CAUSE AND EFFECT OF RAPID CHANGES IN SHALLOW GROUND-WATER QUALITY

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INTRODUCTION

General Overview

Shallow aquifer systems pose a challenge to hydrogeologists because they are located so close to the land surface and are highly susceptible to contamination from a diverse range of sources. The mechanisms by which the contaminants migrate, however, are poorly understood. Comprehension of these controls is further complicated by the fact that shallow aquifers may be subject to rapid changes in chemical and biological quality. An increased understanding of the controls would have several major benefits. It would aid in the development of aquifer protection plans, in reducing the degree of contamination, and in maintaining and restoring shallow aquifer systems. Moreover, it would aid regulatory agencies to develop more accurate methodologies for establishing background concentrations that better represent the dynamics of shallow aquifer systems.

The research was based on a multi-phase program of data collection at two controlled field sites located in north-central Oklahoma. Site 1, where research has been most intensive, is located in a residential neighborhood on the flood plain of a small stream. Nitrate fertilizer is applied to the lawn three times per year. Site 2 lies near the shore of a lake.

Research Objectives

The objectives of this research are fourfold. First, to document and attempt to explain why shallow ground-water quality can change significantly within a matter of hours or days. Second, to gain a greater understanding of the processes that allow contaminants to move at a rapid rate through silt and clay. Third, to document and account for the wide range of values, in both space and time, of the chemical quality of shallow aquifer water. Fourth, to discern the processes by which ground-water recharge occurs during periods of soil-moisture deficiency.

SITE DESCRIPTION

Geography

Both study areas are located in Payne County, Oklahoma. They lie in the Central Redbed Plains physiographic province, which is characterized by rolling plains and broad valleys formed by the weathering of non-resistant red shales. A slope of less than 1% allows for little surface runoff from Site 1. The topography at Site 2 ranges from 942 to 1079 feet above sea level.

Climate

Mean daily temperatures in Payne County range from 39 degrees F in the winter months to 80 degrees F in the summer. Annual precipitation and evapotranspiration average 34 and 30 inches, respectively. Precipitation generally occurs as localized showers of short duration and high intensity during the spring and summer and as regional storms of longer duration during the fall and winter. Effective regional ground-water recharge rates average 1 inch per year (Pettyjohn and others, 1983).

Site 1 Location

Site 1, which contains about 20,000 square feet, is located in a residential neighborhood in Stillwater, Payne County, OK (NE 1/4 sec. 11, T 19 N, R 2 E). The site is situated on the Boomer Creek flood plain and about 350 feet east of a small unnamed tributary (fig. 1).

Site 1 Geology

This investigation focused on a shallow aquifer system located in Quaternary alluvial deposits that infill a steep-walled valley cut into the Upper Pennsylvanian Doyle Shale (fig. 2). Outcrops of the Doyle, which consists of interbedded red shale and sandstone, lie 500 feet east of the site. The alluvium is composed of a nonbedded mixture of sand (50%), silt (25%), and clay (25%) that terminates against the Doyle outcrop.
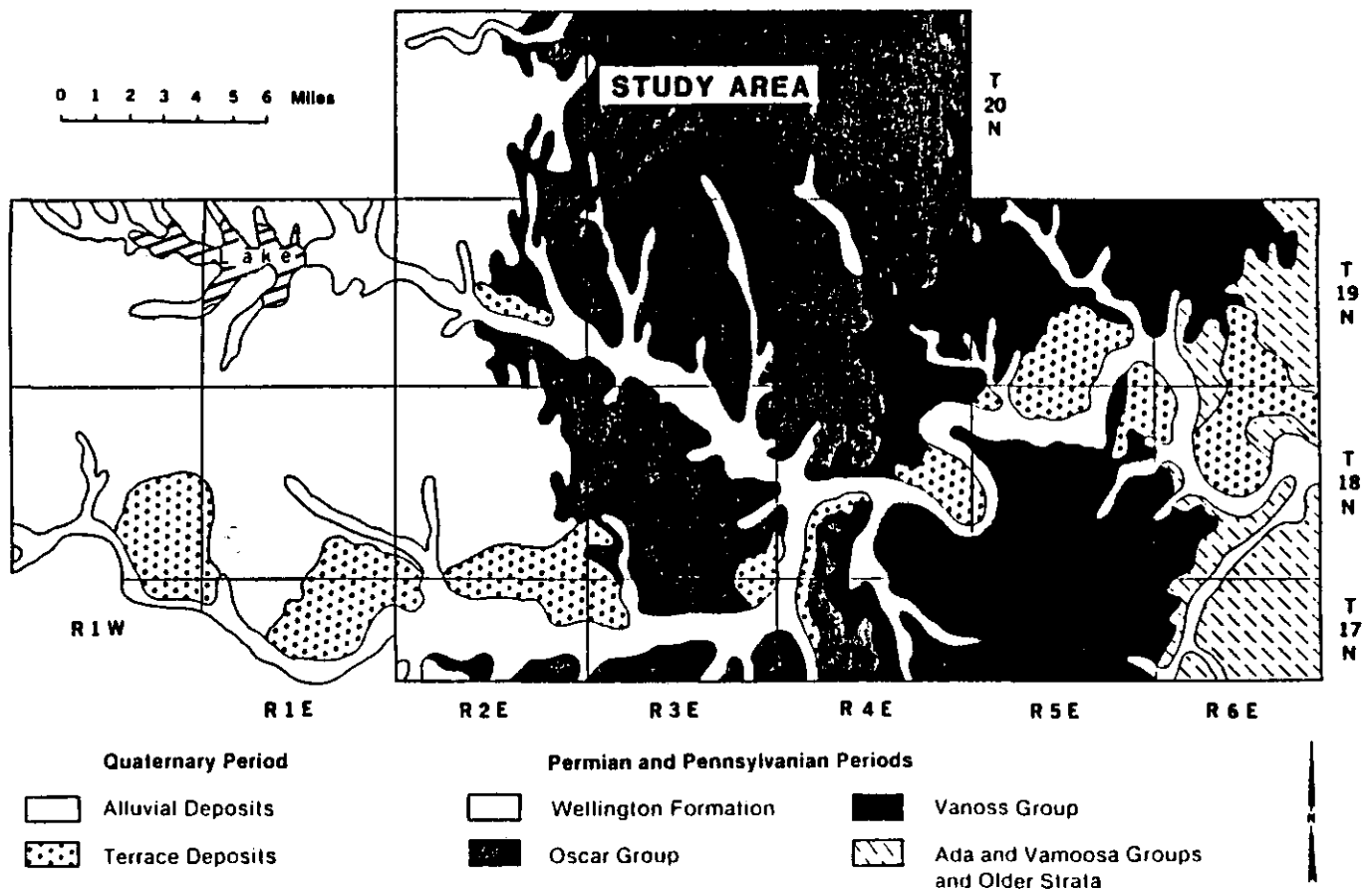
2

