INVESTIGATION OF VERTICAL NITRATE GRADIENTS IN A SHALLOW UNCONFINED AQUIFER IN NORTH DAKOTA

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

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ABSTRACT

Water samples collected from 22 sampling points spaced both vertically and horizontally in the Elk Valley aquifer, northeast North Dakota, indicate a high vertical nitrate gradient. A single-well multi-level sampling device (Oly-probe) was used to collect groups of eight vertically spaced samples from a single 4-inch diameter well. Mini-piezometers constructed of 1/4-inch polyethelene tubing were used to collect water samples from narrow vertical intervals. Comparison of the sampling methods indicates the mini-piezometer method was superior.

The VS2DT contaminant transport model was used to evaluate the dispersive mixing potential of high nitrate waters recharging the aquifer, which may result in eventual elevated nitrate levels throughout the vertical profile of the aquifer. Comparison of the measured and simulated nitrate concentrations indicates that if dispersion were the only mechanism affecting the vertical nitrate distribution in the aquifer, larger concentrations of nitrate than were measured should be present at depth.

Denitrification was confirmed at the study site through isotopic analysis. Samples analyzed for ^{15}N *show increasing* $\delta^{15}N$ *with decreasing nitrate concentration in the vertical profile.*

INTRODUCTION

Nitrate (NO_3^-) concentrations at levels of 45 mg/l in drinking water are potentially hazardous. Methemoglobinemia (blue baby syndrome) can result from the ingestion of high NO_3^- water by human infants (Comly, 1945). This potentially fatal syndrome occurs because NO_3^- can impair the oxygen transport in the bloodstream (Jaffe, 1981). Nitrate is the most prevalent contaminant of ground water systems, originating from a variety of domestic, agricultural, and industrial practices (Smith et al., 1991). Nitrate forms compounds that are highly soluble, allowing it to be easily transported into some ground water systems (Korom, 1992).

The types of ground water environments that are most susceptible to NO_3^- contamination are the relatively shallow, unconfined aquifer systems. These systems typically have continuous sand and/or gravel from the bottom of the soil zone to the water table. The water that escapes the root zone can move freely to the aquifer, carrying the agricultural chemicals and nitrogen that were not attenuated in the soil zone.

Sources of NO_3^- in ground water supplies are mainly from fertilizers and organic residues applied to the soil to enhance crop production (Hallberg, 1989). Elevated NO_3^- levels in the upper zones and diminished levels with depth are common in water table aquifers. Anderson (1989) reported a vertical NO_3^- gradient in surficial sand-plain aquifers in Minnesota. Water samples collected from deeper zones within surficial aquifers in North Dakota also have NO_3^- concentrations that are typically one to two orders of magnitude less than those samples collected near the water table (North Dakota State Water Commission, 1993).

Because elevated NO_3^- concentrations are potentially hazardous in drinking water supplies, a better understanding of the process by which NO_3^- concentrations diminish with depth in certain unconfined shallow aquifer systems is needed. The decrease in NO_3^- concentration may be caused by either of two dominant mechanisms: dispersion or denitrification.

Dispersive mixing of high NO_3^- waters recharging a water table aquifer results in dilution. Eventual redistribution of the NO_3^- concentrations by complete mixing throughout the vertical profile of the aquifer may result. High NO_3^- water reaching the lower portions of the aquifer could contaminate public water supplies that have their wells screened in these zones.

Denitrification is a biologically controlled process where NO_3^- is removed from the ground water system. In the absence of oxygen, certain bacteria respire NO_3^-, leaving N_2 as the end product of denitrification. The N_2 is stable and will migrate out of the saturated zone (Korom, 1992).

Objectives

The objectives of this study were to

1. Investigate methods of sampling vertical nitrate gradients.
2. Determine of the cause of vertical nitrate gradients in a shallow unconfined aquifer.

Tasks to accomplish these objectives were as follows:

1. Measure the vertical nitrate gradient using the following methods:
    - •Bailing from nested piezometers,
    - •Single-well multi-level sampling, and
    - •Multi-level mini-piezometer sampling.
2. Compare methods used for measuring the nitrate gradient.
3. Evaluate the potential causes of the gradient:
    - •Evaluate denitrification by using isotopic analysis.
    - •Evaluate dispersion by using the VS2DT model.
4. Compare the results of the VS2DT model with the measured nitrate values.

The flow chart presented in Figure 1 shows the objectives and the tasks to meet these objectives.

Site Selection and Location

A field site to investigate the vertical NO_3^- gradient in a surficial aquifer had to meet several requirements. First of

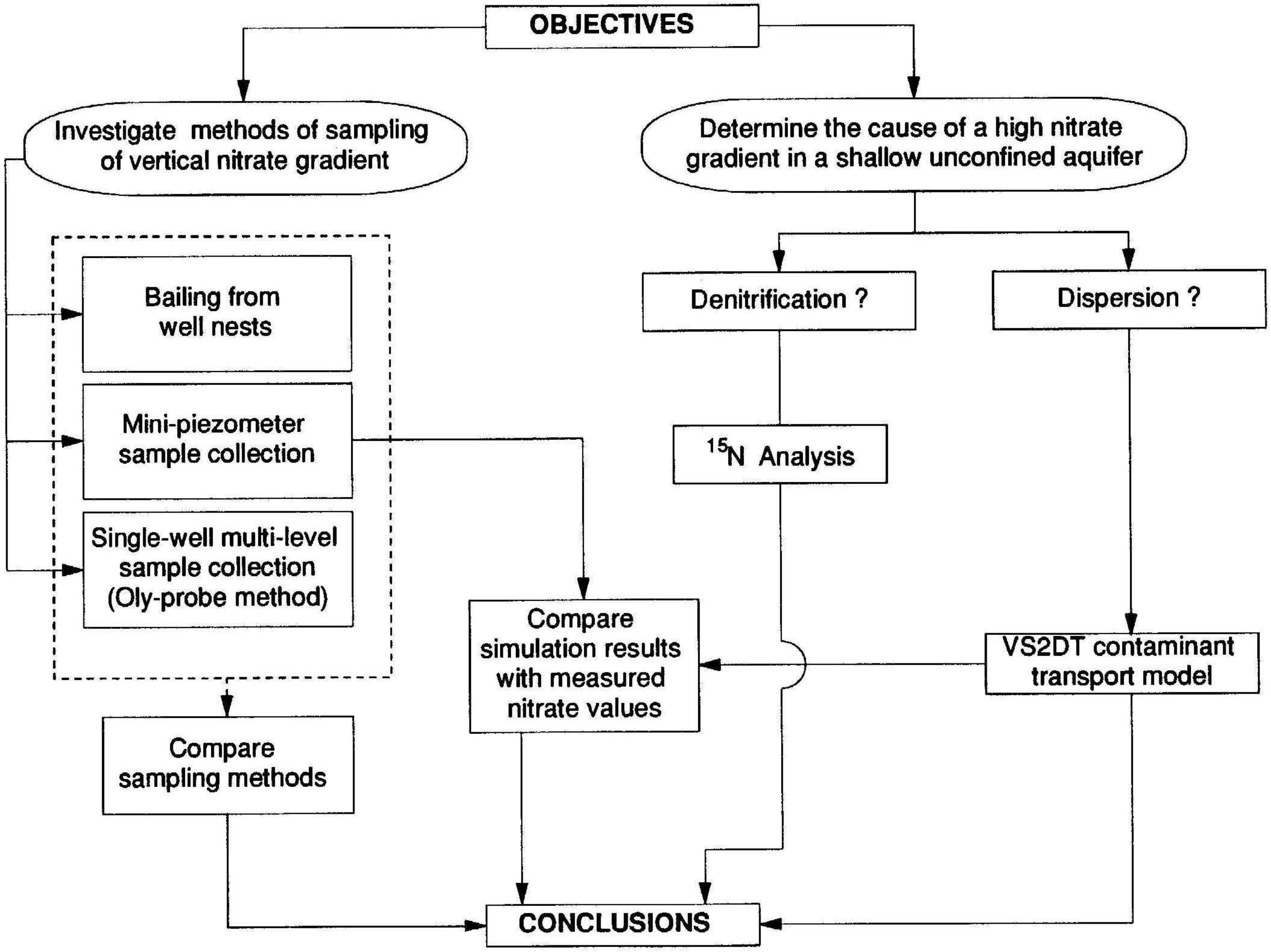

Figure 1. Flow chart of tasks to meet the objectives of the study.

all, the site must overlie an aquifer which is *unconfined*. The Elk Valley aquifer in Grand Forks County, North Dakota (Figure 2) was chosen for several reasons:

1. The Elk Valley aquifer supplies water to about 20,000 people living in and near the Red River Valley of North Dakota. Concern has been expressed that NO_3^- contamination may be occurring in the aquifer and may be affecting the quality of drinking water for these residents.

2. A large amount of hydrogeologic data, including NO_3^- data, is available for this aquifer. Thirteen sites throughout the aquifer had evidence of a high vertical NO_3^- gradient.

Of the 13 locations with preliminary evidence of a high vertical NO_3^- gradient, the site near the southwest corner of Section 29, T154N-R55W (Figure 3) was chosen for this study. The site is near a rural water supply well field (Tri-County Water Users, Inc.).

Geologic Setting

The Elk Valley aquifer is in the western portion of Grand Forks County (Figure 2). The aquifer was deposited during the Pleistocene epoch and is part of the Elk Valley Delta (Kelly and Paulson, 1970). The delta formed as eastern flowing drainage flowed into the western margin of the glacial Lake Agassiz basin. Lake Agassiz is dated in the latter part of the Pleistocene epoch about 10,000 to 15,000 years before present

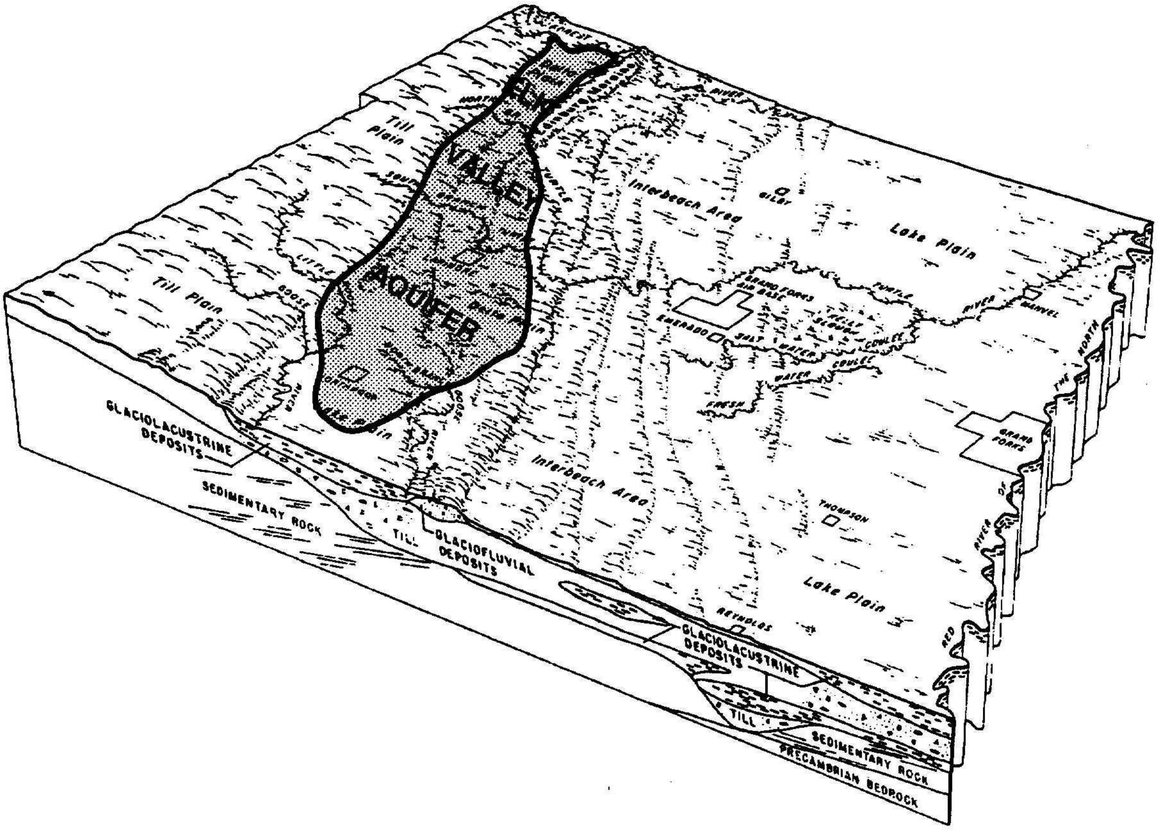

Figure 2. Physiographic map of Grand Forks County showing the boundary of the Elk Valley aquifer.

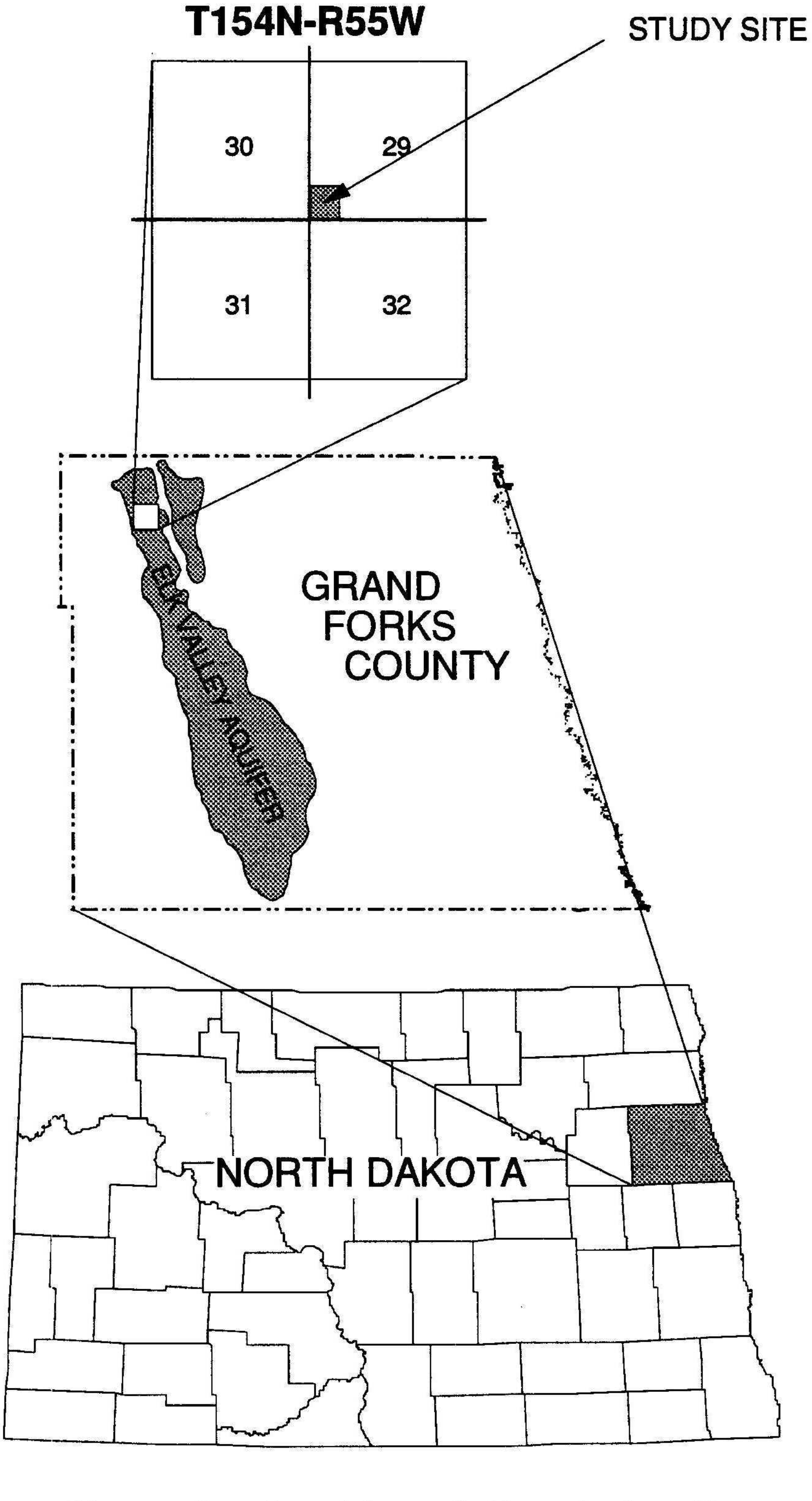

Figure 3. Location of the study site.

(Hansen and Kume, 1970). The aquifer is underlain by glacial drift deposits. The aquifer is bounded by the Pembina escarpment to the west, the Forest River on the north, and the Edinburg moraine in the northern portion of the east side. The aquifer pinches out into the surrounding glacial drift deposits along the remaining perimeter on the south and east.

The Elk Valley aquifer covers approximately 200 square miles of surface area and is about 3 miles wide in the northern end to over 12 miles wide in the south (Kelly and Paulson, 1970). It consists of up to 80 feet (test hole log #11414, NDSWC) of sand and gravel. There is a general gradation of texture from coarser sediments in the north to finer sediments in the south (Kelly and Paulson, 1970). The aquifer is composed primarily of quartzose sand, detrital shale, carbonate rock fragments, and silicate rock fragments.

Soils overlying the aquifer are generally silty loams, sandy loams, and loamy sands of the Hamerly-Svea-Vallers series and the Ulen-Embden-Hecla series (Hansen and Kume, 1970). These permeable soils along with the permeable aquifer deposits allow rainfall and snowmelt to be readily absorbed as recharge in the Elk Valley aquifer. The lack of surface drainage stands out in marked contrast to the surrounding area because most of the precipitation moves into the profile rather than leaving as surface runoff (Kelly and Paulson, 1970).

Ground water flow patterns near the study site are dominated by the discharge to the Forest River, approximately 2 miles north of the study area. The two predominant discharge mechanisms of the Elk Valley aquifer are springs and evapotranspiration. Springs and seeps occur where drainage depressions of rivers and ditches intersect with the water table of the aquifer. Evapotranspiration occurs where the water table is within a few feet of land surface, such as around marshes and sloughs (Kelly and Paulson, 1970).

PREVIOUS STUDIES

High NO_3^- concentrations near the water table and decreased concentrations at a greater depth have been reported by other investigators. Williamson and Peterson (1951) first compared NO_3^- concentration with well depth in North Dakota. Their study showed that 43 percent of the wells less than 30 feet deep had NO_3^- concentrations above 45 mg/l, whereas only 8 percent of the deeper wells exceeded 45 mg/l. Anderson (1989) reported vertical NO_3^- gradients in surficial sand-plain aquifers in Minnesota. Hendry et al. (1983) provided two explanations of the vertical NO_3^- distribution they found in a shallow unconfined aquifer in southwestern Ontario, Canada:

1. Shallow high-nitrate water originated as infiltration through the soil of the study area, and deeper nitrate-free water entered the study area from up-gradient of the study area. Due to the horizontal flow in the aquifer, vertical concentration gradients would be the result of either dispersion or diffusion.

2. The vertical NO_3^- distribution was the result of denitrification in the aquifer.

Previous work, as it pertains to this investigation, will be presented on the topics of dispersion, denitrification, and nitrogen isotope (^{15}N) studies.

Dispersion

Transport of NO_3^- in the subsurface is primarily through advection (Bear, 1972). Therefore, if non-reactive, a solute such as NO_3^- is carried at an average rate equal to the average linear velocity, v, of the water. The average linear velocity is defined by Darcy's Law as

$$v = \frac{K}{n} {}^{dh}\!/_{dl} ,$$

where K is hydraulic conductivity, n is the porosity, and $^{dh}\!/_{dl}$ is the hydraulic gradient. However, the tendency for a solute to spread out from the path that it would normally be expected to follow according to advective hydraulics is called hydrodynamic dispersion (Freeze and Cherry, 1979).

Hydrodynamic dispersion is comprised of two mechanisms: mechanical dispersion and molecular diffusion. Diffusion is the process whereby ionic constituents move under the influence of their kinetic activity in the direction of their concentration gradient (Freeze and Cherry, 1979). In the absence of water flow, molecules of solute will move from areas of high concentration to areas of low concentration to equalize concentrations everywhere. Fick's first law defines the rate of diffusion in terms of the concentration gradient as

$$F = D_d \, {}^{dC}\!/_{dx} ,$$

where F is the rate of diffusion, D_d is the diffusion coefficient, and $^{dC}\!/_{dx}$ is the concentration gradient (Crank, 1956). In the presence of ground water flow, the effect of diffusion compared to mechanical dispersion is negligible (Domenico and Schwartz, 1990).

Mechanical dispersion is caused by variations in the velocity field at the microscopic level. Flow paths in porous media are not straight, but tortuous (Figure 4). Molecules of a solute will spread out as it is carried through the porous media.

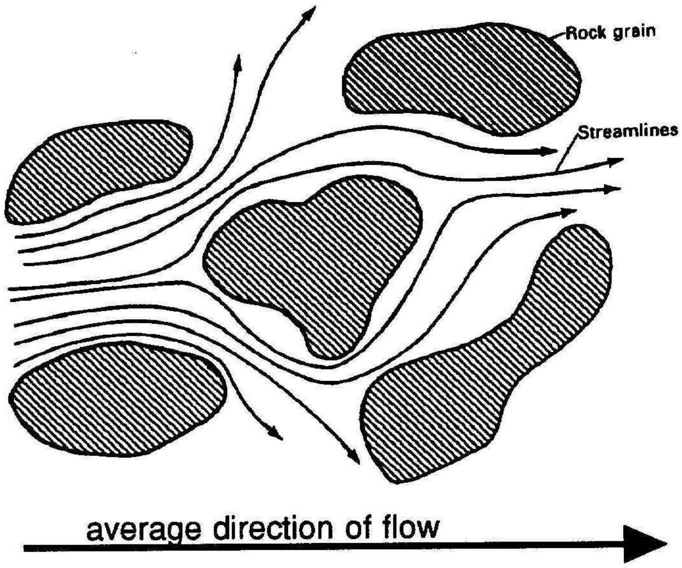

Figure 4. Diagram showing the spreading of flow paths (from Healy, 1990).

Mechanical dispersion can be divided into longitudinal and transverse. Longitudinal dispersion is the spreading of the solute in the direction of bulk flow. Transverse dispersion occurs perpendicular to flow. Longitudinal dispersion is normally much greater than transverse dispersion (Freeze and Cherry, 1979).

The multidimensional transport equation that accounts for both longitudinal and transverse dispersion in addition to advection is as follows (Domenico and Schwartz, 1990):

$$D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - v_x \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} ,$$

where C is the concentration of a solute at time t, and D_x, D_y, and D_z are the coefficients of hydrodynamic dispersion in the x, y, and z directions. The coefficient of hydrodynamic dispersion is comprised of two components:

$$D = D_d^* + D' ,$$

where D' is the coefficient of mechanical dispersion and D_d^* is the bulk diffusion coefficient. The coefficient of mechanical dispersion, D', is related to the velocity of flow by the following relationship:

$$D' = \alpha \bullet v ,$$

where α is the dispersivity of the medium. Dispersivities have units of length and, like hydraulic conductivity, are characteristic properties of a medium (Domenico and Schwartz, 1990).

Gelhar et al. (1992) reviewed dispersivity observations from 59 separate field sites. They compiled the information as longitudinal, horizontal transverse, and vertical transverse dispersivity values. Their work showed that longitudinal dispersivity values for unconsolidated sand were typically about 3 to 30 feet. Vertical transverse dispersivities were usually one to two orders of magnitude less than the longitudinal dispersivities.

A finite-difference model to estimate dispersion was developed by Healy (1990). The model, VS2DT, is a two-dimensional variably saturated contaminant transport model. The model uses a finite difference approximation to the advection-dispersion equation. The program is an extension of an earlier version, VS2D, which simulates water movement through variably saturated porous media. The model has the capability to simulate regions that are one-dimensional columns or two-dimensional vertical cross-sections.

Denitrification

Denitrification occurs when NO_3^- is reduced to N_2O or N_2 through a biologically controlled process. Through denitrification, potentially hazardous NO_3^- concentrations are reduced or eliminated in ground water. In this process, bacteria in an anaerobic environment use NO_3^- as a terminal electron (e^-) acceptor in their metabolic processes.

The term *denitrification* was first used in 1882 by Gayon and Dupetit (Payne, 1981). The presence or absence of NO_3^- in ground water was thought to be of little consequence (George and Hastings, 1951) until Comly (1945) reported that infants who had ingested well waters high in nitrates developed methemoglobinemia, a potentially fatal condition (Korom, 1992). This prompted the establishment of a water quality standard by the U.S. Public Health Service on NO_3^- levels in drinking water of 45 mg/l (U.S. Public Health Service, 1962).

Before the 1970s, although the role of bacteria in the process of denitrification had been recognized, the presence of denitrifying bacteria in aquifers was largely a matter of speculation (Korom, 1992). By the 1980s, a number of studies provided evidence that subsurface environments support an abundant microbial population of great diversity (Korom, 1992). Bacterial communities were found at depths up to 260 m below the land surface (Fredrickson et al., 1989).

Bacteria in aquifers obtain energy from the oxidation of organic or inorganic compounds and can be either heterotrophic or autotrophic. All bacteria need an e^- donor as an energy source (Alexander, 1977). Organic Carbon (OC) is nature's most common e^- donor (Korom, 1992). To complete the oxidation-reduction (redox) reaction, an e^- acceptor is also required. Table 1 (Korom, 1992) shows the preference of electron acceptors with Carbon as the electron donor.

Inorganic e^- donors may also facilitate denitrification. Inorganic e^- donors found in ground water include reduced manganese (Mn^{2+}), ferrous iron (Fe^{2+}), and sulfides. Denitrification, then, can be classified as either *heterotrophic denitrification* with organic carbon serving as the electron donor or *autotrophic denitrification* with reduced inorganic compounds serving as the electron donor.

Autotrophic denitrification occurs when NO_3^- is introduced into a manganese/iron or sulfate-reducing zone. Nitrate is

Table 1. Preferred electron acceptors with Carbon as the electron donor (from Korom, 1992).

