Field evaluation of drainage ditches as controls on the migration of agricultural chemicals in groundwater. [DNR-075] 1990

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Wisconsin Groundwater Management Practice Monitoring Project No. 55

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FINAL REPORT: YEAR 1

FIELD EVALUATION OF DRAINAGE DITCHES AS CONTROLS ON THE MIGRATION OF AGRICULTURAL CHEMICALS IN GROUNDWATER

October 1989 to October 1990

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ABSTRACT

Natural gradient tracer tests were used to evaluate the role of drainage ditches in limiting the spread of agricultural chemicals in groundwater. Groundwater contamination from agricultural chemicals is a serious problem in areas with highly permeable soils, such as the central sand plain of Wisconsin. Recent two-dimensional analytical and numerical modeling by Zheng et al. (1988a, 1988b) suggests that many of the drainage ditches found throughout the central sand plain may perturb the regional flow. Zheng identifies a capture zone or depth above which all water will be captured by the ditch. In this manner, the ditches may create hydraulic barriers to subsurface contaminant migration.

In the summer and fall of 1988 and 1989, a series of natural gradient tracer tests were conducted at a site in the northeast corner of Adams County, in order to delineate the depth of the capture zone and evaluate the predictive capabilities of Zheng's model. Each tracer test involved the introduction of a halogen tracer into injection wells located up-gradient of the ditch. The path of the tracer was monitored by sampling from multilevel sampling wells located on both sides of the ditch. Simultaneous tests using different tracers for each injection depth were conducted to determine the maximum capture depth.

During the summer and fall of 1989, the average groundwater velocity

ranged from 0.3 ft/day at a depth of 20 feet to greater than 1 ft/day near the water table. The capture depth delineated by the tracer path was deeper than 12 feet below the water table. These results are encouraging because they indicate that the capture depth of the ditch should allow for effective removal of shallow agricultural contaminants. The capture depth of the ditch falls within the range predicted by Zheng's analytic solution. However, a sensitivity analysis of the analytic solution using the data collected at the field site reveals that due to the large variability and uncertainty of the parameters used in the model, the capture depth range predicted by the analytic solution is very large. The tracer tests also revealed that the flow system in the vicinity of the ditch is complex and three-dimensional. Thus, it may not be possible to predict the capture depth of the ditch accurately with a two-dimensional model.

ACKNOWLEDGEMENTS

There are numerous organizations and people that have contributed to this project in some way and deserve to be thanked. Financial support within the last year was provided by the Wisconsin Department of Natural Resources and the Graduate School at the University of Wisconsin - Madison. This project has also been supported the Department of Geology and Geophysics, Sigma Xi, and the Geological Society of America. Karl Klingforth has generously allowed us to use his land for the field site in this study. Rod Rustad, Marc Cheyne and Andrew David have provided valuable assistance with field and lab work.

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I. INTRODUCTION

Groundwater contamination is one of the most frequently discussed environmental problems today. In Wisconsin, groundwater contamination caused by the leaching of agricultural chemicals is an important issue. A recent study of grade A dairy farms across the state found that approximately 13% of the farm wells had detectable levels of one or more pesticides (LeMasters and Doyle, 1989). Non-point source pollution, such as the leaching of agricultural chemicals as a result of field applications is a particularly difficult type of groundwater contamination to clean up because the contaminant is widely dispersed. Since most farmers and rural home owners in Wisconsin have their own, relatively shallow, private drinking water wells, practical methods for removing contaminated groundwater from the flow system are needed. This study provides field evidence that drainage ditches may act as significant barriers to groundwater flow and may provide one method to to prevent the spread of agricultural contamination.

Background and Motivations for this Study

The central sand plain of Wisconsin is an important and productive agricultural region. The sandy well drained soils of this area are low in nutrients. Thus, agricultural chemicals are used liberally. The combination of highly permeable soils, a shallow water table and extensive irrigation, permit agricultural chemicals to be transported relatively rapidly through the unsaturated zone to the water table, making the central sand plain particularly susceptible to contamination.

In recent years, groundwater contamination from agricultural chemicals has become an increasing problem in the central sand plain. The village of Whiting, located to the southeast of Stevens Point, shut down its municipal wells in July of 1979, due to nitrate concentrations in excess of drinking water standards (Born et al., 1988). Because nitrate concentrations are still high, the Whiting wells are currently only used for industrial supply (Bradbury, 1990, personal communication). Concentrations of aldicarb exceeding 10 ppb in water samples collected from wells in central Wisconsin during 1984 and 1985 resulted in restrictions on aldicarb use in 11 "moratorium areas" during the 1985 growing season (Holden, 1986). Detection of significant concentrations of pesticides has also resulted in the abandonment and deepening of several domestic wells in the central sand plain (Lulloff, 1987). A number of recent research and monitoring efforts have been designed to determine the extent of contamination and to characterize the processes that control contaminant migration in the unsaturated zone and in the groundwater of the central sand plain (Brasino, 1986; Chesters et al., 1982; Harkin et al. 1986; Jones, 1987; Manser, 1983; Kraft, 1988; Kung, 1988; Rothschild et al., 1982; Stoertz, 1985).

Throughout the central sand plain, a network of drainage ditches serve to control water levels. These ditches were installed early in this century in order to lower the water table and allow farming in areas that have a naturally high water table. A detailed study of groundwater recharge and discharge areas in the Buena Vista Basin, Portage and Wood Counties (Faustini, 1985), indicated the importance of these drainage ditches as internal discharge points within the basin. Faustini suggested that in addition to causing a general lowering of the water table, these ditches also generate a perturbed groundwater flow field with upward flow in the vicinity of the ditch. Shallow groundwater in this perturbed system is "captured" by the ditch and in this manner the ditches serve as passive hydrologic barriers to flow. Elsewhere, interceptor ditches, often equipped with sump pumps, have been used to capture a portion of the groundwater flow at waste management sites, providing a reliable and cost-effective means of pollution control (Canter and Knox, 1986; Gilbert and Gress, 1987). Since agricultural contamination is frequently quite shallow, interceptor ditches should act to remove the contaminated groundwater effectively and discharge it to surface water. Once in the surface water flow system, the contamination is likely to be diluted or degraded, so surface water contamination is not likely to be a serious problem. Some agricultural chemicals such as aldicarb, according to a study done by Union Carbide (Lykins, 1971), may quickly degrade in surface water environments.

The water level data collected by Faustini (1985) suggest that some of the sand plain drainage ditches may cause the passive removal of agricultural chemicals. To test this idea, Zheng et al. (1988a, 1988b) developed analytical and numerical models to simulate groundwater flow patterns in the vicinity of drainage ditches that flowed roughly perpendicular to the direction of groundwater flow. The two-dimensional models developed by Zheng et al. can be used to identify a dividing streamline or surface above which all groundwater is "captured" by the ditch (Figure 1.1). The portion of the aquifer located above the dividing streamline or surface constitutes the "capture zone" of the ditch. The depth of the capture zone is the vertical distance from the water table to the dividing surface at some horizontal distance far enough away from the ditch such that the dividing surface is roughly parallel to the water table.

The two-dimensional models developed by Zheng et al. indicate that the depth and extent of the capture zone depend on the regional water table gradient, the vertical gradient beneath the ditch, the rate of areal recharge, the depth, width and stage of the ditch, and the hydraulic conductivity and anisotropy of the aquifer. Zheng et al. (1988a) also performed simulations incorporating layered heterogeneities to assess the possible effects of low or high conductivity beds on the depth of the "capture zone". A two-dimensional simulation, calibrated to water-level data collected at one of the ditches in the Buena Vista Basin, predicted a capture depth that varies seasonally from over 80 feet (fully penetrating the entire aquifer thickness) in May of 1984 to less than thirty feet in August of 1984 (Zheng et al., 1988b)(Figure 1.2).

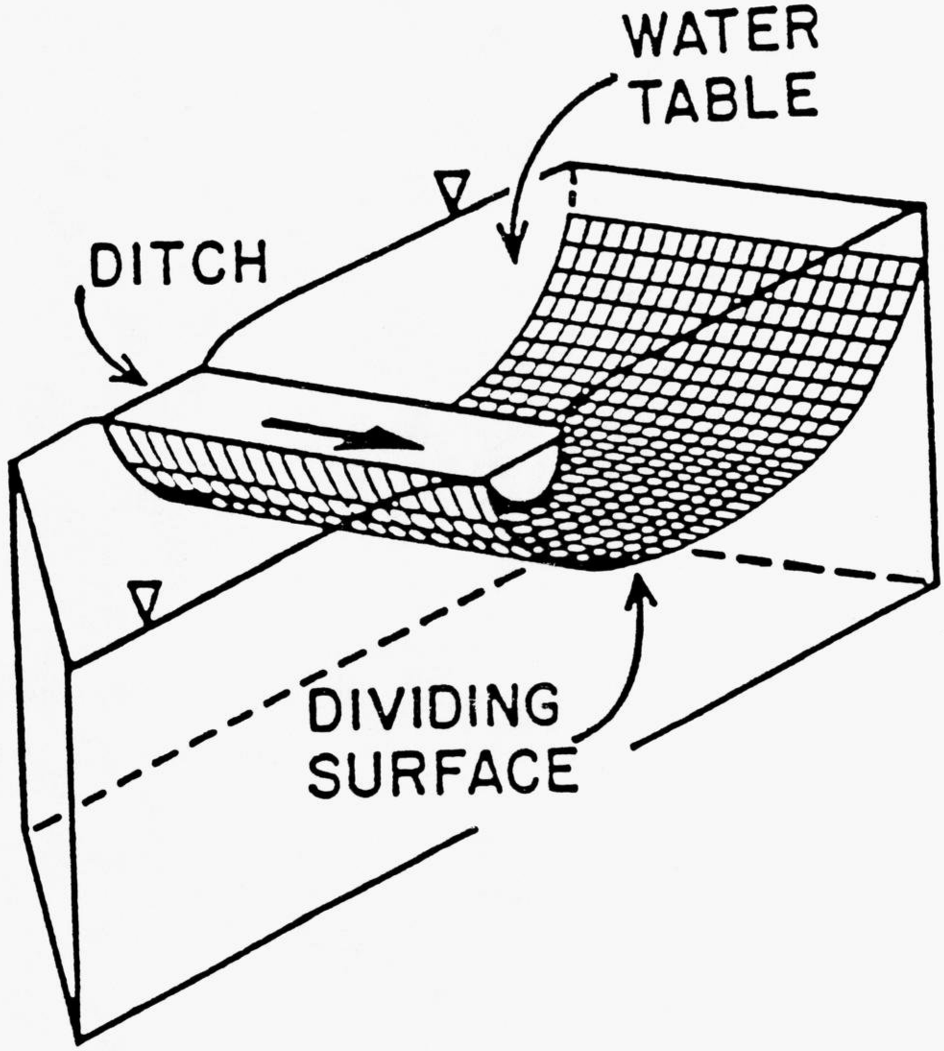


Figure 1.1 The region above the dividing surface is the capture zone of a ditch (modified from Zheng et al., 1988a).

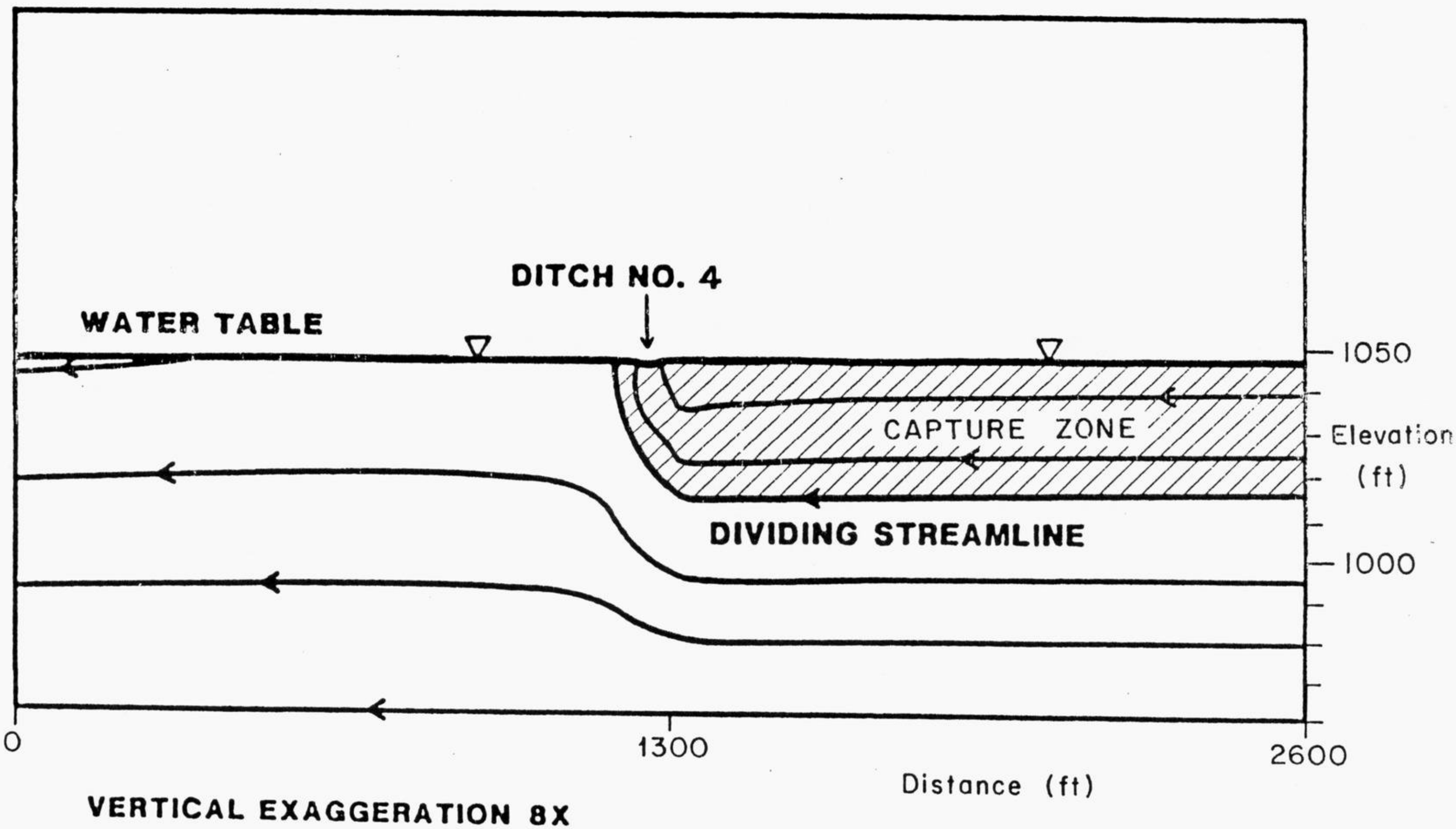


Figure 1.2 The capture zone of ditch no. 4 on August 22, 1984 (modified from Zheng et al., 1988a).

Scope of Study

The objective of this study was to evaluate the depth of the capture zone for a particular drainage ditch and to test the predictive capabilities of the analytic model of Zheng et al. (1988a). The groundwater flow path in the vicinity of a drainage ditch was studied through a series of natural gradient tracer tests. Each tracer test involved the introduction of a conservative, anionic tracer into injection wells located on the up-gradient side of the ditch. The path of the tracer was monitored by sampling from bundle type multilevel sampling wells (Jackson et al., 1985) located on both sides of the ditch. Simultaneous tests using a different tracer for each injection depth were used to determine the maximum capture depth of the ditch. Figure 1.3 is a schematic of a tracer test designed to delineate the capture zone of a ditch.

In the summer of 1988, a field site was selected for this study and preliminary tracer tests were conducted. Due to the limited number of multilevels installed at the time, the complete path of the tracer could not be delineated. The primary results of these tests were preliminary estimates of groundwater flow velocities and directions. Following the installation of a more extensive network of monitoring points, a second series of tracer tests was conducted in the summer of 1989. Results of these tests provide more quantitative information on local groundwater velocities and the effective capture depth of the ditch. The approximate capture zone has been determined for the conditions present during the

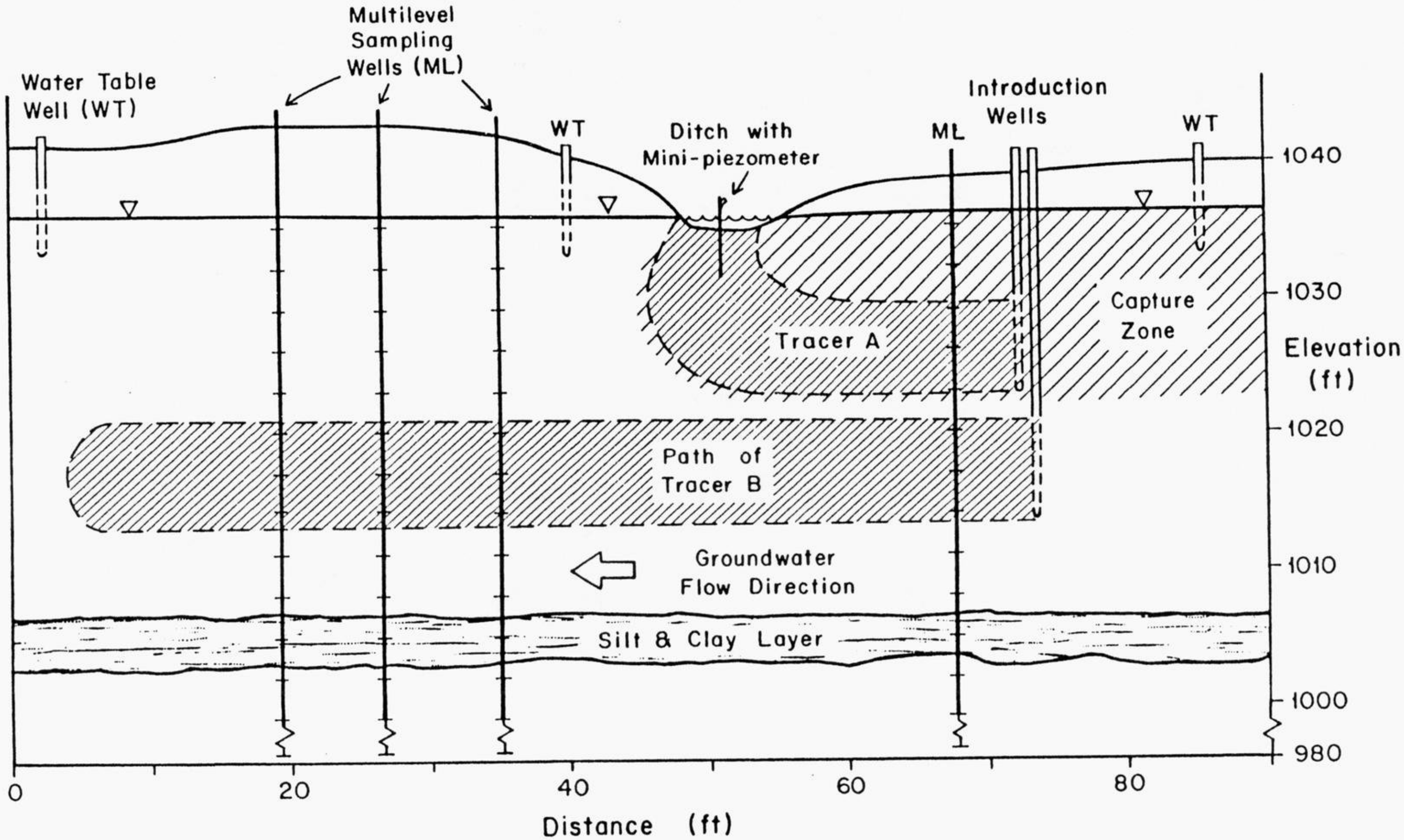


Figure 1.3 Schematic of the tracer test design.

summer and fall of 1989 and 1990.

As part of this research, it was necessary to develop and adapt field techniques for tracer introduction and monitoring. An important modification in the original tracer test technique was the development of a smaller version of the large bundle style multilevel sampling well, the advantage of the smaller version being that it does not require drill rig access. The installation of these "miniature multilevels", described in Chapter 3, causes minimal disturbance of the flow system. The miniature multilevel technique provided the flexibility to add additional sampling wells once the tracer path was known, so the tracer plume could be defined more fully.

Chapter 2 provides a description of the field site, including regional and local characteristics of the geology and hydrogeology near the site. The tracer test design is described in Chapter 3, including the installation of wells, location of wells, tracer injection and the monitoring of the tracer. Chapter 4 presents the results of the natural gradient tracer tests and evaluates Zheng's analytic solution using data collected at the field site for model calibration. Groundwater management implications and suggestions for future research are discussed and the conclusions of this study are summarized in Chapter 5.

II. SETTING OF STUDY

The field site for this study is located in the northeast corner of Adams County, within the region frequently referred to as the central sand plain of Wisconsin (Figure 2.1). The site is located nine miles west of Plainfield, on Akron Road in Bancroft, Wisconsin; NE1/4, Section 4, Township 20 N, Range 7 E (See Figure 2.2).

There are several reasons why this site was selected. It has a north-south ditch (approximately perpendicular to the regional gradient) with relatively easy drill rig access on both sides of the ditch. The land near the ditch is not currently being used for farming, so wells can be installed in a variety of different places without interfering with farm machinery needs. Preliminary estimates of the ditch capture zone suggested that it would be less than the maximum depth (65 feet) to which multilevel wells could be installed at the site. The land owner was also very cooperative, which is important for a long term study.

The remainder of this chapter describes the geology and hydrogeology of the sand plain region and field site.

Geology

The sandy surficial deposits of the central sand plain are underlain

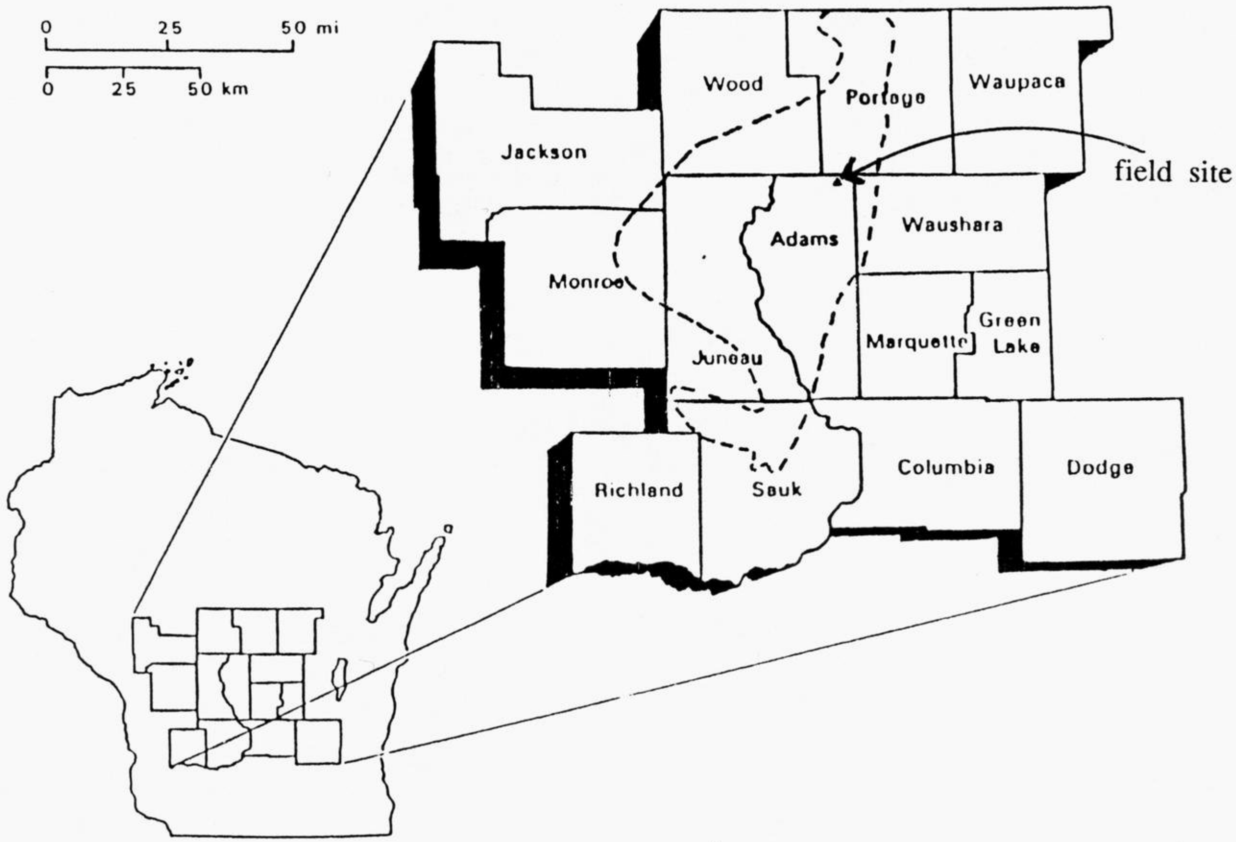


Figure 2.1 The location of the sand plain of central Wisconsin is outlined here with dashes. A triangle marks the location of the field site. (modified from Clayton, 1987)

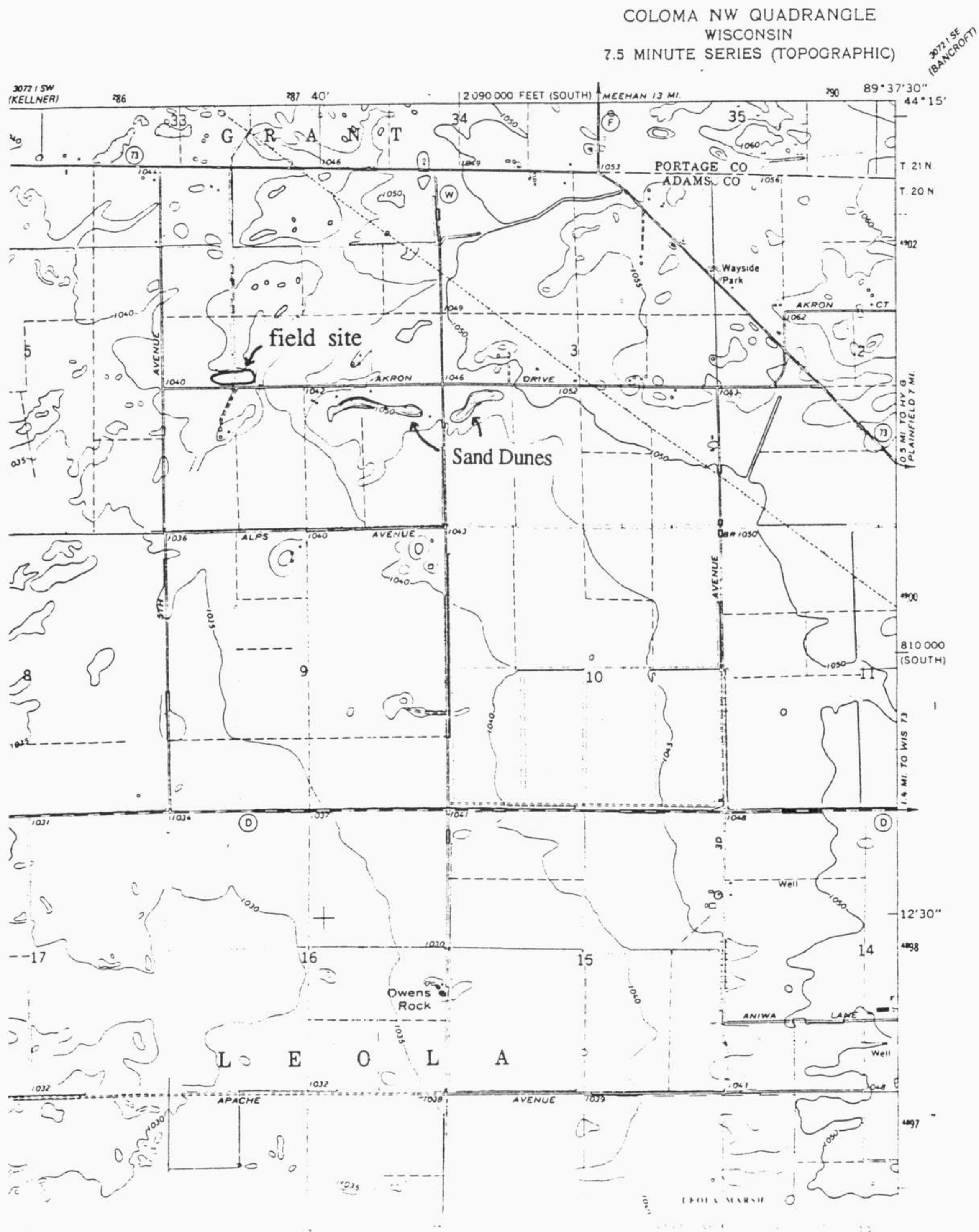


Figure 2.2 The area near the field site.

predominantly by poorly-lithified Cambrian sandstone bedrock. The bedrock beneath the northernmost portion of the central sand plain is Precambrian igneous and metamorphic rock (Brownell, 1986; Clayton, 1986, 1987). In the region to the south of the sand plain, the surficial deposits rest on very-well-lithified Precambrian Baraboo Quartzite or well-lithified Silurian dolomite. The poorly-lithified sandstone was easily eroded by geomorphic processes during the Quaternary and is probably responsible for the existence of the sand plain in central Wisconsin (Brownell, 1986).

The relief of the bedrock surface beneath the Quaternary sediments is over 150 feet (Faustini, 1985; Weeks and Stangland, 1971). It has been suggested that the preglacial topography may have looked similar to the driftless area today. There is evidence of a high degree of bedrock relief near the field site. According to a map of depth to bedrock by Weeks and Stangland (1971), the depth to bedrock at the field site should be about 120 feet; wells have been drilled at the field site to a depth of 65 feet with no evidence of bedrock. Two and a quarter miles south-southeast of the site there is an outcrop of well-lithified (presumably Cambrian) sandstone referred to as Owen's Rock, which stands 20 feet above the surrounding plain (Figure 2.2).

The Pleistocene glacial advances smoothed out the topography of central Wisconsin. Extensive deposits of glaciolacustrine and glacio-fluvial sediments were laid down. The early glacial history of the central sand plain is poorly understood. It appears that some early form of glacial Lake Wisconsin filled and drained one or more times prior to the last major resurgence of the glaciers about 25,000 B.P. As the glaciers advanced, glacial Lake Wisconsin gradually refilled and the offshore silt and clay deposits known as the New Rome Member (Brownell, 1986) were most likely deposited (Figure 2.3) (Clayton and Attig, 1989; Clayton, 1987). When the glacier reached its outer most position, forming the Johnstown moraine (also referred to as the Hancock moraine in Waushara County), the Lewiston Basin was covered by the glacier, causing Lake Wisconsin to drain out the Black River (Figure 2.3). Glacial meltwaters were then able to deposit sand well out into the basin and a broad meltwater stream plain developed between the glacier and Lake Wisconsin. When the ice melted back to the east end of the Baraboo Hills, the southern outlet of Lake Wisconsin opened and the lake drained extremely rapidly, probably in less than a week (Clayton and Attig, 1989; Clayton, 1987). Above the sandy glacial deposits in some portions of the central sand plain, over one meter of windblown sediment can be found (Clayton, 1986; Clayton, 1987). Small hills which appear to be sand dunes are found less than a mile east of the field site (Figure 2.2).

Figure 2.4 is a cross section showing Brownell's (1986) interpretation of the lithology in the region near the field site based on numerous bore holes. Clayton (1987) in his Pleistocene Geology of Adams County, Wisconsin has similar cross sections, but he interprets the New Rome Silt and Clay layer as being more discontinuous.