0 1 2 3 4 5 6 Miles

STUDY AREA

T 20 N

T 19 N

T 18 N

T 17 N

R 1 W

R 1 E   R 2 E   R 3 E   R 4 E   R 5 E   R 6 E

Quaternary Period

☐ Alluvial Deposits

▨ Terrace Deposits

Permian and Pennsylvanian Periods

☐ Wellington Formation

▨ Oscar Group

■ Vanoss Group

▨ Ada and Vamoosa Groups and Older Strata

Figure 1.   Site Location and General Geology of Payne County, Oklahoma.

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W   E

Boomer Creek   **Study Area**

P_h P_{en} P_{en} Q_{al} P_d P_{fr}
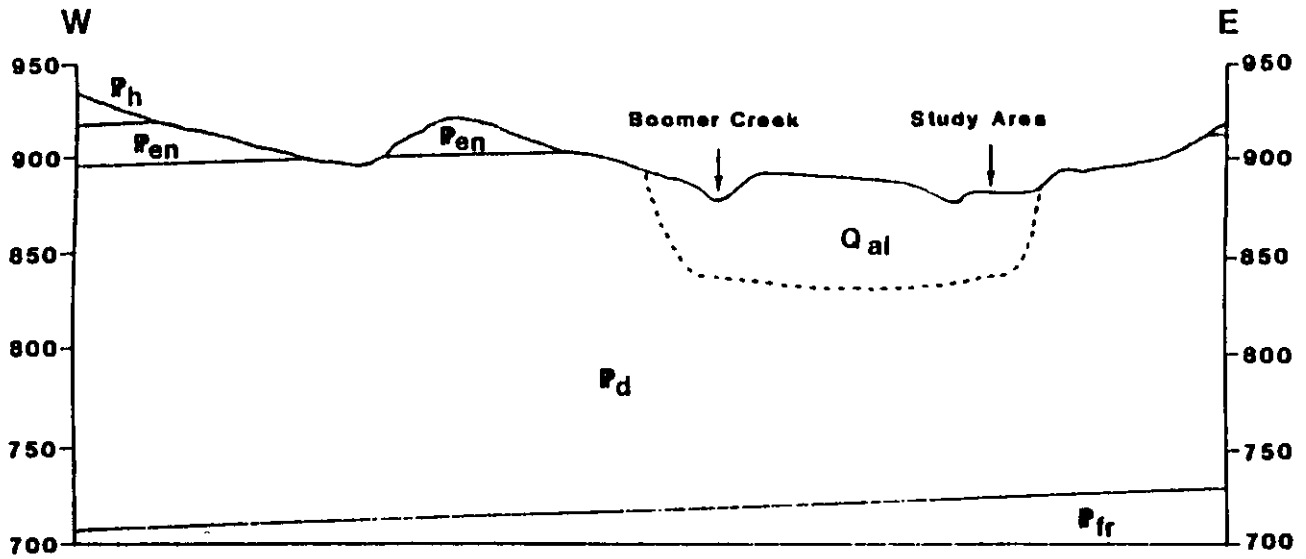
HORIZONTAL SCALE: 1 INCH=1000 FEET

VERTICAL SCALE: 1 INCH=100 FEET

VERTICAL EXAGGERATION: 10X

Q_{al} Alluvium   Quaternary

P_h Herington Limestone

P_{en} Enterprise Shale

P_d Doyle Shale

P_{fr} Fort Riley Limestone

Oscar Group   Pennsylvanian

Figure 2. Geologic Cross–Section at Site 1.

Site 1 Soil Description

Site 1 soil is classified as an Ashport soil that originated from alluvial deposits on a narrow level flood plain. Ashport soils are characteristically moderately permeable, well drained, have a silt-loam texture, and are classified as Fluventic Haplustolls (Soil Conservation Service, Payne County Survey, 1985).

The soil extends to a depth of 43 feet where it rests unconformably on Doyle Shale (fig. 3). Analysis of a 45-foot long composite core by Ross (1987) revealed three soil profiles; surface, upper and lower. The upper and lower profiles, beginning at 4 and 27.5 feet below land surface, respectively, have been radiocarbon dated at 1300 +/-70 and 10,600 +/-170 years B.P. The profiles are composed of loam, silt loam, silty clay loam, and clay loam horizons. Dominant structures include weak to moderate subangular blocky, parting to either coarse to moderate medium platy structure or moderate, medium prismatic. Root casts are present throughout the profile. Iron/manganese nodules increase in abundance upward from 25.5 to 5.3 feet below land surface. Calcite nodules occur 6.5 to 9 feet below land surface. Soil mineralogy is dominated by quartz grains, with feldspar comprising three to five percent of the grains present. Iron-stained clay and silt make up the matrix.

