

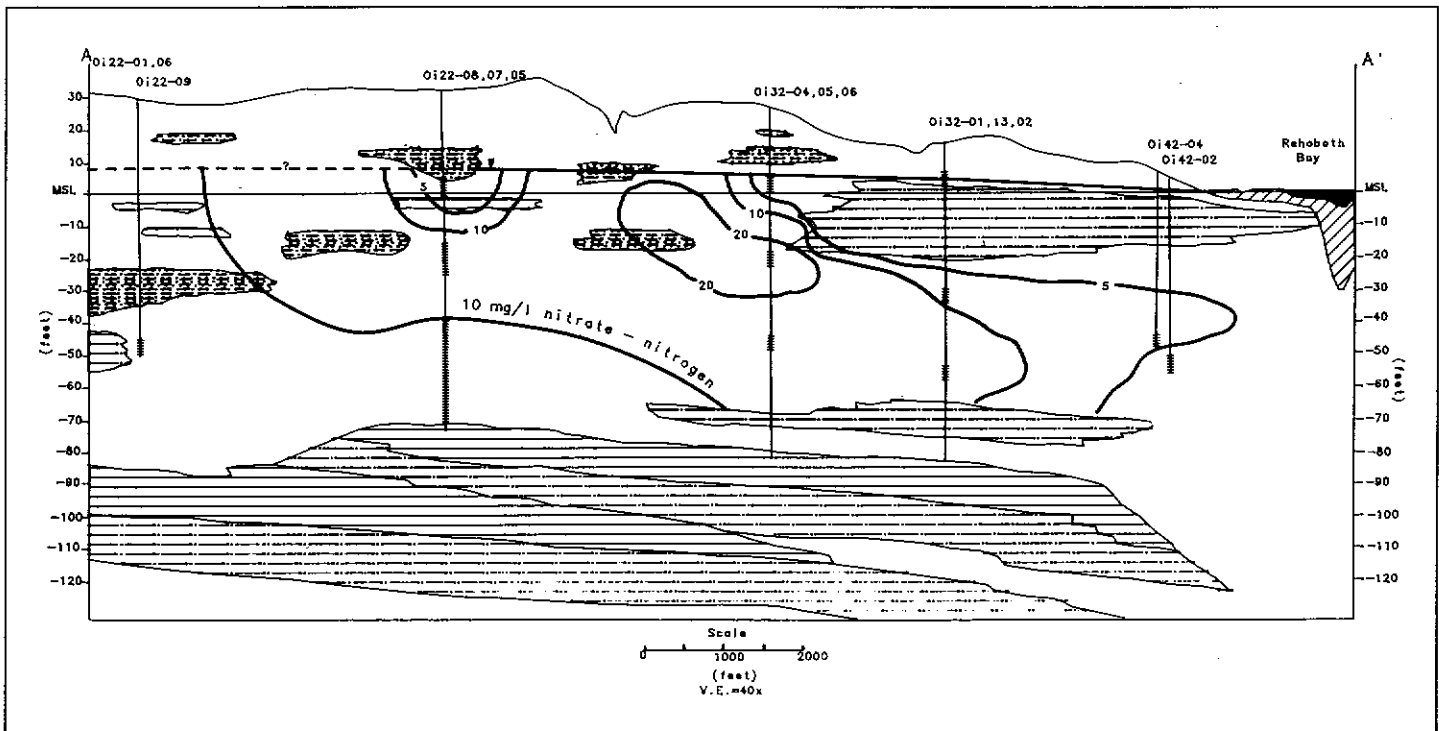
State of Delaware
DELAWARE GEOLOGICAL SURVEY
Robert R. Jordan, State Geologist

REPORT OF INVESTIGATIONS NO. 49

RESULTS OF THE COASTAL SUSSEX COUNTY, DELAWARE
GROUND-WATER QUALITY SURVEY

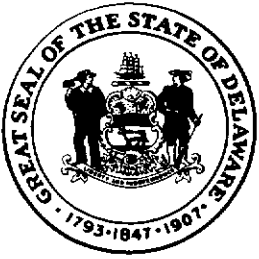
by

A. Scott Andres



University of Delaware
Newark, Delaware

February 1991



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RESULTS OF THE COASTAL SUSSEX COUNTY, DELAWARE GROUND-WATER QUALITY SURVEY

A. Scott Andres

ABSTRACT

The results of this investigation of the Columbia aquifer in coastal Sussex County, Delaware, provide some of the data necessary to evaluate the condition of the area's primary source of fresh water. Chemical analyses of water samples from domestic, agricultural, public, and monitoring wells document the effects of past and present land use practices. Ground-water flow paths and flow systems are inferred from flow-net analysis, ground-water chemistry, and isotopic composition.

Nitrate, primarily from near-surface agricultural and wastewater disposal practices, is a common anthropogenic contaminant in the Columbia aquifer. Nitrate concentrations exceeding the primary maximum contaminant level (MCL) of 10 milligrams per liter (mg/l) nitrate-nitrogen occur in nearly 23 percent of all wells sampled. Where nitrate occurs, it is commonly present at concentrations greater than the MCL throughout the entire thickness of the aquifer. In addition, it is common for nitrate concentration to vary with depth in the aquifer.

In the southern third of the study area, nitrate concentrations commonly are low, less than 0.5 mg/l nitrate-nitrogen. The ground water is anoxic and has a higher than average pH, alkalinity, iron content, and noticeable hydrogen sulfide. It is likely that either nitrification never occurs or denitrification occurs in the soil zone or in the aquifer.

The distribution of nitrate in ground water reflects the interaction between land use, rock and soil type, and ground-water flow patterns. The highest nitrate concentrations (nitrate-nitrogen greater than 20 mg/l) are in most cases near poultry farming operations where a near-surface confining unit (Omar Formation) is relatively thin, coarse-grained, and contains little organic material. Elevated nitrate concentrations (nitrate-nitrogen between 10 and 20 mg/l) are found near many fertilized fields and under areas with mixed land use (agricultural and residential with on-site wastewater disposal systems) where the Omar Formation is as described above. Nitrate-nitrogen concentrations less than 3 mg/l occur where there is no anthropogenic nitrogen input or in a geochemical environment that favors denitrification or precludes nitrification.

Conceptual models of ground-water flow and analysis of ground-water levels indicate that there are both regional and local ground-water flow systems present in the study area. The number of ground-water flow systems and the lengths and directions of ground-water flow paths result from complex interaction between drainage basin size and shape, aquifer thickness, thickness and continuity of intervening fine-grained beds, and the geometry of the base of the aquifer.

INTRODUCTION

Purpose and Scope

Almost all of the fresh water used in coastal Sussex County (Fig. 1) is obtained from the Columbia aquifer. The area is undergoing rapid development that is expected to continue. Because of its near-surface position and favorable hydrologic characteristics, the Columbia aquifer will undoubtedly be the first aquifer developed to meet the expected increased demand for water. Unfortunately, these same factors also cause the Columbia aquifer to be susceptible to contamination from surface and subsurface sources. Nitrate is the most frequently occurring contaminant in the area.

The main objective of this report is to present the results of basic statistical analyses and interpretations of data focusing primarily on ground-water flow and nitrate. More detailed analyses of the data, concentrating on defining the statistical relations between geology, soils, hydrology, land use, and nitrate, and the development of methods to predict nitrate concentration, will be published later. The basic chemistry and water level data from this study are published separately by Andres (1991).

This investigation was designed to provide basic data on the major ion and nitrate content of ground water as well as related geologic and hydrologic characteristics of the Columbia aquifer. These data are necessary to address several important subjects: (1) the status of ground-water quality in the Columbia aquifer, (2) ground-water quality changes in the past 12 years, (3) factors influencing ground-water

flow path; (4) rates and directions of ground-water flow; and (5) methods to estimate the nitrate content of ground water resulting from different hydrogeologic and land-use conditions.

Several areas were excluded from this investigation. The ocean and bay, their beaches, and fringing marsh areas were not investigated because these areas are either not inhabited, are served by public water, or the Columbia aquifer is not

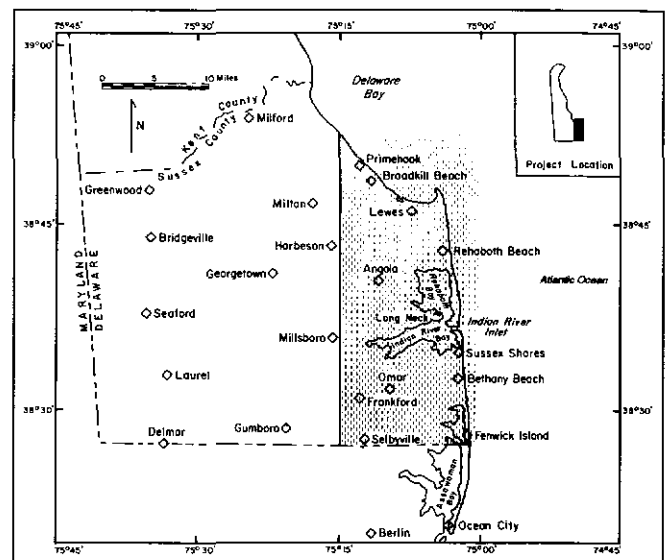


Figure 1. Location of area of investigation.

known to be used as a water-supply source. The southern third of the study area also was not intensively sampled because a previous study by Robertson (1977, 1979) found that nitrate was virtually non-detectable in the ground water of this area; this was also confirmed by my study.