According to maps in Clayton and Attig (1989), the field site appears to be located near the edge of the maximum extent of glacial Lake

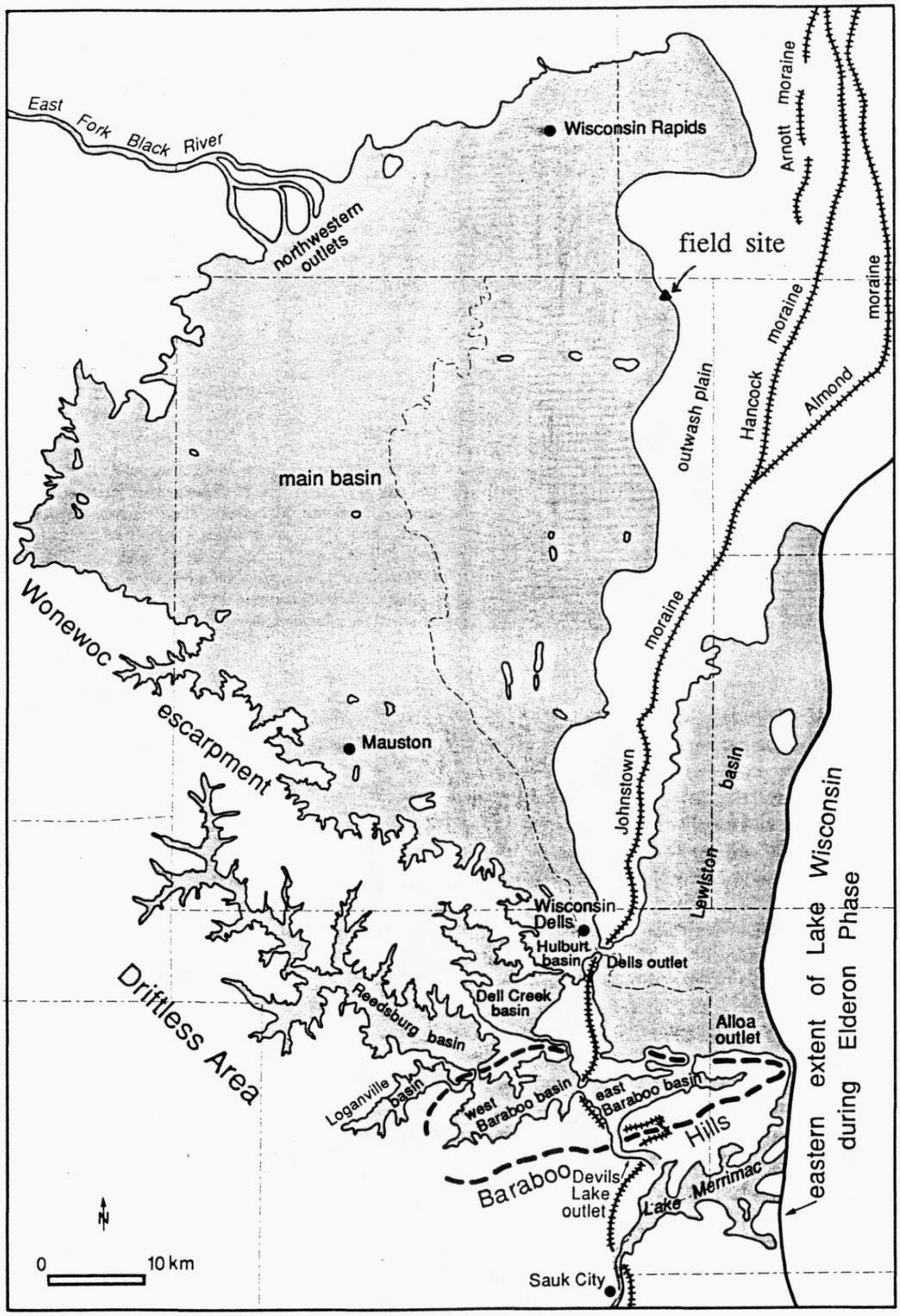
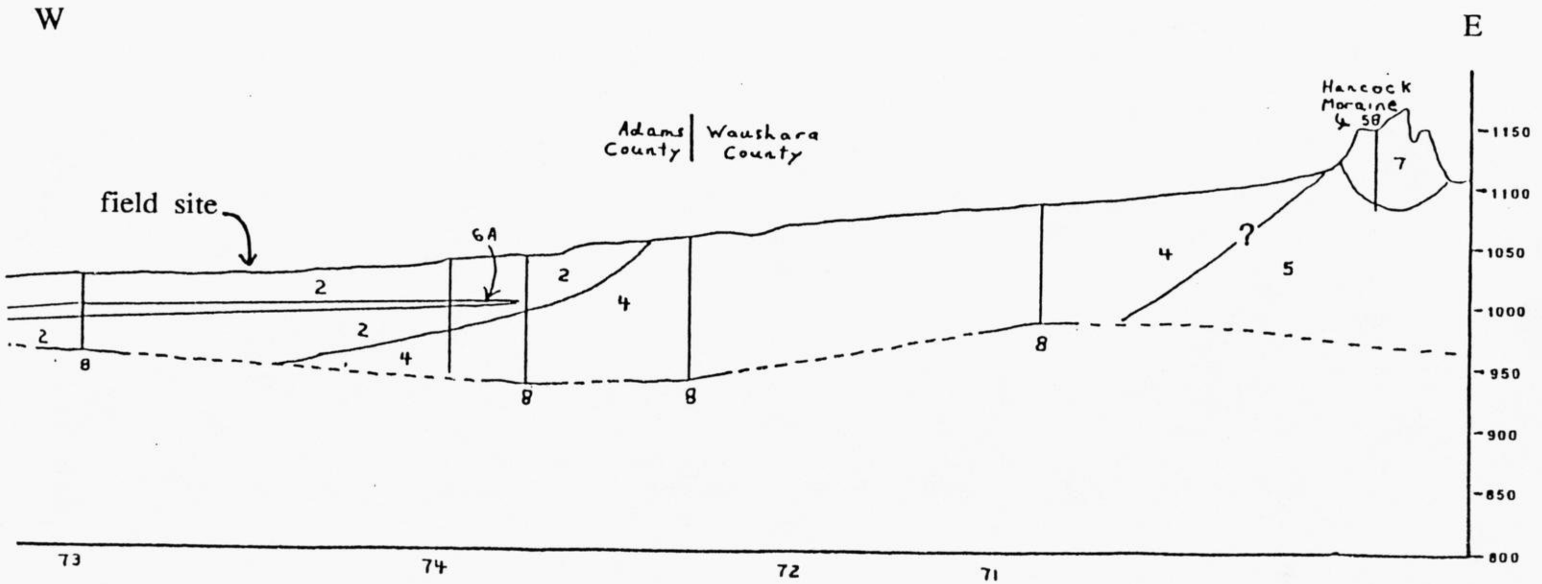
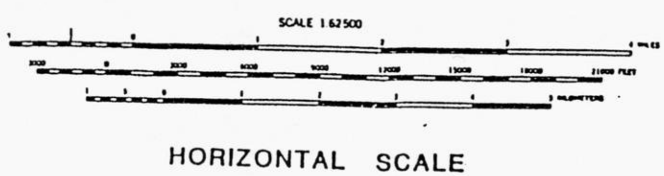


Figure 2.3 The location of Glacial Lake Wisconsin and associated glacial features during the Wisconsin glaciation (from Clayton and Attig, 1989).





Unit 2, 4, 5 are sand or sand and gravel

Unit 6A is silt and clay (New Rome Memeber)

Unit 7 is glacial till

Unit 8 is Cambrian sand and sandstone

Figure 2.4 A geologic cross section of the region of the central sand plain near the field site (from Brownell, 1986).

Wisconsin. Drilling at the site revealed the presence of a silt and clay layer, presumably the New Rome Member deposited in Lake Wisconsin. The silt and clay layer is found at depth of approximately 30 feet (elevation 1005 feet above sea level) and has a thickness of between 3 and 8 feet. The sediment above and below the silt and clay layer is sand down to a depth of at least 65 feet. Grain size analyses were run on two samples, one from 23 feet and one 45 from feet below land surface (See Appendix A). The shallower sample is well sorted fine sand and the deeper sample is moderately well sorted medium sand based on the Folk (1980) classification. The sample from 23 feet below land surface should be within Brownell's (1986) unit 2 (Figure 2.4), which is characterized as fine to medium sand that ranges from very-well-sorted to moderately well sorted. Occasional cobbles of fist size or smaller were also encountered during drilling and auguring.

Hydrogeology of the Sand Plain

The regional hydrogeology of a portion of the central sand plain was intensively studied by Faustini (1985). Faustini focused his work on the Buena Vista Basin, an area of approximately 170 square miles in southern Portage and southeastern Wood Counties, located to the north of the field site. The general groundwater flow direction in this region of the basin is east to west, with water flowing from the groundwater divide between the Almond and Hancock moraines toward the Wisconsin River. Faustini concluded that no regional flow existed within the Buena Vista Basin and that the lengths of individual flow paths are on the order of 3 to 4 miles long. He noted that groundwater flow paths can vary seasonally. In the spring, local flow is likely to be highly developed whereas in the late summer the drainage ditches most likely provide only a local influence and substantial underflow occurs. A study using tritium as an indicator of groundwater age was conducted by Bradbury (in press) in order to expand upon the work of Faustini. Bradbury concluded that the elevated tritium levels found in most of the groundwater samples collected, suggested that the groundwater in much of the Buena Vista basin is less than 30 years old.

In order to calculate the rate of groundwater movement, estimates of the hydraulic conductivity (K) and effective porosity (n) of the sediment and the horizontal hydraulic gradient (I) are needed. Groundwater velocity (v) can be calculated using the equation: $v = -(K\ I)/n$.

Hydraulic conductivity values have been estimated in numerous studies conducted in the central sand plain based on pumping tests (Holt, 1965; Weeks, 1964, 1969; Weeks and Stangland, 1971; Karnauskas, 1977; Rothschild, 1982), specific capacity tests (Bradbury and Rothschild, 1985), slug tests (Allen, 1985), permeameter tests (Stoertz, 1985), and grain size analyses (Brownell, 1986). Both Faustini (1985) and Stoertz (1989a) compiled tables of hydraulic conductivity estimates within the Buena Vista Basin. Stoertz compiled the data from over 400 tests or analyses and calculated the geometric mean and 95% confidence interval for each method. Based on 11 pumping tests the mean hydraulic conductivity is 250 ft/day (8.7 x

10^{-4}m/s). The mean conductivity for the other estimation methods ranged from 37 feet/day for permeameter tests to 181 ft/day for specific capacity tests. The vertical hydraulic conductivity should be somewhat lower due to the horizontal layering within the aquifer. Weeks (1964, 1969; Weeks and Stangland, 1971) calculated the ratio of horizontal to vertical hydraulic conductivity for 5 pumping tests which he conducted in the central sand plain. The calculated ratios ranged from 1 to 20, but Weeks and Stangland (1971) felt that the ratio of 20 was anomalous, and that the ratio was likely to range from 1 to 7 for most of the sand plain.

According to water table maps of the sand plain counties (Lippelt and Hennings, 1981), the regional horizontal gradient ranges from approximately 0.0003 to 0.005. For this range of gradients, the velocity of the shallow water within the sand plain is likely to vary between approximately 0.2 ft/day and 4 ft/day given a hydraulic conductivity of 250 ft/day and a porosity of 0.32 (Holt, 1965). The variation in velocity may be even larger given the range of hydraulic conductivity values calculated for the sand plain.

Hydrogeology of the Field Site

The regional water table slopes toward the west-southwest, with a gradient of approximately 0.0015 in the vicinity of the field site according to a water table map of Adams County (Lippelt and Hennings, 1981). Numerous wells have been installed at the field site in order to assess the local hydrogeology. Details on well installation, location of wells, and monitoring can be found in Chapter 3.

Water levels measured in these wells demonstrate that the drainage ditch at the field site locally perturbs the flow system. (Appendix B is a record of water levels.) Figure 2.5 is a map of the water table in early June of 1989, after there had been a large recharge event. On the east side of the ditch, the water table slopes toward the ditch with a gradient of greater than 0.007. On the west side of the ditch, the water table slopes toward the ditch with a gradient around 0.004.

During the summer of 1989, water levels gradually dropped and the local water table gradient near the ditch decreased, as can be seen in Figures 2.6 and 2.7. The gradient on the east side of the ditch decreased to less than 0.004. On the west side of the ditch the water table flattened out until the gradient was barely measurable. In the previous summer, due to drought conditions, the water table dropped even further and the water table gradient on the east side of the ditch decreased to less than 0.003.

Vertical gradients were calculated from water levels measured in water table wells and the deeper injection wells both located about 20 feet east of the ditch. Within the upper aquifer (the region above the clay and silt layer) there appears to be slight upward gradient, but the difference in water levels between the deep and shallow wells is within measurement error ($\pm$ 0.02 feet). There is a strong vertical gradient across the silt and clay layer (30 feet below land surface). In the lower aquifer water levels

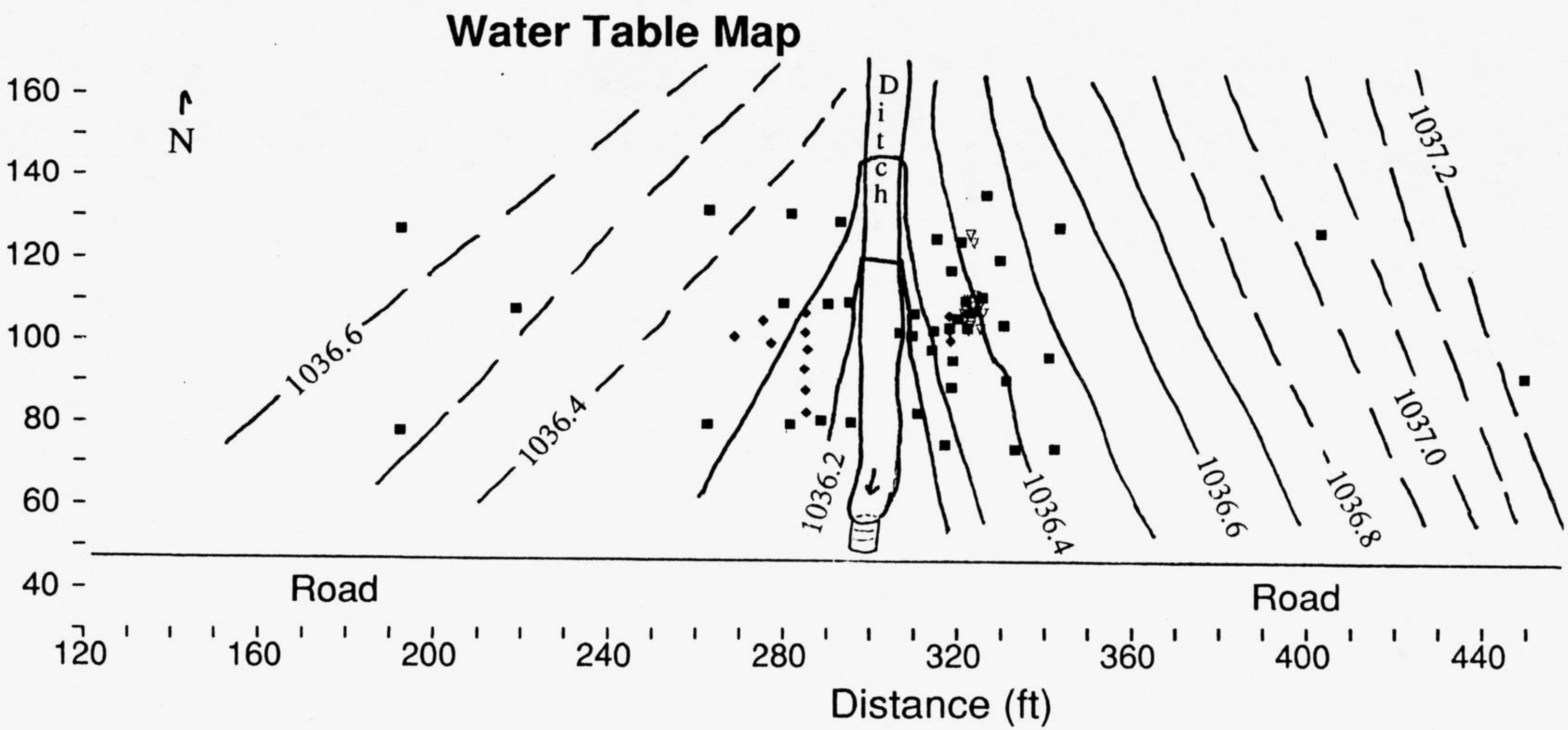


Figure 2.5 Water table map of the field site on June 4, 1989. Squares represent water table wells, diamonds represent multilevel wells and upside-down triangles represent injection wells.

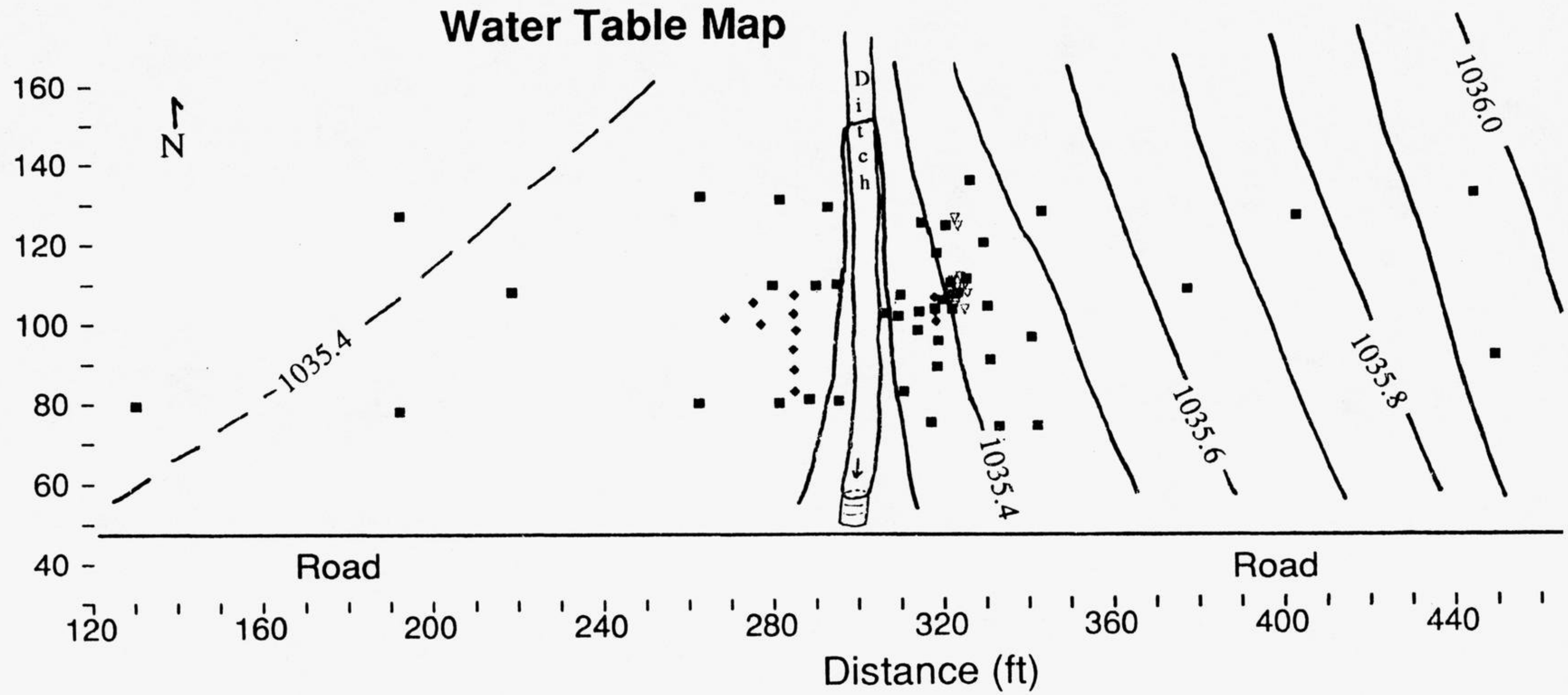


Figure 2.6 Water table map of the field site on July 16, 1989. Squares represent water table wells, diamonds represent multilevel wells and upside-down triangles represent injection wells.

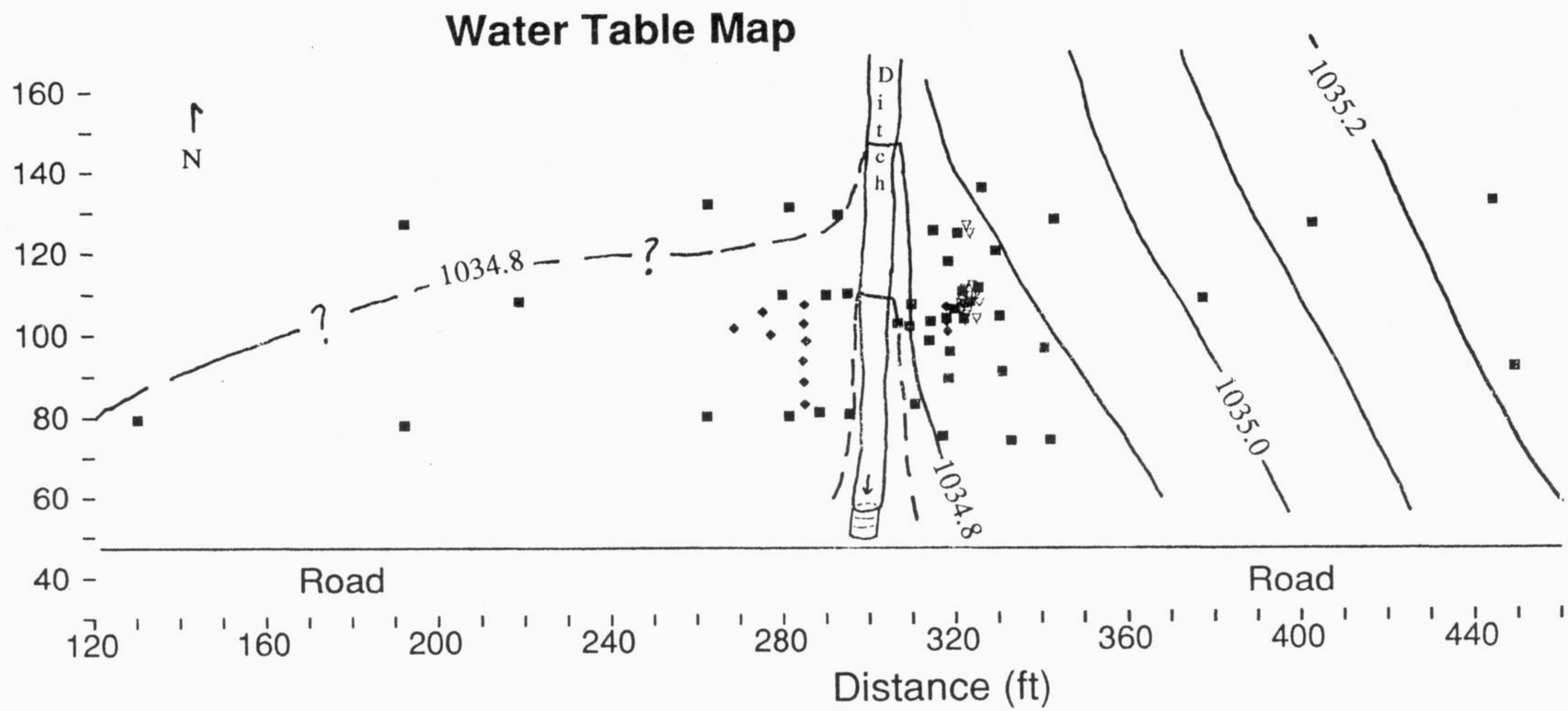


Figure 2.7 Water table map of the field site on September 23, 1989. Squares represent water table wells, diamonds represent multilevel wells and upside-down triangles represent injection wells.

are approximately one foot higher than water levels in the upper aquifer.

Water levels at the field site fluctuate about 2 feet seasonally. Figure 2.8 shows the water level fluctuations for wells Wt2 and Wt5 and the ditch from July 1988 to March 1990. The record for the staff gauge in the ditch is incomplete, because the staff gauge was not installed until May 1989. From Figure 2.8, it is apparent that the primary period of recharge is in the spring and early summer and that significant recharge also occurs in the fall.

At the bottom of Figure 2.8 is a record of daily precipitation (NOAA, 1988, 1989) from the Hancock Research Station, located less than 10 miles southeast of the field site. Hancock gets an annual average rainfall of 29.6 inches a year. Stevens Point, about 20 miles north of the site, gets an average of 30.9 inches a year and Wisconsin Rapids, about 15 miles northwest of the site, gets an average of 31.9 inches a year. Anderson (1986), suggested that recharge in the central sand plain might be as high as 15 inches a year. Recent work by Stoertz (1989b) suggests that recharge may be as low as 7 to 10 inches a year.

The middle portion of Figure 2.8 is a record of the height of water in mini-piezometer number 1, in feet, above the ditch level. (This is similar to a record of the vertical gradient beneath the ditch.) It should be noted that the middle portion of Figure 2.8 shows the difference between the head in the aquifer beneath the ditch and the head in the ditch; this implies that when this value and the ditch stage rise, the level of the head in the aquifer must rise more than the ditch stage. As would be

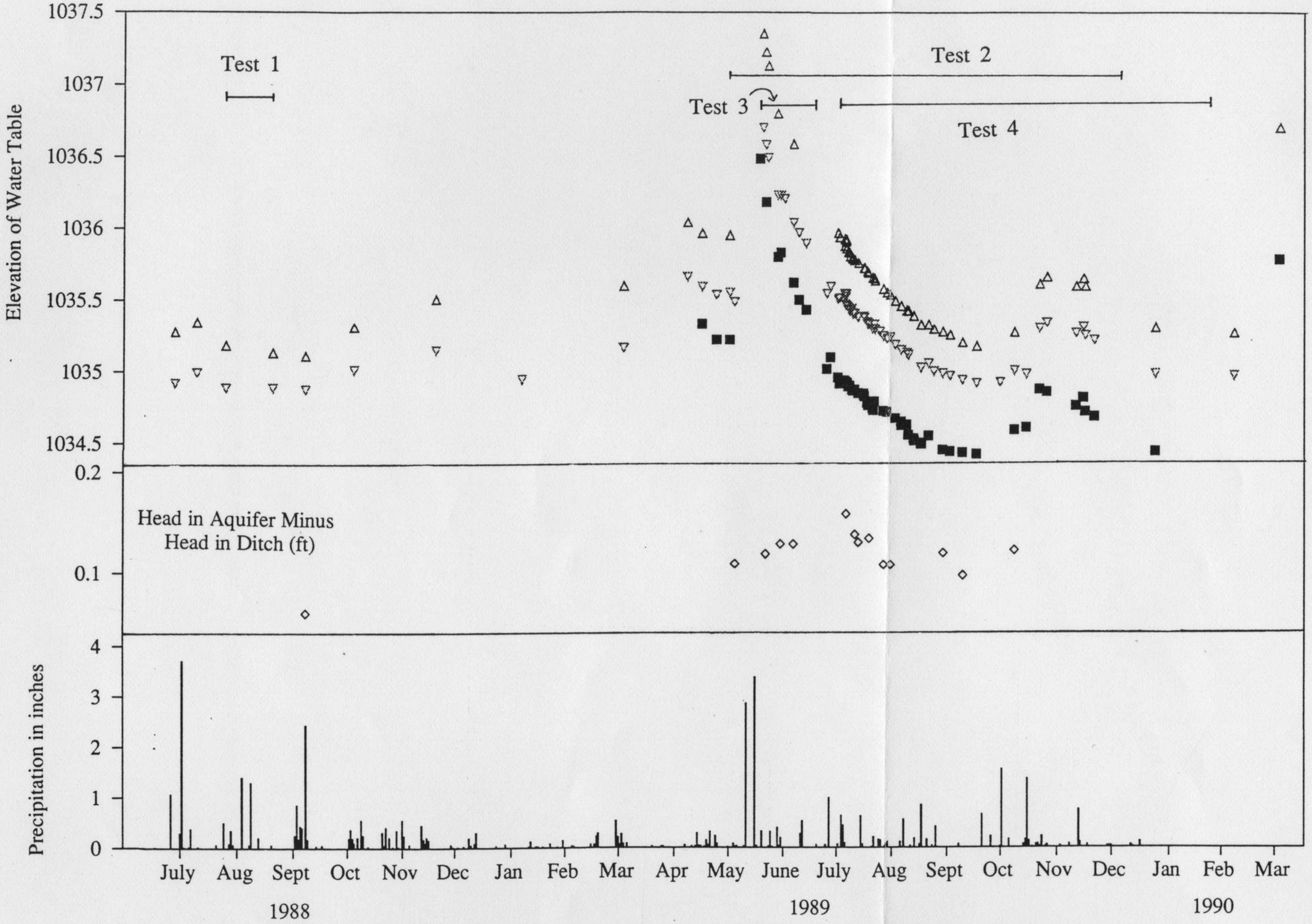


Figure 2.8 The top portion of this graph represents water level fluctuations in feet above sea level. The triangle and the upside down triangle represent the water level in water table wells, Wt5 and Wt2, respectively. The squares represent the water level in the ditch. (The staff gauge was not installed until early May, 1989.) The middle region of this diagram represents the fluctuation in the head in the ditch (at mini-piezometer 2) minus the head in mini-piezometer 2. The bottom portion of the diagram is the daily precipitation record for Hancock, WI which is located about 10 miles southeast of the field site.

expected, after a period of recharge, the water level in the mini-piezometer rises. The ditch level initially rises faster than the level in the mini-piezometer, but as the ditch level drops, the water level in the mini-piezometer continues to rise. Thus, there is a slight time lag between the rise in the ditch stage and the rise in the difference between the water level in the mini-piezometer and the water level in the ditch.

III. TRACER TEST DESIGN

A series of natural gradient tracer tests were conducted at the field site. The design of these tracer tests evolved, as each new test suggested modifications in injection rates, concentration, and sampling frequency. Additionally, each test provided more information on tracer spreading during injection and on the variability of groundwater flow rates and directions. This information was in turn incorporated into the design of subsequent tests. This chapter describes tracer test design factors including methods of well installation, choice of well location, injection and monitoring of tracer.

Well Installation

A variety of different types of wells were installed at the field site. Shallow wells were installed in order to delineate the water table and determine the direction of shallow groundwater flow. Mini-piezometers were installed within the ditch in order to evaluate the vertical gradients. Injection wells for the injection of tracer were installed to deeper depths. Multilevel and miniature multilevel sampling wells were installed for sampling tracer at different discrete levels within the aquifer. In this section, the method of installation of each well type will be briefly discussed. Additional information on screen or sampling point elevation, screen length, well diameter, location and date of installation can be found in Appendix C.

Water Table Wells and Mini-piezometers

Water table wells were installed by using both a hand auger and an auger mounted on a trailer, since the water table was relatively shallow (1-6 feet below land surface). All wells were constructed from schedule 40 PVC ranging in diameter from 0.75 inch to 2 inch. For all water table wells the top of the screen was located above the water table except for a few wells which were submerged by up to 0.5 feet during periods of elevated water levels in the spring. Mini-piezometers of the sort described by Lee and Cherry (1978) were installed within the ditch to depths of between 2 and 7 feet below the base of the ditch.

Injection Wells

Injection wells with total depths ranging from 5 to 27 feet below land surface were installed using a truck mounted drill rig to auger to a depth slightly below the desired depth. Due to the non-cohesive nature of the sandy sediment, when the auger was removed the hole collapsed and considerable force was needed to push the wells down to their intended depth. The injection wells were constructed from 2 inch schedule 40 PVC with flush threaded joints and screen lengths varied from 1.5 to 7 feet.