Site 1 Surface Water Hydrology

Site 1 is located 350 feet east of an unnamed tributary to Boomer Creek. Boomer Creek flows northwest to southeast and is the major drainage in the area. A slope of less than 1% allows for little surface runoff from the site resulting in ponding after significant precipitation events.

Site 1 Ground-Water Hydrology

Transmissivity, hydraulic conductivity, and storativity average 2225 gpd/ft, 60 gpd/ft^2, and .01 respectively. Water levels fluctuate from about 3 to 12 feet below land surface, with the most rapid changes of a foot or two occurring during recharge events. Ground-water velocities fluctuate seasonally from less than 0.4 to greater than 1 foot per day. Water-level gradient varies between .003 and .008. Flow direction, generally southward toward Boomer Creek, varies in direction from 145 to 225 degrees. Hoyle (1987) and Hagen (1986) suggest that flow direction may be controlled by
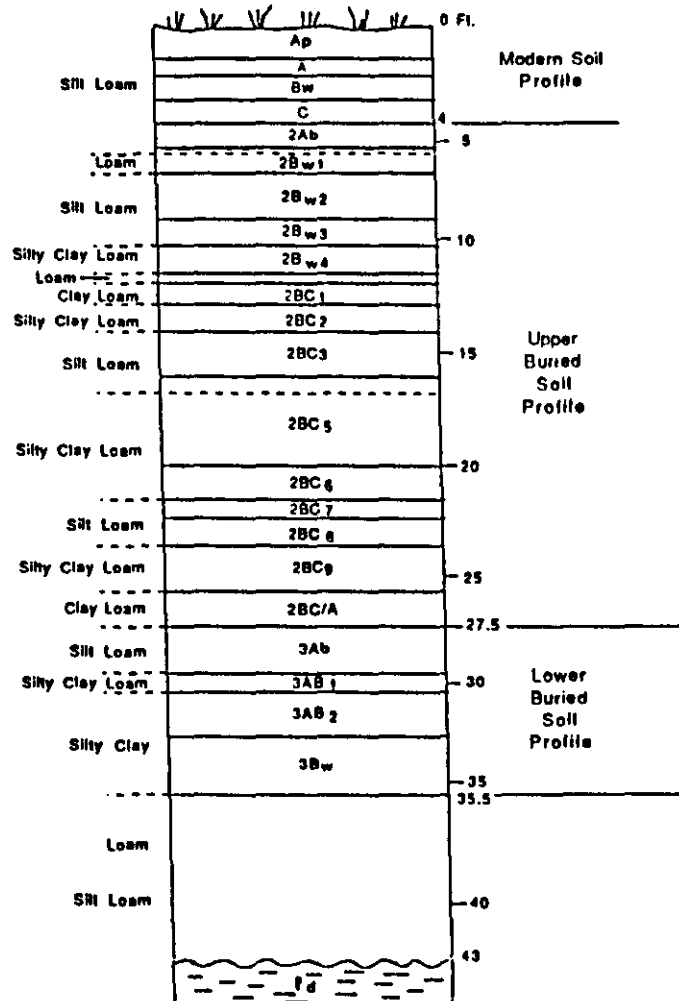
SOIL PROFILE

Figure 3. Soil Profile and
Textures at
Site 1.

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evapotranspiration by large trees that grow along the site's southern boundary.

Site 2 Location

Site 2 is located on the western most bank of Lake Carl Blackwell, Payne County, OK (SW 1/4, NE1/4, Sec. 10, T19N, R1W).

Site 2 Geology

The investigative area is located on Quaternary alluvium underlain by sandstone, mudstone, and conglomerate of the Permian Wellington Formation.

Site 2 Soil Description

The soils of the study area belong to the Port Silt Loam Series and are characterized as fine, silty, mixed, thermic Cumulic Haplustolls. The dominate clays in the soil are montmorillonite and kaolinite (Soil Conservation Service, Payne County Survey, 1985). Observable fractures at the soil surface indicate the presence of macropores.

Site 2 Surface Water Hydrology

Man-made Lake Carl Blackwell covers an area of 1250 hectacres and has an average depth of 16 feet. The lake is fed by Stillwater Creek, which is the major drainage for the area.

Site 2 Ground-Water Hydrology

The water-bearing zone beneath the site is composed of clay loam and sandy clay loam that has a general transmissivity value of 4.7 x 10^{-2} cm/sec. Depth to the water table averages 5 feet below land surface.

SITE INSTRUMENTATION

Laboratory

Site 1 contains an on-site laboratory equipped with a digital thermometer and pH meter sensitive to .1 degrees C and .01 pH units, respectively, a

temperature-compensating conductivity meter, and a Hach digital titrator. A continuously

recording tipping bucket rain gauge and recording barograph, photometer and thermometer monitor meteorologic conditions.

Ground-Water Monitoring Wells

Site 1 is monitored by 42 wells distributed among 10 sites (fig. 4). Holes for most of the monitoring wells were excavated by hand auger. In each of the wells the PVC pipe is screened and sand packed; the annular space is filled with bentonite. The wells were developed by backwashing and surging. Twenty-five of the wells are located in clusters of five wells, each of which is designed to sample a discrete part of the aquifer. Four sets consist of wells that are 8.5, 9.5, 10.5, and 14 (2 wells) feet deep. Four of the wells have the lower 4 inches slotted. The fifth well is slotted along the lowermost 6 feet (fig. 5). Horizontal distance between wells in a cluster varies from less than 1.5 to 3 feet. Clusters are located at sites A, B, C, D, and E.

The well at Site 2 extends 10 feet below land surface and is constructed of 1 inch diameter PVC pipe slotted to 5 feet above the bottom and backfilled with pea-sized gravel. The annular space is filled with bentonite.

