INFLUENCE OF MACROPORES AND SOIL MOISTURE CONTENT ON THE RAPID MOVEMENT OF BROMIDE AND IODIDE TO THE SATURATED ZONE

By

PATTI LYNN ZIETLOW

Bachelor of Science

University of Wisconsin-Oshkosh

Oshkosh, Wisconsin

1987

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1992

INFLUENCE OF MACROPORES AND SOIL MOISTURE CONTENT ON THE RAPID MOVEMENT OF BROMIDE AND IODIDE TO THE SATURATED ZONE

Thesis Approved:

Wayne A Pettyjohn
Thesis Adviser

A Hounslow

Brian J. Carter

Thomas C. Collins
Dean of the Graduate College

ACKNOWLEDGMENTS

The support, help and love of many outstanding people made this research project possible. I am forever indebted to Dr. Pettyjohn for the generous use of his cheerful back yard as a research site. Dr. Pettyjohn's thought provoking questions, gentle suggestions, and enthusiasm for this project helped keep things on track. Dr. Carter is owed a huge thank you for all the hours spent in research discussion offering ideas and advice. His wonderful sense of humor buoyed enthusiasm up during the long hours spent in the field running the tracer tests. Much appreciation goes to Dr. Hounslow whose door was always open for guidance on geochemical matters. His patience in explaining things was endless.

Special thanks go to Dale Froneberger, Randall Ross and Mark Savoca for showing the "newcomer" the ropes in the field. Dale's instruction in running the ion chromatograph and chats on the research site were invaluable. I am especially grateful for the warm friendship and generous help of Phil Ward and Steve Alspach. Phil and Steve spent many long days assisting in set up of the tracer tests and in actually running them. They also provided stimulating discussion on the research that helped bring things into focus. Many of the graphs in this text would not have been possible without the help of Dave Myhre and Fritz Heck. They are due much gratitude for the generous loan of their computer systems and help in running the graphics programs. Thanks to Tom Nunamaker for his patience and assistance in writing a computer program to convert depth to water to feet above sea level for the monitoring wells.

The love and support of my in-laws, Harland and Kate Zietlow, throughout this project was invaluable. Big hugs go to both them and to my parents Bill and Jean Doell. Mom and Dad's never-ending love and support both morally and financially through my bachelors degree helped me obtain the knowledge necessary to tackle this project. Their continued faith in me through graduate school helped me keep going during the frustrating times. Much appreciation goes to Pebbles, who spent many long hours out in the field keeping me company.

To my wonderful husband Jim, I give to you, above all others, my deepest thanks. Thank you for help in the field collecting water samples, inputing data into the computer, proofreading, photocopying, and flying the plane for the aerial shots of the site. Most of all, thank you for always being their for me throughout this project no matter how grumpy I got. This work is dedicated to you.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

Br^-	bromide
Ca^{++}	calcium
Cl^-	chloride
F^-	fluoride
gpd/ft	gallons per day per foot
HCO_3^-	bicarbonate
I^-	iodide
K	hydraulic Conductivity
K^+	potassium
Mg^{++}	magnesium
Na^+	sodium
NO_3^-	nitrate
S	storativity
$SO_4^=$	sulfate
T	transmissivity

CHAPTER I

INTRODUCTION

Shallow ground-water systems pose one of the greatest challenges to hydrogeologists because their nearness to the land surface renders them highly susceptible to contamination from a wide range of sources. Despite years of research, the mechanisms governing pollutant movement to shallow aquifers are only partially understood.

It is generally assumed that overlying silt and clay provide a degree of natural protection to shallow aquifers owing to their low hydraulic conductivity. For example, the drainage characteristics of these soils make them attractive as landfill sites. According to Noble they "allow moisture from the landfill to percolate slowly through the soil structure before reaching the ground-water system" (1976, p. 31). In addition, the presumed ability of silt and clay to absorb and retain water has made such soils desirable as sites for the land application of waste water (Tennyson, 1980).

Preliminary results from the study of a silt and clay aquifer in Payne County, Oklahoma, however, indicate that the low hydraulic conductivity may be far more apparent than real. Rapid changes in both water quality and water level can occur within hours of a rain event. Rapid fluid movement through macropores deprives the shallow aquifer of the natural protection that the soil should provide.

The objective of this research is to document and explain why a shallow silt and clay aquifer can be contaminated by surface-applied pollutants in just a matter of hours. A further objective is to determine how soil-moisture conditions affect this process.

CHAPTER II

LITERATURE REVIEW

Previous Studies at the Site

With the installation of 16 monitoring wells during August 1985, Hagen (1986) launched the original investigation of the site. During the first year research focused primarily on basic site characterization. Hagen (1986) and Hoyle (1987) monitored water-table fluctuations, ground-water quality, and conducted several aquifer tests in order to determine hydraulic characteristics. Both investigators documented considerable variation in water quality with respect to both time and space. They attributed fluctuations in water quality and water level to rapid recharge through macropores.

Acre (1989) and Ross (1988), who studied the unsaturated zone, installed eight soil-water suction lysimeters and four neutron probe access tubes. Ross discovered significant short term water-quality variations in the unsaturated zone. Variations in soil-moisture content also led Acre to conclude that macropores influence infiltration.

Froneberger (1989) examined water movement through the unsaturated zone by means of surface applied bromide and chloride tracers. He found that large spikes of the tracers appeared in the lysimeters after a short time, and he attributed this phenomenon to the vertical movement of water through macropores.

Nelson (1989) addressed water-table fluctuations and the change in the direction of ground-water flow, amounting to as much as 125 degrees, which had been reported by Hoyle (1987) and Hagen (1986). He suggested that this shift is due to a seasonal limitation of ground-water discharge areas.

Melby (1989) measured hydraulic conductivity of the aquifer using constant rate, slug, and lab permeameter tests. Values of hydraulic conductivity based on permeameter tests were several orders of magnitude less than those determined by field methods, which lead Melby to theorize that macropores account for a significant part of the aquifer transmissivity.

Macropores

The idea that macropores could affect water and solute flow through soil was being considered as early as the mid 1800's. Schumacher (1864) and Lawes and others (1882) noted that macropores control infiltration, moving rainwater to considerable depths with little change in composition. Since that time, work on the macropore theory has abounded, and this has resulted in extensive literature on the topic.

Classification

The literature contains many systems for classifying macropores. Brewer (1964) categorized them on the basis of size, using macro to mean pores that are at least 100 micrometers in diameter. Luxmoore (1981), who expanded Brewer's work, described three classes of macropore sizes. Skopp (1981) refined size classification by incorporating function in the definition of macroporosity. Techniques for measuring macropore size include timing and measuring water flow through cores, tracing visible voids, staining with methylene blue, and scanning soil photographs with an image analyzer (Smettem, 1987; Louren and others, 1988; Radulovich and others, 1989; Edwards and others, 1988). Beven and others (1982) group macropores on the basis of type (ie. cracks and fissures, soil fauna, plant roots).

Water Transport

Researchers, such as Cheng (1988), Hoogmoed (1980), Beven and German (1981), Armstrong and Arrowsmith (1986), and McIntrye and Sleeman (1982) demonstrated the importance of macropores in the infiltration of rainwater. Bouma and others (1978) described this process of rapid flow through macropores as "short circuiting".

Rogowski and Simmons (1988) verified that macropores cause field measured hydraulic conductivities to be greater than the nature of aquifer material or lab calculated values might indicate. Further substantiation of this exists in the works of Rogowski and Richie (1984) and Heard and others (1988).

Solute Transport

A considerable number of articles document the fact that macropores enhance chemical migration through the soil. Quisenberry and Phillips (1976) found that macropores caused water laced with chloride to percolate through a silt loam aquifer with very little change in composition. In a similar study, Priebe and Blackmer (1989) observed the same behavior using oxygen-18 labeled water and nitrogen-15 labeled urea. Other studies utilizing tritium, chloride, and lime provide further evidence for enhanced chemical migration (Edwards and others 1988; Minhas and Khosla, 1986; Blake and others, 1973).

Ground-Water Tracer Testing

Roughly 2,000 years ago, Phillip, the tetrarch of Trachonitis, pioneered the art of tracer testing by noting the migration of chaff tossed into Ram Crater Lake, which is located in the Middle East (Mazor, 1976). In the years that followed, tracer testing has grown into an important tool in the understanding of water flow and contaminant transport. The use of salts as tracers is documented as early as 1869 in Europe (Davis and others, 1985). In Germany, Adolph Thiem, in 1889, used a sodium chloride tracer to measure ground-water flow rates in a sandstone aquifer (Davis and others, 1985).

Bromide

There are numerous examples of the use of bromide tracers to evaluate the effect of macropores on infiltration and ground-water recharge, and contaminant transport. Chan and Mead (1989), who tracked the migration of bromide laced "rain" into the soil by taking core samples, concluded that macropores significantly decreased runoff. Zachman and others (1987) used bromide to show that worm burrow-formed macropores increase infiltration to a considerable depth. The fact that macropores cause field measured values of hydraulic conductivity to be greater than those measured in the lab was demonstrated by Tennyson and Settergren (1980) using bromide. Germann and others (1984) employed bromide to verify that water infiltrates deeper into soils containing macropores. Other similar studies include Gerritse and Singh (1988), Smith and Davis (1974), Onken and others (1977), LeBlanc and Garabedian (1986), and D'Lugsoz (1976).

Iodide

Although not as popular as bromide, iodide has proven to be a reliable ground-water tracer. A study by Haaser (1978) demonstrated that iodide can be used successfully as a tracer in shallow soil systems. Osmin (1977) used iodide to determine hydraulic conductivity and ground-water flow direction. Bradbury and Green (1985) measured matrix diffusion with an iodide tracer. In 1965, Rowe and others traced water circulation in underground hot springs and geysers with iodide. Leap and Sun (1987) utilized iodide in tracer tests in southern Nevada. Soil extracts were analyzed for iodide tracer ions by Bowman (1984).

CHAPTER III

SITE DESCRIPTION

Location

Research was conducted in a residential area in Stillwater, Payne County, Oklahoma (figure 1). The 26,000 square foot site is bordered by streets on the north and east and by adjacent yards to the south and west (figure 2). An unnamed tributary to Boomer Creek lies just west of the property.

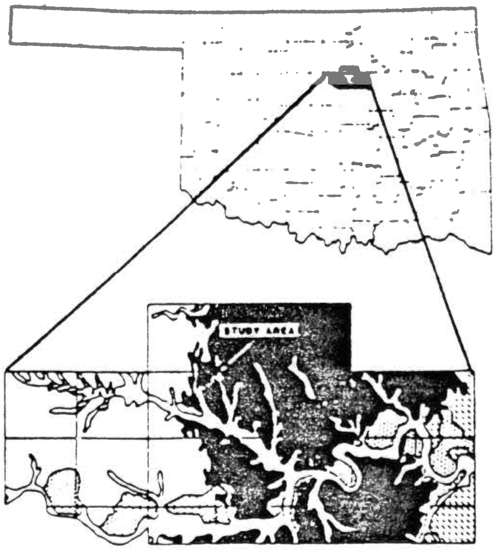


Figure 1. Location of Study Aquifer (after Hagen, 1986)

Figure 2. Aerial Photograph of site

Topography

Lying on Boomer Creek's floodplain, the nearly flat study area is approximately 886 feet above sea level. Total relief across the site is less than half a foot.

About 250 feet to the east, shale crops out, rising nearly 14 feet higher than the site. Approximately 400 feet westward, the elevation declines to 880 feet above sea level on the bank of the tributary (figure 3).

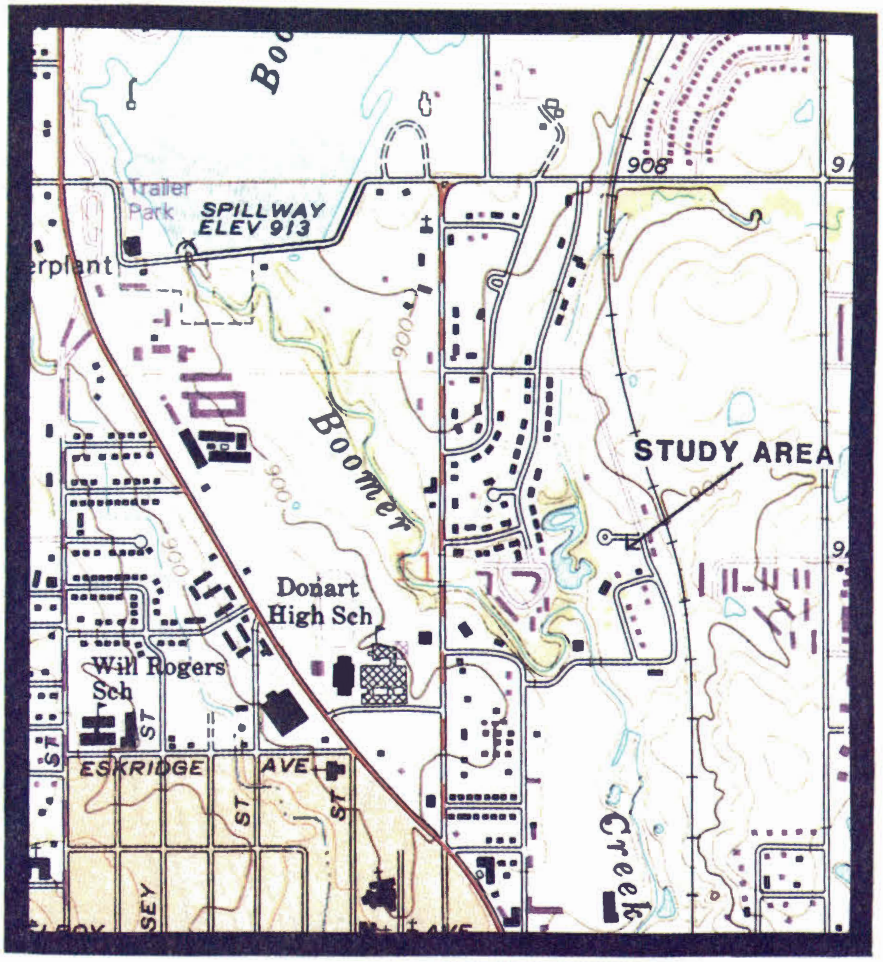


Figure 3. Topographic Map (USGS, 1979)

Site Features

Buildings and Roads

Nearly 27 percent of the yard is covered by concrete driveways, walkways, and one-story buildings that are built on concrete foundation slabs (Froneberger, 1989). Downspouts draining the buildings discharge onto the lawn. The bordering streets have curbs and drains that prevent storm runoff from entering the yard.

Utilities

Underground sewer, water, gas, and telephone lines service the buildings (figure 4). Lying at a depth of five feet is an 8-inch diameter sewer line that trends across site's southern boundary, while a 15-inch diameter sewer eight feet below the surface parallels the western boundary. In the southwestern corner of the yard, the 8-inch pipe discharges into the 15-inch pipe. A water main, 6 inches in diameter, lies between the property line and Wildwood Drive (Hoyle, 1987). Submerged roughly three feet, a telephone cable skirts the site's southern border. A direct hook-ups to the house is located in the southern half of the plot.

Flora

The yard's southern border and much of the western border are outlined by a variety of trees (figure 5). Tree

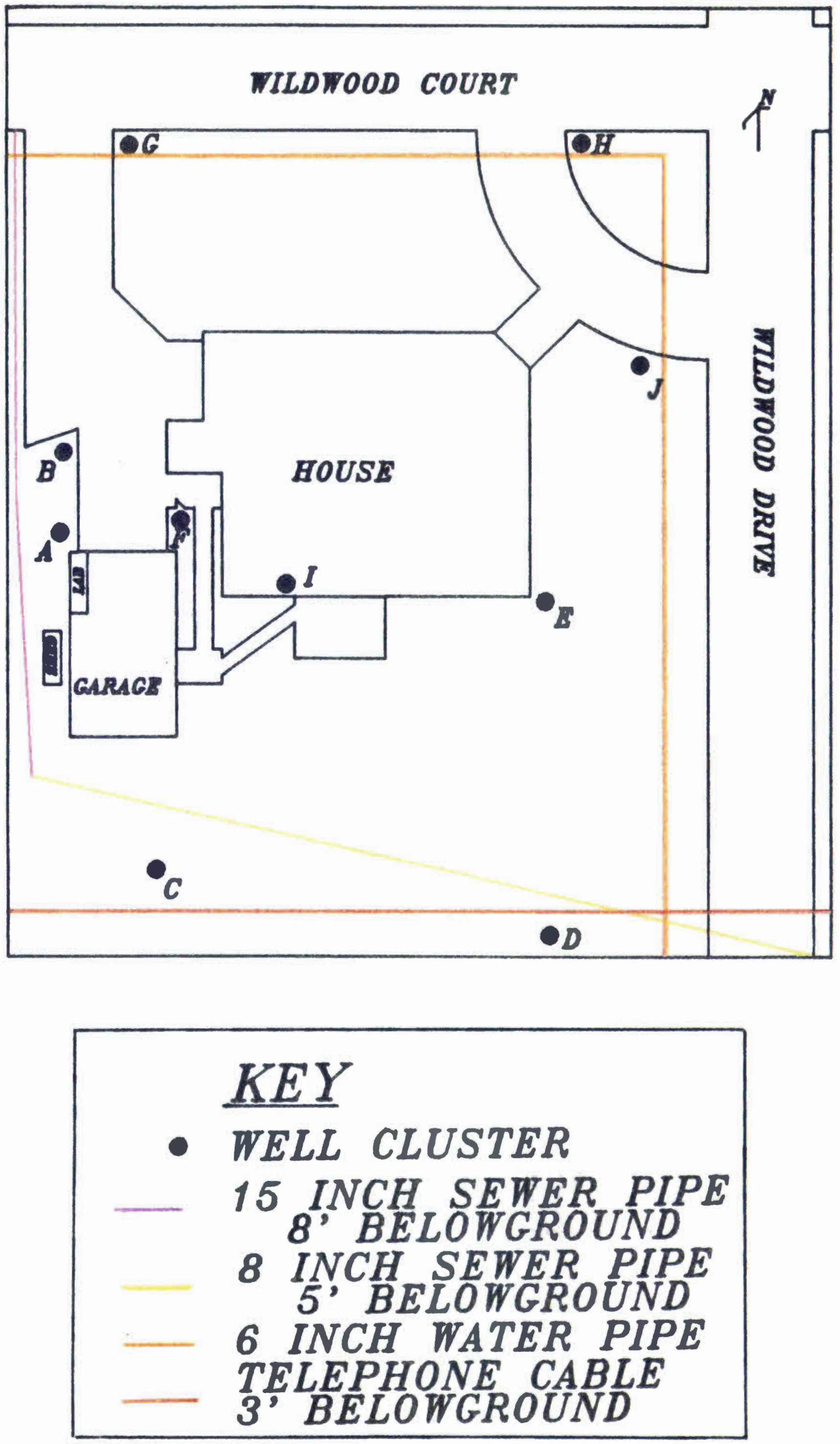


Figure 4. Location of Utilities

types include hackberry, pecan, redbud and pear. The trunks vary from 3 to 48 inches in diameter with dripline diameters ranging from 10 to 86 feet (Nelson, 1989). Flower beds and ornamental shrubs outline the house and garage. The lawn consists primarily of bermuda grass.

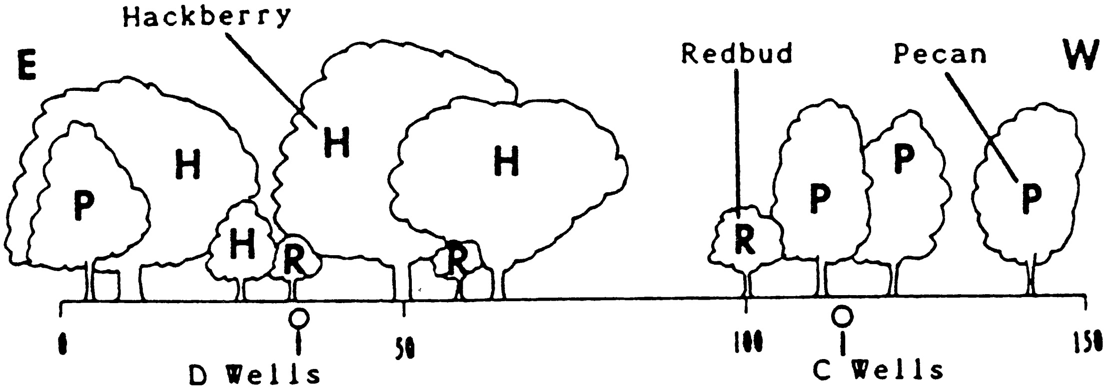


Figure 5. Tree Types Along the Site's Southern Border (after Hoyle, 1987)

Instrumentation

The site is equipped with 43 ground-water monitoring wells, 8 soil-water suction lysimeters, and 5 soil moisture neutron probe access tubes. An on site lab houses equipment for meteorological monitoring and measurement of ground-water field parameters (figure 6).

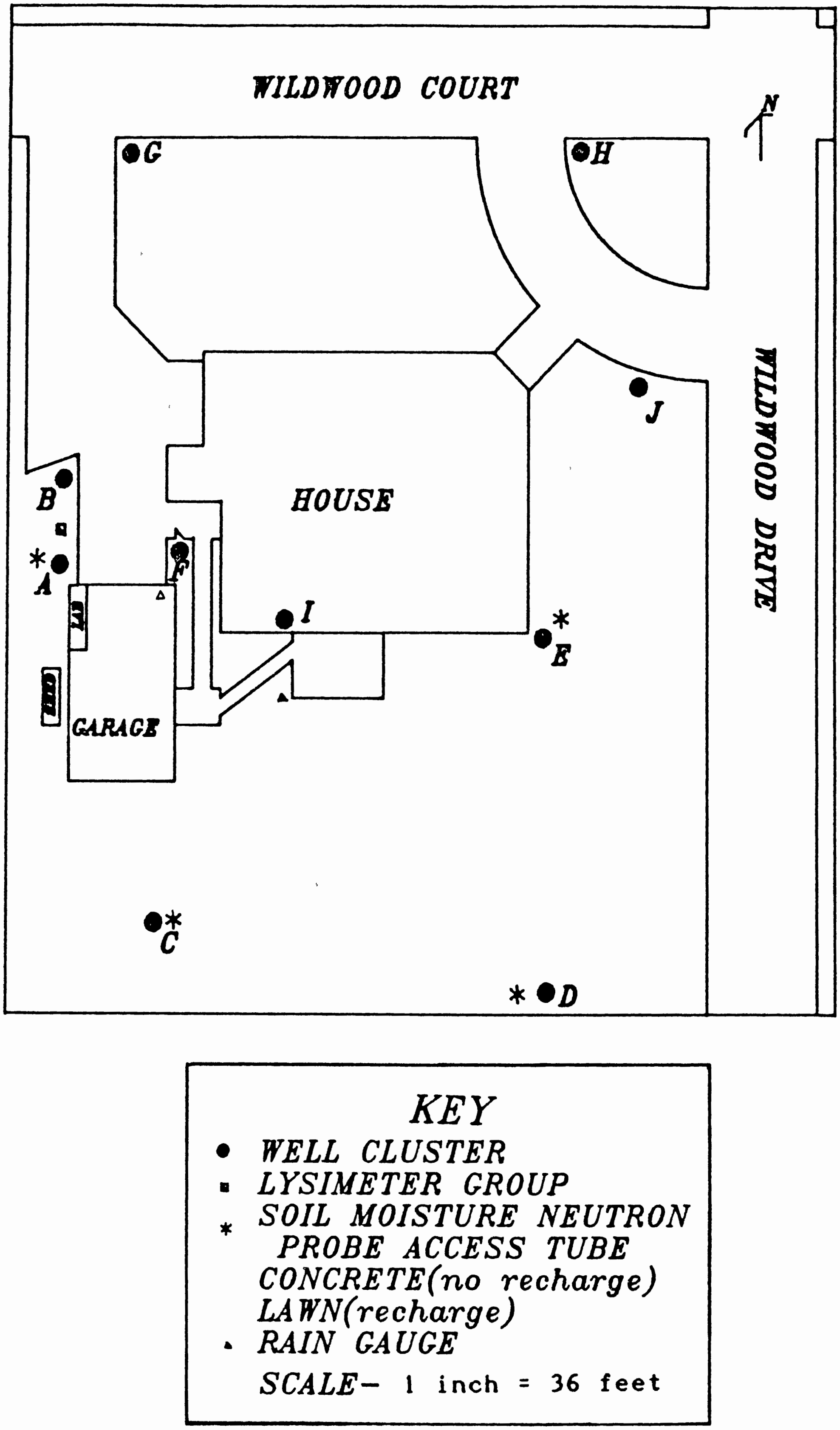


Figure 6. Site Instrumentation

Climate

Central Oklahoma is characterized by warm, humid summers and moderate winters. While summer temperatures average 80° F, temperatures in excess of 100° F during July and August are not uncommon (SCS, 1987). Rains in the form of high intensity, short duration convective thunderstorms mainly occur during spring and early summer. Most of the region's annual 34 inches of rain falls during this period (Pettyjohn and others, 1983).

Winter temperatures average 39°F and snowfall averages 6 inches per year (Pettyjohn and others, 1983). The occasional snows melt in a day or two. Low intensity, steady rains from cyclonic storm systems are typical during the fall and winter.

About 30 inches of water per year is lost due to evapotranspiration (Pettyjohn and others, 1983). The rate of evapotranspiration is highest during the dry summer months. Runoff for the region averages 4.5 inches per year. The mean effective regional ground-water recharge rate is 1 inch per year (Pettyjohn and others, 1983).

Precipitation at the research site totaled 28.9 inches in 1989, 30.9 inches in 1990, and 3.94 inches from January to 5 May 1991.

General Geologic Setting

The research site lies on Late Quaternary alluvial deposits that fill a valley cut into the Doyle Shale, which is Pennsylvanian in age (figure 7). The unconsolidated alluvium extends to a depth of 43 feet where it lies unconformably on the shale (Ross, 1988). Beneath the alluvium, 5000 feet of Paleozoic strata, consisting of shale, limestone and dolomite, lie unconformably on granitic basement rock (Shelton and others, 1985).

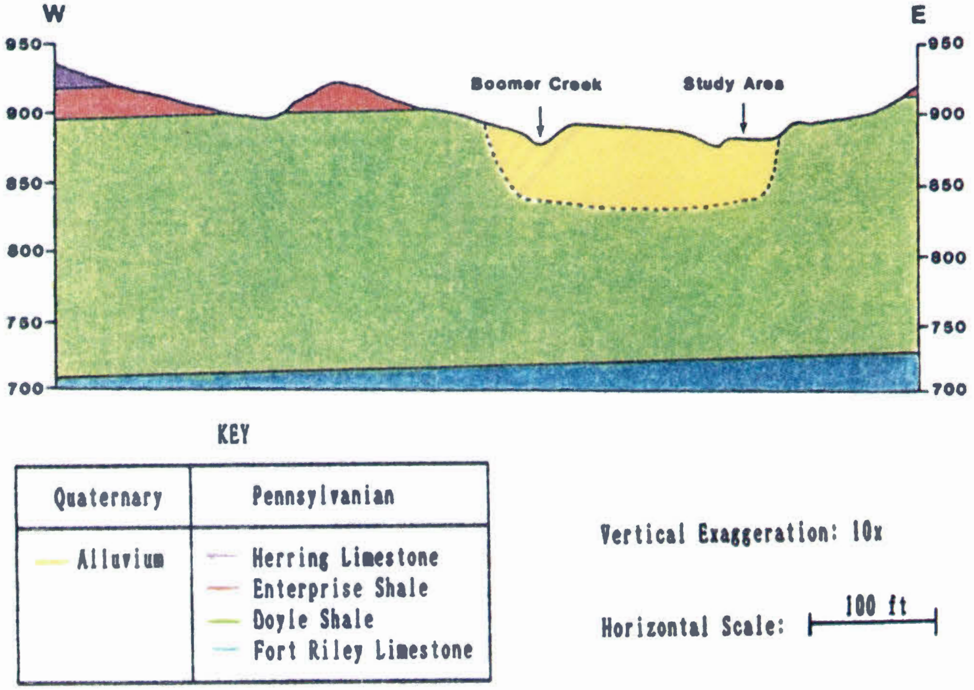


Figure 7. Geologic Cross Section (after Shelton and others, 1985)

CHAPTER IV

SURFACE-WATER HYDROLOGY

Drainage

Flowing sluggishly from northwest to the southeast, Boomer Creek and its tributaries dominate the area (figure 8). While Boomer Creek flows year round, the tributaries are commonly dry during the summer (Hagen, 1986). The tributary lying approximately 200 feet west of the site, which has a drainage areas that is slightly less than two square miles, is dammed near its confluence with Boomer Creek and forms a small, peanut shaped pond, which is known as Chiquita Lake (figure 3). The pond contains water throughout the year (Ross, 1988). Downstream from the confluence of Boomer Creek and its tributary, several pumps remove water from the creek for lawn irrigation during the spring and summer (Nelson, 1989). Nelson (1989) installed gaging staffs in Chiquita Lake and Boomer Creek and made periodic water-level measurements. The pond's maximum stage is controlled by a spillway, which has an elevation of 880.6 feet (Nelson, 1989).

Figure 8. Aerial Photograph Showing Tributary

Surface runoff in the study area is low, attributable to the nearly flat surface of the flood plain. Concrete driveways, streets and sidewalks affect runoff by directing water into city drains. During periods of heavy rain, water may pond on the surface of the site when the infiltration capacity of the soil is exceeded. Even after an hour of ponding, the infiltration rate is approximately one inch per hour.

Surface-Water/Ground-Water Relationships

Withdrawal of water by the pumps installed in Boomer Creek do not appear to affect the water table at the research site. However, the stage of Chiquita Lake may have a significant influence on the direction of ground-water flow (Nelson 1989). The dammed tributary and the alluvial aquifer appear to be hydrologically connected when the water table is less than 7.5 feet below land surface. This results in a west-southwesterly flow of ground water from the yard to the tributary. When the water table drops below the base of the tributary, ground water flow shifts to the southeast, as the tributary changes from a gaining stream to a losing stream, and Boomer Creek becomes the major line of ground-water discharge (Froneberger, 1989).

CHAPTER V

HYDROGEOLOGY

Aquifer Material

Wells at the research site tap a fine grained, silty clay alluvial aquifer that is 43 feet thick (figure 9). The lower 8.5 feet of the aquifer consists of a clay-rich lag gravel that grades upward into very fine sand. The gravel lies on weathered Doyle Shale. The upper 35.5 feet of the aquifer consists of a clay, silt, and very fine sand mixture that contains soil characteristics. The upper four feet belong to the Ashport series (SCS, 1987). Two buried soil horizons have been identified. The first, located at a depth of 4 to 27.5 feet, is approximately 1300 ± 70 years B.P. old. Dated at 10,600 ± 170 years B.P., the second horizon lies at a depth of 27.5 to 29.5 feet (Ross, 1988). Textural classes present include loam, silt loam, silty clay loam, silty clay, and clay loam. A weak to moderate, medium, subangular blocky structure dominates, and soil peds and root casts are present. Bulk density, in the first five feet of the profile, range from 1.50 to 1.75 gm soil/cm^3 (Ross, 1988).

SOIL PROFILE

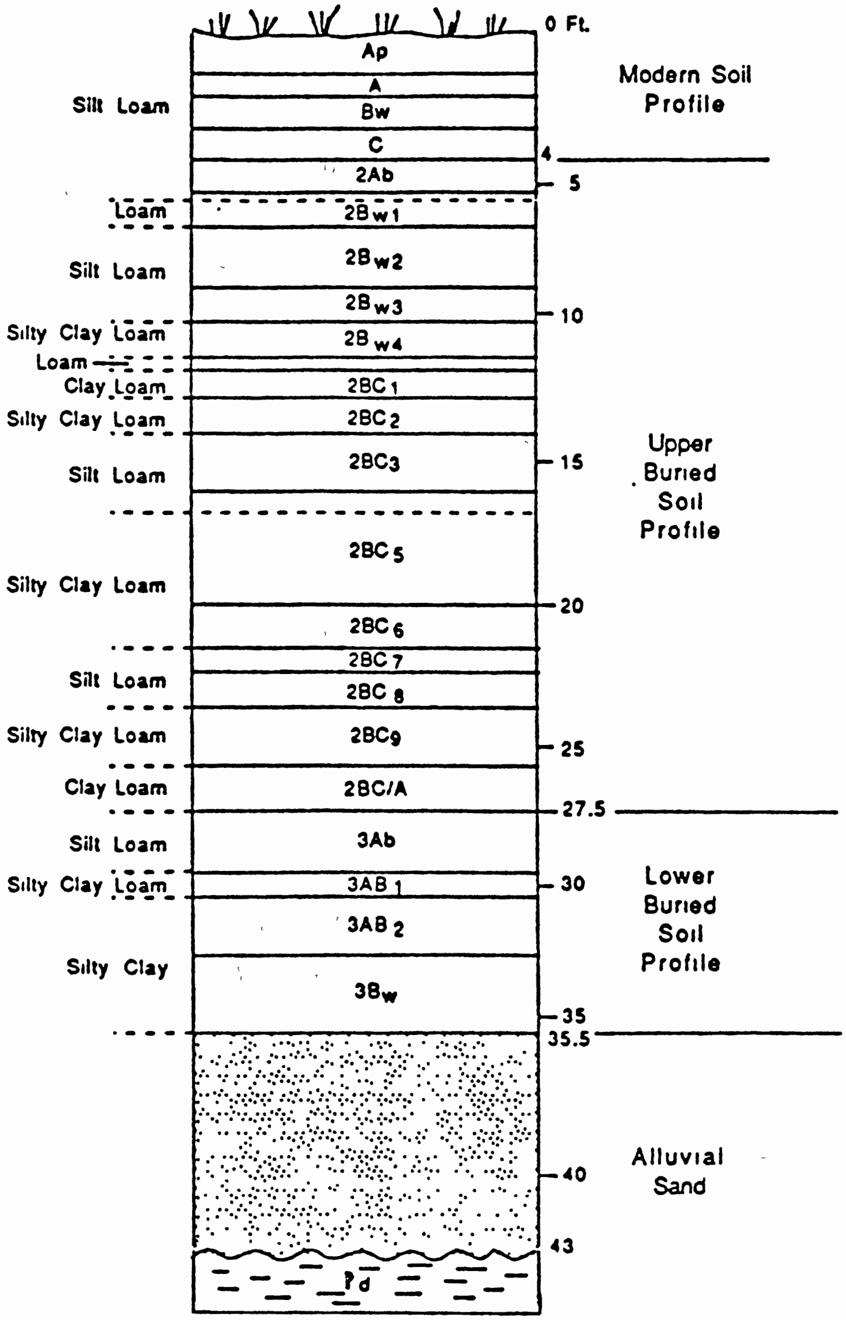


Figure 9. Soil Profile (Ross, 1988)

Mineralogy

The sand and silt is composed largely of quartz grains, with feldspar making up 3 to 5 percent of the grains. Kaolinite, smectite, illite, and mixed layer illite-smectite constitute the clay fraction of the aquifer. Calcite concretions, composed of very fine-grained calcite, are present in the profile. Black nodules, which occur throughout the aquifer, consist of silica, aluminum, iron, and manganese oxides and hydroxides. Cyclic deposition of clays and ferromangans is indicated by concentric coatings of iron and manganese oxide and hydroxide stains on pore walls (Ross, 1988).