Throughout this report the term "nitrate contamination" will be used to refer to nitrate-nitrogen concentrations exceeding 10 milligrams per liter (mg/l). This is a primary maximum contaminant level set by the U.S. Environmental Protection Agency (U. S. EPA, 1988) for drinking water.

Previous Work

A number of reports and maps have been published on the geology and hydrology of the Columbia aquifer in coastal Sussex County over the past 35 years. Marine and Rasmussen (1955), Rasmussen et al. (1960), Johnston (1973, 1976, 1977), Sundstrom and Pickett (1969), Adams, Boggess, and Davis (1964), Adams, Boggess, and Coskery (1964), Boggess and Adams (1964), and Boggess, Adams, and Davis (1964) first developed knowledge of the hydrogeology of the area. Within the past 10 years, the Delaware Geological Survey (DGS) and the U. S. Geological Survey (USGS) have conducted intensive investigations of the hydrology and geology of the area, resulting in a number of publications and reports (Andres, 1986a, b; 1987a, b; 1989; Denver, 1983, 1989; Hodges, 1983; Talley, 1987, 1988a; Talley and Andres, 1987; Talley and Simmons, 1988; Ramsey, 1989; Ramsey and Schenck, 1990). Some other important investigations that have dealt specifically with ground-water quality in the area are by Robertson (1977, 1979) and Ritter and Chirside (1982, 1984). The Delaware Department of Health and Social Services, Division of Public Health, conducts routine sampling and analyses of water from public water supply wells in the area.

Previous ground-water quality investigations in Sussex County and adjacent Maryland have concluded that manure and fertilizer are the primary sources of nitrate in the Columbia aquifer and that septic tank effluent also contributes nitrate in some unsewered residential areas (Robertson, 1977, 1979; Ritter and Chirside, 1982, 1984; Bachman, 1984; Denver, 1986, 1989). In the Columbia aquifer of adjacent Maryland where geologic, hydrologic, and land-use conditions are similar to those in Delaware, Bachman (1984) found that nitrate-nitrogen produced by natural processes is probably below 0.5 mg/l and is certainly below 3 mg/l. Robertson (1977) and Ritter and Chirside (1982) found some of the highest concentrations of nitrate near Indian River Bay, Delaware, where soils are excessively well drained and highly permeable.

Robertson (1977) found that nitrate was present only at low concentrations (less than 0.5 mg/l) in a large area of southeastern Sussex County where soils are poorly drained, the water table is relatively close to land surface, and iron is a significant dissolved constituent in the water. He defined the boundary of this area as the "iron line." Bachman (1984) and Denver (1986) found similar relationships between soil drainage characteristics, iron, and nitrate concentrations in adjacent Maryland and western Sussex County.

In an agricultural area located just west of Rehoboth Bay, Denver (1989) found that ground-water pumping for

irrigation and upgradient land-use characteristics were the most important influences on ground-water quality. She also reported that although the effects of agriculture and septic-tank effluent on water quality can be statistically differentiated, the differences were not distinctive enough to identify the source of nitrate in an individual water sample.

Hydrogeologic Framework

The name Columbia aquifer has been used in a number of reports to describe the near-surface water-yielding rocks of the Delmarva Peninsula (Bachman, 1984; Bachman and Wilson, 1984; Talley and Windish, 1984; Andres, 1987a; Talley, 1988a; Talley and Andres, 1987). The name was derived from the Columbia Formation and Columbia Group as described in Delaware by Jordan (1962, 1964, 1974). A different lithostratigraphic framework was proposed by Owens and Denny (1979). More recent work by Groot et al. (1990) and Ramsey and Schenck (1990) provide new information on the Columbia Formation and Columbia Group. For the purposes of this report, however, the informal name Columbia aquifer has been retained. In addition, use of "the aquifer" will refer to the Columbia aquifer unless noted otherwise.

Over much of Delaware, the Columbia aquifer is a complex hydrologic unit that is generally unconfined, although it may be locally confined or vertically stratified into unconfined and confined sections, especially in coastal Delaware. The known thickness of the Columbia aquifer is highly variable in the study area; it ranges from a minimum of about 75 feet to a maximum of over 200 feet (Andres, 1987a; Talley, 1988a).

Several lithostratigraphic units form the Columbia aquifer in the study area. Their hydrogeologic characteristics are summarized in Table 1. Figure 2 shows a schematic cross section illustrating stratigraphic relationships between the units. Because the units are laterally and vertically heterogeneous, site-specific subsurface geologic information is necessary for analyses of local hydrologic conditions.

Acknowledgments

I thank the Department of Natural Resources and Environmental Control and the Division of Public Health for allowing access to their files, and the Delaware Division of Highways and Department of Health and Social Services for allowing monitoring wells to be installed on state property. J. G. Townsend and Sons, Inc., Broome United Methodist Church, the City of Rehoboth Beach, and Hercules, Inc. allowed monitoring well installation and sampling on their properties. Many farmers and homeowners permitted their wells to be sampled.

This project would not have been completed without the able assistance of Jeffrey D. Burt, William H. Hurlburt, David A. Sinson, Beverly A. Pierson, Allan Fernandez, Dana M. Maxson, Linda L. York, Gregory D. Rubino, and Imchul Shin. DGS staff members Roland E. Bounds, Johan J. Groot, Kelvin W. Ramsey, T. Charles Smith, William S. Schenck, and John H. Talley also made important contributions to the project. Judith M. Denver and Joseph L.

TABLE 1.
Lithologic units comprising the Columbia aquifer and their hydrologic functions.

LITHO- STRATIGRAPHIC UNIT	LITHOLOGY	HYDROLOGIC FUNCTION
Unnamed Holocene deposits	Variable and complex assortment of sand, silt, clay, organic material, and gravel.	Minor component of Columbia aquifer. Controls locations of recharge and discharge. If saturated, capable of yielding minor quantities of water to wells.
Delaware Bay deposits	Sand, medium to coarse, with scattered gravel, compact silty clay, and organic-rich silty clay.	Probably a minor component of Columbia aquifer. Hydrologic function dependent on lithology. May yield small quantities of water to wells.
Omar Formation	Silt, clay, and fine sand, with varying amounts of shell and organic material, and lesser amounts of medium to coarse sand and gravel. Locally, may be fine to coarse sand. Fine-grained beds more common where unit is greater than 30 ft. thick.	Leaky confining layer or confining layer. Has strong influence on chemical composition of ground water and on rates and directions of ground-water flow. At best can yield small quantities of water to wells.
Beaverdam Formation	Sand, medium to coarse, with varying amounts of gravel, fine sand, silt, and clay found in relatively discontinuous lenses and layers. Generally becomes coarser with depth. Fine-grained beds more common in upper one-third of unit.	Major component of Columbia aquifer. Source of stream baseflow and recharge to deeper aquifers. Yields moderate to large quantities of water to wells. Lower half of aquifer usually more permeable than upper half.
Bethany Formation	Silt, clay, and sand in varying proportions with minor amounts of gravel. Silt and clay beds tend to form a relatively continuous layer.	Fine-grained beds form base of the Columbia aquifer and function as a leaky confining layer. Thicker sand layers form the Pocomoke aquifer. Functions as part of the Columbia aquifer where sands are in hydraulic connection with sands of overlying units.

Bachman (both USGS) provided valuable comments and information during the course of the investigation and along with Nenad Spoljaric (DGS) reviewed the manuscript.

METHODS OF STUDY

This investigation consisted of two complementary components, a regional water quality survey and a detailed study of water quality and hydrology of several small drainage basins. For the regional water quality survey, results of chemical analyses of samples were collected from 447 wells comprising 303 domestic and agricultural, 82 monitoring, and 62 public supply wells. Four small drainage basins, designated sites 1 through 4 (Fig. 3), were chosen to study detailed horizontal and vertical distributions of water levels and water quality.

The data are stored in two databases—the DGS Geologic, Hydrologic, Mineralogic, and Outer Continental Shelf Management Information System (Talley and Windish, 1984) and a Lotus 1-2-3 spreadsheet. Each well used in this study was assigned a DGS well number as described by Talley and Windish (1984). To avoid data

integrity problems, strict data quality control and quality assurance procedures were employed throughout the study. Interested readers should contact the author for details.

Values of elevation used throughout this report are referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929). The use of brand names in this report does not represent endorsement of the products by the DGS.