Test Wells

In order to allow high yield aquifer tests to be conducted at Site 1, a test well was installed by hollow-stem auger at the B site. At the F site, a 40 foot production well with 30 feet of screen was installed. An attached 2-inch diameter well of similar length and construction is used to measure well loss during tests.

Soil-Water Suction Lysimeters

Soil water from the unsaturated zone is held at less than atmospheric pressure and therefore must be removed by suction. Eight suction lysimeters, located between the A and B clusters at Site 1, provide a means of effectively sampling the unsaturated zone. Each lysimeter consists of one bar, high flow, porous ceramic sampling cups bonded to PVC tubing. Compressional O-rings located at the top of the chamber and around the stainless steel access tubing form air tight seals (fig. 6). Holes for the lysimeters were excavated with a Giddings truck-mounted soil probe. The lysimeters are installed at

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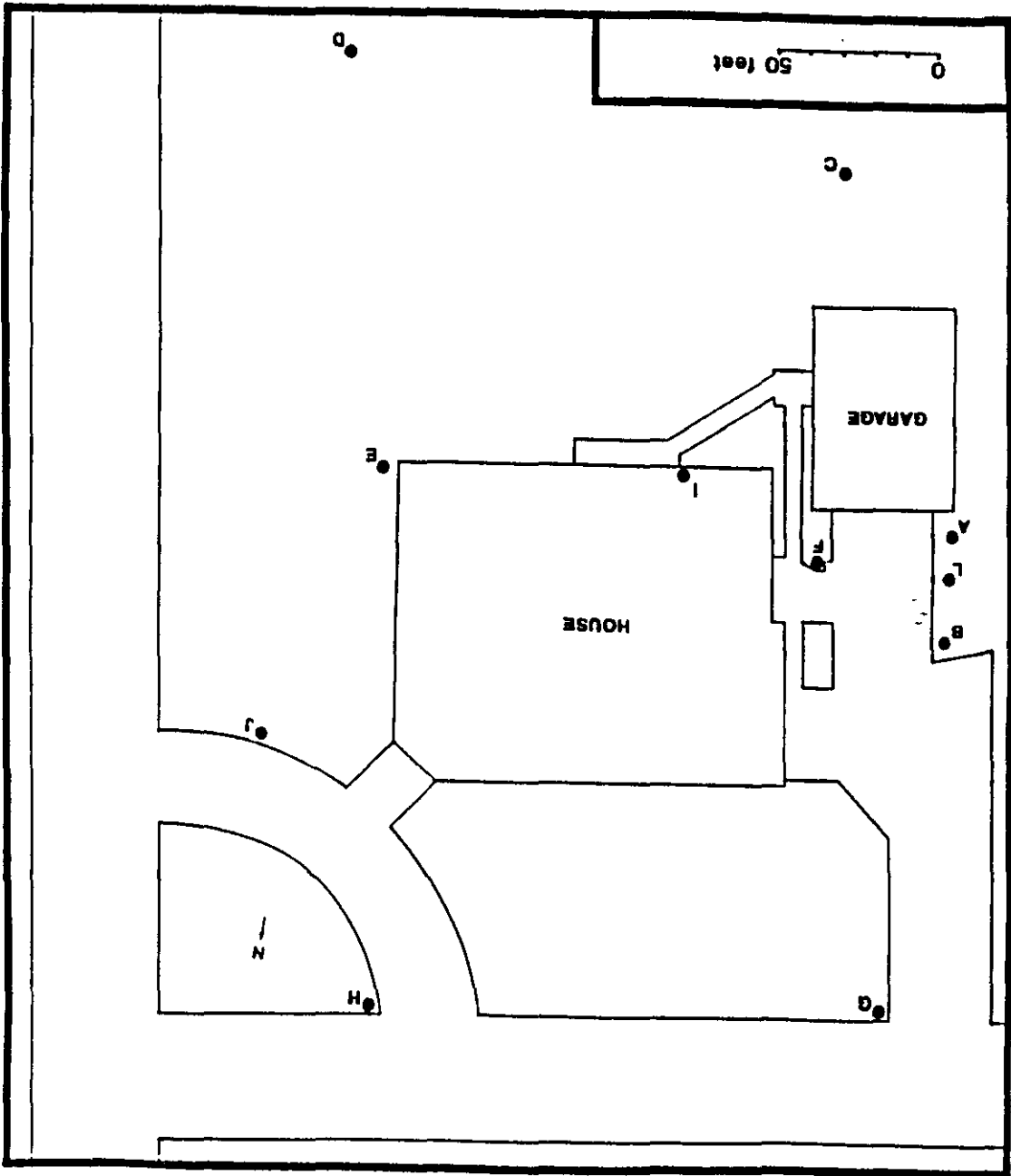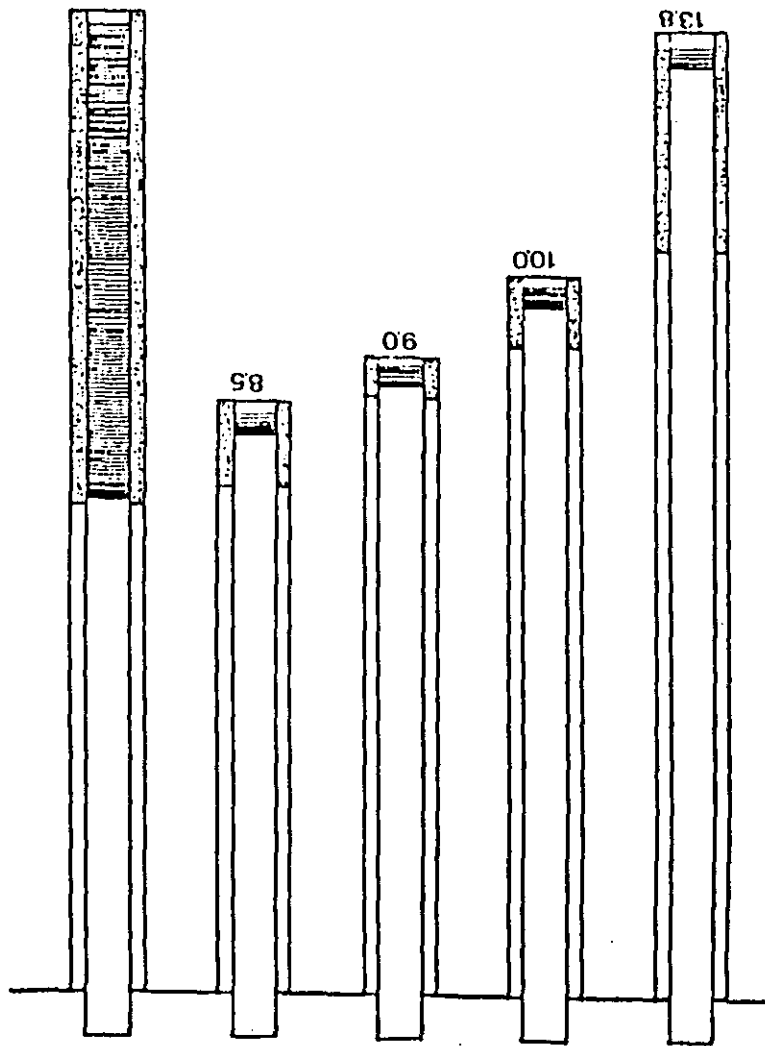Figure 4. Location of Monitoring Wells at Site 1.