Recharge and Discharge

Recharge

Precipitation is the primary source of recharge to the aquifer. Most recharge occurs from March to June and in September, which are traditionally the wettest months of the year. Hagen (1986), estimated that the total amount of recharge equals roughly 47 percent of the total amount of precipitation. This high rate of recharge is most likely due to the flat nature of the area, which favors ponding, and to the presence of macropores. Periodic watering of the lawn during the summer months also contributes to recharge.

Discharge

Evapotranspiration and underflow are the primary sources of discharge from the aquifer. Nelson (1989), found that transpirative losses were greatest from March to August. A small amount of discharge also occurs as resulting of pumping of the wells. On site, wells are pumped regularly for ground-water sample collection and occasionally for aquifer testing. Well F1 may be pumped for short periods during the summer months for lawn watering. A well that may tap the aquifer is located approximately 800 feet south of the D site. This well is also pumped for irrigation purposes. Nelson (1989), however, determined that this off-site well does not affect water levels at the site. During periods of high water table, ground water appears to discharge into the tributary located west of the study site and at other times underflow is southwest toward Boomer Creek (Froneberger, 1989).

Unsaturated Zone Characteristics

Thickness

The thickness of the unsaturated zone varies seasonally from about 3 to 12.5 feet below surface. Ross (1988) estimated that the capillary fringe for the silt loam aquifer rises roughly 2.5 feet above the water table; Froneberger (1989) estimates a rise of 6 feet.

Moisture Content

Soil-moisture levels, on a volume basis, typically range from .11 to .35 cm^3 H_2O/cm^3 soil (Ross, 1988; Froneberger, 1989). The position of the water table, amount of precipitation, and rate of evapotranspiration have a combined effect on the moisture profile. When the water table is high, moisture levels tend to be relatively uniform with depth. Precipitation will commonly cause soil moisture to increase in the lower portion of the unsaturated zone, but little affect has been recorded in the upper 2 feet, except during and immediately following a rain (Froneberger, 1989). When the water table is low, moisture levels tend to show greater variation with depth. During these intervals, generally June through September, precipitation may cause a significant fluctuation in moisture content in the upper 2 feet of the unsaturated zone, while having little effect on moisture content deeper in the unsaturated zone (Froneberger, 1989). Soil-moisture levels are typically lowest along the site's tree dominated southern boundary (Hagen, 1986).

Ground-Water Movement

Direction of Flow

The direction of ground-water flow vacillates between 145 and 225 degrees from true north (Ross, 1988). In general, flow is to the west-southwest when the water table is high and to the southeast when the water table is low (Froneberger, 1989).

Hagen (1986) and Hoyle (1987) hypothesized that the shift in flow direction is due to evapotranspiration from large trees located along the site's southern border. Ground water is constantly discharging into Boomer Creek and, part of the time, into the unnamed tributary to the west. The direction of flow is controlled by the location of the discharge line. Evapotranspiration dewaters the aquifer at a rate of about .1 feet/day, in the absence of recharge. Consequently, evapotranspiration lowers the water table quite rapidly starting in the spring, which causes the water table to decline below the bottom of the unnamed tributary sometime in April, May, or June. Once this occurs, flow direction must change.

Hagen's (1986) 1985-1986 hydrograph (figure 10) shows almost no fluctuation during winter, even though the water table was quite high. This indicates that ground-water runoff was about equal to recharge. Only in the spring of 1986 did the water table begin to decline rapidly, reflecting evapotranspiration.

Froneberger (1989), as discussed in Chapter IV, attributes the shift in flow direction to the relationship between the ground water and the tributary located west of the site.

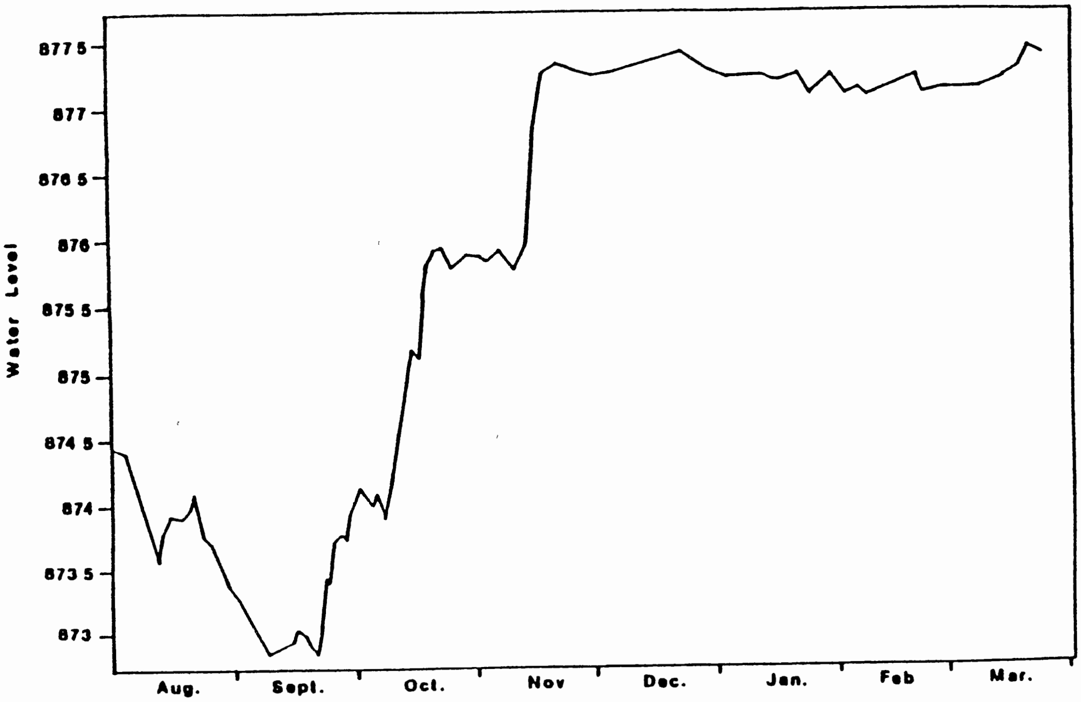


Figure 10. 1985-1986 Hydrograph for Well A4 (Hagen, 1986)

Rate of Flow

Calculations performed by Hoyle (1987) and Froneberger (1989) indicate that the lateral ground-water velocity varies from 0.1 to 1.12 ft/day. Ground water moving at a rate of 0.1 ft/day would take 225 days to migrate beneath Wildwood Court to the research site and 560 days to pass beneath the house to the I wells (Froneberger, 1989). Assuming the velocity is 1.12 ft/day, travel time beneath the Wildwood Court and house decrease to 20 days and 50 days respectively.

Aquifer Test Results. Hagen (1986), Hoyle (1987), and Melby (1989) conducted several aquifer tests at the research site using slug and constant-rate pumping methods. Analysis of the data from these tests provided information on the aquifer parameters contained in Table I. Values of hydraulic conductivity estimated for the D and E wells tend to be high (>100 gpd/ft^2). Hoyle (1987) attributed these higher values to an increase in aquifer material grain size in the vicinity of the D and E sites. Low values of storativity (10^{-4}) were consistently calculated for the B well site by Melby (1989). These low values could be the result of short term pumping during which gravity drainage was not complete. Transmissivity appears to increase from west to east across the site due to increasing grain size and permeability. Within the well clusters, transmissivities are greater in the #5 wells, which penetrate a greater thickness of the aquifer.

Hoyle (1987) estimated a specific yield of 10 to 25 percent and a specific capacity of 0.11 to 1.5 gpm/ft, the latter occurring when the water table was within 5 feet of land surface.

TABLE I

AQUIFER PARAMETERS

Parameter	Minimum	Maximum	Mean
K	27 gpd/ft^2	125 gpd/ft^2	67 gpd/ft^2
S	.0001	.370	.026
T	190 gpd/ft	4930 gpd/ft	2149 gpd/ft

Gradient. The horizontal hydraulic gradient, as calculated from water-table elevation maps, typically varies from 0.003 to 0.009 ft/ft. Vertical gradients were estimated on the basis of head differences between individual wells in a cluster (usually 0 to 0.10 ft). Hoyle (1987), found that the upward hydraulic gradient ranged from .002 to .348 ft/ft. The vertical gradient is greatest during the summer months. Gradients at the tree dominated C and D clusters tend to be steeper than at the other well clusters (Hoyle, 1987). Fluctuations in the water table occur daily as a result of transpiration.

Permeability and Porosity. Effective porosity of the studied aquifer, estimated from volumetric soil-moisture content measurements, is approximately 33 percent (Froneberger, 1989). Fillable porosity varies from .11 to .27 (Nelson, 1989). A continuous series of precipitation events causes fillable porosity to decrease as soil moisture increases. Precipitation events of low volume, however, appear to have little effect on fillable porosity values (Nelson, 1989). Permeability appears to increase eastward across the site and with depth in the C and D wells. Hoyle (1987) suggests that this is due to increasing grain size brought about by an increase in the sand fraction.

CHAPTER VI

METHODS OF DATA COLLECTION

Meteorological Data

Meteorological conditions were constantly monitored throughout the study in an on-site laboratory. A continuously recording aneroid barograph, accurate to ± 0.2 percent full scale, monitored of fluctuations in barometric pressure. Air temperature data were collected using a Springfield Instrument patio thermometer and a continuously recording thermogragh. A clear, cylindrical rain gauge with .01 inch graduations and a continuously recording tipping bucket rain gauge served to measure precipitation.

Depth to Ground Water

Depth to ground water was determined by a weighted, chalked steel tape and two In-Site, Inc. Model SE1000 pressure transducers. Surveyed marks on the well casings served as measuring points. The transducers, installed in wells A5 and D5, recorded continuously at 1 hour intervals. Both the tape and the transducers produced measurements accurate to .01 feet. Water-table elevation for a given well was calculated by subtracting depth to water from the altitude of the top of the well casing at the measuring point.

Soil-Moisture Measurements

A Troxler model 3330 depth-moisture gauge was used to determine the soil-moisture content. Aluminum access tubes, installed by Acre (1989) at sites A,C,D and E, allowed the probe to be lowered into the soil down to a depth of 7 feet. Readings were taken by Alspach (in prep) every 6 inches to a depth of 78 inches. A standard count taken prior to sampling minimized error due to changes in field conditions.

Ground-Water Quality

Monitoring Wells

The site is monitored by 43 wells distributed among 10 sites designated as A through J. As illustrated in figures 11 and 12, the combination of lysimeters and the wells screen each of the 14 horizons located in the upper 15 feet of the soil profile. Sites G and H, located along the upgradient perimeter, provide information on the quality of water flowing into the property. Site I resides inside the house. Because of its unique location, site I provides information on the effect of a building (which prohibits recharge) on ground-water quality.

The wells are grouped in clusters to monitor water quality at discrete depths in the aquifer. Holes for wells

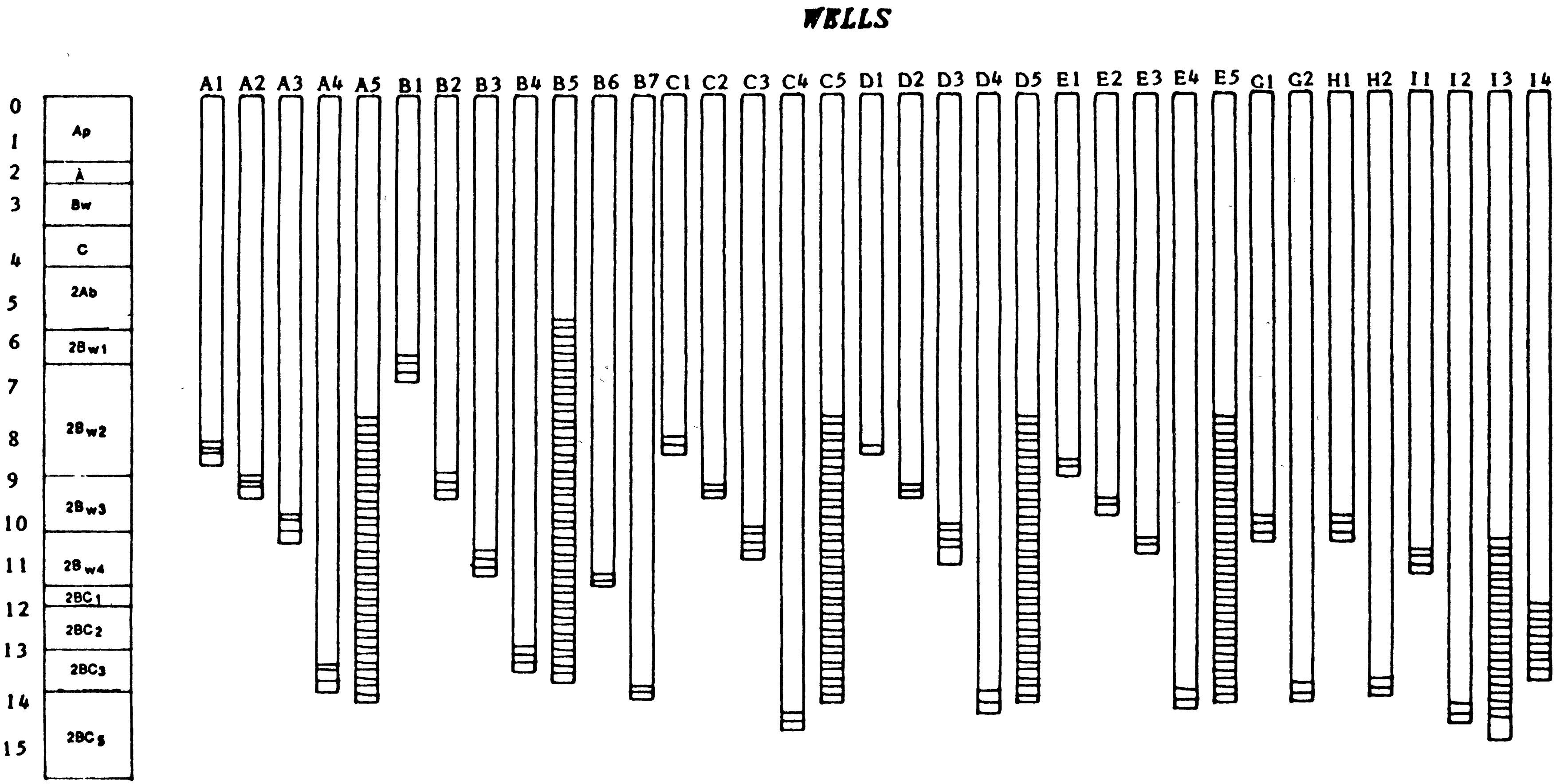


Figure 11. Wells and Soil Profile

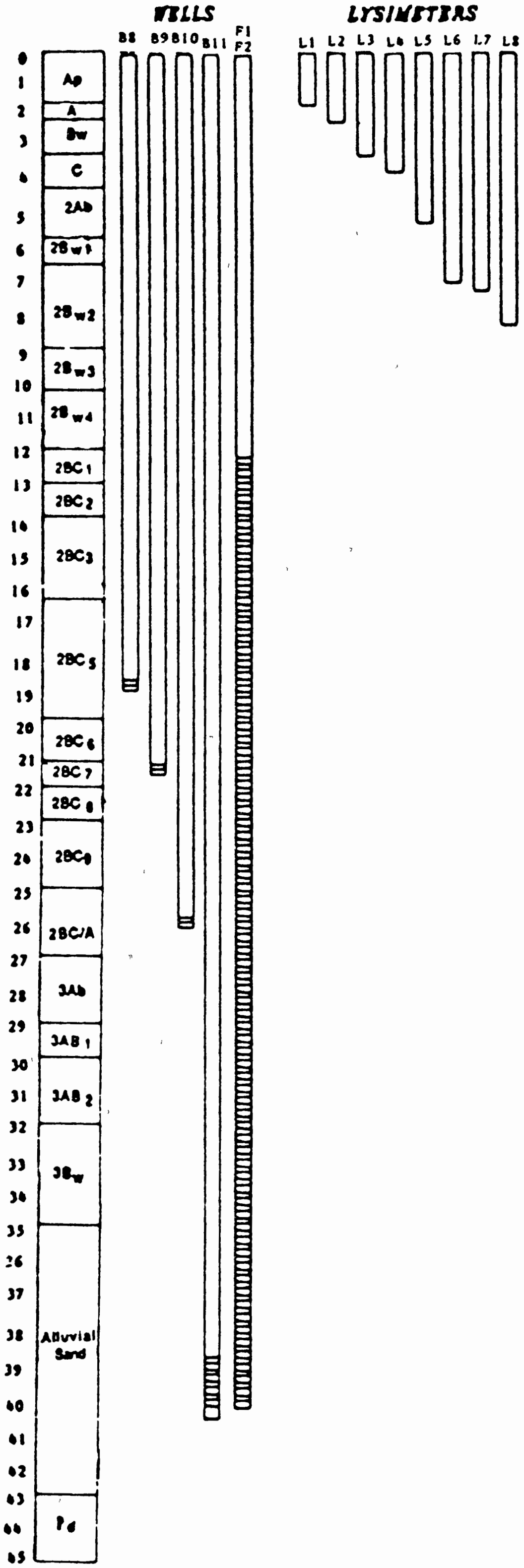


Figure 12. Wells, Lysimeters and Soil Profile

at sites A,C,D,E,G,H,I, and J were excavated by hand auger. A hollow stem auger was used to drill the holes for the wells at sites B and F. All wells except B11, B12, I3, and J1 were completed with hand-slotted polyvinyl chloride casing wrapped with nylon screen. Wells B11, I3, and J1 contain a stainless steel well point attached to the lower end of the casing. Well B12 has a Johnson PVC, 0.006 inch slot well screen (Melby, 1989). The filter pack in all wells is composed of medium-grained sand that extends several inches above the slotted interval. The annular space is filled with bentonite.

Wells B6 through B10 are installed in the same borehole as a nested cluster. Bentonite seals separate each well screen interval. Well pairs F1 and F2, and B12 and B13 share the same hole (Melby, 1989). Specifications for each well are listed in Table 2.

Sample Collection

500 ml Nalgene plastic sample bottles were cleansed before each use following EPA approved procedures. The cleaning method involved washing with a nonphosphate, neutral detergent in hot water, rinsing with deionized distilled water, rinsing with .1 N hydrochloric acid, and rinsing once again with deionized distilled water. A cardboard box with a lid provided storage for the capped, laundered bottles. Prior to sampling, information on the static water level in each well, air temperature,

TABLE II

WELL SPECIFICATIONS

WELL	TOTAL DEPTH (ft. from concrete pad)	SCREENED INTERVAL (ft. from concrete pad)	DIAMETER (inches)	TOP OF CASING ELEVATION (ft. above sea level)
A1	8.5	8.0 - 8.2	2.00	885.97
A2	9.2	8.7 - 8.9	2.00	885.97
A3	10.3	9.9 - 10.1	2.00	885.96
A4	13.8	13.3 - 13.6	2.00	885.94
A5	14.0	7.0 - 14.0	2.00	886.00
B1	6.6	6.1 - 6.4	.75	886.01
B2	9.3	8.8 - 9.1	2.00	885.99
B3	11.0	10.5 - 10.8	2.00	886.10
B4	13.2	12.7 - 13.0	2.00	886.03
B5	13.4	4.4 - 13.2	6.00	886.04
B6	11.3	11.0 - 11.2	.50	885.92
B7	13.9	13.6 - 13.8	.50	885.96
B8	18.7	18.4 - 18.6	.50	885.94
B9	21.2	20.9 - 21.1	.50	885.94
B10	25.7	25.4 - 25.6	.50	885.96
B11	40.3	38.4 - 40.0	1.25	886.19
C1	8.3	7.9 - 8.1	2.00	885.75
C2	9.2	8.9 - 9.1	2.00	885.73
C3	10.6	9.9 - 10.4	2.00	885.70
C4	14.6	14.2 - 14.4	2.00	885.71
C5	14.0	7.0 - 14.0	2.00	885.74
D1	8.2	8.0 - 8.2	2.00	885.82
D2	9.3	9.0 - 9.2	2.00	885.82
D3	10.8	9.9 - 10.4	2.00	885.84
D4	14.2	13.6 - 13.9	2.00	885.80
D5	14.0	7.0 - 14.0	2.00	885.80
E1	8.7	8.3 - 8.5	2.00	886.08
E2	9.7	9.3 - 9.5	2.00	886.08
E3	10.5	10.1 - 10.3	2.00	886.06
E4	14.1	13.6 - 13.9	2.00	886.05
E5	14.0	7.0 - 14.0	2.00	886.03
F1	40.0	10.0 - 40.0	4.00	886.41
F2	40.0	10.0 - 40.0	2.00	886.29
G1	10.3	9.7 - 10.1	1.00	885.07
G2	14.0	13.5 - 13.8	1.00	884.92
H1	10.2	9.6 - 10.0	1.00	885.35
H2	13.9	13.4 - 13.7	1.00	885.38
I1	11.0	10.4 - 10.8	1.00	886.00
I2	14.5	14.0 - 14.3	1.00	886.01
I3	14.9	10.0 - 14.4	2.00	885.99
J1	13.5	11.6 - 13.2	1.25	885.63

barometric pressure, and rainfall were collected. The peristaltic pump and Tygon tubing used in sample collection was bathed using the sample bottle cleaning method described earlier. Before taking samples, one well volume was purged from each well to ensure that fresh formation water was obtained. Hagen (1986) determined experimentally that one well volume achieved this purpose. The evacuated water was discharged 10 feet downgradient from the wells in order to avoid ground-water recharge in the vicinity of the well. Sample bottles received a rinse of water from the well before being filled. The passage of deionized distilled water and at least 200 ml of formation water through the pump and tubing before each sample collection aided in the prevention of cross contamination between wells.

Field Parameters

An on-site laboratory equipped with a digital thermometer, pH meter, Hach digital titrator, and a temperature compensating electrical conductivity meter provided for the measurement of field parameters immediately after sample collection. The instruments were calibrated prior to each sampling event and thoroughly cleansed with deionized distilled water. Continued equipment rinsing between samples prevented cross contamination. Titration of 100 ml of each sample to a pH 4.5 color end-point with 2N HCl furnished bicarbonate concentrations.

Sample Preparation

After the measurement of field parameters, the samples were pressure filtered through .2 micrometer Gelman acetate filters using a hand syringe and then were split into two portions. One portion was acidized with HNO_3 to $pH<2$ for cation analysis. The prepared, filtered samples were stored in a refrigerator set at approximately 4° Celsius in clean, 60 ml Nalgene plastic bottles.

Analytical Methods

A Dionex 2000i ion chromatograph was used to measure F^-, Cl^-, Br^-, NO_3^-, $SO_4^=$, and I^- concentrations. The chromatograph was calibrated using standards prepared by the dilution of 1000 ppm stock solutions of each of the anions. The eluent consisted of .00170 m $NaHCO_3$ and the regenerant of .025 N H_2SO_4. The analyses were conducted in the Noble Center chromotography lab at Oklahoma State University, Stillwater, Oklahoma.

Agronomic Services, a laboratory located at Oklahoma State University, determined Ca^{++}, Mg^{++}, Na^+, K^+, total Fe, and silica concentrations using inductively coupled plasma atomic emission spectroscopy.

Quality Control

Cleanliness of a batch of bathed sample bottles was verified by filling a test bottle with deionized distilled water and subjecting the water to the same analyses as the ground-water samples. Field duplicates tested the precision of both field and laboratory analyses. Performance of the ion chromatograph was documented by frequent analysis of duplicate samples, calibration standards, and Dionex test standards. Further checks on the data included cation-anion balances, which were calculated by the computer program WATEVAL (Hounslow, 1989), and comparison with data collected by past researchers at the site.

Possible Sources of Error

Hydrogen, unrelated to moveable water in clay and organic matter rich soils, may cause the neutron probe to read too high a soil-moisture level (Hillel, 1980). Use of the peristaltic pump may have caused water samples to lose dissolved gasses while gaining atmospheric gas. This could result in a lowering of pH and HCO_3^- values. Because of oxidation, Fe^{++} and Mn^{++} concentrations could have been erroneously lowered by the peristaltic pump and/or by sample filtering (Griffin and others, 1981).

Nitrate

Nitrate values determined by Ross (1988) and Froneberger (1989) are roughly 36 times higher then those measured by Hagen (1986), Hoyle (1987), and the author (figure 13). This discrepancy is most likely due to analytical error. Hagen and Hoyle measured NO_3- levels in the field with a ion sensitive electrode. Ross, Froneberger, and the author used an ion chromatograph. Personal communication with Froneberger and Ross revealed that the nitrate stock solution and the calibration solutions were stored in plastic bottles at room temperature. New calibration standards were not mixed before each analytical session. Storage at room temperature in plastic bottles probably resulted in the breakdown of NO_3-. During calibration, for example, the chromatograph may have been standardized with a 5 mg/l NO_3- solution that in fact was only 1 mg/l. This resulted in the chromatograph reading 1 mg/l as 5 mg/l, hence creating erroneously high NO_3- values.

The discrepancy in nitrate values also may be due to a change in fertilizer. A liquid fertilizer, much more mobile than the pellet type applied from 1988 to present, was used when Hagen (1986) and Hoyle (1987) did their work. The data, however, do not support this theory for elevated nitrate levels. If the switch to solid fertilizer caused the increase in nitrate values, than concentrations recorded by the author should have matched those recorded by Ross (1988) and Froneberger (1989). Furthermore, sample collection by Ross (1988) and Hoyle (1987) overlapped for a period from January 1987 to April 1987. Hoyle (1987),

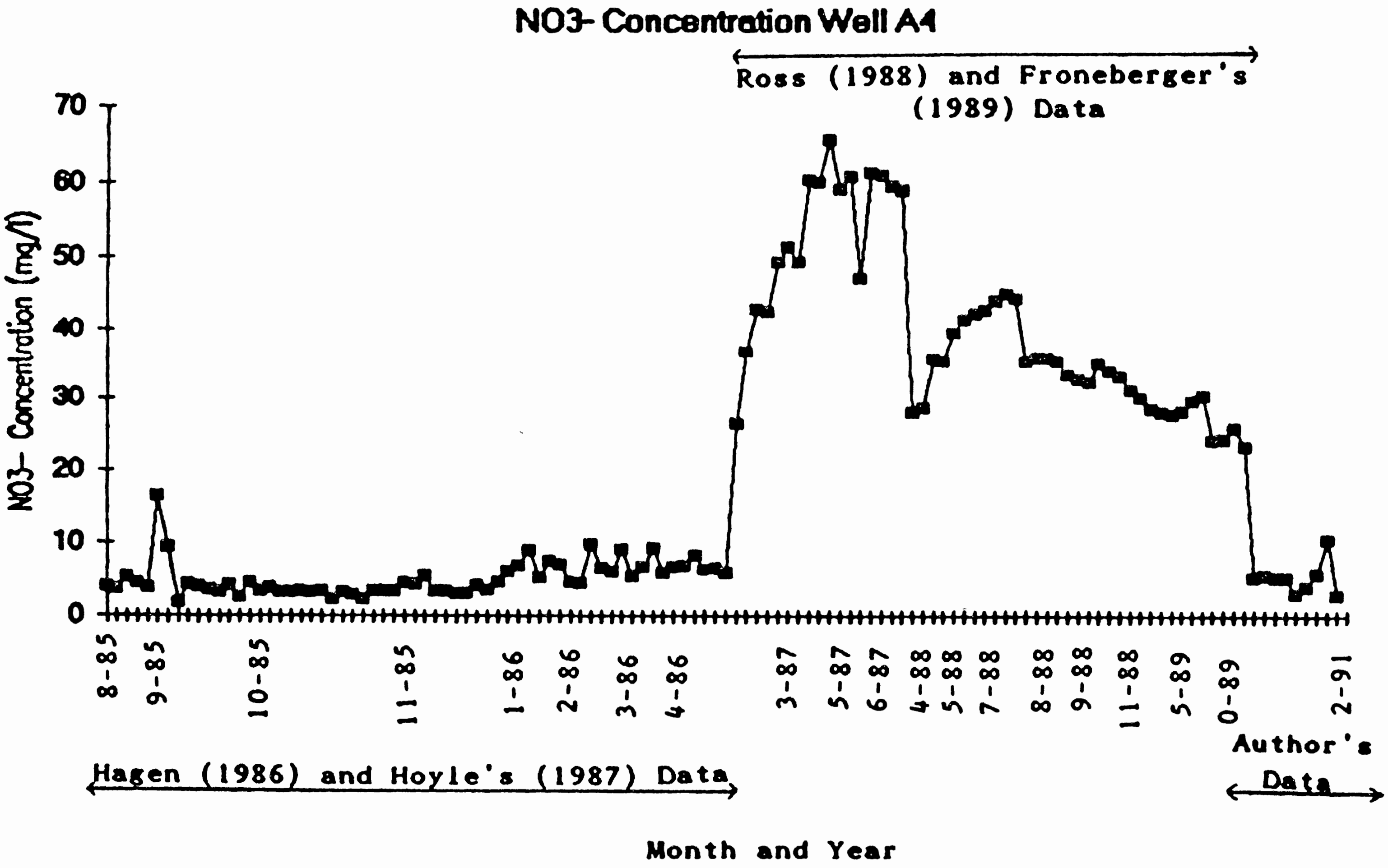


Figure 13. NO_3- Concentration Well A_4

however, makes no mention of a sudden increase in nitrate concentration.

Another possible explanation for the elevated nitrate levels recorded by Ross (1988) and Froneberger (1989) is an upgradient change in water quality during their sampling period. In addition, the site had not been fertilized for several years prior to the time Hagen began sampling.

CHAPTER VII

GROUND-WATER QUALITY

Data Analysis

Methods

Geochemical data for all 41 monitoring wells was compiled from the start of research in 1985 to May 1991. Statistical analysis of the data (appendix D) served to identify maximum, minimum, and average values in ion concentrations over the past 6 years. Graphs of the data aided in the identification of water-quality trends.

Water Quality

Ground water at the research site is classified as high bicarbonate, mixed calcium-magnesium-sodium type (Hoyle, 1987). The geochemical environment is neutral, with pH ranging from 6.4 to 7.8. Hagen (1986), Hoyle (1987), Ross (1988), and Froneberger (1989) established that water quality varies considerably with respect to both time and space. Ion concentrations vary considerably across the yard from well site to well site and with depth. The only exception to this appears to be the Si_2 ion, which, as illustrated in figure 14, shows little variation

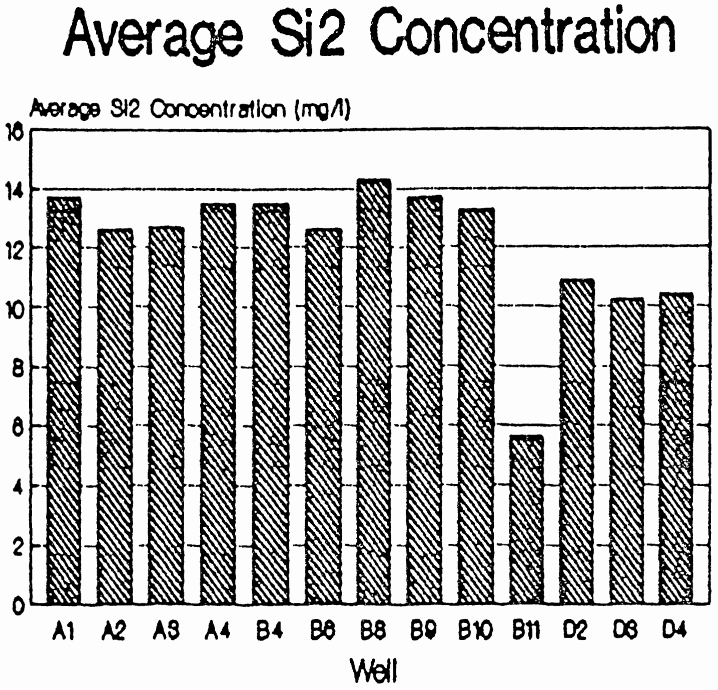


Figure 14. Average Si_2 Concentration

in concentration. Ion levels for a given well also fluctuate considerably. An example of this is a bar graph of the maximum and minimum $SO_4^=$ values of each well (figure 15). Distinct yearly trends in geochemistry are difficult to discern from the compiled data. This is mainly because most of the data collection occurred during the spring and early summer months. Few data are available for fall and early winter. Ranges in ion concentration for the ground water are displayed in Table III. The following sections discuss possible explanations for these ranges.