Small Basin Studies

Site 1 (Fig. 3) near Lewes was investigated in conjunction with William Ullman of the University of Delaware College of Marine Studies (UDCMS). Sites 2 and 3 near Rehoboth Beach and on Champlin Neck, respectively, were investigated by the DGS only. Site 4 was investigated in cooperation with a USGS National Water Quality Assessment Program project and a separate DGS-USGS joint-funded project.

The sites chosen are representative of the range of hydrogeologic conditions that could be encountered in the study area. The DGS installed a number of new monitoring wells to measure ground-water levels and collect samples for water-quality analyses. Ground-water flow paths and the

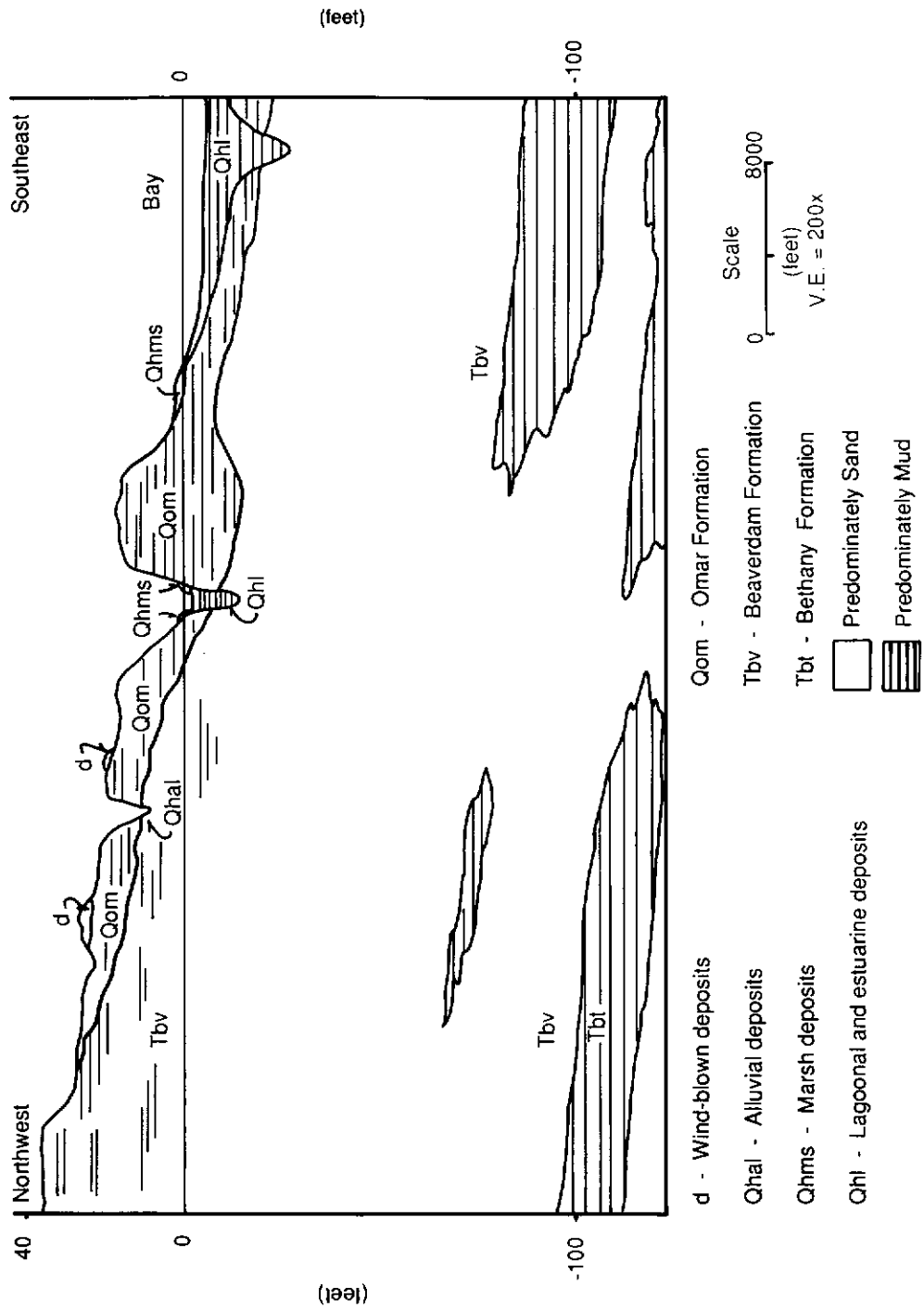


Figure 2. Schematic cross section illustrating distribution of lithostratigraphic units.

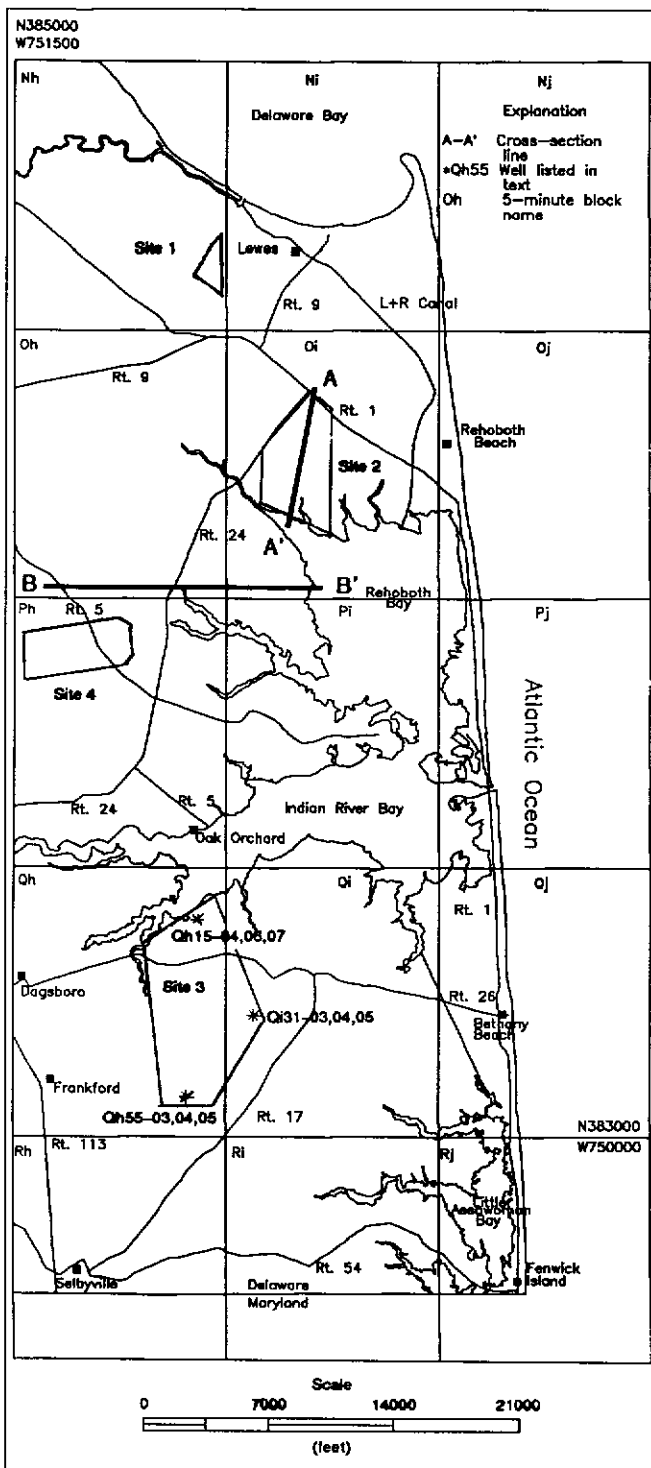


Figure 3. Locations of cross-section lines and small basin study sites. Site 1 includes wells Nh45-02 through Nh45-17 and Nh55-01, -02, and -03. Site 2 is described in Fig. 4. Site 3 includes wells Qh15-04, -06, -07; Qh34-03, -04, -05; Qh55-03, 04, 05; and Qi31-03, -04, -05. Site 4 is described in the text.

boundaries of ground-water flow systems were inferred from these data.

Within each basin, the DGS installed wells in clusters (well screens set at several depths at the same site) near the head, midpoint, and the discharge end of the drainage basin. At most of the well cluster sites, a boring was augered to the

base of the aquifer by the University's truck-mounted hollow-stem auger drill rig and was geophysically logged (natural gamma radiation). A composite lithologic log was constructed from analyses of the geophysical log, the response of the drill rig while advancing the borehole, and cuttings observed on the augers after they were pulled out of the hole. At each well cluster, two or three screen settings (shallow, medium, and deep) were chosen after evaluation of the composite log. Selected samples were analyzed for palynological content in order to assess subsurface stratigraphy (Groot et al., 1990).