Electron acceptors	Resulting inorganic reduced compound	Gibbs free energies released (Kilocalories/electron)
O_2	H_2O	-18.76
NO_3^-	N_2	-17.26
Mn(IV) as MnO_2	Mn(II) as $MnCO_3$	-12.14
Fe(III) as FeOOH	Fe(II) as $FeCO_3$	1.09
SO_4	HS	5.12
Organic Carbon	CH_4	
Organic Carbon	CO_2	

thermodynamically unstable even in the absence of OC (Korom, 1992). If the appropriate bacteria are present, they may denitrify using reduced manganese, reduced iron, and sulfides as e^- donors.

Bacteria that denitrify are diverse (Knowles, 1982). Most denitrifiers are heterotrophic (Payne, 1981) and are facultative anaerobes (Firestone, 1982), that is, organisms that are capable of survival with or without O_2.

Firestone (1982) described four general requirements that must be met for denitrification to occur:

1. The presence of an N oxide (NO_3^-, NO_2^-, NO, and. N_2O) as a terminal e^- acceptor,

2. The presence of bacteria possessing the metabolic capacity to denitrify,
3. Suitable e^- donors, and
4. Anaerobic conditions or restricted O_2 availability.

The denitrification pathway terminates with molecular nitrogen (N_2). An example of a heterotrophic denitrification reaction (Koelle et al., 1983) is as follows:

$$5C + 4NO_3 + 2H_2O = 2N_2 + 4HCO_3 + CO_2$$

Korom (1991) showed that once NO_3^- is leached below the root zone, four possible fates (other than continued leaching) await it:

1. Soil retention,
2. Assimilatory reduction into microbial biomass,
3. Dissimilatory nitrate reduction to ammonium (DNRA), and
4. Denitrification.

He stated that only denitrification removes N from the system. The other fates temporarily immobilize N. Dissimilatory reduction of NO_3^- to ammonium (NH_4^+) generally conserves a system's N, whereas denitrification results in an N loss from the system (Harris, 1982). Tiedje (1982) hypothesized that DNRA is favored when NO_3^- (e^- acceptor) supplies are limiting and that denitrification is favored when carbon (e^- donor) supplies are limiting.

Denitrification has been studied extensively as it pertains to the near-surface vadose zone. Most of this research has been done with respect to the soil zone in the agronomy-related sciences. Knowles (1982) reviewed denitrification in soils.

Measurement techniques to determine the nitrogen loss to denitrification have been analyzed. Duxbury and McConnaughey (1986) utilized an acetylene-block technique to assist in the direct measure of denitrification. Smith and Duff (1988) discussed measuring N_2 and N_2O from highly enriched ^{15}N-labeled NO_3^-. Aulakh et al. (1991) discussed four methods for measuring denitrification. Gillham et al. (1990) described a practical method for measuring rates of biochemical reactions in situ. They used an in situ microcosm (ISM) to isolate a portion of the aquifer.

Studies that have dealt with denitrification in aquifers include Smith et al. (1991), who used multi-level sampling devices in a sand and gravel aquifer on Cape Cod. They used acetylene block techniques to confirm denitrifying activity. Also, they described a technique of monitoring the natural $\delta^{15}N$ of the NO_3^- and N_2. Olson (1992) described denitrification in a portion of the Oakes aquifer in North Dakota. He used a multi-level sampling device to collect vertically spaced samples from the aquifer.

Mayer (1992) evaluated the role of biological denitrification in minimizing concentration and distribution of nitrate in the Elk Valley aquifer in North Dakota. He also explored the effect irrigation practices have on ground water flow and NO_3^- distribution in the saturated zone. Korom (1992) provided an extensive treatment of the denitrification process as it pertains to ground water. He discussed both heterotrophic and autotrophic denitrification. His work was primarily on the unconsolidated deposits of the Heber Valley aquifer, Utah.

Isotope Studies

Vogel et al. (1981) identified isotopic fractionation of the denitrification process. They determined that the $^{15}N/^{14}N$ ratios in the ground water was analogous to Rayleigh distillation where the lighter N isotope (^{14}N) tends to be denitrified before the heavier isotope (^{15}N). The per mil ($^{0}/_{00}$) enrichment of ^{15}N is a straight-line function of the logarithm of the unreacted residual NO_3^-; therefore, the enrichment factor is a constant.

Hendry et al. (1983) listed a number of geochemical criteria that demonstrate that denitrification best explains the NO_3^- distributions in their case study. Nitrogen isotope analysis was done without measuring any N gases.

Other studies (Mariotti, 1986; Mariotti et al., 1988; Boettcher et al., 1990; Smith et al., 1991) also used isotopic fractionation to explain the enrichment of ^{15}N as a result of ground water denitrification.

METHODS

Site Instrumentation

Data were collected at the study site from May, 1990, to December, 1993. These data were obtained from five wells or well nests:

1. A 2-inch diameter monitoring well, screened near the bottom of the aquifer (29CCC, Figure 5),
2. A 4-inch diameter monitoring well, screened at the water table (29CCC2, Figure 5),
3. A 4-inch diameter multi-level sampling well screened from 8 to 18 feet below land surface (29CCC3, Figure 5),
4. A nest of 3 vertically spaced mini-piezometer sampling wells (29CCC4, Figure 5), and
5. A nest of 8 vertically spaced mini-piezometer sampling wells (29CCC5, Figure 5).

2-inch monitoring well installation

A 4-1/2 inch diameter hole was drilled to a depth of 45 feet with a forward-rotary mud drill rig. Then, 37 feet of 2-inch diameter polyvinyl chloride (PVC) casing with a 5-foot long, 0.010-inch slotted PVC screen and check valve were inserted into the hole. Two feet of casing were left above land surface; hence, the screened interval of the well was 35 to 40 feet below land surface.

The hole was back-washed through the well with fresh water, which forced most of the drilling fluid from the annular

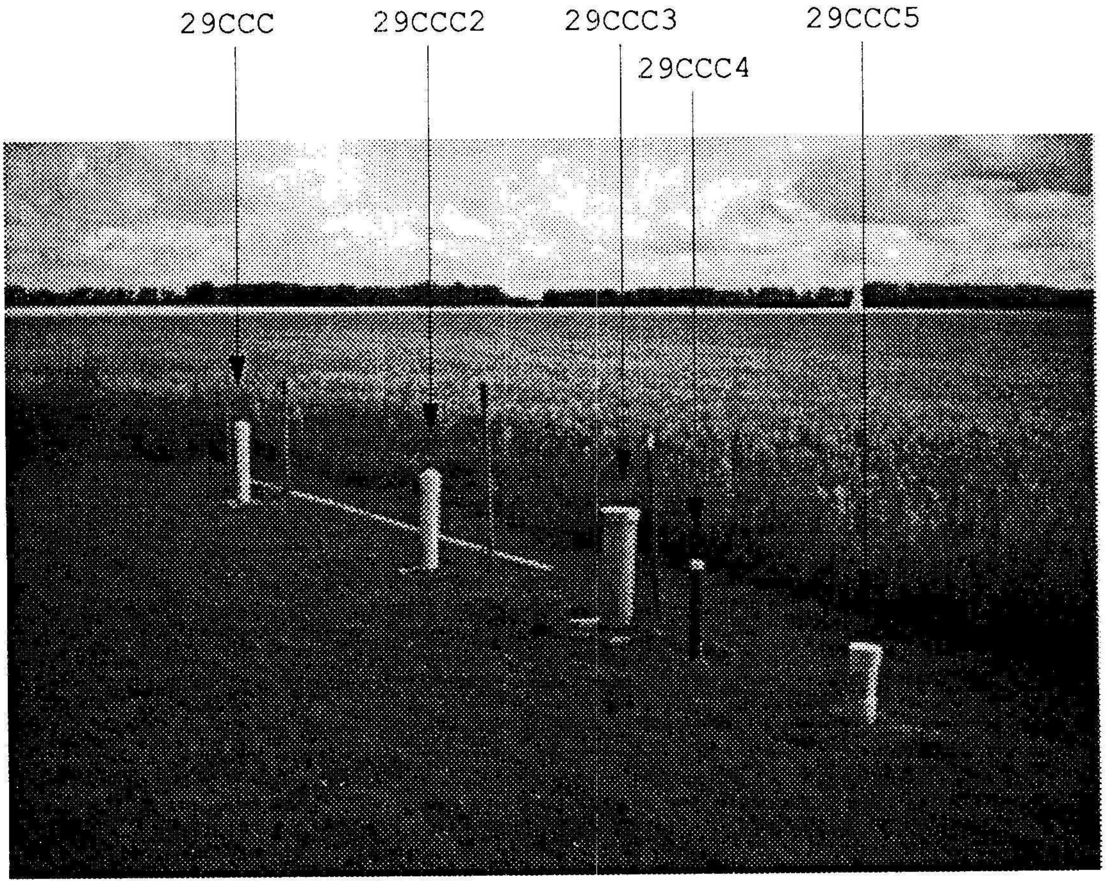

Figure 5. Sampling wells located at the study site, SW1/4 SW1/4 SW1/4, Section 29, T154N-R55W.

space around the well to land surface. The open hole below the water table was collapsed around the well and screen by injecting high pressure air through the well which caused water in the annular space to be purged to land surface. The remaining open hole around the well was filled with a high-solids bentonite grout (Figure 6). A 4-inch diameter protective casing was placed around the 2-inch diameter well above land surface. The protective casing was set into a concrete base.

4-inch monitoring well installation

An 8-inch diameter hole was drilled to a depth of 15 feet with a forward-rotary mud drill rig. A 6-foot length of 4-inch diameter polyvinyl chloride (PVC) casing and 10 feet of 0.010-inch slotted PVC screen were inserted into the hole. Two feet of casing were left above land surface; hence, the screened interval of the well was 4 to 14 feet below land surface. Clean silica sand was placed around the screen through a tremie pipe. Neat cement slurry was used to seal the remaining annular space.

Multi-level sampling well installation

A 4-inch diameter well was used for multi-level sampling (Figure 7). The well was constructed of 10 feet of 4-inch PVC casing and 10 feet of 4-inch diameter, 0.010-inch slotted screen. Two feet of casing were left above land surface;

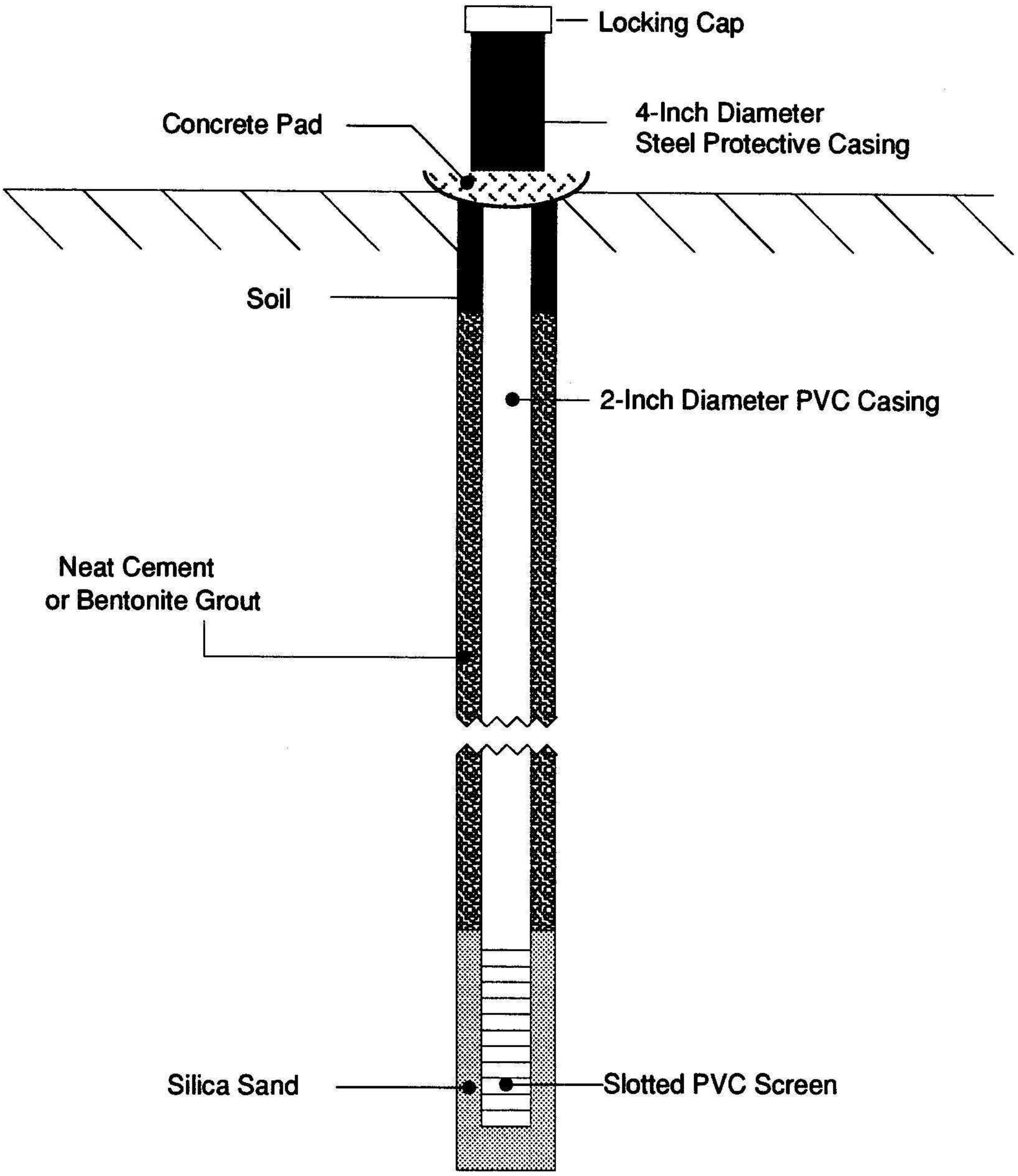

Figure 6. Construction design used for monitoring wells installed at the study site.

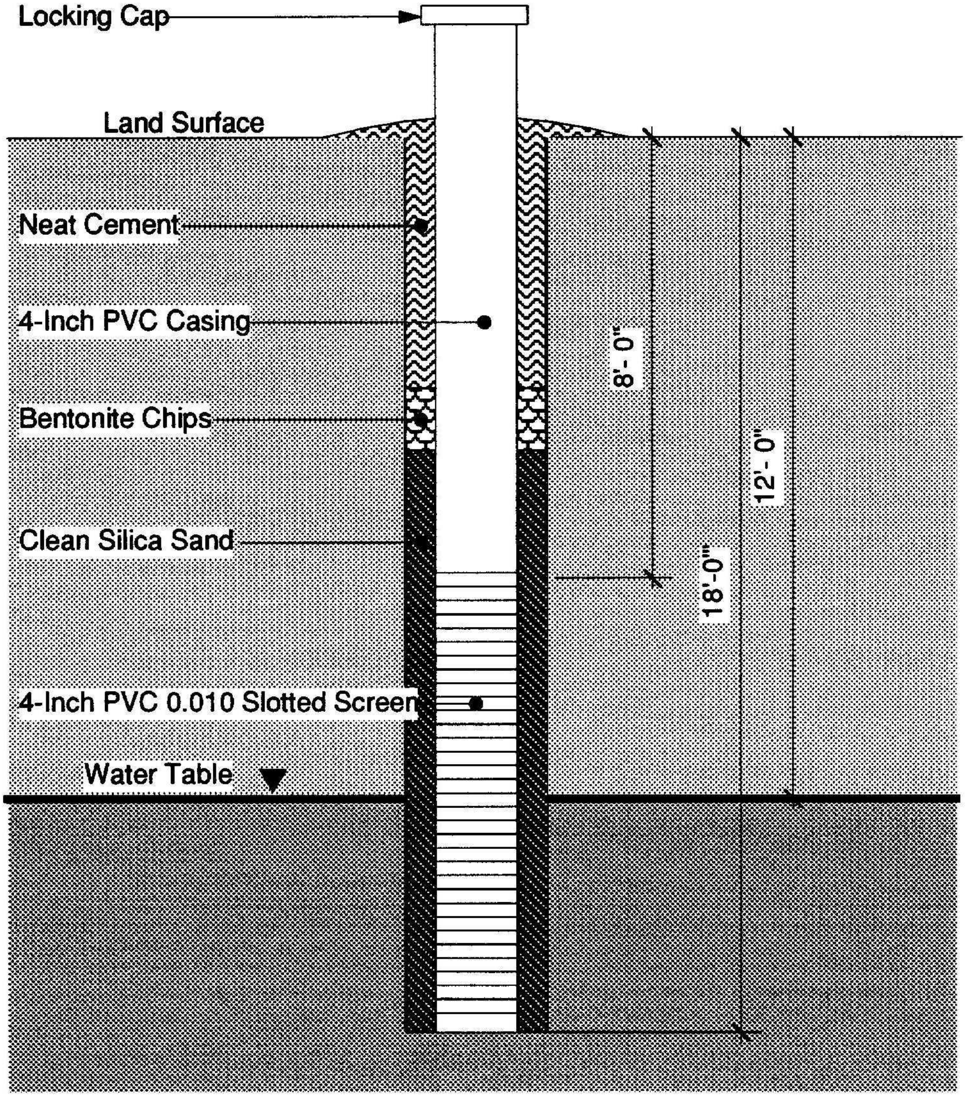

Figure 7. Well construction of the 4-inch well used for multi-level sampling.

hence, the screened interval of the well was 8 to 18 feet below land surface.

A 6 3/4-inch hollow stem auger was used to drill the hole in which the well was installed. A temporary steel plate, which was pounded out when the auger reached the desired depth, was attached to the bottom of the auger. The 4-inch casing and screen were inserted through the hollow stem while the auger was still at the desired depth. The well was held in place as the auger flights were pulled up in 5-foot intervals.

Clean silica sand was poured in the hollow stem as the auger was being pulled up. A 1/2-inch re-bar probe was used to insure the sand pack did not come up into the hollow stem and wedge the casing. The sand was poured in through the hollow stem until it reached about 2 to 3 feet above the top of the screen. Bentonite chips were poured on top of the sand and hydrated with about 4 gallons of water. The remaining auger flights were pulled up, and the annulus was filled with a neat cement slurry up to land surface. The well was repeatedly bailed until the clean formation water was being produced.

Mini-piezometer sampling well installation

Mini-piezometers constructed of 1/4-inch polyethelene tubing were used to collect water samples from narrow vertical intervals. Two nests of mini-piezometer wells were installed at the study site. The first nest installed, 29CCC4, consisted of three piezometers. The second, 29CCC5, consisted of eight piezometers.

The bundle of mini-piezometers were constructed in the lab before the field installation (Figure 8). The 1/4-inch polyethelene tubes were cut to a length so that about 6 feet would protrude above land surface nests when they were installed in the field. Approximately 40 1/32-inch holes were drilled at the bottom 2 to 3 inches of each tube. This perforated area was wrapped with bridal veil organdy and secured with black electrical tape. The end of the tube was plugged with a stainless steel screw. The bundle of tubes were wrapped with electrical tape to hold them together. Each tube was labeled near the top.

At the field site, a 2-inch hole was hand augured to a depth about 6 inches more than where the deepest piezometer would be placed. A soil sampling bucket auger was used. A 1 1/4-inch galvanized steel pipe with an oversized drive point slipped over the bottom end was driven down the augured hole in 5-foot lengths. Reinforced drive couplings were used at each joint to reduce the shearing potential as the pipe was being driven into the hole.

Once the pipe had reached the desired depth, the bundle of mini-piezometer tubes was inserted into the pipe. About 6 feet of the bundle protruded above land surface. While holding the bundle in place, the pipe was jacked out of the ground, using a handyman jack and pipe wrench. The drive point at the bottom of the pipe detached and remained at the bottom of the hole. As the steel pipe was pulled up around the bundle of

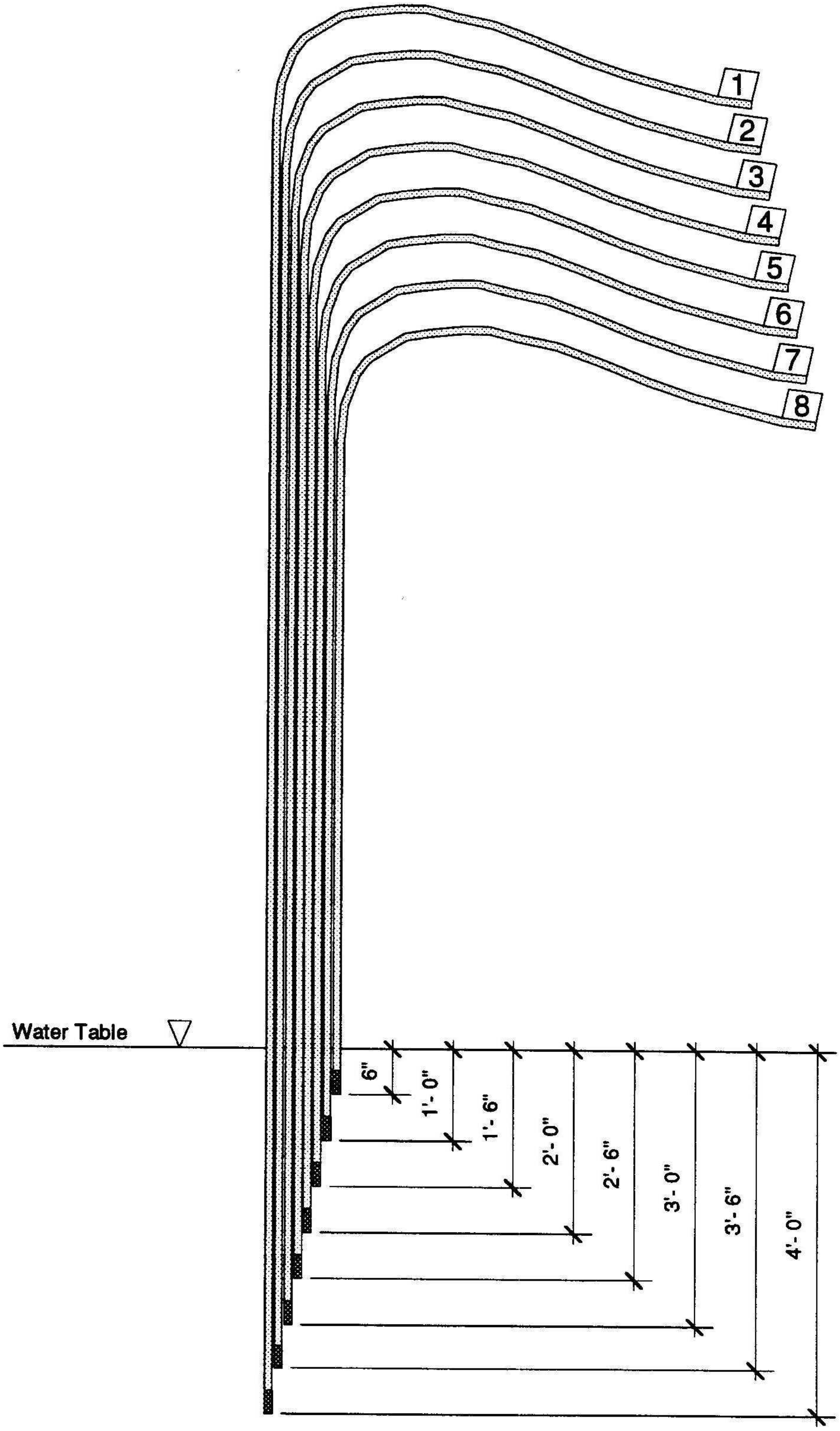

Figure 8. Mini-piezometers bundle design located at 29CCC5.

tubes, the saturated formation collapsed around the tubes, holding them in place.

After the steel pipe had been completely removed, the annular space that remained open in the unsaturated zone was filled with clean silica sand to about 4 feet from land surface. The rest of the annular space to land surface was filled with a neat cement slurry. A protective casing with a concrete pad was placed at the surface to allow access to the piezometers.

Sampling

Three types of sample collection were implemented during this study: bailing from the 2-inch and 4-inch wells, multi-level sample collection from a 4-inch well, and suction sampling from the 1/4-inch mini-piezometer wells.

Bailing from 2- and 4-inch wells

Samples were collected from these wells for major anion-cation, NO_3^-, and ^{15}N analysis. Before sampling, two casing volumes were evacuated, using a PVC point-source bailer. For major anion-cation analysis, three samples were collected in plastic bottles for laboratory analysis:

1. Raw (500 ml),
2. Filtered (0.45 micron) (500 ml), and
3. Filtered (0.45 micron) and acidified (500 ml).

A 2-ml ampule of concentrated nitric acid was added to sample (3) to prevent the precipitation of carbonates and metal oxides. Specific conductance, pH, and concentration of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) were measured in the lab, using the raw sample. Concentrations of sulfate (SO_4^{2-}), chloride (Cl^-), fluoride (F^-), boron (B^{3+}), silica (SiO_2), and dissolved solids were measured in the lab, using the filtered sample. Concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), iron (Fe^{2+}), and manganese (Mn^{2+}) were determined, using the filtered and acidified sample.

Nitrate samples were collected in 20-ml plastic bottles and preserved by adding one to two drops of 6N sulfuric acid (H_2SO_4). The NO_3^- samples were kept chilled until they were analyzed in the laboratory.

The ^{15}N samples were collected in one-liter plastic bottles and preserved with 2 ml of 6N sulfuric acid. The pH of these preserved samples was about 2.5. They were kept chilled until analyzed in the laboratory.