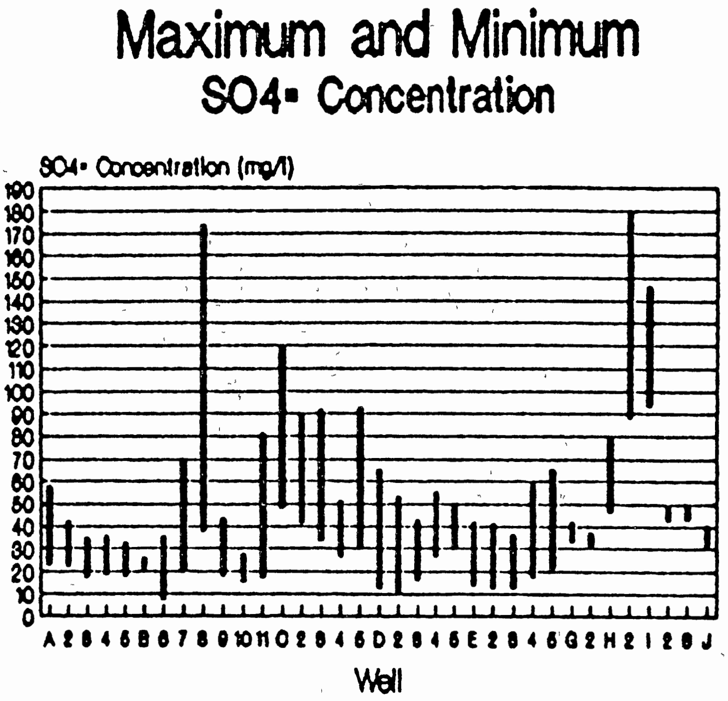


Figure 15. Maximum and Minimum $SO_4^=$ Concentration

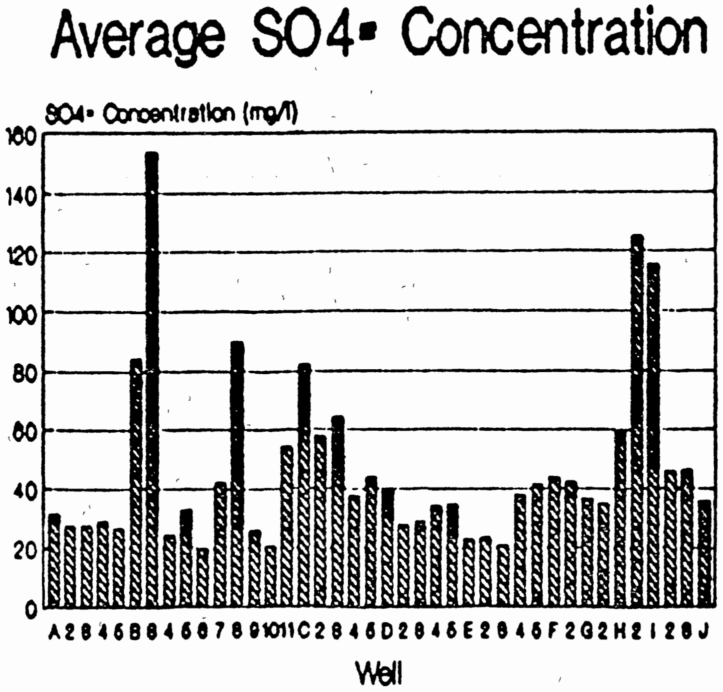


Figure 16. Average $SO_4^=$ Concentration

TABLE III

RANGES IN ION CONCENTRATION

Ion	Maximum (mg/l)	Minimum (mg/l)
Ca^{++}	190.1	16.3
Fe^{++}	15.1	0.001
K^+	4.4	0.03
Mg^{++}	112.0	14.7
Mn^{++}	4.6	0.001
Na^+	179.8	10.8
Si_2	19.9	4.7
Cl^-	163.0	3.5
HCO_3^-	1341.0	198.0
NO_3^-	113.2	0.01
$SO_4^=$	180.1	7.9

Factors Affecting Ground-Water Quality

Fertilizer, Vegetation, and Concrete

Fertilizer, vegetation, and the presence of concrete greatly affect K^+, NO_3^-, and $SO_4^=$ concentrations in the ground water. Fertilizer applied to the lawn in the spring and fall provides a source for the three ions. According to Reasors Lawn Service, Stillwater, Oklahoma, it is typically applied as:

Nitrogen	1 lb/1000 ft^2	as methyl urea
P_2O_5	0.16 lb/1000 ft^2	
K_2O	0.24 lb/1000 ft^2	
S	0.40 lb/1000 ft^2	

Rises in NO_3^- and $SO_4^=$ concentration in many of the monitoring wells following fertilizer application is documented in the works of the previous site researchers

Examination of the compiled data suggests that K^+ concentrations also rise in response to fertilization. Wells A_3, A_4, C_4, D_3, and D_4 reached their peak K^+ concentrations in April 1988 after spring fertilization.

Vegetative cover, or lack of it, also greatly affects water quality. K^+, NO_3^-, and $SO_4^=$ are essential elements for sustaining plant life (Hem, 1985). As such, they are removed by roots, thus reducing concentrations in the soil. Inspection of Figures 16, 17, and 18 illustrate this point. Well sites A, B, C, D, E, and F, which are located near abundant flora, exhibit relatively low average K^+, NO_3^-, and $SO_4^=$ concentrations. In sites G, H, I, and J however, concentrations of the three ions are at their highest. Sites G, H, I, and J are located immediately down gradient of a concrete road, the house, and a concrete driveway respectively (figure 6). Since no vegetation is present to remove the ions, and recharge cannot occur to dilute the ground water, the ions are present in elevated concentrations.

Vegetation further affects water quality by providing a source of ions. Decay of vegetation during the fall and winter months produces a source of NO_3^- and K^+ that can be leached into the ground water (Hem, 1985). Plant root respiration produces CO_2, which increases the HCO_3^- concentrations. Bicarbonate concentrations are greatest in the C and D sites where extensive tree root systems dominate the site (figure 19), but the concentration

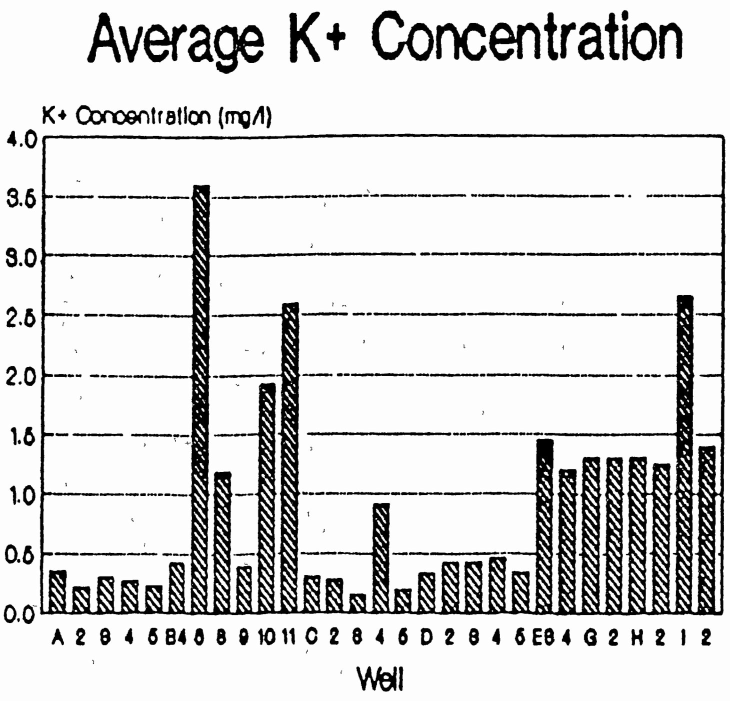


Figure 17. Average K^+ Concentration

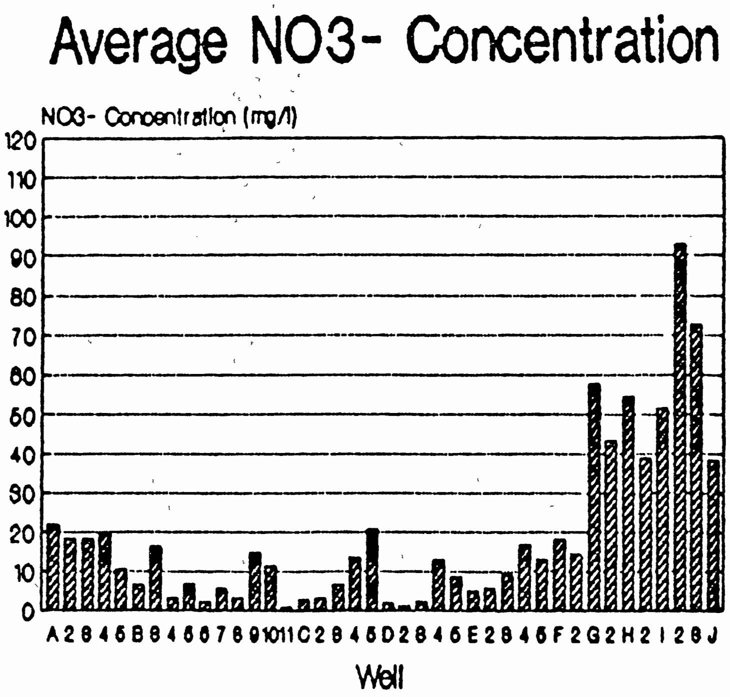


Figure 18. Average NO_3^- Concentration

decreases with depth (from well #1 to well #5) as do the number of plant roots. Since plants affect HCO_3^- concentrations in the aquifer, they also indirectly influence electrical conductivity. Bicarbonate compromises roughly half of the total ions measured in the water, giving the ion control over measured electrical conductivity. The graphs of average conductivity and HCO_3^- concentration (figures 19 and 20) are virtually identical.

Sewer Pipes

Leakage from the 5 foot deep 8 inch diameter sewer line that occurs along the site's southern border appears to affect Cl^- concentrations in the C and D well sites. As illustrated in figures 21 and 22, these two sites possess the most variation in and the highest average Cl^- concentrations. Cl^- contamination from the sewer appears to reach its maximum when the water table drops below the line. Vertical gradients shift from upward to downward indicating that water is flowing out of the sewer line into the ground water (Hoyle, 1987).

Cation Exchange

Clay particles in the aquifer may affect water quality by exchanging Na^+ ions for Ca^{++} ions. In well clusters A, B, D, G, H, and I, average Ca^{++} concentrations decrease with depth while Na^+ concentrations increase, thus suggesting exchange. This is illustrated in figures 23 and

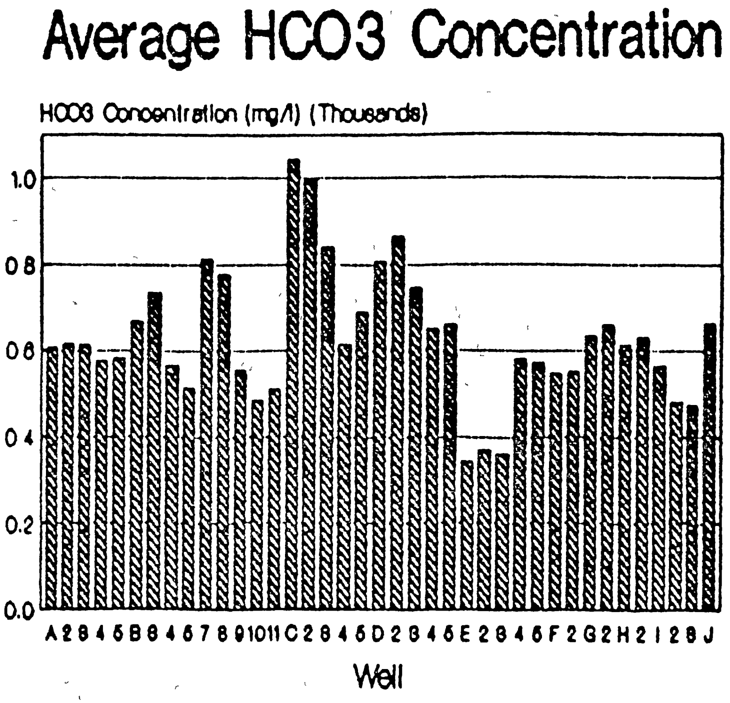


Figure 19. Average HCO3- Concentration

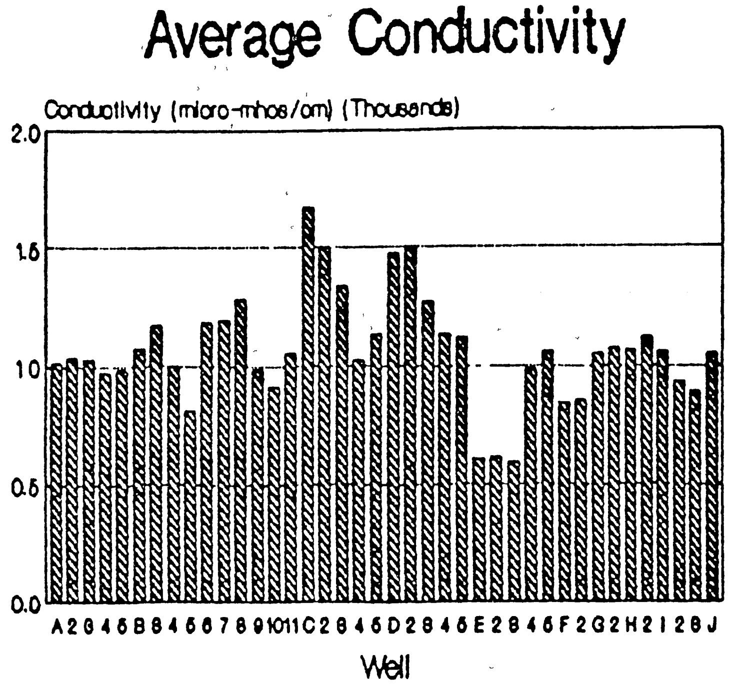


Figure 20. Average Conductivity

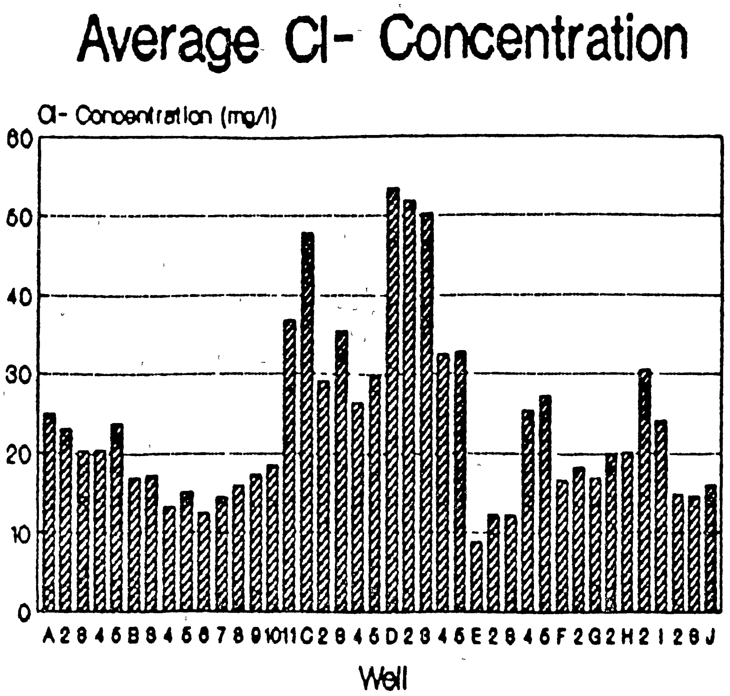


Figure 21. Average Cl⁻ Concentration

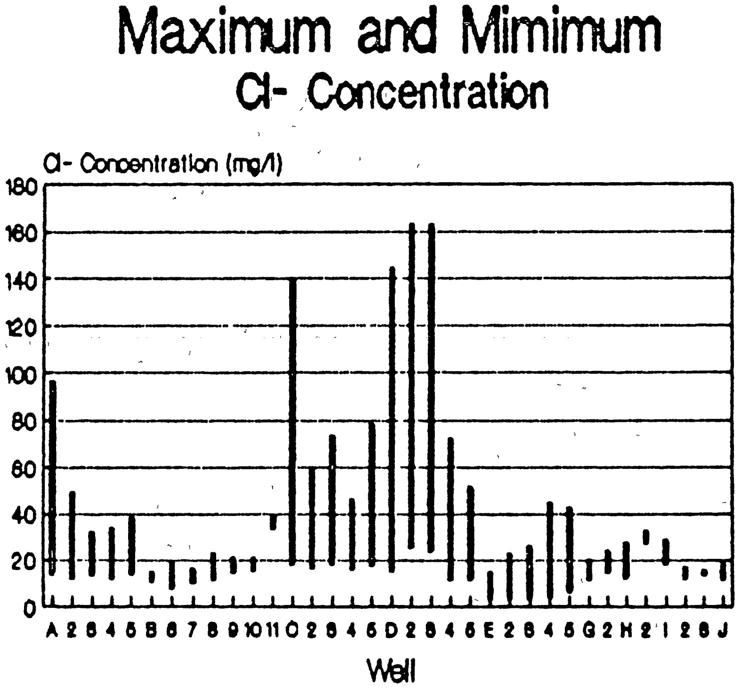


Figure 22. Maximum and Minimum Cl⁻ Concentration

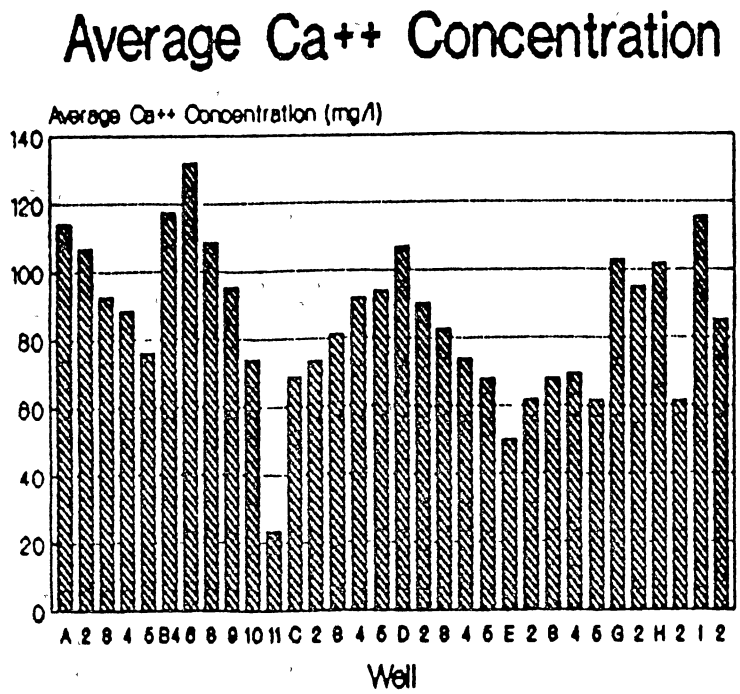


Figure 23. Average Ca⁺⁺ Concentration

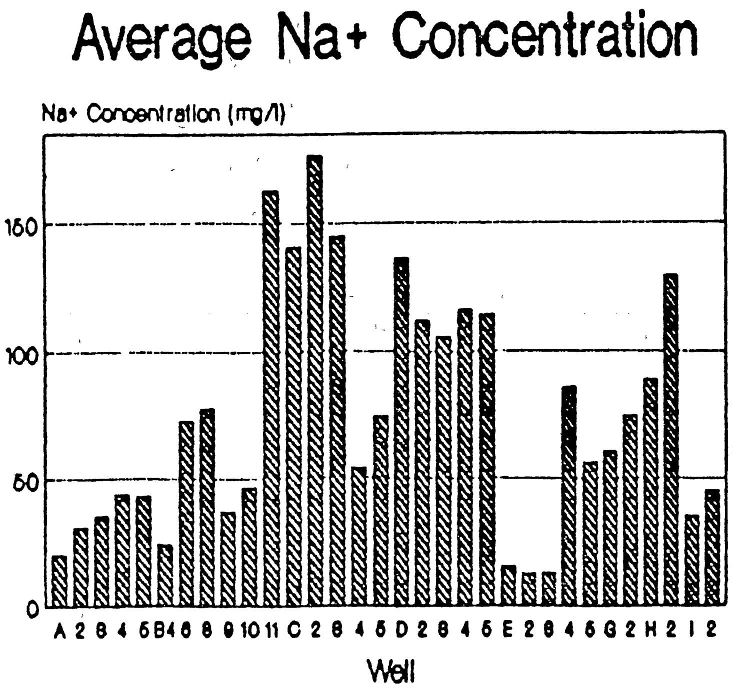


Figure 24. Na⁺ Concentration

24. Ca^{++} concentrations decrease from the shallow #1 wells to the deeper #5 wells, while Na^{+} concentrations increase.

Redox Reactions

Variation in redox potential may be responsible for the elevated Fe^{++}, Mn^{++}, and $SO_4^{=}$ concentrations at the B site. As illustrated in figures 16, 25, and 26, levels of these ions are much higher at B than at the other sites. According to Bricker (1982), the geochemical behavior of these elements is dependent on redox potential. The source of Fe^{++} and Mn^{++} is most likely the iron-manganese nodules that appear throughout the soil profile (Ross, 1988).

Downspout

Water quality at the E cluster is significantly affected by an adjacent downspout. Hagen (1986), Hoyle (1987), and Froneberger (1989) found that ion levels decreased significantly at this site following precipitation events. Rain water that discharges from the downspout apparently quickly infiltrates and dilutes the ground water.

Precipitation

Samples taken during and after rain events show that precipitation has a significant impact on water quality. Ion concentrations rise as contaminants are flushed from the surface and unsaturated zone into the ground water. In

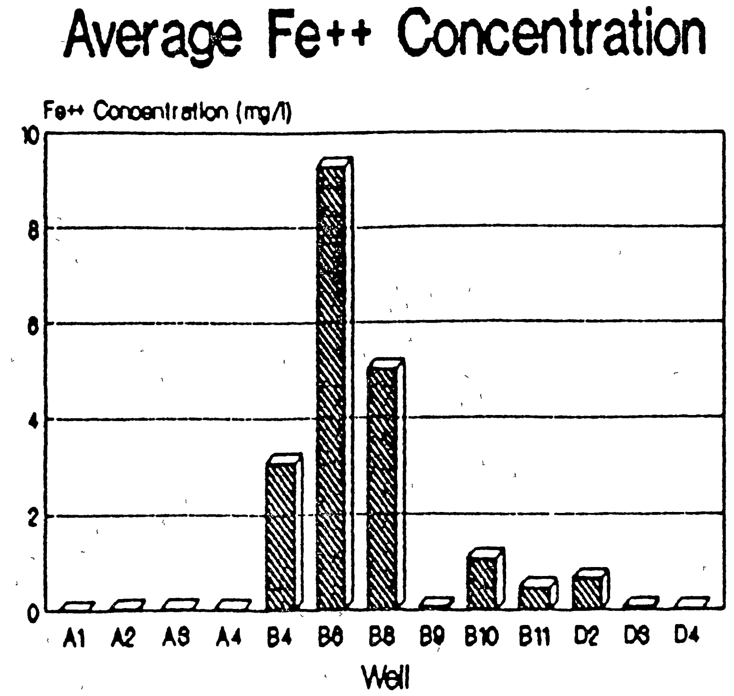


Figure 25. Average Fe⁺⁺ Concentration

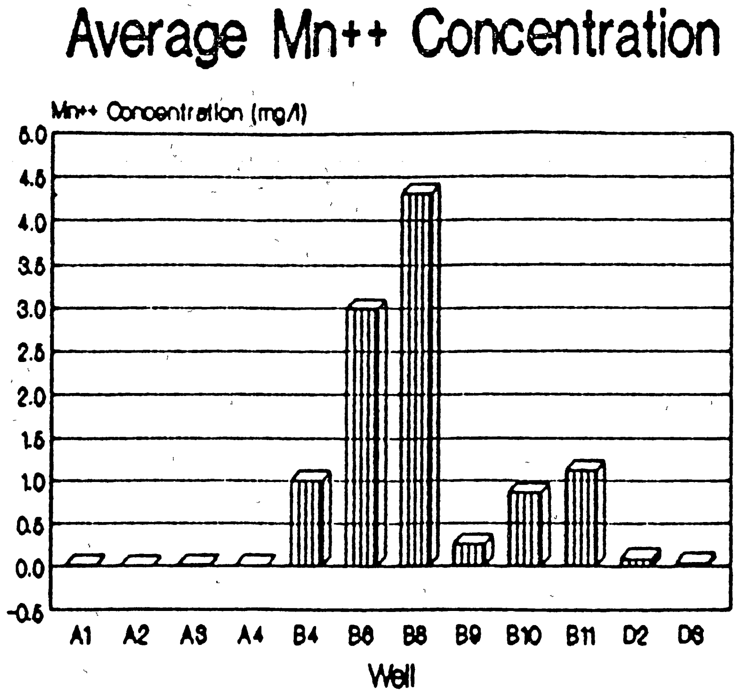


Figure 26. Average Mn⁺⁺ Concentration

addition, the rising water table dissolves water-soluable compounds in the soil matrix. Changes in water quality due to rain occur very quickly, as illustrated in figure 27. Cl- levels quadrupled in D_2 in response to a 1 March 1991 simulated rain falling at the rate of 1 inch/hour. This effect is in part due to macropore flow, as discussed in detail in chapter 8.

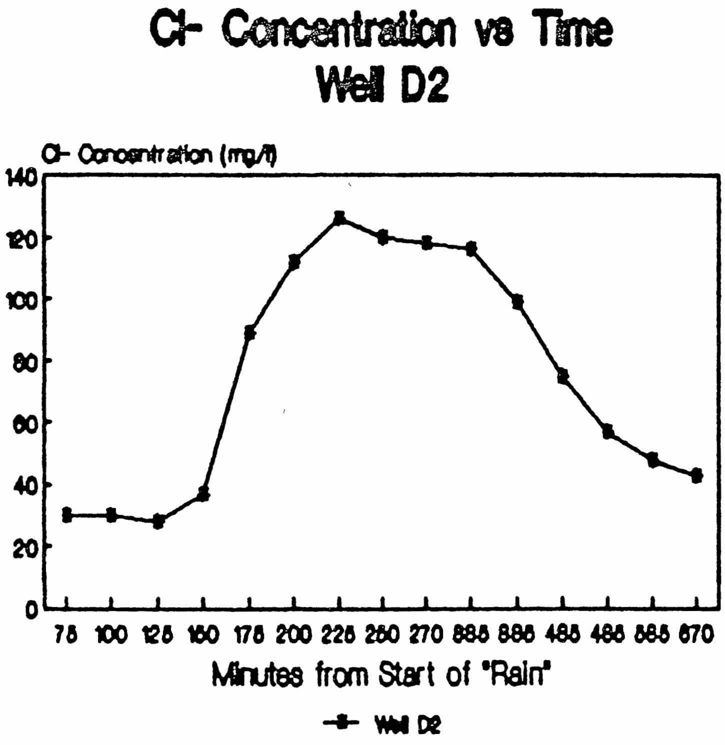


Figure 27. Cl- Concentration vs Time
Well D2

CHAPTER VIII

EVIDENCE OF MACROPORES

Soil Structure

Cracks

Desiccation crack macropores are very effective at transporting precipitation rapidly through the unsaturated zone (Pettyjohn, 1982; Blake and others, 1973; Buol and others, 1980; Hoogmoed and Bouma, 1980). Such cracks, with surface openings as much as a half inch wide, commonly form at the site during prolonged dry periods. Cracks between ped faces also may contribute to macropore flow (Beven, and Germann 1982). Hagen (1986) and Ross (1988) noted the existence of such pathways in the study aquifer.

Roots

Tubular macropores, associated with both live and decayed roots, provide avenues for rapid water transit through the unsaturated zone (Beven and others, 1982). Renyolds (1966) showed that a significant amount of rain water percolates down tree trunks.

Root macropores are abundant at the research site. The earth materials are characterized by deep root zones, which are typical of Ashport soils (SCS, 1986). Large trees with extensive root systems line the site's southern border (figure 5). Root casts are prevalent throughout soil profile (Ross, 1988).

Faunal Channels

Macropores formed by burrowing organisms, such as earthworms and gophers, are effective in conducting water to appreciable depths (Wild and others, 1976; Ehlers, 1975; 1982; Edwards and others, 1988; Zachmann and others 1987). Earthworm channels typically range from 2 to 10 mm in diameter, while those formed by gophers may exceed 50 mm (Beven and others, 1982). Macropores formed by burrowing organisms may play a role in water transport at the study site. Tunneling earthworms were observed in soil cores obtained by use of a Giddings probe.

Recharge Rate

Macropores may cause an aquifer to have a higher vertical infiltration rate than normally expected (Beven and others, 1982). Such is the case at the field site, providing further proof of the significance of macropore flow. Hagen (1986) estimated that 47 percent of total annual precipitation reached the water table as recharge. This value, which is unusually high for such fine-grained material, is indicative of macropore flow. Precipitation, water-table elevation, and soil-moisture data collected by

Hagen (1986), Ross (1988), Nelson (1989), and Froneberger (1989) indicate that ground-water recharge occurs even when soil-moisture levels are well below field capacity. The rapid response of the water table to a short lived but intense 3.76 inch rainfall is illustrated in figure 28. In this case, nearly all of the rain fell within an hour at a time when the water table was about 7.5 feet below land surface. The water table began to rise within a half hour of the start of the rain. This implies that movement of water through the dry unsaturated zone occurs at a rate of 15 feet per hour. Flow through macropores was the probable cause of this rapid recharge.

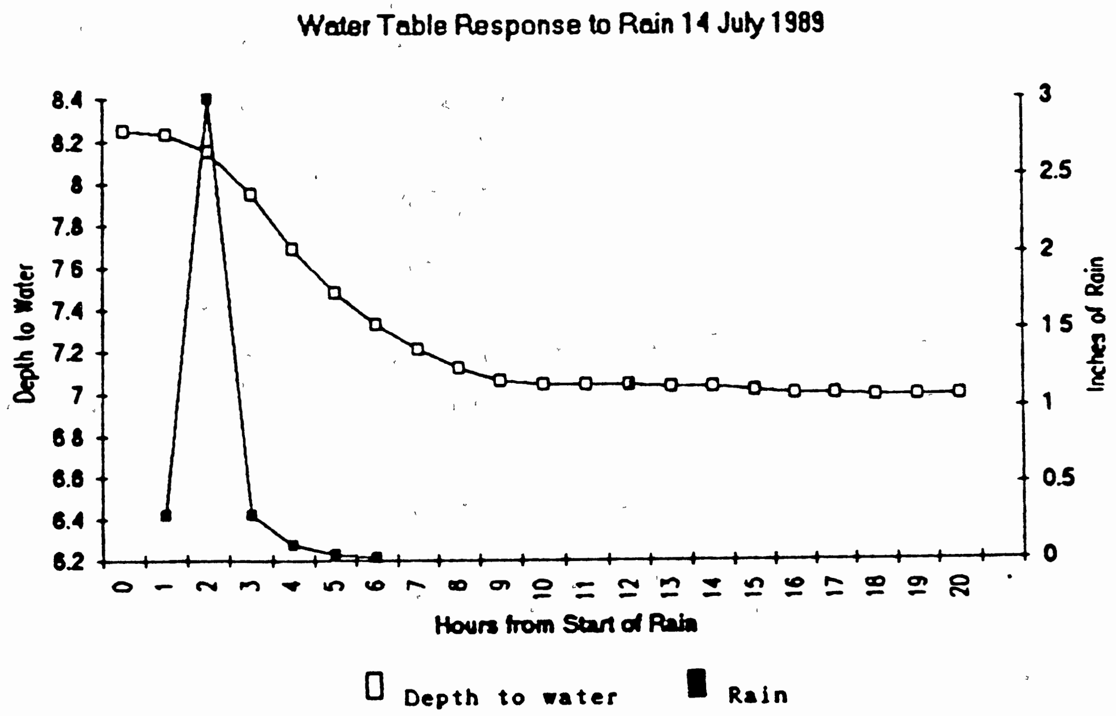


Figure 28. Water Table Response to Rain

Additional evidence of macropore flow is provided by a comparison of horizontal and vertical flow rates. The horizontal flow rate, as determined by hydrograph analyses, is around 1 ft/day. The vertical flow rate, however, is about 5 ft/day (Hoyle, 1987).

Hydraulic Conductivity

Hydraulic conductivity determined by field tests is commonly greater than expected in aquifers with macropores (Rogowski and Simmons, 1988). This also is the case at the study site, where hydraulic conductivity values calculated from aquifer tests are higher than published data for silt loams (Hoyle, 1987). The 27 to 125 gpd/ft^2 range seems high considering the fine grained nature of the alluvium. For a silty clay loam, values around 4 gpd/ft^2 are commonly expected (Li and others, 1976 in Clapp and Hornberger, 1978).

Where macropores play a role in fluid flow, hydraulic conductivities measured in the lab commonly will be much lower than those measured in the field (Olsen and others, 1981; Pollock and others, 1983; Keller and others, 1986). Melby (1989) found this to be the case at the study site. According to Melby (1989), hydraulic conductivity values determined by permeameter tests were three to six orders of magnitude lower than values obtained from aquifer tests. Regardless of the care exercised by Melby, the unconsolidated cores, which were obtained by hollow-stem auger, were compacted during drilling and during permeameter preparation, and the compaction destroyed the secondary openings.