Most monitoring wells were installed in boreholes augered with the University's drill rig. At site 2, Oh25-09, Oi22-05, Oi22-07, Oi32-05, and Oi32-08 were installed in holes drilled by the mud rotary method. At site 1, Nh45-06, Nh45-11, Nh45-15, and Nh45-17 were jetted in. Wells were constructed of either 2-in or 1.25-in (inside diameter) polyvinyl chloride (PVC) casing with 5 ft of slotted PVC well screen. The 1.25-in wells were installed through the drillstem. The 2-in wells were pushed into the borehole. At most sites the hole collapsed before gravel pack could be emplaced. This did not cause any problems with obtaining a sand or silt free water sample. Unless there was a competent layer in the wall of the borehole, collapse of the borehole also precluded grouting the hole more than 10 feet below the water table. Wells were developed by surging with compressed air and by pumping. Elevations of well tops relative to NGVD 1929 were obtained by leveling at sites 1 and 2. Relative elevations were obtained at the remaining well clusters by leveling. Water-level measurements were made on roughly a monthly basis at most of the monitoring wells, and at all monitoring wells before sampling. The water levels were used to evaluate ground-water flow direction and identify periods of ground-water recharge.

Regional Water Quality Survey

The regional water quality survey was designed to obtain the widest possible geographic distribution of reliable data from areas thought to have potential for nitrate contamination. Because nitrate concentration has been found to vary with depth (Robertson, 1977; Ritter and Chirnside, 1982) efforts were made to sample wells for which required well completion reports could be obtained. Well construction information was obtained for over 90 percent of the wells sampled.

Information on water-quality data collection, laboratory methods, and quality assurance procedures are described by Andres (1991).

RESULTS AND DISCUSSION

Geology, Ground-Water Levels, and Ground-Water Flow

The Omar Formation, present over most of the study area (Ramsey and Schenck, 1990), has several significant influences on ground water in the study area. The hydrologic characteristics of the Omar are related to its thickness and lithology. Where the Omar Formation is greater than 30 ft thick, it should function as a confining unit as clay and silt beds are more common, thicker, and more areally continuous than where it is less than 30 ft thick. For example, at

Qh55-03, -04, and -05 (Fig. 3) the Omar consists of about 80 ft of interbedded clay, silt, and sand, and the elevation of the water table is 10 ft or more higher than the piezometric surface in the underlying aquifer (Andres, 1991). In addition, poorly drained soils (Ireland and Matthews, 1974) and closely spaced drainage ditches are common where the Omar is greater than 30 ft thick. Where the Omar is less than 30 ft thick, it generally is sandier, so that it should function as part of the aquifer or as a leaky confining unit. For example, at Qh15-04, -06, and -07 the Omar consists of about 8 ft of silt and sand, and the elevation of the water table is usually within 1 ft of the piezometric surface elevation at depth in the aquifer.

Analysis of ground-water levels is the basis for the evaluation of the behavior of the aquifer in response to climatic variations and for determining ground-water flow directions and flow rates. The study period included two climatic extremes, below normal precipitation from 1987 through February 1989 and above normal precipitation from March 1989 through December 1989. Hydrographs and ground-water level data (Andres, 1991) show water level fluctuations due to these extreme climatic variations. These variations obscure the normally observed pattern of increase in ground-water levels from late October until May, followed by a decrease (Talley, 1988b).

In general, ground water in the Columbia aquifer flows from topographically high recharge areas toward topographically lower discharge areas in streams, drainage ditches, canals, swamps, bays, and the ocean. Within this general pattern, ground water flows downward in recharge areas and upward in discharge areas. It is also likely that some ground water flows into deeper aquifers.

Geologic factors that influence ground-water flow paths include aquifer thickness and permeability, and the location, thickness, and continuity of confining beds. Confining beds tend to increase gradients and in some cases the vertical flow component, e.g., between Oi32-01, -02, -13 and Oi32-04, -05, -06 (Figs. 4 and 5). Coarse-grained beds of the Beaverdam Formation, which are common in the lower third of the aquifer, tend to decrease gradients and the vertical flow component.

The relations between surface-water and ground-water drainage basins vary within the study area. In the simplest case, the water-table surface is a subdued replica of the land surface, surface-water drainage basins coincide with ground-water drainage basins, and there is only one ground-water flow system. Over much of the study area, the hydrologic system is inferred to be more complex in that there is more than one ground-water flow system within the aquifer. Figure 6 illustrates the case where there are two ground-water flow systems. The model is similar to a flow net based on real data developed for Site 4 of this study (J. Denver, pers. comm.). Water moving in the deeper (regional) flow system moves along a longer flow line and has a much longer residence time in the aquifer than water in the shallower (local) flow system.

Isotopic Composition of Ground Water

The isotopic content of ground water can be used as a tool to determine ground-water flow paths and the degree of mixing of water within the aquifer, and to estimate the ages

of waters at different locations and depths in the aquifer (Fontes, 1980).

Deuterium and Oxygen-18

Deuterium and oxygen-18 are heavy isotopes of hydrogen and oxygen, respectively. They are stable isotopes because they do not decay radioactively, and they behave chemically the same as normal hydrogen and oxygen. Because of their greater atomic weight, they fractionate under different environmental conditions (e.g., temperature, altitude, latitude) and therefore can be useful tracers or identifiers of ground waters (Fontes, 1980). By convention, waters enriched relative to Standard Mean Ocean Water (SMOW) in the isotope are heavy (positive) and those depleted are light (negative).

The results of deuterium and oxygen-18 analyses are presented in Table 2 and Figure 7. Observed concentrations plot near the meteoric water line and, therefore, are representative of what would be expected from recent precipitation (Drever, 1982). The values vary in the same well between samples, between wells in the same cluster, and between well clusters. Variability between sampling periods occurs because the composition of ground-water recharge varies yearly and seasonally as a result of differing storm tracks. In addition, variability between sampling periods indicates that water recharged at one time does not completely mix with water recharged at another time. Variability between wells in the same cluster or between clusters is expected if water in the aquifer is stratified, i.e., water at different depths or locations was derived from different recharge events (storms, seasons, or years). There are no obvious seasonal or spatial trends in the data, probably because of the low sampling frequency.

Tritium

Tritium is the radioactive isotope of hydrogen. It has a half-life of approximately 12.35 years (Fontes, 1980). Tritium concentration is commonly expressed in terms of tritium units (T.U.). One T.U. is approximately 3.2 pico Curies per liter (Fritz and Fontes, 1980). Chemically, tritium has the same properties as normal hydrogen and deuterium and also undergoes fractionation during evaporation and condensation. In response to regional climatic trends and characteristics of atmospheric nuclear testing, tritium concentration in precipitation increases with increasing latitude and with distance from the ocean (Gat, 1980). In addition, the maximum input of tritium occurs during the spring and early summer, the minimum during the early winter (Gat, 1980). The spring maximum coincides with a period having a high rate of ground-water recharge (Johnston, 1977; Talley, 1988b).

Tritium is produced naturally at low levels (less than 20 T.U.) in the upper atmosphere (Fontes, 1980). What makes tritium a useful tool in ground-water studies is that enormous quantities of tritium were injected into the atmosphere during the period 1952 through 1969 as a result of atmospheric testing of nuclear weapons (Gat, 1980). Precipitation and, therefore, ground waters originating during that time have tritium concentrations hundreds of times greater than older or current waters.

