00	0.79	2.5	0.85	0.078
mm22 pt4	1028.50	0.675	1.9	0.40	0.047
mm22 pt3	1027.73	0.71	2.5	0.80	0.066
mm22 pt2	1026.23	0.805	2.5	0.36	0.037
mmd12 pt6	1032.97	0.77	2.5	0.40	0.042
mmd12 pt5	1031.47	0.76	2.5	1.0	0.092†
mmd12 pt4	1029.97	0.73	2.5	0.57	0.034
mmd12 pt3	1028.54	0.82	2.5	1.0	0.046

†Questionable value. A good match was not achieved.

SUMMARY AND CONCLUSIONS

The tracer test described in this paper verified the existence of a capture zone in the vicinity of a drainage ditch in the central sand plain of Wisconsin. For conditions during the summer and fall of 1989, the capture depth of the ditch was at least 12 feet below the water table. At distances greater than 25 feet from the ditch, the dividing stream line was probably deeper than that inferred from the tracer test. These results are encouraging because they confirm the hypothesis that drainage ditches in the sand plain can provide an effective means of controlling shallow groundwater contamination.

Heterogeneities within the aquifer are reflected in the breakthrough curves and plume diagrams. There appear to be distinct zones of higher and lower hydraulic conductivity within the aquifer. This conclusion is supported by the bands of coarser and finer sediment which were visible in a vibracore from the site. Flow across aquifer stratification appears to cause an increase in the apparent dispersivity. The macroscale dispersion of the plume seems to be a result of velocity variations due to aquifer heterogeneity, flow across stratification, and fluctuating gradients.

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