Multilevel Sampling Wells

Multilevel sampling wells of the type used by Jackson et al. (1985) were installed during the summers of 1988 and 1989. Each multilevel well consisted of a backbone of 0.5 or 0.25 inch schedule 80 PVC pipe to which approximately 20 tubes of 0.25 inch (outer diameter) polyethylene tubing was attached. The end of each tube had a fine nylon mesh (bridal organdy) wrapped around it to form a screen for the sampling point. Sampling points were spaced at either 1.5 or 3 foot intervals. Multilevel sampling wells were installed by drilling a hole with a hollow stem auger, lowering the multilevel bundle down the inside of the auger and then removing the auger, leaving the multilevel in the ground.

Miniature Multilevels

As the name suggests, miniature multilevels are similar to the large multilevels except they have only 3 sampling points and no PVC backbone. The technique of miniature multilevel installation was initially pioneered in the spring of 1989 by Will Stites (1989, personal communication) and was first used at the field site in June of 1989. The method was further refined as additional miniature multilevel wells were installed at the field site. Each miniature multilevel consisted of a bundle of three 0.25 inch polyethylene tubes with nylon mesh points as described above. The sampling points were evenly spaced at measured intervals between 0.5 and 3 feet, depending on the position in the aquifer. The tubes were fastened to each other using cable ties and duct tape.

The installation of miniature multilevels was similar to that for mini-piezometers; it involved driving a narrow steel pipe with a point on the end down into the ground. The pipe served as a temporary casing into which the bundle of flexible polyethylene tubing was inserted. The pipe was then withdrawn leaving only the tubing (and a disposable metal point) in the ground. Appendix D (Stites and Chambers, in press) gives a detailed description of this method.

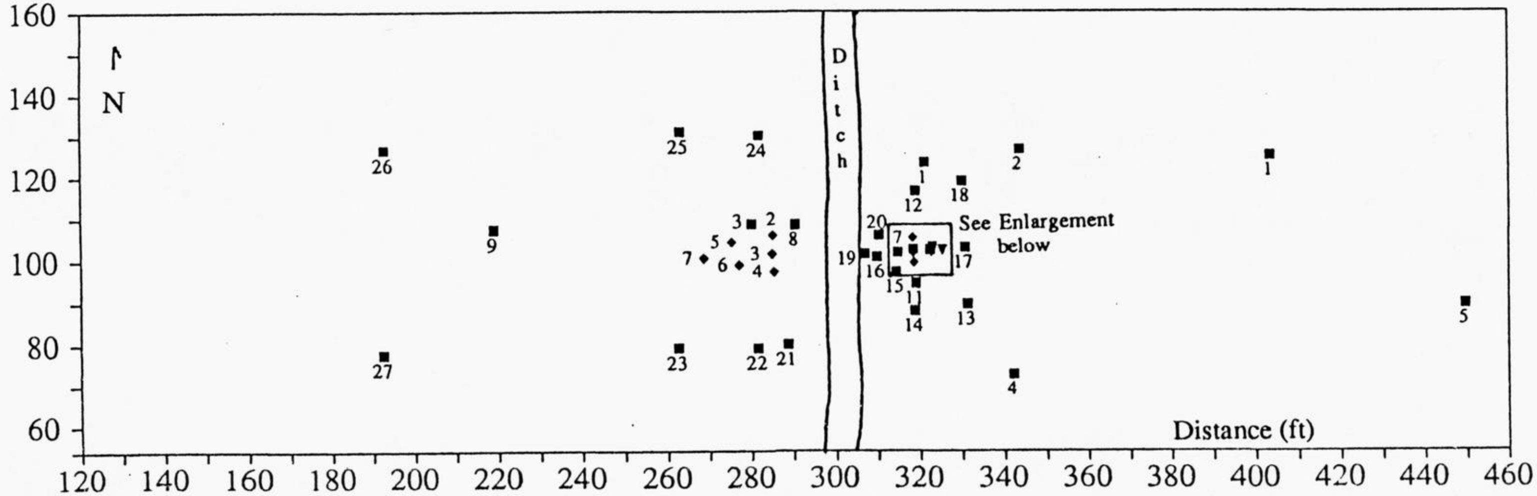
Large multilevels can provide up to 25 vertically spaced sampling points at a given location. However, installation of multilevels with this many points requires drill rig access and is relatively expensive. This method also causes considerable disturbance of the aquifer since the hollow stem auger creates a 6 inch hole and the inside of the auger must be filled with water prior to putting the multilevel down the hollow stem auger. In contrast, the installation of miniature multilevel sampling wells causes very little disturbance of the aquifer, since the hole created is approximately 1 inch in diameter. Miniature multilevels can also be installed within the ditch and numerous places where drill rig access is impossible. In addition, the installation of miniature multilevels requires only hand tools and the equipment and materials are easily obtained and inexpensive.

Location of Wells

The initial tracer test design assumed that the groundwater flow within the aquifer was uniform and close to perpendicular to the ditch.

This assumption was made by Zheng et al. (1988a) in constructing his two-dimensional profile model. Based on a regional groundwater flow map (Faustini, 1985), and 5 initial water table wells (Wt1 to Wt5), it appeared that the groundwater flow path was roughly perpendicular to the ditch. The original array of wells consisted of 3 injection wells (IW1, IW2, IW3), each at a different depth, and 9 multilevel sampling wells (Ml1 to Ml9) (Figure 3.1). Tracer was introduced into one injection well (IW1 for test 1) and the path of the tracer was monitored by sampling from the multilevel sampling wells. The initial tests revealed that under the conditions present in August of 1988, the groundwater flow at 6 to 12.5 feet below the water table was not perpendicular to the ditch (Figure 3.1). The installation of additional water table wells and repeated surveying showed that the water table sloped gently toward the east-southeast, with a gradient of approximately 0.003 near the ditch. Due to the apparent direction of groundwater flow in the summer and fall of 1988, additional multilevel and/or injection wells were clearly needed in order to delineate the flow path of the tracer.

In May of 1989, additional injection wells were added to the north of the already existing injection wells, so that a tracer test (test 2) could be started using the existing array of multilevel sampling well (Figure 3.2). The location of the 3 deep wells (screened from 15.6 to 22.5 feet below the average water table), 2 injection (IW4, IW5) and 1 monitoring well (MW1, screen 1 foot deeper), were selected based on the apparent groundwater flow direction from tests conducted in the summer of



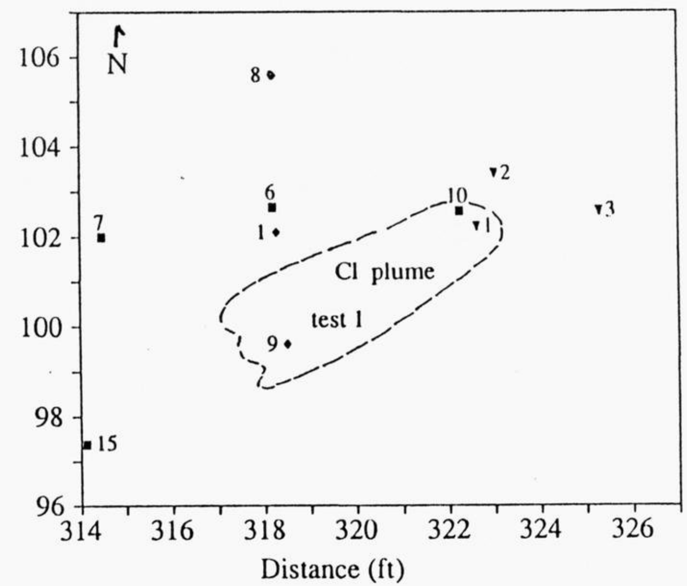
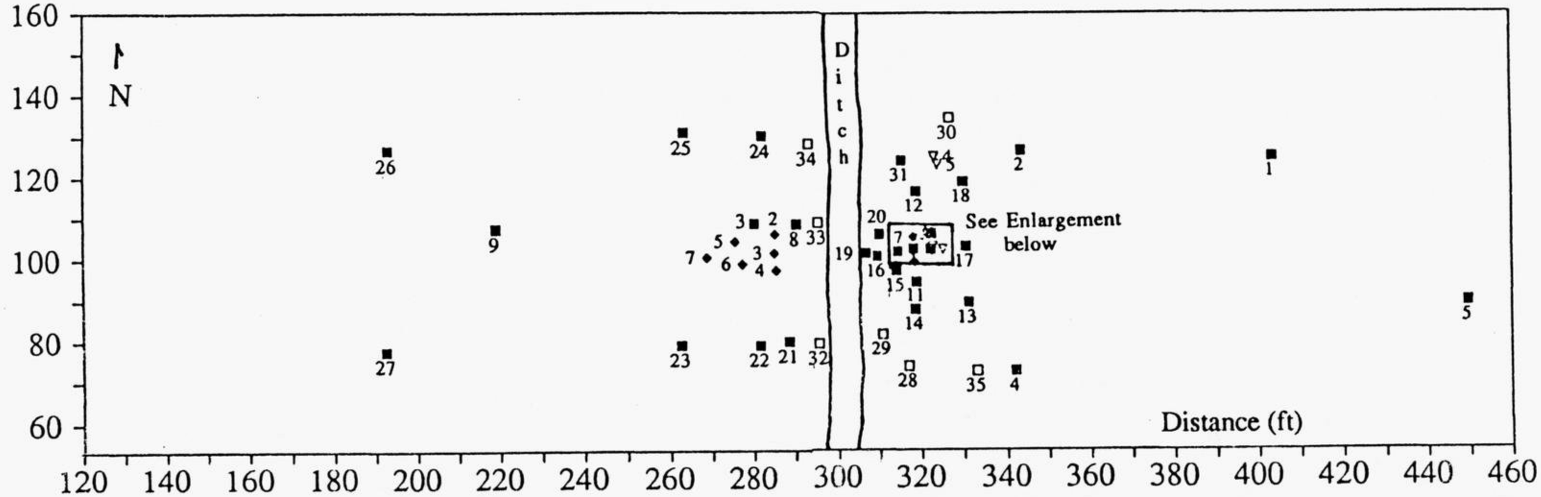


Figure 3.1 Location of all wells installed at the field site in the fall of 1988. The squares represent water table wells (Wt), the triangles represent injection wells (IW) and the diamonds represent multilevel sampling wells (Ml). The expanded view of the area near the injection wells shows the flow path of the tracer plume in the first tracer test.



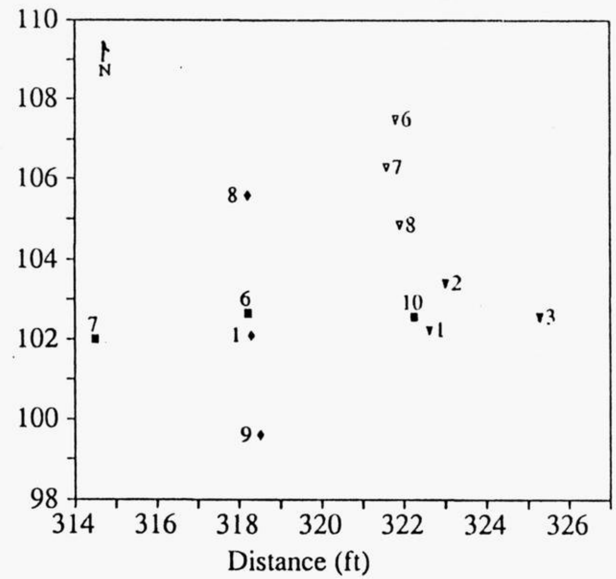
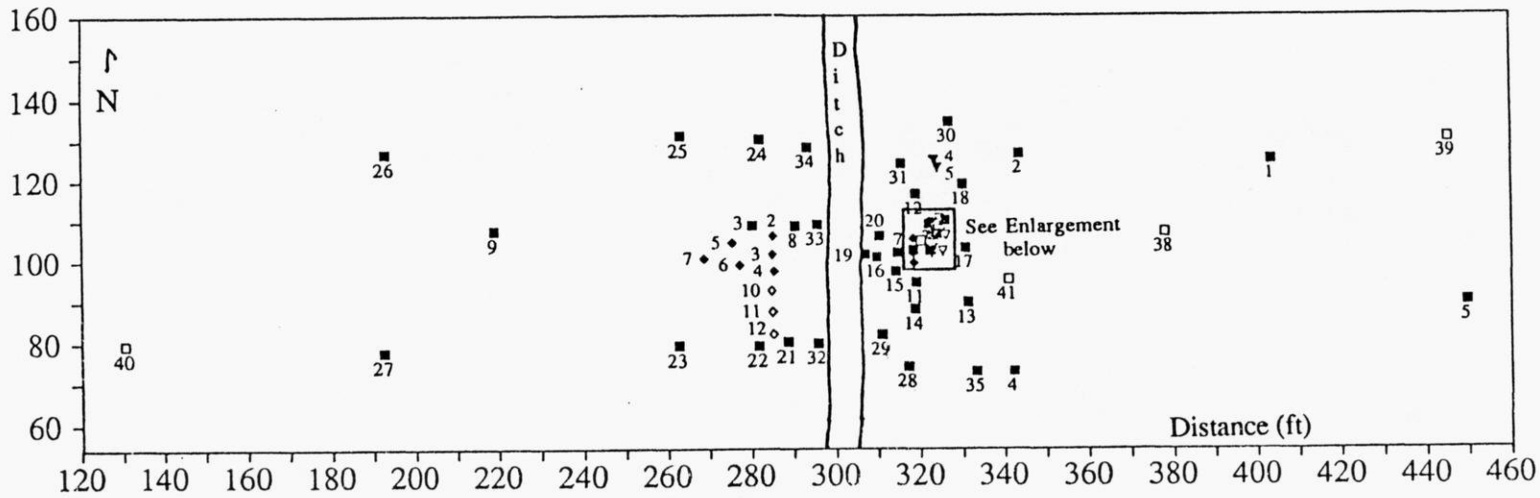


Figure 3.2 Location of all wells installed at the field site in May, 1989. The squares represent water table wells (Wt), the triangles represent injection wells (IW) and the diamonds represent multilevel sampling wells (Ml). The open squares and triangles represent well that have been added since the previous fall. The enlarged area shows more detail in the region near the injection wells.

1988. Three shallow injection wells (IW6, IW7, IW8) and a few shallow monitoring wells and water table wells were also installed for a shallow tracer test (test 3).

In June, additional multilevel sampling wells (Ml10, Ml11, Ml12) were added on the west side of the ditch, to the south of the existing multi-level wells (Figure 3.3). Additional injection wells (IW9 to IW14) and water table wells were also added. These wells were installed for a large scale tracer test (test 4) which involved injection of tracer at three different levels. A detailed chronology of the tracer tests can be found below in Table 3.1 and in Chapter 4.

The use of the miniature multilevel installation technique brought about a major improvement in tracer test design. Prior to June 1989, the only sampling points available for monitoring the path of the tracer plume after it moved beyond the injection well(s) were in a small number of multilevel sampling wells. Only by installing numerous miniature multi-level wells was it possible to gather enough detail about the tracer flow path. Some miniature multilevels were added prior to the start of the tracer test along the expected tracer path. Additional miniature multi-level wells were added as the test progressed in order to delineate the path of the tracer. Figure 3.4 shows the location of all miniature multilevels, and injection wells installed to date.



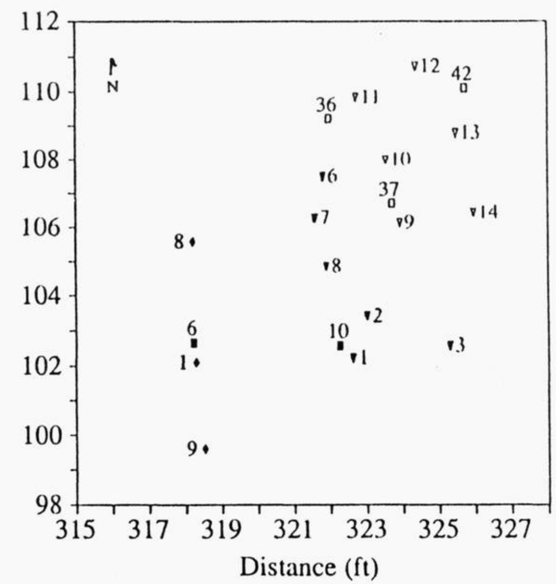


Figure 3.3 Location of all wells installed at the field site in July, 1989. The squares represent water table wells (Wt), the triangles represent injection wells (IW) and the diamonds represent multilevel sampling wells (Ml). The open squares, triangles and diamonds represent well that have been added since the previous May, 1989. The enlarged area shows the many injection wells which were installed for tracer test 4.

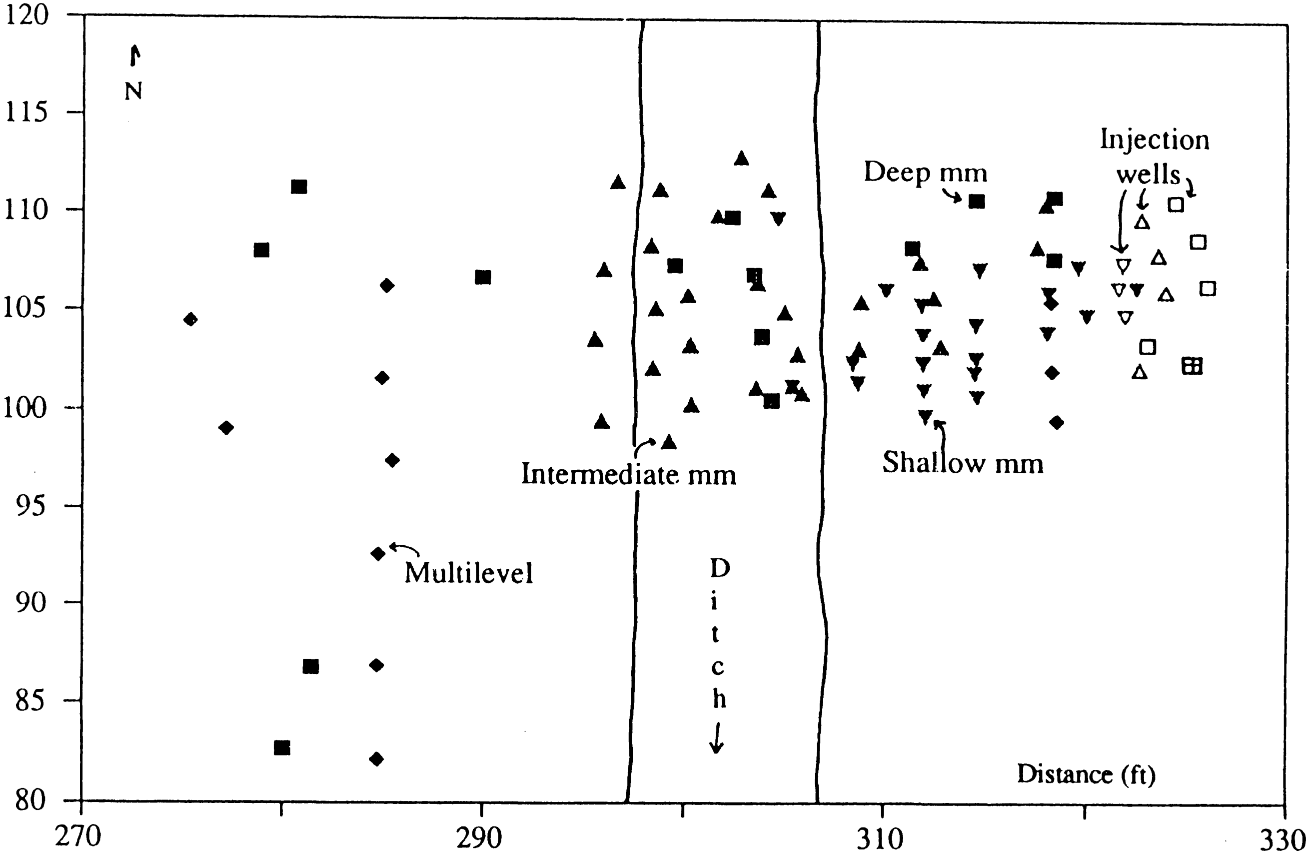


Figure 3.4 This diagram shows the location of all multilevel and miniature multilevel wells at the field site. The open triangles and squares represent injection wells and the solid triangles and squares represent miniature multilevel wells (mm). The squares represent the deeper multilevels of the depth for monitoring the tracer injected into the deeper injection wells (squares). The triangles are for monitoring at an intermediate depth and the upside down triangles are very shallow miniature multilevels and monitoring wells. The diamonds represent multilevel wells.

Tracer Injection

For each tracer test, a dilute solution of a conservative ion was injected over a period of several hours into one or more of the wells. The injection process temporarily perturbed the natural hydraulic gradients of the system, causing tracer to flow out radially from the well across the screened interval at the base of the well. Within a half hour after injection ceased, the water levels returned to normal and the movement of the newly created plume was governed by the groundwater flow field and aquifer heterogeneities. In each test a volume between 100 and 900 liters of tracer was added. The tracer plumes for these tests are small compared to the plumes created for the large scale tracer tests at the Borden Site (Mackay et al., 1986) or the Cape Cod Site (LeBlanc et al., 1987) where 12,000 liters and 7,600 liters were injected respectively. Details about the injection of each tracer are compiled in Table 3.1. The variation in methods of tracer injection and tracer concentrations are described in the following sections.

Injection Method

With the exception of the first test, the tracer solution was injected into more than one well, so as to insure that the plume would be wide enough that the tracer could easily be detected over significant distances. In the first 3 tests, peristaltic pumps were used to pump the tracer solution into the wells. For a short period of time during each test, the

Table 3.1 Injection Information

Test Number	1	2	3	4a	4b	4c
Date	8/7/88	5/15/89	6/2/89	7/16/89	7/17/89	7/17/89
Wells	IW1	IW4,5	IW6,7,8	IW7	IW9,10,11	IW12,13,14
Elevation of Screen (ft)	1022.5-1028.8	1012.9-1019.8	1033.5-1034.9	1033.5-1034.9	1024.4-1029.1	1014.4-1019.1
Tracer	Cl^-	Cl^-	Br^-	I^-	Br^-	I^-
Concentration in (g/l)	11	2.6	1	0.5	1	1
(moles/liter)	0.3	0.07	0.012	0.004	0.012	0.007
Injection Rate (l/hr)	86	100	100	45	235	235
Duration (hr)	3	9	5	2.3	3	3.4
Volume (l)	260	896	509	102	705	800

rate of injection was increased by slowly pouring the tracer directly into the well through the spigot of a carboy. This additional spreading of the plume was desirable in order to increase the likelihood of detecting the plume in wells down gradient. For the fourth test carboys with spigots were used for injection, because peristaltic pumps with a sufficiently high capacity were not available. The flow from the carboy spigots was carefully monitored during injection and carboys were kept nearly full so as to keep the flow rate relatively uniform.

In the first test, chloride was injected into IW1 (at an elevation of 1022.5 to 1028.8 feet) for 3 hours on August 7, 1988. The second test also used a chloride solution, which was injected over a period of 9 hours into IW3 and IW4 (1012.9 to 1019.8 feet) on May 15, 1989. The third test, which began on June 2, 1989, used bromide as the tracer. The bromide was injected into IW5, IW6, and IW7 (1033.5 to 1034.9 feet) for a period of 3 hours. The fourth tracer test included the injection of tracer at 3 different levels within the aquifer on July 16 and 17, 1989. Iodide was injected for a duration of 3.5 hours into IW7 (1033.5 to 1034.9 feet) on the afternoon of July 16. Bromide was injected into IW9, IW10, IW11 (1024.4 to 1029.1 feet) over a 3 hour interval in the morning on July 17 and iodide was injected for 3 hours into IW12, IW13, IW14 (1014.4 to 1019.1 feet) in the afternoon.

Tracer Solutions

The tracer solution was mixed in carboys by combining a measured amount of a crystalline form of sodium chloride, potassium chloride, potassium bromide, or potassium iodide with approximately 20 liters of groundwater from the site. The water had been bailed or pumped into the carboy from a well at least 40 feet from the injection well before or during the test. In order to maintain the tracer solution close to that of ambient groundwater temperature, as opposed to the air temperature, some water for injection was removed from the aquifer during the tracer test. During test 4, the tracer solution was also temporarily stored in new plastic garbage cans with insulation wrapped around them.

In the first test a high concentration of chloride (11 g/l) was injected because during a preliminary tracer test a few weeks earlier the tracer had been injected but was never detected at the monitoring well. At the time, dilution was considered a possible reason why the tracer was never found. For test number 2 a larger volume of potassium chloride solution, with a lower concentration (2.6 g/l) was injected. The tracer was injected into two wells over a 9 hour period in an attempt to create a wide plume, which could be detected over a long distance. In test number 3, a 1 g/l solution of potassium bromide was injected into 3 wells in order to examine the shallow flow system and to test the viability of the miniature multilevel method for use in a larger scale tracer test. In the fourth test, two tracers were injected at 3 different levels over the course of 2 days in order to delineate the flow field at different levels within the aquifer. For tracer test number 4, iodide and bromide were both injected into 3 wells at concentrations near 1 g/l. Iodide tracer was also injected at a lower concentration (0.5 g/l) in a shallower well. A lower concentration was injected at the shallower depth because it was known that the tracer spreading would be limited due to the short path of the shallow plume.

Monitoring of Tracer

In order to delineate the path of the tracer plumes, samples were collected frequently from multilevel and miniature multilevel sampling wells and a few monitoring wells. Sampling from a multilevel sampling point allowed the collection of a water sample from a discrete interval within the aquifer. In contrast, a sample from a monitoring well would come from a region of the aquifer equal to the screen length (0.5 to 7 ft). Thus the sample would be a mixture of the concentrations along the screen length. Details of sample collection and analysis, as well as sampling frequency are provided below.

Sample Collection and Analysis

Prior to sample collection, at least two to three well volumes were pumped from a sampling point. This volume amounted to only 150 to 500 ml depending on the length of the sampling tube. After at least one well volume had been removed, a preliminary sample was collected, and the electrical conductance was measured. The conductivity of the water gave an approximate estimate of the concentration of the tracer present. (In the first test only electrical conductance was used to estimate the tracer concentration.) This was important for determining which portions of the sampling array should be monitored most frequently. Samples were collected in 120 ml polypropylene cups which were labeled and stored for lab analysis.

The samples were analyzed in the lab with an Orion specific ion electrodes. Before and after analyzing a group of samples the electrodes were standardized in solutions close to the concentrations of the samples. If samples were analyzed for over 1.5 to 2 hour, the electrodes were restandardized to check for electrode drift. Ionic strength adjuster (a 5M sodium nitrate solution) was added to all samples suspected of containing tracer prior to the final analysis; 2 ml were added per 100 ml of sample. The Chemcadet electrode meter displayed the electrode potential in millivolts. Millivolt readings were converted to concentrations by calculating the electrode slope for each round of samples analyzed using the average millivolt value of the standards.

Sampling Frequency

Sampling frequency varied from test to test. As the tracer plume patterns were better understood, less frequent sampling was needed. In test number 1, samples were collected every 4 to 6 hours for the first 3.5 days of the test, until the tracer was detected at a sampling point in Ml8 (see Figure 3.1). Groundwater velocities were not known at this time and it was difficult to predict the time period over which tracer would be found at the sampling well.

Test number 2 was begun before the miniature multilevel installation method had been adapted for use at this site. It might be referred to as a hit or miss test because after the plume moved beyond MW1, there were no other monitoring wells on the east side of the ditch. Once the chloride tracer was detected on the west side of the ditch, samples were collected approximately once a week.

In the third test, samples were collected twice a day for the first 6 days, since groundwater velocities were high. For the rest of the test tracer was collected every 2 to 4 days.

In the fourth test samples were collected frequently from sampling points where it was predicted that tracer might be found. For the first 11 days, samples were collected at least once a day. Samples were collected at least every other day for the first month of the test. During the first month samples were collected more frequently at wells that were estimated to be near the center of mass of the plume. For the second month of the test samples were collected on average every third day. After the first two months, samples were collect once a week. For tracer test four alone a total of over 2,500 samples were collected and analyzed.

IV. RESULTS

This chapter presents the results of the tracer tests, with tracer movement displayed through a series of maps and cross sections. The predictive capabilities of the analytic solution by Zheng et al. (1989a) are also evaluated through an examination of the sensitivity of the analytic solution, using data collected at the field site.

Tracer Test Results

The results of tracer test conducted during the summer of 1988, 1989 are discussed. Preliminary results of tracer tests conducted during the summer of 1990 are also described. The fourth test conducted at the field site provided the best resolution of the tracer paths as a result of the improved sampling network and better understanding of the flow system. Therefore, the discussion of results will focus primarily on the results of the fourth test.

The First Test

In the first tracer test, a solution of sodium chloride was injected at 6.4 to 13 feet below the water table on the seventh of August, 1988. Due to the limited number of multilevel sampling wells, the tracer was only detected at one multilevel (ML9) (Figure 3.1). Figure 4.1 shows a cross

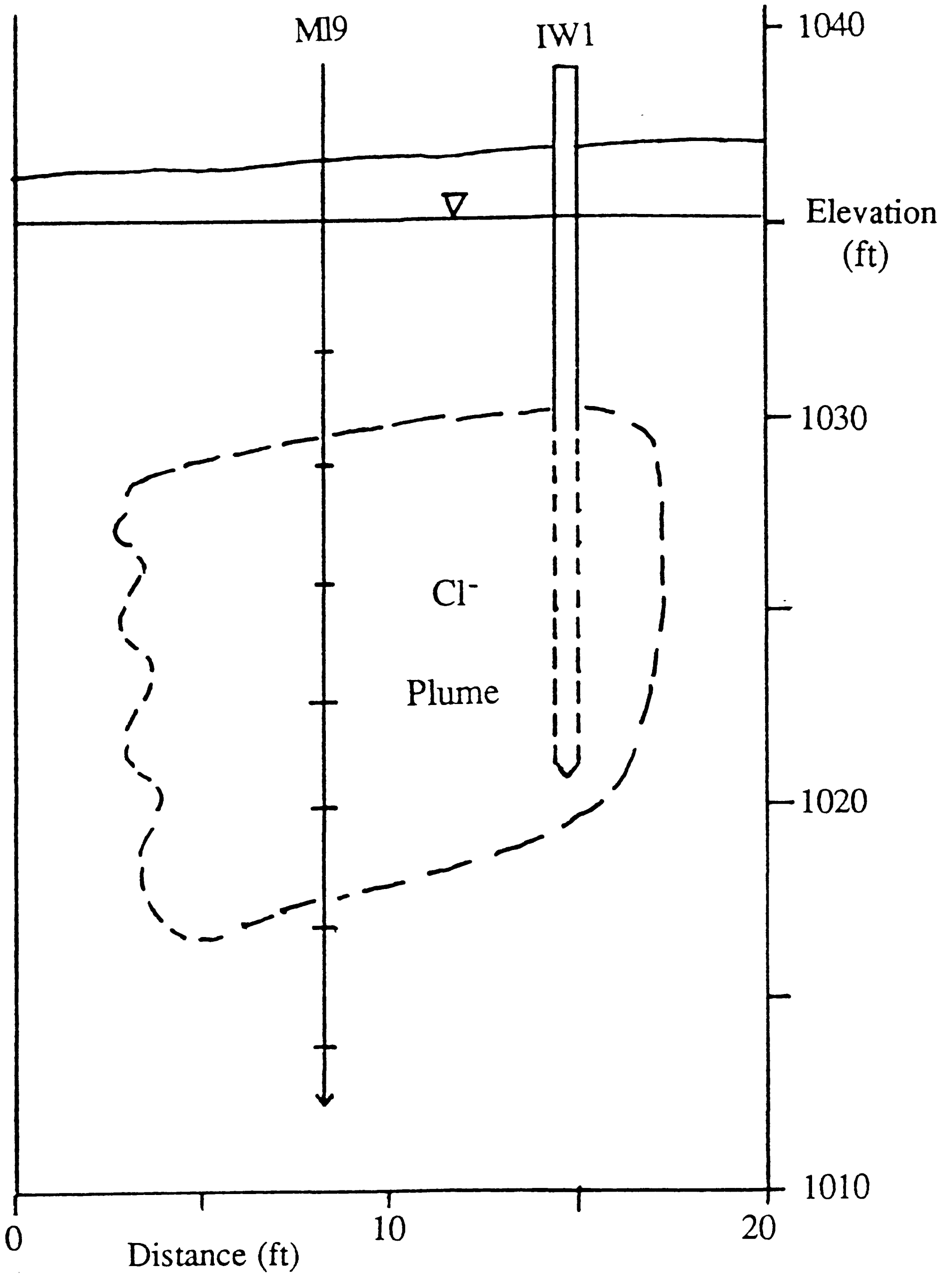


Figure 4.1 Cross section of the detectable total movement of the chloride plume in test 1. Note how the plume appears to be sinking. See Figure 2.1 for a plan view diagram.

section of the total movement of the tracer plume. The tracer appears to be sinking, suggesting that the flow path is influenced by the density of the solution. (The injected concentration was high, 11 g/l, to ensure that the tracer would be detected.) The tracer moved at an average rate of 0.7 ft/day in the distance from the injection well to the multilevel. This is likely to be an overestimate of the groundwater velocity at 6 to 13 feet below the water table, because the process of injecting the tracer temporarily perturbed the flow system.