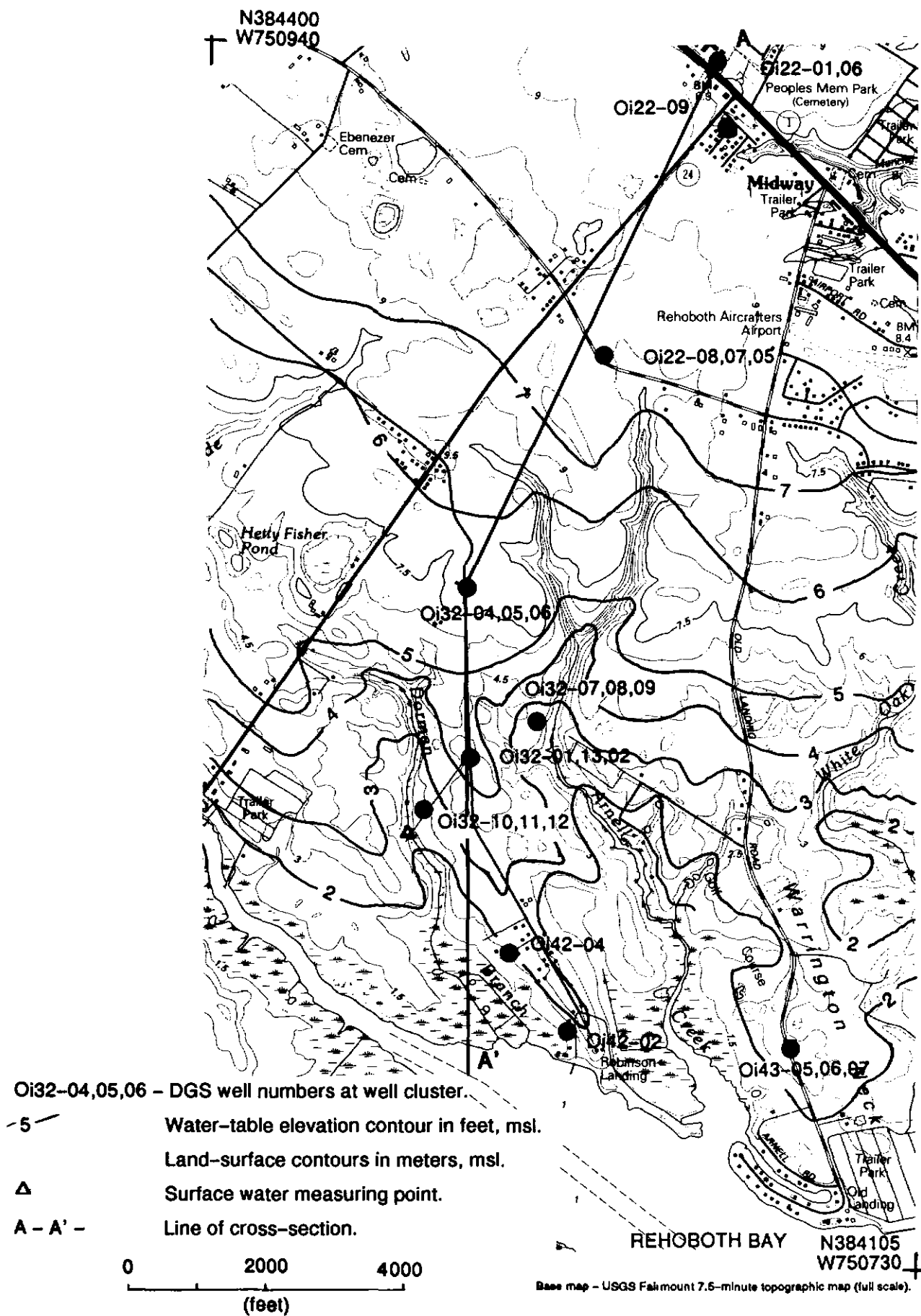


Figure 4. Water table configuration on August 3, 1988, Site 2.

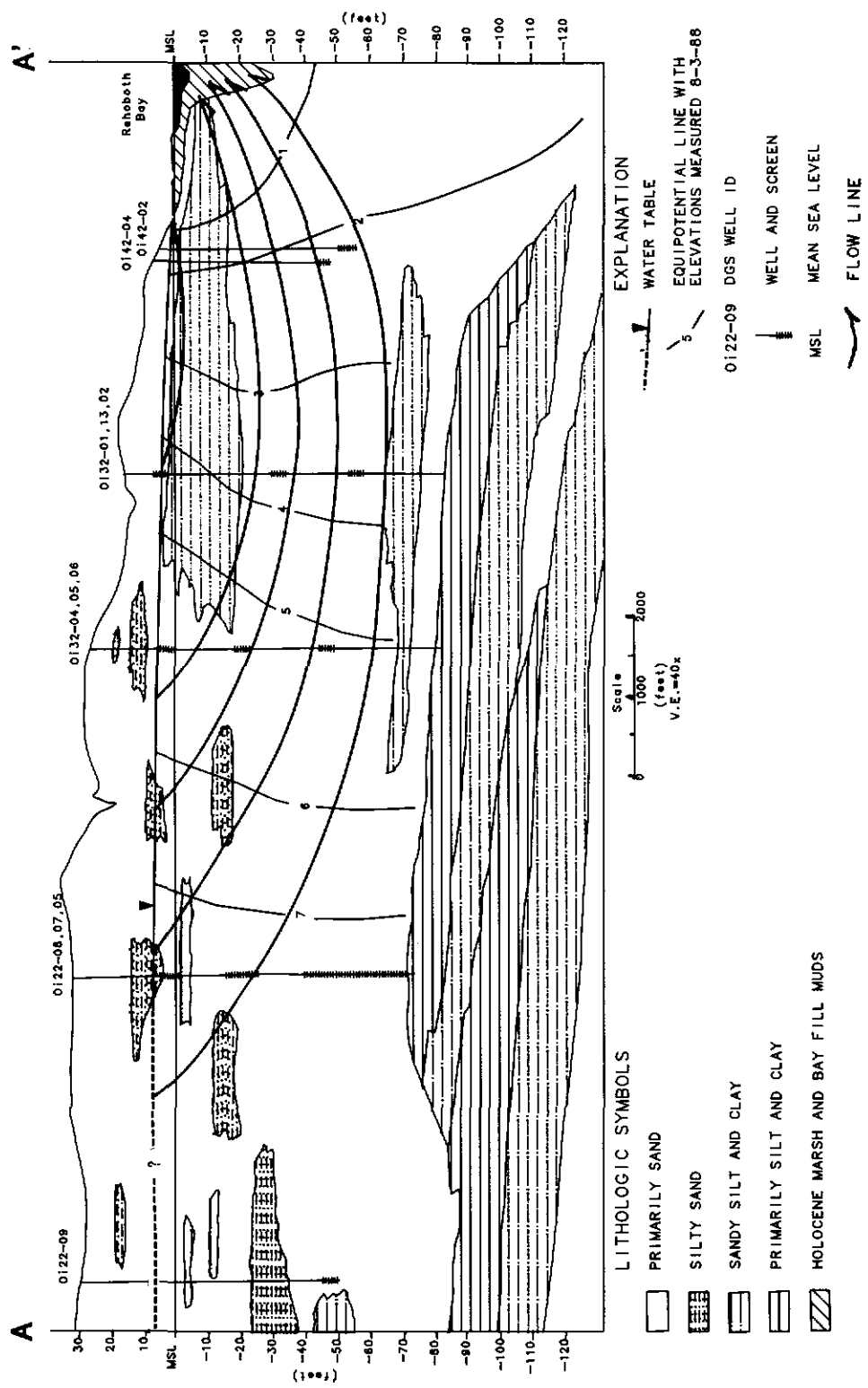


Figure 5. Flow net on August 3, 1988, cross-section A-A'.

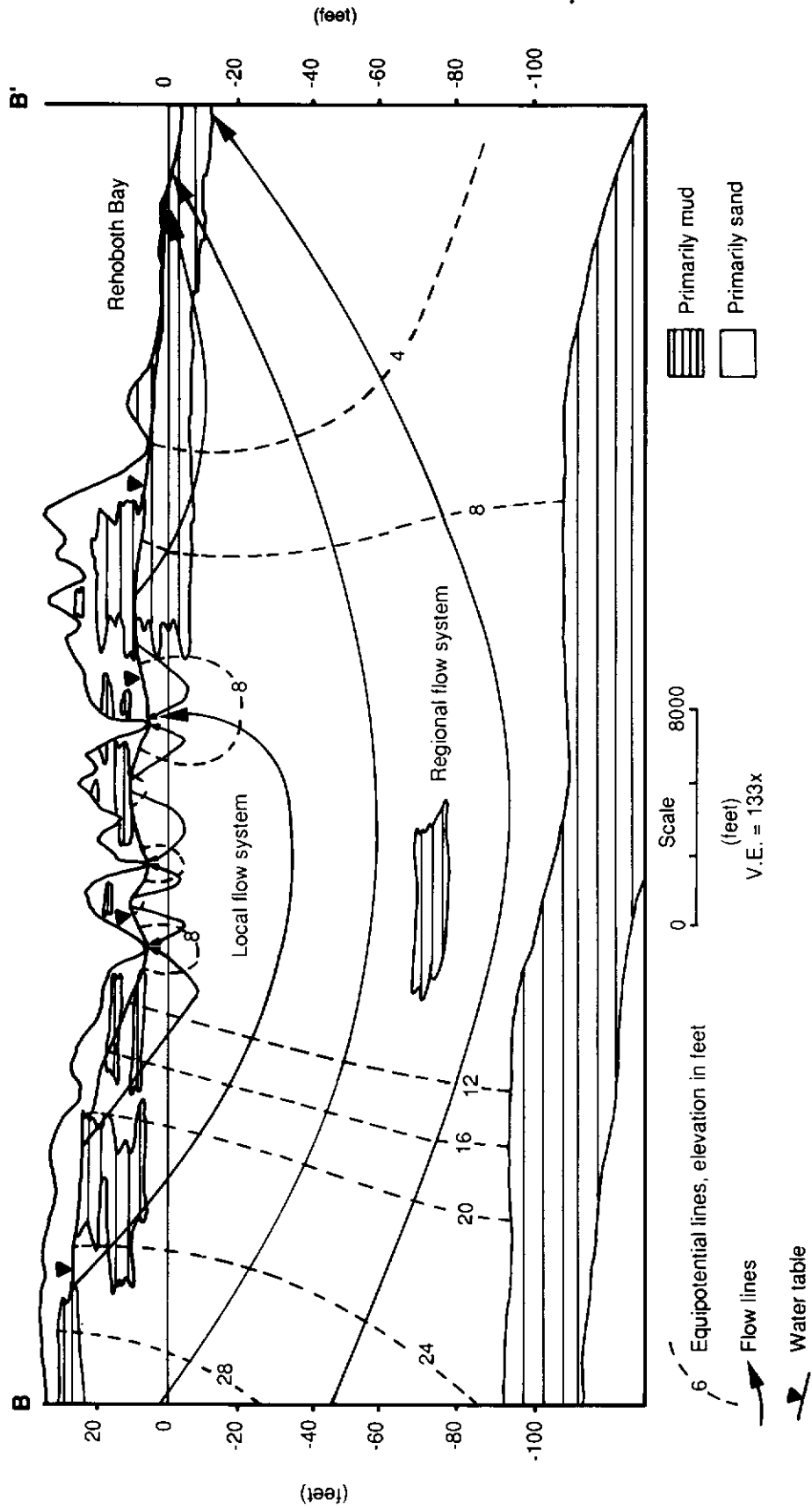


Figure 6. Schematic flow net, cross-section B-B' (see Fig. 2 for location). Water-table elevations from Boggess, Adams, and Davis (1964).