Multi-level nitrate sampling

A sampling device developed by Olson (1992) was used to collect groups of eight vertically spaced samples from a single 4-inch diameter well. A diagram of the sampling device, dubbed the "Oly-probe," is presented in Figure 9. The device was constructed of a 5-foot long, 2-inch diameter PVC body. Teflon baffles (0.038-cm thick) separated chambers that held a 40-ml vial. The chambers were spaced at 0.5 feet vertically. The

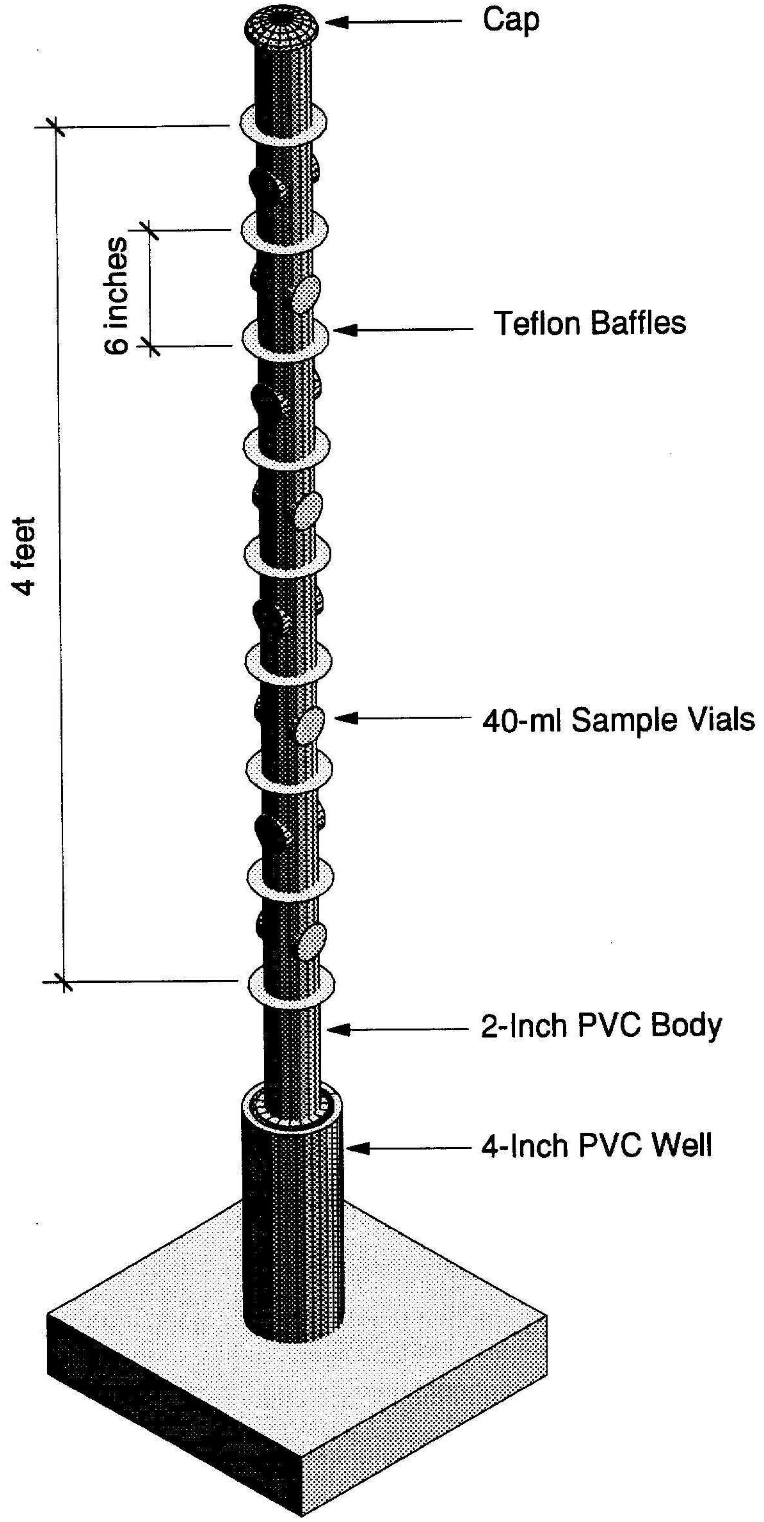

Figure 9. The "Oly-probe" single-well multi-level sample collection device.

vials are constructed of 3-inch long, 1.5-inch diameter tubes that are threaded on both ends. Dialysis membranes (Spectra/Por 4, 12,000 - 14,000 MWCO) cover each end of the vial and are held in place with a threaded polyethylene collar.

Before insertion of the sampler (Oly-probe), the vials were filled with de-ionized water. New membranes were used each time the sampler was installed in the well. The Oly-probe was inserted in the well to a point at which the top Teflon baffle was at the level of the water table. It was held in place with a 3/8-inch threaded rod that allowed for accurate vertical placement in the well. A flange was slipped over the threaded rod and rested on the top of the well. A wing nut was threaded onto the rod and adjusted to raise or lower the sampler to the desired point.

The sampler was left in the well for one to six months. This allowed the natural gradient in the aquifer to carry formation water through the well and allowed the water held in the vials to come to an ionic equilibrium with the formation water. Flow in the aquifer was lateral (horizontal). The Teflon baffles created vertically discrete chambers in which vertical mixing within the well casing should not occur.

The water samples were collected by removing the sampler from the well and transferring the water held in the vials to 20-ml plastic bottles. The samples were preserved with one to two drops of 6N sulfuric acid (H_2SO_4) and kept chilled until they were analyzed. Because of the small volume held in the vials (40 ml), samples collected from the vials were analyzed only for NO_3^- concentrations.

Mini-piezometer nitrate sampling

Nitrate and ^{15}N samples were collected from the mini-piezometer wells installed at the study site. The samples were collected by attaching the suction hose of a peristaltic pump to the top of the 1/4-inch well and pumping at about 0.25 gpm. The discharging water was allowed to clear up before a sample was taken. This usually took about 30 to 60 seconds. A 500-ml sample was collected for ^{15}N analysis, and a 20-ml sample was collected for NO_3^- analysis. Both of these samples were preserved with sulfuric acid and kept chilled until analyzed in the laboratory.

Laboratory Analysis

All samples collected for major anion/cation analysis were performed at the North Dakota State Water Commission laboratory, Bismarck, ND. Concentrations of major cations were determined in the lab, using a Perkin-Elmer Model 4000 atomic absorption spectrophotometer. Concentrations of HCO_3^-, CO_3^{2-}, and Cl^- were determined, using a Fisher Model 741 titralyzer. Concentration of SO_4^{2-} was determined by a gravimetric method.

Nitrate concentrations were determined by the North Dakota State Health Department and Consolidated Laboratories

Bismarck, ND. The NO_3^- analysis was done by a flow-through injection analysis (FIA), using a Lachat Quik-chem System 4.

Nitrogen isotope (^{15}N) concentrations were determined by the University of Illinois N-15 Analysis Service, Urbana, IL. The water samples were neutralized by adding sodium hydroxide (NaOH) before distillation with magnesium oxide (MgO) and Devarda's alloy. The values were reported as $\delta\,^{15}N$.

RESULTS AND DISCUSSION

Hydrogeology

The aquifer at the study site is composed of quartzose sand, detrital shale sand, and carbonate mineral-rich sands, based on visual inspection of lithologic samples collected during the test drilling. The grain size of the aquifer at the study site is very fine to medium sand. The depth to water ranged from 10 to 13 feet below land surface during the study period.

Seven observation wells were used to determine the flow field in the vicinity of the study site. A hydrograph of water levels collected from a well located at the study site is provided in Figure 10. Water level data collected during the study period are presented in Appendix I. Water level fluctuation in the aquifer over the period from which the multi-level samples were collected (March 19, 1992, to September 30, 1993) was about 1 foot. A water table map (Figure 11) was constructed to determine the horizontal gradient in the aquifer. Water level elevations were determined in several observation wells near the study site. The gradient in the vicinity of the study site is about 1 foot per mile or 1.9×10^{-4}. Direction of flow is primarily to the north, parallel to the line of sampling wells.

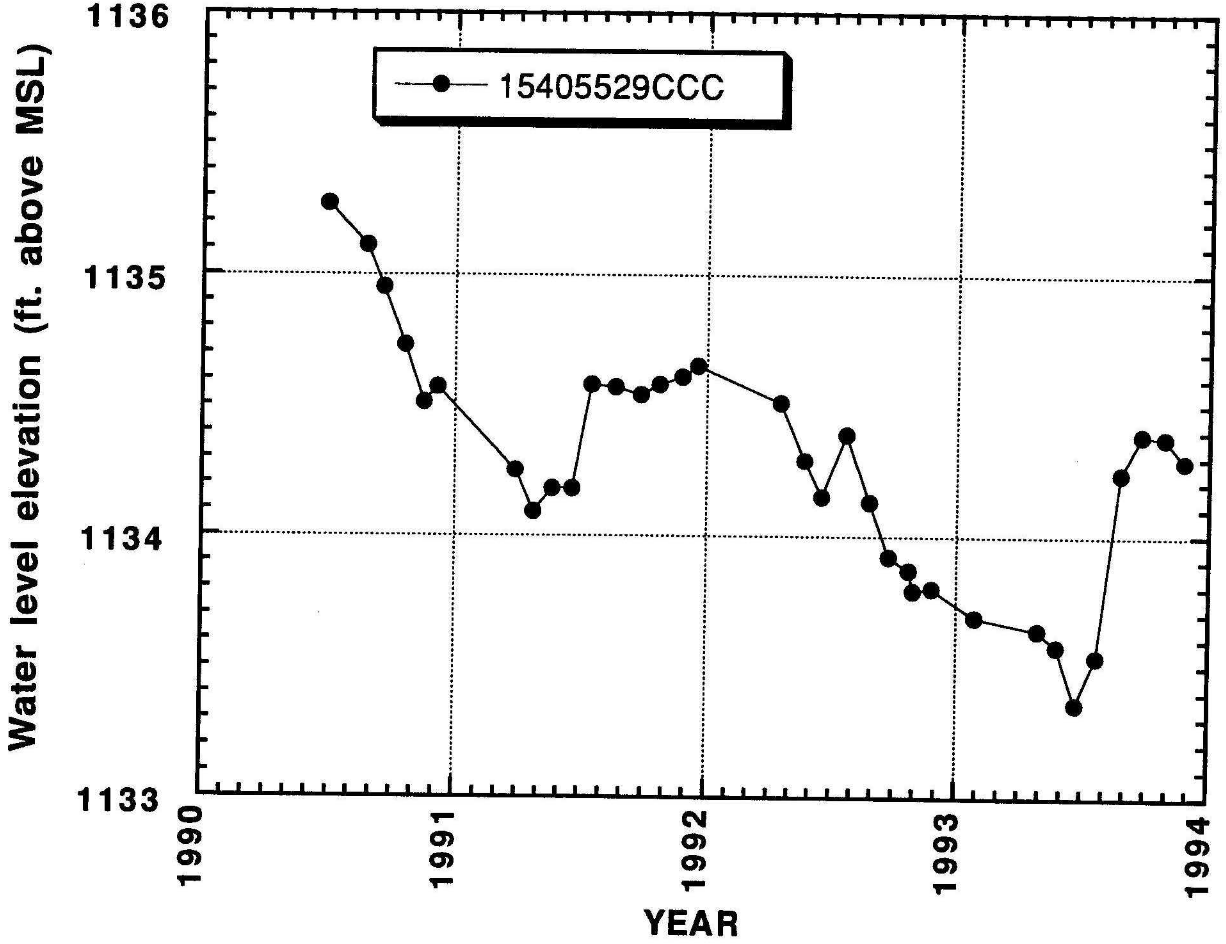

Figure 10. Hydrograph of water level measurements taken from well 154-55-29CCC.

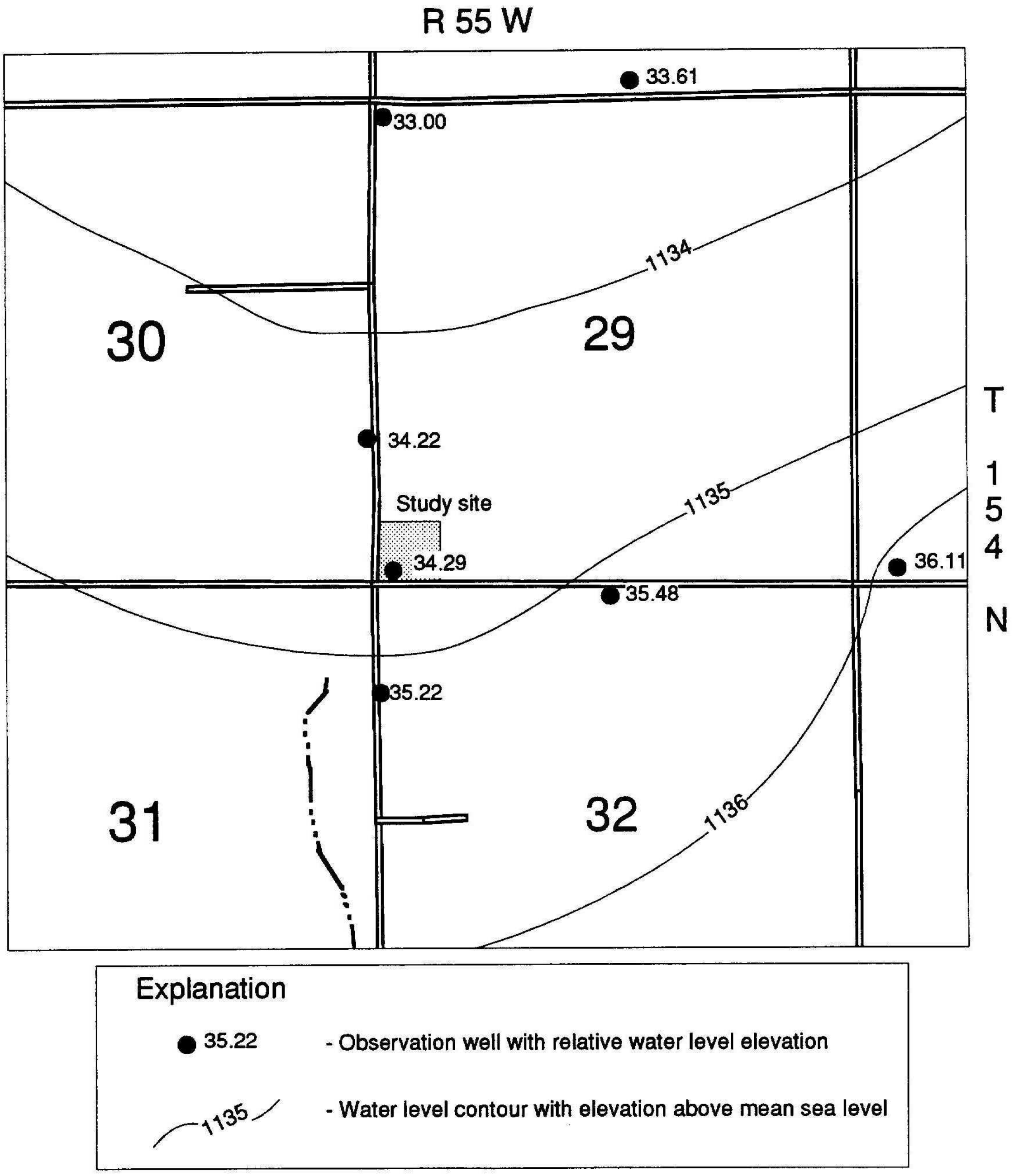

Figure 11. Water table map of the study site (November, 1993).

Vertical Nitrate Distribution

Water samples collected from the 22 sampling points spaced both vertically and horizontally at the study site indicate a high vertical NO_3^- gradient. Water quality data collected through the period of study are presented in Appendix II. Samples were collected on nine different dates from March 19, 1992, to September 30, 1993. The NO_3^- concentrations varied both temporally and spatially; however, the trend was higher concentrations near the water table and decreasing concentrations below the water table.

The vertical NO_3^- distribution was determined by two methods: single well multi-level sampling and multiple mini-piezometer sampling. Comparison of the sampling methods was done since both of these groups of vertical samples were collected at the same time.

Single-well multi-level sampling

The vertical NO_3^- distribution of the samples collected by the single-well multi-level sampling for each sample period are provided in Figures 12 through 20. These samples were collected, using the Oly-probe multi-level sampling device (Figure 9). The principle on which the single-well multi-level sampling was based is that the water held in the vial will come to an ionic equilibrium with the surrounding formation water. For this to occur, flow in the aquifer must be only horizontal

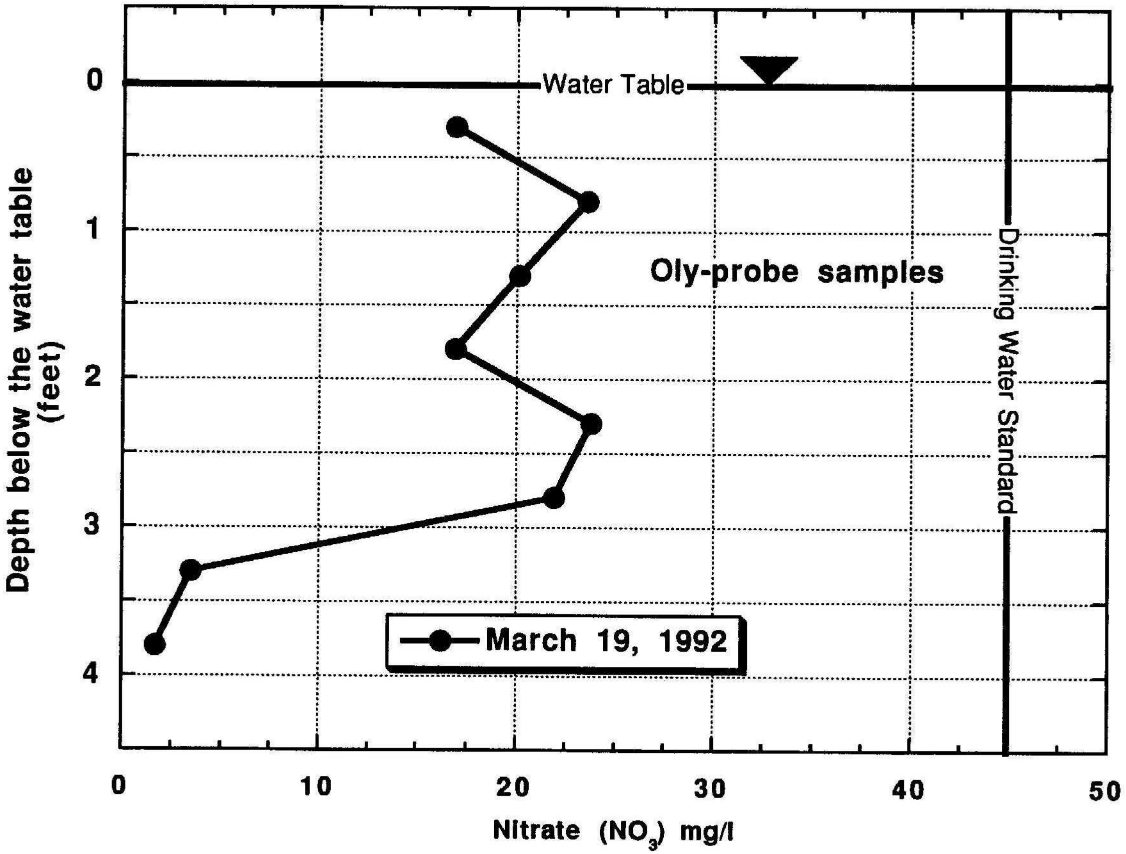

Figure 12. Nitrate concentrations plotted with depth below the water table. Samples were collected on March 19, 1992, from well 154-55-29CCC3.

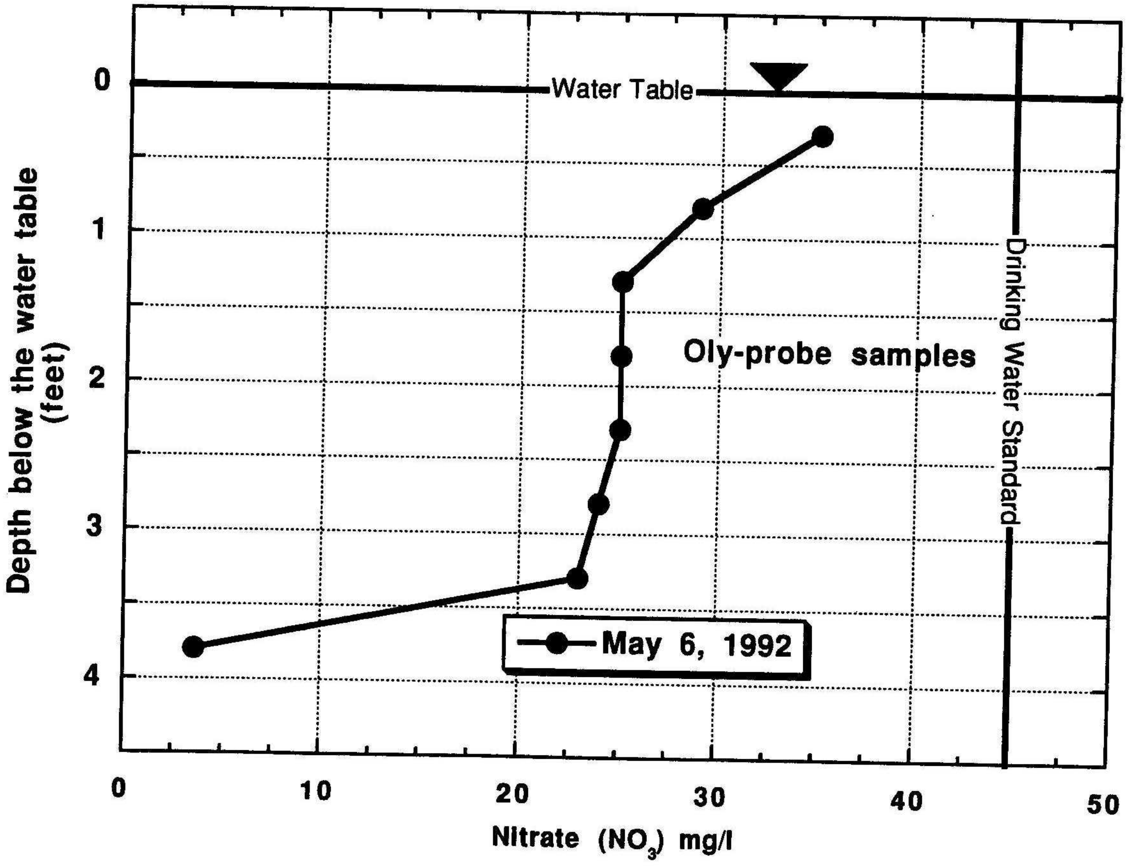

Figure 13. Nitrate concentrations plotted with depth below the water table. Samples were collected on May 6, 1992, from well 154-55-29CCC3.

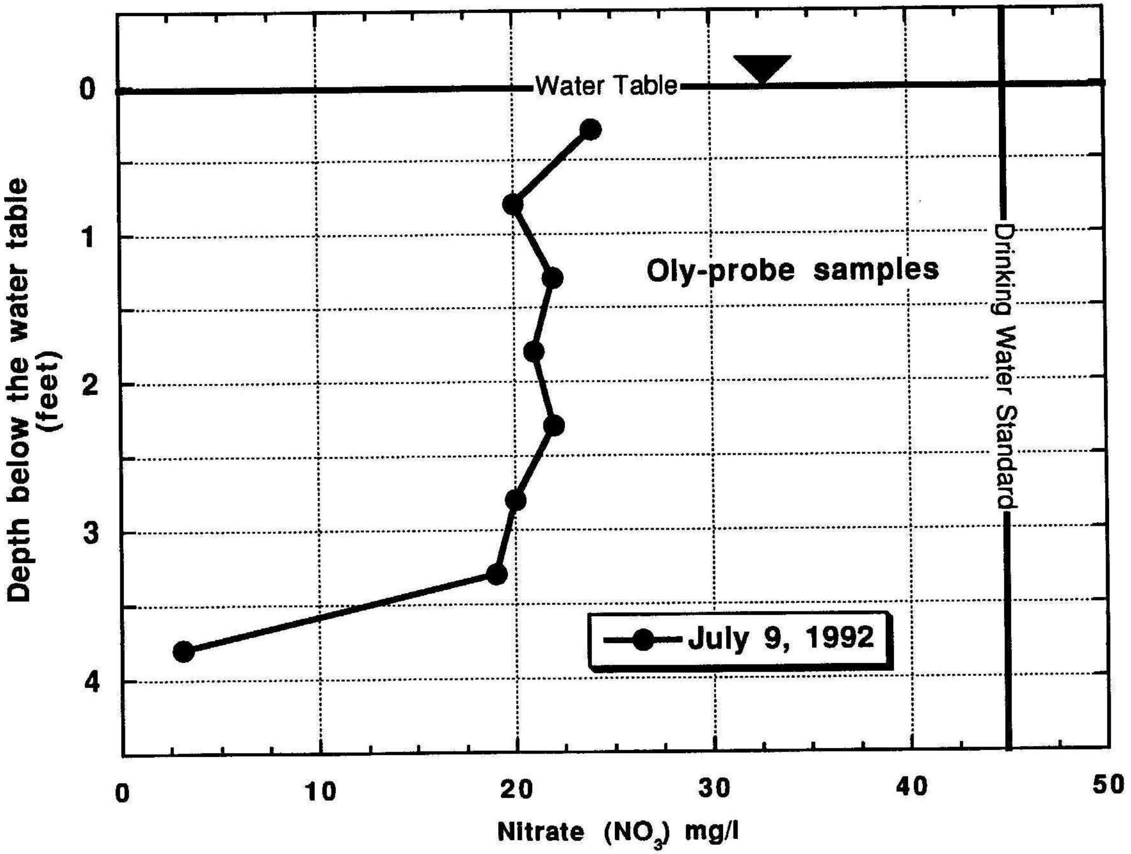

Figure 14. Nitrate concentrations plotted with depth below the water table. Samples were collected on July 9, 1992, from well 154-55-29CCC3.