The Second Test

In the second test, a potassium chloride solution was injected on May 15, 1989 at 15.7 to 22.5 feet below the water table. The overall flow path (Figure 4.2) of the chloride tracer appears to be similar to the deeper iodide plume in test 4, which was injected at approximately the same depth two months later. The chloride plume moved at an average rate of about 0.3 ft/day. Because chloride was only detected at a very few wells, the exact path and velocity of the tracer is not well defined. A vertical cross section of the entire tracer flow path near the assumed longitudinal axis of the plume (Figure 4.3), also indicates a flow path similar to that of the iodide plume in test 4. The flow path of the chloride tracer beyond mm30 is not known. A small number of sampling wells, combined with cold weather and relatively infrequent sampling after early December meant that it was not possible to resolve whether the tracer flowed back toward the ditch or flowed on beyond mm30.

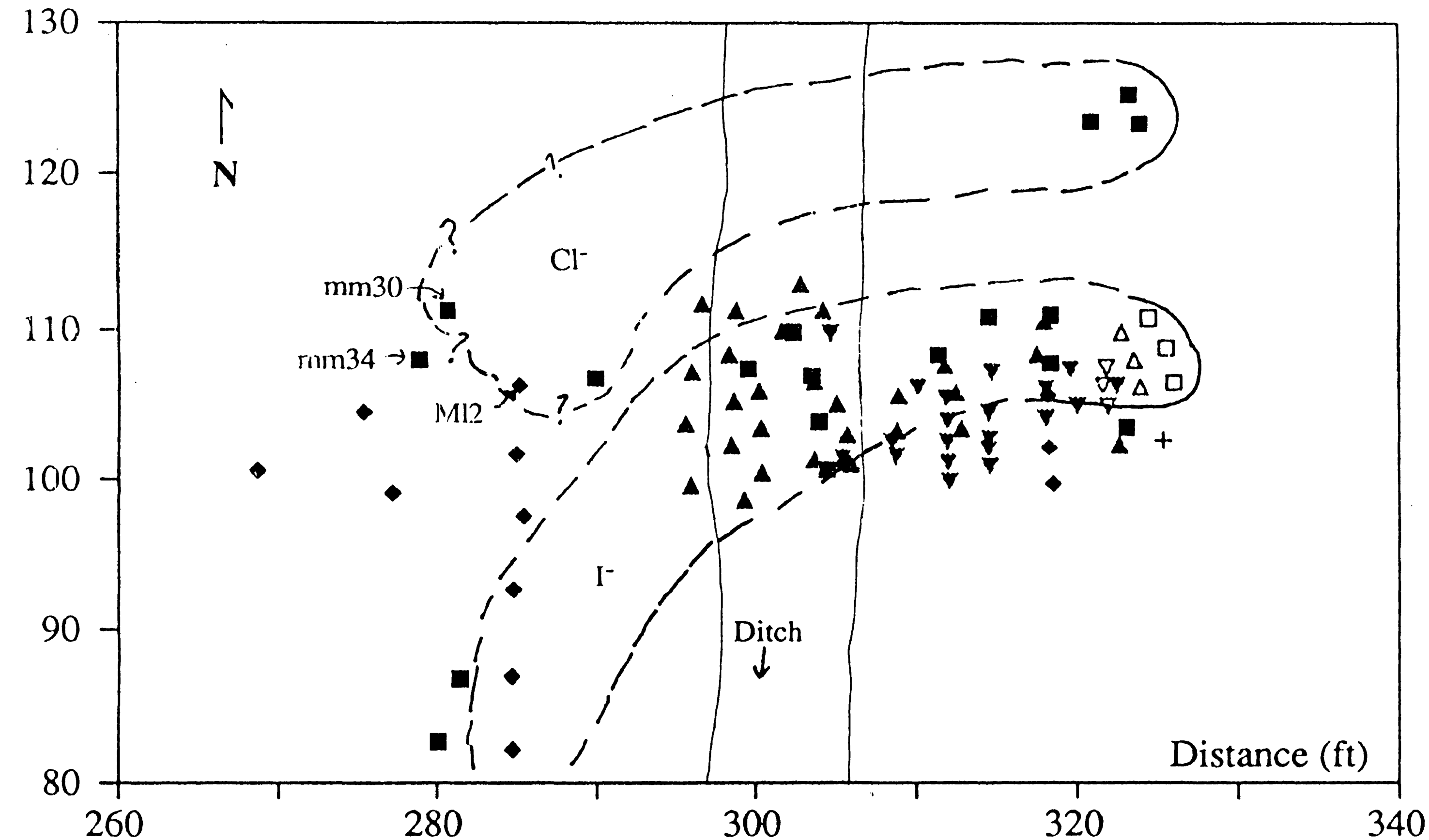


Figure 4.2 Plan view of the total movement (as of December 5, 1989) of the chloride tracer plume in test 2.

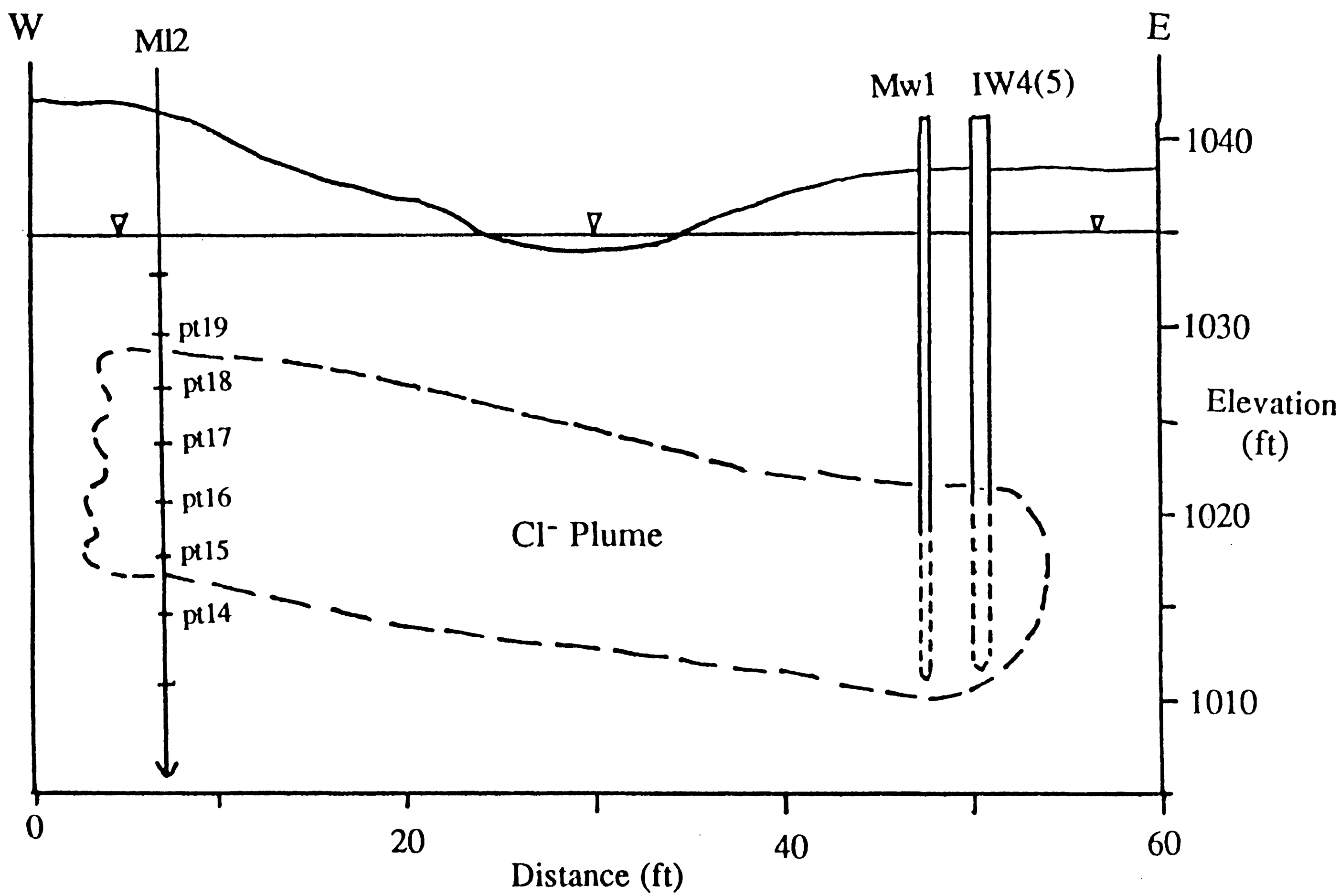


Figure 4.3 Cross section of the approximate flow path of the chloride tracer plume in test 2.

The Third Test

In the third tracer test, a bromide solution was injected at 1.5 to 2.9 feet below the water table on June 2 (Figure 4.4). Tracer was injected at the same elevation as the shallow iodide injection during test 4. The tracer moved very rapidly toward the ditch; it flowed at about 2 ft/day. The rapid flow rate is probably the result of the steep gradient near the ditch (approximately 0.007 to 0.008).

The Fourth Test

In the fourth test, two different tracers were injected into three different levels within the aquifer. On the afternoon of July 16, 1989, an iodide solution was injected at 0.6 to 2.0 feet below the water table. On the morning of July 17, a bromide solution was injected at 6.4 to 11.1 feet below the water table and in the afternoon, an iodide solution was injected at 16.4 to 21.1 feet below the water table. See Table 3.1 for additional details on injection.

A series of plan view maps and cross sections (Figures 4.5 to 4.12) show the approximate distribution of maximum concentration within each multilevel observed on a particular sampling day. Figure 4.5 shows the concentration distributions 15 days after the tracers were introduced. The relative positions of the three plumes demonstrate that the shallower bromide plume had moved faster than the deep iodide plume, but slower than the very shallow iodide plume which already had reached the ditch. By day 61 of the test (Figure 4.6), a large portion of the bromide plume and all

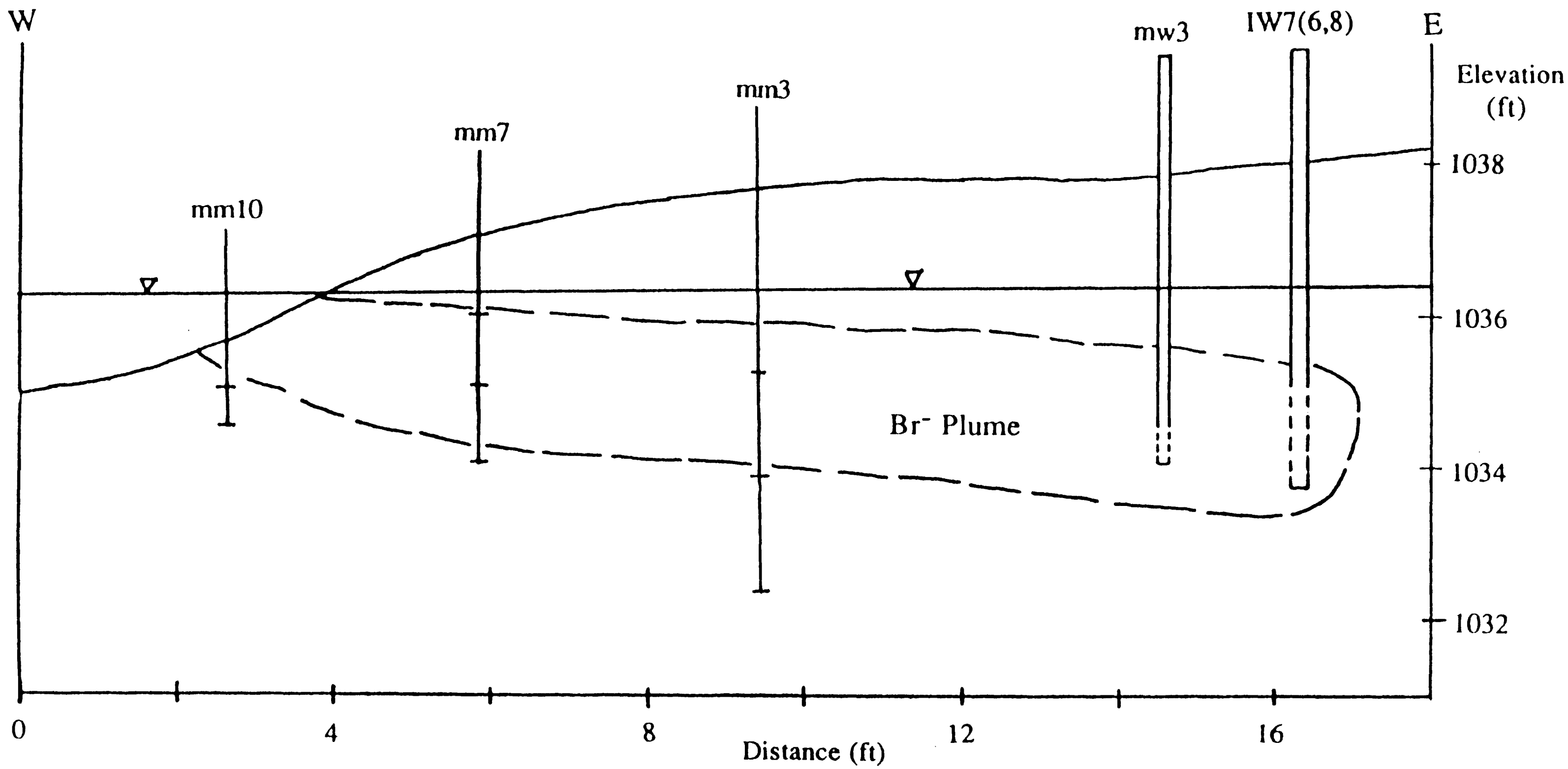


Figure 4.4 Cross section of the total movement of the bromide tracer plume in test 3.

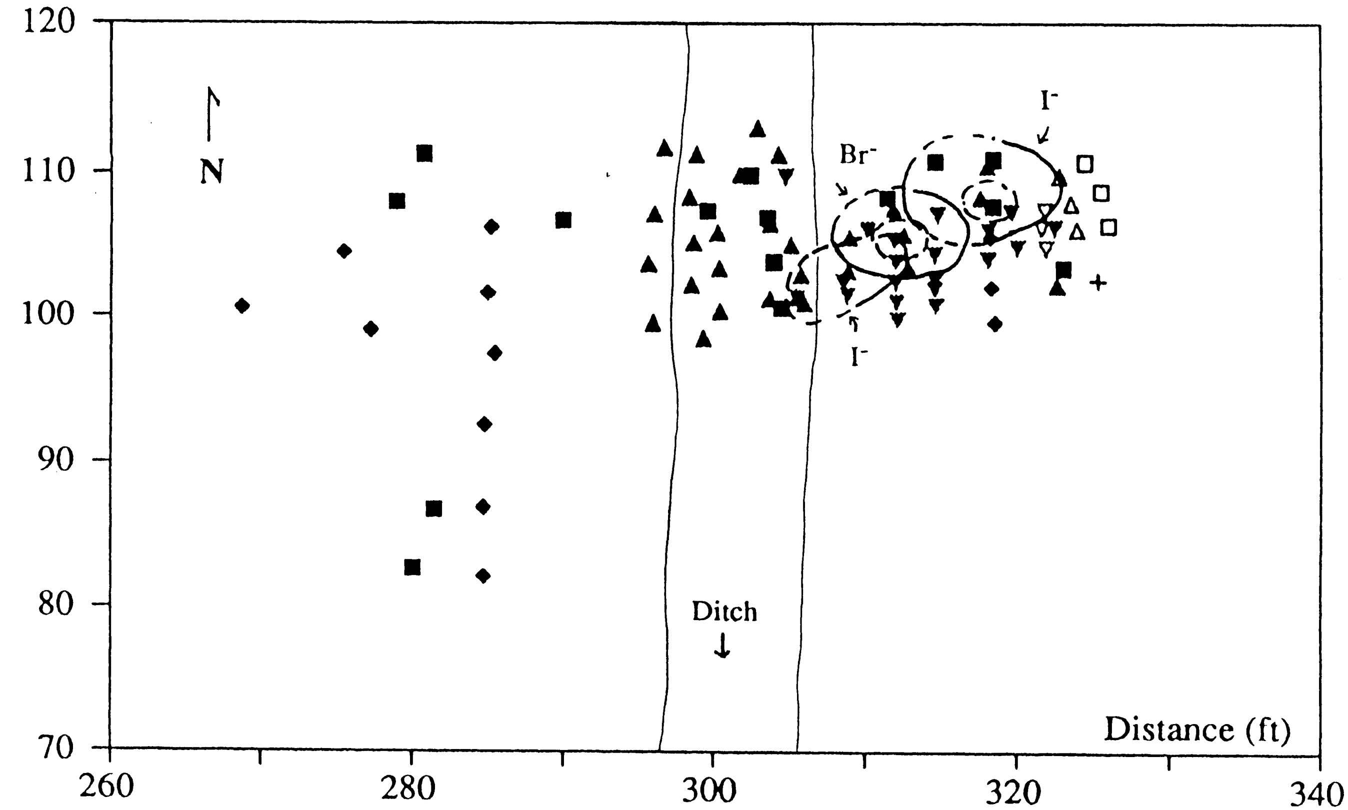


Figure 4.5 Plan view of tracer plumes on August 1, 1989, day 15 of test. The multilevel sampling wells (diamonds) can be used to sample for the deep /iodide plume and the bromide plume. Deep miniature multilevels (squares) have points at the appropriate elevation to sample for the iodide plume. Intermediate miniature multilevels (triangles) have points at the level to sample for the bromide plume and shallow miniature multilevels (upside-down triangles) have sampling points at the elevation to sample for the shallow iodide plume. The outer contour represents a contour of 0.0001M and the inner countour where present represents a concentration of 0.001M.On day 15 the shallow iodide plume was east of the bromide plume, which was east of the deep iodide plume.

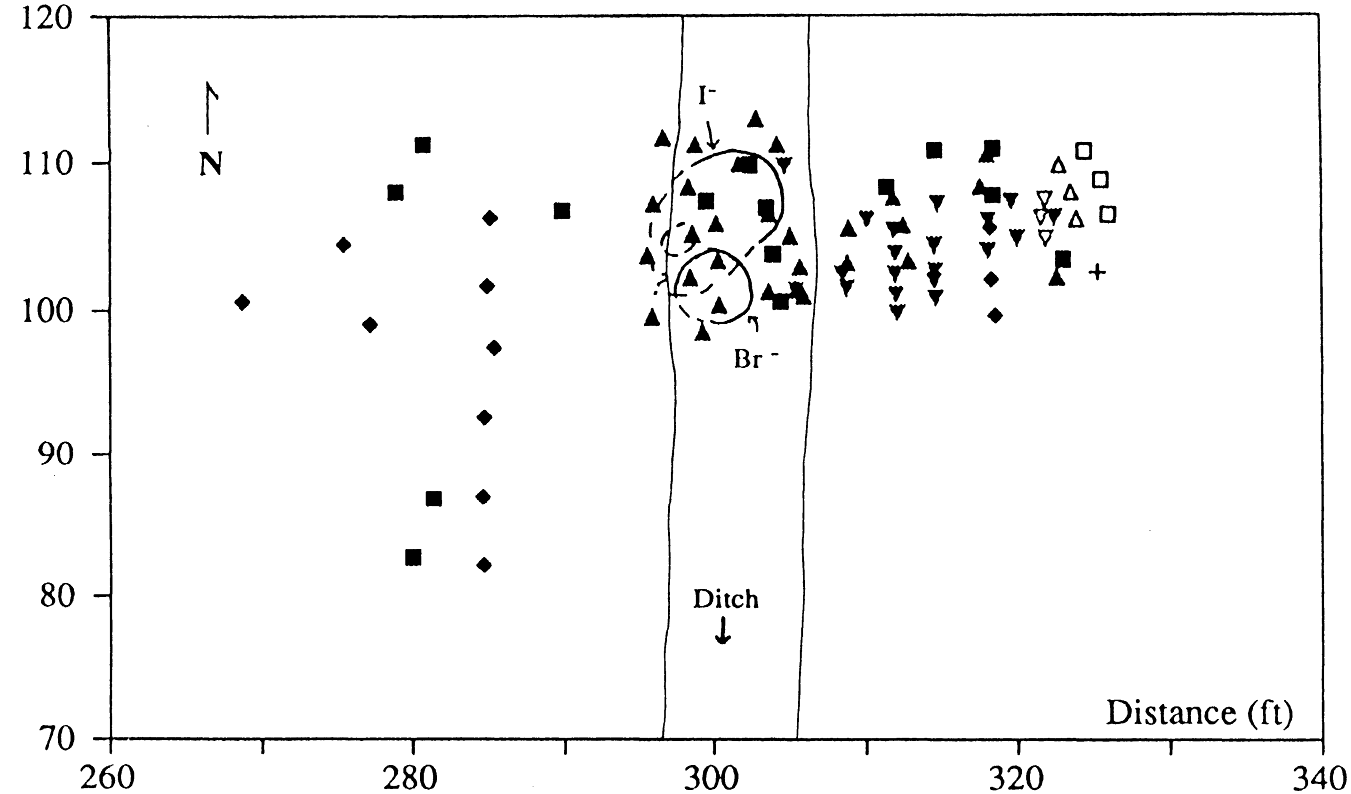


Figure 4.6 Plan view of tracer plumes on September 16, 1989, day 61 of test. The multilevel sampling wells (diamonds) can be used to sample for the deep iodide plume and the bromide plume. Deep miniature multilevels (squares) have points at the appropriate elevation to sample for the iodide plume. Intermediate miniature multilevels (triangles) have points at the level to sample for the bromide plume and shallow miniature multilevels (upside-down triangles) have sampling points at the elevation to sample for the shallow iodide plume. The outer contour represents a contour of 0.0001M and the inner countour where present represents a concentration of 0.001M.On day 61 the deep iodide plume is north of the bromide plume which has partially flowed into the ditch.

of the shallow iodide plume had flowed up into the ditch. The deeper iodide plume was north of the bromide plume and was beginning to move beyond the ditch. Beyond the ditch, the iodide plume flowed in a south-westerly direction. On day 131 (Figure 4.7) the deep iodide plume was located about 40 feet west and 16 feet south of where it had been injected.

Figure 4.8 shows the total movement of the deep iodide and the bromide tracer plumes. The bromide tracer did not move directly toward the ditch, but flowed at a slight angle. The shallow iodide plume followed in a similar path to the bromide, but is not shown on Figure 4.8 for the sake of simplicity. The bromide moved upward and flowed completely into the ditch. Frequent sampling of the wells on the west side of the ditch, revealed no signs of the bromide tracer. The deep iodide plume flowed more directly toward the ditch and then changed direction by about 45 degrees. This change in flow direction has several possible causes. The groundwater flow to the west of the ditch, might have been more consistent with the regional gradient which slopes toward the southwest. If this is the case the plume then flowed on beyond the ditch (Arrow A on Figure 4.8). The other possible, and more likely, cause for the change in flow direction is that the tracer plume may have risen enough that it was being affected by the very shallow flow, which according to the water table maps (Figures 2.6 and 2.7) is flowing toward the ditch. If this is the case, it is possible that all or a portion of the tracer plume became so shallow that it curved around back toward the ditch and flowed into the ditch (Arrow B on Figure 4.8). The limited number of multilevels, combined with the onset of

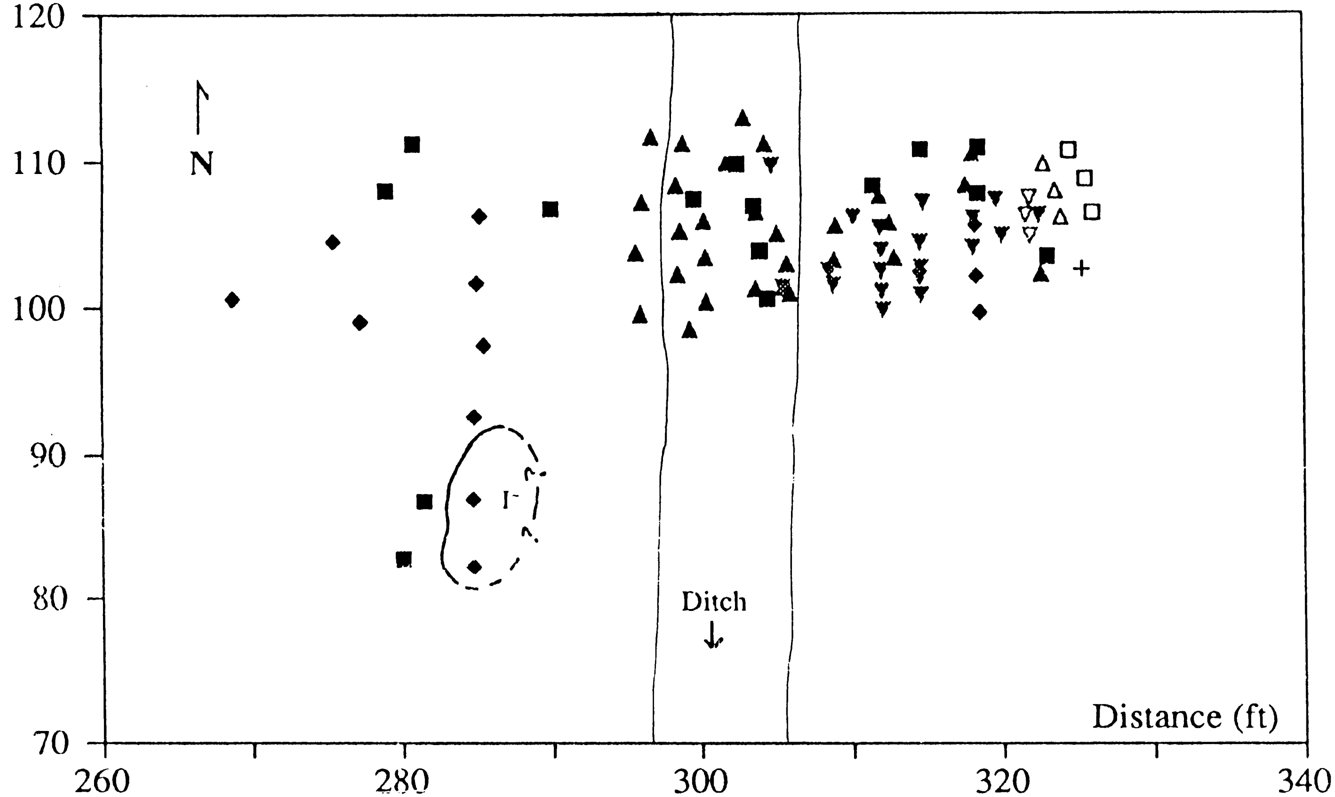


Figure 4.7 Plan view of tracer plumes on November 25, 1989, day 131 of test. The multilevel sampling wells (diamonds) can be used to sample for the deep iodide plume and the bromide plume. Deep miniature multilevels (squares) have points at the appropriate elevation to sample for the iodide plume. The contour represents a concentration of 0.0001M. Intermediate miniature multilevels (triangles) have points at the level to sample for the bromide plume. On day 131 the deep iodide plume is located on the west side of the ditch.

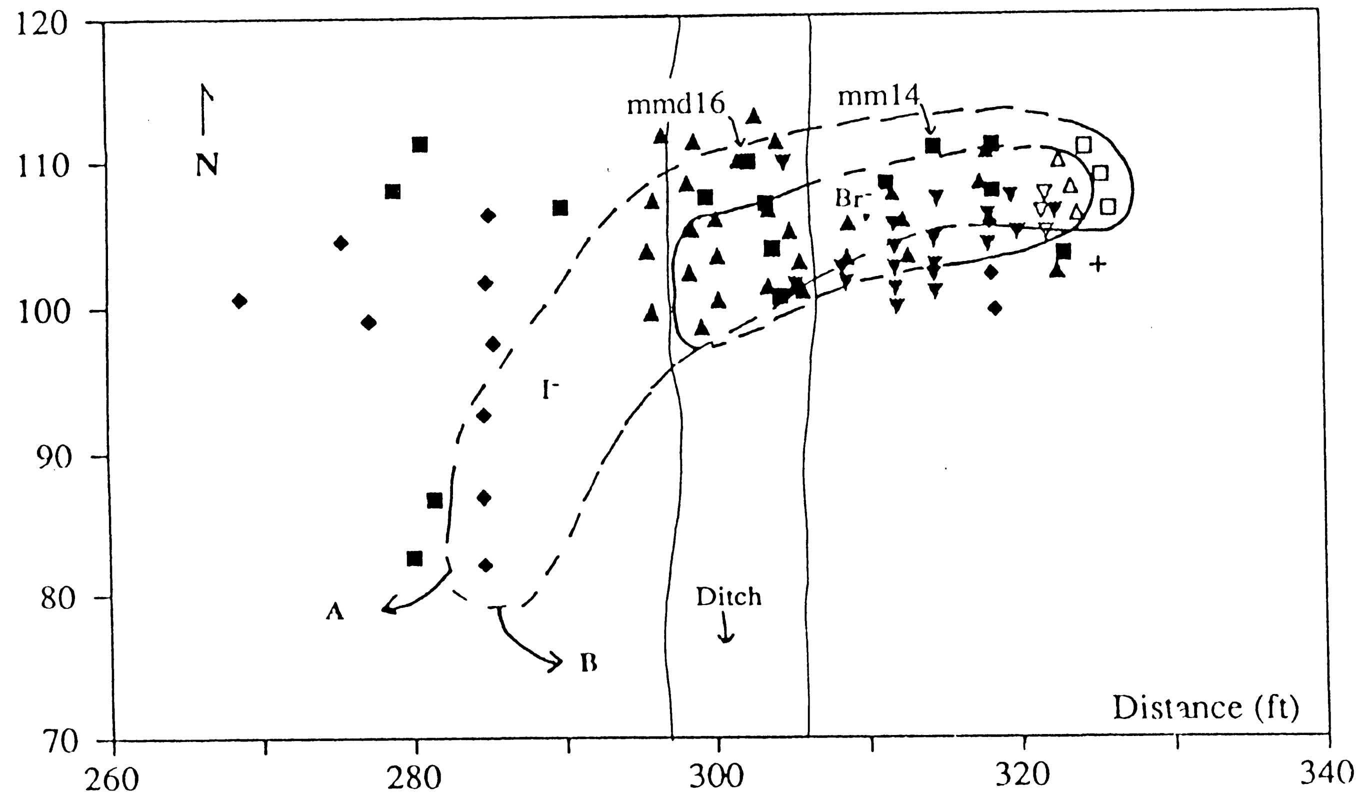


Figure 4.8 Plan view of tracer plumes of the total movement of the tracer plume. The multilevel sampling wells (diamonds) can be used to sample for the deep iodide plume and the bromide plume. Deep miniature multilevels (squares) have points at the appropriate elevation to sample for the iodide plume. Intermediate miniature multilevels (triangles) have points at the level to sample for the bromide plume. The combination of the onset of very cold winter conditions and the small number of sampling wells meant it was not possible to determine whether the tracer plume followed path A, path B or some other route after December 5, 1989.

winter meant that it was not possible to determine the direction of the complete flow path of the iodide plume.