Geochemical Evidence

Rapid variations in water quality frequently occur in aquifers recharged through macropores (Gerhart, 1986; Thomas and Phillips, 1979; Pettyjohn, 1971, 1976, 1982). Rapid change in ground-water quality is characteristic of the research site. Changes in the concentration of a given ion may occur in the deeper #4 and #5 wells, while the shallower #1, #2, and #3 wells remain unaffected. Examination of the nitrate data for the D wells illustrates this point (figure 29). Nitrate concentrations in D4 peaked in April in response to rainfall events occurring after nitrate based fertilizer has been applied to the yard. Nitrate concentrations in the shallower D1, D2, and D3 wells for April remained unchanged.

Hoyle (1987), attributed dilution of ground water at the E well site to the rapid infiltration of downspout water via macropores. Hoyle also credited infiltration through macropores for causing wells C4 and E4 to become undersaturated with respect to calcite (diluted), while calcite saturation in other wells remained unchanged.

The effect of macropores on water quality also is evidenced by geochemical data from lysimeters. Ross (1988) reported an order of magnitude increase in nitrate in

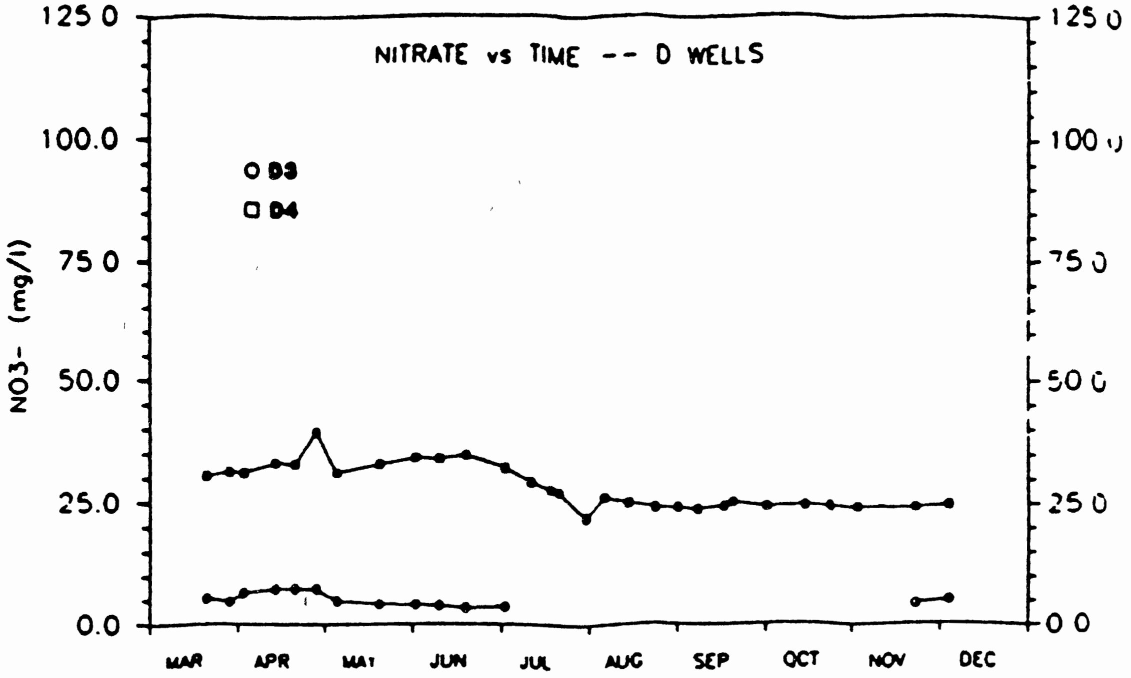


Figure 29. NO3- Data D Wells (Froneberger, 1989)

lysimeter L4 following fertilizer application to the yard, while nitrate concentrations in shallower lysimeters showed little to no change. Ross (1988) attributed this phenomenon to the vertical movement of nitrate-enriched water though macropores.

Bromide and chloride tracer testing of the unsaturated zone by Froneberger (1989) indicated preferential movement along macropores. Froneberger (1989) reported the presence of bromide in lysimeters L6B and L7 just one day after application of the tracer to the land surface. He theorized that short circuiting via macropores enabled the tracer to reach these lysimeters. The distribution of a surface applied chloride tracer in an 8-foot long soil core obtained from the tracer plot provided Froneberger (1989) with further evidence of macropore flow. Froneberger (1989) recorded a chloride peak of 42.1 mg/l at the 28 to 32 inch depth interval, indicating preferential movement to this depth.

CHAPTER IX

TRACER TESTING

Selection of Tracers

Bromide and iodide were selected as tracers for this experiment because they met the following criteria. Both move with the infiltrating water, interacting very little with the aquifer material. They are inexpensive tracers and are easily detected with the Geology Department's Dionex ion chromatograph. Background concentrations of bromide and iodide are low to none. Work done by other researchers has helped define the chemical and physical behavior of bromide and iodide in ground water, proving they are effective ground-water tracers (Davis and others, 1985).

Bromide

Background levels of bromide in the study aquifer are less than 1 mg/l. It is biologically stable and does not tend to precipitate (Davis and others, 1985). Some sorption of Br^- by plants, organic material in soils and certain soil minerals may occur, however, this tendency of sorption is weak (Bowman, 1983; Smith, 1974). Bromide is easily detected by ion chromatography in concentrations as low as 50 ppb (Stezenbach and Thompson, 1983). A number of potential sources could contribute to the background bromide levels, although none are likely at the research site. Wheat farmers may fumigate their soils with methyl bromide (Trent and others, 1989). Bromine is present in the atmosphere, and in oil-field brines typical of Oklahoma (Faiq and others, 1988; Hem, 1985). Rain and snow commonly contain bromine in concentrations ranging from 5 to 150 µg/l (Hem, 1985).

Iodide

Background levels of iodide in the study aquifer are below the set detection limits of the ion chromatograph. Muramatsu and others (1990), found that iodide was not well sorbed by clay minerals or quartz sand. Iodide may be affected by microbiological activity (Davis and others, 1985). The ion chromatograph is capable of detecting iodide at levels ranging from 0 to 10 µg/l (Ubom and Tsuchiya, 1988).

Bromide Versus Iodide

Bromide and iodide differ slightly in their behavior as tracers. The iodide ion, with a radius of 2.19 Å, is slightly larger than the bromide ion, whose radius is 1.96 Å (Brown, 1981). Because of its larger size, the iodide ion may migrate more slowly than the bromide ion. Iodide may be sorbed to a greater extent than Br^- thereby reducing its concentration in the ground water (Davis, 1978; Leap, 1978).

Experimental Methods

Set Up

The D site was selected for the tracer study because it is the only site in which there is a large, unobstructed area upgradient of the wells. This area allowed for easy installation of the tracer plot and ready accesses by a truck mounted Gidding's probe. The test plot encompassed an area approximately 25 ft x 23 ft. Plastic landscape border, buried 1 inch deep, partitioned off two 4 ft x 4 ft areas and a 6 ft x 10 ft area for tracer application (figure 30). The intentional location of these plots away from the wells and buried utilities prevented the tracer solution from flowing down the well casings, sewer pipe and utility cables. Drip irrigation tubing, with 6 inch spacing, surrounded the tracer application plots (figure 30). Based on work done by Bouwer (1986), tap water flowing from the tubing served to minimize lateral flow of the tracer during the experiment.

Preparation of the tracer solutions involved adding a calculated amount of oven dried KI and KBr salt to deionized distilled water. Five 30 gallon containers and one 22 gallon container held the prepared tracer solution in the field (figure 31). The containers were bathed with nonphosphate, neutral detergent in hot water and given a

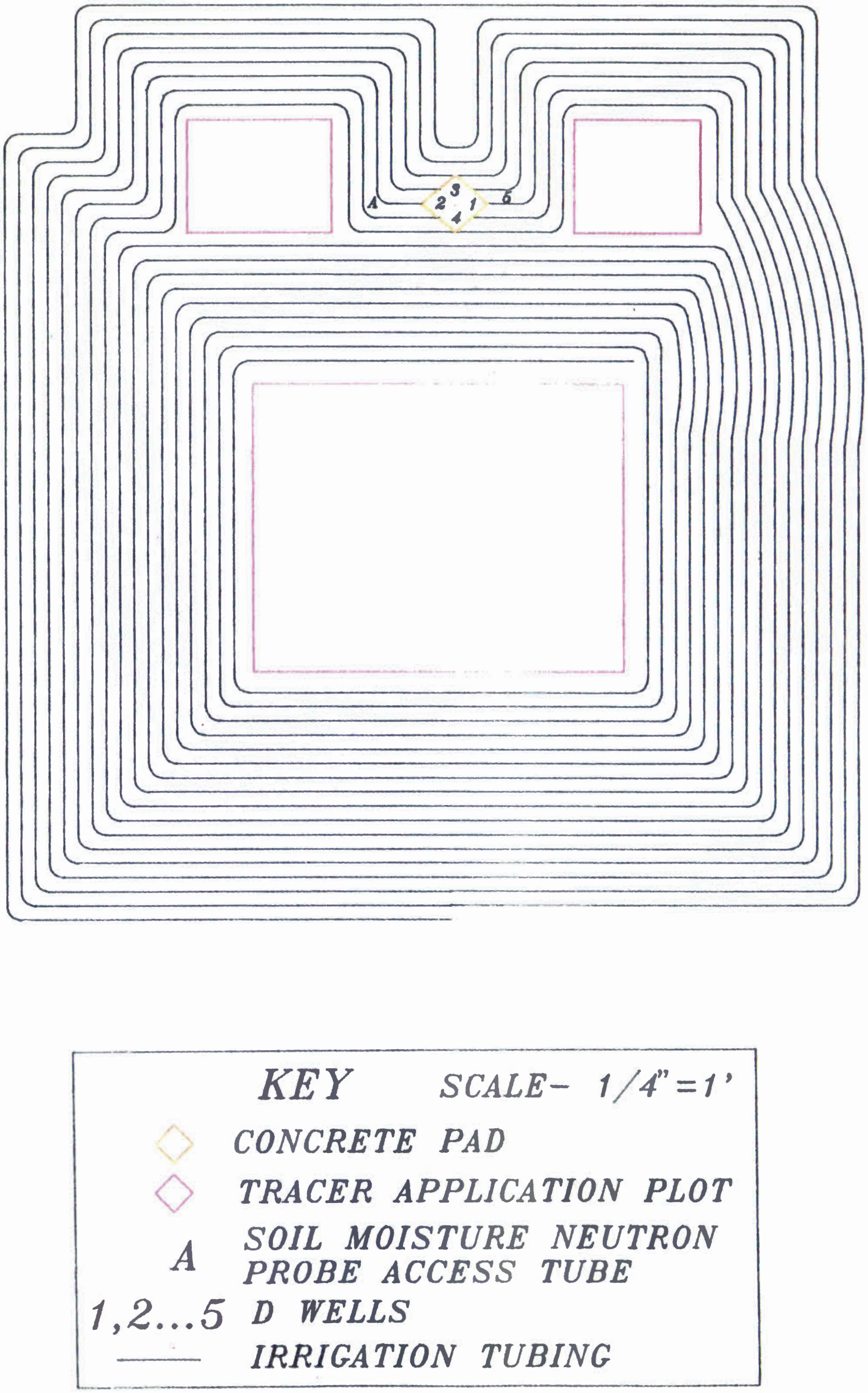


Figure 30. Tracer Test Set Up

Figure 31. Photographs of Test Set Up

deionized distilled water rinse before being used. The tracer water flowed by gravity through Tygon tubing from the elevated containers (figure 31).

Procedure

The bromide tracer test was conducted on March 1, 1991 under initially "dry" (.093 cc/cc at 30 inches) soil-moisture conditions. The iodide tracer test was performed on April 29, 1991, when "wetter" (.185 cc/cc at 30 inches) soil-moisture conditions prevailed. The difference in initial soil-moisture content between the two tests is illustrated in figure 32. Measurements of soil moisture were made in order to compare the effect of the initial soil-moisture content on solute movement. The initial soil-moisture content in the I^- test was two times higher than the Br^- test at the 30 inch depth (figure 32).

In both tracer tests, a 3 inch rain event, falling at the rate of 1 inch/hour, was simulated over the entire tracer plot area. Ground-water samples were taken approximately every 5 minutes for the first five hours of the experiment, and then every 10 to 15 minutes for the remainder of the test. Alspach (in prep.) measured soil moisture in 6-inch depth increments, and also took soil cores from the 6 ft x 10 ft tracer application area. The holes left by the coring were immediately packed with bentonite to prevent the tracer solution from flowing down them. Water levels measured prior to testing verified ground water flow toward the D wells (figures 33 and 34). A pressure transducer in well D5 continuously measured depth to water during the bromide experiment.

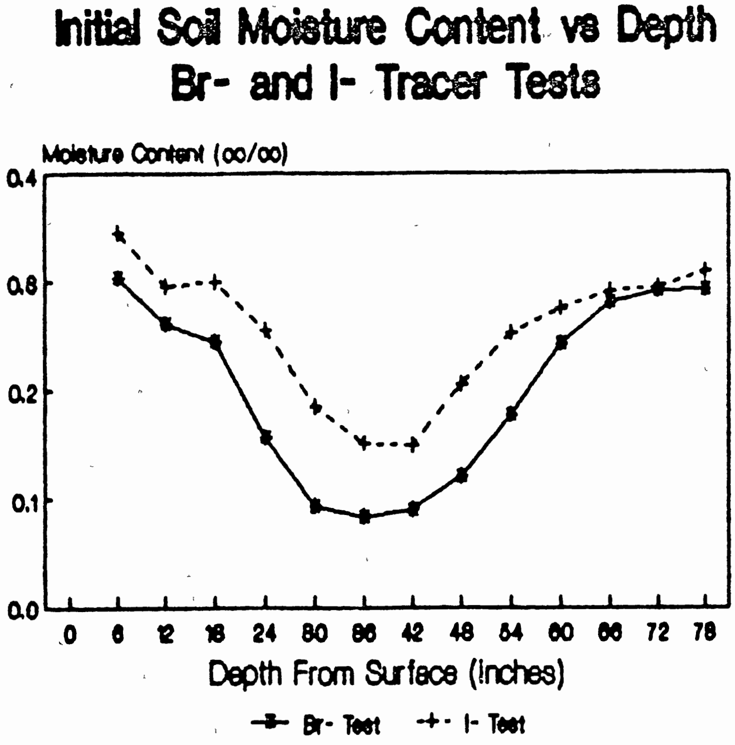


Figure 32. Initial Soil-Moisture Profile

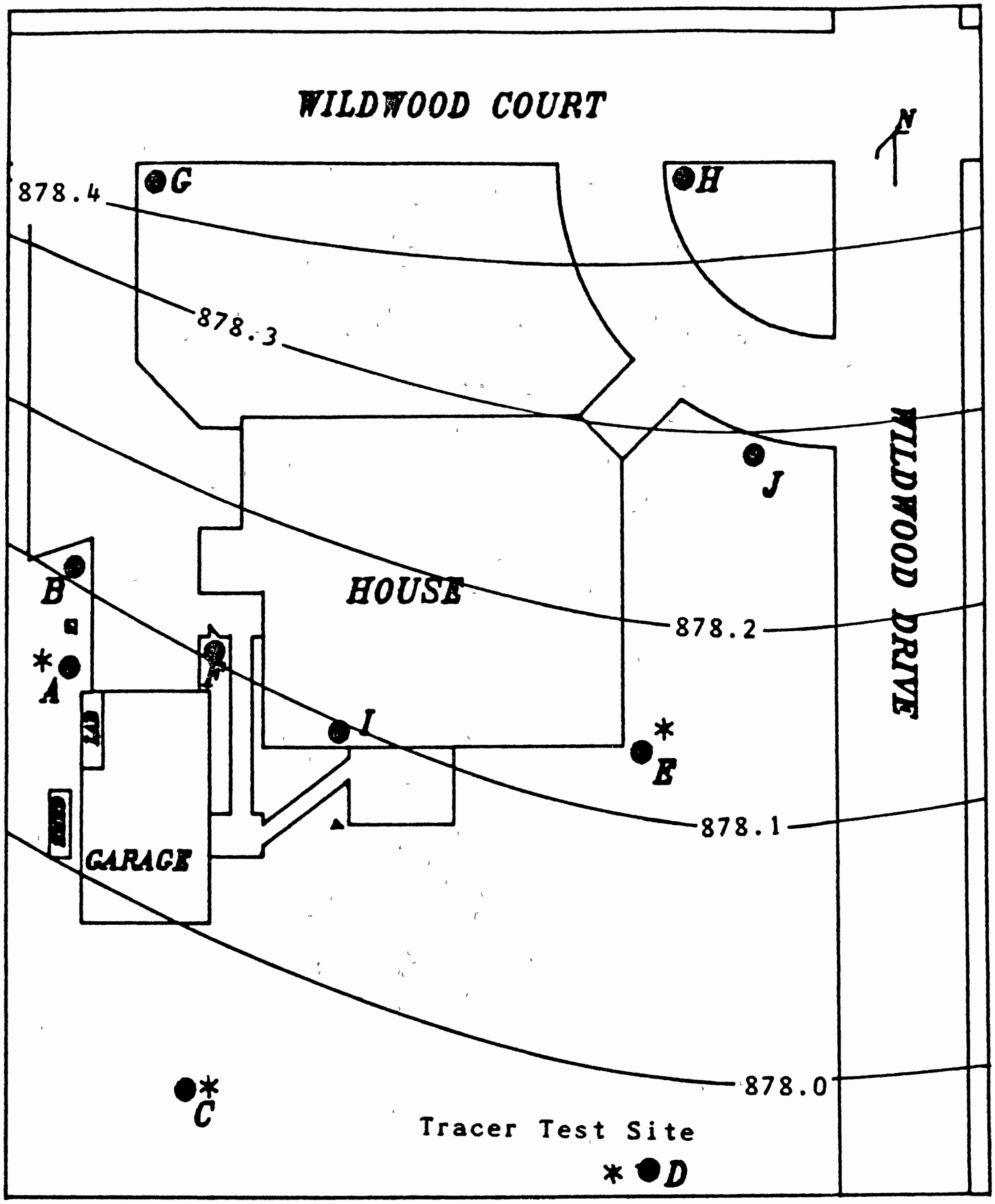


Figure 33. Water-Level Map I- Tracer Test

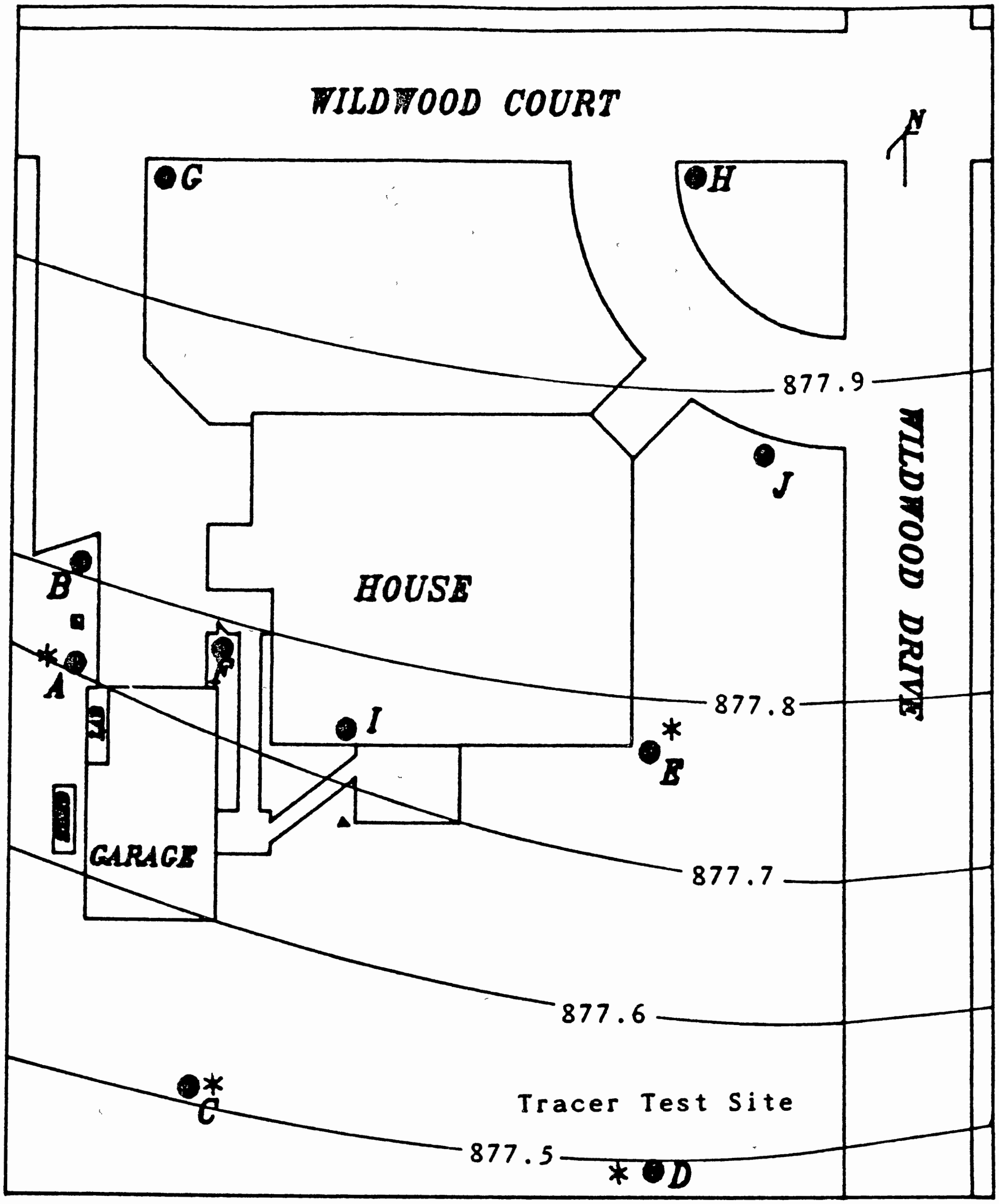


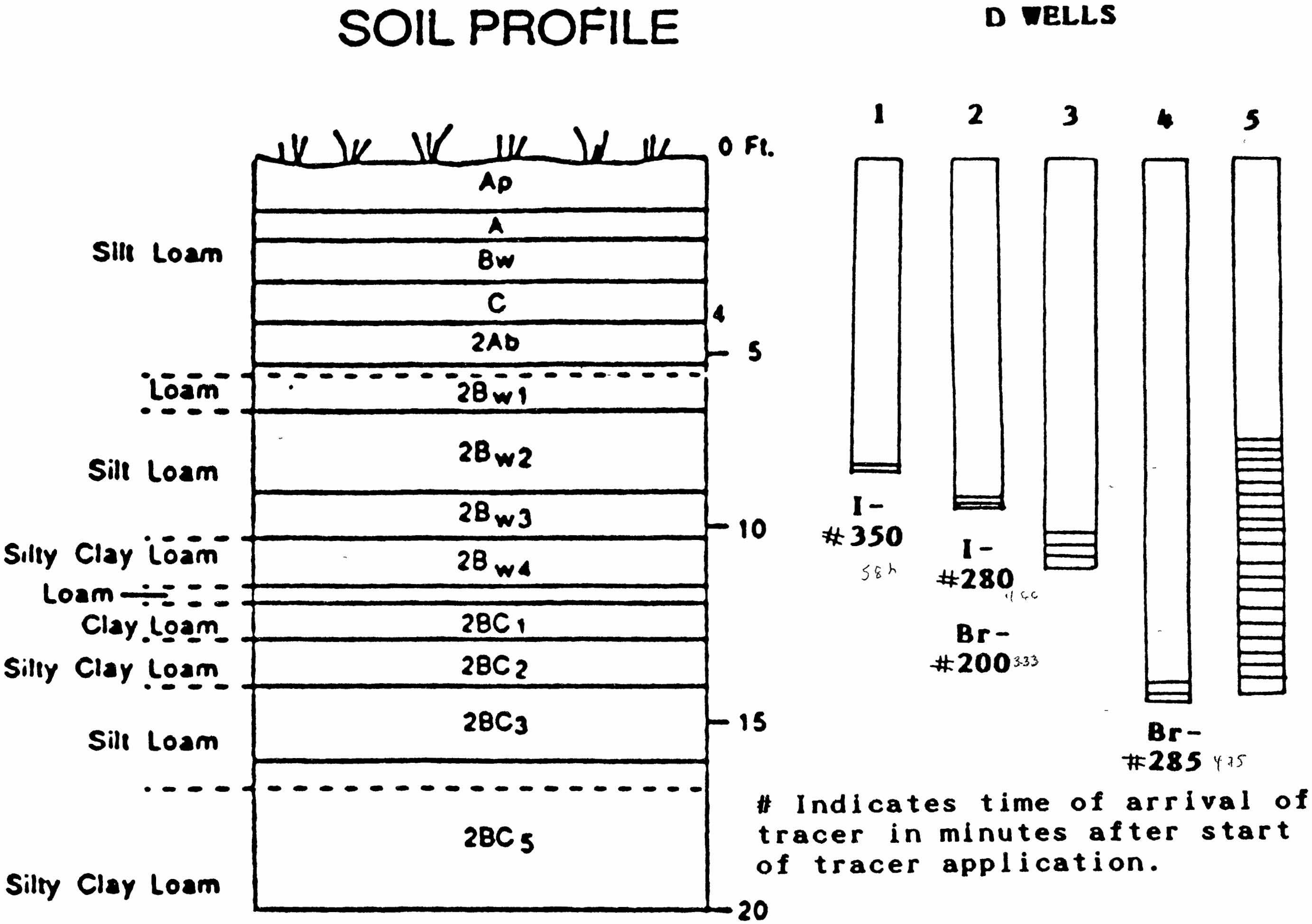
Figure 34. Water-Level Map Br- Tracer Test

Bromide Tracer Test Results

Bromide appeared in two wells, D_2 and D_4, during the experiment (figure 35). Desiccation cracks were present on the land surface prior to the start of the test. A summary of the estimated rates of Br^- movement are given in Table IV.

The bromide tracer appears to have reached a depth of 9 feet in the soil profile between 125 minutes and 485 minutes after application of the tracer. As seen in figure 36, Br^- concentrations for well D_2, which is screened from 9 to 9.2 feet, gradually increased, peaked at 335 minutes, and then declined to background levels during this time period. Potassium concentrations also peaked during this interval, providing further evidence that the KBr tracer reached this well (figure 36). Bromide concentrations at the 9 foot depth increased from .289 mg/l to .798 mg/l during this period. It was not possible to explicitly indentify the arrival time of Br^- at this depth, however, the arrival of the tracer at 9 feet between 125 and 485 minutes indicates the rate of movement of bromide to be somewhere between 1.11 ft/hr and 4.32 ft/hr.

Bromide levels dramatically peaked in well D_4, which is screened at a depth of 13.6 to 13.9 feet, 285 minutes after application of the tracer. Concentrations of both Br^- and K^+ hovered near natural background levels, suddenly peaked, then immediately dropped back to background level as illustrated in figure 37. Further evidence that this



# Indicates time of arrival of tracer in minutes after start of tracer application.

Figure 35. Distribution of Br- and I- in D Wells

peak represented tracer solution is provided by the conductivity data for well D_4. The peak in Br^- and K^+ levels in the well was accompanied by a sharp drop in conductivity (figure 38). The tracer solution had a lower conductivity, 880 μmhos/cm, than the background ground water, which had a conductivity of 1180 μmhos/cm.

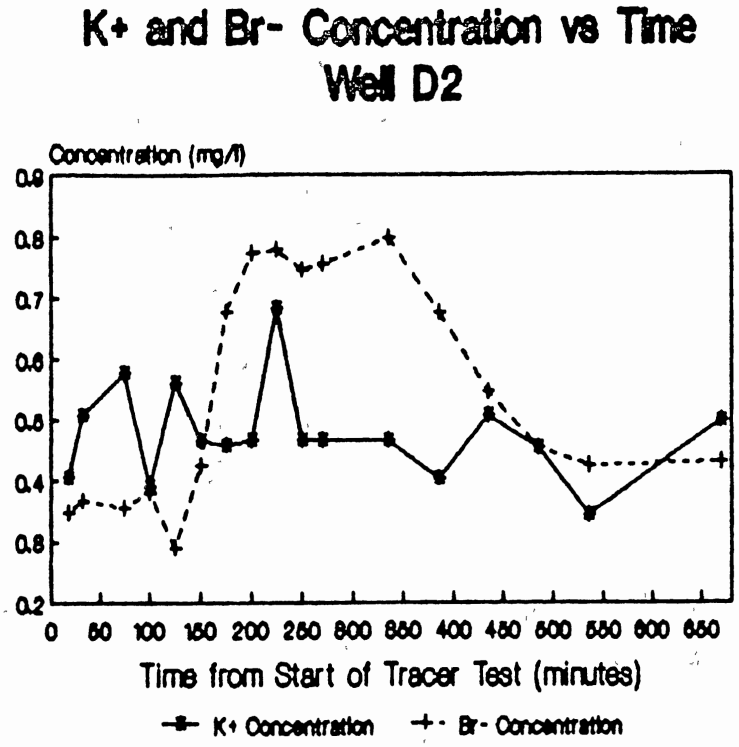


Figure 36. K^+ and Br^- Concentration vs Time Well D2

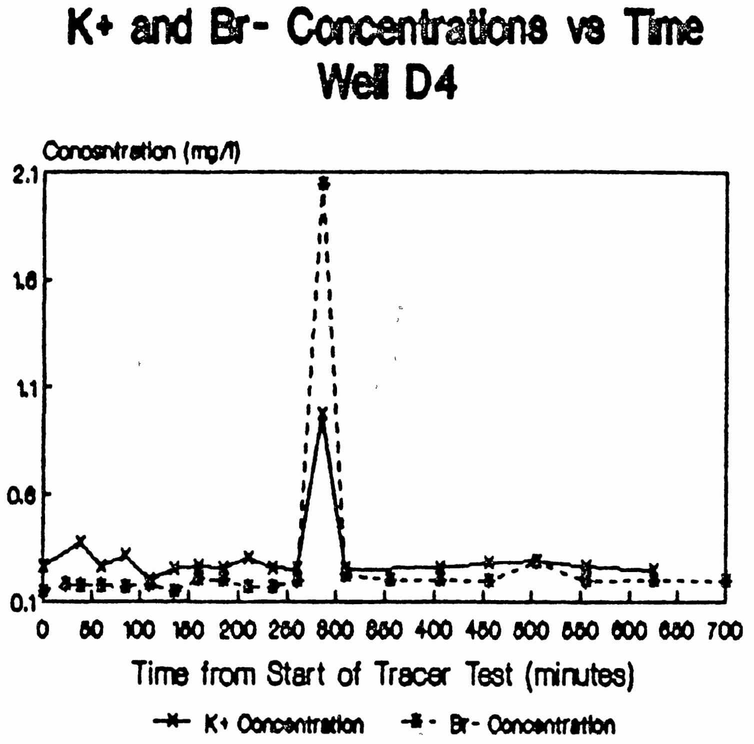


Figure 37. K+ and Br- Concentration vs Time Well D4

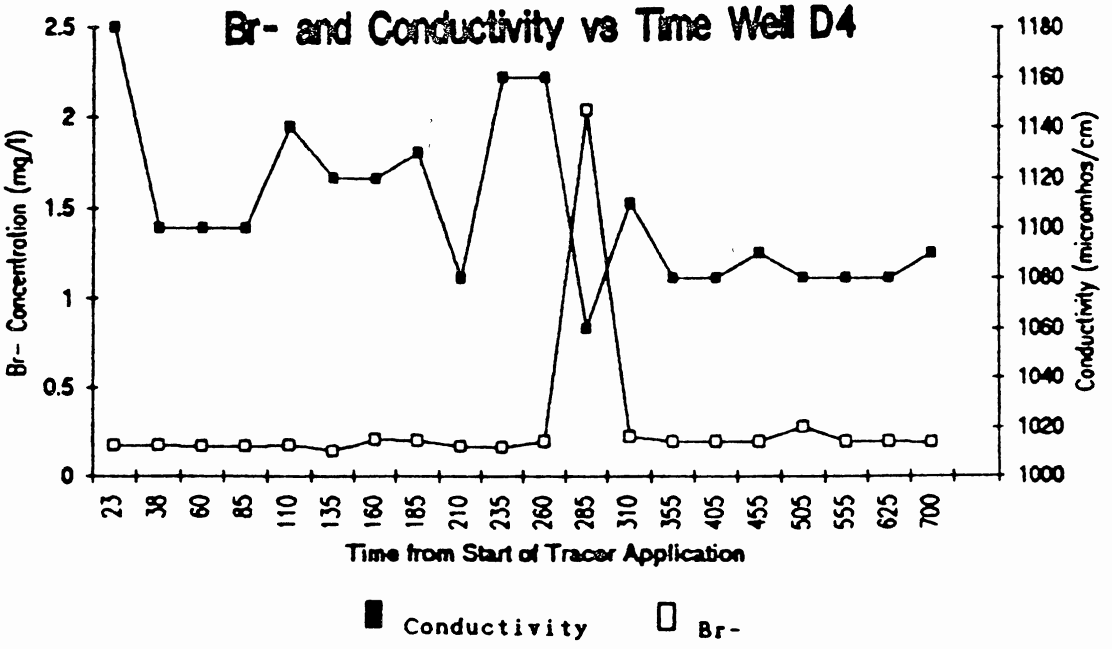


Figure 38. Br- and Conductivity vs Time Well D4

The data for well D4 suggest that the tracer moved through the upper 13.9 feet of the soil within 4.75 hours. Bromide levels increased from a background level of .144 mg/l to 2.04 mg/l in 285 minutes, indicating a rate of Br- movement at 2.86 ft/hour. In order to verify the Br- peak of 2.04 mg/l, another portion of the sample was taken from the original collection bottle, filtered, and analyzed. In repeated analyses done on different days, the Br- concentration remained at 2 mg/l.