In general, waters pre-dating atmospheric testing have tritium levels less than 5 T.U. (Fontes, 1980). Since atmospheric testing was halted, tritium concentrations in the atmosphere and precipitation have steadily declined. Figure 8 shows plots of tritium concentration in precipitation reported by the International Atomic Energy Agency (IAEA), corrected for radioactive decay, for stations located in Hatteras, North Carolina, Washington, D.C., and Boston, Massachusetts (IAEA, 1969, 1970, 1971, 1973, 1975, 1978, 1983, 1986, 1990). Tritium levels in recent (less than 5 years) precipitation are in the range of 10 to 50 T.U. Given the similarities in latitude and distances from the ocean between the precipitation monitoring stations and the study area, input of tritium in precipitation and therefore ground-water recharge in the study area should have had tritium concentrations in the ranges shown in Figure 8.

Tritium concentrations in ground water of the study area (Table 2) exhibit several noteworthy features. As with deuterium and oxygen-18, tritium concentration varies in the

same well between sampling periods, between wells in the same cluster, and between well clusters. This indicates that waters from different recharge periods are not completely mixed within the aquifer.

Tritium concentrations in Oi32-01 and Qi31-03 (screened within 10 feet of the water table) should reflect very recent (less than one year old) precipitation. Tritium concentrations in Oi43-05, Oi32-13, Oi43-06, Qi31-04 (intermediate-depth wells, screened 10 to 35 feet below the water table), and Oi32-02 (screened 60 ft below the water table near the base of the aquifer) are higher than those in the shallowest wells, indicating slightly "older" water. Comparison of tritium concentrations in ground water with that in precipitation (Fig. 8) indicates ground-water ages of less than 20 years. The 20-year maximum age is inferred from the much larger tritium concentrations seen in spring-time precipitation before 1972. Tritium concentrations observed in Oi43-07 (screened nearly 80 ft below the water table) are similar to those observed in the shallowest wells.

TABLE 2
Isotopic content of selected water samples.

May 1988					October 1988			
Well	Deuterium d D	O-18 d O-18	Tritium T.U.	Error +/-	Deuterium d D	O-18 d O-18	Tritium T.U.	Error +/-
Oi32-01	-40	-6.5	25.1	1.7	-37	-4.2	11.7	2.1
Oi32-13	-39	-6.5	32.0	1.8				
Oi32-02	-43	-6.7	44.8	1.9	-40	-6.8	33.3	2.3
Oi43-05	-35	-5.7	37.6	1.9	-31	-5.5	20.7	2.2
Oi43-06	-38	-5.8	26.3	1.8				
Oi43-07	-42	-6.4	23.2	1.7	-37	-6.3	11.5	2.1
Qi31-03	-41	-6.9	23.0	1.7	-48	-7.2	12.6	2.1
Qi31-04	-44	-6.4	51.3	1.7	-39	-6.5	32.9	2.3
Qi31-05	-38	-6.1	12.7	1.7	-38	-6.2	2.2	2.0
Qh54-06					-37	-6.0	0.0	2.0
Qh54-07					-34	-5.8	2.4	2.0

March 1989					October 1989			
Well	Deuterium d D	O-18 d O-18	Tritium T.U.	Error +/-	Deuterium d D	O-18 d O-18	Tritium T.U.	Error +/-
Oi32-01	-37	-6.5	18.4	2.2	-37	-6.1	17.1	2.2
Oi32-13	-39	-6.7	19.0	2.4	-33	6.5	15.1	2.4
Oi32-02	-39	-7.0	43.0	2.2	-33	6.9	35.3	2.2
Qi31-03					-35	-6.3	17.9	2.2
Qi31-04					-35	-5.8	27.8	2.3
Qi31-05					-36	-6.1	5.1	2.1

Note: Deuterium and Oxygen-18 values are given as delta values relative to Standard Mean Ocean Water (SMOW). Tritium values are given in tritium units (T.U.).

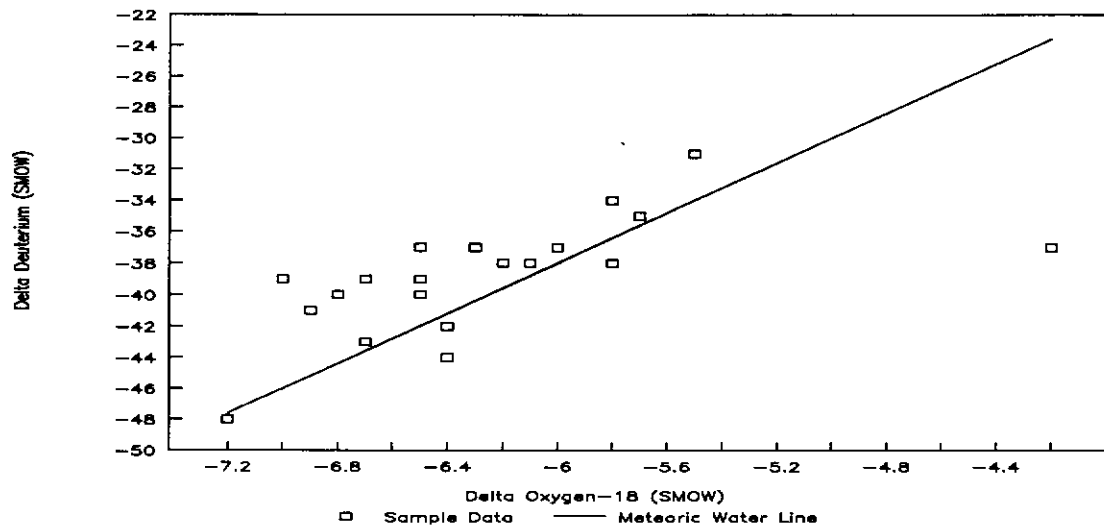


Figure 7. Graph showing stable isotope content of samples from selected wells.