Figure 4.9 shows the approximate concentration distribution of bromide and iodide in vertical cross section on or near the longitudinal axis of each plume 15 days after the tracer test began. The deeper iodide plume in this figure reveals the strong upward component to the flow system. In the approximately 8 feet it had traveled since injection, it had risen almost 3 feet. After 15 days, the shallow iodide plume already was flowing into the ditch. The shallow iodide plume is moving faster than the bromide plume, which was moving more quickly than the deeper iodide plume. On Figure 4.9, the front of the interpolated bromide plume has been exaggerated somewhat to emphasize that the tracer plume did not travel as one mass. Bromide was found at sampling points 2 and 5 (elevation 1026.2 and 1030.0 feet), but not at the 2 sampling points in between. Beds or zones of higher and lower hydraulic conductivity within the aquifer, appear to have created a complex plume with zones of faster and slower moving tracer.

Figure 4.10 shows the positions of the tracer plumes 61 days after the tracer test began. By this time the bromide plume had flowed almost entirely up into the ditch. The iodide plume had moved upward approximately 7 feet in the 25 feet from its point of injection to the ditch. The iodide plume had started to move beyond the ditch. On day 131 (Figure 4.11), the iodide plume was located on the west side of the ditch, with the top of the plume only 6 feet below the water table.

Figure 4.12 shows the total movement of the tracer plumes in vertical

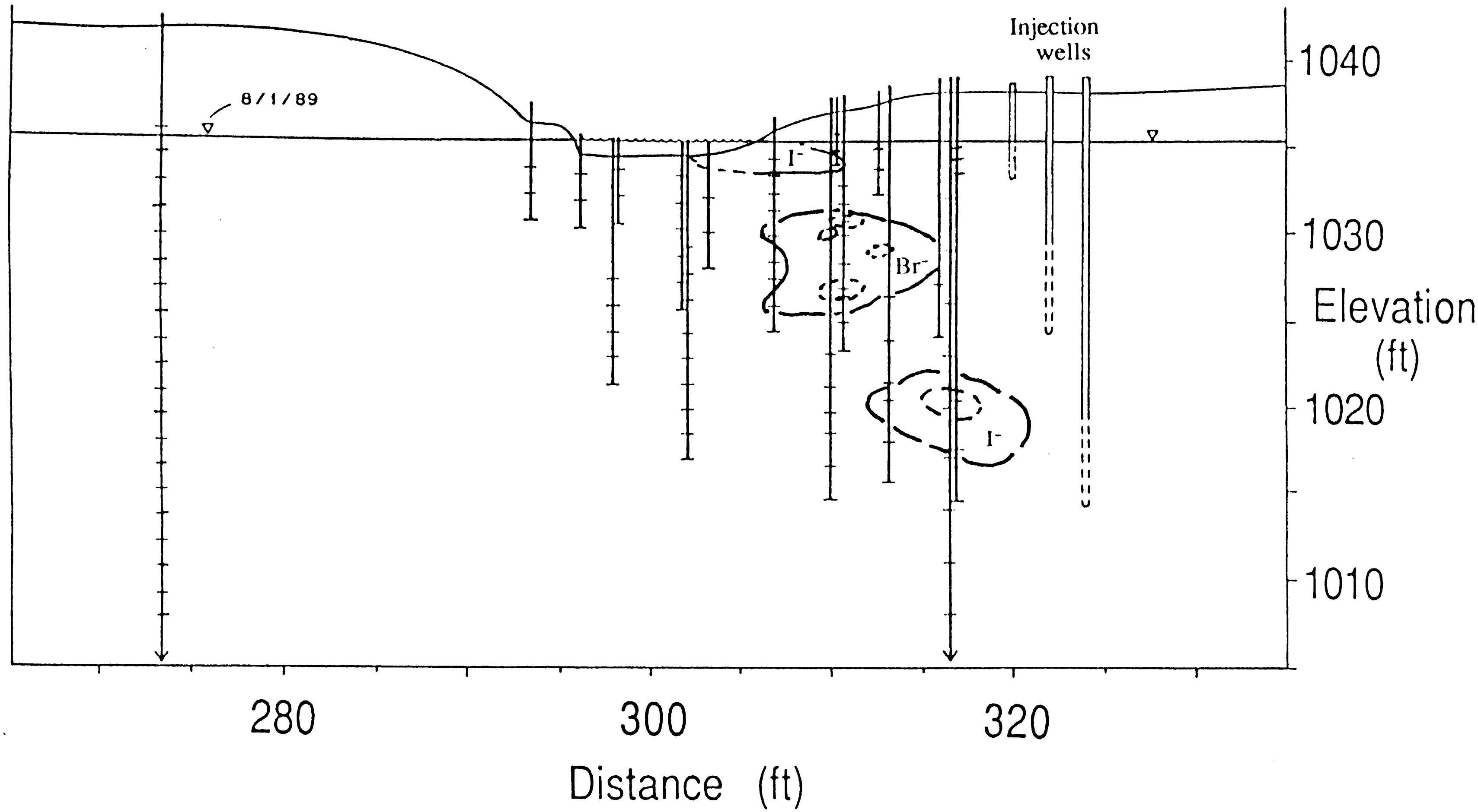


Figure 4.9 Cross section of the tracer plumes on August 1, 1989, day 15 of test. The outer contour represents a contour of 0.0001M and the inner countour where present represents a concentration of 0.001M.

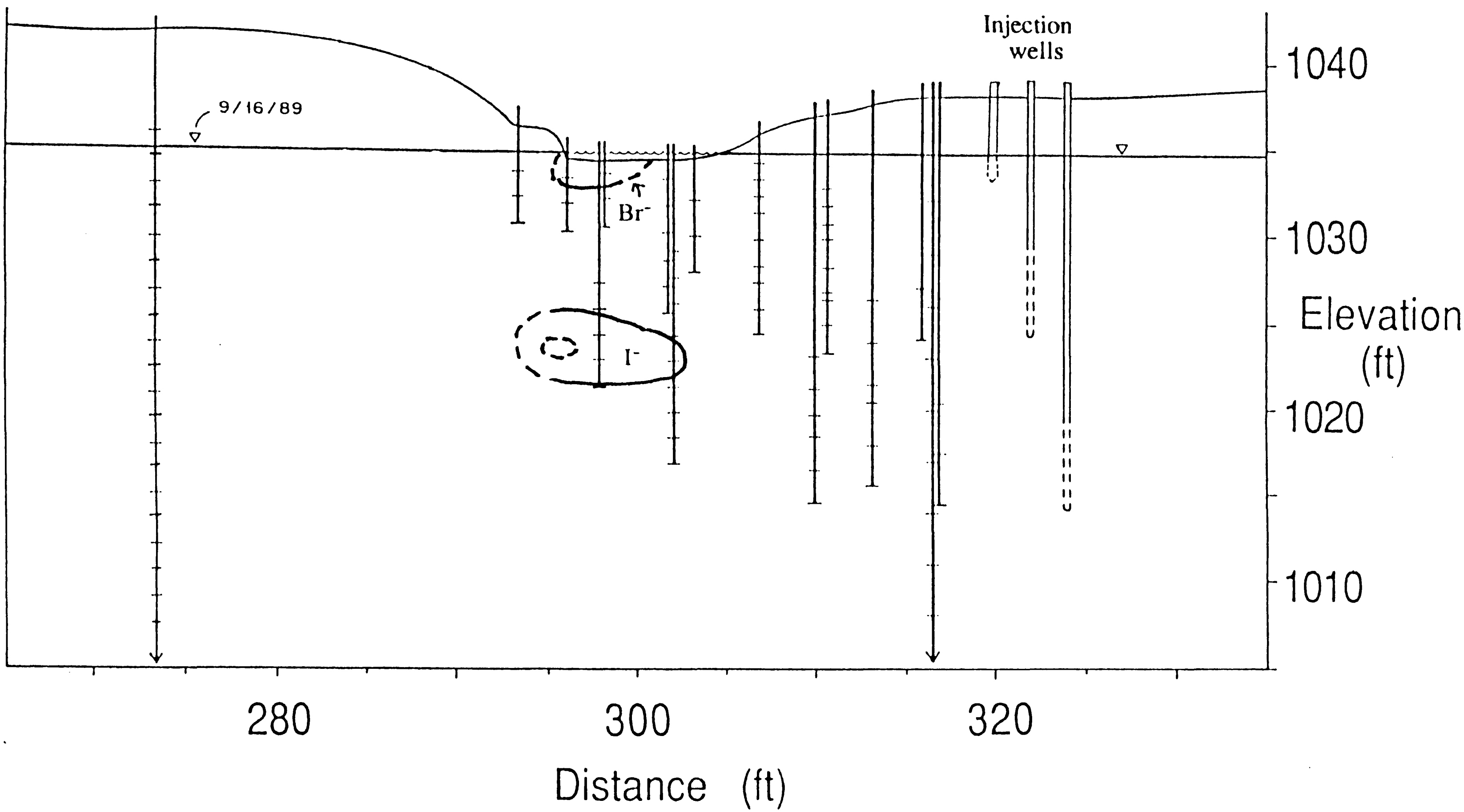


Figure 4.10 Cross section of the tracer plumes on September 16, 1989, day 61 of test. The outer contour represents a contour of 0.0001M and the inner countour where present represents a concentration of 0.001M.

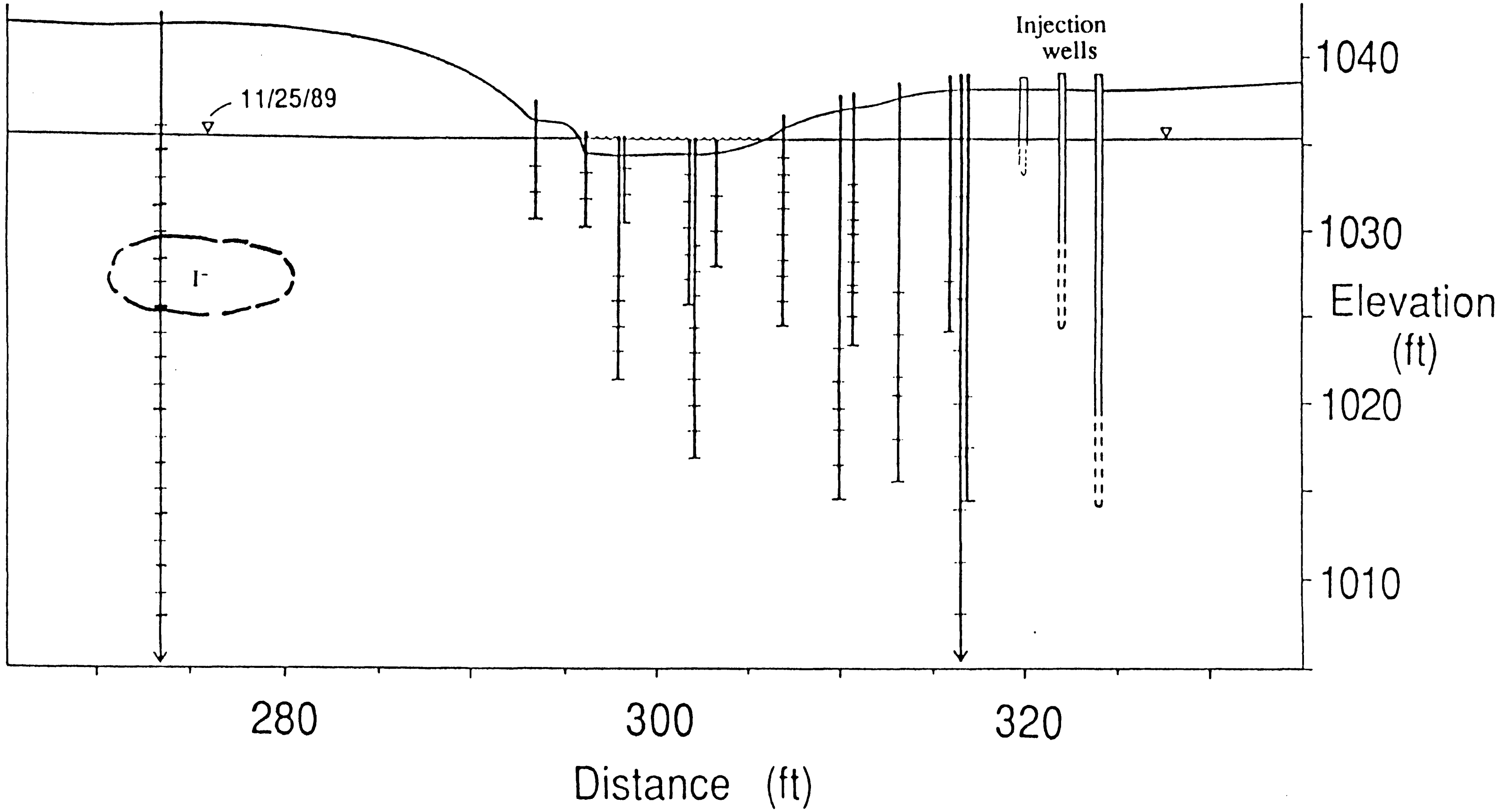


Figure 4.11 Cross section of the tracer plumes on November 25, 1989, day 131 of test. The contour represents a concentration of 0.0001M.

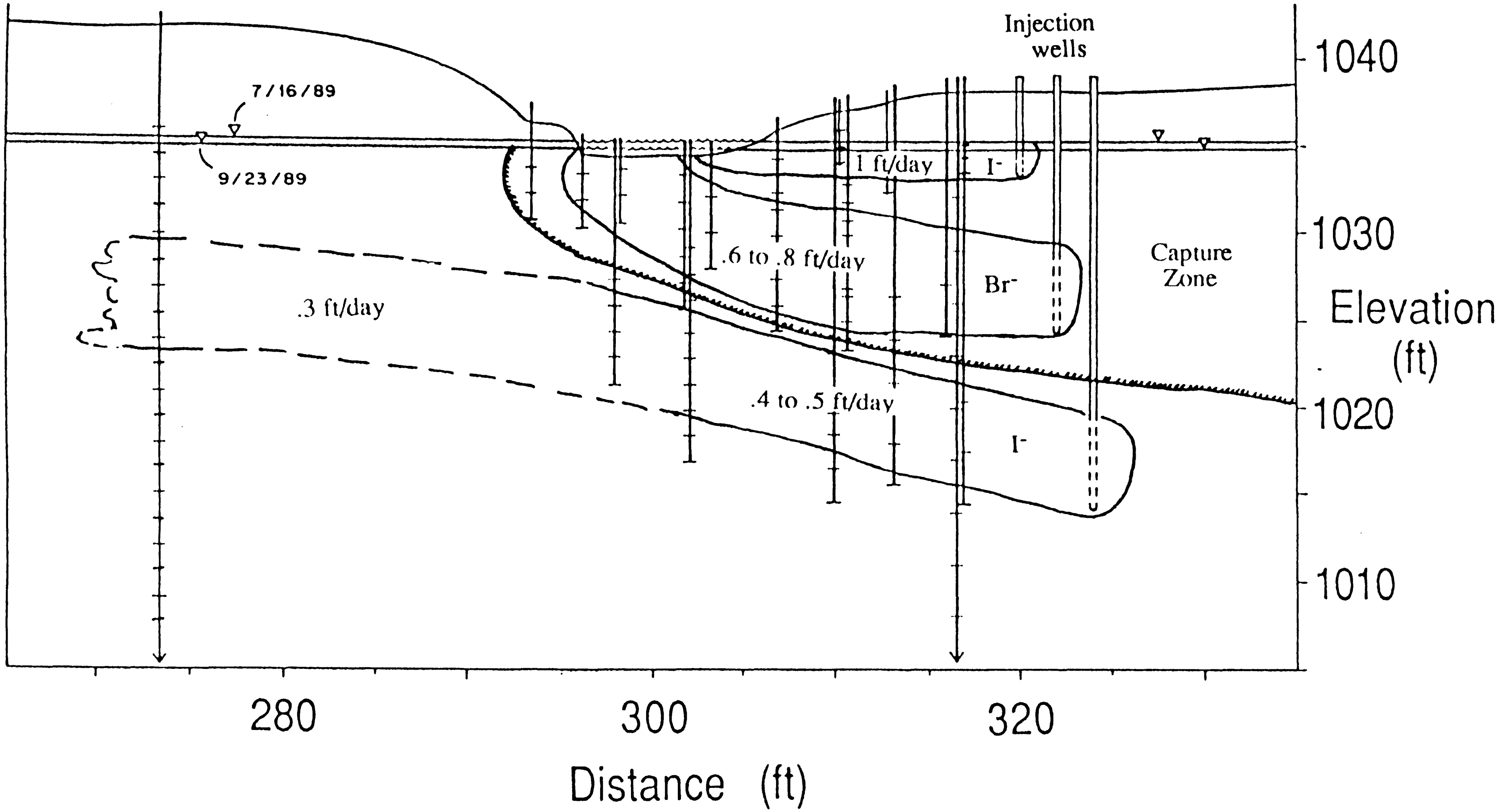


Figure 4.12 Cross section of the total movement of the tracer plumes. The average velocity of each plume is shown. The dividing surface appears to be between the bromide and the deep iodide plume.

section. The path of the shallow iodide tracer showed that the groundwater close to the water table was moving at an average velocity of around 1 ft/day. The bromide plume moved at an approximate rate of 0.6 to 0.8 ft/day. It should be stressed that this is an approximate range of flow rates and that there were areas where the tracer moved faster or slower as a result of variations in hydraulic conductivity. The iodide plume moved upward 7 feet as it traveled the 25 feet from the injection well to the ditch at an approximate velocity of 0.4 to 0.5 ft/day. Beyond the ditch, it continued to rise as it traveled at an average rate of 0.3 ft/day. The decrease in velocity is probably due to the change in the hydraulic gradient.

The shallow bromide plume in test 3 moved roughly twice as fast as the shallow iodide plume in test 4. In test 3 tracer was injected at the same elevation as the shallow iodide injection during test 4. The decline in the shallow water velocity appears to be a result of the declining water table gradient. The summer of 1989 was a very dry summer. The water table and ditch stage dropped over a foot in the 1.5 months between the beginning of test 3 and test 4 (Figure 2.8). Thus, as would be expected the flow of the shallow water near the ditch is greatly affected by transient conditions.

The approximate velocity of the plumes was calculated by examining the changes through time in concentrations at individual multilevel sampling points. Figure 4.13 shows the tracer breakthrough curves for miniature multilevel sampling wells number 14 (mm14) and d16 (mmd16). (See Figure

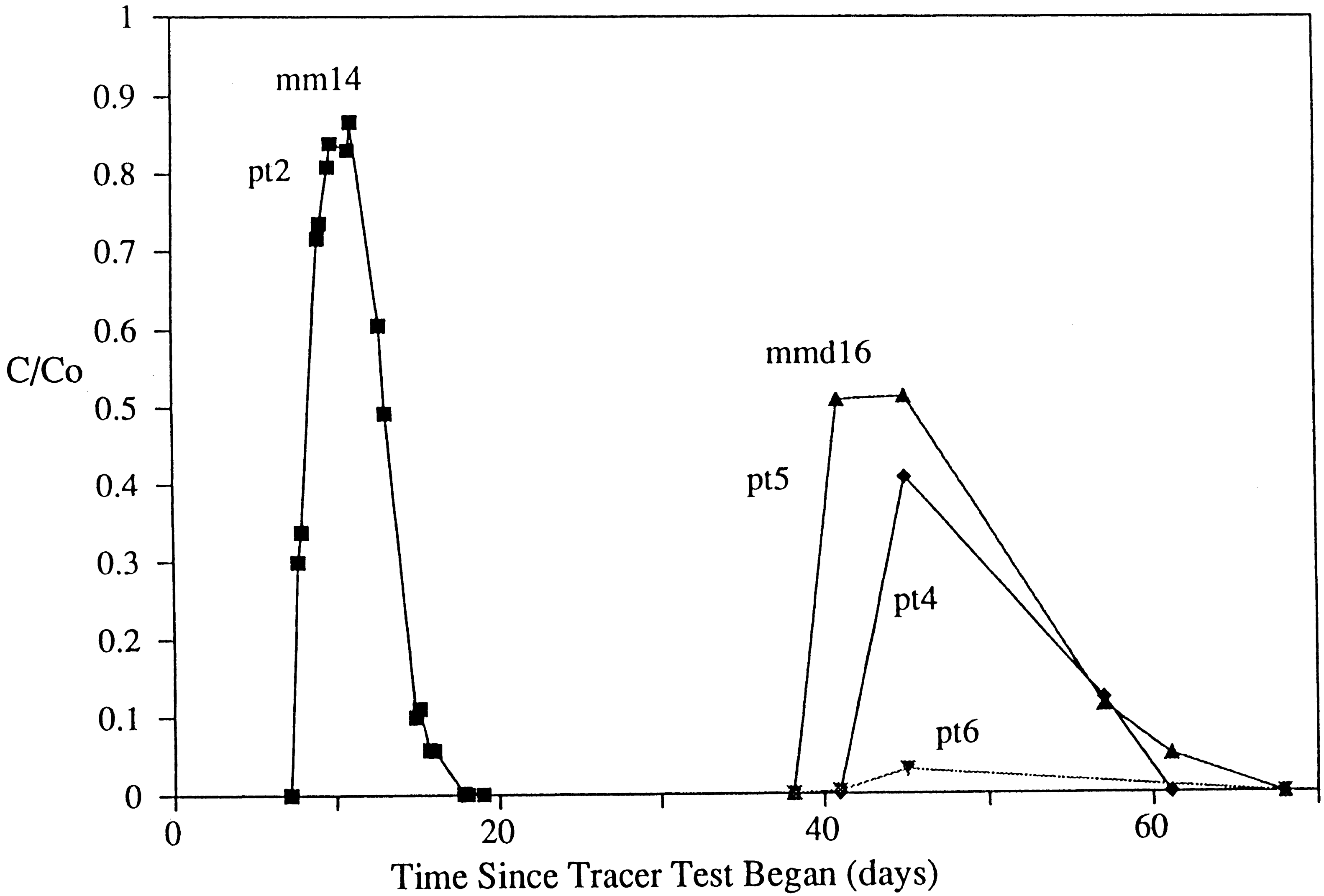


Figure 4.13 The breakthrough curves for miniature multilevels (mm) 14 and d16.

4.8 for the location of multilevels.) The peak tracer concentration at mm14 was on day 11 of the test and at mmd16 on day 44. Thus, the center of mass of the tracer plume was near mm14 on day 11, and 33 days later it was near mmd16. Since the distance between mm14 and mmd16 is 15 feet, the velocity of the plume is close to 0.45 ft/day. Based on the comparison between several other points, the average velocity of the deeper iodide plume appears to have been approximately between 0.4 and 0.5 ft/day on the east side of the ditch.

The results from the third test and the shallow portion of the fourth test can be used to calculate the hydraulic conductivity of the shallow portion of the aquifer. The hydraulic conductivity, K, was computed from $K = \frac{v\,n}{I}$, where v is the groundwater velocity, n is the effective porosity, and I is the horizontal hydraulic gradient. The velocity of the shallow groundwater was calculated from the rate of plume movement in tests 3 and 4. The porosity estimates for the sand plains range from approximately 32% (Holt, 1965) up to 40% (Stoertz, 1985). The horizontal hydraulic gradient is equivalent to the slope of the water table for the shallow flow. Based on these estimates of v, n and I, the calculated hydraulic conductivity of the shallow portion of the aquifer is approximately 50 to 130 ft/day. This is on the lower end of the hydraulic conductivity estimates for the central sand plain (Stoertz, 1989a).

Based on the flow paths of the iodide and bromide plume, the capture zone of the ditch can be defined for conditions in the summer and fall of 1989. At a distance of 25 feet from the ditch the depth of the dividing streamline is between 11.3 and 15.7 feet below the average water table position during the test (Figure 4.12). At a greater distance from the ditch, the dividing streamline is likely to be deeper, since there is a strong upward component to the flow even at a distance of 25 feet from the ditch. A conservative estimate for the minimum capture zone depth is between 12 to 16 feet below the water table for the summer and fall of 1989.

The Fifth and Sixth Test

The results of tests 5 and 6, conducted during the summer of 1990, are only just beginning to be evaluated. Preliminary results of summer of 1990 tests are discussed below. In the fifth test, 650 liters of a 0.6 g/l potassium iodide solution was injected into one well (IW10) at a depth of 6.6 to 11.3 feet below the water table on July 23rd. On August 9th the sixth test was begun. 800 liters of a 0.9 g/l potassium bromide solution was injected into on well (IW13) at a depth of 17.6 to 22.3 feet below the water table. Figure 4.14 shows the total movement of the tracer plumes. The tracers were injected at the same elevations as the tracers injected in test 4 (Figure 4.12). In 1990 both plumes showed a much larger vertical component in the flow path of the tracer. The plumes also moved at a somewhat greater velocity. The capture depth for late July, August and early September of 1990 appears to be at least 24 feet below the water table.

The dramatic variation in flow path from the summer of 1989 to 1990 appears to be the result of transient flow conditions. There was a larger

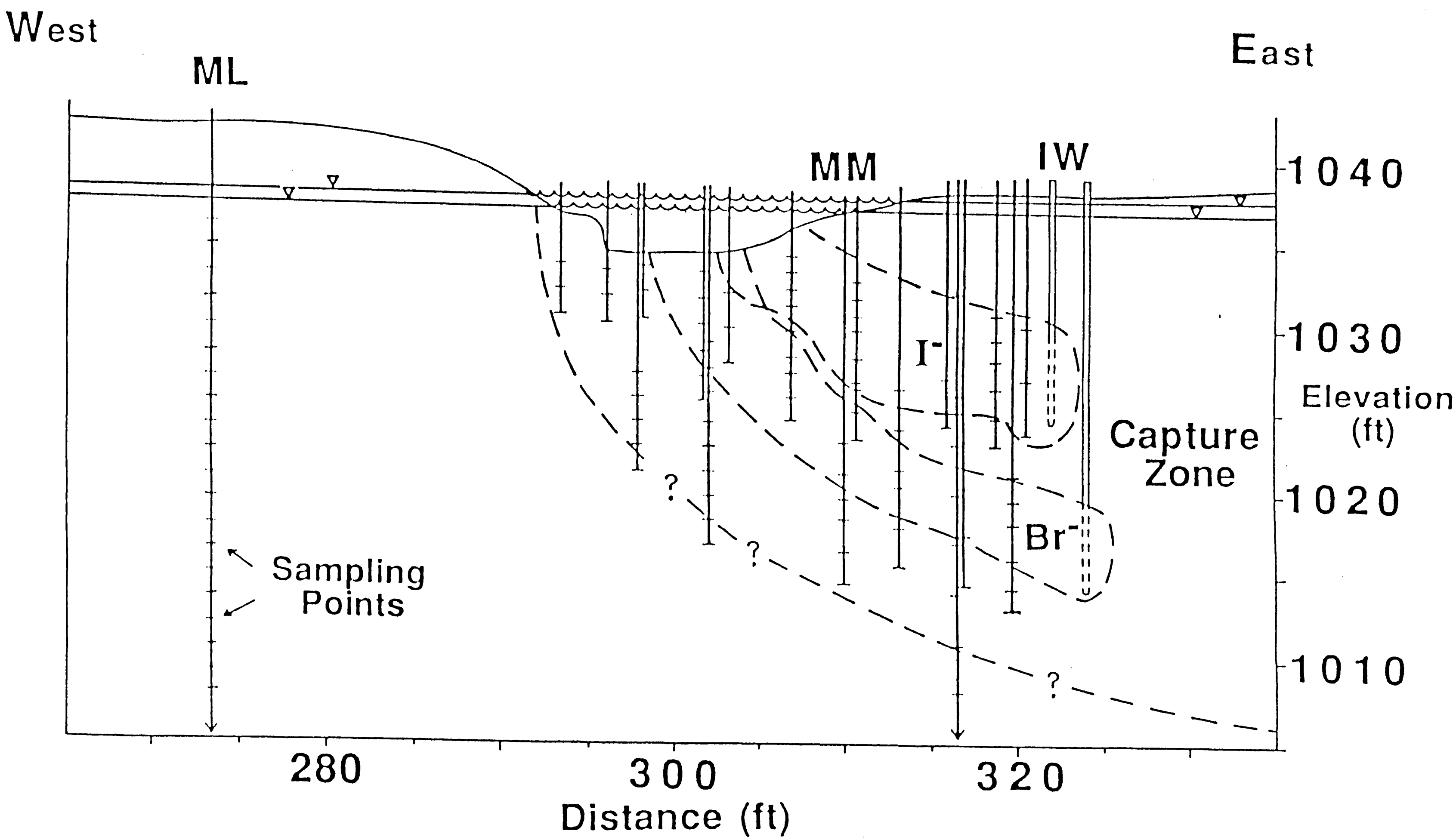


Figure 4.14 Cross section of the total movement of the tracer plumes in the summer of 1990. The dashed line represents the approximate base of the capture zone.

than usual quantity of recharge in late July and August of 1990. As a result of the elevated water table the ditch appears to have caused a greater perturbation in the flow field. Additional evaluation of the effects of stronger upward gradients in the vicinity of the ditch is in progress.

Summary

The capture zone for conditions in the summer and fall of 1989 was about 14 feet or more below the water table. Because the tests revealed upward flow near the injection points, the dividing surface is likely to be deeper at greater distances from the ditch. If the deep iodide or chloride tracers curved around and back to the ditch, the capture depth was greater than 21 feet below the water table. The limited number of wells and the onset of winter, prevented the collection of data, which could have been used to confirm or rule out this flow pattern. The direction of the shallower flow appears to be more affected by the ditch. The shallower flow within the aquifer has a greater and more variable velocity.

The preliminary results of test 5 and 6 show that there is a large transient variation in the groundwater flow path in the vicinity of the ditch. It appears that the depth of the capture zone is very sensitive to seasonal variations.

Evaluation of the Analytic Solution

The two-dimensional analytic solution of Zheng et al. (1988a) can be used to predict the dividing streamline or surface above which all ground-water is captured by the ditch. Recall that the portion of the aquifer located above the dividing streamline or surface constitutes the capture zone of the ditch. The depth of the capture zone is the vertical distance from the water table to the dividing surface at some horizontal distance far enough away from the ditch such that the dividing surface is roughly parallel to the water table. For conditions in the summer and fall of 1989, the observed capture depth was greater than 12 to 16 feet below the water table as seen in Figure 4.12.

In this section, the ability of the two-dimensional analytic solution to predict the capture zone of the ditch will be examined and evaluated. A detailed evaluation of the analytic solution is used to understand the relationship between the predicted capture depth and various parameters used in the model. The results of a sensitivity analysis of the four parameters used in the model, using data collected at the field site during test 4, will be discussed.

Examination of the Analytic Solution

The analytic solution of Zheng et al. (1988a) was derived from a two-dimensional solution by Slichter (1899) for the steady-state flow beneath a shallow ditch. The solution assumes that the water table can be approximated by a linear slope which intersects the ditch and that the aquifer is homogeneous and infinite in areal extent.