Little change appeared to occur in the elevation of the water table during the bromide test (figure 39). The sharp peaks in the graph correspond to times the well was pumped for sample collection, thus quickly dropping depth to water in the well. There are two reasons why the expected rise in the elevation of the water table did not occur. First, the simulated 3 inch tracer "rain" fell on only a small 23 ft x 25 ft area. The 3.76 inch natural rain that produced the dramatic water-table rise discussed in Chapter VIII fell over several square miles, thereby providing a much greater volume of infiltrating water. The larger area also provided access to a greater number of macropores, increasing the amount of water reaching the water table. Secondly, any water-table rise from the tracer "precipitation" in the monitored well was cancelled out by the continuous withdrawal of water for sampling.

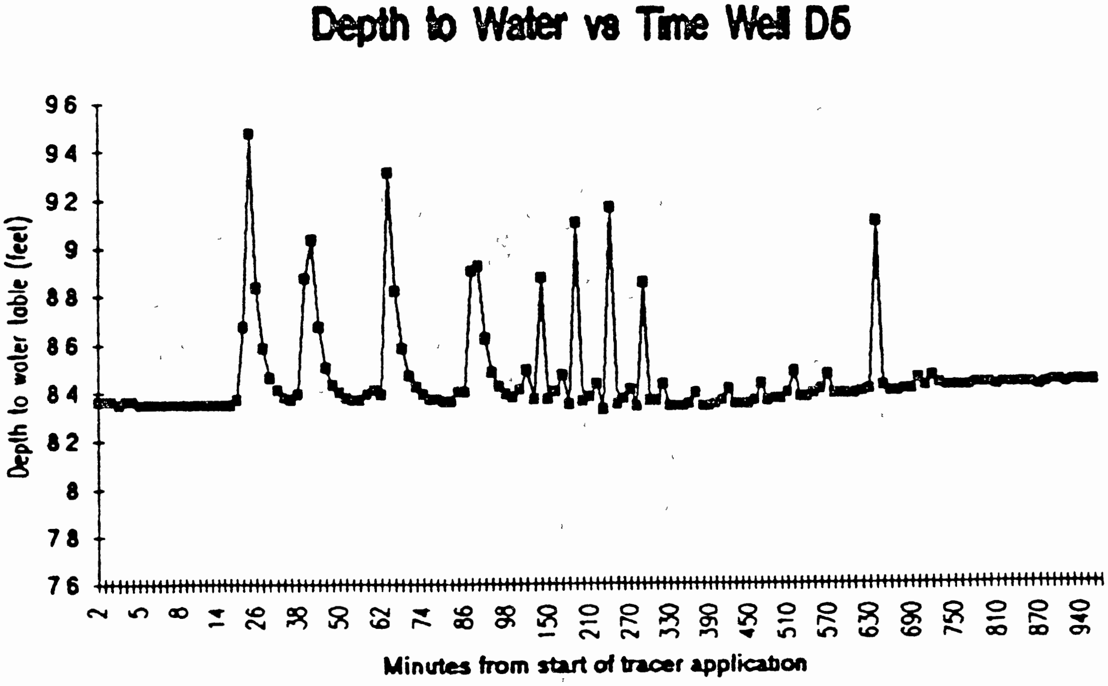


Figure 39. Depth to Water vs Time Well D5

Iodide Tracer Test Results

Considerable ponding occurred during the iodide test in which the initial soil-moisture level was high (.185 vs .093 cc/cc at 30 inches during the Br^- test). Because of the higher moisture levels, the soil rapidly became saturated at the surface causing the infiltration rate to decrease and ponding to occur. During this test, plastic landscape border surrounding the application plots prevented surface runoff of the tracer solution. A summary of the estimated rates of I^- movement are shown in Table

IV. No depth to water data were collected due to transducer failure.

Breakthrough curves for the I^- tracer test are shown in figure 40. The arrival of the tracer in well D_1 (screened from 8.0 to 8.2 feet) at 350 minutes after the start of tracer application indicates the rate of movement of I^- to be around 1.41 feet per hour. Concentrations of I^- ranged from .233 to .994 mg/l. After its initial appearance at 350 minutes, I^- continued to be present in the well throughout the remainder of the experiment.

I^- reached a depth of 9 feet 280 minutes after the tracer was applied to the surface, thus indicating a rate of I^- movement of around 1.93 ft/hour. As seen in figure 40, I^- in well D_2 (screened from 9 to 9.2 feet), first appeared at 280 minutes, peaked at 3.23 mg/l, leveled out at around 1 mg/l, and persisted throughout the remainder of the study.

Discussion

The I^- and Br^- tracer tests showed that the applied solution did not move as a steady, even front through the soil profile, but rather moved erratically due to short-circuiting through macropores. Both tracer tests used the same site, soil profile, tracer volume, and application rate, but varied in initial soil-moisture content. The initial soil-moisture content appeared to affect the depth, rate, and volume of tracer movement. A summary of the test results is given in Tables IV and V.

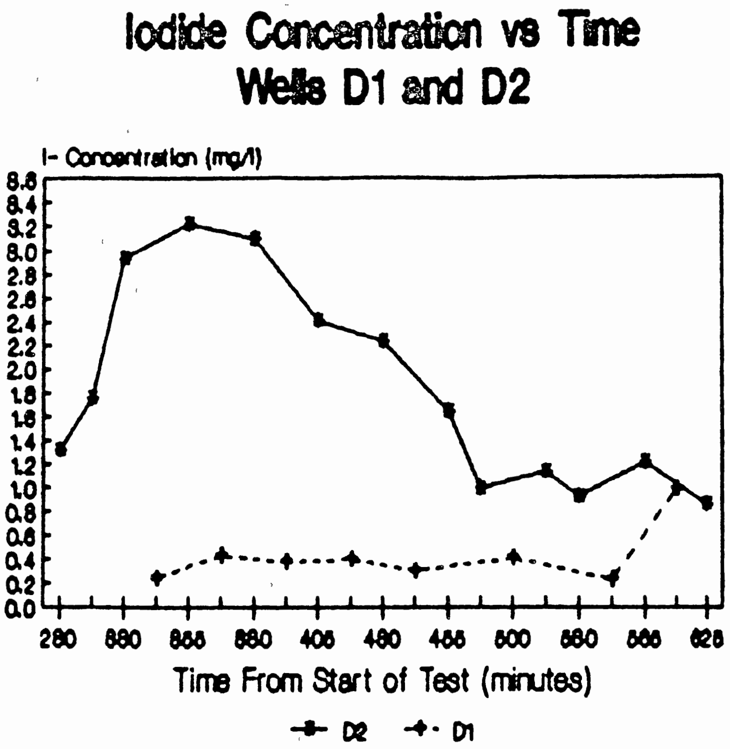


Figure 40. I^- Concentration vs Time
Wells D1 and D2

TABLE IV

ESTIMATED RATES OF TRACER MOVEMENT

Well #	Tracer	Depth (feet)	Time of Arrival (minutes)	Rate (ft/hour)
D_1	I^-	8.2	350	1.41
D_2	I^-	9.0	280	1.93
D_2	Br^-	9.0	125-485	1.11-4.32
D_4	Br^-	13.9	285	2.93

TABLE V

BROMIDE AND IODIDE TEST RESULTS

	Bromide Test	Iodide Test
Initial Depth to Water (feet)	8.36	7.83
Tracer Water pH (units)	5.90	6.22
Tracer Water Conductivity (µmhos/cm)	880	540
Initial Soil Moisture Content at 30 inches (cc/cc)	.093	.185
Background Concentration of Tracer (mg/l)	.192	0
Time from Start of Tracer Application to First Breakthrough of Tracer (minutes)	around 200	280
Wells Tracer Appeared In	D2, D4	D1, D2
Concentration of Tracer Detected in Ground-Water (mg/l)	.798-2.04	.233-3.23

The 1.11 to 4.32 ft/hour rates of tracer movement calculated for the Br- and I^- tests are much higher than the 3×10^{-7} to 2×10^{-4} ft/hour saturated hydraulic conductivities measured in the lab by Melby (1989). This indicates that the tracer moved through the soil at least 2×10^4 times faster than it would have moved had macropores not been present.

With fast flow rates (around 3 ft/hour) the anions flowing through macropores had little time to associate with the resident soil water before passing through the profile to the wells. The macropores acted like a straw, limiting lateral dispersion of the tracer, and favoring downward vertical dispersion and movement. This enabled slugs of the tracer, such as the 2.04 mg/l slug detected in well D_4, to reach depth at such high concentrations. When the flow rate was slower (around 1.1 ft/hour), however, the tracer solution had more time to mix with the resident water. This diluted the tracer solution causing it to be present in lower concentrations at depth (.798 mg/l Br^- in D_2 for example).

Tracer ions appeared in deeper wells before they were detected in the shallower wells during both studies. Iodide appeared first in well D_2, and then arrived at well D_1 70 minutes later. During the Br^- experiment, tracer levels peaked at the 13.6 foot depth (well D_4) 50 minutes before the shallower 9 foot depth (well D_2). In both cases, the tracer moved to the deeper wells first by way of root channels and other types of macropores in the profile, as discussed in Chapter VIII.

An increase in Br⁻ concentration occurred in well D2 during the I⁻ tracer test (figure 41). As the I⁻ tracer water moved into the soil profile it displaced some of the residual soil solution containing Br⁻ from the previous experiment. The displacement of the Br⁻ enriched water could have significance in terms of the leaching of mobile toxins.

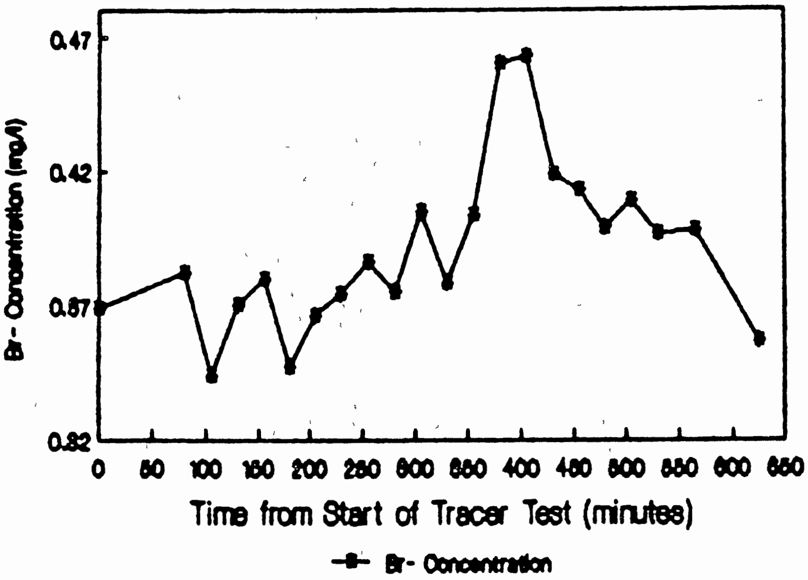


Figure 41. Br⁻ Concentration Well D2 I⁻ Tracer Test

The amount of water pumped from each well during both tests was kept at a low value in order to reduce any effect of drawdown on increasing the rate of flow from the water table to the well screen. Less than 500 ml was withdrawn each time a sample was collected. The effort appeared to be successful as illustrated in figure 39. With the exception of the peaks caused by pumping of the well D_5 for sample collection, no significant decline in depth to water occurred. The position of the water table remained fairly constant throughout the experiment.

The time it took for the tracer to first appear in the saturated zone remained the same for the two tests (table IV). In both experiments the tracers were first detected roughly 4 hours after the tracer solution was first applied to the land surface.

Data indicate that the initial soil-moisture content affected the depth of tracer movement, although the depth to water differed by 0.53 feet (8.36 during the Br^- test versus 7.83 feet duing the I^- test). The tracer penetrated the soil profile the farthest when the initial soil-moisture content was lower. The greatest recorded depth reached by a tracer was 13.6 ft in well D_4 during the Br^- experiment. In this experiment, the initial soil-moisture content was only half that of the I^- test, and desiccation cracks abounded on the soil surface. For comparison, the greatest depth reached by the I^- test was only 9 feet (figure 35). Perhaps the period of drying prior to the Br^- test enlarged the macropores to depth allowing the tracer to move further. When higher initial soil-moisture conditions prevailed, as in the I^- test, macropore flow affected the shallower D_1 and D_2 wells. Tracer movement seemed to be slowest when the initial soil-moisture content was higher. The data suggest that the tracer traveled 1.5 times slower during the I^- test than during the Br^- test, when the initial soil-moisture content was highest (table IV). The infiltration capacity was exceeded much more quickly during the I^- test, resulting in considerable ponding of the tracer on the surface. As a result, it took a longer period of time for the tracer to infiltrate. The variation in travel time between the two tests also may be due, in part, to the presence of more surface desiccation crack macropores were during the Br^- test. The greater number of desiccation cracks perhaps served to increase the infiltration rate (Beven and Germann, 1982). Another factor that may have slowed the rate of tracer movement under "wetter" initial soil-moisture conditions is the expansion of clays. The clay fraction of the aquifer contains smectite, an expanding clay (Ross, 1988). Swelling of the smectite under the "wet" conditions perhaps narrowed or closed some flow pathways reducing the rate of tracer flow.

It appears that a greater volume of tracer migrated into the saturated zone during the I^- test, in which the initial soil-moisture content was twice as high as the Br$^-$ study and the fillable porosity was smaller. Iodide appeared in two wells and continued to be present in both of them for the remainder of the experiment (figure 40). In the Br$^-$ test, however, the tracer appeared once as a slug in the D$_4$ well, and for approximately 360 minutes in well D$_2$. Unlike the I$^-$, Br$^-$ did not persist throughout the experiment. Perhaps the high levels of ponding reached during the I$^-$ experiment increased cumulative vertical infiltration. Because the initial soil-moisture content was higher, the soil did not adsorb as much water, hence more of the tracer flowed through. Once in the ground, the rate of loss of tracer water from saturated macropores to the surrounding "wet" micropores slowed. During the Br$^-$ study, the dryer upper few feet of the soil accepted most of the tracer solution. Much of the tracer entering through cracks on the surface may have moved from the macropores to the unsaturated matrix due to capillarity. Therefore, less Br$^-$ solution was available for short-circuit flow.

CHAPTER X

SUMMARY AND CONCLUSIONS

Tracer testing confirmed that surface-applied pollutants may quickly migrate through silt and clay to the ground water via macropores. In both the Br^- and I^- tests, it took only a little over four hours for the tracer to reach the saturated zone. The rate of tracer movement was 2×10^4 times faster than the rate measured in the lab by Melby (1989). The tracer experiments showed that some of the applied water moved through the soil profile without displacing much of the resident water. The tracer solution did not move as a steady front through the soil, but rather moved erratically due to short-circuiting through macropores.

Initial soil-moisture content appeared to affect the depth, rate, and volume of tracer movement. The tracer penetrated the soil profile the farthest when the initial soil-moisture content was lower, the unsaturated zone thicker, and fillable porosity larger. Tracer movement seemed to be 1.5 times slower when the initial soil-moisture content was higher. Apparently, a greater volume of tracer migrated to the saturated zone during the I^- test, in which the initial soil-moisture was twice as high as the Br- study.

The quantity of tracer reaching the ground water, relative to the total input, is easy to dismiss as insignificant. Applied to the surface at a concentration of 500 mg/l, the tracers appeared at depth at a level of only 0.798 to 3.23 mg/l. This may not seem like a significant amount of pollutant, but had the contaminant been a toxin, such as TEPP, it would have been considered high enough to pose a potential health risk. Detected at these levels, a hazardous waste facility would be required to notify the EPA and perhaps enter into corrective action. In addition, storage in the unsaturated zone may be measured in months or years, but it is the short term, concentrated mass released during a period of infiltration that determines the rate of leaching.

Considering the total amount of tracer applied at the surface, the amount actually reaching the water table also may seem negligible. On the other hand, if the tracer had been applied over a large area instead of over a small one the total mass reaching the ground-water reservoir would have been significant. The evidence (water-table rise in response to precipitation illustrated in figure 28) indicates that cumulative macropore flow could add up to allow a significant volume of pollutant to reach the ground water, enough to even cause the water table to rise.

This research illustrates the danger in assuming that silt and clay-rich soils provide shallow ground water protection from surface applied pollutants. Siting a landfill or land treatment unit on a soil of this type, especially if recharge is affected by macropores, may no more guard the aquifer then if the facility were situated a more coarse-grained material. Hazardous chemical spills or waste water applied on silt and clay may migrate more quickly to ground water than previously realized. As a result, this research highlights the necessity of taking macropore contaminant flow into account when developing protection plans for shallow, silt and clay aquifer systems.

Suggestions For Further Research

More research at the study site needs to be done in order to develop a better understanding of contaminant migration to the saturated zone. The 13.6 foot interval appears to be most susceptible to contamination from the surface (table 5). Geochemical evidence for this is discussed in Chapter VIII. Coring of the soil at least to this depth and measurement of macropore size may shed some light on this phenomenon. Another interesting experiment would be to see how different application rates affect tracer movement. Tracer migration may occur differently if the rate of application were slow enough to prohibit ponding, or if the tracer were applied as a solid to the land surface and moved into the aquifer via natural rain events.

TABLE VI

WELLS SHOWING GEOCHEMICAL EVIDENCE OF RAPID CONTAMINATION VIA MACROPORES

Well	Start of Screen (ft below surface)	Soil Horizon Screened
D_4	13.6	2BC2
E_4	13.6	2BC2
C_4	14.2	2BC3

REFERENCES CITED

Acre, T.J., 1989. The Influence of Macropores on Water Movement in the Unsaturated Zone. Unpublished M.S. Thesis, Oklahoma State University, 84 p.

Alspach, S., in prep. Movement of Bromide Through Soil to an Aquifer. Unpublished M.S. Thesis, Oklahoma State University.

Armstrong, A.C., and Arrowsmith, R., 1986. Field evidence for a bi-porous soil water regime in clay soils. Agricultural Water Management, v. 11, pp. 117-125.

Beven, K., and German, P., 1981. Water flow in soil macropores II. A combined approach. Journal of Soil Science, v. 32, pp. 15-29.

Beven, K., and Germann, P., 1982. Macropores and water flow in soil. Water Resoures Research, v. 18, pp. 1311-1325.

Blake, G., Schlichting, E., and Zimmerman, V., 1973. Water recharge in a soil with shrinkage cracks. Soil Science Society of America Proceedings. N. 37, pp. 669-672.

Bowman, R.S., 1983. Evaluation of some new tracers for soil water studies. Agronomy Abstracts, p. 139.

Bowman, R.S., 1985. Analysis of soil extracts for inorganic and organic tracer anions via high performance liquid chromatography. Journal of Chromatography, v. 285, pp. 467-477.

Bouma, J., Dekker, W., and Wosten, J.H.M., 1978. A case study on infiltration into dry clay soil: physical measurements. Geoderma, v. 20, pp. 41-51.

Bouwer, H., 1986. Intake rate: cylinder infiltrometer. in Methods of Soil Analysis Part 1 - Physical and Mineralogical Methods Second Edition, American Society of Agronomy Inc. and Soil Science Society of America Inc., Madison, Wisconsin, pp. 825-845.

Bricker, O.P., 1982. Redox potential: its measurement and importance in water systems. in Water Analysis Volume 1, Academic Press, pp. 55-76.

Bradbury, M.H., and Green, A., 1985. Measurement of important parameters determining aqueous diffusion rates through crystalline rock matrices. Journal of Hyrology, v. 82, pp. 39-55.

Brewer, R., 1964. Fabric and Mineral Analysis of Soils. John Wiley and Sons Inc., New York, 470 p.

Brown, T.B., and LeMay, H.E., 1981. Chemistry the Central Science, 2nd Edition. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 840 p.

Buol, S.W., Hole, F.D., and McCracken, R.J., 1980. Soil Genesis and Classification, 2nd Edition. Iowa State University Press, Ames, Iowa, 404 p.

Chan, K.Y., and Mead, J.A., 1989. Water movement and macroporosity of an Australian alfisol under different tillage and pasture conditions. Soil Tillage and Research, v. 14, pp. 301-310.

Cheng, J.D., 1988. Subsurface stormflows in the highly permeable forested watersheds of southwestern British Columbia. Journal of Contaminant Hydrology, v. 3, pp. 171-191.

Davis, S.N., Campbell, D.J., Bentley, H.W., and Flynn, T.J., 1985. An Introduction to Ground-Water Tracers. U.S. Environmental Protection Agency, EPA/600/2-85/022, 201 p.

D'Lugsoz, J.J., 1976. Degradation of water quality by salt water infiltration in east-central Oklahoma. Geological Society of America Abstracts of Programs, v. 8, pp. 837-838.

Edwards, W.M., Shipitalo, M.J., Norton, L.D., 1988. Contribution of macroporosity to infiltration into a continuous corn no-tilled watershed: implications for contaminant movement. Journal of Contaminant Hydrology, V. 3, pp. 193-205.

Edwards, W.M., Norton, L.D., and Redmond, C.E., 1988. Characterizing macropores that affect infiltration into nontilled soil. Soil Science Society of America Journal, v. 52, pp. 483-487.

Ehlers, W., 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Science, v. 119, pp. 242-249.

Faiq, S.Y., and Al-Taie, F.A., 1988. Atmospheric lead and bromine levels in downtown Baghdad. Water, Air and Soil Pollution, v. 42, pp. 153-158.

Froneberger, D.F., 1989. Influence of Prevailing Hydrologic Conditions on Variation in Shallow Groundwater Quality. Unpublished M.S. Thesis, Oklahoma State University, 153 p.

Gerhart, J.M., 1986. Groundwater recharge and its effects on nitrate concentration beneath a manured field site in Pennsylvania. Ground Water, v. 24, pp. 237-244.

Germann, P., and Beven, K., 1981. Water flow in soil macropores I. An experimental approach. Journal of Soil Science, v. 32, pp. 1-13.

Germann, P.F., Edwards, W.M., and Owens, L.B., 1984. Profiles of bromide and increased soil moisture after infiltration into soils with macropores. Soil Science Society of America Journal, v. 48, pp. 237-244.

Gerritse, R.G., and Singh, R., 1988. The relationship between pore water velocity and longitutindal dispersivity of Cl-, Br-, and D_2O in soils. Journal of Hydrology, v. 104 pp. 173-180.

Griffin, R.A., Gibbs, J.P., and Schuller, R.M., 1981. Procedure for the Collection of Representative Water Quality Data From Monitoring Wells. Cooperative Groundwater Report 7, Champaign, Illinois, Illinois State Water Survey.

Haaser, F.G., Jester, W.A., Heald, W.R., Rogowski, A.S., and Pionke, H.B., 1978. Use of Neutron Activatable Tracers for Simulating Water and Chemical Flow Through Porous Media. Research Project Technical Completion Report,Pennsylvania State University, OWRT A-046-PA(2), 14-34-0001-6039.

Hagen, D.J., 1986. Spatial and Temporal Variability of Ground Water Quality in a Shallow Aquifer in North-central Oklahoma. Unpublished M.S. Thesis, Oklahoma State University, 191 p.

Heard, J.R., Kladivko, E.J., and Mannering, J.V., 1988. Soil macroporosity, hydraulic conductivity and air permeability of silty soils under long term conservation tillage in Indiana. Soil Tillage and Research, v. 11, pp. 1-18.

Hem, J.D., 1985. Study and Interpretation of the Chemical Characteristics of Natural Water. U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Hillel, D., 1971. Soil and Water, Physical Principles and Processes. Academic Press, New York, 288 p.

Hoogmoed, W.B., amd Bouma, J., 1980. A simulation model for predicting infiltration into cracked clay soil. Soil Sci. Soc. Am. J., v. 44, pp.458-461.

Hounslow, A.W., 1989. WATEVAL: A Non-Thermodynamic Computer Model for Water Quality Interpretation. School of Geology, Oklahoma State University.

Hoyle, B.L., 1987. Suburban Hydrogeology and Ground-water Geochemistry of the Ashport Silt Loam, Payne County, Oklahoma. Unpublished M.S. Thesis, Oklahoma State University, 277 p.

Keller, C.K., Van Der Kamp, G., and Cherry, J.A., 1986. Fracture permeability and groundwater flow in clayey till near Saskatoon, Saskatchewan. Canadian Geotechnical Journal, V. 23, pp. 229-240.

Lawes, J.B., Gilbert, J.H., and Warington, R., 1882. On the Amount and Composition of the Rain and Drainage Water Collected at Rothamsted. Williams, Clowes and Sons Ltd., London.

Leap, D.I., and Sun, R.J., 1978. Iodide and Bromide Tracer Studies in Carbonate Rock. U.S. Geological Survey Professional Paper 1100, p. 223.

LeBlanc, D.R., and Garabedian, S.P., 1986. Preliminary results of a natural gradient aquifer test in a sand and gravel aquifer, Cape Cod, Massachusetts. EOS, v. 67, p. 286.

Li, E.A., Shanholtz, V.O., and Carson, E.W., 1976. Estimating saturated hydraulic conductivity and capillary potential at the wetting front: Deparment of Agricultural Engineering, Virginia Polytechnical Institute and State University, Blacksburg, in Clapp, R.B., and Hornberger, G.M., 1978. Empirical equations for some soil hydraulic properties. Water Resources Research, v. 14, pp. 601-604.

Louren, J.G., Wagenet, R.J., Bouma, J., and Wosten, J.M., 1988. Variability of saturated hydraulic conductivity in a glossaquic hapludalf with macropores. Soil Science, v. 145, pp. 20-28.

Luxmoore, R.J., 1981. Micro-, meso-, and macroporosity of soil. Soil Science Society of America Journal, v. 45, pp. 671-672.

Mazor, E., 1976. The Ram Crater Lake, a note on the revival of a 2,000 year old ground-water tracing experiment. In Interpretation of Environmental Isotope and Hydrochemical Data in Groundwater Hydrology, IAEA, Vienna, pp. 179-181.

McIntyre, D.S., and Sleeman, J.R., 1982. Macropores and hydraulic conductivity in a swelling soil. Australian Journal of Soil Research, v. 20, pp. 251-254.

Melby, J.T., 1989. A Comparitive Study of Hydraulic Conductivity Determinations for a Fine Grained Alluvium Aquifer. Unpublished M.S. Thesis, Oklahoma State University, 79 p.

Minhas, P.S., and Khosla, B.K., 1986. Solute displacement in a silt loam soil as affected by the method of water application under different evaporation rates. Agricultural Water Management, v. 12, pp. 63-74.

Muramatsu, Y., Uchida, S., Sriyotha, P., and Sriyotha, K., 1990. Some considerations on the sorption and desorption phenomena of iodide and iodate on soil. Water, Air and Soil Pollution, v. 49, pp. 125-138.

Nelson, M.J., 1989. Cause and Effect of Water Table Flucuations in a Shallow Aquifer System. Unpublished M.S. Thesis, Oklahoma State University, 95 p.

Noble, G., 1976. Sanitary Landfill Design Handbook. Technomic Publishing Company, Westport, Connecticut.

Olsen, R.E., and Daniel, D.E., 1981. Measurement of the hydraulic conductivity of fine grained soils. In T.F. Zimmie and C.O. Riggs (Eds.), Permeability and Groundwater Contaminant Transport, ASTM STP 746, American Society for Testing and Materials, pp. 18-64.

Onken, A.B., Wendt, C.W., Hargrove, R.S., and Wilke, O.C., 1977. Relative movement of bromide and nitrate in soils under three irrigation systems. Soil Science Society of America Journal, v. 41, pp. 50-52.

Osmin, W.L., 1977. Groundwater Tracing with Post Sampling Activation Analysis Using Bromide and Iodide Ions Injected Simultaneously into a Shallow Well System. M.S. Thesis, Pennsylvania State University, 132 p.

Pettyjohn, W.A., 1982. Cause and effect of cyclic changes in ground-water quality. Ground Water Monitoring Review, v. 2, pp. 43-49.

Pettyjohn, W.A., and Miller, A., 1982. Preliminary Estimates of Effective Ground-Water Recharge Rates in Central Oklahoma. Final Report Submitted to the Oklahoma Water Resources Board, Dept. of Geology, Oklahoma State University, Stillwater, Oklahoma, 32 p.

Pettyjohn, W.A., White, H., and Dunn, S., 1983. Water Atlas of Oklahoma. University Center for Water Research, Oklahoma State University, Stillwater, 72 p.

Pettyjohn, W.A., 1971. Water pollution by oil-field brines and related industrial wastes in Ohio. Ohio Journal of Science, v. 71, pp. 257-269.

Pettyjohn, W.A., 1976. Monitoring cyclic fluctuations in ground-water quality. Ground Water, v. 14, pp. 472-480.

Pollock, C.R., Robbins, G.A., and Mathewson, C.C., 1983. Groundwater monitoring in clay rich strata - techniques difficulties, and potential solutions. In Proceedings of the 3rd National Symposium on Aquifer Restoration and Groundwater Monitoring, National Water Well Association, Dublin, Ohio.

Priebe, D.L., and Blackmer, A.M., 1989. Preferential movement of oxygen-18-labeled water and nitrogen-15-labeled urea through macropores in a Nicollet soil. Journal of Environmental Quality, v. 18, pp. 66-71.

Quisenberry, V.L., and Phillips, R.E., 1976. Percolation of surface applied water in the field. Soil Science Society of America Journal, v. 40, pp. 484-489.

Radulovich, R., Soloranzo, E., and Sollins, P., 1989. Soil macropore size distribution from water breakthrough curves. Soil Science Society of America Journal, v. 53, pp. 556-559.

Reynolds, E.R.C., 1966. The percolation of rainwater through soil demonstrated by fluroescent dyes. Journal of Soil Science, v. 17, pp. 127-132.

Roogowski, A.S., and Richie, E.B., 1984. Relationship of laboratory and field determined hydraulic conductivity in compacted clay soils. In Toxic and Hazardous Wastes. Technomic Publishing Company, Lancaster, PA, pp. 520-533.

Rogowski, A.S., Simmons, D.E., 1988. Geostatistical analysis of field hydraulic conductivity in compacted clay. Mathematical Geology, v. 20, pp. 423-445.

Ross, R.R., 1988. Temporal and Vertical Variability of the Soil and Ground-water Geochemistry of the Ashport Silt Loam, Payne County, Oklahoma. Unpublished M.S. Thesis, Oklahoma State University, 116 p.

Rowe, J.J., Fournier, R.O., and Morey, G.W., 1965. Use of Sodium Iodide to Trace Underground Water Circulation in Hot Springs and Geysers of the Daisy Geyser Group, Yellowstone National Park. U.S. Geological Survey Professional Paper 525-B, pp. B184-B186.

Shelton, J.W., Ross, J.S., Garden, A.J., and Franks, J.L., 1985. Geology and Mineral Resources of Payne County, Oklahoma. Oklahoma Geological Survey Bulletin 137, 85 p.

Skopp, J., 1981. Comment on micro-, meso-, and macroporosity of soil. Soil Science Society of America Journal, v.45, p. 1246.

Smettem, K.R.J., 1987. Characterization of water entry into a soil with contrasting textural class: spatial variability of infiltration parameters and influence of macroporosity. Soil Science, v. 144, pp. 167-174.

Smith, S.J., and Davis, R.J., 1974. Relative movement of bromide and nitrate through soils. Journal of Environmental Quality, v. 3, pp. 152-155.

Soil Conservation Service, 1987. Soil Survey of Payne County, Oklahoma. U.S. Department of Agriculture, 268 p.

Stetzenbach, K.J., and Thompson, G.M., 1983. A new method for simultaneous measurement of Cl-, Br-, NO_3 -, SCN-, and I- at sub-ppm levels in ground water. Ground Water, v. 21, pp. 36-41.

Tennyson, L.C., and Settergren, C.D., 1980. Percolate water and bromide movement in the root zone of effluent irrigation sites. Water Resources Bulletin, v. 16. pp. 433-437.

Thomas, G.W., and Phillips, R.E., 1979. Consequences of water movement in macropores. Journal of Environmental Quality, v. 8, pp. 149-152.

Trent, J.D., Svejcar, T.J., and Christiansen, S., 1989. Effects of fumigation on growth, photosynthesis, water relations and mycorrhizal development of winter wheat in the field. Canadian Journal of Plant Science, v. 69, pp. 535-540.

Ubom, G.A., and Tsuchiya, Y., 1988. Determination of iodide in natural water by ion chromatography. Water Resources, v. 22, pp. 1455-1458.

U.S. Geological Survey, 1979. Topographic Map of Stillwater North Quadrangle, Oklahoma, 7.5 Minute Series.

Wild, A., and Babiker, I.A., 1976. The assymetric leaching pattern of nitrate and chloride in a loamy sand under field conditions. Journal of Soil Science, v. 27, pp. 460-466.

Zachmann, J.E., Linden, D.R., and Clapp, C.E., 1987. Macroporous infiltration and redistribution as affected by earthworms, tillage and residue. Soil Sci. Soc. Am. J., v. 51, pp. 1580-1586.