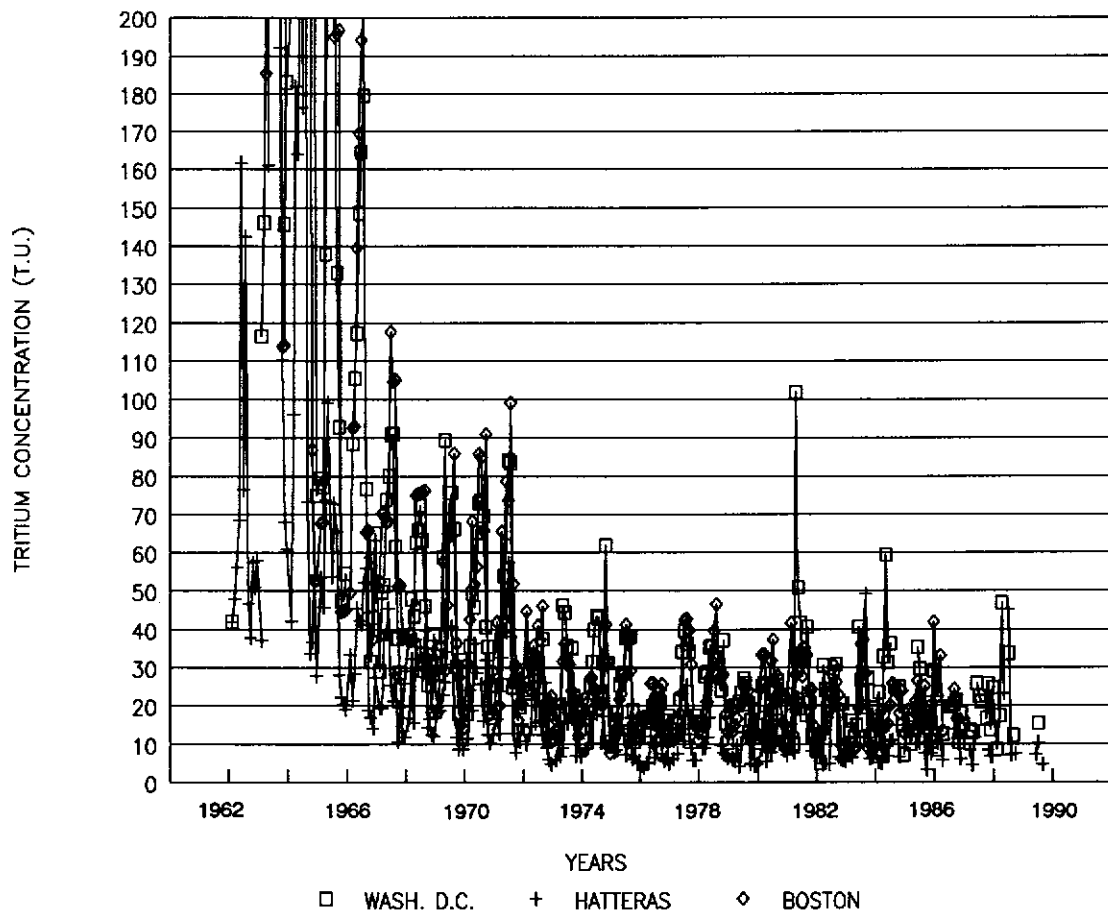


Figure 8. Graph showing tritium concentration in precipitation. Tritium values are corrected for decay to January 1989. Data from IAEA (see text for references).

Assuming that water 80 ft down in the aquifer must be older than water at the water table, the results indicate either water ages of less than 20 years or mixing of old (before nuclear weapons testing) and young waters. Zero or near zero tritium concentrations observed in deep wells Qi31-05, Qh54-06, and Qh54-07 (screened deeper than 80 ft below land surface) indicate the presence of relatively old water (greater than 35 years), probably representing a more regional, deeper flow system. Tritium concentrations vary from non-detectable to 12 T.U. in Qi31-05, indicating intermittent mixing of old and younger waters. The variation of tritium in well Qi31-05 indicates that the position of the bottom of the upper flow system changes with time, probably in response to climatic variations.

Ground-Water Quality

Water-quality data are published separately (Andres, 1991). Locations of wells sampled are shown in Figure 9. Table 3 contains the results of basic statistical analyses of all of the data. Figures 10 and 11 show frequency distributions of total iron, dissolved solids, chloride, and pH. Nitrate-nitrogen is discussed in more detail in a following section.

Most of the water samples tested during this study can be characterized as slightly to moderately acidic (median pH 5.53) and low in dissolved solids (median 110 mg/l). There are, however, significant ranges in the concentrations of many of the chemical constituents. For example, the maximum values of most constituents reported in Table 3 are one or more orders of magnitude greater than the mean or median. The samples with extremely high values greatly affect the values of the maximum, mean, and variance.

Samples with the highest concentrations of dissolved constituents were in almost all cases collected from wells located close to the bays and are attributed to the presence of salty water. These samples typically contain high concentrations of chloride, dissolved solids, and metals. Some of the samples with higher than average alkalinity and iron concentrations were collected from wells located in the southern third of the study area, an area known to have naturally occurring higher than average concentrations of these constituents. Only a few samples were collected in this area.

It is not easy to discern which samples, if any, record natural water quality. Natural water quality refers to water that has not been chemically altered by human activities. First, human activities have affected almost all land in the area at one time or another, and this, in turn, usually affects ground-water quality in some way. Second, it is difficult to determine precisely where on the land surface the water in a particular well originated. However, because nitrate is an indicator of the effects of land-use practices, low concentrations of nitrate may be an identifier of natural water quality. In order to test if nitrate is an indicator of natural water quality, several samples that contained less than 2 mg/l nitrate-nitrogen were investigated further. The 2 mg/l concentration was chosen for two reasons. First, too few samples could be evaluated if a lower concentration was used. Second, the 2 mg/l concentration is a compromise between the results of Bachman's (1984) estimate of the natural background nitrate concentration and Denver's (1986) estimation of the potential nitrate content of infiltrating rainwater. The samples

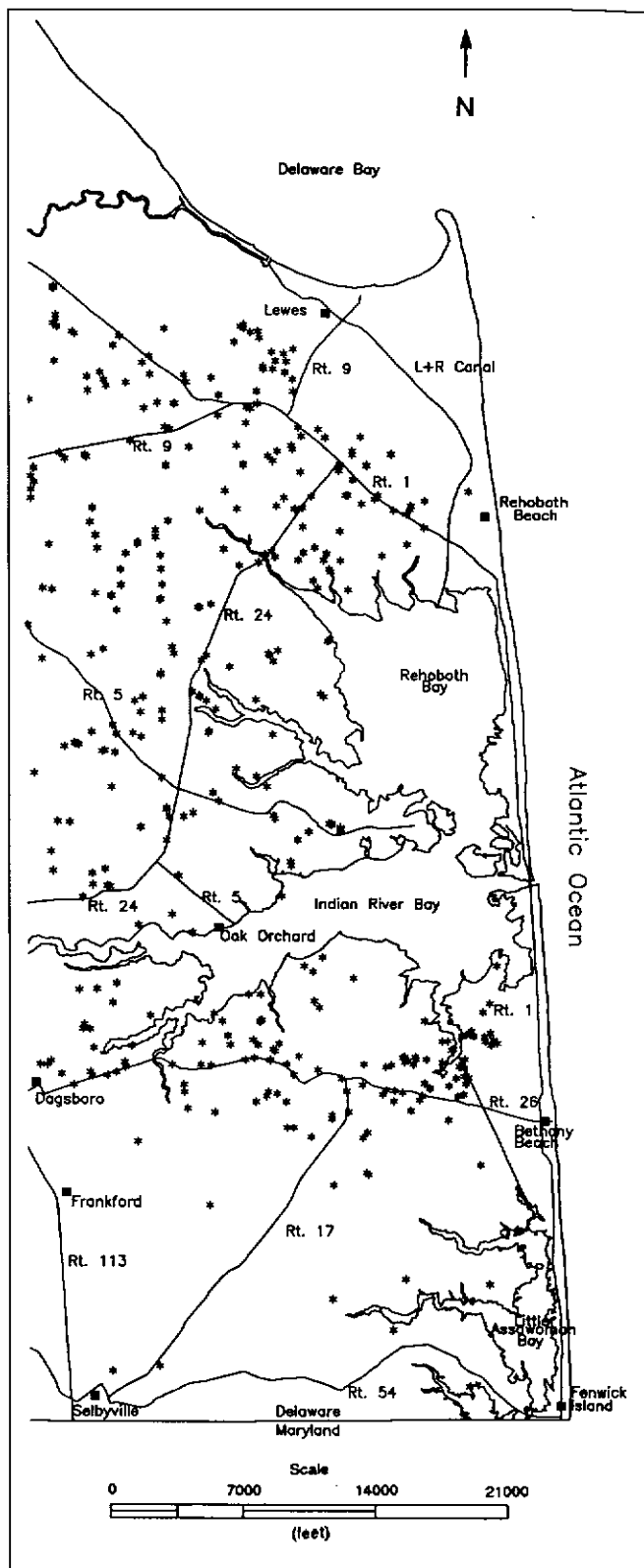


Figure 9. Map showing locations of wells sampled.

selected were further subdivided into three groups: salty water (chloride greater than 500 mg/l, Qh15-05, Rj11-09); low nitrate (nitrate-nitrogen less than 1 mg/l, Oi32-01, Nh45-02, Ph13-30, Qh55-03, -04, -05, Qi31-05, Qj21-06); and moderate nitrate (nitrate-nitrogen between 1 and 2 mg/l, Oh24-03, Oi32-04, Ph12-08, Ph13-14, Qh15-04, Qh23-01).

TABLE 3.
Statistical summary of water quality data.