Zheng et al. (1988a) approximate D, the depth of the capture zone as,

$$D = \left(\frac{2\ S}{\pi\ I}\right)^{1/2} \bullet R^{-1/2} \tag{1}$$

In (1), I is the regional gradient, S is the product of ditch width (2a) and the difference between the head in the ditch and the head in the aquifer (h_o-h_d) (similar to the vertical gradient beneath the ditch), and R is the ratio of the horizontal to vertical hydraulic conductivity (Kx/Ky) (anisotropy ratio). Figure 4.15 diagrammatically shows the parameters in the equation. The form of (1) does not permit ready identification of the sensitivity of D to the physical and hydrologic characteristics of the system that can be measured or estimated, i.e., ditch width, anisotropy, vertical gradients beneath the ditch and the regional horizontal gradient. However, if the equation is rearranged and a few variables are renamed, the relationship between D and the controlling parameters becomes more clear. Setting h_o-h_d = H and 2a = w, equation (1) becomes

$$D = \left(\frac{2\ w\ H}{\pi\ I}\right)^{1/2} \bullet R^{-1/2} \tag{2}$$

$$= B \left(\frac{w\ H}{I\ R}\right)^{1/2} \qquad \text{for } B = \left(\frac{2}{\pi}\right)^{1/2}. \tag{3}$$

From equation 3, it is easier to investigate how changes in the four parameters, w, H, I, R affect the capture depth, D: the depth of the

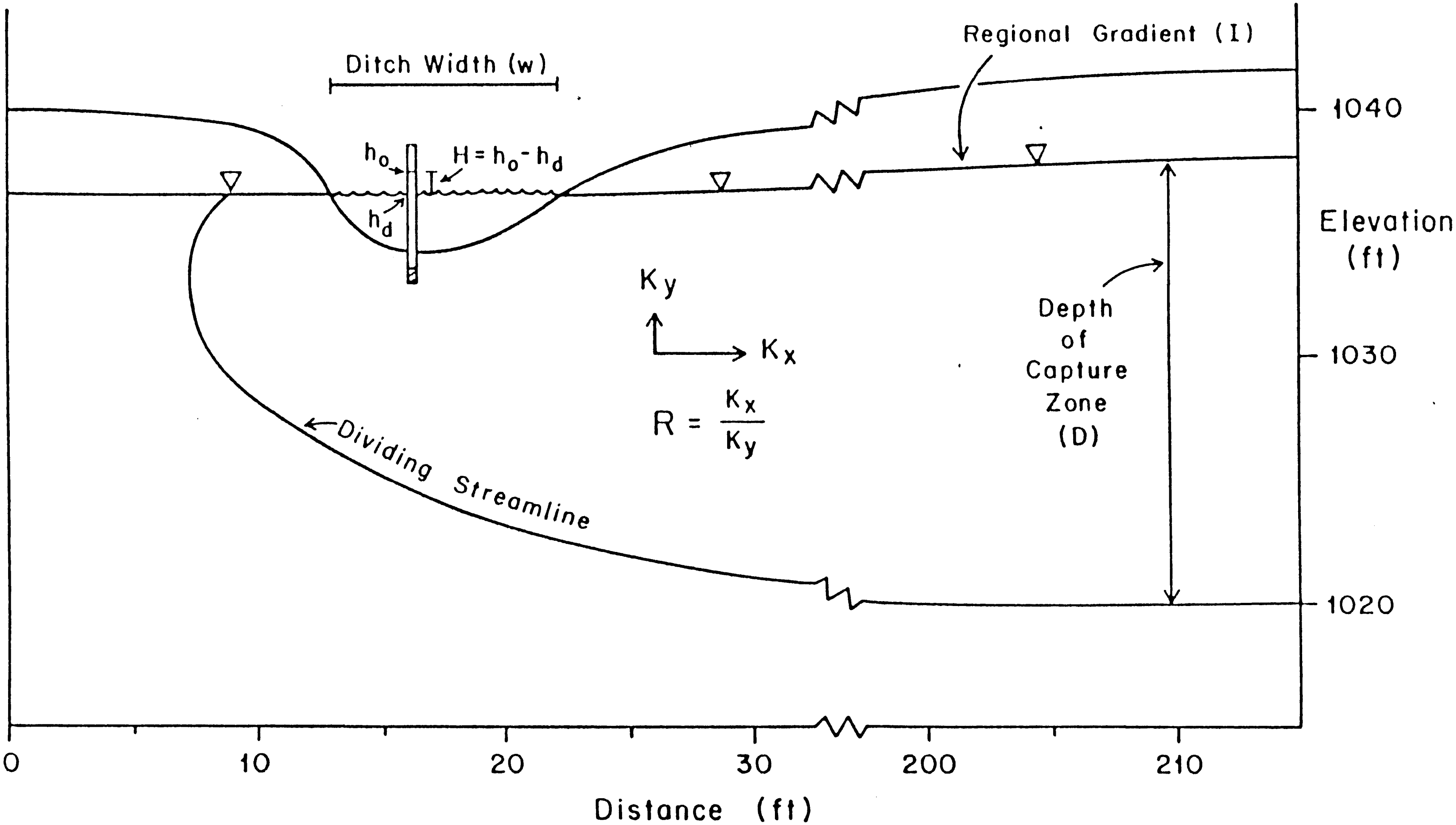


Figure 4.15 The parameters for the two-dimensional analytic solution.

capture zone, D, increases as w or H increases or as I or R decreases. Zheng et al. (1988a) noted that when I and R are small the effect of a change in H or w is more significant than when the product IR is large. Mathematically, this is apparent by taking the partial derivative with respect to w of equation 3:

$$\frac{\partial D}{\partial w} = w^{-1/2}\,\frac{B}{2}\left(\frac{H}{I\ R}\right)^{1/2}. \tag{4}$$

thus,

$$\frac{\partial D}{\partial w} \propto w^{-1/2}. \tag{5}$$

It follows that

$$\frac{\partial D}{\partial H} \propto H^{-1/2}, \tag{6}$$

$$\frac{\partial D}{\partial I} \propto I^{-3/2}, \tag{7}$$

and

$$\frac{\partial D}{\partial R} \propto R^{-3/2}. \tag{8}$$

Since the parameters are raised to fractional odd powers these derivatives have no local maxima or minima. Because the power is negative, the slope ($\frac{\partial D}{\partial w}$) will be largest when the parameter w, is less than 1. (Note that R and I are dimensionless; R will always be greater than or equal to 1 and I will always be much less than 1.) The form of the derivatives means that when a parameter is small a change of one unit will have a larger effect on the capture depth than a change of one unit where the parameter has a large value.

Sensitivity Analysis

In order to understand the predictive capabilities of the model the effect of each parameter on the predicted depth of the capture zone is quantified below. Each parameter will be discussed in terms of the range of values found at the field site during the fourth tracer test and the range that one might expect to find throughout the central sand plain.

Ditch Width

The ditch width (w), is simply the measured width of the portion of the ditch that is filled with water. The width of the ditch varies both seasonally and along the length of the 50 feet of the ditch close to the tracer test site. In periods of very low or very high ditch stage, the variations in ditch width are quite large. At low ditch stage, a 15 foot section of the ditch may vary in width from 9 feet to 4 or 5 feet. The variation in the shape of the ditch bank causes some areas to be "flooded" more than others at high ditch stage. During the fourth tracer test, the region of the ditch near where tracer was found was approximately 7.5 to 10 feet wide, with a median estimate of 8.5 feet.

To understand the relationship between the width of the ditch (w) and the capture zone depth (D), recall that from equation (3) it is clear that D is proportional to $w^{1/2}$. The capture depth, D, equals $C_1 \cdot w^{1/2}$ for $C_1 = B(H/IR)^{1/2}$. In order to graphically portray the relationship between D and w, without fixing the value of each parameter in equation (3) to a defined value, C_1 can be used as a constant of proportionality. If we use the median ditch width estimate of 8.5 feet and a value for D of 14 feet, the value for C_1 can be calculated as $C_1 = 14/(8.5)^{1/2} = 4.802$. Figure 4.16a is a graph of D versus w, for the range of ditch widths during the fourth test, using the value of C_1 as calculated above. For the range of w observed during test 4, it is clear that w would have only a very small effect on the predicted capture zone depth. Figure 4.16b shows a graph for the range of w values one might expect to find in the central sand plain. Since there is very little uncertainty in the measurement of w and it varies only within a relatively small range, it does not contribute a large amount of uncertainty to the calculation of D.

Difference Between Ditch Stage and Aquifer Head

H, the difference between the head in the ditch and the head in the aquifer, is similar to the vertical gradient beneath the ditch. It is relatively easy to measure. The measurements can be made by finding the difference between the water level in a mini-piezometer in the ditch and the water level in the ditch. The screen at the base of the mini-piezometer should be about 2 feet below the base of the ditch, so it is just below the ditch bed sediment. The level to which water will rise in mini-piezometers installed to the same depth appears to be somewhat variable along the length and width of the ditch. Enough mini-piezometers have not been installed to the same depth to discern a pattern if one exists. The difference between the head in the ditch and the head in the aquifer, H, varies with time. During test 4, H varied from 0.08 to 0.18

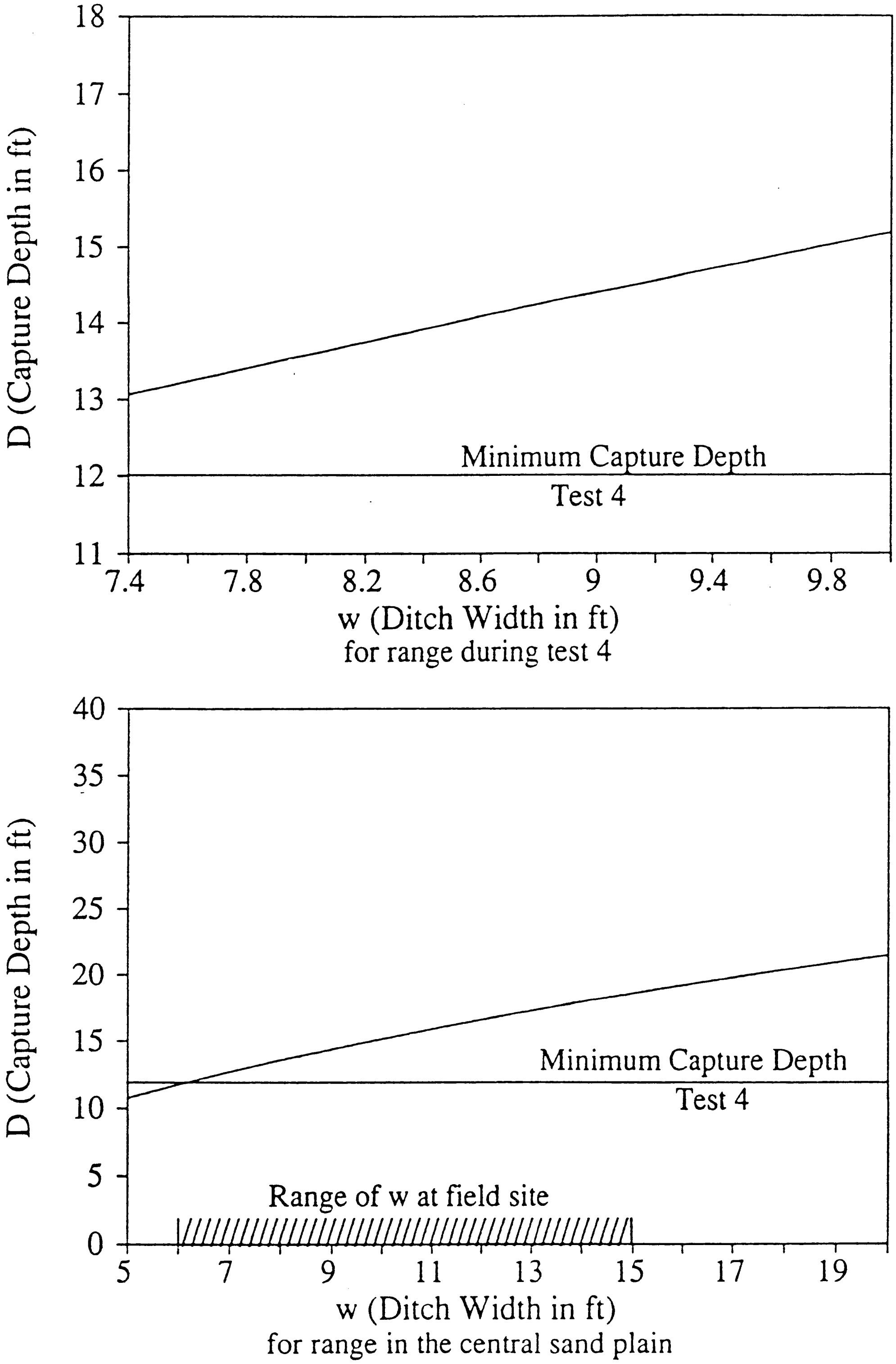


Figure 4.16 Variations in the capture depth due to variations in ditch width.

feet, with a median value of 0.12 feet. A graph of D versus H (Figure 4.17a) was created in the same manner as the graph of D versus w. The constant of proportionality, $C_2 = B(w/IR)^{1/2} = D/(H)^{1/2}$, was calculated using a value of 14 for D and 0.12 for H. For the range of H values observed during test 4, there is a slightly larger predicted variation in the capture depth than for the range of w values. For the range of possible values of H that might be found in the central sand plain, there is a very large range (Figure 4.17b) of predicted values for D, since H can vary from 0 to around 1 feet.

The ditch used by Zheng et al. (1988b) for a computer model analysis of capture depth, had a large variation in H in 1984; H was 0.85 feet in May, 1984 and 0.35 feet in August, 1984. The variation in the regional horizontal gradient was small enough during the summer of 1984, that H was essentially the controlling parameter in determining the depth of the capture zone. For the simulation by Zheng et al. (1988b), the capture zone depth varied from over 80 feet in May to 30 feet in August.

Regional gradient

I is the regional gradient of the water table and can be obtained from water table maps. The water table maps (Figure 2.5 to 2.7) in Chapter 2 only cover an area within a couple hundred feet of the ditch. Analysis of regional water table maps (Lippelt and Hennings, 1981; Weeks and Stangland, 1971), reveals that the local water table gradient within 200 feet of the ditch is 2 or 3 times steeper than the estimated regional gradient.

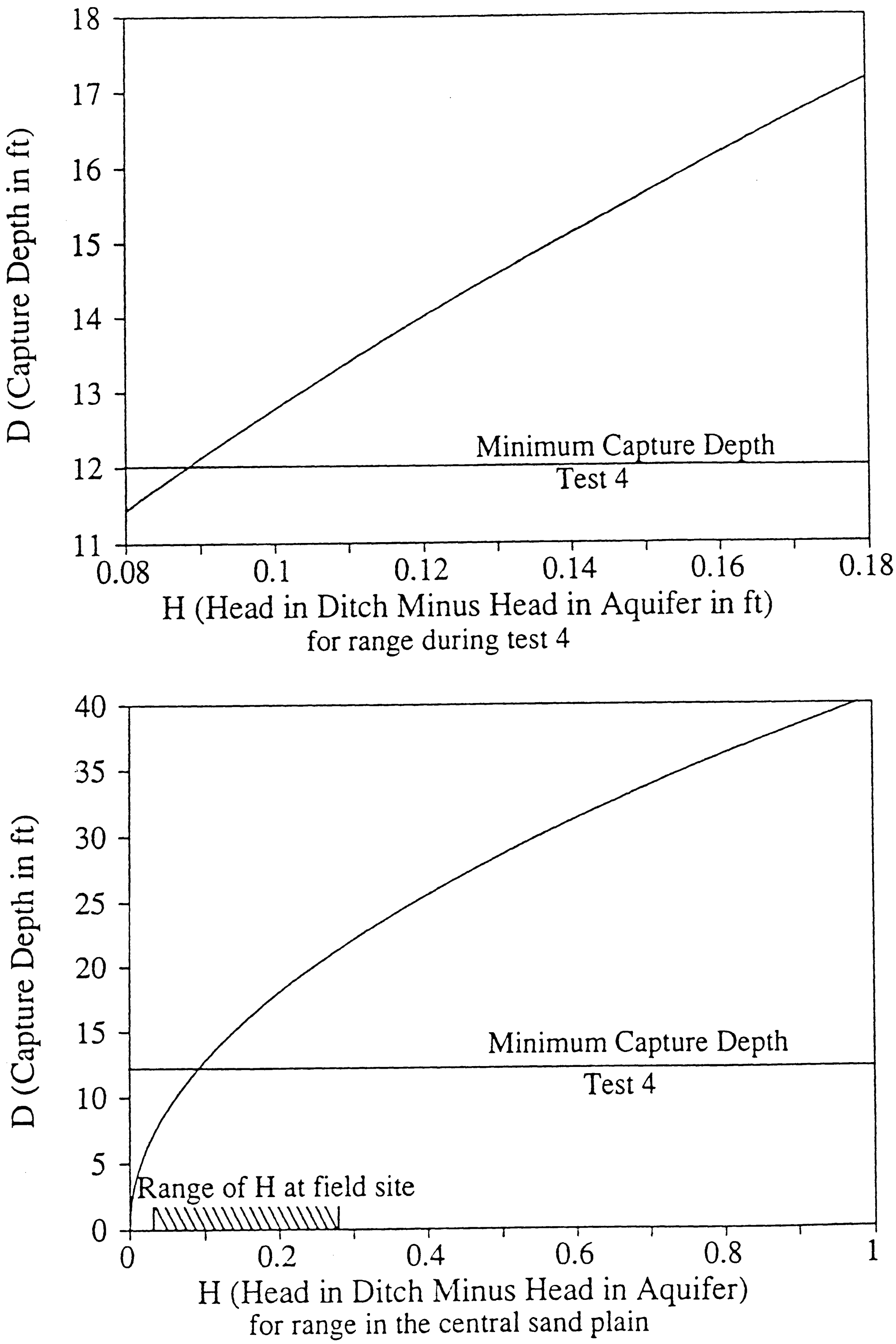


Figure 4.17 Variations in capture depth due to variations in the difference between the head in the aquifer and the head in the ditch.

According to the regional groundwater maps, for the area near the field site the regional gradient is between 0.001 and 0.002, with a median value of 0.0015.

A graph of D versus I was constructed in the same manner as the graphs for w and H (Figure 4.18a). Since no measurements are available for the regional gradient near the field site in the summer of 1989, the uncertainty in the value of I is high. However, for the estimated range of I (0.001 to 0.002) from the regional water table map (Lippelt and Hennings, 1981), the predicted range of D values is similar to the range of D values predicted for the estimated range of H values. It is unlikely that the regional gradient would vary more than 0.001 during the summer and fall in the central sand plain. Therefore, the magnitude of the effect of I on D is likely to be similar to the magnitude of the effect of H on D. H is likely to change more rapidly and more frequently than I, thus changes in H are probably the most significant in terms of the short term variations in the capture depth. For the range of possible I values within the central sand plain, however the estimated range of D is very large (Figure 4.18b).

Anisotropy

Within the central sand plain the estimates of the anisotropy of the aquifer, the ratio of horizontal to vertical hydraulic conductivity (R), range from 1 to 7 (Weeks and Stangland, 1971) based on 5 pumping test analyses by Weeks (1969) in different portions of the central sand plain. No clear pattern of the distribution of R within the central sand plain

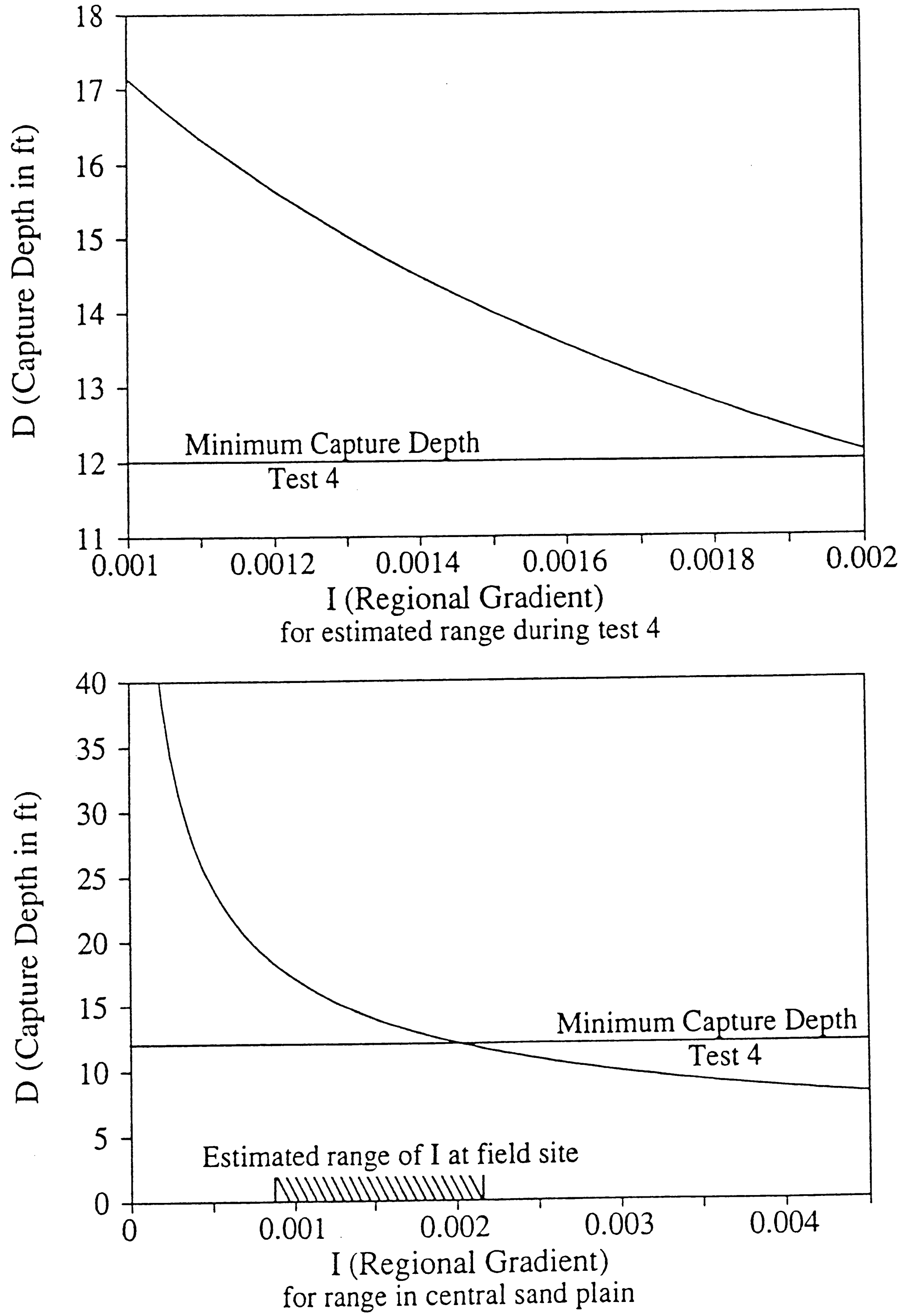


Figure 4.18 Uncertainty in the capture depth due to uncertainty in the regional gradient.

arises from the tests by Weeks and no tests have been done at the field site to evaluate the value of R, so the value can only be estimated. Since R is difficult to calculate, model calibration model may aid in limiting the estimated range of values. Figure 4.19 is a graph of D versus R for a range of values for the other three parameters. The lower line represents the combination of w, H, and I, which gives the smallest estimate of D for the range of values estimated for each parameter during test 4. The middle line represents the value for D for the median estimated values of w, H, and I during test 4. The upper line represents the largest estimate of D for the range of estimated values for each parameter during test 4. Since the capture depth for tracer test 4 was greater than 12 feet, R is estimated to be 3 or less using the median values of w, H and I.

Summary

The capture depth of the ditch is more sensitive to changes in I and H, than to changes in w. The value of I for the summer of 1989 is not known, but the temporal variation is not likely to be large. Thus the range of I values reflects the uncertainty in the estimate of I, as opposed to an actual change during the tracer test. However, H may vary significantly during the course of the test. H appears to be the most important parameter in determining variations in the capture depth. It is important to note that in the physical system, these parameters are unlikely to vary independently. For example, during a period of recharge, one would expect w and H to increase, but the value of I would most likely increase also, so

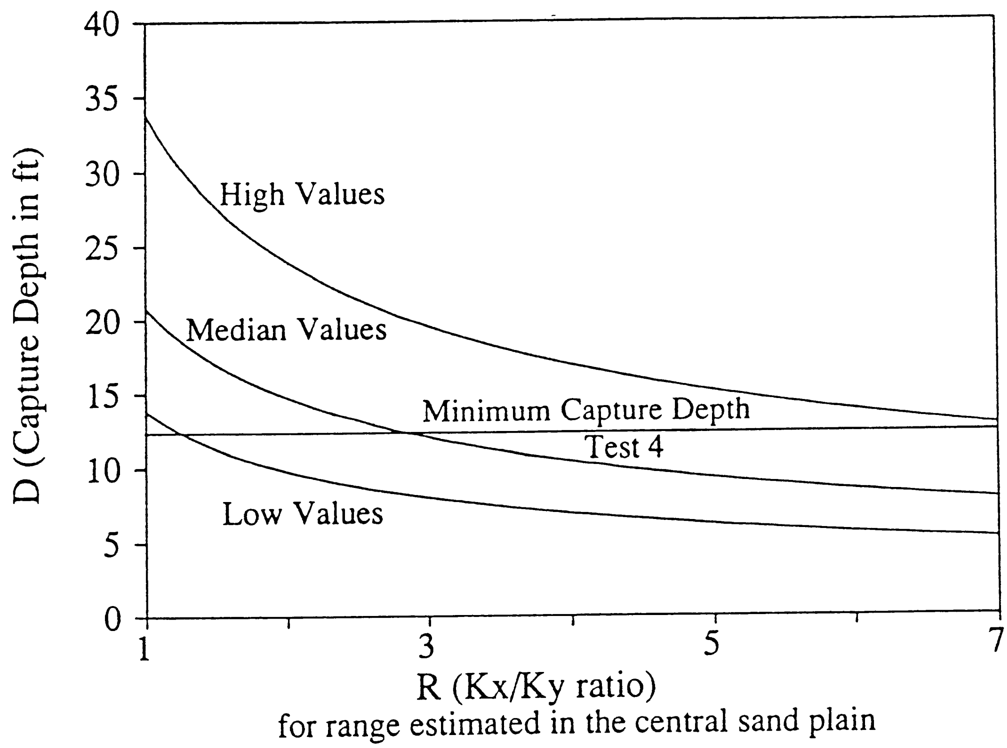


Figure 4.19 Uncertainty in the capture depth due to uncertainty in the ratio of the vertical to horizontal hydraulic conductivity for the low, median and high estimates of the capture depth for the range of each parameter observed or estimated during test 4.

there might be very little net change in D. There probably is a time lag between changes in w and H and a change in I. If so, there may be large transient changes in D, which could lead to increased dispersion of a contaminant in the vicinity of a ditch.

R is an extremely difficult parameter to measure and is unlikely ever to be known with very much certainty. Due to the range of possible R values for the central sand plain, it is unlikely that the depth of the capture zone will ever be predicted with a great deal of certainty using the analytic solution. The maximum estimated value of R for the sand plain, 7, gives the minimum capture depth, thus R equal to 7 could be used for estimates of the minimum capture depth. Additional tracer tests may reduce the uncertainty in the estimated value of R at the field site.

V. DISCUSSION AND CONCLUSIONS

The results compiled and discussed in this report are part of an ongoing research project. In this chapter, groundwater management implications are discussed and the conclusions of this portion of the study are briefly summarized.

Discussion of Groundwater Management Implications

A series of tracer tests have delineated the capture zone for a drainage ditch within the sand plain. The capture zone appears to be of sufficient depth to act as a barrier to shallow agricultural contamination. Numerous other ditches within the central sand plain have characteristics similar to those of the ditch at the study site and therefore should also act as barriers to shallow contamination. An estimate of the minimum capture zone of a particular ditch would allow for improved management recommendations. This section presents a methodology for the evaluation of the minimum capture depth of a ditch and provides a simple diagram for making this estimate. In addition, the limitations on ditch effectiveness and recommendations for future research are discussed.

Estimating the Minimum Capture Depth

In order to estimate the minimum capture depth (D_{min}) for a particular drainage ditch, a conservative estimate of the four parameters used in the analytic solution, equation (3):

$$D = B \cdot \left(\frac{wH}{IR}\right)^{1/2} \qquad \text{for } B = \left(\frac{2}{\pi}\right)^{1/2},$$

must be made. For a given ditch, the smallest estimates of w and H and the largest estimates of I and R will give a conservative estimate of D. Field examination of a particular ditch should allow one to measure and estimate the minimum ditch width, w, in the area of interest. The width of the ditch is usually the narrowest in late summer, after several days with almost no rain. Within the central sand plain w varies from about 4 to 20 feet. In order to estimate H, the head in the ditch minus the head in the aquifer, one or more mini-piezometers should be installed (see Lee and Cherry, 1978) into the ditch to a depth of at least 2 feet below the base of the ditch. H is measured as the difference between the water level in the mini-piezometer and the water level in the ditch. H is likely to be smallest in late summer, when the aquifer has received very little recharge over several months. Within the central sand plain, for ditches roughly perpendicular to the ground water flow path, H probably varies from 0 to 1 foot. The regional gradient, I, can be estimated from water table maps of the central sand plain (Lippelt and Hennings, 1981; Weeks and Stangland, 1971). The largest regional gradient in the area of interest should be used. The regional gradient appears to vary from 0.0003 to 0.005, within the central sand plain. The anisotropy ratio, R, should be taken as 7, the maximum estimated value for the sand plain region (Weeks and Stangland, 1971).

Using a conservative estimate for each parameter (described above), a conservative estimate of the capture depth can be calculated using equation (3). Figure 5.1 can also be used to determine the minimum capture depth for a particular ditch.

Limitations on Ditch Effectiveness

Geologic or hydrogeologic conditions may preclude or limit the effectiveness of drainage ditches in removing shallow groundwater contamination. In some areas of the central sand plain the depth to water is greater than 15 or 20 feet below the water table. In these areas a network of drainage ditches are not likely to be economically feasible. It also may not be desirable to lower the water table with ditches. In areas where the water table gradient is quite steep the capture depth of a drainage ditch will be very shallow. In regions where the capture depth is shallow, widening of the ditches may serve to increase the capture depth. Figure 5.2 is a water table map compiled by Stoertz (1989) from Lippelt and Hennings (1981). The regions where depth to water is greater than 15 feet have been superimposed on this diagram by comparing water table elevations to land surface elevations on topographical maps.

Model predictions of ditch capture zones are based on the assumption that the ditch is roughly perpendicular to the groundwater flow direction. Many ditches within the central sand plain run roughly parallel to groundwater flow directions. These ditches which flow roughly parallel to groundwater flow are not likely to capture groundwater from a large area.