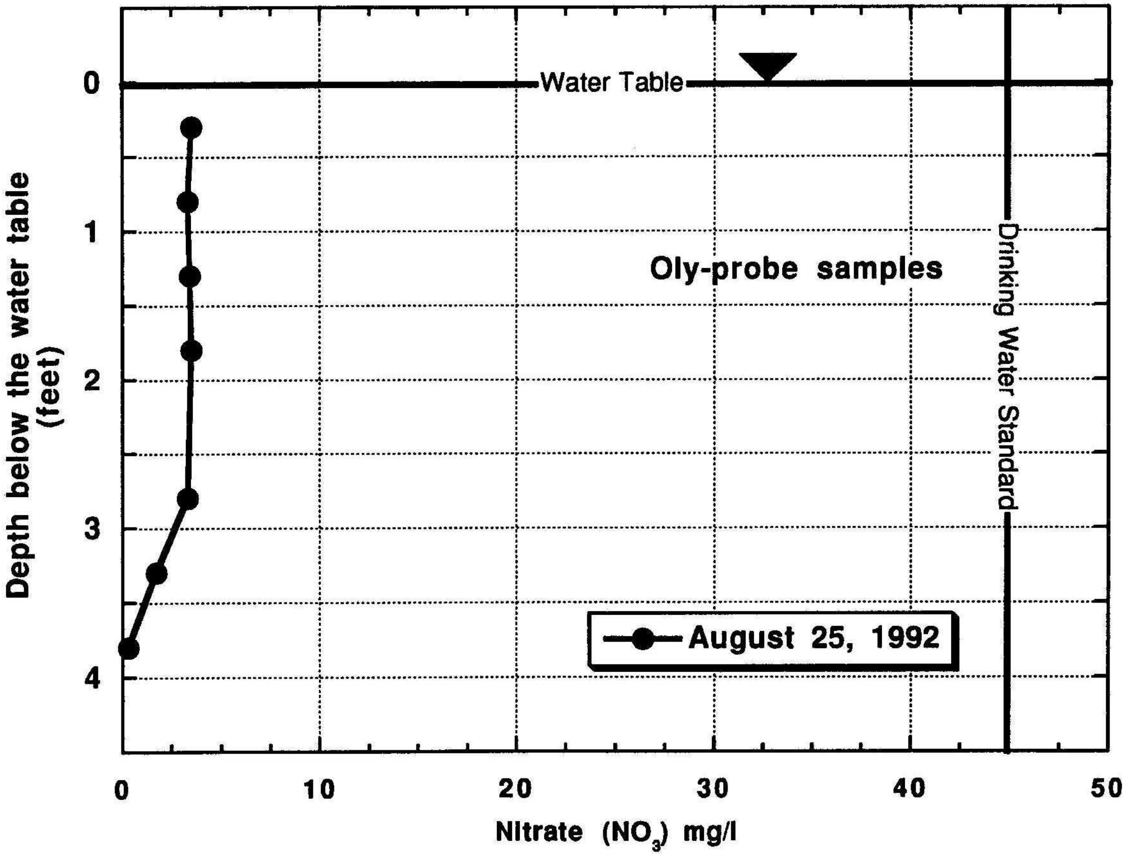

Figure 15. Nitrate concentrations plotted with depth below the water table. Samples were collected on August 25, 1992, from well 154-55-29CCC3.

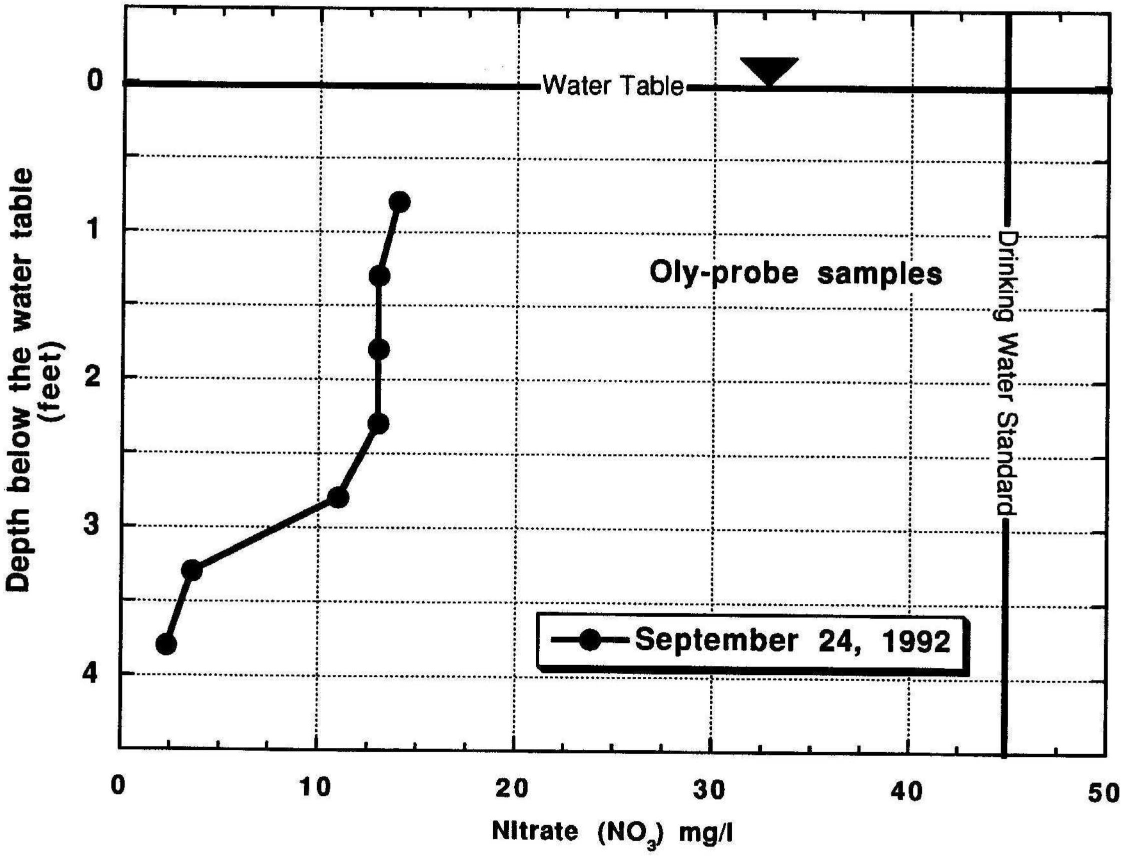

Figure 16. Nitrate concentrations plotted with depth below the water table. Samples were collected on September 24, 1992, from well 154-55-29CCC3.

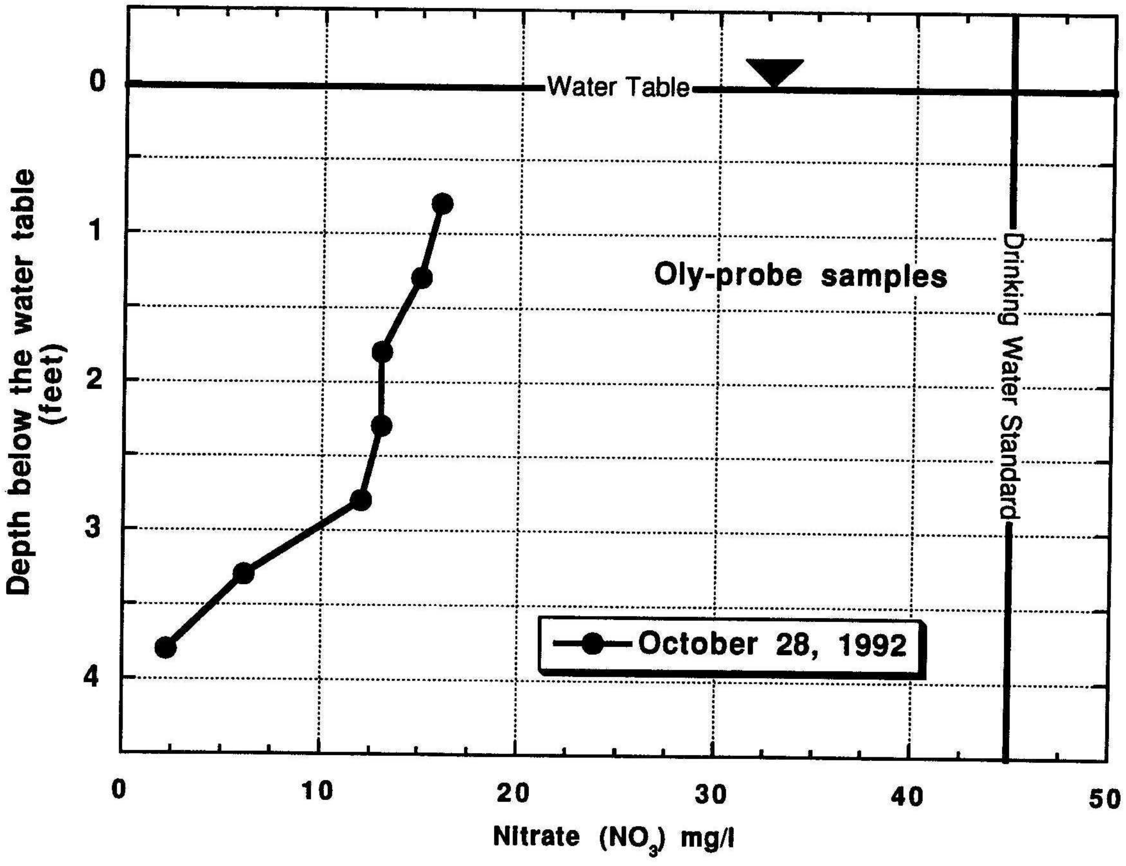

Figure 17. Nitrate concentrations plotted with depth below the water table. Samples were collected on October 28, 1992, from well 154-55-29CCC3.

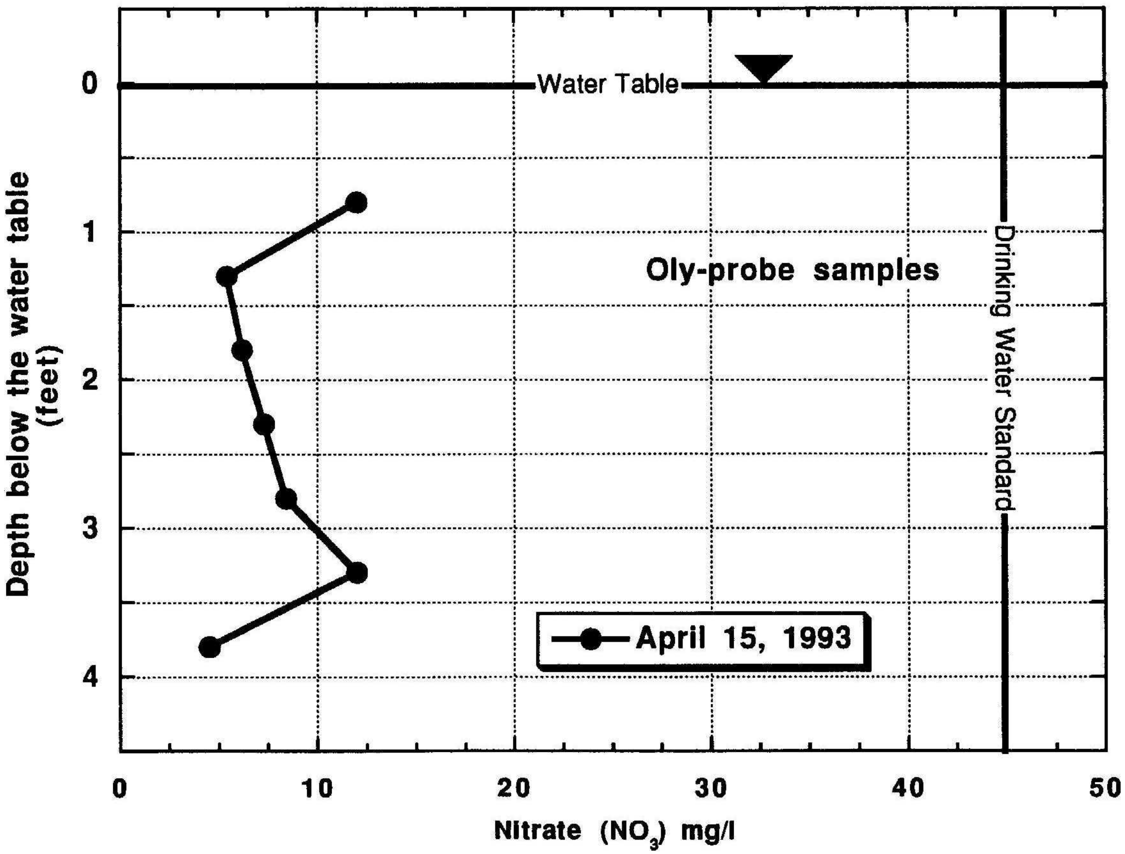

Figure 18. Nitrate concentrations plotted with depth below the water table. Samples were collected on April 15, 1993, from well 154-55-29CCC3.

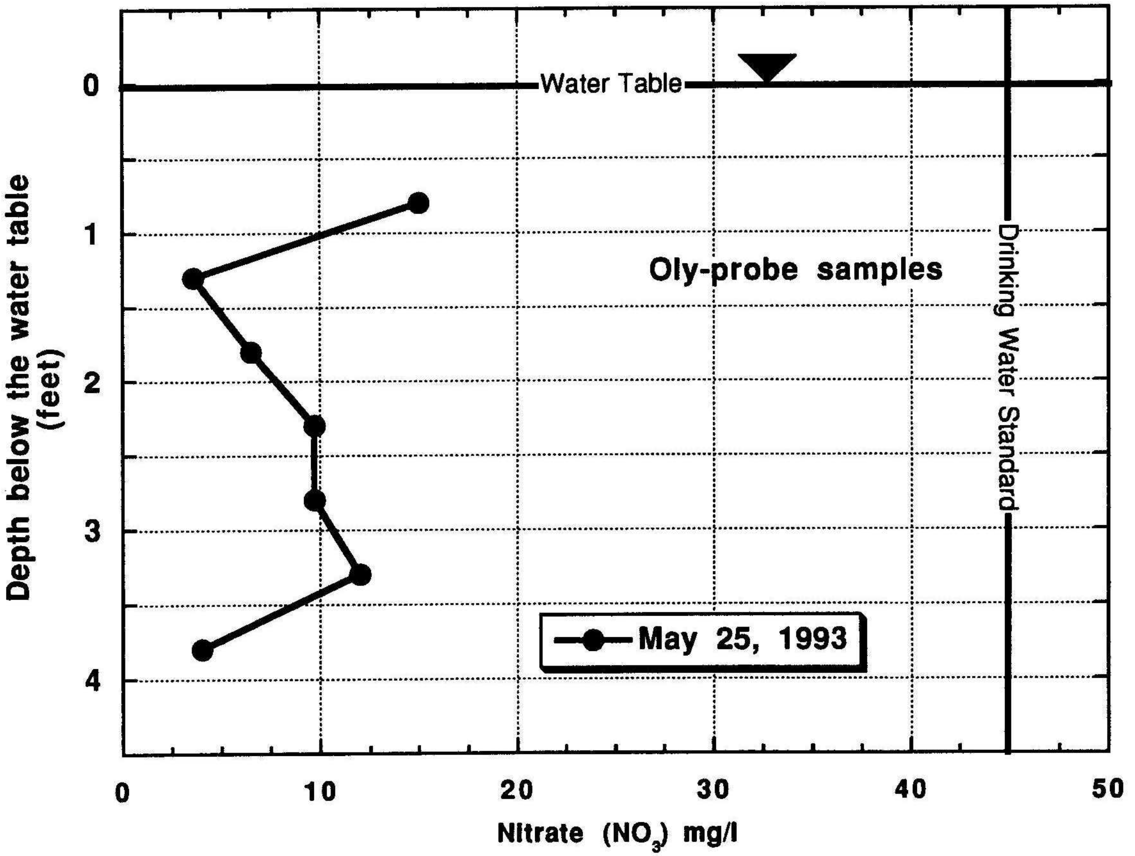

Figure 19. Nitrate concentrations plotted with depth below the water table. Samples were collected on May 25, 1993, from well 154-55-29CCC3.

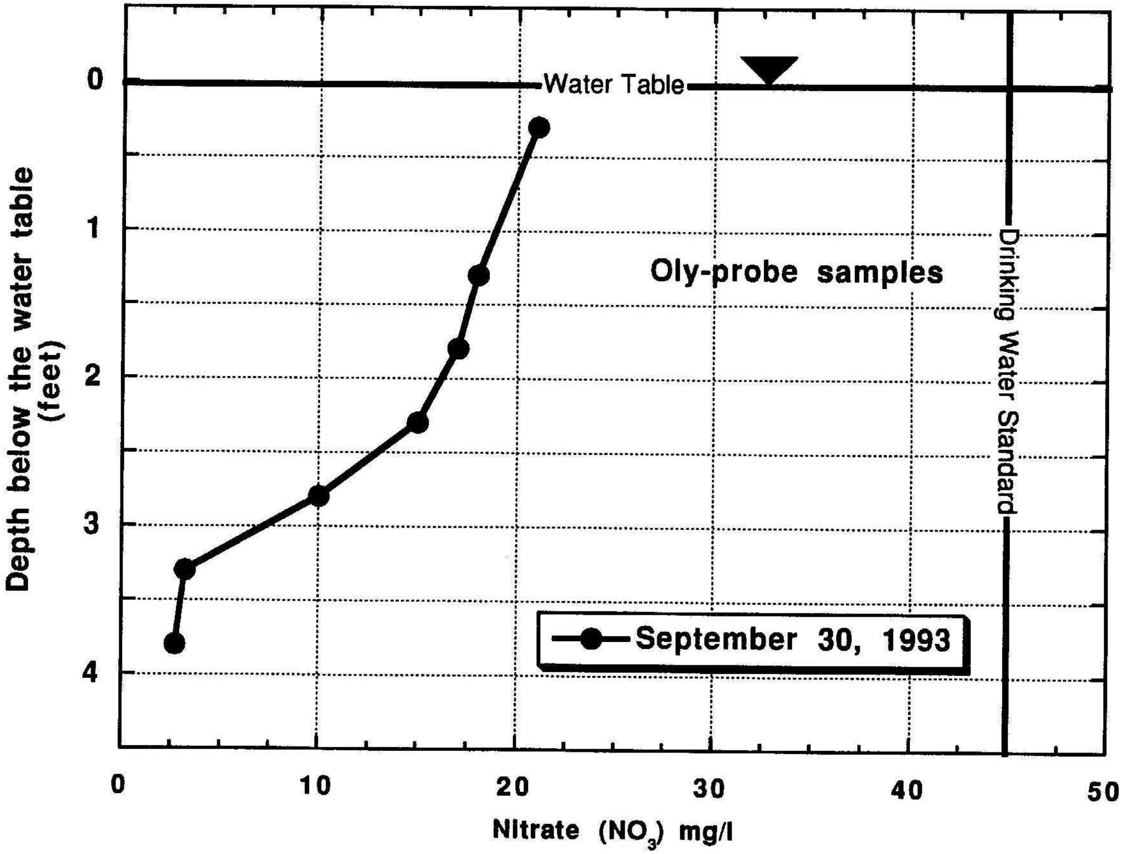

Figure 20. Nitrate concentrations plotted with depth below the water table. Samples were collected on September 30, 1993, from well 154-55-29CCC3.

and bring water through the disturbed annular sand pack, through the screen, and into contact with the dialysis membrane. Determination of natural NO_3^- stratification in the aquifer requires that artificial vertical mixing must not occur. The natural hydraulic gradient will move formation water past the disturbed zone of the well.

Mixed water resulting from the disturbance of the formation and the stirring of the casing water during insertion of the sampling device should be purged by the horizontal advective flow in the aquifer. Velocities of flow in the aquifer determine the length of time the water in the sample chambers takes to come to a quasi-equilibrium with the surrounding formation water. Flow velocity at the study site was about 0.02 ft/day. Travel time for an advective front to completely purge the one-foot horizontal disturbance of the formation by the annular area of the well was about 50 days.

The multi-level sampler was first installed in the well on October 15, 1991. The sample periods and number of days that the multi-level sampler was in the well before sampling are listed in Table 2.

The first group of Oly-probe samples was collected on March 19, 1992 (Figure 12). The vertical distribution had a general trend of higher NO_3^- concentrations near the water table that diminished with depth; however, the samples from vials 1, 5, and 6 had concentrations that did not fit the conceptual model. Sample 1 may be the result of the vial placement too near the water table and possibly being outside

Table 2. Multi-level sampler (Oly-probe) sample dates and number of days the sampler was left in the well prior to sampling.

Sample date	Days in well before sampling
3/19/92	156
5/6/92	48
7/9/92	64
8/25/92	47
9/24/92	30
10/28/92	34
4/15/93	169
5/25/93	40
9/30/93	128

of the saturated conditions for some time. An influx of lower NO_3^- water may also have occurred before sample collection. The higher NO_3^- concentrations in samples 5 and 6 may be the result of a pulse of high NO_3^- water moving laterally into the study site. Samples 7 and 8 have low NO_3^- concentrations.

The samples collected on May 6, 1992, show diminishment in NO_3^- concentration with each subsequent vial below the water table; however, samples 3 through 7 are similar in concentration (Figure 13). The difference between the top and bottom samples (nos. 1 and 8) shows a significant decrease in concentration in the upper four feet of saturated thickness of the aquifer.

The July 9, 1992, sampling (Figure 14) again shows a significant decrease in NO_3^- concentration between samples 1 and 8. Samples 2 through 7 have similar NO_3^- concentrations.

The samples collected on August 25, 1992, are all relatively low (Figure 15). The deepest sample, no. 8, has the lowest concentration of the group. Once again, several of the samples show a consistent NO_3^- concentration.

The groups of samples collected with the Oly-probe on September 24 and October 28, 1992, were similar to one another (Figures 16 and 17). Each group had a general gradation of NO_3^- concentration from a level of about 15 mg/l at the top to about 1 mg/l at the bottom of the sample section. The upper four samples in each set had consistent NO_3^- concentrations.

The April 15, 1993, and May 25, 1993, samplings provided odd results (Figures 18 and 19). The NO_3^- concentration increased a small amount between samples 3 and 7 in each group. An ineffective seal between sample chambers may have resulted in vertical mixing; hence, the results of these samples may not represent the concentrations of NO_3^- in the formation at that specific horizon.

The group of samples collected on September 30, 1993, showed a fairly uniform diminishment in NO_3^- concentration with depth below the water table (Figure 20).

Mini-piezometer sampling

The vertical NO_3^- distribution of the samples collected from the mini-piezometers is provided in Figures 21 through 29. Two groups of mini-piezometers were used. The first, labeled 29CCC4, had three sampling points. The second, labeled

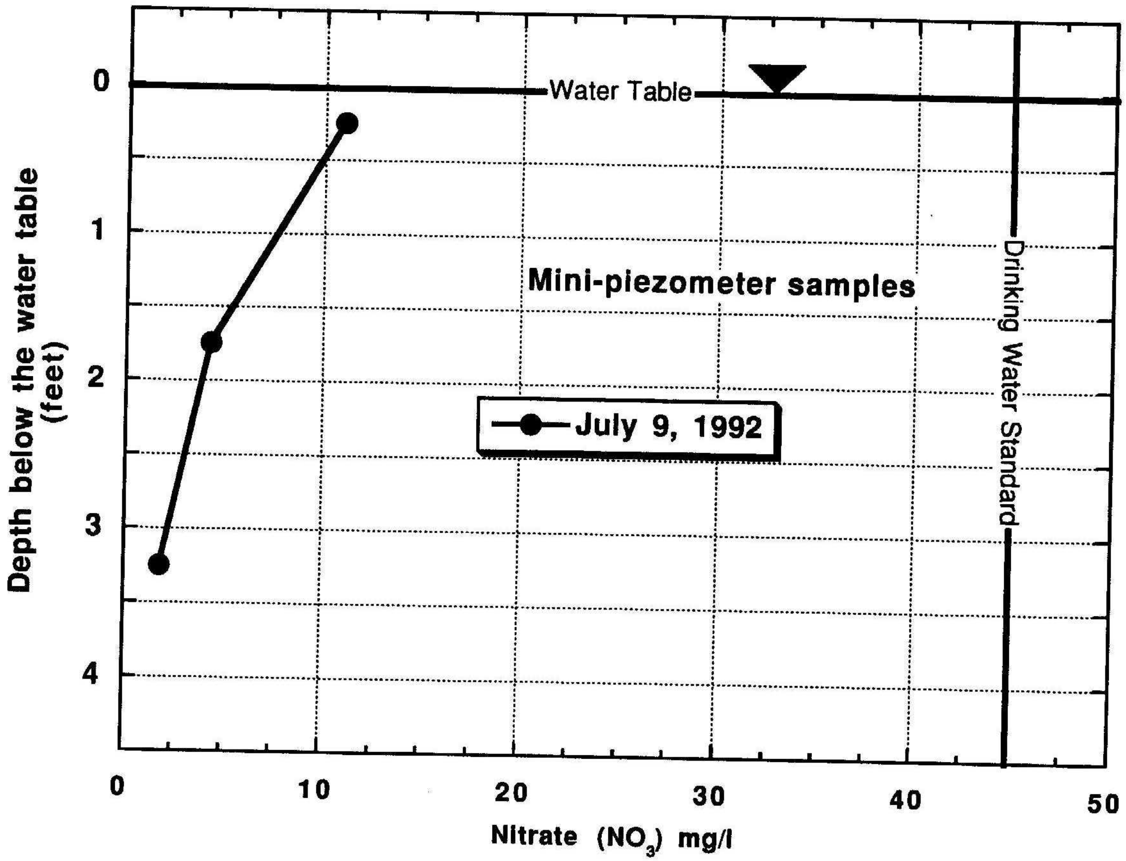

Figure 21. Nitrate concentrations plotted with depth below the water table. Samples were collected on July 9, 1992, from well 154-55-29CCC4.

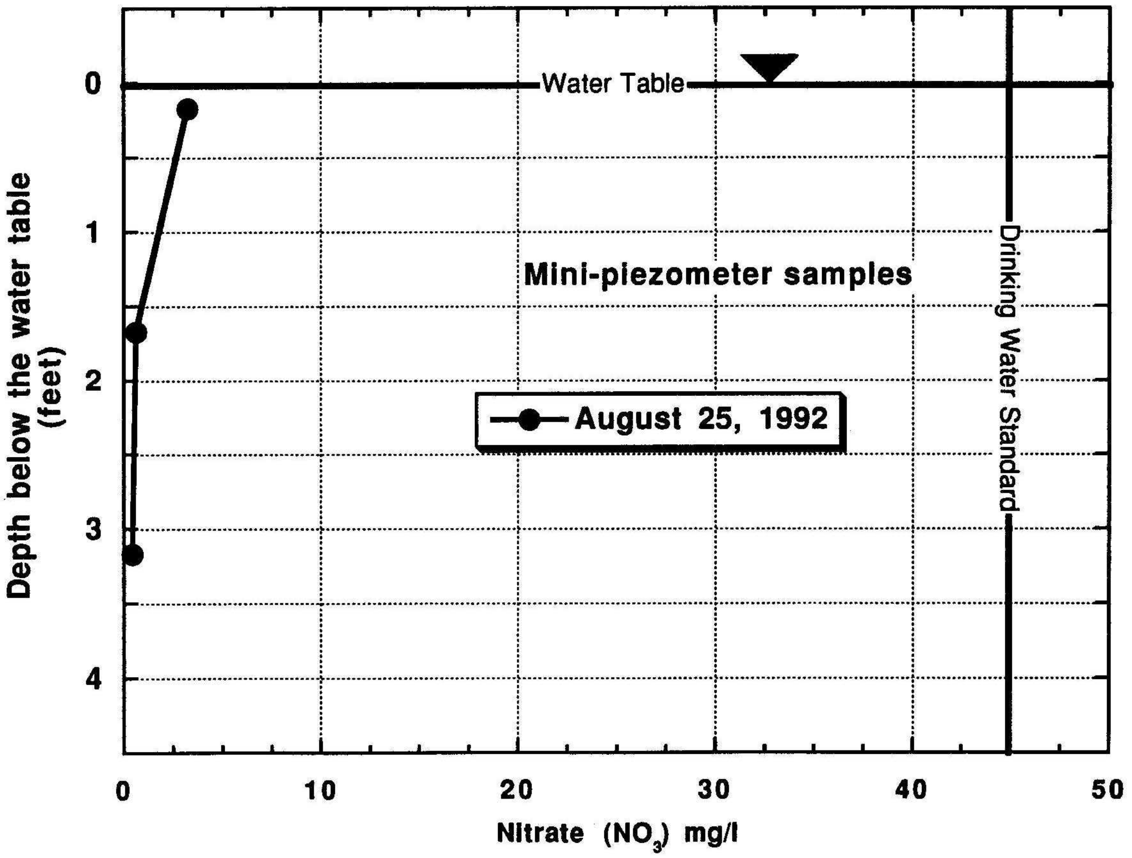

Figure 22. Nitrate concentrations plotted with depth below the water table. Samples were collected on August 25, 1992, from well 154-55-29CCC4.