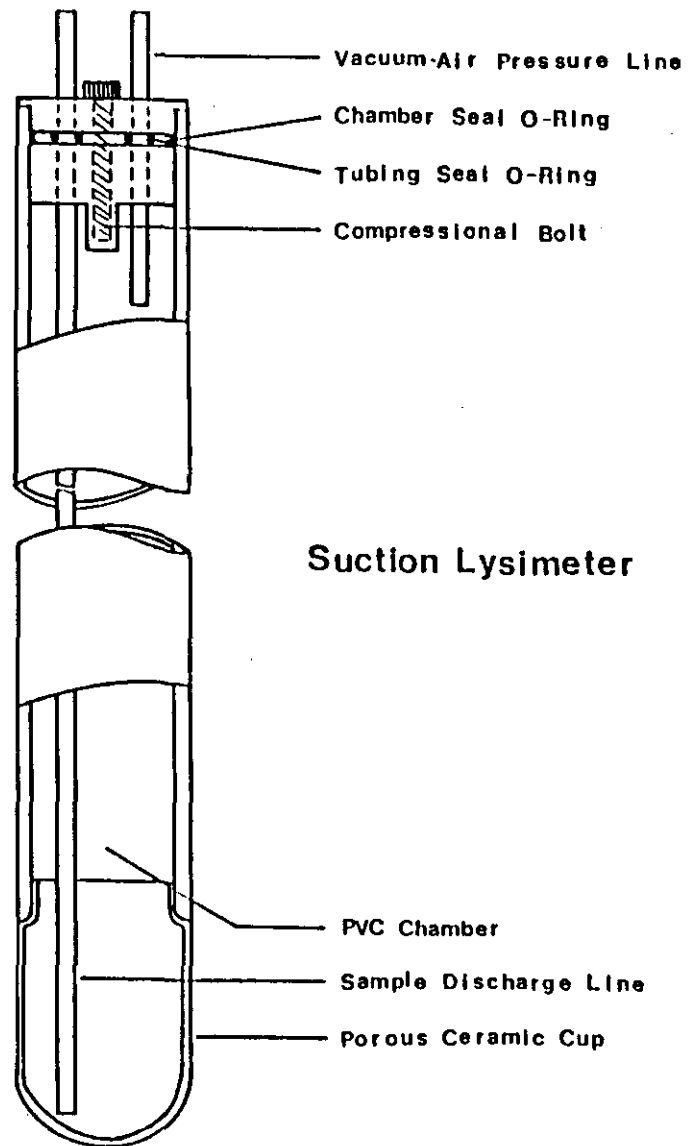Figure 5. Typical details of a well
cluster at Site 1.

Figure 6. Schematic diagram of a suction
lysimeter.

depths that correspond with major soil horizons (fig. 7). The ceramic cups are in contact with 200 mesh silica flour; bentonite pellets and native backfill fill the annulus.

Soil-Moisture Neutron Probe

Data on soil moisture were obtained by inserting a Troxler model 330 depth moisture gauge into neutron probe access tubes (7 feet deep) adjacent to each well cluster. The 1.7 inch diameter aluminum access tubes are open at the bottom. The tubes were installed by pounding the pipe into the soil and augering out the inside until the desired depth was reached. Site 2 contains 8 access tubes placed in a grid pattern around the observation wells (fig. 8).

METHODOLOGY

Ground-Water Geochemistry

Nalgene plastic sample bottles (500 ml) were cleansed before each use, following EPA approved procedures. Bottles were washed with detergent in hot water, rinsed 3 times with tap water, rinsed three times with deionized distilled water, rinsed once with either dilute hydrochloric or nitric acid, and rinsed three times again with deionized distilled water.

Prior to each sampling event, data on static water levels in each of the monitoring wells, air temperature, barometric pressure, and rainfall amounts were collected.

To ensure that fresh formation water was obtained, three well volumes were purged from each well by peristaltic pump before samples were taken. The evacuated water was discharged 10 feet from the well to avoid immediate recharge. Samples were withdrawn by peristaltic pump through Tygon tubing and discharged into the sample bottles. The bottles were rinsed with water from the well before being filled. Since approximately 200 milliliters of formation water passed through the tubing before samples were collected, cross contamination of water samples collected at different wells was prevented. Ground-water samples were collected weekly and before, during, and after several rain events.