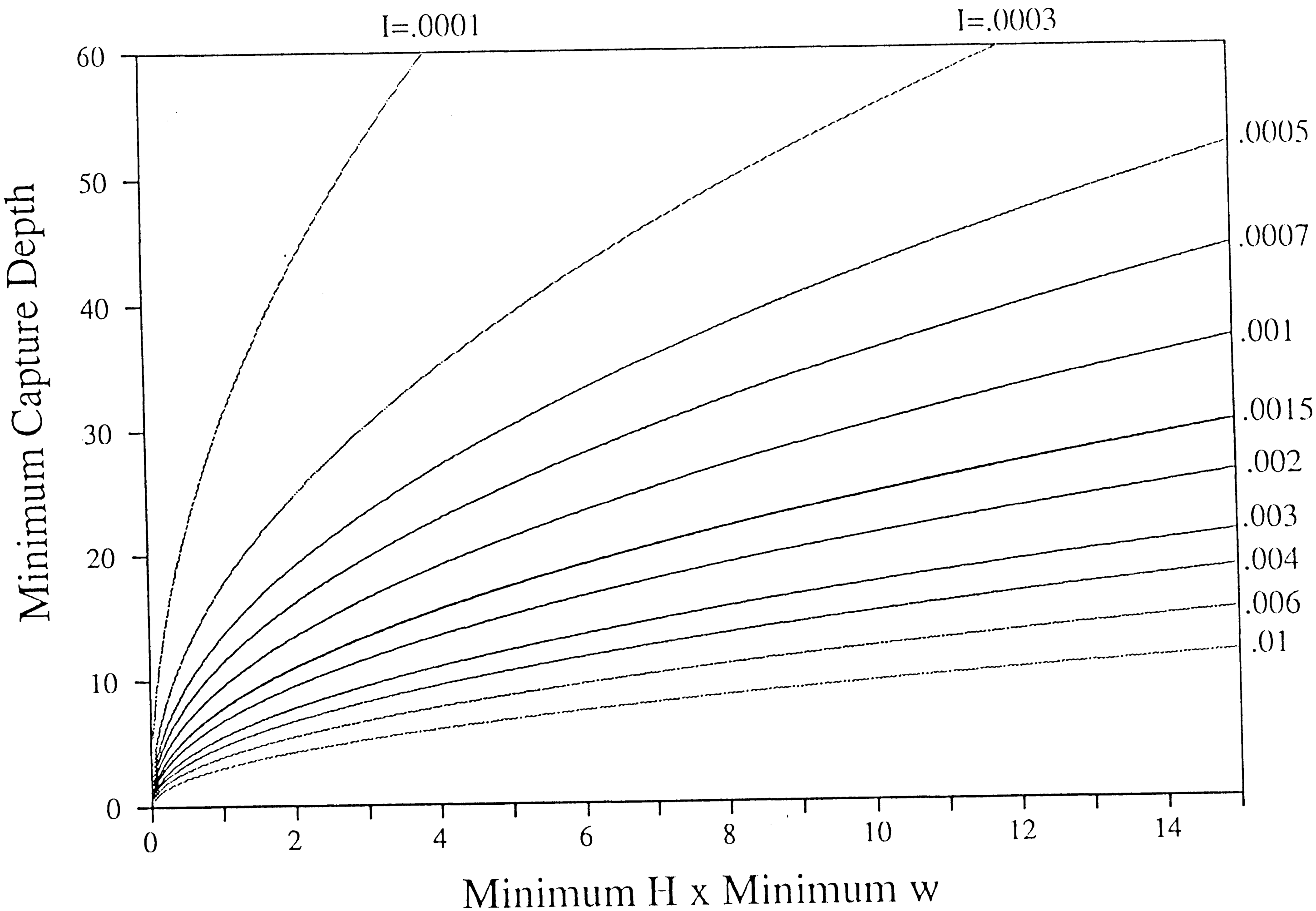


Figure 5.1 The relationship between the minimum capture depth and the product of H and w. Each line represents a particular value of I. R is assumed to be 7.

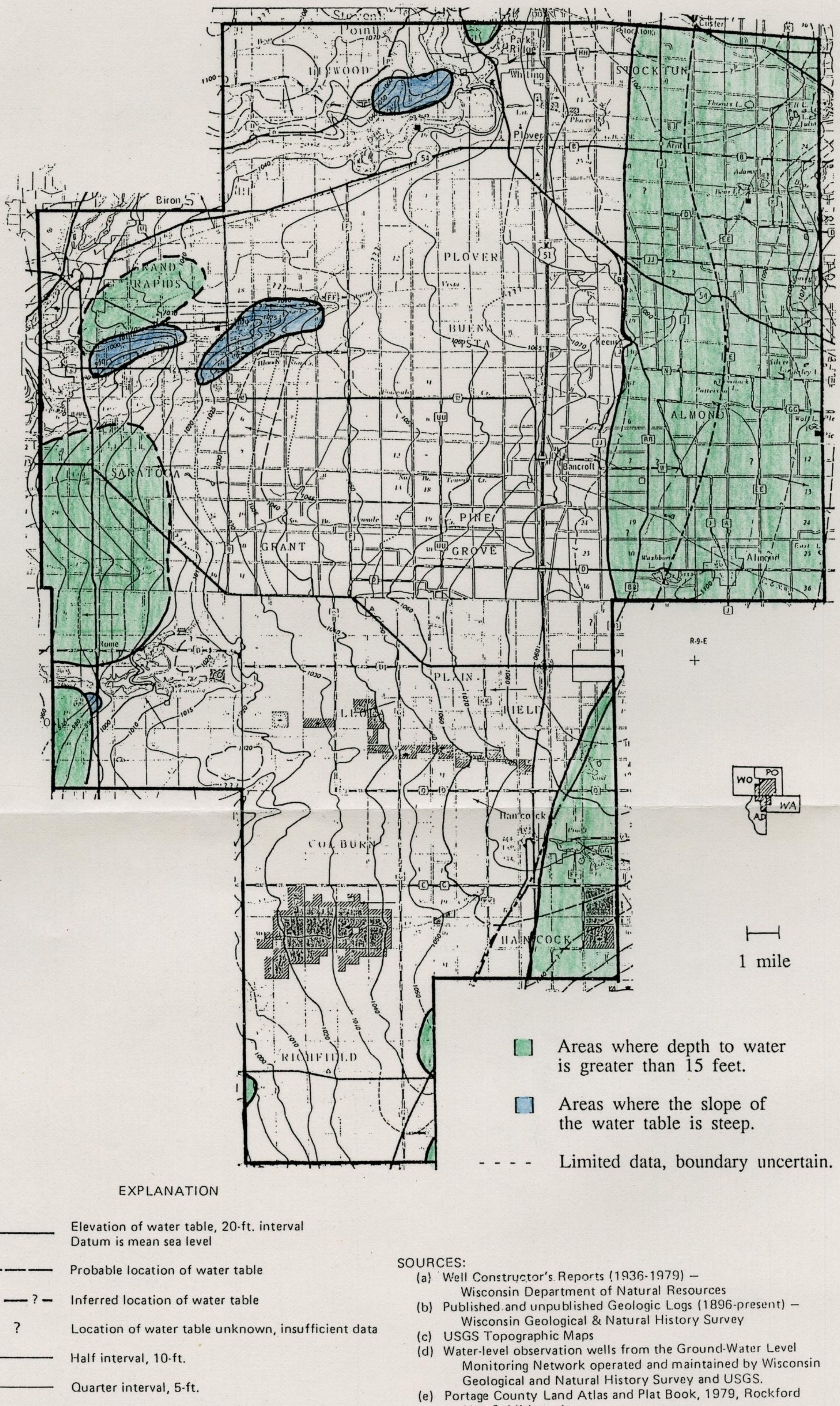


Figure 5.2 Areas where drainage ditches may not be a practical method of removing shallow groundwater contamination. Water table map compiled by Stoertz (1989) from Lippelt and Hennings (1981).

EXPLANATION

- Elevation of water table, 20-ft. interval. Datum is mean sea level
- Probable location of water table
- Inferred location of water table
- ? Location of water table unknown, insufficient data
- Half interval, 10-ft.
- Quarter interval, 5-ft.
- Direction of ground-water movement
- Ground-water divide, approximate location
- Probable ground-water divide
- Federal/state lands

SOURCES:
(a) Well Constructor's Reports (1936-1979) – Wisconsin Department of Natural Resources
(b) Published and unpublished Geologic Logs (1896-present) – Wisconsin Geological & Natural History Survey
(c) USGS Topographic Maps
(d) Water-level observation wells from the Ground-Water Level Monitoring Network operated and maintained by Wisconsin Geological and Natural History Survey and USGS.
(e) Portage County Land Atlas and Plat Book, 1979, Rockford Map Publishers, Inc.
(f) Geology and Water Resources of Portage County, Wisconsin, USGS Water-Supply Paper 1796, C.L.R. Holt, Jr., 1965.

Data have not been field checked.

Some of the existing ditches within the sand plain are choked with vegetation and organic matter. The near stagnation of the flow within these ditches suggests that there is very little flow into the ditch (H is likely to be near 0). In these areas dredging of the ditches might increase the ditches effectiveness in removing shallow agricultural contaminants. The placing of dams within ditches is also likely to locally decrease the flow up into the ditch.

In some areas of the central sand plain the New Rome Member, a silt and clay layer at a depth of 30 or more feet (see Chapter 2 for details), may restrict the total depth of the capture zone. If the silt and clay layer is fairly extensive in an area, it is unlikely that the capture zone would extend below the silt and clay layer. However, agricultural contaminants are also not likely to migrate through the silt and clay layer, due to its low hydraulic conductivity and the strong upward gradient that exists across the silt and clay layer in some areas.

Recommendations for Future Research

In addition to delineating the capture zone of the ditch, the evaluation of the tracer tests conducted have helped to determine areas for future research. In order to improve estimates of the depth of the capture zone a better estimate and understanding of the parameters used in the model are needed. A more complete understanding of the flow field in the vicinity of the ditch is also essential to improve capture zone estimates. A better understanding of contaminant movement within the sand plain would also be useful for broader management questions. This research has demonstrated that local scale contaminant transport is significantly affected by aquifer heterogeneity. A characterization of the physical and chemical heterogeneities within the flow system would improve our ability to predict contaminant movement.

Improvement of Capture Zone Estimates

The uncertainty in the estimates of the capture depth is tied to the uncertainty of the parameters used to make the estimates. The variability and uncertainty in estimates of the ditch width, w, or the head in the ditch minus the head in the aquifer, H, are due to both spatial and temporal variations of the parameters. Temporal variations in w and H appear to cause large seasonal variations in the capture depth. Further studies are needed in order to predict the timing and magnitude of these variations. Regional scale studies of water table fluctuations, combined with local studies of ditch response to storm events and seasonal recharge, would provide important data for such predictions.

The anisotropy ratio, R, is a difficult parameter to measure and it is likely to vary at least over a small range throughout the sand plains. Improved estimates of R are needed in order to reduce the uncertainty in estimating the depth of the capture zone. At the field site it may be possible to develop a better local understanding of the anisotropy ratio by comparing the horizontal and vertical gradients to the velocity field delineated by tracer tests. The anisotropy ratio should be affected by the nature of the layering system within the aquifer. Further study is needed to delineate whether, on a regional scale, R can be correlated to geologic facies. For example, is there a correlation between R and the distance from the moraine? A combination of pumping test analyses and detailed studies of grain-size distribution and stratification could be used to address this question.

A better and more complete understanding of flow field is needed. The flow field in the vicinity of the ditch should be evaluated through additional tracer tests and monitoring of gradients. The depth to the dividing surface is likely to be deeper at greater distances from the ditch. In order to evaluate the capture zone depth, tracer should be injected into wells at greater distances from the ditch. However, for every 20 feet further from the ditch, approximately an additional month is added to the length of a test.

The groundwater flow field varied significantly between the summer of 1989 and 1990, resulting in not only a variable capture depth, but also changes in horizontal direction of flow. The effects of high recharge rates on the groundwater flow field are not well understood at present for this environment. Information about the flow field can be inferred from horizontal and vertical gradients, calculated from water level measurements. Additional water table wells and deeper wells have been installed at the site, but additional data collection and analysis of the data are needed.

Three-dimensional numerical models should also be used to evaluate the flow field. Simple models such as Zheng's analytic solution are frequently preferred because they are easy to apply. However, the observed tracer paths indicate that there is significant variability in the groundwater velocity due to both the three-dimensional, non-uniform nature of the flow field and aquifer heterogeneity. A computer model is needed to evaluate the importance of factors, such as recharge, which are not incorporated in the analytic model and to assess the importance of the three-dimensional nature of the aquifer. Additional modeling efforts should also focus on the transient nature of the flow system. These models can be used as predictive tools to provide additional information needed to make better management practice recommendations.

Better Understanding of Contaminant Movement

The paths of the tracer plumes clearly indicated that the flow field is complex and three-dimensional. Breakthrough curves such as those shown in Figure 5.3, taken from 5 points within a single multilevel (Ml2), indicate that there are significant small scale variations in groundwater velocities due to variations in hydraulic conductivity. It is important to understand these non-uniformities in the flow field, because they may have an even greater effect on reacting contaminants. Recent theories on the dispersion of solutes (Moltz et al., 1983; Wheatcraft and Tyler, 1988; Sudicky, 1986; Mackay et al., 1986) suggest that contaminant movement is strongly influenced by microscale and macroscale variations in the hydraulic properties of the aquifer even in relatively homogeneous materials.

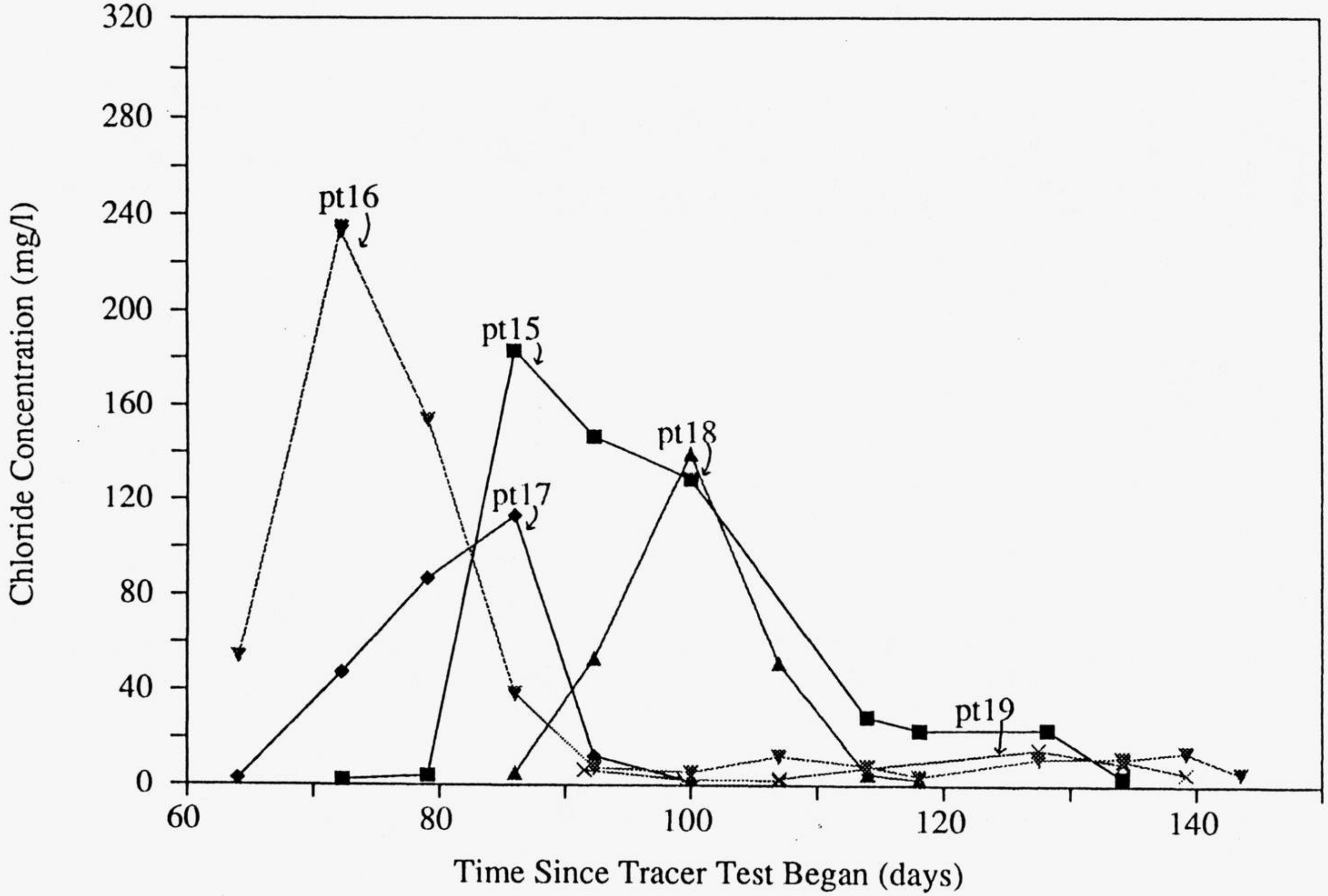


Figure 5.3 Breakthrough curves for 5 points within multilevel 2 for the chloride plume during test 3. At point 16 the peak concentration arrived on approximately day 71. At point 18, 6 feet above pint 16, the peak concentration broke through approximately 29 days later. (See figure 4.12)

The hydraulic conductivity of the aquifer and variations in the physical hydraulic properties of the aquifer need to be characterized in order to understand the effects of aquifer heterogeneity on contaminant migration in the sand plain. Variations in hydraulic parameters need to continue to be evaluated by a variety of different methods including slug tests, grain size analyses, and examination of sedimentary structures and stratification from vibracores. Each of these tests provides estimates of the physical hydrogeologic properties at a different scale.

It would also be valuable to examine the composition of sediment grains and the degree of internal porosity. A recent study by Wood et al. (1990) suggests that the internal porosity in sands may play a significant and important role in solute transport.

The water chemistry and the chemical composition of the sediment also influences the movement of many groundwater contaminants. Recent experiments with chromium, which can undergo chemical reactions during transport, revealed the importance of variations in geochemical parameters such as dissolved oxygen in determining the speciation and mobility of contaminants (Kent et al., 1989). The water chemistry of the site needs to be characterized in order to determine spatial variability of the water chemistry. Tracer tests using actual agricultural chemicals should also be conducted in the shallow portion of the aquifer which is known to be captured by the ditch. A field evaluation of contaminant movement is important in understanding the degree of mobility of such compounds within the actual groundwater flow system.

Conclusions

The groundwater flow field around a drainage ditch was evaluated through a series of natural gradient tracer tests. For the conditions in the summer and fall of 1989, the capture depth was at least 12 to 16 feet below the water table. In the late summer of 1990 the capture depth was at least 24 feet below the water table. At distances greater than 25 feet from the ditch, the dividing streamline was presumably deeper. These results are encouraging because they suggest that drainage ditches should allow for the effective removal of shallow groundwater contamination.

A capture depth greater than 12 feet below the water table falls within the range of values predicted for the summer and fall of 1989 using the two-dimensional analytic model by Zheng. However, due to the large uncertainty and variability in the parameters used in the model, the range of predicted depths for the capture zone is very large, from 6 to 34 feet below the water table. A sensitivity analysis of Zheng's analytic model, using data collected at the field site, reveals that the predicted depth of the capture zone is relatively sensitive to small changes in the anisotropy ratio, R, the regional horizontal gradient, I, and the difference between the head in the ditch and the head in the aquifer, H. Uncertainty in the appropriate anisotropy ratio which should be used in the model causes most of the uncertainty in the predicted capture depth, because I and H can be estimated fairly accurately, whereas R cannot. Seasonal variations in the capture depth appear to be directly related to variations in H. The most important parameter in determining temporal variations in the predicted capture depth appears to be H.

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Appendix A: I. Water Table and Injection Wells

well name	elev. screen base (ft)	elev. screen top (ft)	elev. of well top (ft)	screen length (ft)	well dia-meter (in)	slot size	install-ation date
wt1	1033.1	1037.7	1042.85	4.65	2	0.018	7/88
wt2	1032.6	1037.3	1039.87	4.65	2	0.018	7/88
wt3	1032.8	1037.5	1042.61	4.65	2	0.018	7/88
wt4	1032.6	1037.3	1039.45	4.65	2	0.018	7/88
wt5	1032.6	1037.3	1042.69	4.65	2	0.01	7/88
wt6	1032.8	1035.3	1037.39	2.5	0.75	cut	7/88
wt7	1033.3	1036.0	1038.35	2.7	0.75	cut	7/88
wt8	1032.4	1035.3	1040.34	2.9	1	cut	7/88
wt9	1032.5	1035.3	1041.19	2.8	1	cut	7/88
wt10	1033.5	1036.4	1038.90	2.9	0.75	cut	7/88
wt11	1034.1	1037.1	1038.41	3	1	cut	8/88
wt12	1033.9	1036.9	1039.40	3	1	cut	8/88
wt13	1034.1	1036.1	1038.67	2	1	cut	8/88
wt14	1033.9	1035.9	1037.08	2	0.75	cut	8/88
wt15	1033.9	1035.9	1038.18	2	1	cut	8/88
wt16	1033.4	1035.4	1037.83	2	1	cut	8/88
wt17	1033.2	1035.9	1039.54	2.75	0.75	cut	8/88
wt18	1032.6	1035.6	1039.07	3	1	cut	8/88
wt19	1033.1	1034.0	1036.69	0.83	0.75	cut	8/88
wt20	1032.6	1034.3	1038.03	1.7	1	cut	8/88
wt21	1032.3	1037.0	1039.62	4.72	1.25	0.01	8/88
wt22	1033.7	1038.5	1041.57	4.75	1.25	0.01	8/88
wt23	1031.9	1036.6	1041.04	4.75	1.25	0.01	8/88
wt24	1030.5	1035.2	1042.46	4.7	1.25	0.01	8/88
wt25	1031.7	1036.4	1042.17	4.7	1.25	0.01	8/88
wt26	1032.2	1036.9	1041.17	4.7	1.25	0.01	8/88
wt27	1031.1	1035.8	1040.96	4.7	1.25	0.01	8/88
wt28	1034.2	1036.1	1037.65	1.9	1	0.01	4/89
wt29	1034.1	1035.5	1036.87	1.4	1	cut	4/89
wt30	1034.3	1036.2	1039.22	1.9	1	0.01	4/89
wt31	1034.2	1036.1	1039.15	1.9	1	0.01	4/89
wt32	1034.0	1036.0	1036.91	2	1	0.01	4/89
wt33	1034.2	1035.7	1037.11	1.5	1		4/89
wt34	1033.4	1035.3	1038.22	1.9	1	0.01	4/89
wt35	1035.5	1037.3	1039.35	1.8	1	cut	4/89
wt36	1035.2	1037.2	1039.04	2	1.25	0.06	6/89
wt37	1035.0	1037.0	1039.01	2	1.25	0.06	6/89
wt38	1034.8	1036.7	1040.79	1.9	1.25	0.01	6/89
wt39	1034.7	1036.4	1042.01	1.76	1.25	0.01	6/89
wt40	1034.5	1036.2	1040.77	1.76	1.25	0.01	6/89
wt41	1035.9	1037.4	1038.40	1.5	1	0.01	6/89
wt42	1034.4	1036.2	1039.5	1.84	1.25	0.01	7/89

well name	elev. screen base (ft)	elev. screen top (ft)	elev. of well top (ft)	screen length (ft)	well dia- meter (in)	slot size	install- ation date
iw1	1022.5	1028.8	1039.09	6.25	2	0.01	7/88
iw2	1012.2	1018.8	1038.91	6.64	2	0.01	7/88
iw3	1003.3	1010.0	1039.13	6.65	2	0.01	7/88
iw4	1012.9	1019.8	1040.66	6.9	2	0.01	5/89
iw5	1012.9	1019.8	1040.76	6.9	2	0.01	5/89
iw6	1033.5	1034.9	1039.34	1.4	2	0.01	5/89
iw7	1033.4	1034.8	1039.47	1.4	2	0.01	5/89
iw8	1033.5	1034.9	1039.32	1.4	2	0.01	5/89
iw9	1024.4	1029.1	103[illegible].41	4.67	2	0.01	7/89
iw10	1024.4	1029.1	1039.41	4.68	2	0.01	7/89
iw11	1024.4	1029.1	1039.37	4.68	2	0.01	7/89
iw12	1014.4	1019.1	1039.41	4.68	2	0.01	7/89
iw13	1014.4	1019.1	1039.40	4.68	2	0.01	7/89
iw14	1014.4	1019.1	1039.39	4.68	2	0.01	7/89
mw1	1012.1	1019.0	1039.93	6.9	2	0.01	5/89
mw2	1033.9	1034.4	1039.05	0.5	1.25	0.01	7/89
mw3	1034.0	1034.5	1038.82	0.5	1.25	0.01	7/89

Figure 3.3 (p. 35) shows the location of all wells listed above.

abbreviations: wt = water table well
iw = injection well
mw = monitoring well
cut = hand cut screen with bridal organdy secured by cable ties and duct tape

Point	Elevation (ft)
ml1 pt1	972.92
ml1 pt2	976.92
ml1 pt3	980.95
ml1 pt4	984.94
ml1 pt5	988.98
ml1 l1	990.51
ml1 pt6	992.98
ml1 pt7	996.99
ml1 l2	1003.42
ml1 pt9	1005.11
ml1 pt10	1009.11
ml1 pt11	1013.12
ml1 l3	1014.01
ml1 pt12	1017.13
ml1 pt13	1021.13
ml1 pt14	1025.14
ml1 pt15	1029.12
ml1 pt16	1033.12
ml2 pt1	976.13
ml2 pt2	979.13
ml2 pt3	982.13
ml2 pt4	985.13
ml2 pt5	988.09
ml2 pt6	991.13
ml2 pt7	994.13
ml2 l1	996.22
ml2 pt8	997.13
ml2 pt9	1000.13
ml2 pt10	1003.05
ml2 pt11	1006.05
ml2 pt12	1009.09
ml2 pt13	1011.97
ml2 pt14	1014.88
ml2 l2	1016.30
ml2 pt15	1017.88
ml2 pt16	1020.88
ml2 pt17	1023.97
ml2 pt18	1026.88
ml2 pt19	1029.88
ml2 pt20	1032.88
ml2 pt21	1036.05

Point	Elevation (ft)
ml3 pt1	982.09
ml3 pt2	977.76
ml3 pt3	980.76
ml3 pt4	983.76
ml3 pt5	986.76
ml3 pt6	989.76
ml3 pt7	992.76
ml3 l1	994.76
ml3 pt8	995.76
ml3 pt9	998.76
ml3 pt10	1001.76
ml3 pt11	1004.76
ml3 pt12	1007.76
ml3 pt13	1010.76
ml3 pt14	1013.76
ml3 l2	1014.67
ml3 pt15	1016.76
ml3 pt16	1019.76
ml3 pt17	1022.76
ml3 pt18	1025.76
ml3 pt19	1028.76
ml3 pt20	1031.76
ml3 pt21	1034.76
ml4 pt1	983.91
ml4 pt2	978.57
ml4 pt3	981.57
ml4 pt4	984.66
ml4 pt5	987.57
ml4 pt6	990.62
ml4 l1	992.07
ml4 pt7	993.57
ml4 pt8	996.57
ml4 pt9	999.57
ml4 pt10	1002.66
ml4 pt11	1005.57
ml4 l2	1007.66
ml4 pt12	1008.57
ml4 pt13	1011.57
ml4 l3	1013.57
ml4 pt14	1014.57
ml4 pt15	1017.57
ml4 pt16	1020.53
ml4 pt17	1023.57
ml4 pt18	1026.57
ml4 pt19	1029.57
ml4 pt20	1032.53
ml4 pt21	1035.57

Point	Elevation (ft)
ml5 pt1	982.49
ml5 pt2	978.66
ml5 pt3	981.66
ml5 pt4	984.66
ml5 pt5	987.70
ml5 pt6	990.70
ml5 pt7	993.74
ml5 pt8	996.66
ml5 pt9	999.74
ml5 pt10	1002.74
ml5 pt11	1005.74
ml5 pt12	1008.70
ml5 pt13	1011.70
ml5 pt14	1014.70
ml5 l1	1015.70
ml5 pt15	1017.70
ml5 pt16	1020.66
ml5 pt17	1023.66
ml5 pt18	1026.70
ml5 l2	1027.74
ml5 pt19	1029.70
ml5 pt20	1032.66
ml5 l3	1033.62
ml5 pt21	1035.70
ml6 pt1	982.62
ml6 pt2	978.24
ml6 pt3	981.29
ml6 pt4	984.29
ml6 pt5	987.27
ml6 pt6	990.31
ml6 pt7	993.22
ml6 pt8	996.24
ml6 pt9	999.24
ml6 pt10	1002.22
ml6 pt11	1005.22
ml6 pt12	1008.22
ml6 pt13	1011.29
ml6 pt14	1014.24
ml6 pt15	1017.22
ml6 pt16	1020.22
ml6 pt17	1023.22
ml6 pt18	1026.22
ml6 pt19	1029.20
ml6 pt20	1032.20
ml6 pt21	1035.20

Point	Elevation (ft)
ml7 pt1	975.56
ml7 pt2	978.56
ml7 pt3	982.40
ml7 pt4	984.56
ml7 pt5	987.61
ml7 pt6	990.61
ml7 pt7	988.61
ml7 pt8	996.61
ml7 l1	998.98
ml7 pt9	999.61
ml7 pt10	1002.61
ml7 pt11	1005.61
ml7 pt12	1008.61
ml7 pt13	1011.61
ml7 pt14	1014.61
ml7 pt15	1017.56
ml7 l2	1018.98
ml7 pt16	1020.59
ml7 pt17	1023.61
ml7 pt18	1026.61
ml7 pt19	1029.61
ml7 pt20	1032.61
ml7 pt21	1035.61
ml8 pt1	971.74
ml8 pt2	974.74
ml8 pt3	977.74
ml8 pt4	980.74
ml8 pt5	983.74
ml8 pt6	986.74
ml8 pt7	989.74
ml8 pt8	992.70
ml8 pt9	995.72
ml8 pt10	998.74
ml8 pt11	1001.74
ml8 l1	1001.07
ml8 pt12	1004.72
ml8 pt13	1007.74
ml8 pt14	1010.76
ml8 pt15	1013.72
ml8 pt16	1016.74
ml8 l2	1015.78
ml8 pt17	1019.70
ml8 pt18	1022.74
ml8 pt19	1025.74
ml8 pt20	1028.74
ml8 pt21	1031.74
ml9 pt1	971.21
ml9 pt2	974.23
ml9 pt3	977.21
ml9 pt4	980.21
ml9 pt5	983.21
ml9 pt6	986.21
ml9 pt7	989.21
ml9 pt8	992.21
ml9 pt9	995.23
ml9 pt10	998.23
ml9 pt11	1001.23
ml9 pt12	1004.23
ml9 l1	1006.19
ml9 pt13	1007.23
ml9 pt14	1010.21
ml9 pt15	1013.23
ml9 l2	1015.60
ml9 pt17	1016.21
ml9 pt18	1019.12
ml9 pt19	1022.21
ml9 pt20	1025.12
ml9 l3	1026.17
ml9 pt21	1031.17
ml9 l4	1032.08
ml10 pt1	1011.18
ml10 l1	1011.18
ml10 pt2	1011.34
ml10 pt3	1014.20
ml10 pt4	1015.68
ml10 l2	1016.14
ml10 pt5	1017.24
ml10 pt6	1018.64
ml10 pt7	1020.13
ml10 l3	1021.08
ml10 pt8	1021.68
ml10 pt9	1023.15
ml10 pt10	1024.63
ml10 pt11	1026.13
ml10 l4	1026.11
ml10 pt12	1027.68
ml10 pt13	1029.11
ml10 pt14	1030.65
ml10 l5	1031.13
ml10 pt15	1032.13
ml10 pt16	1033.60
ml10 pt17	1035.08
ml10 pt18	1036.56
ml11 pt1	1009.47
ml11 pt2	1010.87
ml11 l1	1010.95
ml11 pt3	1012.37
ml11 pt4	1013.93
ml11 pt5	1015.37
ml11 l2	1015.97
ml11 pt6	1016.93
ml11 pt7	1018.37
ml11 pt8	1019.72
ml11 l3	1020.97
ml11 pt9	1021.22
ml11 pt10	1022.72
ml11 pt11	1024.23
ml11 pt12	1025.73
ml11 l4	1025.98
ml11 pt13	1027.18
ml11 pt14	1028.68
ml11 pt15	1030.18
ml11 l5	1030.98
ml11 pt16	1031.63
ml11 pt17	1033.13
ml11 pt18	1034.63
ml11 pt19	1036.07
ml11 pt20	1037.52
ml12 pt1	1008.37
ml12 pt2	1009.80
ml12 l1	1009.77
ml12 pt3	1011.32
ml12 pt4	1012.80
ml12 pt5	1014.32
ml12 l2	1014.82
ml12 pt6	1015.81
ml12 pt7	1017.28
ml12 pt8	1018.83
ml12 l3	1019.76
ml12 pt9	1020.21
ml12 pt10	1021.77
ml12 pt11	1023.24
ml12 pt12	1024.77
ml12 l4	1024.78
ml12 pt13	1026.33
ml12 pt14	1027.72
ml12 pt15	1029.32
ml12 l5	1029.72
ml12 pt16	1030.85
ml12 pt17	1032.36
ml12 pt18	1033.92

abbreviations: ml = multilevel sampling well
pt = sampling point
l = water level tube (can be used for sampling)