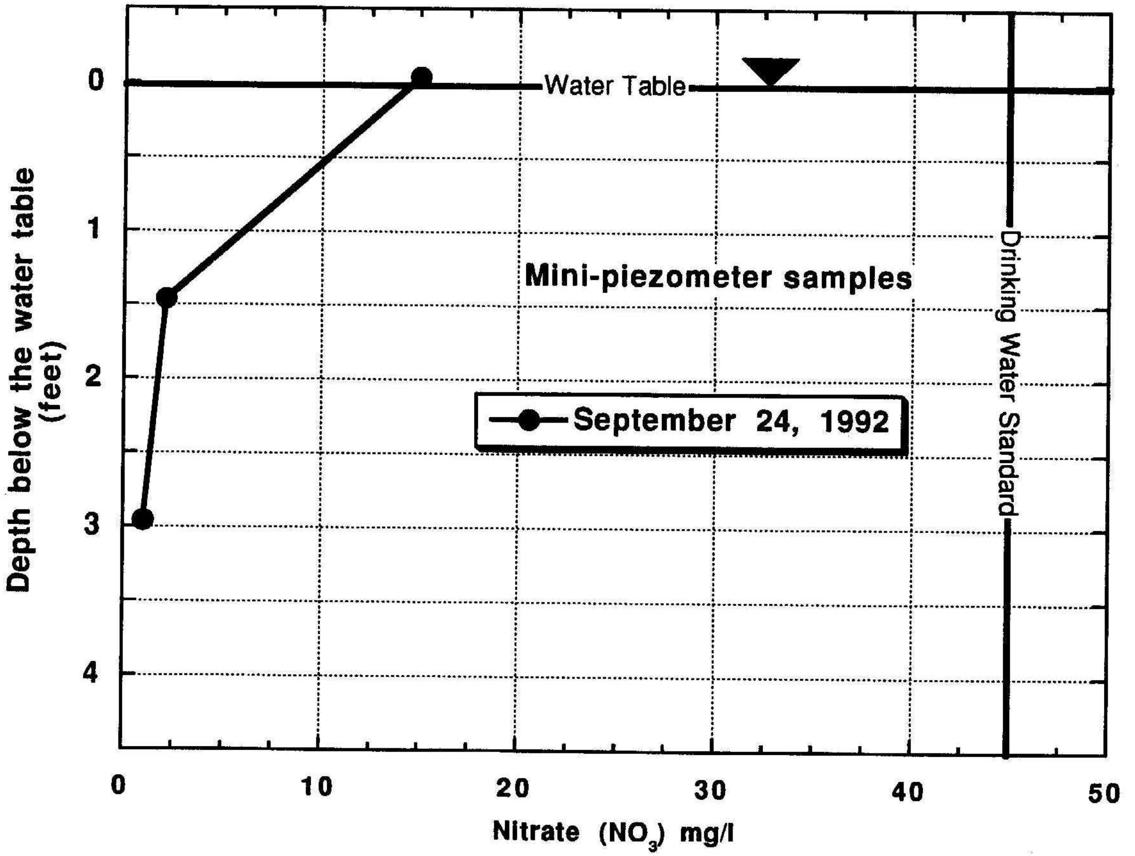

Figure 23. Nitrate concentrations plotted with depth below the water table. Samples were collected on September 24, 1992, from well 154-55-29CCC4.

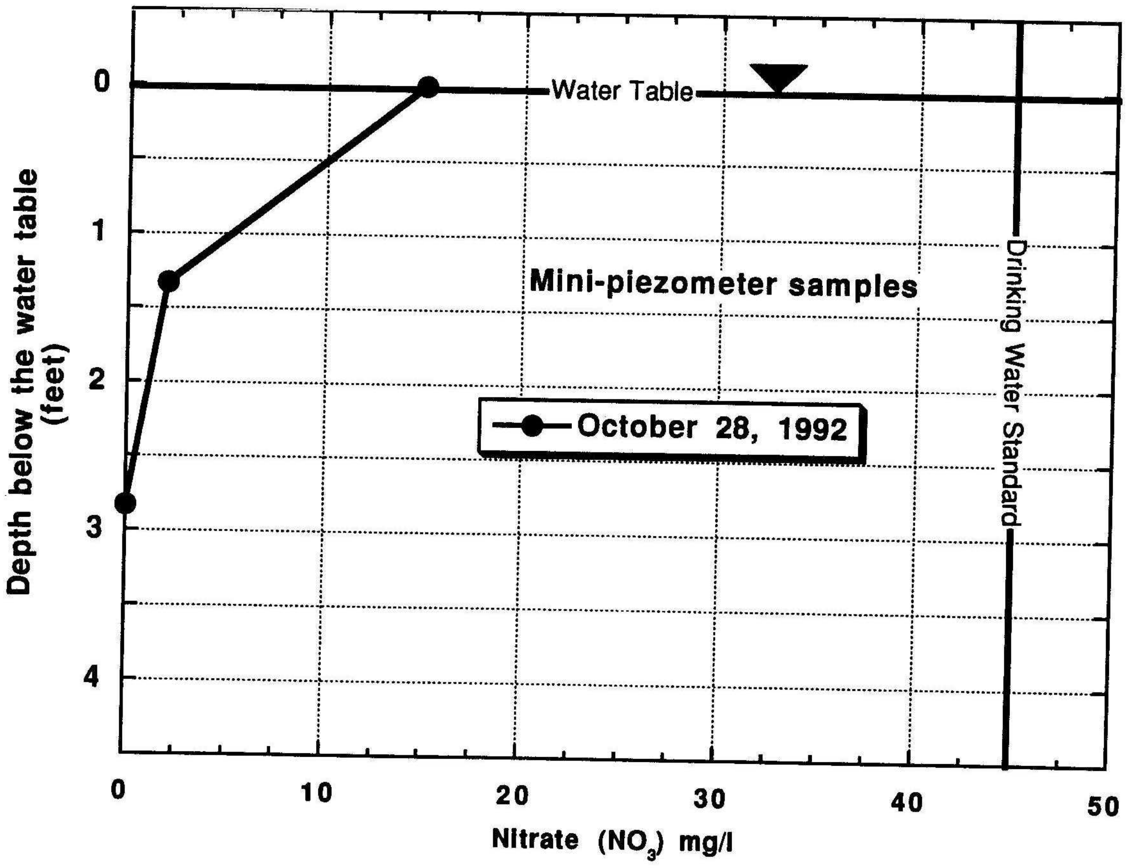

Figure 24. Nitrate concentrations plotted with depth below the water table. Samples were collected on October 28, 1992, from well 154-55-29CCC4.

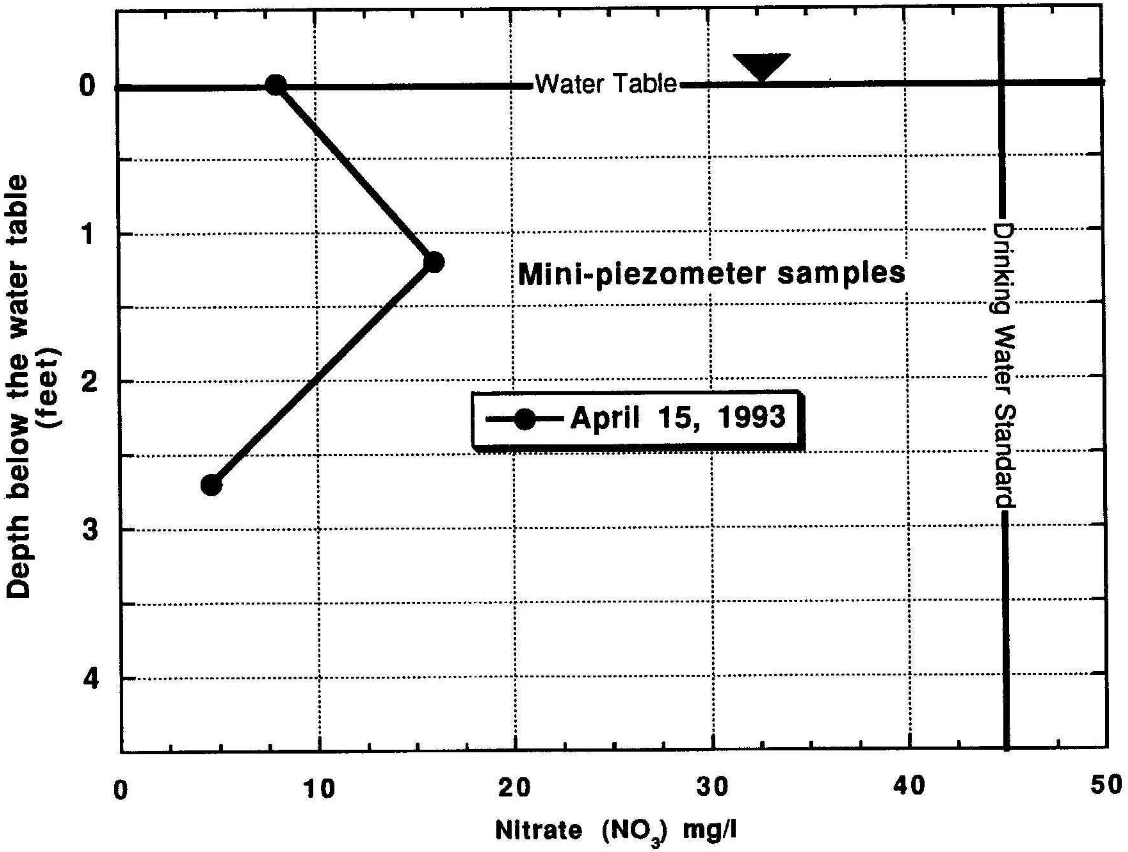

Figure 25. Nitrate concentrations plotted with depth below the water table. Samples were collected on April 15, 1993, from well 154-55-29CCC4.

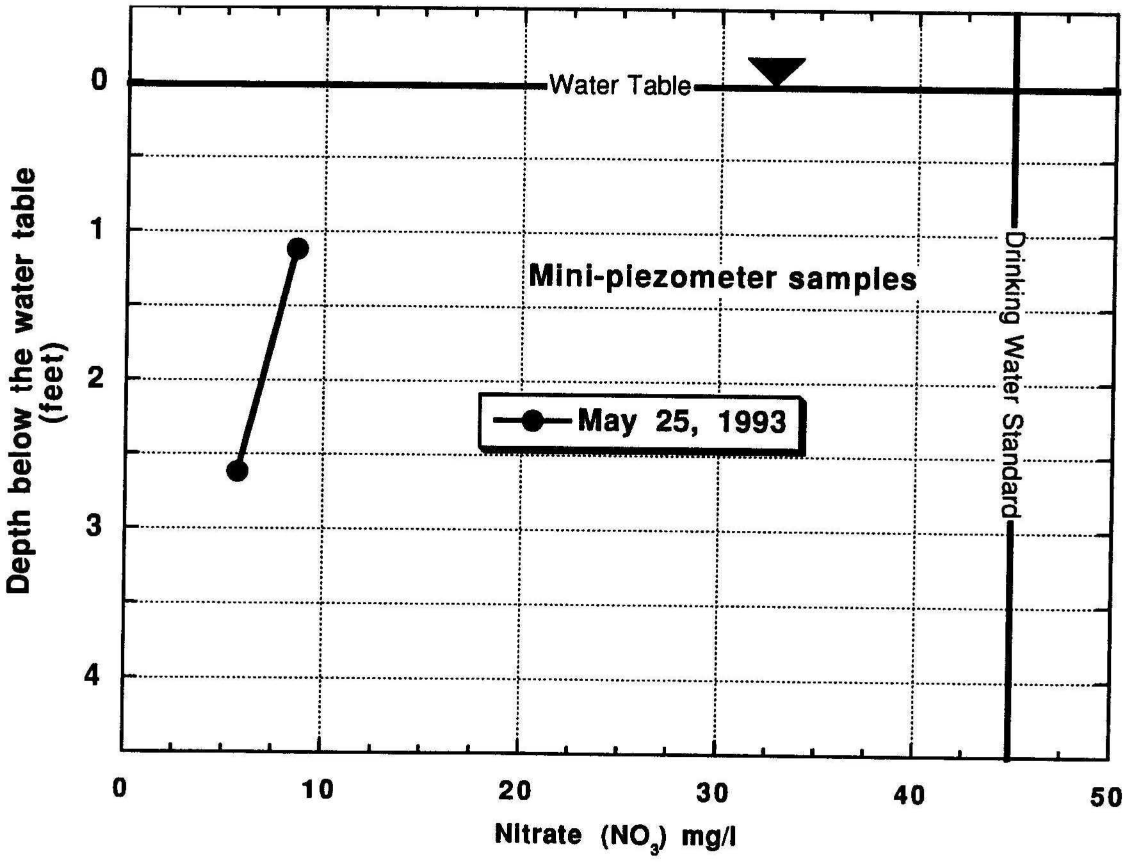

Figure 26. Nitrate concentrations plotted with depth below the water table. Samples were collected on May 25, 1993, from well 154-55-29CCC4.

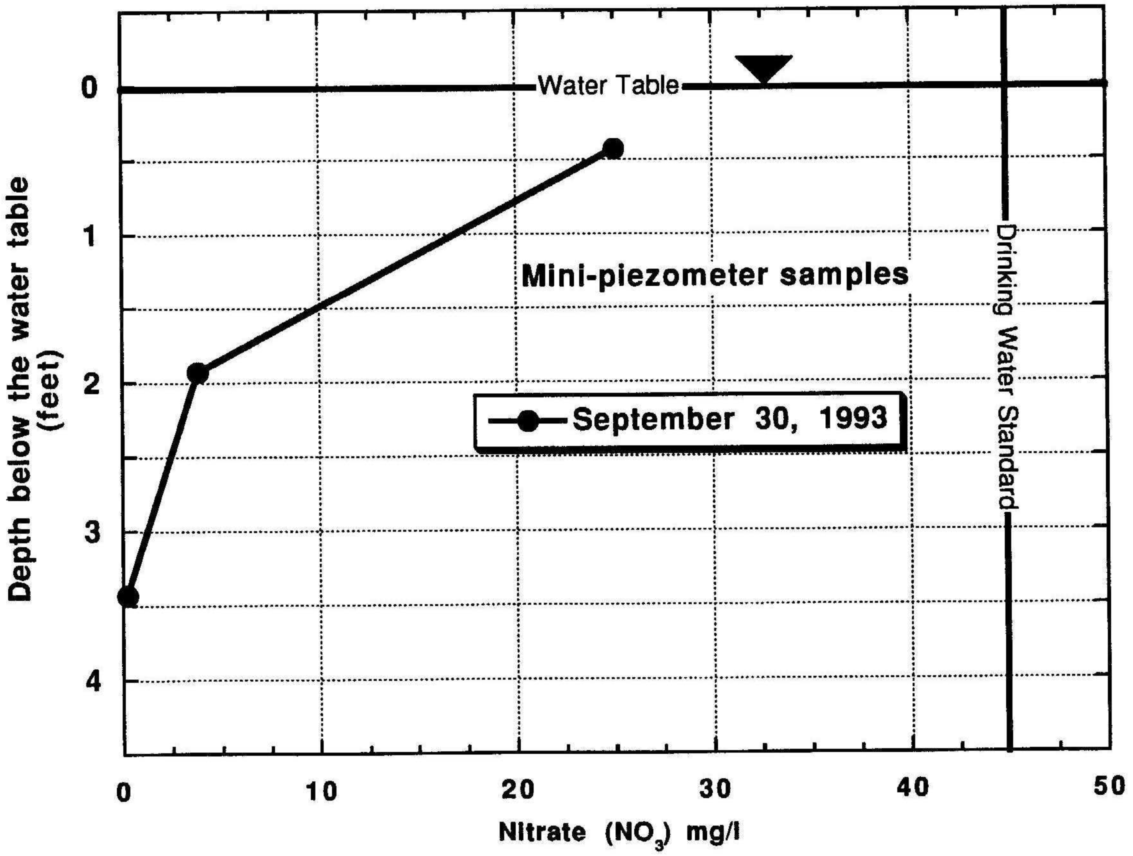

Figure 27. Nitrate concentrations plotted with depth below the water table. Samples were collected on September 30, 1993, from well 154-55-29CCC4.

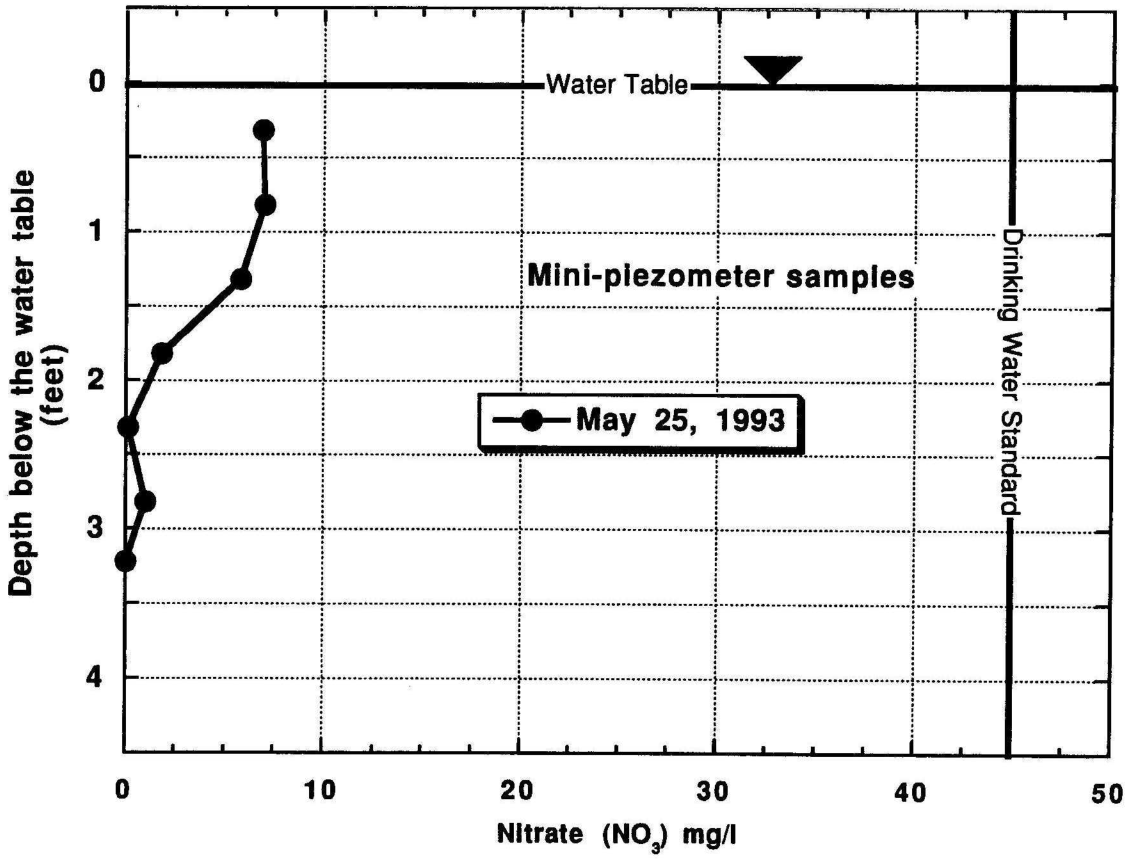

Figure 28. Nitrate concentrations plotted with depth below the water table. Samples were collected on May 25, 1993, from well 154-55-29CCC5.

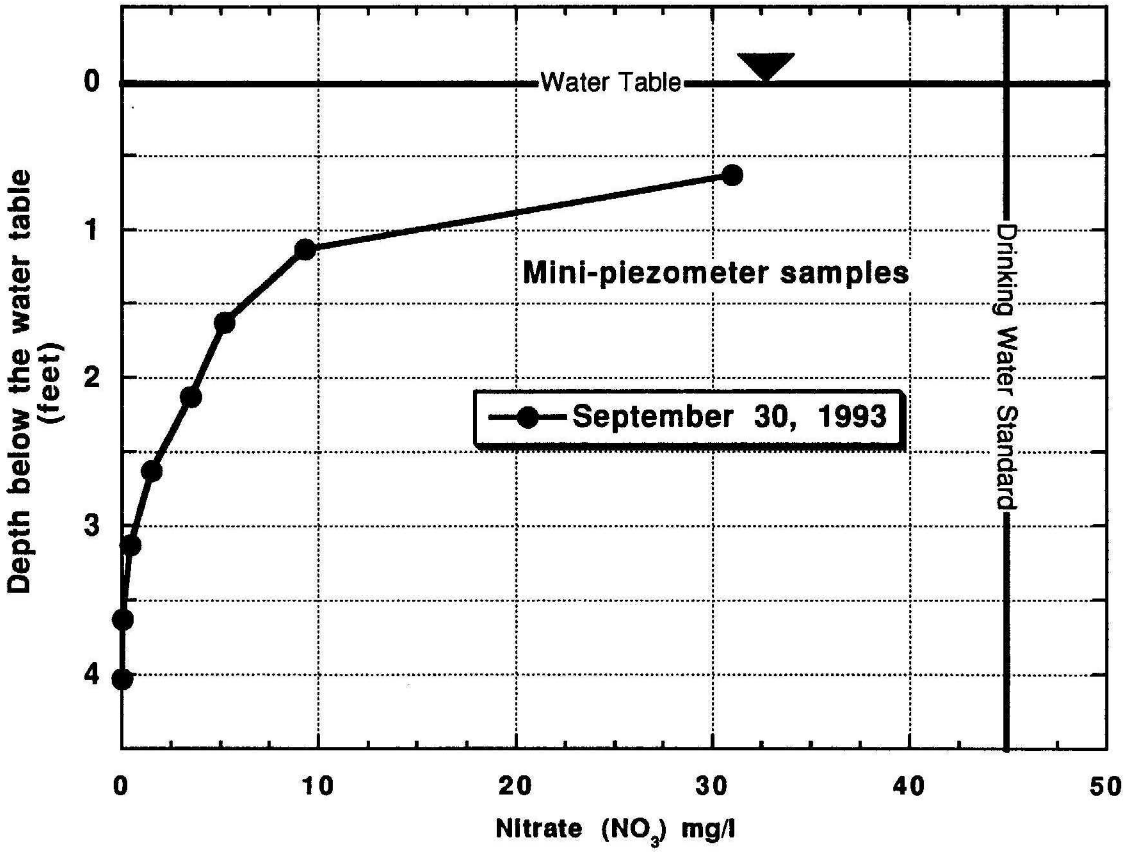

Figure 29. Nitrate concentrations plotted with depth below the water table. Samples were collected on September 30, 1993, from well 154-55-29CCC5.

29CCC5, had eight sampling points. Table 3 lists the sample dates of the two mini-piezometer nests.

Table 3. Mini-piezometer nests sample dates.

Sample Date	29CCC4	29CCC5
7/9/92	√	
8/25/92	√	
9/24/92	√	
10/28/92	√	
4/15/93	√	
5/25/93	√	√
9/30/93	√	√

Comparison of multi-level sampling methods

In general, the samples collected from the mini-piezometer nests showed a more uniform diminishment of NO_3^- with depth when compared to the Oly-probe samples. The reason for this may be that the mini-piezometer well screen was in direct contact with the aquifer formation. Disturbance to the natural stratification of the aquifer sediments was minimal. Water collected from these wells was derived from the immediate vicinity of the well screen. The water collected by the Oly-probe sampler, on the other hand, was not direct formation water at the time it was collected.

The vials in the Oly-probe were filled with de-ionized water at the time the sampler was installed. Formation water must pass through the disturbed annular space of the well, move through the screen, and come into contact with dialysis membrane. The water held in the vials must come to an ionic equilibration with the water that has moved into the well. The Teflon baffles that separate the sample chambers should prevent vertical mixing in the well casing. The length of time required to insure an ionic-equilibrium state has been reached with the surrounding water can be great if the natural flow velocity in the aquifer is small.

Figure 30 shows a potential source of error with the Oly-probe method of multi-level sample collection. Figure 30 (A) shows how the device is designed to work in theory. Figure 30 (B) shows what may be happening in reality. As water moves into the disturbed annular space of the well, the chance of vertical mixing is increased because the sand grains no longer have natural stratification. Also, vertical mixing may occur through the Teflon baffles that separate the sample chambers.

Advantages and disadvantages of the two multi-level sampling methods are provided in Table 4.