Variations in the quality of water in the unsaturated zone were monitored by analyzing suction lysimeter samples. A vacuum of negative 24 inches of mercury was
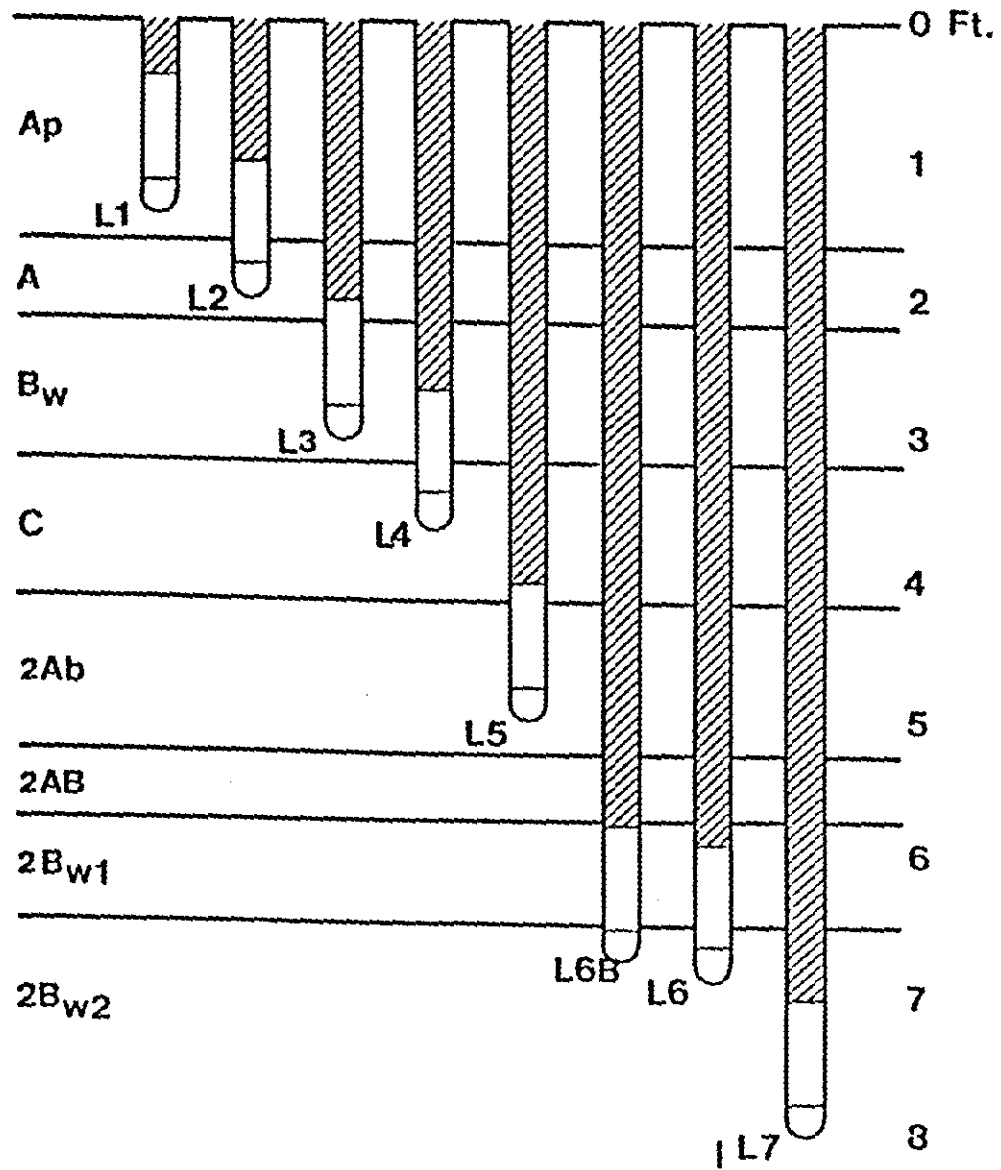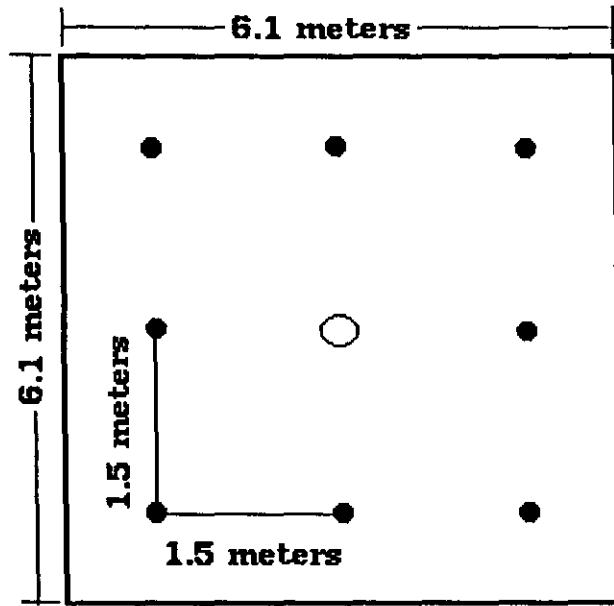
Figure 7. Cross-section through lysimeter
set at Site 1.

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Figure 8. Neutron access tube
locations at Site 2.

placed on each lysimeter using a 42 liter displacement capacity vacuum pump. Vacuum pressure was maintained by sealing the Tygon tubing with a clamp. Samples, collected by peristaltic pump through Tygon tubing attached to the lysimeter's stainless steel discharge tube, were discharged into Nalgene bottles. The peristaltic pump discharge line was cleaned after each use by flushing with deionized distilled water.