APPENDIXES

APPENDIX A

PRECIPITATION

INCHES OF PRECIPITATION 1989

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	0.00	0.00	0.00	0.00	0.00	0.84	0.00	*	0.57	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.97	0.32	0.46	*	0.00	0.00	0.02	0.33
3	0.00	0.00	0.00	0.00	0.00	0.68	0.00	*	0.00	0.00	0.00	0.04
4	0.36	0.00	0.00	0.00	0.46	0.38	0.00	*	1.80	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*	0.00	0.00	0.00	0.00
6	0.00	0.20	0.00	0.00	0.00	0.02	0.00	*	0.00	0.77	0.00	0.00
7	0.00	0.25	0.00	0.00	0.00	0.02	0.00	*	0.00	0.00	0.00	0.00
8	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00
12	0.01	0.45	0.00	0.00	*	0.38	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	*	0.78	0.00	0.00	0.00	0.00	0.00	0.00
14	0.12	0.00	0.00	0.00	*	0.00	3.76	1.16	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	*	0.00	0.00	0.48	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	*	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.32	0.00	0.01	0.00	0.00	0.00	0.00	0.01
18	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	2.04	0.56	0.32	0.24	0.00	0.00	0.00	0.00
23	0.00	0.10	0.00	0.00	0.00	0.58	0.24	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	0.00	0.12	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	0.50	0.00	1.44	0.00	0.00	0.54	0.00	0.00	0.00	0.02	0.00	0.00
28	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.06
29	0.00		0.00	0.00	0.00	0.00	*	0.00	0.00	1.31	0.00	0.00
30	0.00		0.34	0.00	0.00	0.00	*	0.01	0.00	0.00	0.00	0.00
31	0.00		0.00		0.00		*	0.00		0.00		0.00
Total	1.53	1.30	1.78	0.11	3.85	5.23	4.91	2.16	4.59	2.27	0.02	0.44

Total Annual: 28.91

* Data unavailable due to equipment failure.

INCHES OF PRECIPITATION 1990

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	0.00	0.38	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.02	0.00	0.00	0.00	1.74	0.32	0.00	0.44	0.00	0.84	0.00	0.02
3	0.00	0.00	0.00	0.00	0.02	0.00	0.00	1.80	0.00	0.00	0.30	0.00
4	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00
5	0.00	0.00	0.12	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.26	0.00
9	0.00	0.02	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	2.36	0.20	0.00	0.00	0.00	0.06	1.34	0.00	0.00	0.00
11	0.00	0.00	0.86	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.04	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.62	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.06	0.06	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.06	0.18	0.00	1.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15
17	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.04	0.23	0.00	0.00	0.56
18	0.04	0.00	0.00	0.06	0.64	0.00	0.00	0.04	0.41	0.00	0.00	0.00
19	0.97	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.36	0.00	0.00	0.00
20	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.66	0.01	0.00	0.00
21	0.00	0.56	0.00	0.00	0.00	0.52	0.08	0.00	0.15	0.00	0.00	0.00
22	0.00	0.52	0.00	0.02	0.00	0.00	0.52	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.38	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.08	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	0.00	0.18	0.23	0.24	0.00	0.18	0.02	0.00	0.00	0.00	0.00	0.00
28	0.00	1.16	0.10	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
29	0.00		0.12	0.00	0.28	0.00	0.31	0.00	1.37	0.00	0.00	0.00
30	0.00		0.18	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00
31	0.00		0.00		0.00		*	0.00		0.00		0.02
Total	1.15	3.14	5.40	4.29	3.26	1.02	1.61	3.31	4.53	1.19	1.20	0.75

Total Annual: 30.85

INCHES OF PRECIPITATION 1991

Day	Jan.	Feb.	Mar.	Apr.	May	June
1	0.00	0.00	0.00	0.00	0.00	
2	0.00	0.00	0.02	0.00	0.71	
3	0.00	0.00	0.00	1.43	0.00	
4	0.00	0.00	0.00	0.00	0.15	
5	0.14	0.00	0.00	0.00	0.00	
6	0.00	0.00	0.00	0.00		
7	0.00	0.00	0.00	0.00		
8	0.00	0.00	0.00	0.00		
9	0.02	0.00	0.00	0.00		
10	0.01	0.00	0.00	0.00		
11	0.00	0.00	0.00	0.00		
12	0.00	0.00	0.00	0.00		
13	0.00	0.00	0.00	0.00		
14	0.08	0.00	0.00	0.00		
15	0.05	0.00	0.00	0.00		
16	0.00	0.00	0.00	0.00		
17	0.00	0.00	0.27	0.00		
18	0.00	0.00	0.00	0.00		
19	0.00	0.00	0.00	0.00		
20	0.00	0.00	0.00	0.00		
21	0.00	0.00	0.00	0.08		
22	0.00	0.00	0.00	0.00		
23	0.00	0.00	0.00	0.00		
24	0.00	0.02	0.00	0.55		
25	0.00	0.00	0.00	0.00		
26	0.00	0.00	0.00	0.16		
27	0.00	0.00	0.06	0.00		
28	0.00	0.00	0.00	0.00		
29	0.00		0.19	0.00		
30	0.00		0.00	0.00		
31	0.00		0.00			
Total	0.30	0.02	0.54	2.22	0.86	

Total To Date: 3.94

APPENDIX B

WATER LEVELS

WATER TABLE ELEVATION
(Feet Above Sea Level)
1989

Month and Day

WELL	4-12	4-23	5-3	5-11	5-17	5-31	6-1
A1	878.37	879.04	878.78	878.51	878.75	878.81	878.92
A2	878.85	879.06	878.78	878.51	878.80	878.80	878.92
A3	878.88	879.07	878.78	878.52	878.83	878.81	878.96
A4	878.89	879.09	878.79	878.53	878.83	878.82	878.94
A5	878.88	879.09	878.80	878.54	878.87	878.82	878.97
B2	878.50	879.17	878.98	878.69	878.95	878.95	878.09
B3	878.52	879.19	878.89	878.64	878.76	878.95	878.93
B4	878.53	879.20	878.90	878.63	878.97	878.98	879.11
B5	878.54	879.23	879.02	879.70	879.02	879.01	879.13
B6	878.56	879.22	878.93	878.66	878.93	879.00	879.01
B7	878.53	879.21	878.94	878.65	879.09	878.98	879.05
B8	878.54	879.22	878.93	878.66	879.05	878.98	879.00
B9	878.52	879.19	878.89	878.64	879.08	878.97	879.06
B10	878.57	879.19	878.94	878.67	879.10	879.01	879.17
C1	879.51	879.15	878.79	878.51	878.63	878.77	878.90
C2	878.51	879.16	878.80	878.51	878.83	878.79	878.92
C3	878.47	879.14	878.79	878.49	878.76	878.76	878.88
C4	878.46	879.15	878.79	878.49	878.83	878.77	878.93
C5	878.47	879.13	878.78	878.50	878.84	878.78	878.90
D1	879.77	879.44	878.95	878.64	878.78	879.06	879.02
D2	878.79	879.46	878.96	878.67	878.79	879.07	879.15
D3	877.78	879.43	878.92	878.65	878.70	879.07	879.01
D4	877.75	879.39	878.97	878.65	878.88	879.02	879.11
D5	877.77	879.41	878.96	878.68	878.88	879.05	879.04
E1	879.38	879.53	879.08	878.82	879.38	879.28	879.39
E2	879.87	879.52	879.99	878.82	879.28	879.25	879.37
E3	878.90	879.50	879.39	878.83	879.61	879.28	879.45
E4	878.88	879.51	879.10	878.82	879.12	879.25	879.36
E5	878.89	879.52	879.03	878.83	879.14	879.26	879.39
F1	878.04	879.23	879.92	878.63	878.95	878.96	879.10
F2	878.04	879.24	878.91	878.65	879.01	878.96	879.12
G1	879.83	879.49	879.36	879.07	879.32	879.60	879.53
G2	879.81	879.47	879.24	879.07	879.31	879.41	879.52
H1	879.25	879.77	879.44	879.30	879.27	880.13	879.98
H2	878.15	879.75	879.49	879.30	879.43	879.83	879.74
I1		879.34				879.13	
I2		879.33				879.10	
I3		879.30				879.05	
J1	879.03	879.65	879.28	878.99	879.22	879.49	879.46

WATER TABLE ELEVATION
(Feet Above Sea Level)
1989 - 1990

Month and Day

	1989					1990	
WELL	6-12	6-14	6-20	10-6	11-7	1-11	6-11
A1	879.23	879.59	878.99	877.39	877.42	877.42	879.06
A2	879.23	879.57	878.99	876.97	877.55	877.52	879.04
A3	879.21	879.59	879.00	877.01	877.57	877.54	879.07
A4	879.24	879.58	879.00	876.99	876.56	876.52	879.06
A5	879.25	879.50	879.03	877.01	877.59	877.56	879.09
B1		879.92					879.39
B2	879.36	879.76	879.13	877.49	877.66	877.65	879.22
B3	879.36	879.72	879.15	877.15	877.66	877.66	879.21
B4	879.38	879.75	879.15	877.16	877.67	877.66	879.26
B5	879.42	879.79	879.20	877.20	877.67	877.68	879.27
B6	879.37	879.78	879.17	877.15	877.69	877.65	879.25
B7	879.38	879.79	879.18	877.17	877.70	877.75	879.25
B8	879.38	879.78	879.17	877.15	877.69	877.66	879.26
B9	879.39	879.79	879.17	877.15	877.67	877.63	879.24
B10	879.42	879.79	879.20	877.29	877.80	877.75	879.36
C1	879.28	879.66	879.00	877.38			879.28
C2	879.29	879.64	879.01	876.73	877.37	877.43	879.14
C3	879.26	879.63	878.98	876.71	877.34	877.40	879.16
C4	879.27	879.63	879.00	876.73	877.38	877.42	879.13
C5	879.26	879.61	879.00	876.74	877.37	877.41	879.16
D1	879.47	879.77	879.27	876.68			879.13
D2	879.47	879.77	879.27	876.69	877.25	877.42	879.53
D3	879.47	879.81	879.26	876.75	877.28	877.46	879.54
D4	879.51	879.86	879.27	876.77	877.33	877.42	879.53
D5	879.49	879.88	879.26	877.02	877.34	877.43	879.52
E1	879.72	880.09	879.51	877.08	877.51	877.53	879.53
E2	879.71	880.08	879.48	877.09	877.54	877.59	879.74
E3	879.71	880.08	879.50	877.06	877.54	877.63	879.73
E4	879.68	880.09	879.51	877.08	877.54	877.58	879.73
E5	879.75	880.12	879.53	877.06	877.57	877.58	879.72
F1	879.38	879.77	879.18	877.06	877.57	877.58	879.74
F2	879.40	879.78	879.18	877.69	877.58	877.58	879.28
G1	879.94	880.09	879.70	877.70	878.11	877.92	879.31
G2	879.96	880.15	879.92	877.68	878.08	877.93	879.68
H1	880.19	880.31	880.20	877.69	877.94	877.87	880.28
H2	880.31	880.49	880.15	879.30	877.91	877.86	880.27
I1		879.94					
I2		879.86					
I3		879.83					
J1	879.91	880.25	879.75				879.99

WATER TABLE ELEVATION
(Feet Above Sea Level)
1991

Month and Day

WELL	2-7	3-1	4-29
A1	877.17	877.64	878.05
A2	877.56	877.65	878.05
A3	877.61	877.68	878.03
A4	876.58	876.67	878.01
A5	877.63	877.73	878.04
B2	877.69	877.81	878.14
B3	877.69	877.80	878.15
B4	877.72	877.81	878.17
B5	877.72	877.82	878.17
B6	877.72		
B7	877.73		
B8	877.73		
B9	877.72		
B11		877.83	
C1	877.46	877.57	877.92
C2	877.45	877.58	877.95
C3	877.43	877.57	877.91
C4	877.45	877.58	877.93
C5	877.45	877.57	877.92
D1			877.90
D2	877.37		877.94
D3	877.37		877.92
D4	877.39		877.97
D5	877.39	877.44	877.97
E1	877.56	877.75	878.15
E2	877.56	877.74	878.13
E3	877.55	877.75	878.12
E4	877.61	877.72	878.11
E5	877.63	877.73	878.13
F1			878.06
F2	877.62	877.74	878.09
G1	878.17	878.10	878.49
G2	878.11	878.07	878.38
H1	877.85	877.85	878.44
H2	877.97	877.04	878.46
J1	877.73	877.85	879.25

APPENDIX C

WATER QUALITY DATA

WATER QUALITY DATA
Date Of Sample Collection:
12 April 1989

Well #

	A_1	A_2	A_3	A_4	A_5
Ca^{++} (mg/l)	80.25			23.16	
Mg^{++} (mg/l)	37.76			43.56	
Na^{+} (mg/l)	18.50			44.56	
Cl^{-} (mg/l)	30.373	18.182	15.283	12.596	14.758
NO_3^{-} (mg/l)	57.680	31.174	23.781	24.115	25.723
$SO_4^{=}$ (mg/l)	54.757	33.975	27.582	24.031	24.018
pH (units)	6.97	6.86	6.67	6.90	6.69
Temperature (°C)	15.2	14.9	15.1	15.5	15.5
Hardness (mg/l HCO_3)	450	476	633	410	564
Conductivity (µmhos/cm)	900	832	985	873	897
Cation/Anion Balance (%)	-8.42			-6.18	

WATER QUALITY DATA
Date Of Sample Collection:
23 April 1989

Well #

	A_1	A_2	A_3	A_4	A_5
Cl^- (mg/l)	22.572	20.783	17.535	16.269	16.554
NO_3^- (mg/l)	26.017	27.675	25.615	25.771	26.554
$SO_4^=$ (mg/l)	37.843	33.642	28.181	26.824	26.161
pH (units)	6.44	6.66	6.68	6.68	6.71
Temperature (°C)	21.0	18.0	17.2	18.2	18.2
Hardness (mg/l HCO_3)	587	598	657	642	651
Conductivity (µmhos/cm)	958	932	980	950	926

WATER QUALITY DATA
Date Of Sample Collection:
5 May 1989

Well #

	A_1	A_2	A_3	A_4
Cl^- (mg/l)	21.050	20.705	17.515	17.515
NO_3^- (mg/l)	22.380	25.703	25.338	23.338
$SO_4^=$ (mg/l)	35.217	32.644	28.208	28.208
pH (units)	6.57	6.55	6.89	6.72
Temperature (°C)	18.1	17.5	16.7	16.8
Hardness (mg/l HCO_3)	638	629	645	640
Conductivity (µmhos/cm)	954	960	987	953

WATER QUALITY DATA
Date Of Sample Collection:
17 May 1989

Well # and Time Of Collection (24 hour clock)

	A_1 1020	A_1 1240	A_1 2145	A_2 1050	A_2 1245	A_2 2155
Cl^- (mg/l)	96.263	72.202	61.404	28.863	27.178	26.616
NO_3^- (mg/l)	14.871	17.115	15.899	26.109	24.827	24.635
$SO_4^=$ (mg/l)	57.678	48.278	43.816	32.887	32.895	32.708
pH (units)	6.56	6.40	6.66	6.36	6.44	6.64
Temperature (°C)	17.3	17.7	17.3	17.1	17.3	17.1
Hardness (mg/l HCO_3)	452	496	528	565	593	589
Conductivity (μmhos/cm)	1011	1002	991	914	908	961

NOTE: Samples were taken during a rainstorm.

WATER QUALITY DATA
Date Of Sample Collection:
17 May 1989

Well # and Time Of Collection (24 hour clock)

	A3 1105	A3 1300	A3 2205	A4 1115	A4 1315	A4 2215
Cl^- (mg/l)	21.188	20.537	19.869	30.214	17.773	17.935
NO_3^- (mg/l)	26.081	26.988	27.320	24.155	28.336	29.010
$SO_4^=$ (mg/l)	30.306	30.404	30.657	33.238	29.914	30.932
pH (units)	6.49	6.51	6.77	6.57	6.51	6.78
Temperature (°C)	17.0	17.2	17.1	17.3	17.1	17.3
Hardness (mg/l HCO_3)	625	610	594	593	603	581
Conductivity (μmhos/cm)	950	940	975	994	896	904

NOTE: Samples were taken during a rainstorm.

WATER QUALITY DATA
Date Of Sample Collection:
17 May 1989

Well # and Time Of Collection (24 hour clock)

	A5 1325	A5 2225
Cl^- (mg/l)	17.869	17.991
NO_3^- (mg/l)	29.088	28.763
$SO_4^=$ (mg/l)	29.124	29.301
pH (units)	6.52	6.71
Temperature (°C)	17.1	17.0
Hardness (mg/l HCO_3)	587	599
Conductivity (µmhos/cm)	884	884

NOTE: Samples were taken during a rainstorm.

WATER QUALITY DATA
Date Of Sample Collection:
17 May 1989

Well #

	B_2	B_3	B_4	B_5	B_6	B_7
Cl^- (mg/l)	16.872	17.629	11.408	15.137	12.394	10.427
NO_3^- (mg/l)	6.411	16.284	5.953	6.841	5.834	*
$SO_4^=$ (mg/l)	84.163	153.416	26.016	32.878	25.689	29.463
pH (units)	6.64	6.61	6.77	6.70	6.60	6.90
Temperature (°C)	19.1	19.0	19.2	18.8	19.9	19.7
Hardness (mg/l HCO_3)	667	732	639	515	#	882
Conductivity (µmhos/cm)	1076	1172	874	811	1226	1131

* Concentration below detectable limit.
\# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
17 May 1989

Well #

	B_8	B_9	B_{10}	C_1	C_2	C_3
Ca^{++} (mg/l)					57.15	
Mg^{++} (mg/l)					62.86	
Na^{+} (mg/l)					105.60	
Cl^{-} (mg/l)	17.683	15.853	17.405	139.956	59.329	73.330
NO_3^{-} (mg/l)	4.389	27.282	4.739	7.486	5.729	12.809
$SO_4^{=}$ (mg/l)	82.993	23.534	32.605	119.537	63.092	78.626
pH (units)	6.64	6.68	6.82	6.76	6.83	6.56
Temperature (°C)	18.5	18.4	18.5	15.7	15.8	15.4
Hardness (mg/l HCO_3)	793	552	526	755	637	805
Conductivity (μmhos/cm)	1176	823	792	1583	1127	1405
Cation/Anion Balance (%)					-3.18	

WATER QUALITY DATA
Date Of Sample Collection:
17 May 1989

Well #

	C_4	C_5	D_1	D_2	D_3	D_4
F^- (mg/l)	1.554	1.247	1.233	2.153	1.008	1.437
Cl^- (mg/l)	45.781	78.394	74.205	80.610	80.691	22.766
NO_3^- (mg/l)	24.849	17.676	4.681	*	5.149	29.786
$SO_4^=$ (mg/l)	45.704	92.053	53.328	42.921	35.833	34.163
pH (units)	6.68	6.59	7.18	6.82	7.00	7.00
Temperature (°C)	15.8	14.8	17.1	16.2	15.9	15.5
Hardness (mg/l HCO_3)	653	766	729	749	770	654
Conductivity (µmhos/cm)	1118	1415	1062	1088	1160	1042

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
17 May 1989

Well #

	D_5	E_1	E_2	E_3	E_4	E_5
Ca^{++} (mg/l)		62.53		41.33	22.46	
K^{+} (mg/l)		.3809		1.744	*	
Mg^{++} (mg/l)		19.47		16.74	51.57	
Na^{+} (mg/l)		2.944		4.181	36.29	
Cl^{-} (mg/l)	28.228	3.616	3.504	3.798	8.793	6.635
NO_3^- (mg/l)	24.957	8.530	7.008	10.416	22.546	19.490
$SO_4^=$ (mg/l)	34.730	14.325	13.045	13.065	29.535	25.218
pH (units)	7.03	6.75	6.62	7.03	6.90	6.89
Temperature (°C)	15.2	17.8	17.3	16.9	16.7	16.3
Hardness (mg/l HCO_3)	641	272	253	198	458	402
Conductivity (µmhos/cm)	1053	463	378	313	643	640
Cation/Anion Balance (%)		-0.01		0.58	-9.32	

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
17 May 1989

Well #

	F_1	F_2	G_1	G_2	H_1	I_1
Ca^{++} (mg/l)				45.15		
Mg^{++} (mg/l)				53.65		
Na^{+} (mg/l)				77.37		
Cl^{-} (mg/l)	16.691	18.320	17.122	23.015	21.084	22.056
NO_3^{-} (mg/l)	18.123	14.252	55.812	27.336	52.348	61.455
$SO_4^{=}$ (mg/l)	43.682	41.840	51.540	29.734	83.281	86.614
pH (units)	6.63	6.61	6.87	6.91	6.87	6.68
Temperature (°C)	17.8	18.2	18.6	17.0	19.0	19.3
Hardness (mg/l HCO_3)	545	551	616	664	639	595
Conductivity (μmhos/cm)	845	857	1028	1033	1048	1137
Cation/Anion Balance (%)				-9.55		

WATER QUALITY DATA

Date Of Sample Collection:
17 May 1989

	Well #				
	I_2	J_1	Rain	Puddle	Downspout
Cl^- (mg/l)	15.390	17.560	*	*	*
NO_3^- (mg/l)	81.606	33.508	*	*	*
$SO_4^{=}$ (mg/l)	49.863	36.192	6.560	8.536	9.818
pH (units)	6.75	6.88	6.57	6.56	6.88
Temperature (°C)	18.5	17.1	20.3	19.6	19.3
Hardness (mg/l HCO_3)	477	648	35	48	
Conductivity (µmhos/cm)	920	1050	14	76	10

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
31 May 1989

Well #

	A_1	A_2	A_{3A}	A_4	A_5	Tap
Ca^{++} (mg/l)						29.35
K^+ (mg/l)						4.798
Mg^{++} (mg/l)						15.45
Na^+ (mg/l)						150.8
F^- (mg/l)	.095	.185	.386	.307	.332	1.342
Cl^- (mg/l)	50.682	31.440	22.683	16.689	17.294	224.049
Br^- (mg/l)	.913	.579	.429	.334	.295	.253
NO_3^- (mg/l)	3.915	4.448	4.747	5.293	5.925	.351
$SO_4^=$ (mg/l)	42.826	32.682	29.742	28.823	28.777	117.267
pH (units)	6.64	6.56	6.94	6.44	6.50	8.54
Temperature (°C)	20.3	20.0	19.5	19.6	19.0	21.1
Hardness (mg/l HCO_3)	429	578	609	593	580	53
Conductivity (µmhos/cm)	1026	986	1058	987	982	1085
Cation/Anion Balance (%)						-1.11

WATER QUALITY DATA
Date Of Sample Collection:
1 June 1989

Well #

	A_1	A_2	A_3	A_4	A_{5A}
F^- (mg/l)	.123	.162	.356	.342	.333
Cl^- (mg/l)	42.565	25.845	22.646	17.431	15.908
Br^- (mg/l)	.816	.542	.462	.364	.353
NO_3^- (mg/l)	3.473	4.717	4.756	5.466	5.481
$SO_4^=$ (mg/l)	39.812	30.649	29.593	30.374	29.373
pH (units)	&	&	&	&	&
Temperature (°C)	18.7	18.2	18.1	18.5	18.1
Hardness (mg/l HCO_3)	523	531	596	569	566
Conductivity (µmhos/cm)	956	924	1010	973	973

& Unable to measure pH due to field equipment failure.

WATER QUALITY DATA
Date Of Sample Collection:
12 June 1989

	Well #				
	A_1	A_2	A_3	A_4	A_{5A}
F^- (mg/l)	.074	.193	.356	.316	.309
Cl^- (mg/l)	25.764	20.670	19.415	14.956	16.028
Br^- (mg/l)	.897	.577	.443	.293	.286
NO_3^- (mg/l)	4.635	4.647	4.742	5.311	5.700
$SO_4^=$ (mg/l)	35.382	30.034	29.623	29.946	29.741
pH (units)	6.32	6.25	6.32	6.33	6.33
Temperature (°C)	20.4	20.5	20.2	21.4	20.1
Hardness (mg/l HCO_3)	615	554	590	589	567
Conductivity (µmhos/cm)	995	946	996	992	965

WATER QUALITY DATA

Date Of Sample Collection:
14 June 1989

Well #

	D_1	D_2	D_3	D_4	D_5
Ca^{++} (mg/l)	13.1	26.2	27.6	13.3	18.9
Mg^{++} (mg/l)	48.7	53.1	51.7	39.6	41.6
Na^{+} (mg/l)	134.6	104.8	116.3	119.1	114.4
F^{-} (mg/l)	.636	.608	.631	.571	.577
Cl^{-} (mg/l)	64.820	42.307	48.943	19.970	20.010
Br^{-} (mg/l)	.631	.466	.462	.255	.224
NO_3^{-} (mg/l)	.411	.341	1.629	7.038	6.074
$SO_4^{=}$ (mg/l)	42.378	32.421	30.171	29.686	30.344
pH (units)	6.92	6.73	6.68	6.82	6.76
Temperature (°C)	18.5	17.6	17.1	16.0	15.8
Hardness (mg/l HCO_3)	776	567	555	613	485
Conductivity (µmhos/cm)	1284	1169	1165	1005	986
Cation/Anion Balance (%)	-19.0	-4.25	-1.88	-10.48	0.73

WATER QUALITY DATA
Date Of Sample Collection:
20 June 1989

Well #

	A_1	A_2	A_3	A_4	A_5A
F^- (mg/l)	.094	.172	.327	.316	.310
Cl^- (mg/l)	22.532	19.064	17.895	15.274	15.239
Br^- (mg/l)	.895	.583	.460	.316	.275
NO_3^- (mg/l)	4.602	4.821	4.561	5.200	5.549
$SO_4^=$ (mg/l)	34.116	29.993	29.977	30.635	30.892
pH (units)	6.21	6.23	6.38	6.22	6.26
Temperature (°C)	21.2	21.8	20.4	21.1	20.2
Hardness (mg/l HCO_3)	453	586	609	589	587
Conductivity (µmhos/cm)	1023	1050	1039	1013	1007

WATER QUALITY DATA
Date Of Sample Collection.
6 October 1989

Well #

	A_2	A_3	A_4	B_{10}	B_{11}	B_6
Ca^{++} (mg/l)	118.100	118.200	110.300	73.210	16.310	135.700
Fe^{++} (mg/l)	0.163	0.096	0.048	1.116	0.459	15.140
K^{+} (mg/l)	0.236	0.497	0.119	2.286	2.142	4.356
Mg^{++} (mg/l)	29.710	48.510	46.780	33.310	14.730	33.550
Mn^{++} (mg/l)	0.013	0 088	0.006	0 942	0.566	3.550
Na^{++} (mg/l)	18.600	33.860	36.730	45.950	151.400	76.870
Si_2 (mg/l)	10.510	14.070	14.760	13.110	4.661	12.530
F^- (mg/l)	0.130	0.366	0.362	0.499	0.964	0.370
Cl^- (mg/l)	12.638	19.797	18.443	17 317	39.224	8.483
Br^- (mg/l)	0.556	1.353	1.122	0.287	0.212	0.714
NO_3^- (mg/l)	1 452	2.105	3.013	2.660	0.022	0.352
$SO_4^=$ (mg/l)	22.647	25.738	25.988	15.879	26.008	7.905
pH (units)	6.34	6.49	6.41	6.83	7.95	6.83
Temperature (°C)	17.9	19 2	18.4	17.9	17.7	22.0
Hardness (mg/l HCO_3)	1108	473	624	342	517	552
Conductivity (μmhos/cm)	832	1184	1147	945	1050	974
Cation/Anion Balance (%)	-34.95	-12.50	-1.51	13.62	-7.75	15.76

WATER QUALITY DATA
Date Of Sample Collection:
6 October 1989

	Well #				
	B_8	B_9	D_2	D_3	D_4
Ca^{++} (mg/l)	108.300	95.660	91.610	82.920	66.980
Fe^{++} (mg/l)	5.501	0.093	0.627	0.079	0 039
K^+ (mg/l)	1.244	0.326	0 308	0 101	0 089
Mg^{++} (mg/l)	35.820	37.870	43.190	42 680	33.770
Mn^{++} (mg/l)	4.621	0.223	0.179	0.024	#
Na^{++} (mg/l)	79.670	36.980	86.300	96.380	105 800
Si_2 (mg/l)	14.380	16.650	9.816	10.360	10.290
F^- (mg/l)	0.490	0.354	0.607	0.622	0.690
Cl^- (mg/l)	13 940	15.261	32.935	24.917	22.664
Br (mg/l)	0 575	0.368	#	0.267	0.243
NO_3^- (mg/l)	1.025	5.822	0.034	1.121	6.351
$SO_4^=$ (mg/l)	54.232	20.165	24.402	22.875	29.313
pH (units)	6.60	6.44	7.01	6.90	7.03
Temperature (°C)	20.5	19.4	16.0	15.8	15.3
Hardness (mg/l HCO_3)	674	384	#	676	488
Conductivity (µmhos/cm)	1285	1068	1271	1248	1224
Cation/Anion Balance (%)	-2.95	14.19		-1.72	7.40

Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection
7 November 1989

Well #	A_2	A_3	A_4	B_{10}	B_{11}	B_4
Ca^{++} (mg/l)	96.490	109.900	108.000	73.980	27.920	117.400
Fe^{++} (mg/l)	0.158	0.075	0.094	1.185	0.433	3.080
K^{+} (mg/l)	0.246	0.157	0.163	2.210	2.358	0.423
Mg^{++} (mg/l)	33.140	44.960	45.710	33.260	18.320	28.970
Mn^{++} (mg/l)	*	0.032	0.024	0.874	1.549	1.003
Na^{++} (mg/l)	21.260	31.390	35.900	46.350	166.200	23.830
Si_2 (mg/l)	10.600	12.990	14.420	13.290	6.299	13.500
F (mg/l)	0.227	0.589	0.615	0.622	0.961	0.248
Cl^- (mg/l)	21.459	21.229	18.632	17.722	34.716	14.991
Br^- (mg/l)	1.083	1.891	1.386	0.268	0.181	0.585
NO_3^- (mg/l)	2.213	3.652	4.037	2.639	0.027	0.699
$SO_4^{=}$ (mg/l)	28.939	26.433	25.024	15.552	70.604	21.609
pH (units)	6.35	6.74	6.73	6.80	7.84	6.65
Temperature (°C)	15.7	16.5	17.1	17.2	17.7	19.1
Hardness (mg/l HCO_3)	639	639	611	348	398	490
Conductivity (µmhos/cm)	1184	1185	1118	931	1193	1125
Cation/Anion Balance (%)	-15.84	-4.82	-1.59	13.13	6.35	2.12

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
7 November 1989

Well #

	B_6	B_8	B_9	D_2	D_3	D_4
Ca^{++} (mg/l)	129.600	106.600	95.110	99.410	83.660	70.420
Fe^{++} (mg/l)	5.744	5.493	0.054	1 038	0.067	0.026
K^{+} (mg/l)	3.600	1.141	0.483	0.186	0.122	0.134
Mg^{++} (mg/l)	33.410	35.460	37.270	49.120	43.890	35.230
Mn^{++} (mg/l)	2.869	4.459	0.259	0.055	0.055	*
Na^{++} (mg/l)	71.560	83.040	37.410	91.270	98.680	110.700
Si_2 (mg/l)	13.450	14.440	13.750	11.520	10.530	10.670
F^- (mg/l)	0.576	0.445	0.427	0.699	0.703	0.783
Cl^- (mg/l)	18.764	13.338	16.179	33.953	24.139	20.788
Br^- (mg/l)	0.899	0.602	0.299	0.471	0.345	0.235
NO_3^- (mg/l)	0.368	0.859	5.684	0.095	1.197	6.326
$SO_4^{=}$ (mg/l)	13.328	57.670	19.352	28.137	24.392	30.765
pH (units)	7.12	6.84	6.78	7.06	6.83	7.05
Temperature (°C)	20.4	21.2	18.5	15.6	15.6	15.1
Hardness (mg/l HCO_3)	622	688	403	671	612	537
Conductivity (µmhos/cm)	1330	1263	1035	1431	1287	1190
Cation/Anion Balance (%)	6.06	-3.94	11.75	1.71	3.70	5.66

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection
11 January 1990

Well #

	A_3	A_4	B_{10}	B_{11}	B_6	B_8
Ca^{++} (mg/l)	116.600	105 600	74.260	25.580	130.500	111.300
Fe^{++} (mg/l)	0.053	0.037	0.913	0.508	7.138	4.126
K^{+} (mg/l)	0.312	0.320	1.264	3.178	2.767	1.228
Mg^{++} (mg/l)	46.380	44.170	33.740	18.420	32 960	36.540
Mn^{++} (mg/l)	0.024		0.754	1.292	2.483	3.811
Na^{++} (mg/l)	31.530	34.910	47.370	170.100	69.440	70.290
Si_2 (mg/l)	12 000	13.270	13.450	6.027	11.930	14.150
F^- (mg/l)	0.640	0.480	0.634	0.868	0.448	0.426
Cl^- (mg/l)	19.483	15.929	18.269	38.164	11.521	12.115
Br (mg/l)	1 514	0.784	0.267	0.174	0.815	0.525
NO_3^- (mg/l)	4.537	5.736	2.904	3.399		2.857
$SO_4^=$ (mg/l)	26.089	23.900	15.618	75.590	15.828	43.280
pH (units)	6.69	6.75	6.90	7.88	6.64	6.80
Temperature (°C)	11.9	13.3	15.0	14.3	11.1	13.7
Hardness (mg/l HCO_3)	*	*	*	*	*	*
Conductivity (μmhos/cm)	1175	1090	913	1150	1330	1161
Cation/Anion Balance (%)						

* Hardness data unavailable due to field equipment failure

WATER QUALITY DATA
Date Of Sample Collection
11 January 1990

Well #	B_9	D_2	D_3	D_4
Ca^{++} (mg/l)	94.660	107.400	85.100	72.120
Fe^{++} (mg/l)	0.044	0.312	0.039	0.026
K^{+} (mg/l)	0.354	0.082	0.053	0.077
Mg^{++} (mg/l)	36.530	52.900	44.410	36.210
Mn^{++} (mg/l)	0.275	0.055		
Na^{++} (mg/l)	37.010	97.450	97.800	112.000
Si_2 (mg/l)	13.610	11.320	9.616	10.290
F^- (mg/l)	0.530	0.559	0.705	0.646
Cl (mg/l)	15.931	32.542	24.460	20.400
Br^- (mg/l)	0.288	0.399	0.298	0.207
NO_3^- (mg/l)	5.328	2.584		8.347
$SO_4^=$ (mg/l)	18.207	27.567	20.464	31.970
pH (units)	6.70	6.86	6.90	7.00
Temperature (°C)	15.6	10.9	11.1	12.2
Hardness (mg/l HCO_3)	*	*	*	*
Conductivity (µmhos/cm)	976	1533	1346	1225
Cation/Anion Balance (%)				

* Hardness Data unavailable due to field equipment failure.