Appendix A: III. Miniature Multilevels

Well		Elevation of point (ft)	Installation Date (1989)
mm1	pt.1	1032.89	6.02
	pt.2	1033.72	
	pt.3	1034.49	
mm2	pt.1	1032.22	6.06
	pt.2	1033.72	
	pt.3	1035.22	
mm3	pt.1	1032.34	6.06
	pt.2	1033.84	
	pt.3	1035.34	
mm4	pt.1	1032.50	6.06
	pt.2	1034.00	
	pt.3	1035.50	
mm5	pt.1	1031.87	6.06
	pt.2	1033.37	
	pt.3	1034.87	
mm6	pt.1	1034.14	6.06
	pt.2	1035.14	
	pt.3	1036.14	
mm7	pt.1	1034.03	6.06
	pt.2	1035.03	
	pt.3	1036.03	
mm8	pt.1	1033.64	6.06
	pt.2	1034.64	
	pt.3	1035.64	
mm9	pt.1	1033.82	6.06
	pt.2	1034.82	
	pt.3	1035.82	
mm10	pt.1	1034.87	6.07
	pt.2	1035.37	
mm11	pt.1	1034.58	6.07
	pt.2	1035.08	
mm12	pt.1	1024.05	7.01
	pt.2	1027.05	
	pt.3	1030.05	
mm13	pt.1	1014.40	7.11
	pt.2	1017.40	
	pt.3	1020.40	
mm14	pt.1	1014.24	7.11
	pt.2	1017.24	
	pt.3	1020.24	
mm15	pt.1	1023.90	7.11
	pt.2	1026.90	
	pt.3	1029.90	
mm16	pt.1	1033.53	7.15
	pt.2	1034.53	
	pt.3	1035.53	
mm17	pt.1	1033.53	7.15
	pt.2	1034.53	
	pt.3	1035.53	
mm18	pt.1	1033.51	7.19
	pt.2	1034.41	
	pt.3	1035.31	
mm19	pt.1	1023.25	7.24
	pt.2	1025.00	
	pt.3	1026.75	
	pt.4	1026.39	7.24
	pt.5	1028.14	
	pt.6	1029.89	
	pt.7	1030.65	7.28
	pt.8	1031.65	
	pt.9	1032.65	
mm20	pt.1	1024.27	7.25
	pt.2	1026.02	
	pt.3	1027.77	
	pt.4	1028.25	7.25
	pt.5	1030.00	
	pt.6	1031.75	

mm = miniature multilevel
pt = sampling point

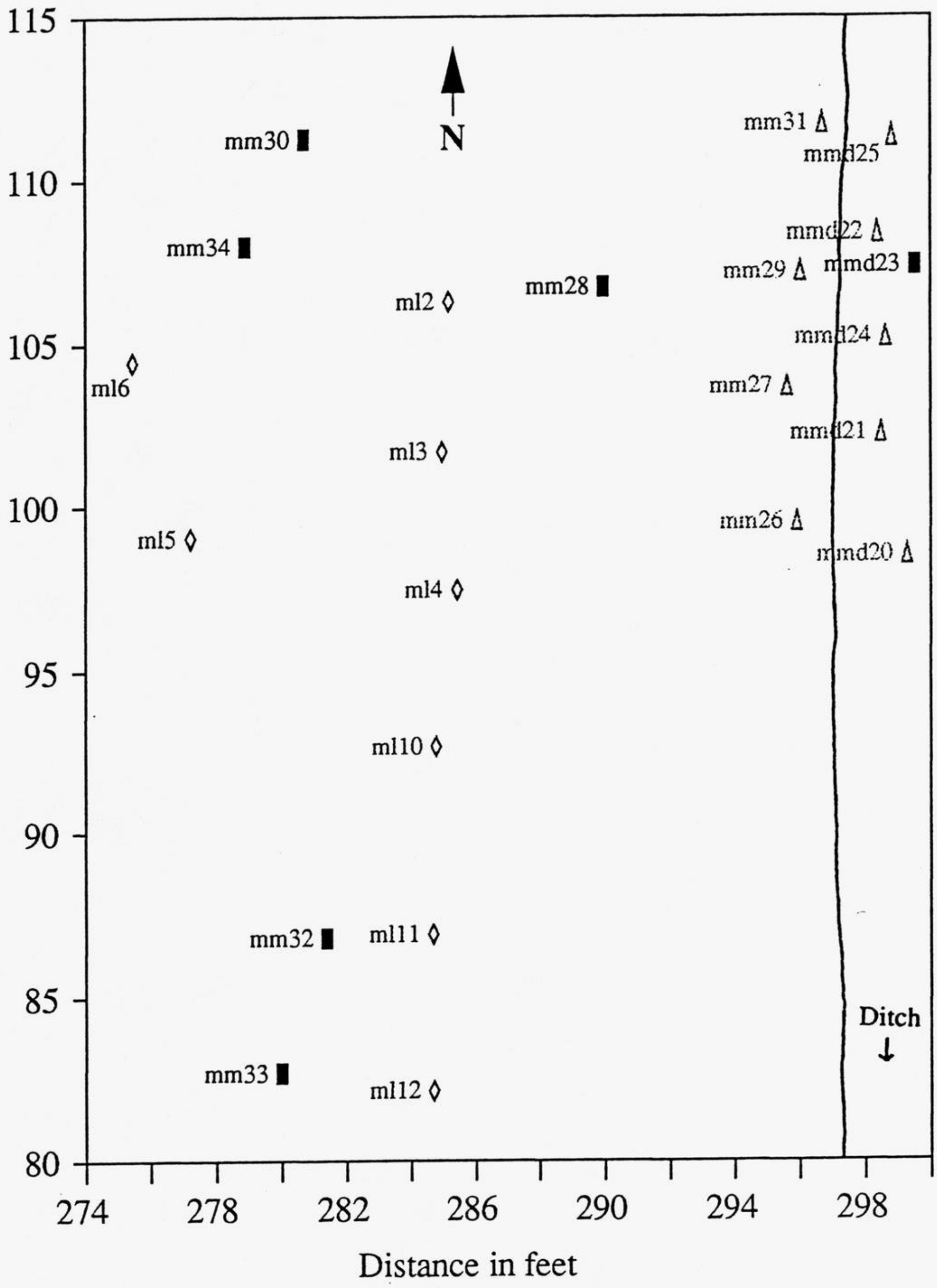
Well		Elevation of point	Installation Date
mm21	pt.1	1024.35	8.02
	pt.2	1025.85	
	pt.3	1027.35	
	pt.4	1028.35	7.30
	pt.5	1029.85	
	pt.6	1031.35	
	pt.7	1032.24	8.02
	pt.8	1033.24	
	pt.9	1034.24	
mm22	pt.1	1024.73	8.02
	pt.2	1026.23	
	pt.3	1027.73	
	pt.4	1028.50	7.30
	pt.5	1030.00	
	pt.6	1031.50	
	pt.7	1032.32	8.02
	pt.8	1033.32	
	pt.9	1034.32	
mm23	pt.1	1015.48	7.30
	pt.2	1017.98	
	pt.3	1018.48	
	pt.4	1021.45	8.02
	pt.5	1023.95	
	pt.6	1026.45	
mm24	pt.1	1024.05	8.01
	pt.2	1025.80	
	pt.3	1027.55	
	pt.4	1028.39	8.01
	pt.5	1030.14	
	pt.6	1031.89	
mm25	pt.1	1014.38	8.04
	pt.2	1016.38	
	pt.3	1018.38	
	pt.4	1019.47	8.04
	pt.5	1020.97	
	pt.6	1022.97	
mm26	pt.1	1030.30	9.04
	pt.2	1031.80	
	pt.3	1033.30	
mm27	pt.1	1030.67	9.04
	pt.2	1032.17	
	pt.3	1033.67	

Well		Elevation of point	Installation Date
mm28	pt.1	1018.58	9.16
		1020.58	
	pt.3	1022.58	
	pt.4	1024.15	9.16
	pt.5	1026.15	
	pt.6	1028.15	
mm29	pt.1	1023.65	10.01
	pt.2	1026.65	
	pt.3	1029.65	
	pt.4	1029.54	10.08
	pt.5	1031.54	
	pt.6	1033.54	
mm30	pt.1	1018.11	10.08
	pt.2	1021.11	
	pt.3	1024.11	
mm31	pt.1	1029.70	10.08
	pt.2	1031.70	
	pt.3	1033.70	
mm32	pt.1	1022.63	11.30
	pt.2	1025.13	
	pt.3	1027.63	
mm33	pt.1	1023.97	11.30
	pt.2	1026.47	
	pt.3	1028.97	
mm34	pt.1	1016.71	11.30
	pt.2	1019.21	
	pt.3	1021.71	
mmd4	pt1	1029.84	6.15
	pt2	1031.84	
	pt3	1033.84	
mmd6	pt1	1027.93	6.15
	pt2	1029.93	
	pt3	1031.93	
mmd9	pt1	1028.49	6.15
	pt2	1030.49	
	pt3	1032.49	
mmd10	pt1	1028.08	6.15
	pt2	1030.08	
	pt3	1032.08	

Well		Elevation of point	Installation Date
mmd11	pt.1	1025.60	8.05
	pt.2	1027.10	
	pt.3	1028.60	
	pt.4	1029.75	8.05
	pt.5	1031.25	
	pt.6	1032.75	
mmd12	pt.1	1025.54	8.05
	pt.2	1027.04	
	pt.3	1028.54	
	pt.4	1029.97	8.05
	pt.5	1031.47	
	pt.6	1032.97	
mmd13	pt.1	1031.92	8.05
	pt.2	1032.92	
	pt.3	1033.92	
mmd14	pt.1	1032.07	8.05
	pt.2	1033.07	
	pt.3	1034.07	
mmd15	pt.1	1016.72	8.11
	pt.2	1018.22	
	pt.3	1019.72	
	pt.4	1021.06	8.11
	pt.5	1022.56	
	pt.6	1024.06	
	pt.7	1025.56	8.12
	pt.8	1027.06	
	pt.9	1028.56	
	pt.10	1028.98	8.12
	pt.11	1030.48	
	pt.12	1031.98	
mmd16	pt.1	1015.76	8.12
	pt.2	1017.26	
	pt.3	1018.76	
	pt.4	1019.96	8.12
	pt.5	1021.46	
	pt.6	1022.96	
	pt.7	1024.84	8.12
	pt.8	1026.59	
	pt.9	1028.34	
	pt.10	1030.70	8.12
	pt.11	1032.45	
	pt.12	1034.20	

Well		Elevation of point	Installation Date
mmd17	pt.1	1030.53	8.12
	pt.2	1032.03	
	pt.3	1033.53	
mmd18	pt.1	1030.66	8.12
	pt.2	1032.16	
	pt.3	1033.66	
mmd19	pt.1	1030.63	8.12
	pt.2	1032.13	
	pt.3	1033.63	
mmd20	pt.1	1030.25	9.04
	pt.2	1031.75	
	pt.3	1033.25	
mmd21	pt.1	1030.17	9.04
	pt.2	1031.67	
	pt.3	1033.17	
mmd22	pt.1	1030.52	9.04
	pt.2	1032.02	
	pt.3	1033.52	
mmd23	pt.1	1019.71	9.04
	pt.2	1021.21	
	pt.3	1022.71	
	pt.4	1023.87	9.04
	pt.5	1025.37	
	pt.6	1026.87	
mmd24	pt.1	1029.05	10.22
	pt.2	1031.05	
	pt.3	1033.05	
mmd25	pt.1	1028.93	10.22
	pt.2	1029.93	
	pt.3	1030.93	

abbreviations: mm = miniature multilevel
mmd = miniature multilevel in ditch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110
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100
95
90
85
80
274
278
282
286
290
294
298
Distance in feet
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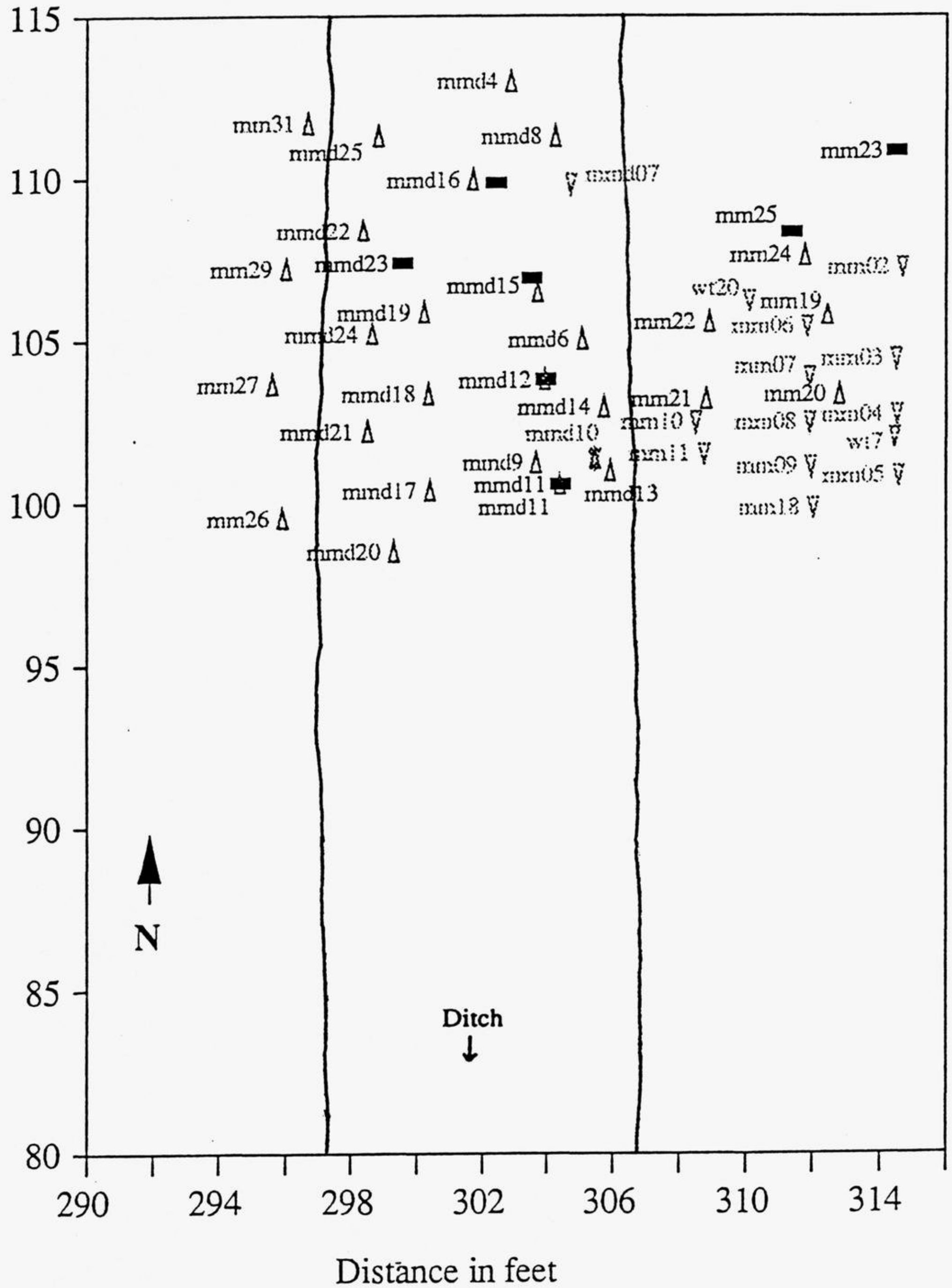
Ditch
mm30
mm34
mm28
ml2
ml6
ml3
ml5
ml4
ml10
mm32
ml11
mm33
ml12
mm31
mmd25
mmd22
mm29
mmd23
mmd24
mm27
mmd21
mm26
mmd20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110
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100
95
90
85
80
290
294
298
302
306
310
314
Distance in feet
N
Ditch
mmd4
mm31
mmd25
mmd8
mm23
mmd16
mm25
mmd22
mm24
mm29
mmd23
mmd15
mm19
mmd19
mm22
mmd24
mmd6
mm27
mmd18
mmd12
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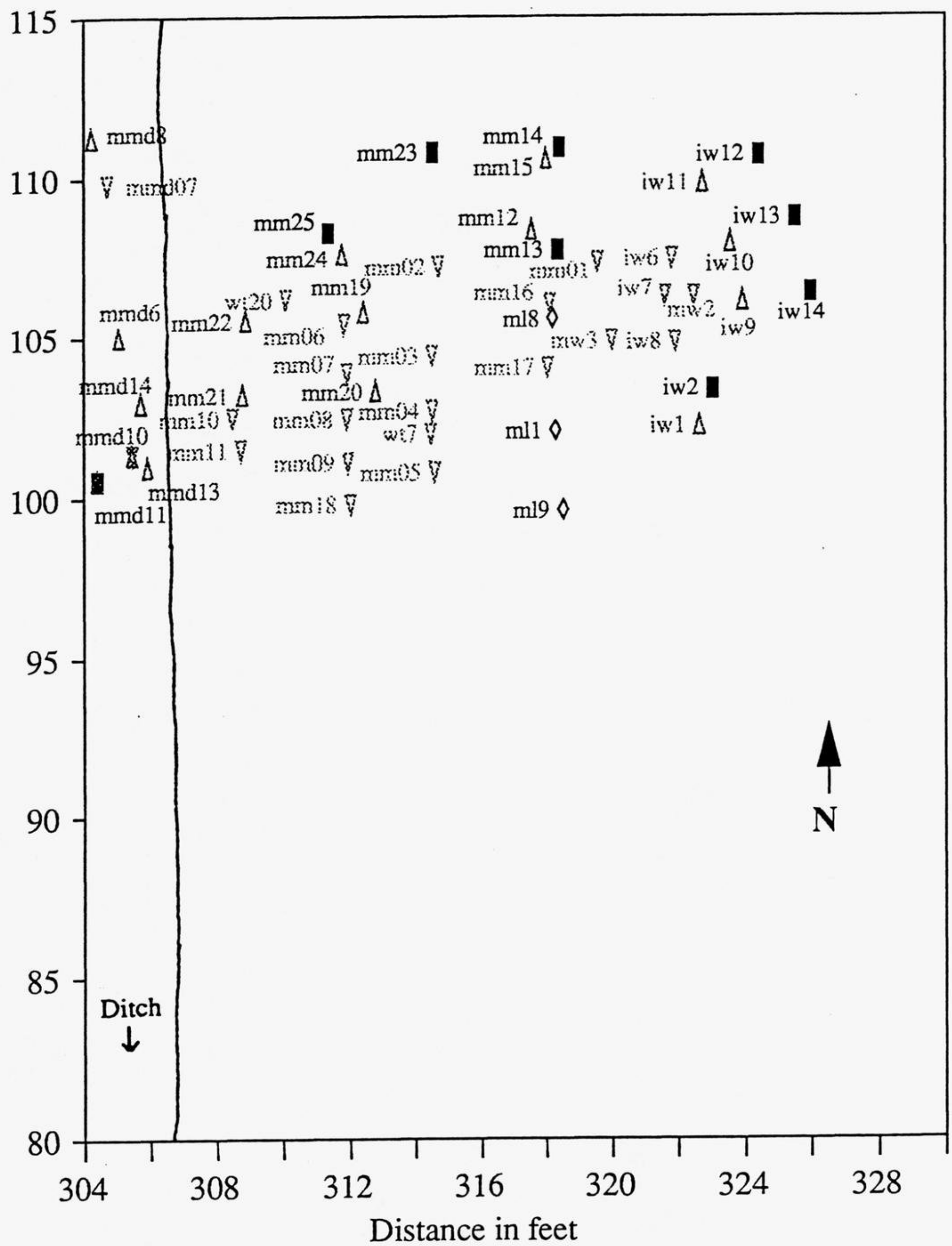
mmd13
mm26
mmd20


115
110
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100
95
90
85
80
304
308
312
316
320
324
328
Distance in feet
Ditch
N
mmd8
mmd07
mmd6
mmd14
mmd10
mmd13
mmd11
mm23
mm14
mm15
mm25
mm24
mm02
mm12
mm13
mm01
mm19
wt20
mm16
ml8
mm22
mm06
mm07
mm03
mm17
mm21
mm10
mm20
mm08
mm04
wt7
ml1
mm11
mm09
mm05
mm18
ml9
iw12
iw11
iw13
iw6
iw10
iw7
iw2
iw9
iw14
iw3
iw8
iw2
iw1

Appendix B

A METHOD FOR INSTALLING MINIATURE MULTILEVEL SAMPLING WELLS[a]

Abstract

A method has been developed to install miniature multilevel ground water sampling wells in shallow, unconsolidated aquifers at sites without truck access. An advantage of these wells over the traditional bundle type multilevels is that this type of installation causes minimal aquifer disturbance. Thus miniature multilevels can be installed while a tracer test is in progress. Furthermore, only hand tools are needed in the field, and equipment and materials are easily obtained and inexpensive. The time required for installation is comparable to other methods.

Introduction

Ground-water tracer test studies or contamination studies frequently require the removal of small quantities of water from specific depths. Multilevel ground-water

a) This appendix is a copy of most of a manuscript submitted to Ground Water by Will Stites and Lucy Chambers sampling devices as described by Pickens et al. (1978), Cherry et al. (1983) and Jackson et al. (1985) frequently have been used for shallow aquifers in unconsolidated sediments. The methods previously described all require a large borehole drilled by a hollow stem auger or casing driven by a cable tool, which requires access for trucks or heavy machinery. This report describes a method for miniature multilevel installation in which a small hole is created by driving a steel pipe into the ground. The pipe serves as a temporary casing into which a bundle of flexible polyethylene tubing is inserted. The pipe is then withdrawn, leaving only the tubing (and a disposable metal point) in the ground. This method was developed for a site where there was no truck access. Additional advantages of this method are that it causes minimal disturbance of the aquifer materials, only hand tools are needed in the field, and equipment and materials are easily obtained and inexpensive. This technique has been used successfully to install miniature multilevels to depths of over 25 ft below land surface in glaciolacustrine sand of central Wisconsin. The method described below includes the exact size and type of equipment that was used. For applications in other areas, slight variations in the equipment may be desirable.

Method

The miniature multilevel sampling wells were prepared by joining together a bundle of three or fewer 1/4-in. o.d. polyethylene tubes with tape or cable ties. A fine nylon mesh was wrapped and secured to the end of each tube with a nylon cable tie to serve as a screen. The other end of each tube was labeled with duct tape and on the longest tube several accurate marks of length were made using a waterproof marker (Figure 1a). Drive points were constructed by flattening and sealing one end of a 6-in. length of 1-in. thin walled steel electrical conduit. A drive stub, onto which the point slipped, was constructed from a 3-in. length of 3/4-in. steel plumbing pipe which was threaded on one end and screwed into a 3/4-in. pipe coupling. The exposed part of the pipe was turned down to 9/10 in. on a lathe, so that it slid freely into and out of the drive point (Figure 1b).

The drive stub was threaded onto a 5-ft section of 3/4-in. steel plumbing pipe. Before sliding the drive point onto the drive stub, a bead of silicone caulk was put on the outside of the drive stub. The point was rotated on the stub to ensure that the caulk made a good seal to prevent sediment from seeping into the bottom of the pipe. A "drive cap", consisting of a coupling and a 3/4-in. threaded plug, was screwed onto the other end of the pipe to protect the pipe threads. For greater strength, all pipes had threads about 1 in. long, so that pipe ends almost met inside couplings. All the couplings had continuous inside threads.

The drive point was pushed into the ground at the site selected for a miniature multilevel. A 35-lb fence post driver was used to drive the pipe into the ground. Ear plugs are recommended. A level was periodically placed against the pipe to check that the pipe was being driven vertically. Additional 5-ft sections of pipe were attached to the original length with couplings and tightened firmly with a pipe wrench (Figure 1b). The string of pipes was driven 1 ft deeper than the deepest intended sampling depth. Since the fence post driver we used is 2 ft long, each 5-ft section of pipe can only be driven 3 ft into the ground. A 3-ft section of pipe was attached temporarily to

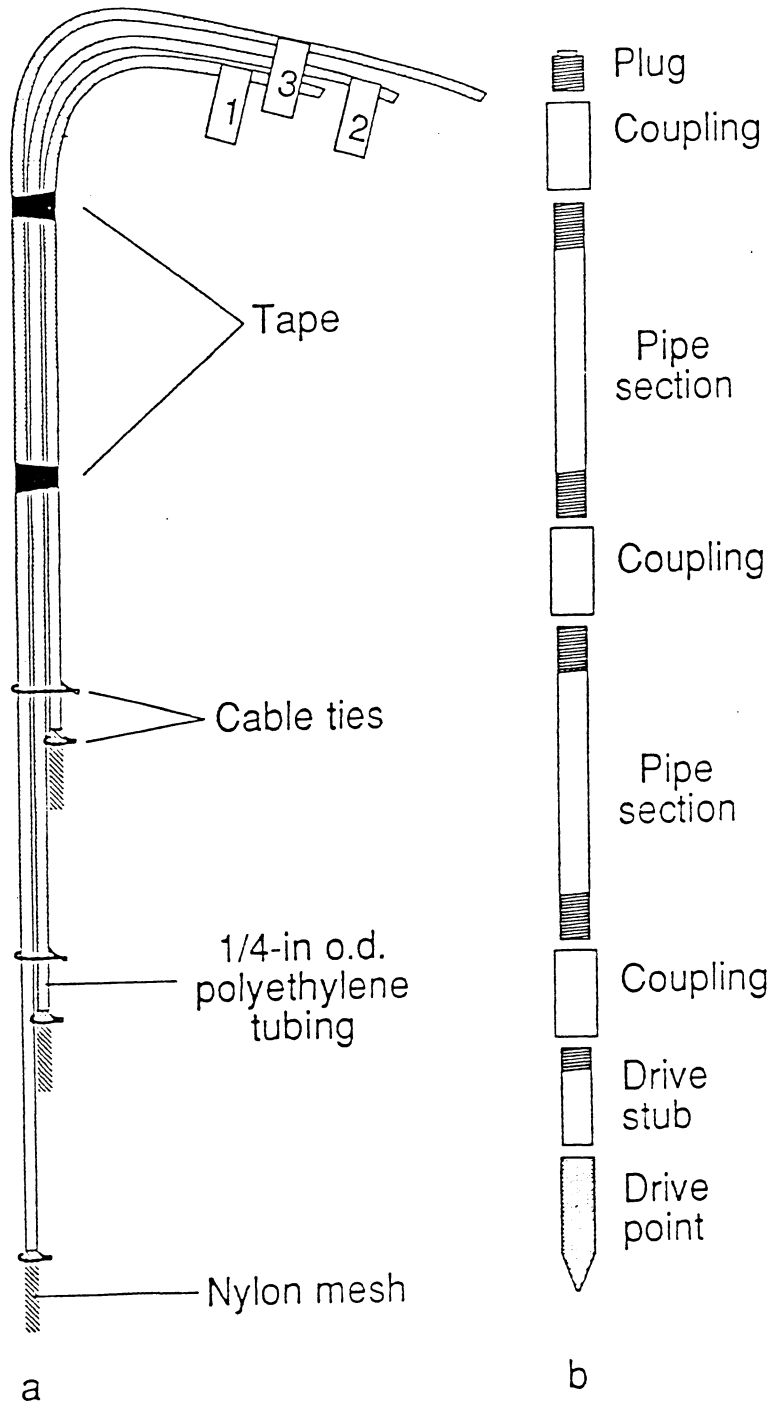

Fig. 1.a. Miniature multilevel sampling well. b. Exploded view of drive point and pipe assembly for miniature multilevel well installation.

each 5-ft section to drive the top of the 5-ft section to near ground level before adding an additional 5-ft section of pipe.

Once the pipe had been driven to the desired depth, the drive plug was removed and a 6-ft length of 3/8-in. threaded rod was lowered into the pipe. Additional lengths of threaded rod were attached with couplers until the rod reached the bottom of the string of pipes. The 3/4-in. pipe was then filled with water to ensure that water and sediment would not surge into the pipe, when the threaded rod was used to help separate the point from the pipe. This separation was accomplished by firmly holding the rod down in the pipe, while a pipe jack was used to raise the pipe just enough to lift the drive stub out of the point. A pipe jack is an excellent tool for raising the pipe, but an arrangement using a lever with a chain looped around the pipe is also satisfactory. The loop of chain can be adjusted with a nut and bolt to grip under tension and slip when released.

The sections of 3/8-in. threaded rod were removed and the bundle of polyethylene sampling tubes was inserted into the 3/4-in. pipe to the intended depth. The marks on the longest tube were used to determine the depth of the points. Sections of pipe were slowly jacked out of the ground by one person, while another person carefully held the the tubes so they would not slip down or rise up along with the pipe. It is easier to hold the tubes and judge that they are at the proper depth if they extend at least 6 ft above land surface. After the pipe was removed, the hole was backfilled with soil and bentonite. A 3-in. PVC pipe was driven down about 1.5 ft into the soil around the tubes to serve as a cover, taking care not to damage the tubing. The tubes were then relabeled and trimmed to fit in the cover.

In areas where the water table was deeper than 10 ft, we found it desirable to bore a hole to the water table with a 2-in. bucket auger. Once the hole had been augured sections of 3/4-in. pipe were joined together to reach the bottom. Masking tape in addition to silicone caulk was used to hold the drive point in place while the pipe was lowered down the hole. When numerous sections of pipe were needed to reach the bottom of the hole, locking pliers were used to suspend the pipe temporarily in the hole while additional sections were added. To keep the 3/4-in. pipe from flexing and breaking in the augured hole, a $1\frac{1}{4}$-in. steel pipe was used as a sleeve around the 3/4-in. pipe. The $1\frac{1}{4}$-in. pipe hung from a coupling held at the ground surface by a piece of plywood with a $1\frac{3}{4}$-in. hole. The sleeve extended to within 3 ft of the bottom of the augured hole. In this manner, it was possible to place 2 sets of 3 sampling tubes in a single augured hole by driving twice in the same hole, and forcing the pipe toward opposite sides of the bottom of the hole.

Conclusion

Numerous miniature multilevels have been installed at two sites in the central sand plains of Wisconsin. At the first site 20 miniature multilevels were installed to monitor ground-water chemistry. There was no truck access at this site. Ninety-four percent of the 120 points are working, and refinements have been made in the method since then. At the second site over 70 miniature multilevels were installed before and during a tracer test (Chambers and Bahr, 1989). Traditional multilevels (Jackson et al., 1985) had previously been installed, but they did not provide the well density needed to delineate the small tracer plume. The miniature multilevel technique provided the flexibility to add additional sampling wells once the tracer path was known, so the tracer plume could be defined more fully. Using this technique, sampling wells were also added within a stream and between other wells where a drill rig could not have been used.

Acknowledgments

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