Information on the downward movement of chemical species in the unsaturated zone was acquired by monitoring tracers applied at the land surface. The tests, designed to simulate precipitation events, were performed under both wet and dry initial soil-moisture conditions. A 6 x 8 foot plot surrounding the lysimeters was inundated with 500 mg/l KBr solution (wet conditions) and 500 mg/l CaCl solution (dry conditions) in amounts equivalent to 3 inches of rain. Samples were taken from the 10 suction lysimeters and analyzed for bromide and chloride.

Field parameters were determined in an on-site laboratory immediately after collection by means of a digital thermometer, a pH meter, and a conductivity meter. Prior to each sampling event, calibration of the pH and conductivity meters was completed. A Hach digital titrator was used to measure bicarbonate concentrations. The sample was titrated to a 4.5 pH color endpoint with 2N HCl. A simple equation allows the number of digits required to reach the endpoint to be converted into mg/l HCO_3.

Immediately after the determination of field parameters, samples were refrigerated and stored at 4 degrees Celsius. Samples were filtered through .2 micrometer Gelman acetate filters and split into two parts. One part was acidized with 1N HCl to a pH of <2 and stored for cation analyses. The remaining portion was stored for anion analyses.

A Dionex 2000i ion chromatograph was used to measure chloride (Cl), nitrate (NO_3), sulfate (SO_4), and bicarbonate (HCO_3) concentrations. Prior to the start of sample analyses, calibration of the chromatograph, using standard solutions prepared by the dilution of 1000 mg/l Cl, NO_3, and SO_4 stock solutions, was completed. Recalibration was done following the analyses of 20 samples.

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Samples were analyzed for calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), total iron (Fe), manganese (Mn), aluminum (Al), and silica (Si) using inductively coupled plasma atomic emission spectroscopy (ICP). Decade standards for each element were prepared by the dilution of stock solutions made by the dilution of standard reagent solutions. Each sample was analyzed four times and reported as an average concentration.

Cleanliness of a batch of precleaned sample bottles was verified by filling test bottles with deionized distilled water and subjecting the water to the same analysis as the ground-water samples. Duplicate samples were taken in the field to test the accuracy of field and analytical methods. During anion analyses, duplicate samples and calibration standards were analyzed approximately every fifth sample to measure the chromatograph's performance. Samples of known cation concentrations were analyzed on a regular basis to ensure that the ICP was functioning properly. Performance was further documented by the analyses of E.P.A. water along with the samples.

Aquifer Performance

The validity of various methods for estimating the hydrologic parameters of silty clay alluvial aquifers was evaluated using data obtained from pumping tests, slug tests, and laboratory analysis of aquifer material. Several tests were conducted by pumping water from the fifth well of a cluster with a peristaltic pump at a rate of .32 to .72 gpm and recording drawdown in the other wells of a cluster by pressure transducer and steel tape. Other methods involved removing water from 4 or 6 inch diameter test wells by a submersible pump at a rate of 2.7 gpm and recording drawdown at other wells at the site. Slug tests were performed by removing a known volume of water from a well with a bailer and recording water-level recovery with a pressure transducer. Aquifer test data were interpreted using techniques developed by Theis, Jacob, Franke, Prickett, and Neuman. Slug test data were evaluated using a variety of techniques. A constant head permeameter was used to obtain laboratory determinations of hydraulic conductivity.

Ground-Water Hydraulics

Information on horizontal and vertical gradients was obtained by the measurement of water levels in each of the 42 monitoring wells. Depth from the top of the well casing

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to the top of the water table was measured by chalked steel tape and by pressure transducers. Top of casing elevation was surveyed for each well to allow for the calculation of water table elevation. To maintain consistency, water levels were taken from a marked point at the top of each well casing. Hydrographs and water-level maps were constructed from data gathered.

Infiltration

In order to gain a greater understanding of the roles that macropores play in the movement of water through the unsaturated zone, infiltration experiments were conducted at Site 2. A known volume of water was applied to the surface, and changes in soil-moisture were monitored by inserting a Troxler Depth Moisture Gauge into neutron probe access tubes. Data collection began 15 minutes after water was applied to the surface. Readings were taken at 15 centimeter intervals to a total depth of 120 centimeters. Monitoring continued until stabilization of soil moisture occurred. The resulting data were plotted using a variety of computer graphing techniques. Photographs of soil surface cracks were taken during wetting and drying cycles to document macropore development.

Soil Analyses

Physical and chemical characteristics of earth materials were determined by detailed analysis of cores. A composite core, 45 feet long, was obtained by combining cores taken from six 8-inch diameter holes drilled by a continuous flight hollow-stem auger at the B and F sites. The core was logged and photographed in the field. Textural classification involved particle-size analyses and the determination of clay fraction by pipet method. Bulk density was determined by wrapping samples in preweighed foil, oven drying for 48 hours at 105 degrees C, and comparing "wet" and "dry" weights. In order to examine soil mineralogy, selected soil samples were impregnated with epoxy resin, slabbed, thin sections prepared and polished to a thickness of 30 micrometers. Thin sections were viewed in plane-polarized, cross-polarized, and reflected light. Clay mineralogy was examined using x-ray diffraction analysis.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Evaluation of the data collected during the course of this study revealed the following:

1. There is considerable variation in inorganic chemical concentrations with respect to both time and space. In four years of data collection, no two wells have ever had the same concentration of any constituent. Stratification of anions at any given sampling point is present, but cannot be correlated from point to point. At a single sample point, one anion may increase and another may decrease in concentration with depth (Froneberger, in prep). The most significant changes in water quality (NO_3), resulting in at least fourfold increases, were observed within hours after a rainfall event, and this was followed over the next two days by a fivefold decrease.