Dispersion Effects

The computer model VS2DT (Healy, 1990) was used to simulate dispersion effects under a variety of conditions. A statement of the problem is as follows:

> High nitrate water infiltrates through the vadose zone to the water table at a constant rate. Flow in the aquifer is strictly horizontal. The nitrate concentration in the aquifer is originally

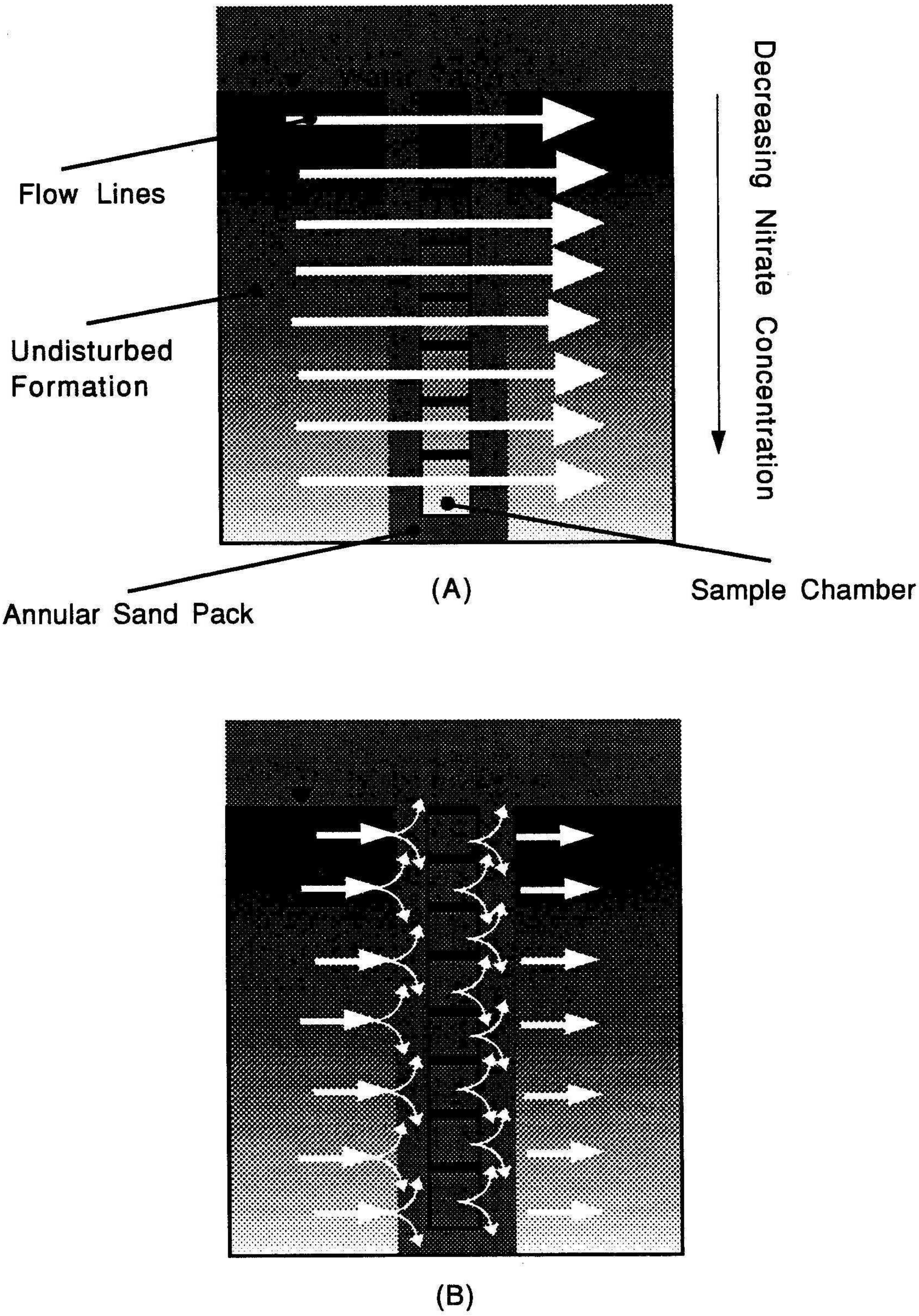

Figure 30. (A) Multi-level sample device where concentration in sample chambers is the same as the adjacent formation water. (B) Mixing has occurred in annular space or well casing causing concentrations to be consistent and averaged in the vertical profile.

Table 4. Advantages and disadvantages of the two multi-level sampling methods used.

	Mini-piezometers	**Oly-probe**
Advantages	•Low-cost installation. •No sophisticated equipment needed. •Ease of sample collection. •Minimal disturbance to natural hydrogeologic environment. •Sampling frequency can be high.	•Samples may be collected from depths to water greater than 25 feet. •Placement of sampler can be varied to account for changing water levels.
Disadvantages	•Suction lift requires water level to be less than about 25 feet. •Water level changes cause variable depth below water table to well screens.	•Expensive to install. Special equipment needed (auger drilling rig). •Requires flow in aquifer to move water past dialysis membranes on sample vials. •Long intervals between sample collections may be required. •Drilling method and size of well boring cause natural environment to be substantially disturbed. •Insertion and removal of sampler cause complete mixing in the well casing.

> zero everywhere. Transverse dispersion causes nitrate to move out perpendicular to the direction of flow. A vertical distribution of nitrate concentration decreasing downward results.

The flow velocity at the site was calculated from the Darcy equation to be about 0.022 ft/day. VS2DT is a finite difference model; thus, a grid was established to obtain this velocity of flow across a vertical profile in the model (Figure 31). A grid of 5 columns and 42 rows was created. Spacing in the horizontal direction was 3000 feet and in the vertical was 0.5 feet. The exterior cells of the model were automatically defined by the program as no flow cells. The total head in the cells in columns 2 and 4 were held constant at 100.3 and 99.7 feet, respectively. This created a uniform flow field across the vertical profile of concern, column 3. The NO_3^- concentration in the cell at the top of this column was held to a constant of 50 mg/l.

This concentration was based on extrapolation to the water table of the concentration trend from the samples collected on September 30, 1993, from well nest 29CCC5. Initial concentrations at all other cells in the model were zero. Because the spatial derivatives in the flow equation were based on central differences about the cell boundaries, the concentrations calculated for each cell applied to the center of the cell.

Four simulations were done using transverse dispersivity (α_t) values of 0.1, 1, 10, and 100 feet. Time since start of

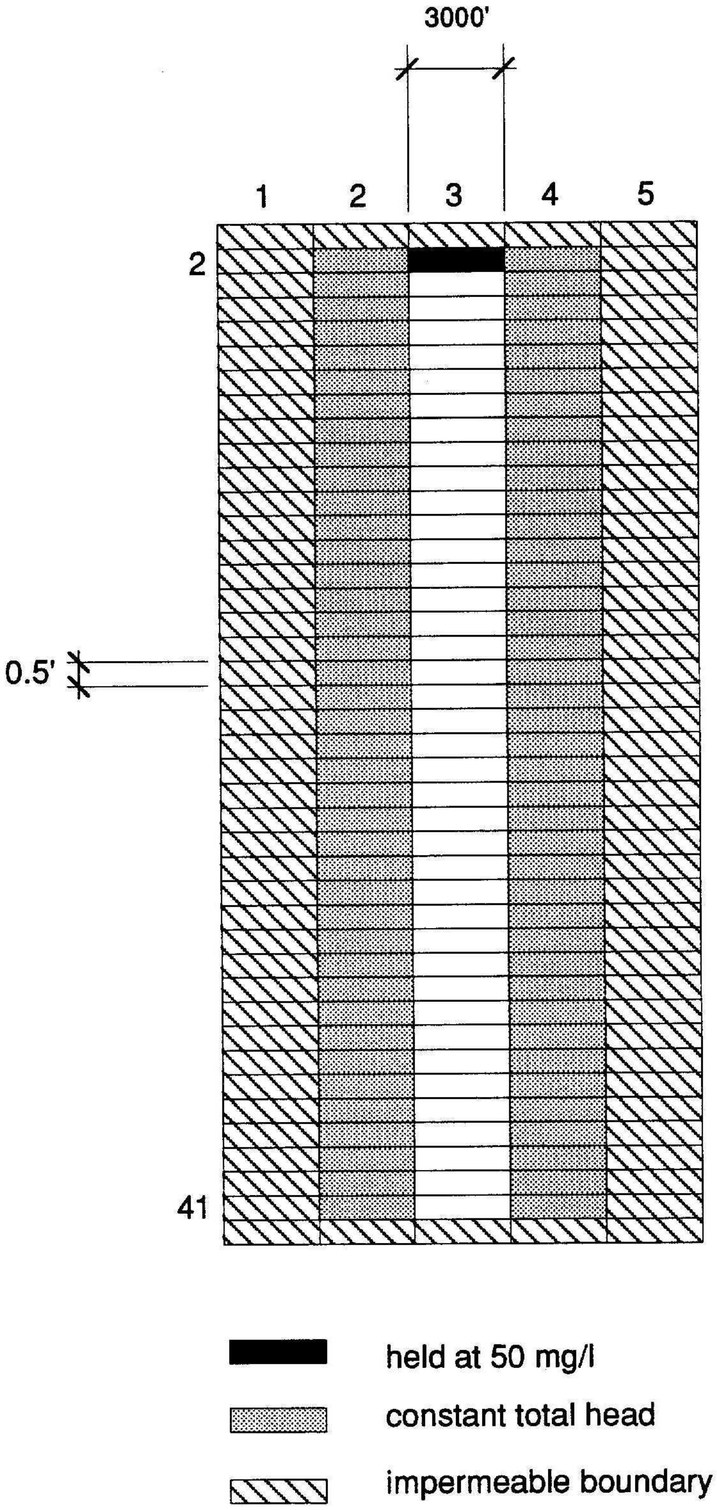

Figure 31. Finite difference model grid used for VS2DT contaminant transport model simulations.

simulation of 90 days, 1, 2, 4, and 8 years was calculated in each simulation. The input files for the four simulations are provided in Appendix III. Output from the simulations are provided in Appendix IV. Figures 32 through 35 show the vertical NO_3^- distribution calculated by the model for each of the times and dispersivities. Figure 36 shows the effects of different α_t values at a specific time (365 days).

Comparison of Simulated Dispersion Values With Measured Values

In all but very short simulation time periods, the predicted NO_3^- concentrations in the profile greatly exceeded the measured values of NO_3^-. Comparison of the measured NO_3^- concentrations with a series of simulated concentration profiles is presented in Figure 37. Comparison was made between the measured NO_3^- values obtained from the September 30, 1993, sampling of the nest of mini-piezometers located at 29CCC5 and a series of simulated concentration profiles from the VS2DT model. The simulated profiles from the VS2DT model were created, using dispersivity values of 0.1, 1, 10, and 100 feet and times since the start of the simulation of 8 years.

Mixing through hydrodynamic dispersion caused NO_3^- to approach a uniform concentration throughout the saturated thickness of an aquifer. The comparison of the measured and simulated NO_3^- concentrations indicated that if dispersion were

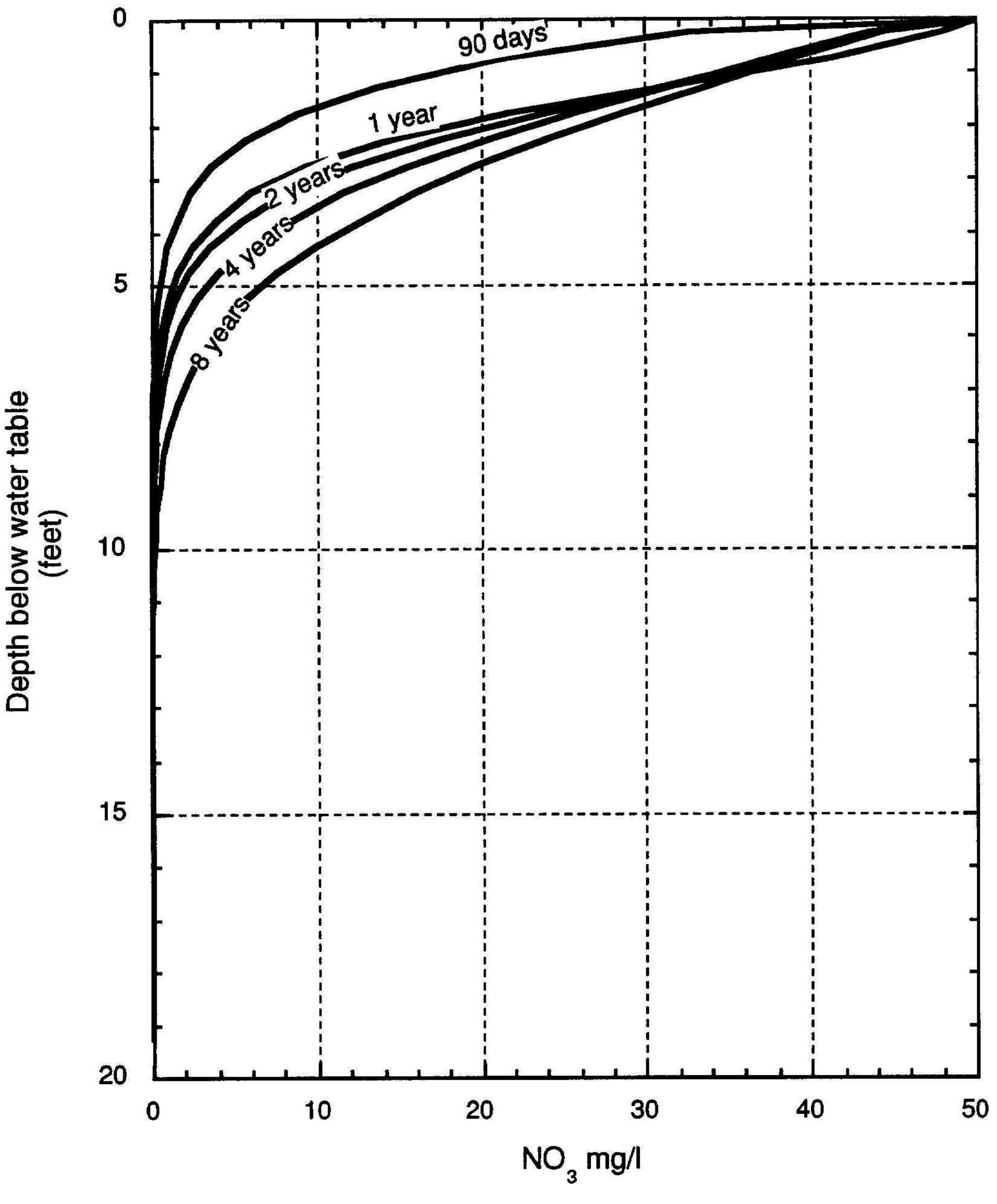

Figure 32. Effects of dispersion from the VS2DT contaminant transport model. Transverse dispersivity value used for simulation = 0.1 feet.

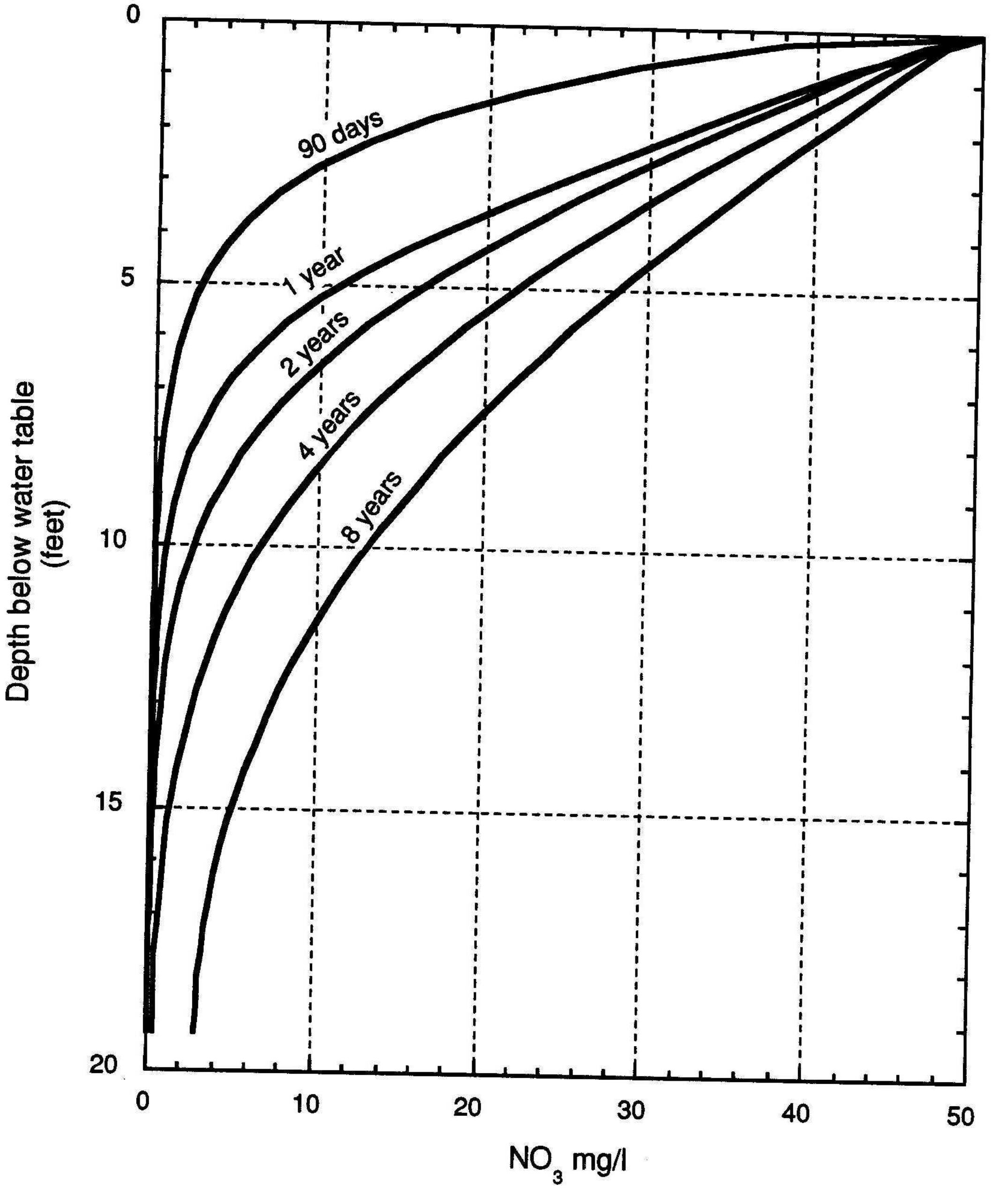

Figure 33. Effects of dispersion from the VS2DT contaminant transport model. Transverse dispersivity value used for simulation = 1 foot.

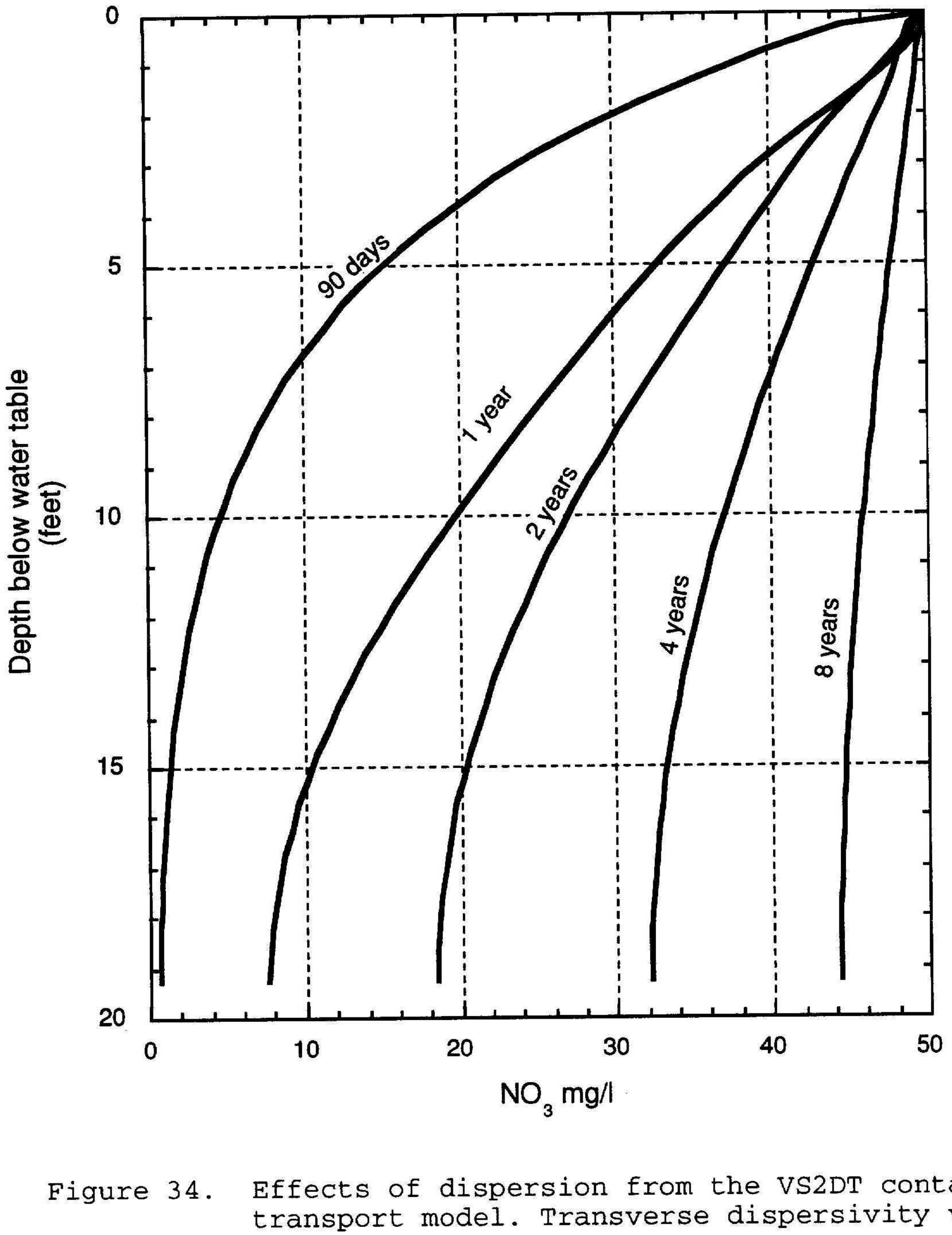

Figure 34. Effects of dispersion from the VS2DT contaminant transport model. Transverse dispersivity value used for simulation = 10 feet.

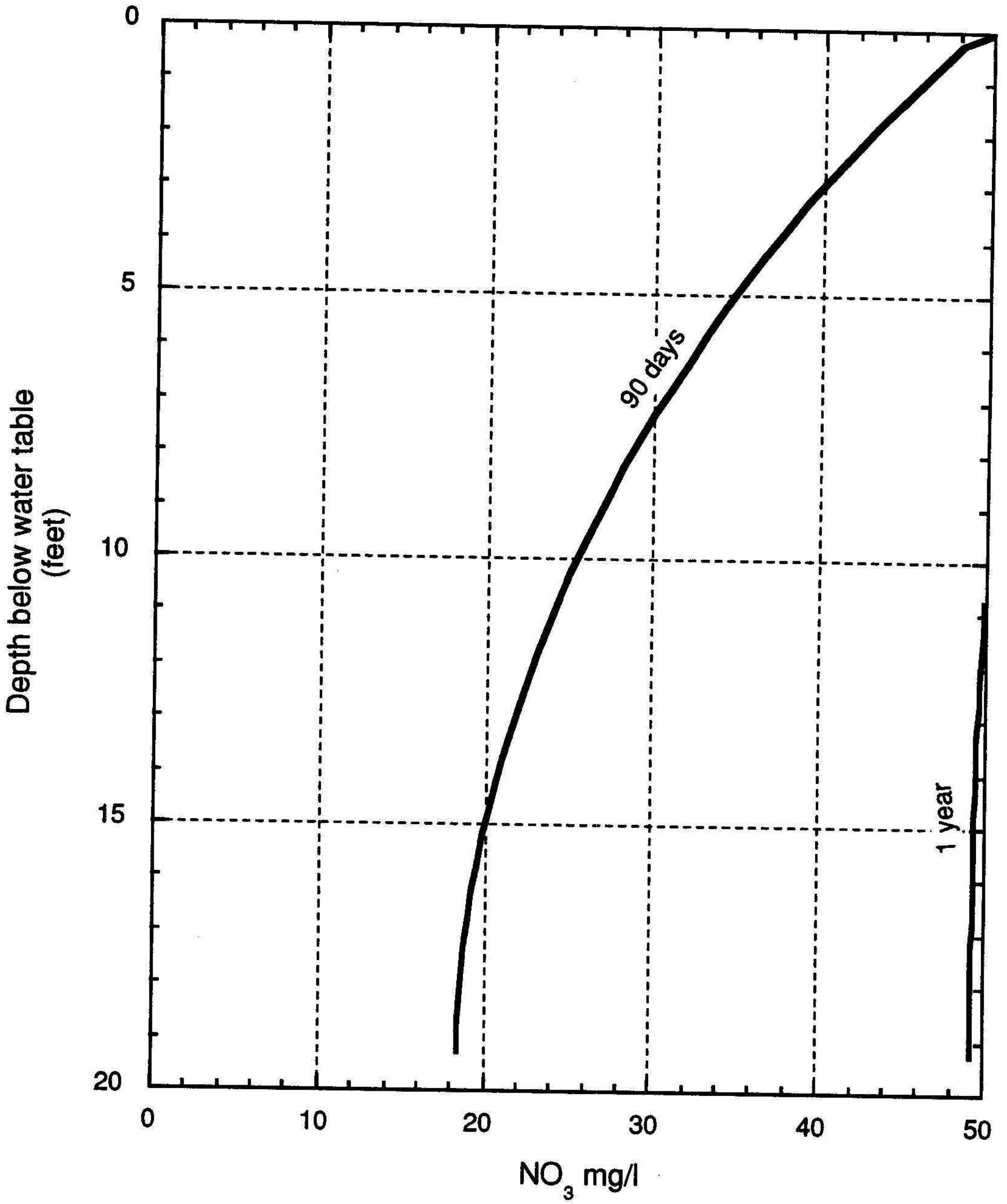

Figure 35. Effects of dispersion from the VS2DT contaminant transport model. Transverse dispersivity value used for simulation = 100 feet.