WATER QUALITY DATA
Date Of Sample Collection:
7 February 1991

Well #

	A_2	A_3	A_4	A_5	A_{5Q}
Ca^{++} (mg/l)	96.41	92.02	52.40	69.79	64.31
K^{+} (mg/l)	.3764	.2161	*	*	*
Mg^{++} (mg/l)	53.68	50.81	42.86	40.15	40.27
Na^{+} (mg/l)	26.55	35.97	49.85		
F^{-} (mg/l)	.442	.617	.618	.599	.605
Cl^{-} (mg/l)	17.931	11.937	14.618	15.335	15.234
Br^{-} (mg/l)	.774	.490	.326	.264	.299
NO_3^{-} (mg/l)	2.243		2.862	2.946	2.849
$SO_4^{=}$ (mg/l)	26.638	22.193	22.082	18.179	18.178
pH (units)	6.65	6.64	6.83	6.64	6.67
Temperature (°C)	10.7	12.4	13.2	13.2	13.2
Hardness (mg/l HCO_3)	671	622	529	510	505
Conductivity (µmhos/cm)	1120	950	880	900	900
Cation/Anion Balance (%)	-7.42	-3.05	-6.53	-14.94	-16.42

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
7 February 1991

Well #

	D_2	D_3	D_4	D_5	TAP	C_5
Ca^{++} (mg/l)	28.42	37.28	54.22	47.22	38.84	70.04
K^{+} (mg/l)	.533	*	*	*	5.683	.219
Mg^{++} (mg/l)	59.92	47.96	41.57	43.32	17.44	60.95
Na^{+} (mg/l)	105.9	107.8	124.0	121.6	153.3	56.01
F^{-} (mg/l)	.641	.672	.733	.737	1.279	.758
Cl^{-} (mg/l)	32.225	31.638	13.599	15.38		27.666
Br^{-} (mg/l)	.399	.341	.184	.207	.255	.374
NO_3^{-} (mg/l)			5.626	4.535		5.53
$SO_4^{=}$ (mg/l)	11.114	19.766	32.257	32.664	107.659	33.426
pH (units)	6.66	6.9	6.72	6.70	7.42	6.55
Temperature (°C)	11.6	11.8	11.9	11.5	7.1	11.4
Hardness (mg/l HCO_3)	841	670	665	659	87	586
Conductivity (µmhos/cm)	1280	1120	1120	1020	1040	1000
Cation/Anion Balance (%)	-15.8	-7.86	-1.85	-3.05	-47.05	-.59

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
28 February 1991

Well #

	D_2	D_3	D_4	D_5
Ca^{++} (mg/l)	50.15	60.07	45.22	50.07
K^+ (mg/l)	.8500	.3108	.3014	.2996
Mg^{++} (mg/l)	59.68	47.16	40.77	42.84
Na^+ (mg/l)	110.90	107.90	122.90	121.50
F^- (mg/l)	.814	.788	.836	.851
Cl^- (mg/l)	31.453	30.042	12.587	13.903
Br^- (mg/l)	.410	.403	.194	.218
NO_3^- (mg/l)	.034	.641	5.682	4.854
$SO_4^=$ (mg/l)	12.499	20.709	31.600	32.029
pH (units)	7.10	6.74	6.83	6.90
Temperature (°C)	15.5	12.5	12.5	12.1
Hardness (mg/l HCO_3)	761	664	680	667
Conductivity (µmhos/cm)	1240	1040	1040	1080
Cation/Anion Balance (%)	-5.26	-2.45	-5.16	-2.91

WATER QUALITY DATA
Date Of Sample Collection:
11 June 1990

Well #

	A_1	A_2	A_3	A_4	A_4Q
F^- (mg/l)	.399	.318	.513	.544	.608
Cl^- (mg/l)	16.599	17.228	14.720	13.675	14.069
Br^- (mg/l)	1.019	.666	.375	.220	.222
NO_3^- (mg/l)	4.595	6.142	7.780	10.424	10.284
$SO_4^=$ (mg/l)	25.752	26.440	27.166	27.611	28.292
pH (units)	6.34	6.51	6.75	6.86	6.83
Temperature (°C)	19.5	19.0	17.7	19.4	19.8
Hardness (mg/l HCO_3)	584	555	534	491	491
Conductivity (µmhos/cm)	904	978	915	895	897

WATER QUALITY DATA
Date Of Sample Collection:
11 June 1990

Well #

	B_6	B_8	B_9	B_{10}	B_{11}
F^- (mg/l)	.318	.431	.449	.496	.892
Cl^- (mg/l)	10.129	12.398	18.902	20.339	33.751
Br^- (mg/l)	.559	.519	.314	.298	.179
NO_3^- (mg/l)	.386	1.929	6.896	4.864	.137
$SO_4^=$ (mg/l)	15.599	38.019	24.361	24.347	81.003
pH (units)	6.81	6.81	6.90	6.92	7.48
Temperature (°C)	24.2	20.3	17.7	18.2	20.3
Hardness (mg/l HCO_3)	586	920	725	572	581
Conductivity (μmhos/cm)	1015	1051	977	938	1041

WATER QUALITY DATA
Date Of Sample Collection:
11 June 1990

	Well #			
	D_1	D_2	D_3	D_4
F^- (mg/l)	.560	.593	.589	.759
Cl^- (mg/l)	26.824	25.792	25.871	39.915
Br^- (mg/l)	.367	.355	.332	.347
NO_3^- (mg/l)	1.623	.746	1.551	8.416
$SO_4^=$ (mg/l)	28.908	21.518	18.884	26.827
pH (units)	6.74	6.88	7.08	7.04
Temperature (°C)	17.6	19.1	19.2	14.7
Hardness (mg/l HCO_3)	702	799	747	638
Conductivity (µmhos/cm)	1100	1230	1128	1028

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_2 0909	D_3 0912	D_4 0914	D_5 0915	D_2 0952	D_3 0955
Ca^{++} (mg/l)	69.95	53.53	51.18	54.39	58.35	85.37
K^{+} (mg/l)	.5068	.2555	.2602	.3707	.4062	.2256
Mg^{++} (mg/l)	59.77	47.03	41.40	42.96	58.41	50.24
Na^{+} (mg/l)	115.0	105.5	124.1	120.6	109.8	108.9
F^{-} (mg/l)	.721	.714	.765	.730	.716	.729
Cl^{-} (mg/l)	30.581	30.803	12.904	14.124	30.937	31.396
Br^{-} (mg/l)	.401	.362	.144	.186	.347	.358
NO_3^{-} (mg/l)	.220	.647	5.699	4.805	.023	.660
$SO_4^{=}$ (mg/l)	16.466	16.664	32.634	31.719	20.942	16.933
pH (units)	6.89	6.85	7.08	6.97	7.11	6.77
Temperature (°C)	16.8	14.4	15.1	14.9	14.7	11.8
Hardness (mg/l HCO_3)	842	708	683	688	805	711
Conductivity (µmhos/cm)	1320	1190	1180	1180	1340	1130
Cation/Anion Balance (%)	-5.57	-7.03	-3.70	-3.49	-30.45	.94

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_4 0958	D_5 1000	D_2 1007	D_3 1009	D_4 1013	D_5 1015
Ca^{++} (mg/l)	27.73	51.53	36.73	47.59	70.85	40.43
K^{+} (mg/l)	*	.2883	5072	.2396	.3707	.3145
Mg^{++} (mg/l)	39.87	42.30	53.93	49.36	41.96	42.24
Na^{+} (mg/l)	117.0	118.0	105.3	108.6	124.8	118.1
F^{-} (mg/l)	.708	.730	.652	.725	.815	.867
Cl^{-} (mg/l)	13.223	14.124	28.616	29.958	12.993	15.829
Br^{-} (mg/l)	.177	.186	.367	.328	.175	.181
NO_3^{-} (mg/l)	5.365	4.805	.641	.789	5.139	4.383
$SO_4^{=}$ (mg/l)	31.939	31.719	25.065	17.928	32.030	33.091
pH (units)	7.04	6.98	7.73	6.98	7.08	7.02
Temperature (°C)	14.5	16.7	14.4	16.3	12.3	13.7
Hardness (mg/l HCO_3)	682	685	#	722	676	693
Conductivity (μmhos/cm)	1180	1160	1140	1220	1100	1160
Cation/Anion Balance (%)	-11.21	-4.66		-7.79	1.27	-8.02

* Concentration below detectable limit.
\# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 1030	D_4 1035	D_5 1040	D_2 1050	D_3 1055	D_4 1100
Ca^{++} (mg/l)	72.59	48.23	65.69	27.91	81.72	48.43
K^+ (mg/l)	*	.2621	.3875	.5586	*	.3108
Mg^{++} (mg/l)	48.94	41.03	43.57	55.87	48.51	41.06
Na^+ (mg/l)	108.9	123.1	122.4	108.9	107.5	123.1
F^- (mg/l)	.710	.815	.815	.733	.728	.812
Cl^- (mg/l)	29.838	12.796	15.561	30.134	29.798	12.878
Br^- (mg/l)	.346	.173	.214	.355	.350	.169
NO_3^- (mg/l)	.910	5.439	4.259	.243	.929	5.311
$SO_4^=$ (mg/l)	18.115	32.313	32.532	25.184	18.415	32.312
pH (units)	6.84	7.12	7.01	7.20	6.92	7.06
Temperature (°C)	11.8	13.4	12.7	15.7	13.5	12.6
Hardness (mg/l HCO_3)	00	532	665	#	696	676
Conductivity (µmhos/cm)	1120	1100	1100	1080	1120	1100
Cation/Anion Balance (%)	-1.22	6.65	.75		.45	-4.12

* Concentration below detectable limit.

\# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_5 1105	D_2 1115	D_3 1120	D_4 1125	D_5 1130	D_2 1140
Ca^{++} (mg/l)	46.33	52.63	59.91	45.24	42.07	64.15
K^{+} (mg/l)	.3220	.3913	.2707	.2003	.2584	.5606
Mg^{++} (mg/l)	42.62	55.92	48.53	40.76	42.44	54.21
Na^{++} (mg/l)	121.4	109.8	110.8	121.1	119.1	111.1
F^{-} (mg/l)	.796	.755	.736	.800	.727	.787
Cl^{-} (mg/l)	15.987	29.531	28.463	12.770	15.168	27.740
Br^{-} (mg/l)	.217	.381	.335	.176	.211	.289
NO_3^{-} (mg/l)	4.593	.424	.950	5.364	4.677	.900
$SO_4^{=}$ (mg/l)	33.198	26.078	18.244	31.982	32.983	27.103
pH (units)	7.02	7.43	7.00	7.08	7.00	7.34
Temperature (°C)	16.2	16.1	14.8	15.9	16.3	21.1
Hardness (mg/l HCO_3)	711	#	709	638	662	#
Conductivity (μmhos/cm)	1160	1240	1140	1140	1140	1320
Cation/Anion Balance (%)	-7.06		-4.04	-2.68	-5.22	

Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 1145	D_4 1150	D_5 1155	D_2 1205	D_3 1210	D_4 1215
Ca^{++} (mg/l)	54.32	54.24	42.65	67.70	58.00	50.82
K^{+} (mg/l)	.2509	.2509	.3295	.4665	*	.2621
Mg^{++} (mg/l)	49.77	41.61	42.67	56.94	48.33	40.70
Na^{++} (mg/l)	111.3	121.6	120.8	113.8	107.4	121.6
F^{-} (mg/l)	.732	.830	.800	.771	765	.779
Cl^{-} (mg/l)	28.702	12.519	15.445	37.350	29.478	13.432
Br^{-} (mg/l)	.308	.144	.212	.425	.345	.207
NO_3^{-} (mg/l)	.863	5.419	4.734	.049	.982	5.624
$SO_4^{=}$ (mg/l)	18.559	32.404	32.925	31.565	19.377	31.675
pH (units)	6.93	7.08	7.04	7.11	6.94	7.08
Temperature (°C)	16.6	15.7	15.0	17.6	16.2	15.7
Hardness (mg/l HCO_3)	685	662	682	#	668	662
Conductivity (μmhos/cm)	1180	1120	1100	1320	1160	1120
Cation/Anion Balance (%)	-3.20	-1.94	-6.02		-2.70	-3.07

* Concentration below detectable limit.
\# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_5 1220	D_2 1230	D_3 1235	D_4 1240	D_5 1245	D_2 1255
Ca^{++} (mg/l)	48.81	82.77	65.88	40.32	53.21	80.81
K^{+} (mg/l)	.2546	.4584	*	.2546	.2509	.4665
Mg^{++} (mg/l)	41.96	57.31	49.14	40.44	42.03	53.67
Na^{++} (mg/l)	117.6	132.1	109.2	122.3	117.9	129.8
F^{-} (mg/l)	.832	.949	.730	.770	.833	.822
Cl^{-} (mg/l)	15.433	88.645	28.961	13.565	15.862	112.039
Br^{-} (mg/l)	.215	.678	.293	.202	.263	.772
NO_3^{-} (mg/l)	4.662	.158	.921	5.764	4.842	.269
$SO_4^{=}$ (mg/l)	32.970	59.827	18.628	31.925	33.257	67.519
pH (units)	6.96	7.04	6.88	7.06	7.02	7.07
Temperature (°C)	16.6	16.4	15.4	19.6	14.6	16.4
Hardness (mg/l HCO_3)	657	699	688	700	699	#
Conductivity (µmhos/cm)	1160	1420	1140	1130	1090	1420
Cation/Anion Balance (%)	-3.85	-2.01	-1.63	-8.00	-5.66	

* Concentration below detectable limit.
# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 1300	D_4 1305	D_5 1310	D_2 1320	D_3 1325	D_4 1330
Ca^{++} (mg/l)	62.85	47.34	37.30	95.22	65.61	50.54
K^{+} (mg/l)	*	.2996	.3707	.6826	*	.2584
Mg^{++} (mg/l)	49.02	41.17	41.79	53.80	49.47	41.04
Na^{++} (mg/l)	109.3	122.6	118.0	136.7	110.2	122.9
F^{-} (mg/l)	.743	.803	.736	.878	.789	.749
Cl^{-} (mg/l)	26.061	13.503	13.618	125.749	29.625	12.922
Br^{-} (mg/l)	.332	.169	.183	.779	.316	.167
NO_3^{-} (mg/l)	.871	5.692	5.405	.295	.741	5.720
$SO_4^{=}$ (mg/l)	18.515	32.269	31.849	69.659	18.530	32.038
pH (units)	6.97	7.03	7.07	7.08	6.97	7.13
Temperature (°C)	15.6	14.8	14.6	17.2	17.0	17.4
Hardness (mg/l HCO_3)	726	644	625	741	761	679
Conductivity (µmhos/cm)	1140	1080	1090	1440	1180	1160
Cation/Anion Balance (%)	-4.40	-2.28	-3.91	-6.29	-6.03	-3.89

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_5 1335	D_1 1340	D_2 1345	D_3 1350	D_4 1355	D_5 1400
Ca^{++} (mg/l)	90.76	57.08	75.15	53.30	26.61	51.73
K^+ (mg/l)	.2771	.2012	.4665	*	.2509	.3183
Mg^{++} (mg/l)	40.55	44.46	52.58	50.00	40.01	42.62
Na^+ (mg/l)	118.7	136.2	132.7	111.1	120.6	120.1
F^- (mg/l)	.762	.798	.842	.730	.627	.761
Cl^- (mg/l)	15.095	19.182	119.871	32.025	13.321	13.597
Br^- (mg/l)	.225	.186	.745	.386	.197	.157
NO_3^- (mg/l)	4.667	1.953	.288	.835	5.819	5.347
$SO_4^=$ (mg/l)	32.839	37.652	67.665	20.490	32.071	31.758
pH (units)	7.07	7.68	7.19	6.95	7.18	7.11
Temperature (°C)	17.4	16.1	18.3	17.5	17.5	16.8
Hardness (mg/l HCO_3)	682	#	728	726	665	722
Conductivity (µmhos/cm)	1160	1040	1460	1220	1160	1160
Cation/Anion Balance (%)	2.94		-9.36	-6.54	-9.49	-6.44

* Concentration below detectable limit.
# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_1 1405	D_2 1410	D_3 1415	D_4 1420	D_5 1425	D_1 1430
Ca^{++} (mg/l)	27.82	86.86	59.87	54.33	29.15	33.28
K^{+} (mg/l)	*	.4665	*	.9698	.2172	*
Mg^{++} (mg/l)	42.28	53.08	35.10	42.18	41.65	42.68
Na^{++} (mg/l)	126.0	134.7	77.67	122.6	118.0	121.6
F^{-} (mg/l)	.742	.897	.443	.813	.775	.720
Cl^{-} (mg/l)	17.175	117.703	26.618	14.115	16.728	14.921
Br^{-} (mg/l)	.201	.756	.269	2.040	.216	.166
NO_3^{-} (mg/l)	2.987	.302	.597	5.557	4.782	4.680
$SO_4^{=}$ (mg/l)	34.524	66.165	16.166	31.935	33.474	32.971
pH (units)	#	7.20	7.10	7.08	7.15	#
Temperature (°C)	17.2	18.7	18.6	15.9	18.4	18.7
Hardness (mg/l HCO_3)	#	708	767	664	723	#
Conductivity (µmhos/cm)	#	1420	1220	1060	1100	990
Cation/Anion Balance (%)		-5.60	-19.22	-1.73	-13.02	

* Concentration below detectable limit.
\# Not enough sample to perform field test.

WATER QUALITY DATA

Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_2 1435	D_3 1440	D_4 1445	D_5 1450	D_1 1500	D_2 1510
Ca^{++} (mg/l)	30.73	50.58	51.67	48.67	20.39	88.98
K^+ (mg/l)	.2180	.3203	.2509	.3744	.2609	.4658
Mg^{++} (mg/l)	15.89	49.16	41.00	42.72	40.24	53.89
Na^{++} (mg/l)	38.17	111.7	121.4	121.1	116.1	139.9
F^- (mg/l)	.169	.697	.777	1.790	.768	.881
Cl^- (mg/l)	26.379	37.934	14.377	14.629	17.144	116.027
Br^- (mg/l)	.173	.388	.223	.184	.179	.798
NO_3^- (mg/l)	.144	.889	5.233	5.486	3.802	.384
$SO_4^=$ (mg/l)	14.827	22.951	32.201	31.649	31.286	66.578
pH (units)	7.24	7.16	7.13	7.08	#	7.17
Temperature (°C)	17.8	19.7	18.6	17.9	20.1	15.6
Hardness (mg/l HCO_3)	694	714	647	691	#	679
Conductivity (µmhos/cm)	1440	1200	1110	1080	980	1360
Cation/Anion Balance (%)	-46.77	-7.35	-1.87	-4.98		-2.66

Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 1520	D_4 1530	D_5 1540	D_1 1550	D_2 1600	D_3 1610
Ca^{++} (mg/l)	76.18	32.40	48.33	23.66	77.24	49.34
K^{+} (mg/l)	.3775	*	.2509	.2007	.4053	.2996
Mg^{++} (mg/l)	49.65	40.38	42.25	41.08	52.72	49.66
Na^{++} (mg/l)	113.4	120.8	119.2	116.0	128.6	112.1
F (mg/l)	.708	.719	.849	.575	.866	.793
Cl^{-} (mg/l)	34.775	13.860	16.422	15.292	99.283	32.747
Br^{-} (mg/l)	.379	.199	.218	.166	.676	.463
NO_3^{-} (mg/l)	.915	5.341	4.776	4.037	.298	1.165
$SO_4^{=}$ (mg/l)	21.699	32.668	33.461	32.489	59.127	22.562
pH (units)	7.03	7.14	7.14	#	7.21	7.03
Temperature (°C)	17.5	17.2	17.1	19.6	18.0	16.4
Hardness (mg/l HCO_3)	760	667	635	#	635	729
Conductivity (µmhos/cm)	1140	1080	1080	1020	1360	1130
Cation/Anion Balance (%)	-3.97	-8.15	-2.16		-2.28	-7.71

* Concentration below detectable limit.

\# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_4 1620	D_5 1630	D_2 1650	D_3 1700	D_4 1710	D_5 1720
Ca^{++} (mg/l)	46.65	28.90	58.88	47.76	47.66	48.78
K^+ (mg/l)	.2546	.2677	.5072	.2958	.2808	.2771
Mg^{++} (mg/l)	41.16	41.86	54.38	49.94	41.05	42.40
Na^{++} (mg/l)	122.7	119.1	123.4	112.2	122.6	119.8
F^- (mg/l)	.786	.787	.824	.700	.801	.863
Cl^- (mg/l)	14.247	14.444	75.110		13.634	15.128
Br^- (mg/l)	.199	.188	.546	.488	.197	.174
NO_3^- (mg/l)	5.309	5.665	.178	.876	5.339	4.816
$SO_4^=$ (mg/l)	32.520	33.177	48.089	21.724	32.649	33.511
pH (units)	7.22	7.19	7.16	6.99	7.08	7.07
Temperature (°C)	17.9	16.0	15.6	17.7	16.6	16.3
Hardness (mg/l HCO_3)	676	670	734	740	709	694
Conductivity (µmhos/cm)	1080	1060	1280	1140	1090	1060
Cation/Anion Balance (%)	-4.74	-9.06	-8.44	-5.01	-6.68	-5.75

WATER QUALITY DATA

Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_1 1730	D_2 1740	D_3 1750	D_4 1800	D_5 1810	D_2 1830
Ca^{++} (mg/l)	16.28	73.87	70.16	48.02	53.46	65.17
K^+ (mg/l)	*	.4550	.3775	.2883	.3145	.3442
Mg^{++} (mg/l)	41.86	55.63	49.64	40.94	43.29	55.51
Na^{++} (mg/l)	116.2	118.1	113.5	122.6	122.5	111.8
F^- (mg/l)	.637	.789	.693	.816	.733	.770
Cl^- (mg/l)	13.889	56.868	34.723	15.248	13.479	47.922
Br^- (mg/l)	.181	.455	.372	.282	.183	.425
NO_3^- (mg/l)	5.130	.081	.920	6.113	5.486	.067
$SO_4^=$ (mg/l)	31.396	40.194	21.322	32.848	31.872	36.551
pH (units)	#	7.04	6.97	7.03	7.04	7.02
Temperature (°C)	17.9	16.8	17.1	10.8	14.3	15.3
Hardness (mg/l HCO_3)	#	772	709	680	680	772
Conductivity (µmhos/cm)	#	1360	1170	1080	1070	1250
Cation/Anion Balance (%)		-5.90	-2.00	-4.94	-2.62	-7.56

* Concentration below detectable limit.
\# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 1840	D_4 1850	D_5 1900	D_2 1930	D_3 1945	D_4 2000
Ca^{++} (mg/l)	52.11	52.65	44.99	50.65	38.65	40.51
K^+ (mg/l)	*	.2602	.3707	.4385	.3707	.2434
Mg^{++} (mg/l)	49.49	41.72	43.11	54.42	50.22	40.63
Na^{++} (mg/l)	110.3	122.3	121.9	110.3	112.6	121.8
F^- (mg/l)	.776	.771	.768	.813	.661	.769
Cl^- (mg/l)	33.337	14.574	14.578	44.642	33.321	13.347
Br^- (mg/l)	.373	.197	.218	.448	.391	.199
NO_3^- (mg/l)	.892	5.401	4.892	.095	.782	5.862
$SO_4^=$ (mg/l)	21.365	32.802	33.465	35.761	21.724	32.348
pH (units)	6.82	7.04	7.05	6.97	7.03	7.02
Temperature (°C)	14.8	13.9	13.2	13.0	13.3	12.7
Hardness (mg/l HCO_3)	683	680	632	743	705	661
Conductivity (µmhos/cm)	1160	1080	1070	1260	1130	1080
Cation/Anion Balance (%)	-4.62	-3.61	-1.61	-9.11	-8.28	-5.39

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
1 March 1991
Bromide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_5 2015	D_2 2045	D_3 2100	D_4 2115	D_5 2130
Ca^{++} (mg/l)	43.03	65.70	24.62	47.21	51.89
K^{+} (mg/l)	.2883	.4995	.2546	*	.2659
Mg^{++} (mg/l)	42.07	53.85	48.95	41.54	42.44
Na^{++} (mg/l)	118.9	109.0	111.1	122.3	119.2
F^{-} (mg/l)	.851	.772	.646	.748	.839
Cl^{-} (mg/l)	16.427	42.652	32.925	13.533	15.977
Br^{-} (mg/l)	.214	.432	.383	.193	.212
NO_3^{-} (mg/l)	5.012	.063	.798	5.359	4.898
$SO_4^{=}$ (mg/l)	34.335	34.899	21.662	32.538	31.180
pH (units)	6.98	6.93	6.87	6.99	7.02
Temperature (°C)	12.2	11.5	11.6	10.9	10.6
Hardness (mg/l HCO_3)	670	783	719	674	711
Conductivity (μmhos/cm)	1080	1260	1170	1090	1110
Cation/Anion Balance (%)	-5.98	-8.45	-13.20	-4.37	-6.16

* Concentration below detectable limit.

WATER QUALITY DATA

Date Of Sample Collection:
2 March 1991

Well #

	D_2	D_3	D_4	D_5	Tap
Ca^{++} (mg/l)	53.950	56.700	77.480	58.360	37.510
K^{+} (mg/l)	0.380	*	*	*	5.810
Mg^{++} (mg/l)	58.020	50.830	42.020	43.160	16.220
Na^{+} (mg/l)	110.600	112.500	123.600	119.300	151.600
F^{-} (mg/l)	0.755	0.701	0.762	0.726	1.319
Cl^{-} (mg/l)	40.617	31.723	13.312	13.245	224.005
Br^{-} (mg/l)	0.441	0.335	0.180	0.173	0.356
NO_3^{-} (mg/l)	1.400	*	5.965	5.813	0.217
$SO_4^{=}$ (mg/l)	34.726	20.259	32.856	32.160	106.992
pH (units)	7.01	7.08	6.92	6.98	11.27
Temperature (°C)	3.9	5.5	8.8	7.8	15.8
Hardness (mg/l HCO_3)	841	734	676	659	82
Conductivity (µmhos/cm)	1230	1040	1060	890	1100
Cation/Anion Balance (%)	-12.05	-5.71	2.26	-0.80	0.30

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
4 March 1991

Well #

	D_2	D_3	D_4	D_5
Ca^{++} (mg/l)	59.100	91.030	78.490	63.360
K^{+} (mg/l)	0.693	*	*	*
Mg^{++} (mg/l)	59.840	50.730	42.020	43.320
Na^{+} (mg/l)	112.100	113.800	125.200	121.700
F^{-} (mg/l)	0.762	0.686	0.765	0.735
Cl^{-} (mg/l)	38.814	30.611	12.365	13.205
Br^{-} (mg/l)	0.433	0.365	0.182	0.210
NO_3^{-} (mg/l)	0.046	0.925	6.180	4.878
$SO_4^{=}$ (mg/l)	31.060	19.521	32.221	32.049
pH (units)	6.98	6.89	6.95	6.93
Temperature (°C)	12.8	12.1	12.2	12.1
Hardness (mg/l HCO_3)	#	723	706	683
Conductivity (µmhos/cm)	1400	1210	1160	1140
Cation/Anion Balance (%)		2.04	0.90	-0.89

* Concentration below detectable limit.
\# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
6 March 1991

Well #

	D_2	D_3	D_4	D_5
Ca^{++} (mg/l)	83.690	87.360	68.260	79.300
K^+ (mg/l)	0.314	.272	*	*
Mg^{++} (mg/l)	58.400	51.000	42.530	43.850
Na^+ (mg/l)	112.000	115.600	125.500	121.900
F^- (mg/l)	0.796	0.710	0.763	0.781
Cl^- (mg/l)	38.465	29.320	12.229	13.365
Br^- (mg/l)	0.433	0.344	0.169	0.189
NO_3^- (mg/l)	0.072	0.919	5.654	4.953
$SO_4^=$ (mg/l)	32.402	20.112	32.151	32.760
pH (units)	7.01	6.99	7.03	7.07
Temperature (°C)	10.1	9.9	10.9	10.6
Hardness (mg/l HCO_3)	#	738	682	679
Conductivity (µmhos/cm)	1260	1140	1130	1060
Cation/Anion Balance (%)		0.92	0.70	2.71

* Concentration below detectable limit.
\# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
10 March 1991

	Well #			
	D_2	D_3	D_4	D_5
Ca^{++} (mg/l)	94.250	88.530	77.710	77.500
K^+ (mg/l)	0.359	*	*	0.222
Mg^{++} (mg/l)	59.140	50.250	41.700	44.510
Na^+ (mg/l)	113.800	112.500	124.200	125.700
F^- (mg/l)	0.755	0.681	0.739	0.758
Cl^- (mg/l)	39.090	29.730	12.491	13.162
Br^- (mg/l)	0.419	0.337	0.166	0.175
NO_3^- (mg/l)	0.025	0.833	5.815	4.698
$SO_4^=$ (mg/l)	29.376	19.791	31.768	31.462
pH (units)	7.01	6.98	7.02	7.01
Temperature (°C)	13.4	12.7	12.2	12.3
Hardness (mg/l HCO_3)	685	722	682	670
Conductivity (µmhos/cm)	1340	1140	1100	1080
Cation/Anion Balance (%)	5.78	1.36	2.08	3.98

* Concentration below detectable limit.
# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
13 March 1991

Well #

	D_2	D_3	D_4	D_5
Ca^{++} (mg/l)	96.470	86.050	79.840	78.570
K^{+} (mg/l)	0.462	*	*	*
Mg^{++} (mg/l)	60.160	49.890	42.280	43.320
Na^{+} (mg/l)	117.600	110.000	125.300	120.000
F^{-} (mg/l)	0.778	0.696	0.781	0.789
Cl^{-} (mg/l)	37.600	29.308	12.699	13.768
Br^{-} (mg/l)	0.408	0.313	0.141	0.175
NO_3^{-} (mg/l)	0.029	0.785	5.631	4.869
$SO_4^{=}$ (mg/l)	26.777	19.603	32.846	31.720
pH (units)	7.01	6.99	7.03	7.03
Temperature (°C)	6.7	8.9	9.9	9.6
Hardness (mg/l HCO_3)	#	699	661	697
Conductivity (µmhos/cm)	1290	1050	1140	1140
Cation/Anion Balance (%)		1.90	4.18	.92

* Concentration below detectable limit.
# Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
17 March 1991

Well #

	D$_2$	D$_3$	D$_4$	D$_5$
Ca^{++} (mg/l)	99.010	88.900	77.540	62.950
K^{+} (mg/l)	0.555	*	*	*
Mg^{++} (mg/l)	60.760	50.750	42.240	43.590
Na^{+} (mg/l)	115.400	112.600	124.400	121.200
F^{-} (mg/l)	0.762	0.722	0.780	0.777
Cl^{-} (mg/l)	35.002	27.735	11.937	12.741
Br^{-} (mg/l)	0.371	0.327	0.159	0.173
NO$_3^{-}$ (mg/l)	0.015	0.825	5.708	4.597
SO$_4^{=}$ (mg/l)	21.408	19.636	32.132	31.785
pH (units)	7.17	7.19	7.15	7.14
Temperature (°C)	8.8	8.2	10.2	9.9
Hardness (mg/l HCO$_3$)	857	741	673	697
Conductivity (µmhos/cm)	1260	920	1120	980
Cation/Anion Balance (%)	-1.66	.64	2.90	-1.82

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
24 March 1991

Well #

	D_2	D_3	D_4	D_5
Ca^{++} (mg/l)	99.460	87.370	80.450	77.610
K^{+} (mg/l)	0.451	*	*	*
Mg^{++} (mg/l)	58.970	48.840	42.140	43.430
Na^{+} (mg/l)	111.700	111.200	125.600	121.800
F^{-} (mg/l)	0.846	0.697	0.752	0.778
Cl^{-} (mg/l)	36.656	26.994	11.885	12.847
Br^{-} (mg/l)	0.367	0.312	0.156	0.167
NO_3^{-} (mg/l)	0.081	0.899	5.986	4.459
$SO_4^{=}$ (mg/l)	18.926	19.819	32.441	31.521
pH (units)	7.14	7.18	7.28	7.23
Temperature (°C)	17.8	17.1	17.1	17.3
Hardness (mg/l HCO_3)	856	714	696	697
Conductivity (µmhos/cm)	1260	990	1040	1020
Cation/Anion Balance (%)	-2.56	1.30	2.08	1.20

* Concentration below detectable limit.

WATER QUALITY DATA

Date Of Sample Collection:
13 April 1991

	Well #				
	D_1	D_2	D_3	D_4	D_5
Ca^{++} (mg/l)	76.320	106.700	81.770	81.890	80.540
K^{+} (mg/l)	0.321	0.458	*	*	*
Mg^{++} (mg/l)	45.910	58.360	47.470	42.100	43.600
Na^{+} (mg/l)	129.900	113.100	109.500	126.000	123.100
F^{-} (mg/l)	0.863	0.896	0.714	0.782	0.787
Cl^{-} (mg/l)	15.734	35.619	24.477	13.474	14.040
Br^{-} (mg/l)	0.245	0.421	0.308	0.182	0.146
NO_3^{-} (mg/l)	0.103	0.018	1.284	5.472	4.542
$SO_4^{=}$ (mg/l)	24.642	15.146	20.511	31.370	30.368
pH (units)	7.46	7.25	7.27	7.36	7.38
Temperature (°C)	8.5	23.5	23.6	32.4	37.5
Hardness (mg/l HCO_3)	775	863	728	683	696
Conductivity (µmhos/cm)	1020	1170	1020	1030	1020
Cation/Anion Balance (%)	-1.54	-1.34	-1.17	3.18	2.07

* Concentration below detectable limit.