2. Urban features can exert a strong influence on shallow water quality. Dilution of ground water was observed after rainfall events in wells located adjacent to a downspout. The presence of a large enclosed area (about 4000 square feet covered by a building) was seen to have an effect on nitrate concentrations. Nitrate levels in wells located within the enclosed area were significantly higher than those in other wells, perhaps owing to a lack of direct recharge from above. Elevated chloride concentrations were present in wells located in the vicinity of a sewer line.

3. Vegetation was found to have a significant effect on both water quality and direction of ground-water flow. C and D well clusters, located near a number of large trees, consistently had the highest bicarbonate concentrations. Maps of the potentiometric surface revealed that the direction of ground-water flow, generally southward toward Boomer Creek, varies in direction from 145 to 225 degrees from summer to late spring (fig.9). Hoyle (1987) and Hagen (1986) suggest that flow direction may be controlled by the evapotranspiration of trees growing along the site's southern boundary.

4. Fertilizer application has a short-lived but significant effect on the concentration of nitrogen in ground water. Nitrogen concentrations rapidly increased after a recharge event following application.

HORIZONTAL

HYDRAULIC GRADIENT

N

W   E

.0040

Jun 86

GRADIENT

foot / foot

.0065

.0045   .0048

Jan, Feb   .0078

.0046   .0056

Mar   .0050   Sep

Dec   .0033   Oct

Jun 87   .0047

May Apr   .0045   Aug
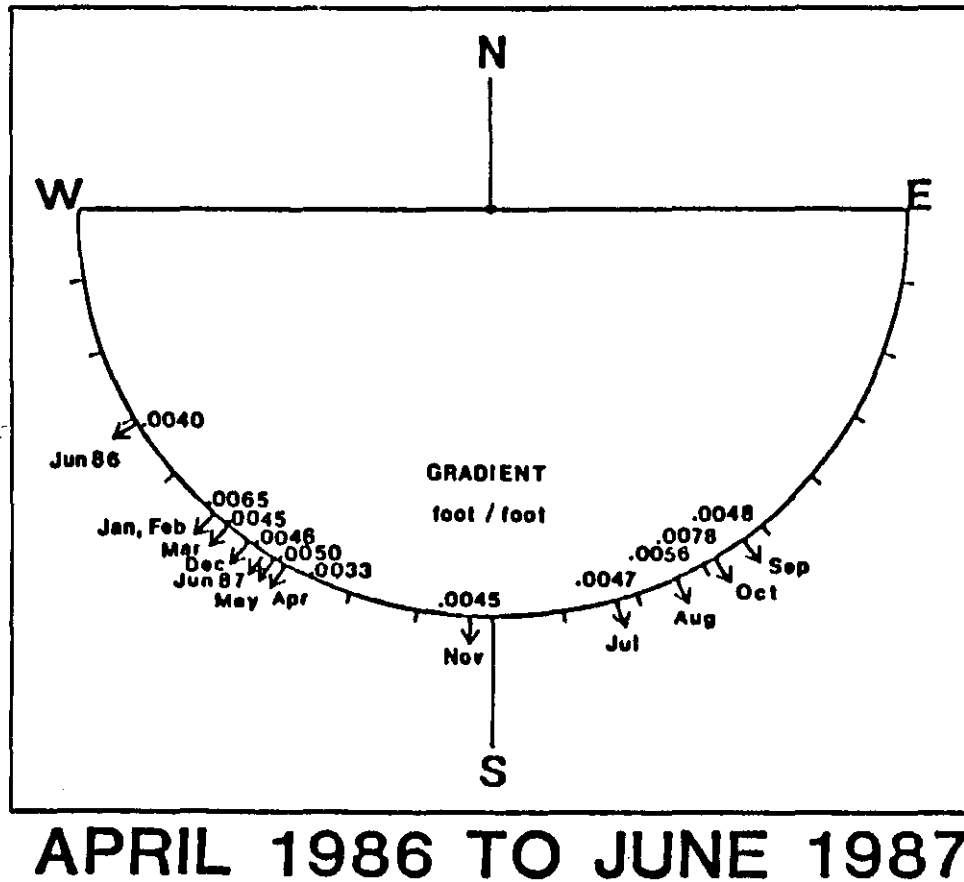
Nov   Jul

S

APRIL 1986 TO JUNE 1987

Figure 9. Horizontal Hydraulic Gradient,
Direction and Magnitude,
April 1985 to June 1987.

5. Ground-water recharge occurs during periods of soil-moisture deficiency. This is evidenced by the fact that significant changes in water level and water quality were observed within a few hours of a rain event, even when soil-moisture was well below field capacity.

6. Macropores play a significant role in the movement of water through the unsaturated zone. At Site 2, rapid infiltration to depths of 90 centimeters was seen in sections where macropores were well developed. In contrast, infiltration in areas with poorly developed macropores was only observed to a maximum depth of 45 centimeters.

7. Macropore development is not completely random. Observation of photos taken before and during wetting and drying cycles indicate that well-developed macropores tend to reform in the same pattern, shape, and location.

8. Aquifer test results produced reasonable estimates of the hydraulic parameters indicating that they were valid for certain soil profiles. Laboratory determinations of hydraulic conductivity, however, were several orders of magnitude lower than field determinations.

The observations made during the course of this study indicate the need for the re-evaluation of several widely held beliefs and practices. The general assumption that ground-water recharge cannot occur during periods of soil-moisture deficiency is challenged by the fact that changes in both water level and water quality were observed shortly after a rain event, even though soil moisture was well below field capacity. Photos of macropores reforming in the same shape, pattern, and location after wet periods invalidates the belief that macropore formation is completely random. The wide range in the concentration of constituents with respect to both time and space calls into question the practice of assuming that shallow ground-water quality is rather uniform, and therefore, samples collected at regular intervals will adequately describe the quality that exists. Perhaps ground-water quality monitoring techniques should take into account the wide range in the quality of shallow ground-water, gradient shifts that may be caused by vegetation, and possible macropore participation in the migration of constituents to the water table.

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