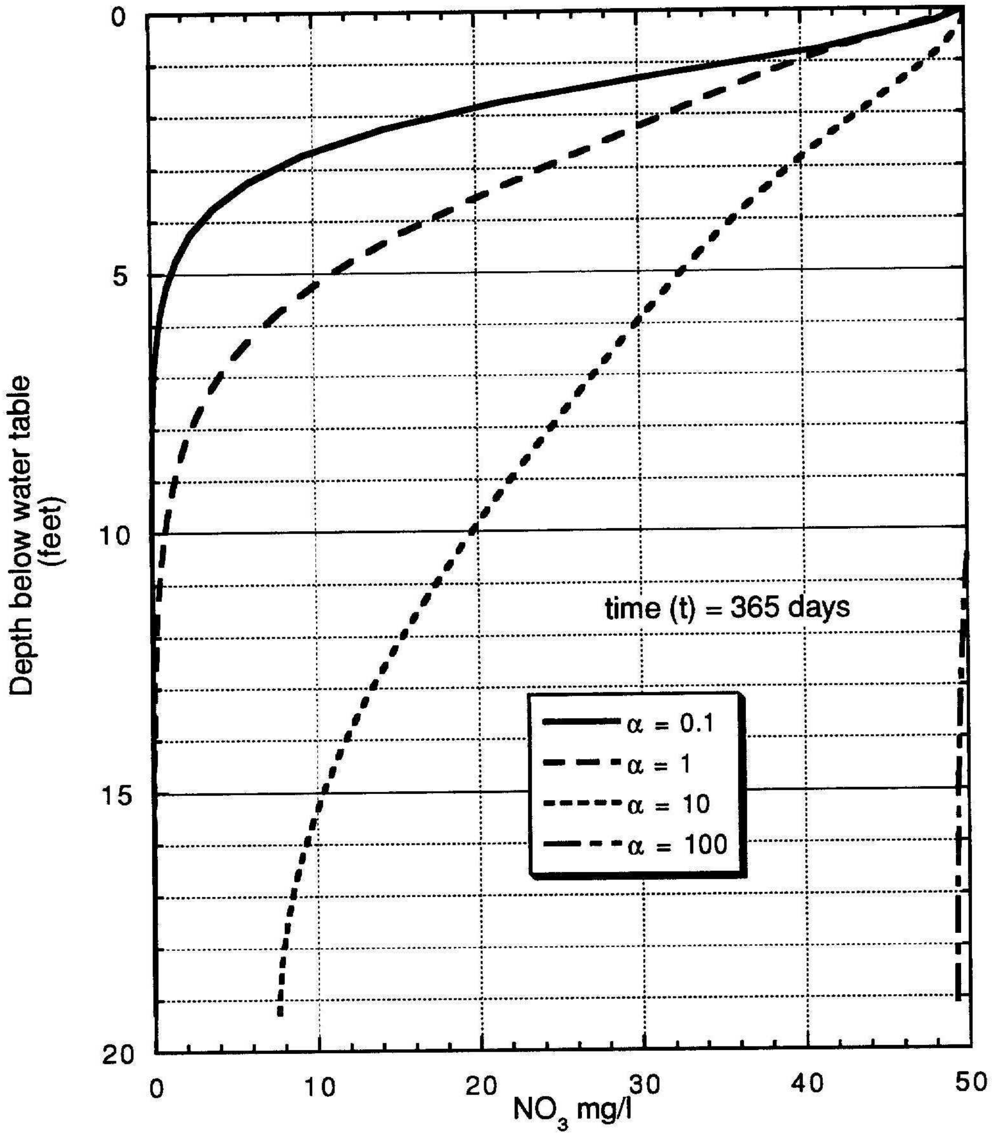

Figure 36. Comparison of dispersivity values of 0.1, 1, 10, and 100 feet used in the VS2DT contaminant transport model.

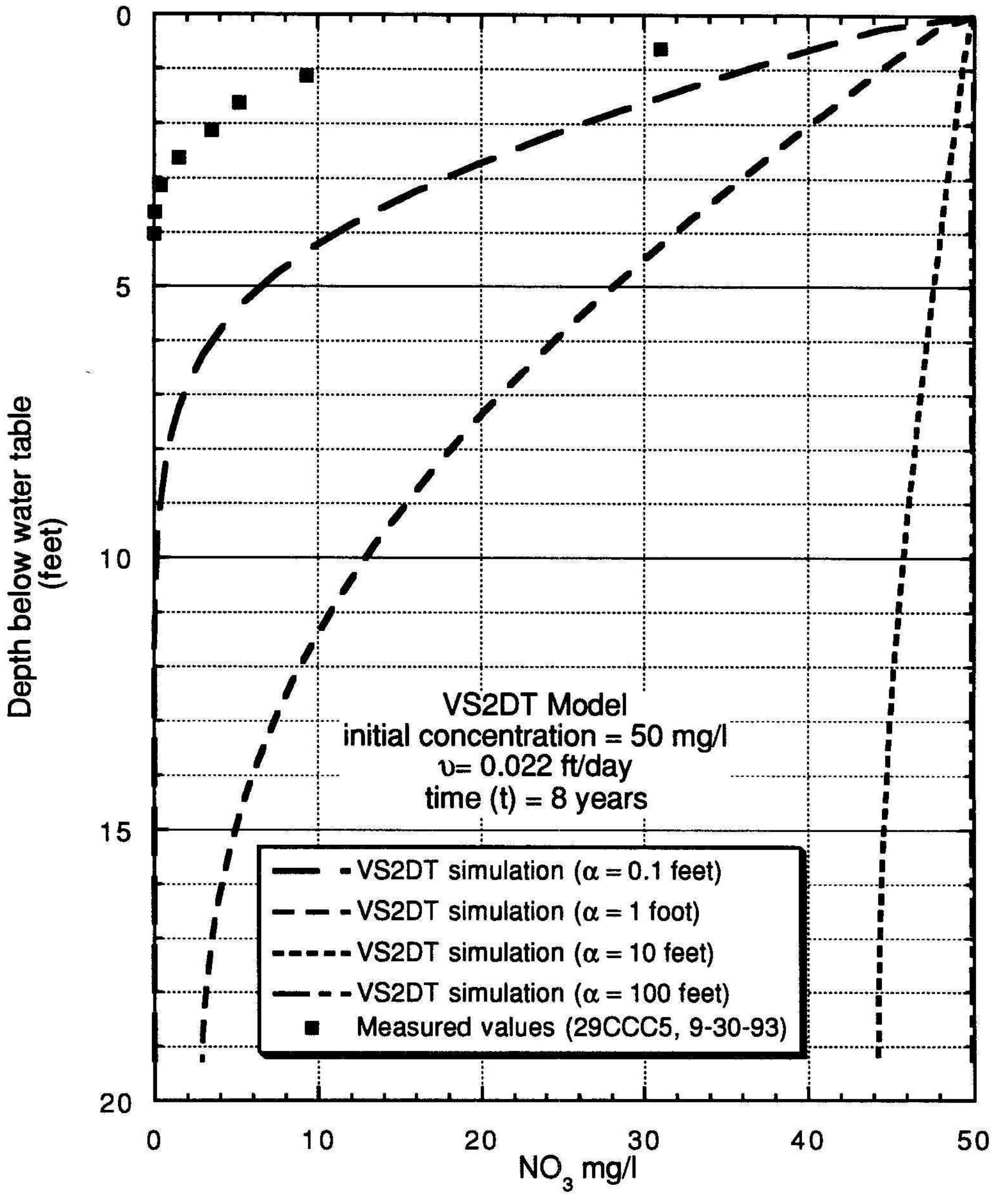

Figure 37. Comparison of measured nitrate concentrations with the simulated nitrate concentrations from the VS2DT model.

the only mechanism affecting the vertical profile distribution in the aquifer, larger concentrations of NO_3^- than were measured should be present at depth.

Denitrification

As high-nitrate aquifer-recharge waters escape the root zone and migrate downward, the NO_3^- is stable because of the abundant O_2 in the unsaturated zone. As this water reaches the water table, oxygen supplies become limited. Resulting oxygen deficits facilitate the use of other e^- acceptors in the oxidation of organic carbon (OC). NO_3^- is the next e^- acceptor preferred in the absence of O_2 to oxidize OC through heterotrophic denitrification. This mechanism explains why NO_3^- is often found in much greater concentrations near the saturated surface than at depth in the aquifer.

Denitrification is a NO_3^- sink. Once it occurs, the only way for NO_3^- levels to increase is by replenishment of high NO_3^- water moving down from the surface. During the sample collection phase of this study, the wells were sampled on nine different dates. In all cases, the mini-piezometer sampling showed that NO_3^- concentration decreased with depth.

Denitrification was confirmed at the study site through isotopic analysis. Samples collected and analyzed for ^{15}N show increasing $\delta^{15}N$ with decreasing NO_3^- concentration. Only two ^{15}N analyses from the mini-piezometer nest located at 29CCC4 were obtained; nevertheless, the $\delta^{15}N$ increased as the NO_3^- decreased (Figure 38). Five ^{15}N analyses were obtained from the eight mini-piezometers in the nest at 29CCC5. Except for one outlier, these also have increasing $\delta^{15}N$ with decreasing NO_3^- (Figure 39).

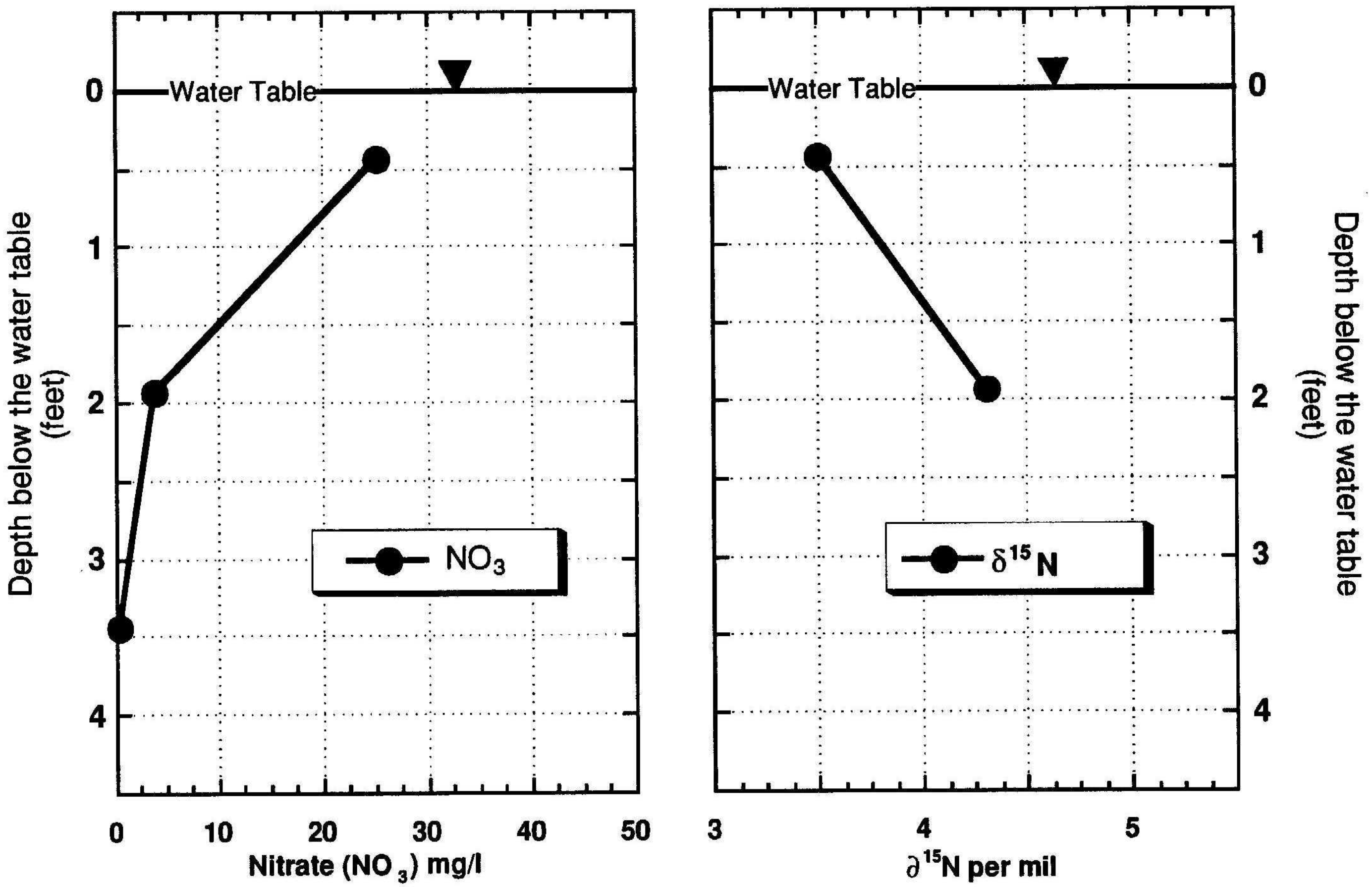

Figure 38. Graph of nitrate and 15N samples with depth below water table. Samples collected on September 30, 1993, from well 29CCC4.

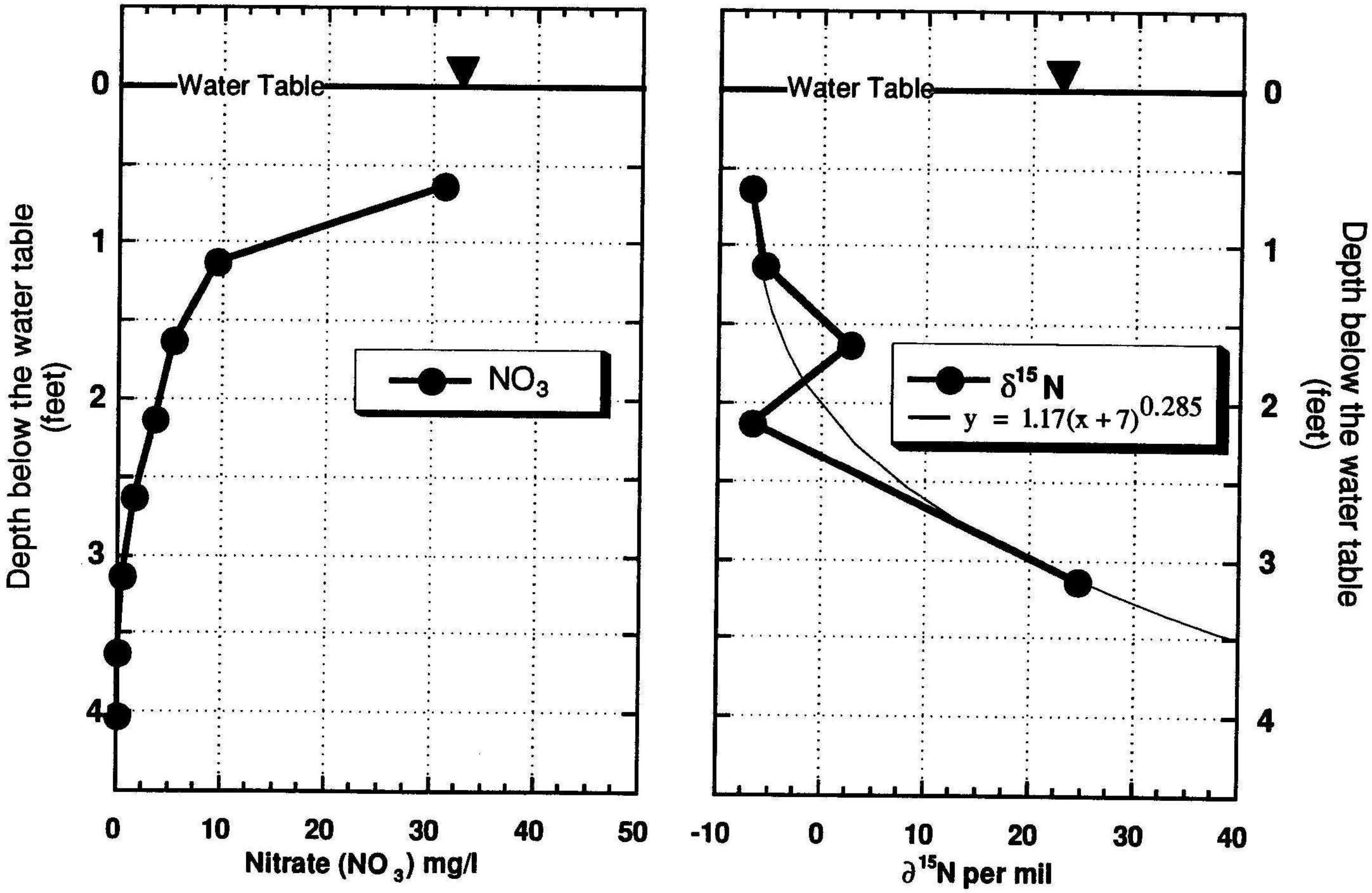

Figure 39. Graph of nitrate and 15N samples with depth below water table. Samples collected on September 30, 1993, from well 29CCC5.

CONCLUSIONS

The objectives of this study were to

1. Investigate methods of sampling of vertical nitrate gradients, and
2. Determine the cause of vertical nitrate gradients in a shallow unconfined aquifer.

These objectives were met.

Three methods of sampling were compared: bailing from 2-inch diameter or larger well nests, collection from a single-well multi-level sampling device (Oly-probe), and collection from mini-piezometer nests. Bailing from the 2-inch or larger wells provided initial indication of the existence of a vertical NO_3^- gradient, however, because of the large screen lengths of these wells, detailed information on the NO_3^- stratification is not possible.

The Oly-probe method and mini-piezometer methods of sample collection provided information on small vertically discrete intervals; however, these methods have advantages and disadvantages. The main advantage of the mini-piezometer method is its high reliability for obtaining samples that represent the formation water. Low cost and ease of installation are also important advantages. The main disadvantage is that it is not suitable for conditions where the depth to water is more than about 25 feet because of the suction lift requirement.

The Oly-probe method's main advantage is its ability to be used in situations where the water level is lower than about 25 feet below land surface. Its disadvantages are the expense to install the wells suitable for collection and the lack of confidence that the samples collected truly represent the adjacent formation water.

Denitrification is the most likely cause for the vertical NO_3^- distribution observed at the study site. Comparison of the measured and simulated NO_3^- concentrations indicate that if dispersion were the only mechanism affecting the vertical profile distribution in the aquifer, larger concentrations of NO_3^- than were measured should be present at depth. Denitrification also was confirmed at the study site through isotopic analysis. Samples collected and analyzed for ^{15}N show increasing $\delta^{15}N$ with decreasing NO_3^- concentration.

Future work

A natural process, denitrification, removes potentially hazardous NO_3^- from the ground water system given the right conditions. Further study in the area of aquifer denitrification can lead to a better understanding of this process.

Future work in the area of measurement of aquifer denitrification rates may lead to the development of a *denitrifying capacity index* for aquifers. Classification of an aquifer's *susceptibility* to nitrate contamination of drinking water supplies may help to identify risky areas for surface application of nitrogen or placement of septic systems. An index may give insight on the number of pounds per acre of nitrogen that could escape the root zone to the ground water system without risk of contaminating a drinking water supply. An *index* could account for the necessary ingredients for denitrification and apply them in a quantitative manner. Measurement of the key ingredients for denitrification to occur (facultative anaerobes, electron donors, and restricted O_2) may be enough data on which to base the creation of such an index. Other relationships, such as the C/N (carbon-nitrogen) ratio, may indicate the capacity of the aquifer to denitrify.

Exploitation of an aquifer's natural denitrification ability might be increased by adding e^- donor amendments to encourage in situ denitrification. Likewise, injection of high NO_3^- water into an organic-compound contaminated ground water system as an e^- acceptor amendment might increase the in situ biological degradation of these wastes.

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APPENDIXES

Appendix I. Water Quality Data.

List of Abbreviations

SI	Screened interval of well in feet below land surface
SiO2	Silica in milligrams per liter
Fe	Iron in milligrams per liter
Mn	Manganese in milligrams per liter
Ca	Calcium in milligrams per liter
Mg	Magnesium in milligrams per liter
Na	Sodium in milligrams per liter
K	Potassium in milligrams per liter
HCO3	Bicarbonate in milligrams per liter
CO3	Carbonate in milligrams per liter
SO4	Sulfate in milligrams per liter
Cl	Chloride in milligrams per liter
F	Fluoride in milligrams per liter
NO3	Nitrate in milligrams per liter
B	Boron in milligrams per liter
TDS	Total dissolved solids in milligrams per liter
CaCO3	Calcium Carbonate Hardness in milligrams per liter
NCH	Non-carbonate hardness in milligrams per liter
PerNa	Percent sodium
SAR	Sodium adsorption ratio
Cond	Electrical Conductivity in millimhos per centimeter
Temp	Temperature in degrees Celsius

Table 5. Water quality data for wells located at the study site.

Location	SI	Date	SiO2	Fe	Mn	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl	F	NO3	B	TDS	CaCO3	NCH	PerNa	SAR	Cond	Temp	pH
154-055-29CCC	35-40	6/13/90	26	0	0.8	92	24	39	4.2	363	0	120	8.2	0.2	1	0.1	494	330	31	20	0.9	780	8	
154-055-29CCC	35-40	3/19/92													0									
154-055-29CCC	35-40	7/9/92													1									
154-055-29CCC	35-40	8/25/92													0.2									
154-055-29CCC	35-40	9/24/92													1.2									
154-055-29CCC	35-40	10/28/92													0.8									
154-055-29CCC	35-40	4/15/93													0.4									
154-055-29CCC	35-40	5/25/93													0.4									
154-055-29CCC	35-40	9/30/93	27	0.6	0.7	100	28	43	5.9	432	0	120	9.5	0.2	0	0.1	548	360	11	20	1	1074	7.6	7.3
154-055-29CCC2	4-14	6/13/90	26	0	0	75	24	22	1.9	348	0	47	3.9	0.1	22	0.1	393	290	1	14	0.6	653	7	
154-055-29CCC2	4-14	11/8/90	33	0	0	78	24	25	2.3	337	0	56	3.1	0.1	23	0.1	411	290	17	16	0.6	673	7	
154-055-29CCC2	4-14	12/11/91													12									
154-055-29CCC2	4-14	3/19/92													1.9									
154-055-29CCC2	4-14	7/9/92													11									
154-055-29CCC2	4-14	8/23/92													1.9									
154-055-29CCC2	4-14	9/24/92													7.9									
154-055-29CCC2	4-14	10/28/92													6.1									
154-055-29CCC2	4-14	4/15/93													20									
154-055-29CCC2	4-14	5/25/93													21									
154-055-29CCC2	4-14	9/30/93	29	0.4	0.1	83	28	34	4.6	402	0	56	4	0.1	13	0.1	450	320	0	18	0.8	875	9.5	7.4
154-055-29CCC3	4-14	9/30/93													13									
154-055-29CCC3 1	0-0.5 BWT	3/19/92													17									
154-055-29CCC3 1	0-0.5 BWT	5/6/92													35									
154-055-29CCC3 1	0-0.5 BWT	7/9/92													24									
154-055-29CCC3 1	0-0.5 BWT	8/25/92													3.5									
154-055-29CCC3 1	0-0.5 BWT	9/24/92													0									
154-055-29CCC3 1	0-0.5 BWT	10/28/92													0.8									
154-055-29CCC3 1	0-0.5 BWT	4/15/93													0									
154-055-29CCC3 1	0-0.5 BWT	5/25/93													0									
154-055-29CCC3 1	0-0.5 BWT	9/30/93													21									
154-055-29CCC3 2	0.5-1 BWT	3/19/92													24									
154-055-29CCC3 2	0.5-1 BWT	5/6/92													29									
154-055-29CCC3 2	0.5-1 BWT	7/9/92													20									

(continued)

Table 5. (continued)

Location	SI	Date	SiO2	Fe	Mn	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl	F	NO3	B	TDS	CaCO3	NCH	PerNa	SAR	Cond	Temp	pH
154-055-29CCC3 2	0.5-1 BWT	8/25/92													3.3									
154-055-29CCC3 2	0.5-1 BWT	9/24/92													14									
154-055-29CCC3 2	0.5-1 BWT	10/28/92													16									
154-055-29CCC3 2	0.5-1 BWT	4/15/93													12									
154-055-29CCC3 2	0.5-1 BWT	5/25/93													15									
154-055-29CCC3 3	1-1.5 BWT	3/19/92													20									
154-055-29CCC3 3	1-1.5 BWT	5/6/92													25									
154-055-29CCC3 3	1-1.5 BWT	7/9/92													22									
154-055-29CCC3 3	1-1.5 BWT	8/25/92													3.4									
154-055-29CCC3 3	1-1.5 BWT	9/24/92													13									
154-055-29CCC3 3	1-1.5 BWT	10/28/92													15									
154-055-29CCC3 3	1-1.5 BWT	4/15/93													5.4									
154-055-29CCC3 3	1-1.5 BWT	5/25/93													3.6									
154-055-29CCC3 3	1-1.5 BWT	9/30/93													18									
154-055-29CCC3 4	1.5-2 BWT	3/19/92													17									
154-055-29CCC3 4	1.5-2 BWT	5/6/92													25									
154-055-29CCC3 4	1.5-2 BWT	7/9/92													21									
154-055-29CCC3 4	1.5-2 BWT	8/25/92													3.5									
154-055-29CCC3 4	1.5-2 BWT	9/24/92													13									
154-055-29CCC3 4	1.5-2 BWT	10/28/92													13									
154-055-29CCC3 4	1.5-2 BWT	4/15/93													6.2									
154-055-29CCC3 4	1.5-2 BWT	5/25/93													6.5									
154-055-29CCC3 4	1.5-2 BWT	9/30/93													17									
154-055-29CCC3 5	2-2.5 BWT	3/19/92													24									
154-055-29CCC3 5	2-2.5 BWT	5/6/92													25									
154-055-29CCC3 5	2-2.5 BWT	7/9/92													22									
154-055-29CCC3 5	2-2.5 BWT	9/24/92													13									
154-055-29CCC3 5	2-2.5 BWT	10/28/92													13									
154-055-29CCC3 5	2-2.5 BWT	4/15/93													7.3									
154-055-29CCC3 5	2-2.5 BWT	5/25/93													9.7									
154-055-29CCC3 5	2-2.5 BWT	9/30/93													15									
154-055-29CCC3 6	2.5-3 BWT	3/19/92													22									
154-055-29CCC3 6	2.5-3 BWT	5/6/92													24									

(continued)

Table 5. (continued)