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_1 0953	D_1 1200	D_1 1225	D_1 1250	D_1 1315	D_1 1340
I^- (mg/l)						
F^- (mg/l)	1.369	.948	.765	.657	.632	.614
Cl^- (mg/l)	15.868	16.337	17.943	16.993	36.612	17.272
Br^- (mg/l)	.261	.258	.220	.226	.218	.189
NO_3 (mg/l)	.083	.016	.307	.935	1.250	.946
$SO_4^=$ (mg/l)	12.951	15.640	17.874	21.693	23.287	21.459
pH (units)	7.42	7.49	8.42	8.25	8.29	8.52
Temperature (°C)	14.2	14.6	16.6	16.9	17.4	17.3
Hardness (mg/l HCO_3)	767	#	#	#	#	#
Conductivity (µmhos/cm)	1080	980	970	830	1010	900

Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D1 1405	D1 1430	D1 1455	D1 1520	D1 1545	D1 1610
I^- (mg/l)						
F^- (mg/l)	.672	.588	.594	.634	.687	.692
Cl^- (mg/l)	16.958	16.187	17.135	15.853	16.817	17.273
Br^- (mg/l)	.203	.197	.191	.220	.227	.226
NO_3^- (mg/l)	2.325	1.551	.622	1.209	.594	.624
$SO_4^=$ (mg/l)	25.319	23.620	21.400	24.083	23.886	25.069
pH (units)	8.36	8.29	8.42	7.90	7.85	7.86
Temperature (°C)	19.3	19.8	20.0	20.2	19.7	19.6
Hardness (mg/l HCO_3)	#	#	#	#	#	#
Conductivity (μmhos/cm)	970	1010	920	1040	1040	1000

Not enough sample to perform field test.

WATER QUALITY DATA

Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_1 1635	D_1 1700	D_1 1725	D_1 1750	D_1 1815	D_1 1840
I^- (mg/l)	.246	.431	.376	.399	.300	.378
F^- (mg/l)	.769	.723	.739	.683	.619	.622
Cl^- (mg/l)	18.845	19.710	27.033	20.864	20.029	17.966
Br^- (mg/l)	.220	.206	.215	.214	.210	.178
NO_3^- (mg/l)	.653	1.048	1.564	1.828	2.440	3.057
$SO_4^=$ (mg/l)	26.692	28.677	29.014	30.204	31.462	31.132
pH (units)	7.73	7.71	7.99	8.06	8.11	8.14
Temperature (°C)	19.3	19.5	19.6	19.3	19.2	19.0
Hardness (mg/l HCO_3)	#	#	#	#	#	#
Conductivity (µmhos/cm)	1030	1040	1020	1010	1000	#

Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_1 1905	D_1 1930	D_1 2000	D_1 2055	Barrel	Tap
I^- (mg/l)	.413		.233	.994	6.73	
F^- (mg/l)	.606	.619	.608	.759		1.110
Cl^- (mg/l)	18.667	14.539	17.506	21.020	.676	247.440
Br^- (mg/l)	.196	.143	.192	.209		.217
NO_3^- (mg/l)	2.992	5.378	3.526	1.604		.528
$SO_4^=$ (mg/l)	31.689	33.637	31.584	31.219	31.600	132.072
pH (units)	8.22	8.17	8.13	7.77	6.22	8.46
Temperature (°C)	18.6	17.9	17.0	15.5	18.8	17.5
Hardness (mg/l HCO_3)	#	#	#	#	61	49
Conductivity (µmhos/cm)	940	960	970	1010	540	1040

Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_2 1021	D_2 1205	D_2 1230	D_2 1255	D_2 1320	D_2 1345
I^- (mg/l)						
F^- (mg/l)	1.302	1.184	.527	.575	1.182	.554
Cl^- (mg/l)	37.053	35.474	35.299	35.219	35.766	35.234
Br^- (mg/l)	.369	.382	.344	.370	.380	.347
NO_3^- (mg/l)	.008	.030	.029	.039	.036	.035
$SO_4^=$ (mg/l)	12.355	26.359	27.501	30.181	30.701	30.809
pH (units)	7.22	7.09	7.99	7.27	7.27	7.29
Temperature (°C)	14.7	14.8	16.5	15.7	16.3	16.9
Hardness (mg/l HCO_3)	819	822	#	763	747	#
Conductivity (µmhos/cm)	1230	1160	1080	1140	1180	1180

Not enough sample to perform field test.

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_2 1410	D_2 1435	D_2 1500	D_2 1525	D_2 1550	D_2 1615
I^- (mg/l)				1.319	1.759	2.938
F^- (mg/l)	1.241	.600	.615	.636	.652	.776
Cl^- (mg/l)	37.104	35.851	36.489	40.452	51.630	59.672
Br^- (mg/l)	.366	.374	.386	.375	.405	.378
NO_3^- (mg/l)	.045	.044	.036	.044	.067	.125
SO_4^- (mg/l)	32.580	31.863	33.440	36.129	41.289	43.935
pH (units)	7.31	7.28	7.26	7.22	7.23	7.20
Temperature (°C)	18.1	18.5	18.0	18.4	18.2	18.0
Hardness (mg/l HCO_3)	860	648	801	805	775	729
Conductivity (µmhos/cm)	1180	1180	1180	1180	1190	1200

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D2	D2	D2	D2	D2	D2
	1640	1705	1730	1755	1820	1845
I^- (mg/l)	3.227	3.090	2.417	2.239	1.647	1.003
F^- (mg/l)	.793	1.167	1.189	1.199	1.201	1.217
Cl^- (mg/l)	66.541	69.572	62.881	62.520	63.074	56.455
Br^- (mg/l)	.404	.460	.463	.419	.413	.399
NO_3^- (mg/l)	.103	.103	.082	.066	.057	.060
$SO_4^=$ (mg/l)	46.542	47.171	45.220	45.189	44.536	41.242
pH (units)	7.22	7.24	7.26	7.28	7.24	7.30
Temperature (°C)	17.5	18.2	17.8	17.6	17.7	17.6
Hardness (mg/l HCO_3)	722	723	747	726	792	776
Conductivity (µmhos/cm)	1210	1220	1220	1220	1180	1200

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_2 1910	D_2 1935	D_2 2010	D_2 2110	D_3 1042	D_3 1210
I^- (mg/l)	1.136	.926	1.217	.858		
F^- (mg/l)	1.231	1.199	.134	1.191	.739	.788
Cl^- (mg/l)	48.876	44.583	45.682	45.632	24.881	24.874
Br^- (mg/l)	.409	.397	.398	.357	.218	.273
NO_3^- (mg/l)	.056	.069	.059	.052	1.722	1.642
$SO_4^=$ (mg/l)	37.566	35.630	36.267	36.848	24.286	21.869
pH (units)	7.32	7.31	7.25	7.20	7.24	7.11
Temperature (°C)	17.5	16.7	15.7	14.6	15.0	14.9
Hardness (mg/l HCO_3)	796	786	821	780	699	683
Conductivity (μmhos/cm)	1190	1170	1180	1160	1040	1040

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 1235	D_3 1300	D_3 1325	D_3 1350	D_3 1415	D_3 1440
I^- (mg/l)						
F^- (mg/l)	.708	.755	.750	.773	.791	.783
Cl^- (mg/l)	23.087	23.829	24.204	24.694	258.242	24.825
Br^- (mg/l)	.234	.275	.238	.279	.266	.275
NO_3^- (mg/l)	1.712	1.702	1.667	1.801	1.769	1.756
$SO_4^=$ (mg/l)	21.656	21.792	21.740	22.561	22.708	22.795
pH (units)	7.12	7.16	7.15	7.16	7.08	7.11
Temperature (°C)	14.9	15.3	15.8	16.2	16.6	17.7
Hardness (mg/l HCO_3)	715	712	734	743	705	815
Conductivity (µmhos/cm)	970	990	1030	1040	1050	1040

WATER QUALITY DATA

Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 1505	D_3 1530	D_3 1555	D_3 1620	D_3 1645	D_3 1710
I^- (mg/l)						
F^- (mg/l)	.775	.780	.729	.714	.822	.753
Cl^- (mg/l)	25.094	24.883	26.119	26.612	26.675	27.275
Br^- (mg/l)	.281	.277	.280	.284	.284	.236
NO_3^- (mg/l)	1.710	1.722	1.581	1.707	1.606	1.700
SO_4^- (mg/l)	22.968	23.033	23.959	23.509	24.530	24.572
pH (units)	7.13	7.12	7.15	7.16	7.10	7.13
Temperature (°C)	17.5	17.9	18.1	17.8	17.8	17.6
Hardness (mg/l HCO_3)	714	755	720	918	859	728
Conductivity (µmhos/cm)	1030	1050	1050	1050	1050	1050

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 1735	D_3 1800	D_3 1825	D_3 1850	D_3 1915	D_3 1940
I^- (mg/l)						
F^- (mg/l)	.741	.769	.751	.783	.764	.717
Cl^- (mg/l)	27.404	27.398	27.647	27.621	26.781	27.344
Br^- (mg/l)	.272	.285	.228	.227	.295	.291
NO_3^- (mg/l)	1.700	1.678	1.729	1.730	1.754	1.674
$SO_4^=$ (mg/l)	25.435	25.226	25.684	25.791	25.360	25.495
pH (units)	7.18	7.13	7.12	7.07	7.16	7.13
Temperature (°C)	17.3	17.7	17.5	17.2	16.7	16.5
Hardness (mg/l HCO_3)	715	705	781	743	747	722
Conductivity (µmhos/cm)	1040	1050	1050	1050	1040	1060

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_3 2020	D_3 2125	D_4 1052	D_4 1215	D_4 1240	D_4 1305
I^- (mg/l)						
F^- (mg/l)	.772	.803	.816	.852	.822	.823
Cl^- (mg/l)	28.195	27.572	12.143	12.114	12.138	12.230
Br^- (mg/l)	.245	.269	.122	.133	.145	.148
NO_3^- (mg/l)	1.631	1.490	7.101	4.762	5.935	6.067
$SO_4^=$ (mg/l)	25.830	24.940	35.654	36.156	36.025	36.370
pH (units)	7.15	7.21	7.18	7.26	7.30	7.30
Temperature (°C)	15.4	14.3	14.7	15.1	15.6	15.8
Hardness (mg/l HCO_3)	755	761	661	642	746	699
Conductivity (µmhos/cm)	1050	1050	1030	1010	1020	1020

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D4 1330	D4 1355	D4 1420	D4 1445	D4 1510	D4 1535
I^- (mg/l)						
F^- (mg/l)	.873	.819	.863	.919	.867	.886
Cl^- (mg/l)	12.429	12.289	12.124	12.982	12.329	12.247
Br^- (mg/l)	.150	.126	.145	.126	.120	.150
NO_3^- (mg/l)	6.635	6.848	7.063	6.833	7.034	7.075
$SO_4^=$ (mg/l)	36.928	36.585	37.703	36.595	37.506	37.153
pH (units)	7.28	7.31	7.28	7.30	7.27	7.26
Temperature (°C)	16.0	16.9	17.7	17.5	17.7	17.5
Hardness (mg/l HCO_3)	697	712	659	700	657	705
Conductivity (µmhos/cm)	1000	1020	1020	1000	1020	1020

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_4 1600	D_4 1625	D_4 1650	D_4 1715	D_4 1740	D_4 1805
I^- (mg/l)						
F^- (mg/l)	.860	.885	.907	.884	.933	.875
Cl^- (mg/l)	12.975	12.966	13.607	13.079	13.971	13.313
Br^- (mg/l)	.149	.145	.136	.134	.144	.134
NO_3^- (mg/l)	7.345	7.579	7.740	7.710	7.812	7.875
$SO_4^=$ (mg/l)	37.415	38.175	39.051	39.661	39.352	39.551
pH (units)	7.28	7.25	7.25	7.27	7.29	7.27
Temperature (°C)	18.1	17.7	17.6	17.4	17.1	17.3
Hardness (mg/l HCO_3)	834	703	744	708	665	657
Conductivity (µmhos/cm)	1020	1010	1010	1000	1000	1000

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D4 1830	D4 1855	D4 1920	D4 1945	D4 2030	D4 2140
I^- (mg/l)						
F^- (mg/l)	.957	.978	.899	.924	.996	.908
Cl^- (mg/l)	13.689	14.136	13.484	13.670	14.018	13.413
Br^- (mg/l)	.138	.138	.139	.139	.117	.130
NO_3^- (mg/l)	7.875	7.807	7.744	8.207	7.785	7.706
$SO_4^=$ (mg/l)	39.532	39.236	38.901	41.274	41.164	39.193
pH (units)	7.24	7.26	7.25	7.29	7.32	7.30
Temperature (°C)	17.3	17.1	16.6	16.2	15.2	14.7
Hardness (mg/l HCO_3)	683	665	665	657	676	670
Conductivity (µmhos/cm)	1000	1010	1000	990	980	990

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_5 1100	D_5 1220	D_5 1245	D_5 1310	D_5 1335	D_5 1400
I^- (mg/l)						
F^- (mg/l)	.740	.739	.734	.737	.733	.736
Cl^- (mg/l)	12.544	11.703	11.690	12.732	12.601	11.521
Br^- (mg/l)	.137	.130	.111	.136	.137	.134
NO_3^- (mg/l)	4.692	5.360	5.932	6.005	6.043	5.962
$SO_4^=$ (mg/l)	31.335	32.213	34.567	34.672	35.197	34.336
pH (units)	7.05	7.24	7.29	7.29	7.28	7.28
Temperature (°C)	14.4	15.4	15.6	15.8	15.8	17.0
Hardness (mg/l HCO_3^-)	697	677	695	703	696	679
Conductivity (µmhos/cm)	1000	990	1030	1020	920	1020

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_5 1425	D_5 1450	D_5 1515	D_5 1540	D_5 1605	D_5 1630
I^- (mg/l)						
F^- (mg/l)	.736	.749	.748	.765	.791	.774
Cl^- (mg/l)	12.492	11.902	11.736	11.878	12.032	11.816
Br^- (mg/l)	.108	.138	.107	.129	.125	.125
NO_3^- (mg/l)	6.157	6.089	6.224	6.291	6.334	6.158
$SO_4^=$ (mg/l)	35.190	34.909	35.369	35.560	35.437	35.645
pH (units)	7.27	7.26	7.26	7.28	7.29	7.24
Temperature (°C)	17.9	17.6	18.1	17.6	18.2	17.7
Hardness (mg/l HCO_3)	796	694	719	702	674	679
Conductivity (µmhos/cm)	1020	1020	1020	1000	1020	1010

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_5 1655	D_5 1720	D_5 1745	D_5 1810	D_5 1835	D_5 1900
I^- (mg/l)						
F^- (mg/l)	.790	.776	.758	.771	.795	.758
Cl^- (mg/l)	11.986	11.757	11.834	11.689	11.890	11.595
Br^- (mg/l)	.133	.133	.134	.138	.131	.137
NO_3^- (mg/l)	6.356	6.433	6.369	6.420	6.480	6.446
$SO_4^=$ (mg/l)	36.008	36.377	35.716	35.869	36.381	35.617
pH (units)	7.24	7.26	7.27	7.26	7.26	7.26
Temperature (°C)	17.7	17.6	17.5	17.5	17.3	17.2
Hardness (mg/l HCO_3)	693	686	676	711	668	642
Conductivity (μmhos/cm)	1010	1000	1000	1000	1000	1000

WATER QUALITY DATA
Date Of Sample Collection:
29 April 1991
Iodide Tracer Test

Well # and Time Of Collection (24 hour clock)

	D_5 1925	D_5 1950	D_5 2040
I^- (mg/l)			
F^- (mg/l)	.740	.752	.743
Cl^- (mg/l)	12.916	12.578	11.324
Br^- (mg/l)	.137	.135	.131
NO_3^- (mg/l)	6.415	6.667	6.373
$SO_4^=$ (mg/l)	35.578	35.612	35.710
pH (units)	7.25	7.26	7.29
Temperature (°C)	16.6	16.2	15.1
Hardness (mg/l HCO_3)	664	700	674
Conductivity (µmhos/cm)	1000	1000	1000

APPENDIX D

STATISTICS

DESCRIPTIVE STATISTICS FOR
Ca++

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	179.4	38.9	113.8	38.5	25
A2	144.1	22.1	106.4	31.3	28
A3	118.8	44.4	92.5	20.4	28
A4	190.1	29.5	88.4	26.2	30
A5	93.1	41.0	75.9	19.4	5
B6	135.7	129.6	131.9	2.7	3
B8	111.3	106.6	108.7	1.9	3
B9	95.7	94.7	95.2	0.41	3
B10	74.3	73.2	73.8	0.45	3
B11	27.9	16.3	23.3	5.0	3
C1	74.0	64.0	68.5	4.1	3
C2	80.3	65.0	73.1	5.5	4
C3	99.7	68.0	80.9	13.0	6
C4	103.4	81.0	91.9	10.2	7
C5	154.0	70.0	94.0	27.9	6
D1	127.0	76.3	106.4	21.8	3
D2	137.7	28.4	89.9	27.7	18
D3	112.0	37.3	82.8	18.6	19
D4	109.0	45.2	73.5	14.3	20
D5	80.5	47.2	67.8	11.3	15
E1	63.3	32.0	50.1	13.2	3
E2	67.6	58.0	61.7	3.6	4
E3	81.0	59.1	67.8	8.7	6
E4	87.1	55.0	69.4	11.7	7
E5	71.9	55.0	61.5	6.5	4
G1	104.9	100.2	102.6	3.3	2
G2	95.9	93.8	94.9	1.5	2
H1	102.3	101.1	101.7	0.85	2
H2	62.5	59.9	61.2	1.8	2
I1	118.3	112.2	115.3	4.3	2
I2	88.1	82.2	85.2	4.2	2

DESCRIPTIVE STATISTICS FOR
Fe++

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	0.08	0.002	0.01	0.24	10
A2	0.16	0.002	0.04	0.06	11
A3	0.10	0.002	0.03	0.04	12
A4	0.10	0.001	0.02	0.04	12
B6	15.10	5.700	9.30	5.07	3
B8	5.50	4.100	5.03	0.81	3
B9	0.09	0.044	0.06	0.02	3
B10	1.19	0.922	1.08	0.14	3
B11	0.51	0.433	0.47	0.04	3
D2	1.04	0.312	0.66	0.37	3
D3	0.08	0.039	0.06	0.02	3
D4	0.04	0.026	0.03	0.01	3

DESCRIPTIVE STATISTICS FOR K+

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	1.70	0.06	0.35	0.35	20
A2	0.38	0.08	0.22	0.09	23
A3	1.30	0.10	0.30	0.25	22
A4	1.40	0.03	0.27	0.27	22
B6	4.40	2.80	3.60	0.65	3
B8	1.23	1.14	1.19	0.64	3
B9	0.48	0.35	0.39	0.06	3
B10	2.29	1.26	1.92	0.47	3
B11	3.20	2.14	2.58	0.45	3
C4	1.40	0.24	0.91	0.49	3
C5	0.22	0.18	0.19	0.02	2
D1	0.34	0.32	0.33	0.01	2
D2	0.85	0.08	0.42	0.20	15
D3	1.40	0.05	0.42	0.51	9
D4	1.40	0.08	0.46	0.56	8
D5	0.37	0.29	0.34	0.04	2
E3	1.60	1.30	1.45	0.15	2
E4	1.30	1.10	1.20	0.10	2
G1	1.40	1.20	1.30	0.14	2
G2	1.40	1.20	1.30	0.14	2
H1	1.40	1.20	1.30	0.14	2
H2	1.40	1.10	1.25	0.21	2
I1	2.70	2.60	2.65	0.07	2
I2	1.40	1.40	1.40	1.40	2

DESCRIPTIVE STATISTICS FOR Mg^{++}

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	49.2	41.0	44.6	25.0	25
A3	58.8	43.8	47.3	2.9	28
A4	55.0	42.9	46.0	2.2	30
A5	43.8	40.2	41.6	1.2	5
B6	33.6	32.9	33.3	0.29	3
B8	36.5	35.5	35.9	0.42	3
B9	37.9	36.5	37.2	0.57	3
B10	33.7	33.3	33.4	0.19	3
B11	18.4	14.7	17.1	1.7	3
C1	112.0	96.3	102.4	6.9	3
C2	70.0	64.0	67.8	2.5	4
C3	66.8	48.0	57.9	7.7	6
C4	56.6	49.0	52.3	2.7	7
C5	60.9	51.0	55.8	3.8	6
D1	69.2	45.9	59.7	9.9	3
D2	75.4	43.2	59.5	6.9	18
D3	63	42.7	50.8	5.3	19
D4	47.7	33.8	41.3	3.3	18
D5	48.3	42.0	43.6	1.4	15
E1	28.8	23.0	25.6	2.4	3
E2	39.0	31.0	36.1	3.1	4
E3	38.0	30.5	33.6	2.9	6
E4	68.3	55.0	61.2	5.8	7
E5	60.4	52.0	56.1	3.1	4
G1	52.4	51.7	52.1	0.49	2
G2	52.7	51.8	52.3	0.64	2
H1	46.8	45.5	46.2	0.92	2
H2	52.0	49.9	50.9	1.5	2
I1	67.9	65.4	66.7	1.8	2
I2	56.2	55.6	55.9	0.42	2

DESCRIPTIVE STATISTICS FOR
Mn++

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	0.040	0.001	0.014	0.012	10
A2	0.013	0.001	0.006	0.003	10
A3	0.088	0.003	0.020	0.024	11
A4	0.024	0.004	0.011	0.006	10
B6	3.550	2.500	2.980	0.430	3
B8	4.600	3.800	4.300	0.360	3
B9	0.275	0.223	0.252	0.020	3
B10	0.942	0.754	0.857	0.080	3
B11	1.500	0.566	1.120	0.400	3
D2	0.179	0.055	0.096	0.072	3
D3	0.055	0.024	0.039	0.022	3

DESCRIPTIVE STATISTICS FOR Na+

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	27.4	10.8	20.3	3.6	23
A2	45.7	18.6	30.4	5.7	26
A3	47.0	27.5	35.2	4.0	26
A4	55.0	34.9	43.8	5.2	30
A5	43.5	42.0	42.9	0.5	4
B6	76.9	69.4	72.6	3.1	3
B8	83.0	70.3	77.7	5.4	3
B9	37.4	36.9	37.1	0.22	3
B10	47.4	45.9	46.6	0.61	3
B11	170.1	151.4	162.6	8.1	3
C1	158.0	116.1	141.0	18.0	3
C2	179.8	171.0	176.5	3.3	4
C3	177.0	115.5	144.9	23.3	6
C4	61.8	47.4	54.0	5.5	7
C5	98.0	49.0	74.6	20.0	6
D1	139.7	129.9	136.2	4.5	3
D2	128.0	86.3	112.1	11.4	18
D3	115.6	93.2	105.5	7.4	19
D4	126.0	102.0	116.3	9.0	20
D5	123.1	97.4	114.6	9.9	15
E1	20.3	12.0	15.1	3.7	3
E2	15.0	9.7	12.2	2.4	4
E3	17.0	8.7	12.8	3.0	6
E4	110.0	57.3	85.5	24.0	7
E5	100.0	41.4	56.6	38.1	4
G1	60.8	60.3	60.6	0.35	2
G2	74.9	74.3	74.6	0.42	2
H1	89.4	88.6	89.0	0.57	2
H2	130.0	128.3	129.2	1.2	2
I1	35.6	34.7	35.2	0.64	2
I2	45.6	45.1	45.4	0.36	2

DESCRIPTIVE STATISTICS FOR
Si_2

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	19.9	11.9	13.7	2.08	15
A2	13.7	10.5	12.6	0.88	17
A3	14.1	10.3	12.7	1.06	15
A4	14.8	11.4	13.5	0.94	16
B6	13.5	11.9	12.6	0.81	3
B8	14.4	14.2	14.3	0.12	3
B9	13.8	13.6	13.7	0.10	3
B10	13.5	13.1	13.3	0.20	3
B11	6.3	4.7	5.7	0.88	3
D2	11.5	8.2	10.9	0.93	3
D3	10.6	9.6	10.2	0.54	3
D4	10.7	10.3	10.4	0.22	3

DESCRIPTIVE STATISTICS FOR CONDUCTIVITY

Well	Maximum	Minimum (µmhos/cm)	Mean	Standard Deviation	Number of Samples
A1	1210	584	1018	108.9	88
A2	1280	832	1038	75.9	102
A3	1455	902	1029	76.1	120
A4	1160	840	978	65.2	172
A5	1165	803	985	68.1	77
B4	1125	874	999	125.5	2
B6	1341	974	1186	160.5	7
B7	1270	1131	1196	49.5	4
B8	1479	1051	1277	152.9	7
B9	1068	864	986	66.2	7
B10	990	793	916	60.9	7
B11	1193	848	1056	133.4	5
C1	1979	1411	1673	130.7	53
C2	1768	1127	1502	136.5	57
C3	1800	990	1335	162.9	93
C4	1208	862	1025	57.1	140
C5	1486	933	1138	134.4	68
D1	1881	1020	1479	210.8	46
D2	1879	1169	1504	172.6	73
D3	1904	920	1271	148.9	99
D4	1329	1004	1134	63.5	156
D5	1302	890	1123	76.6	79
E1	720	437	611	64.4	55
E2	879	255	613	143.8	68
E3	875	284	595	144.1	87
E4	1433	407	986	228.8	138
E5	1333	481	1060	173.3	68
G1	1104	936	1050	43.0	20
G2	1169	981	1078	48.0	29
H1	1136	970	1068	47.0	15
H2	1274	1147	1121	29.0	29
I1	1171	865	1063	98.0	14
I2	991	839	934	30.0	29
I3	960	825	895	55.3	3
J	1077	1026	1054	18.6	4

DESCRIPTIVE STATISTICS FOR
Cl-

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	96.3	14.4	24.9	12.7	51
A2	49.2	12.6	22.9	6.1	62
A3	32.4	13.8	20.3	4.7	76
A4	33.7	12.6	20.4	5.2	108
A5	38.4	14.6	23.7	5.9	58
B4	14.9	11.4	13.2	1.8	2
B6	18.8	8.4	12.4	3.3	7
B7	16.5	10.4	14.6	2.4	4
B8	23.0	12.1	15.9	4.3	7
B9	21.0	15.1	17.4	2.3	7
B10	21.2	15.8	18.5	1.8	7
B11	39.2	33.8	36.8	2.4	5
C1	139.9	18.4	47.8	28.0	25
C2	59.3	17.0	29.1	10.9	29
C3	73.3	18.7	35.4	16.8	48
C4	45.8	16.3	26.4	5.6	82
C5	78.4	18.1	29.8	8.6	51
D1	144.3	15.7	53.5	27.1	20
D2	163.0	25.8	51.9	31.2	42
D3	162.7	24.1	50.4	31.6	61
D4	72.0	11.9	32.5	10.2	97
D5	51.2	11.7	32.8	10.6	62
E1	14.8	3.6	8.9	2.9	26
E2	22.3	3.5	12.2	3.9	30
E3	26.3	3.8	12.1	5.9	47
E4	44.4	4.4	25.3	9.8	80
E5	42.4	6.64	27.2	8.7	50
G1	20.3	12.1	16.9	2.5	20
G2	24.0	14.8	19.9	2.5	29
H1	27.6	12.9	20.1	4.6	15
H2	32.9	27.5	30.5	1.6	29
I1	28.8	18.7	24.0	2.5	14
I2	17.1	12.6	14.9	1.4	29
I3	15.9	14.0	14.7	.85	3
J	18.4	11.9	16.0	2.5	4

DESCRIPTIVE STATISTICS FOR
HCO_3 =

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	802	429	606	69.6	47
A2	1108	476	615	78.4	60
A3	781	473	612	52.9	76
A4	653	410	577	42.7	105
A5	732	497	581	35.2	55
B4	639	490	564	105.4	2
B7	882	757	809	57.9	4
B8	920	674	773	99.2	5
B9	725	384	552	134.1	6
B10	592	342	484	111.5	6
B11	581	398	509	78.3	4
C1	1137	755	1041	98.1	20
C2	1341	638	996	119.2	26
C3	1028	686	838	101.2	47
C4	691	551	613	24.7	78
C5	868	568	687	84.8	48
D1	982	639	808	94.4	15
D2	1016	516	865	99.9	37
D3	1056	555	743	61.2	59
D4	742	488	651	28.5	92
D5	796	485	657	33.4	53
E1	414	271	345	38.9	18
E2	497	232	369	69.9	30
E3	491	198	359	64.2	46
E4	690	237	578	116.3	77
E5	795	254	571	96.9	47
G1	690	584	633	32.0	20
G2	683	623	657	15.0	29
H1	633	583	612	16.0	14
H2	662	573	629	26.0	29
I1	659	397	562	80.0	14
I2	505	458	479	13.0	29
I3	500	424	474	43.0	3
J	675	648	661	11.9	4

DESCRIPTIVE STATISTICS FOR
NO_3 =

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	57.7	3.5	21.9	10.8	58
A2	41.8	1.5	18.3	12.3	67
A3	53.4	2.1	18.3	16.2	85
A4	65.6	1.8	19.6	18.9	120
A5	44.5	2.7	10.5	10.3	33
B4	5.95	.7	3.3	3.7	2
B6	5.0	.4	2.2	2.5	5
B7	7.1	4.4	5.3	1.5	3
B8	6.5	.9	3.1	2.2	7
B9	30.4	5.3	14.7	11.2	7
B10	29.6	2.6	11.4	10.8	7
B11	3.4	.02	0.89	1.7	4
C1	9.1	.95	2.5	1.9	29
C2	9.8	1.9	3.3	1.4	31
C3	31.6	1.3	6.5	6.5	54
C4	35.5	1.8	13.5	11.8	89
C5	31.5	5.5	20.7	9.9	5
D1	8.6	.08	1.7	1.6	29
D2	4.4	.01	0.99	.9	45
D3	7.4	0.3	2.3	1.9	63
D4	39.7	3.2	12.8	10.5	104
D5	30.0	3.4	8.6	6.2	37
E1	19.9	2.7	4.9	3.1	31
E2	19.9	1.4	5.6	3.6	38
E3	24.7	0.7	8.9	7.2	51
E4	40.9	4.4	16.9	10.2	90
E5	37.2	4.5	13.1	7.3	25
G1	77.9	40.7	57.6	14.4	20
G2	60.8	21.1	43.4	11.5	29
H1	63.9	49.2	54.4	4.2	15
H2	43.5	34.2	38.7	3.1	29
I1	60.9	27.0	51.6	11.0	14
I2	113.2	74.5	92.9	13.5	29
I3	80.5	67.7	72.6	6.9	3
J	46.4	33.5	38.3	5.7	4

DESCRIPTIVE STATISTICS FOR $SO_4^=$

Well	Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)	Standard Deviation	Number of Samples
A1	57.7	23.4	31.3	8.2	32
A2	41.9	22.6	27.7	3.79	38
A3	34.7	18.0	27.5	2.82	47
A4	35.0	19.0	28.9	3.3	64
A5	32.1	18.2	26.4	4.1	15
B4	26.0	21.6	23.8	3.1	2
B6	35.2	7.9	20.1	9.74	7
B7	69.3	20.1	41.9	21.8	4
B8	172.8	38.0	89.9	55.4	7
B9	42.9	18.2	25.6	8.9	7
B10	27.7	15.6	20.5	5.4	7
B11	81.0	18.0	54.2	29.8	5
C1	119.5	48.4	82.1	32.5	5
C2	88.8	42.0	57.8	16.7	6
C3	91.0	33.8	64.2	20.2	19
C4	50.8	27.0	37.5	5.2	35
C5	92.0	30.1	43.6	18.9	10
D1	64.7	13.0	39.9	18.9	7
D2	52.7	11.1	27.6	11.7	21
D3	42.0	16.7	28.8	7.7	35
D4	54.6	26.8	34.1	5.2	51
D5	50.0	30.3	34.2	5.2	21
E1	41.3	14.3	22.8	12.5	4
E2	41.0	13.0	23.0	10.0	6
E3	36.0	13.1	20.7	5.7	19
E4	58.3	18.0	37.8	8.0	35
E5	65.0	21.7	41.5	14.5	8
G1	41.3	33.2	36.3	2.3	20
G2	36.8	31.9	34.9	1.3	29
H1	78.8	46.7	59.2	9.8	15
H2	180.1	88.7	124.8	29.1	29
I1	145.6	93.9	115.8	15.3	14
I2	48.3	43.0	45.5	1.6	29
I3	49.6	43.7	46.3	3.0	3
J	40.4	31.9	35.6	3.7	4

VITA

Patti Lynn Zietlow

Candidate for the Degree of

Master of Science

Thesis: INFLUENCE OF MACROPORES AND SOIL MOISTURE CONTENT ON THE RAPID MOVEMENT OF BROMIDE AND IODIDE TO THE SATURATED ZONE

Major Field: Hydrogeology

Biographical:

Personal Data: Born in Appleton, Wisconsin, April 4, 1965, the daughter of Wilbur O. and Jean Doell.

Education: Graduated from Appleton East, Appleton Wisconsin, in June 1983; received Bachelor of Science Degree in Geology from the University of Wisconsin at Oshkosh in August, 1987; completed requirements for the Master of Science degree at Oklahoma State University in December, 1992.

Professional Experience: Teaching Assistant, Department of Geology, University of Wisconsin Oshkosh, September 1986, to May, 1987. Research Assistant, Department of Geology, Oklahoma State University, January 1990 to August 1990.