Location	SI	Date	SiO2	Fe	Mn	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl	F	NO3	B	TDS	CaCO3	NCH	PerNa	SAR	Cond	Temp	pH
154-055-29CCC3 6	2.5-3 BWT	7/9/92													20									
154-055-29CCC3 6	2.5-3 BWT	8/25/92													3.3									
154-055-29CCC3 6	2.5-3 BWT	9/24/92													11									
154-055-29CCC3 6	2.5-3 BWT	10/28/92													12									
154-055-29CCC3 6	2.5-3 BWT	4/15/93													8.4									
154-055-29CCC3 6	2.5-3 BWT	5/25/93													9.7									
154-055-29CCC3 6	2.5-3 BWT	9/30/93													10									
154-055-29CCC3 7	3-3.5 BWT	3/19/92													3.5									
154-055-29CCC3 7	3-3.5 BWT	5/6/92													23									
154-055-29CCC3 7	3-3.5 BWT	7/9/92													19									
154-055-29CCC3 7	3-3.5 BWT	8/25/92													1.7									
154-055-29CCC3 7	3-3.5 BWT	9/24/92													3.6									
154-055-29CCC3 7	3-3.5 BWT	10/28/92													6.1									
154-055-29CCC3 7	3-3.5 BWT	4/15/93													12									
154-055-29CCC3 7	3-3.5 BWT	5/25/93													12									
154-055-29CCC3 7	3-3.5 BWT	9/30/93													3.2									
154-055-29CCC3 8	3.5-4 BWT	3/19/92													1.7									
154-055-29CCC3 8	3.5-4 BWT	5/6/92													3.6									
154-055-29CCC3 8	3.5-4 BWT	7/9/92													3.1									
154-055-29CCC3 8	3.5-4 BWT	8/25/92													0.3									
154-055-29CCC3 8	3.5-4 BWT	9/24/92													2.3									
154-055-29CCC3 8	3.5-4 BWT	10/28/92													2.2									
154-055-29CCC3 8	3.5-4 BWT	4/15/93													4.5									
154-055-29CCC3 8	3.5-4 BWT	5/25/93													4									
154-055-29CCC3 8	3.5-4 BWT	9/30/93													2.7									
154-055-29CCC4 1	12-12.2	7/9/92													11									
154-055-29CCC4 1	12-12.2	8/25/92													3.2									
154-055-29CCC4 1	12-12.2	9/24/92													15									
154-055-29CCC4 1	12-12.2	10/28/92													15									
154-055-29CCC4 1	12-12.2	4/15/93													8									
154-055-29CCC4 1	12-12.2	9/30/93													25									
154-055-29CCC4 2	13.5-13.7	7/9/92													4.3									
154-055-29CCC4 2	13.5-13.7	8/25/92													0.6									

(continued)

Table 5. (continued)

Location	SI	Date	SiO2	Fe	Mn	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl	F	NO3	B	TDS	CaCO3	NCH	PerNa	SAR	Cond	Temp	pH
154-055-29CCC4 2	13.5-13.7	9/24/92													2.1									
154-055-29CCC4 2	13.5-13.7	10/28/92													2									
154-055-29CCC4 2	13.5-13.7	4/15/93													16									
154-055-29CCC4 2	13.5-13.7	5/25/93													8.6									
154-055-29CCC4 2	13.5-13.7	9/30/93													3.8									
154-055-29CCC4 3	15-15.2	7/9/92													1.8									
154-055-29CCC4 3	15-15.2	8/25/92													0.4									
154-055-29CCC4 3	15-15.2	9/24/92													1									
154-055-29CCC4 3	15-15.2	10/28/92													0									
154-055-29CCC4 3	15-15.2	4/15/93													4.6									
154-055-29CCC4 3	15-15.2	5/25/93													5.7									
154-055-29CCC4 3	15-15.2	9/30/93													0.2									
154-055-29CCC5 1	12.2-12.4	9/30/93													31									
154-055-29CCC5 2	12.7-12.9	5/25/93													6.9									
154-055-29CCC5 2	12.7-12.9	9/30/93													9.3									
154-055-29CCC5 3	13.2-13.4	5/25/93													7									
154-055-29CCC5 3	13.2-13.4	9/30/93													5.2								11	7.5
154-055-29CCC5 4	13.7-13.9	5/25/93													5.8									
154-055-29CCC5 4	13.7-13.9	9/30/93													3.5									
154-055-29CCC5 5	14.2-14.4	5/25/93													1.8									
154-055-29CCC5 5	14.2-14.4	9/30/93													1.5									
154-055-29CCC5 6	14.7-14.9	5/25/93													0.1									
154-055-29CCC5 6	14.7-14.9	9/30/93													0.4									
154-055-29CCC5 7	15.2-15.4	5/25/93													1									
154-055-29CCC5 7	15.2-15.4	9/30/93													0									
154-055-29CCC5 8	15.7-15.9	5/25/93													0									
154-055-29CCC5 8	15.7-15.9	9/30/93													0									

* BWT = BELOW WATER TABLE

Table 6. N-15 data obtained from samples collected at the study site.

Sample	Nitrate concentration (mg/l)	Delta N-15 (per mil)
29CCC2	8.95	110.5
29CCC4-1	22.60	3.5
29CCC4-2	2.02	4.3
29CCC4-3	0.00	ND*
29CCC5-1	8.36	-6.9
29CCC5-2	1.20	-5.7
29CCC5-3	4.86	2.6
29CCC5-4	1.69	-6.8
29CCC5-5	0.00	ND*
29CCC5-6	0.06	24.6

* Not determined.

Appendix II. Water Level Data.

154-055-29CCC
Elk Valley Aquifer

LS Elev (msl,ft)=1146.06
SI (ft.)=35-40

Date	Depth to Water (ft)	WL Elev (msl, ft)
06/28/90	10.79	1135.27
08/23/90	10.95	1135.11
09/17/90	11.11	1134.95
10/18/90	11.33	1134.73
11/15/90	11.55	1134.51
12/05/90	11.49	1134.57
03/28/91	11.81	1134.25
04/24/91	11.97	1134.09
05/21/91	11.88	1134.18
06/19/91	11.88	1134.18
07/16/91	11.48	1134.58
08/20/91	11.49	1134.57
09/25/91	11.52	1134.54
10/23/91	11.48	1134.58
11/25/91	11.45	1134.61
12/17/91	11.41	1134.65
04/17/92	11.55	1134.51
05/22/92	11.77	1134.29
06/17/92	11.91	1134.15
07/22/92	11.67	1134.39
08/25/92	11.93	1134.13
09/22/92	12.14	1133.92
10/21/92	12.19	1133.87
10/28/92	12.27	1133.79
11/24/92	12.26	1133.80
01/26/93	12.37	1133.69
04/27/93	12.42	1133.64
05/25/93	12.48	1133.58
06/22/93	12.70	1133.36
07/21/93	12.52	1133.54
08/24/93	11.82	1134.24
09/23/93	11.67	1134.39
10/27/93	11.68	1134.38
11/24/93	11.77	1134.29

Appendix III. Input files for VS2DT model simulation.

Table 7.   Input file for VS2DT Simulation 1.

```
VS2DT Simulation 1        α = 0.1 feet
2920. 0.  0.                     A2--TMAX,STIM,ANG
FEETDAYSMG                       A3--ZUNIT,TUNIT,CUNX
5 42                             A4--NXR,NLY
2 1000                           A5--NRECH,NUMT
F T T                            A6--RAD,ITSTOP,TRANS
T T F                            A6A--CIS,CIT,SORP
F T T T F                        A7--F11P,F7P,F8P,F9P,F6P
F F T F T                        A8--THPT,SPNT,PPNT,HPNT,VPNT
1 3000.                          A9--IFAC,FACX
1 0.5                            A11--JFAC,FACZ
3                                A13--NPLT
50 100 200                       A14--PLTIM
6                                A17--NMB9
31 33 40 42 70 72                A18--MB9
.0005 .90  0.00 0.00001          B1--EPS,HMAX,WUS,EPS1
2   199                          B3--MINIT,ITMAX
T                                B4--PHRD
1 6 6                            B5--NTEX,NPROP,NPROP1
1                                B6--ITEX
1. 100. .004 .45 -0.1 .40 2.75   B7--ANIZ,HK
0.1 0.1 0.00000003 0. 0. 0.      B7A--HT
1                                B8--IROW
1 12 42 1                        B10--IL,IR,JBT,JRD
0 90.                            B11--IREAD,FACTOR   *** 12 '(12f5.0)'
F F                              B14--BCIT,ETSIM
0 0.0                            B24--IREAD,FACTOR   ***13 '(12f4.0)'
100. 10.                         C1--TPER,DELT
1.0 10. 10. 0.1                  C2--TMLT,DLTMX,DLTMIN,TRED
100. 0.                          C3--DSMAX,STERR
0.                               C4--POND
T                                C5--PRNT
F F F                            C6--BCIT,ETSIM,SEEP
1                                C10--IBC
2 2 3 3 4 90. 1 50.              C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
2 41 2 2 4 90.3 0 0.0            C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
2 41 4 4 4 89.7 0 0.0            C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
999999 /                         C13
999999 /                         C13
```

Table 8. Input file for VS2DT Simulation 2.

```
VS2DT Simulation 2        α = 1 foot
2920. 0.  0.                                A2--TMAX,STIM,ANG
FEETDAYSMG                                  A3--ZUNIT,TUNIT,CUNX
5 42                                        A4--NXR,NLY
2 1000                                      A5--NRECH,NUMT
F T T                                       A6--RAD,ITSTOP,TRANS
T T F                                       A6A--CIS,CIT,SORP
F T T T F                                   A7--F11P,F7P,F8P,F9P,F6P
F F T F T                                   A8--THPT,SPNT,PPNT,HPNT,VPNT
1 3000.                                     A9--IFAC,FACX
1 0.5                                       A11--JFAC,FACZ
3                                           A13--NPLT
50 100 200                                  A14--PLTIM
6                                           A17--NMB9
31 33 40 42 70 72                           A18--MB9
.0005 .90  0.00 0.00001                     B1--EPS,HMAX,WUS,EPS1
2   199                                     B3--MINIT,ITMAX
T                                           B4--PHRD
1 6 6                                       B5--NTEX,NPROP,NPROP1
1                                           B6--ITEX
1. 100. .004 .45 -1. .40 2.75               B7--ANIZ,HK
1. 1. 0.00000003 0. 0. 0.                   B7A--HT
1                                           B8--IROW
1 12 42 1                                   B10--IL,IR,JBT,JRD
0 90.                                       B11--IREAD,FACTOR  *** 12 '(12f5.0)'
F F                                         B14--BCIT,ETSIM
0 0.0                                       B24--IREAD,FACTOR  ***13 '(12f4.0)'
100. 10.                                    C1--TPER,DELT
1.0 10. 10. 0.1                             C2--TMLT,DLTMX,DLTMIN,TRED
100. 0.                                     C3--DSMAX,STERR
0.                                          C4--POND
T                                           C5--PRNT
F F F                                       C6--BCIT,ETSIM,SEEP
1                                           C10--IBC
2 2 3 3 4 90. 1 50.                         C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
2 41 2 2 4 90.3 0 0.0                       C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
2 41 4 4 4 89.7 0 0.0                       C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
999999 /                                    C13
999999 /                                    C13
```

Table 9.   Input file for VS2DT Simulation 3.

```
VS2DT Simulation 3          α = 10 feet
2920. 0.  0.                         A2--TMAX,STIM,ANG
FEETDAYSMG                           A3--ZUNIT,TUNIT,CUNX
5 42                                 A4--NXR,NLY
2 1000                               A5--NRECH,NUMT
F T T                                A6--RAD,ITSTOP,TRANS
T T F                                A6A--CIS,CIT,SORP
F T T T F                            A7--F11P,F7P,F8P,F9P,F6P
F F T F T                            A8--THPT,SPNT,PPNT,HPNT,VPNT
1 3000.                              A9--IFAC,FACX
1 0.5                                A11--JFAC,FACZ
3                                    A13--NPLT
50 100 200                           A14--PLTIM
6                                    A17--NMB9
31 33 40 42 70 72                    A18--MB9
.0005 .90  0.00 0.00001              B1--EPS,HMAX,WUS,EPS1
2   199                              B3--MINIT,ITMAX
T                                    B4--PHRD
1 6 6                                B5--NTEX,NPROP,NPROP1
1                                    B6--ITEX
1. 100. .004 .45 -10. .40 2.75       B7--ANIZ,HK
10. 10. 0.00000003 0. 0. 0.          B7A--HT
1                                    B8--IROW
1 12 42 1                            B10--IL,IR,JBT,JRD
0 90.                                B11--IREAD,FACTOR   *** 12 '(12f5.0)'
F F                                  B14--BCIT,ETSIM
0 0.0                                B24--IREAD,FACTOR   ***13 '(12f4.0)'
100. 10.                             C1--TPER,DELT
1.0 10. 10. 0.1                      C2--TMLT,DLTMX,DLTMIN,TRED
100. 0.                              C3--DSMAX,STERR
0.                                   C4--POND
T                                    C5--PRNT
F F F                                C6--BCIT,ETSIM,SEEP
1                                    C10--IBC
2 2 3 3 4 90. 1 50.                  C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
2 41 2 2 4 90.3 0 0.0                C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
2 41 4 4 4 89.7 0 0.0                C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
999999 /                             C13
999999 /                             C13
```

Table 10. Input file for VS2DT Simulation 4.

```
VS2DT Simulation 4      α = 100 feet
2920. 0.  0.                       A2--TMAX,STIM,ANG
FEETDAYSMG                         A3--ZUNIT,TUNIT,CUNX
5 42                               A4--NXR,NLY
2 1000                             A5--NRECH,NUMT
F T T                              A6--RAD,ITSTOP,TRANS
T T F                              A6A--CIS,CIT,SORP
F T T T F                          A7--F11P,F7P,F8P,F9P,F6P
F F T F T                          A8--THPT,SPNT,PPNT,HPNT,VPNT
1 3000.                            A9--IFAC,FACX
1 0.5                              A11--JFAC,FACZ
3                                  A13--NPLT
50 100 200                         A14--PLTIM
6                                  A17--NMB9
31 33 40 42 70 72                  A18--MB9
.0005 .90  0.00 0.00001            B1--EPS,HMAX,WUS,EPS1
2   199                            B3--MINIT,ITMAX
T                                  B4--PHRD
1 6 6                              B5--NTEX,NPROP,NPROP1
1                                  B6--ITEX
1. 100. .004 .45 -100. .40 2.75    B7--ANIZ,HK
100. 100. 0.00000003 0. 0. 0.      B7A--HT
1                                  B8--IROW
1 12 42 1                          B10--IL,IR,JBT,JRD
0 90.                              B11--IREAD,FACTOR  *** 12 '(12f5.0)'
F F                                B14--BCIT,ETSIM
0 0.0                              B24--IREAD,FACTOR  ***13 '(12f4.0)'
100. 10.                           C1--TPER,DELT
1.0 10. 10. 0.1                    C2--TMLT,DLTMX,DLTMIN,TRED
100. 0.                            C3--DSMAX,STERR
0.                                 C4--POND
T                                  C5--PRNT
F F F                              C6--BCIT,ETSIM,SEEP
1                                  C10--IBC
2 2 3 3 4 90. 1 50.                C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
2 41 2 2 4 90.3 0 0.0              C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
2 41 4 4 4 89.7 0 0.0              C12--JJT,JJB,NNL,NNR,NTX,PFDUM,NTC,CF
999999 /                           C13
999999 /                           C13
```

Appendix IV. Output from VS2DT model simulations.

Table 11. Output from VS2DT Simulation 1, α_t = 0.1 feet.

Depth below water table (feet)	90 days	180 days	365 days	730 days	1460 days	2920 days
0	50.00	50.00	50.00	50.00	50.00	50.00
0.25	32.60	59.60	48.10	44.40	43.80	44.40
0.75	21.10	43.10	41.30	38.10	37.60	38.90
1.25	13.70	28.70	31.20	31.10	31.50	33.70
1.75	8.85	18.70	21.60	23.90	25.70	28.60
2.25	5.71	12.10	14.40	17.40	20.40	24.00
2.75	3.68	7.82	9.36	12.20	15.60	19.70
3.25	2.36	5.03	6.05	8.20	11.60	16.00
3.75	1.51	3.22	3.89	5.41	8.41	12.70
4.25	0.96	2.06	2.49	3.52	5.92	9.88
4.75	0.61	1.31	1.59	2.27	4.07	7.56
5.25	0.39	0.83	1.01	1.46	2.74	5.68
5.75	0.24	0.52	0.64	0.93	1.82	4.19
6.25	0.15	0.33	0.40	0.59	1.19	3.04
6.75	0.09	0.20	0.25	0.37	0.77	2.16
7.25	0.06	0.12	0.16	0.23	0.49	1.52
7.75	0.03	0.08	0.10	0.14	0.31	1.05
8.25	0.02	0.05	0.06	0.09	0.20	0.71
8.75	0.01	0.03	0.04	0.05	0.12	0.48
9.25	0.01	0.02	0.02	0.03	0.08	0.32
9.75	0.00	0.01	0.01	0.02	0.05	0.21
10.25	0.00	0.01	0.01	0.01	0.03	0.14
10.75	0.00	0.00	0.00	0.01	0.02	0.09
11.25	0.00	0.00	0.00	0.00	0.01	0.06
11.75	0.00	0.00	0.00	0.00	0.01	0.04
12.25	0.00	0.00	0.00	0.00	0.00	0.02
12.75	0.00	0.00	0.00	0.00	0.00	0.01
13.25	0.00	0.00	0.00	0.00	0.00	0.01
13.75	0.00	0.00	0.00	0.00	0.00	0.01
14.25	0.00	0.00	0.00	0.00	0.00	0.00
14.75	0.00	0.00	0.00	0.00	0.00	0.00
15.25	0.00	0.00	0.00	0.00	0.00	0.00
15.75	0.00	0.00	0.00	0.00	0.00	0.00
16.25	0.00	0.00	0.00	0.00	0.00	0.00
16.75	0.00	0.00	0.00	0.00	0.00	0.00
17.25	0.00	0.00	0.00	0.00	0.00	0.00
17.75	0.00	0.00	0.00	0.00	0.00	0.00
18.25	0.00	0.00	0.00	0.00	0.00	0.00
18.75	0.00	0.00	0.00	0.00	0.00	0.00
19.25	0.00	0.00	0.00	0.00	0.00	0.00

Table 12. Output from VS2DT Simulation 2, α_t = 1 foot.

Depth below water table (feet)	90 days	180 days	365 days	730 days	1460 days	2920 days
0	50.00	50.00	50.00	50.00	50.00	50.00
0.25	38.10	55.20	47.50	46.60	47.10	47.80
0.75	29.00	50.90	42.10	42.60	44.20	45.60
1.25	22.00	43.40	37.60	39.10	41.30	43.40
1.75	16.70	35.40	33.70	35.60	38.50	41.30
2.25	12.70	28.20	30.00	32.20	35.70	39.10
2.75	9.62	22.00	26.20	28.90	33.00	37.00
3.25	7.28	17.10	22.40	25.80	30.40	35.00
3.75	5.51	13.10	18.80	22.80	27.80	32.90
4.25	4.16	10.00	15.40	20.00	25.40	31.00
4.75	3.14	7.62	12.50	17.40	23.10	29.10
5.25	2.36	5.77	9.96	15.10	20.90	27.20
5.75	1.77	4.36	7.85	12.90	18.90	25.40
6.25	1.33	3.29	6.14	11.00	16.90	23.70
6.75	0.99	2.47	4.75	9.22	15.10	22.00
7.25	0.74	1.85	3.66	7.70	13.40	20.40
7.75	0.55	1.38	2.80	6.37	11.90	18.90
8.25	0.41	1.03	2.13	5.23	10.50	17.40
8.75	0.30	0.76	1.61	4.26	9.20	16.10
9.25	0.22	0.56	1.22	3.44	8.03	14.80
9.75	0.16	0.41	0.92	2.76	6.98	13.50
10.25	0.12	0.30	0.69	2.19	6.03	12.40
10.75	0.08	0.22	0.51	1.73	5.19	11.30
11.25	0.06	0.16	0.38	1.36	4.45	10.30
11.75	0.04	0.12	0.28	1.06	3.79	9.36
12.25	0.03	0.08	0.21	0.82	3.22	8.50
12.75	0.02	0.06	0.15	0.64	2.72	7.71
13.25	0.02	0.04	0.11	0.49	2.28	6.99
13.75	0.01	0.03	0.08	0.37	1.91	6.33
14.25	0.01	0.02	0.06	0.28	1.59	5.73
14.75	0.01	0.01	0.04	0.21	1.33	5.20
15.25	0.00	0.01	0.03	0.16	1.10	4.73
15.75	0.00	0.01	0.02	0.12	0.91	4.31
16.25	0.00	0.00	0.02	0.09	0.76	3.95
16.75	0.00	0.00	0.01	0.07	0.63	3.65
17.25	0.00	0.00	0.01	0.05	0.53	3.40
17.75	0.00	0.00	0.01	0.04	0.46	3.20
18.25	0.00	0.00	0.00	0.03	0.40	3.05
18.75	0.00	0.00	0.00	0.03	0.37	2.95
19.25	0.00	0.00	0.00	0.03	0.35	2.90

Table 13. Output from VS2DT Simulation 3, α_t = 10 feet.

Depth below water table (feet)	90 days	180 days	365 days	730 days	1460 days	2920 days
0	50.00	50.00	50.00	50.00	50.00	50.00
0.25	44.65	52.22	49.95	49.49	49.01	49.85
0.75	39.86	52.77	48.65	48.13	48.48	49.53
1.25	35.58	52.09	46.74	46.55	47.90	49.29
1.75	31.76	50.54	44.60	45.03	47.24	49.08
2.25	28.34	48.39	42.44	43.62	46.52	48.87
2.75	25.29	45.84	40.38	42.34	45.79	48.65
3.25	22.56	43.06	38.45	41.13	45.08	48.43
3.75	20.12	40.17	36.66	39.98	44.39	48.21
4.25	17.94	37.25	35.00	38.85	43.71	47.99
4.75	15.98	34.37	33.44	37.73	43.06	47.78
5.25	14.24	31.58	31.97	36.62	42.41	47.57
5.75	12.68	28.91	30.55	35.51	41.78	47.37
6.25	11.28	26.37	29.18	34.41	41.15	47.17
6.75	10.03	23.99	27.85	33.33	40.54	46.97
7.25	8.92	21.77	26.53	32.27	39.94	46.78
7.75	7.92	19.71	25.23	31.23	39.36	46.60
8.25	7.03	17.81	23.96	30.22	38.80	46.42
8.75	6.23	16.06	22.70	29.24	38.25	46.24
9.25	5.52	14.45	21.46	28.30	37.72	46.07
9.75	4.89	12.99	20.26	27.40	37.21	45.91
10.25	4.33	11.66	19.08	26.53	36.73	45.76
10.75	3.83	10.45	17.94	25.70	36.26	45.61
11.25	3.38	9.36	16.85	24.91	35.81	45.46
11.75	2.98	8.38	15.80	24.16	35.39	45.33
12.25	2.63	7.49	14.80	23.45	34.99	45.20
12.75	2.32	6.70	13.86	22.79	34.61	45.08
13.25	2.05	5.99	12.98	22.16	34.26	44.97
13.75	1.81	5.37	12.16	21.58	33.94	44.86
14.25	1.60	4.81	11.41	21.05	33.63	44.77
14.75	1.41	4.32	10.72	20.56	33.36	44.68
15.25	1.25	3.90	10.10	20.12	33.11	44.60
15.75	1.11	3.53	9.54	19.72	32.89	44.53
16.25	1.00	3.21	9.06	19.37	32.69	44.47
16.75	0.90	2.95	8.64	19.08	32.52	44.41
17.25	0.82	2.74	8.29	18.82	32.38	44.37
17.75	0.76	2.57	8.02	18.62	32.27	44.33
18.25	0.72	2.44	7.81	18.47	32.18	44.30
18.75	0.69	2.36	7.67	18.37	32.13	44.29
19.25	0.67	2.32	7.60	18.32	32.10	44.28

Table 14. Output from VS2DT Simulation 4, α_t = 100 feet.

Depth below water table (feet)	90 days	180 days	365 days	730 days	1460 days	2920 days
0	50.00	50.00	50.00	50.00	50.00	50.00
0.25	48.24	51.21	50.71	50.41	49.77	50.12
0.75	46.55	52.21	51.24	50.65	49.69	50.14
1.25	44.92	53.03	51.60	50.77	49.69	50.10
1.75	43.37	53.69	51.84	50.79	49.73	50.06
2.25	41.88	54.19	51.98	50.76	49.80	50.02
2.75	40.45	54.55	52.03	50.69	49.87	49.99
3.25	39.08	54.80	52.02	50.59	49.93	49.97
3.75	37.77	54.94	51.95	50.48	49.98	49.96
4.25	36.51	54.98	51.85	50.37	50.02	49.96
4.75	35.30	54.93	51.71	50.26	50.05	49.97
5.25	34.14	54.81	51.56	50.16	50.07	49.98
5.75	33.04	54.63	51.40	50.08	50.08	49.98
6.25	31.98	54.38	51.23	50.00	50.08	49.99
6.75	30.96	54.10	51.05	49.94	50.07	50.00
7.25	29.99	53.77	50.88	49.89	50.06	50.00
7.75	29.06	53.40	50.72	49.85	50.05	50.00
8.25	28.18	53.01	50.56	49.82	50.04	50.01
8.75	27.33	52.60	50.41	49.81	50.03	50.01
9.25	26.52	52.18	50.27	49.80	50.02	50.01
9.75	25.76	51.75	50.14	49.80	50.01	50.00
10.25	25.03	51.31	50.02	49.80	50.00	50.00
10.75	24.34	50.87	49.91	49.81	50.00	50.00
11.25	23.69	50.43	49.81	49.83	49.99	50.00
11.75	23.07	50.00	49.73	49.85	49.99	50.00
12.25	22.49	49.58	49.65	49.86	49.98	50.00
12.75	21.95	49.18	49.58	49.89	49.98	50.00
13.25	21.45	48.79	49.52	49.91	49.98	50.00
13.75	20.98	48.42	49.47	49.93	49.98	50.00
14.25	20.54	48.08	49.43	49.95	49.98	50.00
14.75	20.15	47.76	49.39	49.97	49.99	50.00
15.25	19.79	47.47	49.36	49.99	49.99	50.00
15.75	19.47	47.20	49.33	50.01	49.99	50.00
16.25	19.19	46.97	49.31	50.02	49.99	50.00
16.75	18.95	46.76	49.29	50.04	49.99	50.00
17.25	18.75	46.59	49.28	50.05	50.00	50.00
17.75	18.59	46.45	49.27	50.06	50.00	50.00
18.25	18.46	46.35	49.26	50.06	50.00	50.00
18.75	18.38	46.28	49.26	50.07	50.00	50.00
19.25	18.34	46.24	49.26	50.07	50.00	50.00