	Water Level ft bls	Flow Rate gpm	Temp. deg. C	pH	Spec. Cond. µmho	Disolved Oxygen mg/l	Alkalinity as CaCO ₃ mg/l	Chloride mg/l	Nitrate-Nitrogen mg/l	Disolved Solids mg/l	Screen top ft bls	Screen bottom ft bls	Sulfate mg/l	Potassium mg/l	Sodium mg/l	Magnesium mg/l	Calcium mg/l	Iron total mg/l	
DOMESTIC WELLS																			
Number of Samples	—	273	287	303	302	—	289	295	300	90	281	281	—	—	—	—	—	—	—
Minimum	—	1	7.6	4.23	40	—	<1	1	<0.5	26	20	25	—	—	—	—	—	—	—
Maximum	—	60	23	7.37	14000	—	188	9875	34	11000	130	140	—	—	—	—	—	—	—
Mean	—	5.64	15.19	5.48	192.84	—	10.07	58.48	6.33	264.10	62.88	70.12	—	—	—	—	—	—	—
Median	—	5	15.2	5.51	105	—	6	15	4.8	100	60	68	—	—	—	—	—	—	—
Variance	—	15.45436	1.607782	0.200741	739231.8	—	308.8717	332134.1	36.78274	1329730.	259.3718	265.6152	—	—	—	—	—	—	—
MONITOR WELLS																			
Number of Samples	81	81	81	81	62	74	80	80	80	51	81	81	84	80	79	79	80	80	80
Minimum	0.00	<0.1	11.35	4.1	62	<0.5	<1	7.3	<0.5	57	2	7	<1	0.65	2.85	0.6	1.45	<0.003	<0.003
Maximum	22.02	60	18.75	7.51	9910	11.6	133	2496.951	33	700	88	100	900	45	2906	390	260	80	80
Mean	8.71	5.286527	14.7181	5.324729	526.0562	5.934752	12.06030	79.03709	9.710665	148.1601	36.91975	42.56049	32.12141	4.445041	52.63736	11.58677	15.59668	2.52344	2.52344
Median	8.61	1.64	14.5	5.2225	120.25	6.9	5.66	18.0833	7.6	120.6666	32	39	14.73847	2.46666	10.5	6.1	8.4	0.037	0.037
Variance	27.37979	109.6157	1.121076	0.358276	2328065.	8.872671	617.6653	126615.7	76.51734	9127.529	607.5240	672.2865	11606.87	45.67201	113461.5	2007.089	831.1449	8.4	42.74044
PUBLIC WELLS																			
Number of Samples	—	—	—	58	—	—	59	57	61	49	58	60	—	—	52	—	—	—	51
Minimum	—	—	—	5.2	—	—	5.5	10	<0.5	46	25	35	—	—	6.5	—	—	<0.01	<0.01
Maximum	—	—	—	7.3	—	—	152	101	14	271.5	125	147	—	—	85	—	—	4.17	4.17
Mean	—	—	—	6.02	—	—	16.94	24.68	5.10	104.06	75.70	93.20	—	—	13.28	—	—	0.285980	0.285980
Median	—	—	—	5.95	—	—	12	20	5.65	94.5	82	97	—	—	11	—	—	<0.01	<0.01
Variance	—	—	—	0.156296	—	—	540.8074	322.4779	12.21882	1658.904	434.7934	584.36	—	—	112.8597	—	—	0.892315	0.892315
ALL WELLS																			
Number of Samples	—	354	368	442	364	—	428	432	441	190	420	422	—	—	130	—	—	—	131
Minimum	—	0.00	7.6	4.1	40	—	<1	1	<0.5	26	2	7	—	—	2.85	—	—	<0.003	<0.003
Maximum	—	60	23	7.51	14600	—	188	9875	34	11000	130	147	—	—	2906	—	—	80	80
Mean	—	5.56	15.08	5.52	249.59	—	11.39	57.83	6.76	193.01	59.59	68.10	—	—	37.15270	—	—	1.653531	1.653531
Median	—	5	15	5.53	110	—	7	16	5.60	110	60	68	—	—	10.35	—	—	0.025	0.025
Variance	—	37.02059	1.539832	0.264582	1025548.	—	405.0832	250523.1	42.77779	637820.8	493.5591	607.6597	—	—	65252.17	—	—	72.43311	72.43311
Standard Deviation	—	6.084455	1.240899	0.514375	1012.693	—	20.12667	500.5228	6.540473	798.6368	22.21619	24.65075	—	—	255.4450	—	—	8.510764	8.510764

Notes:

Multiple samples from any well have been averaged.
Includes selected data reported in James et al. (1989, 1990).
Sulfate and metals results from domestic wells are included in the monitoring well data set.
mg/l = milligrams per liter, ft bls = feet below land surface, µmho = micromhos, deg C = degrees Celsius, gpm = gallons per minute
All analyses with the result non-detectable are treated as 0s in calculations.

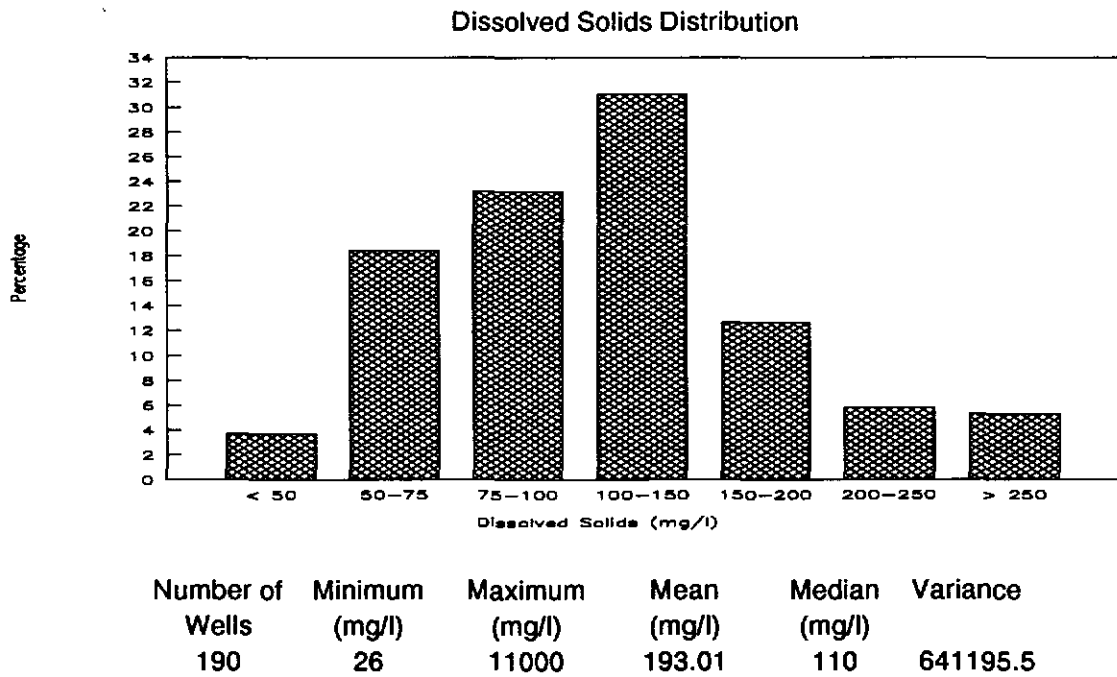
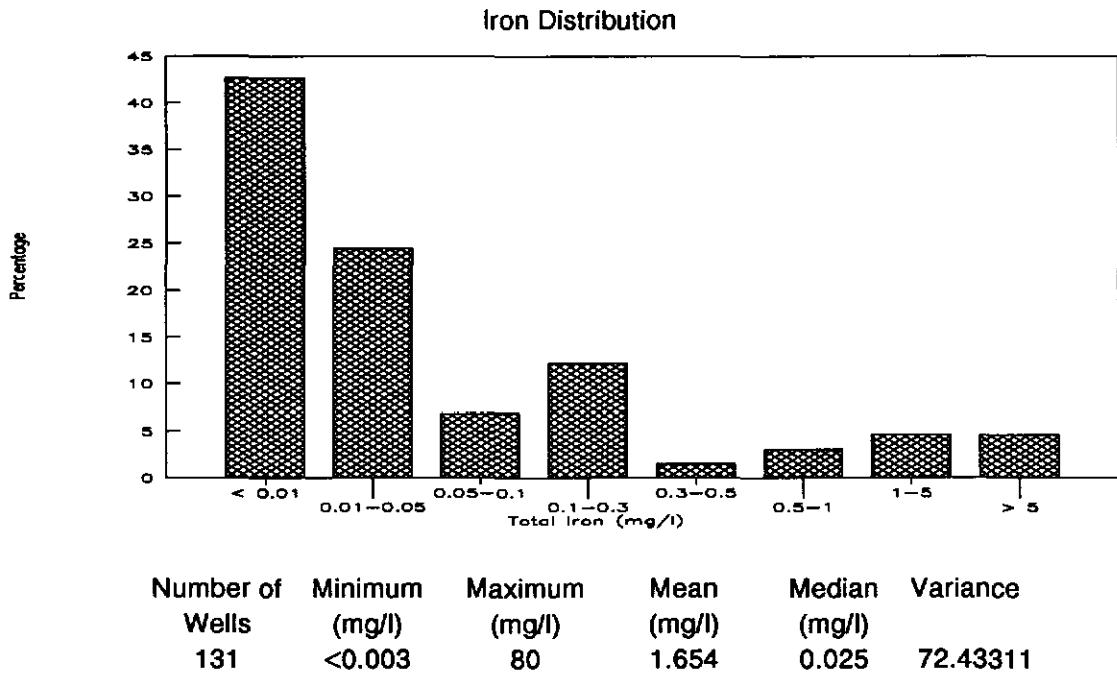
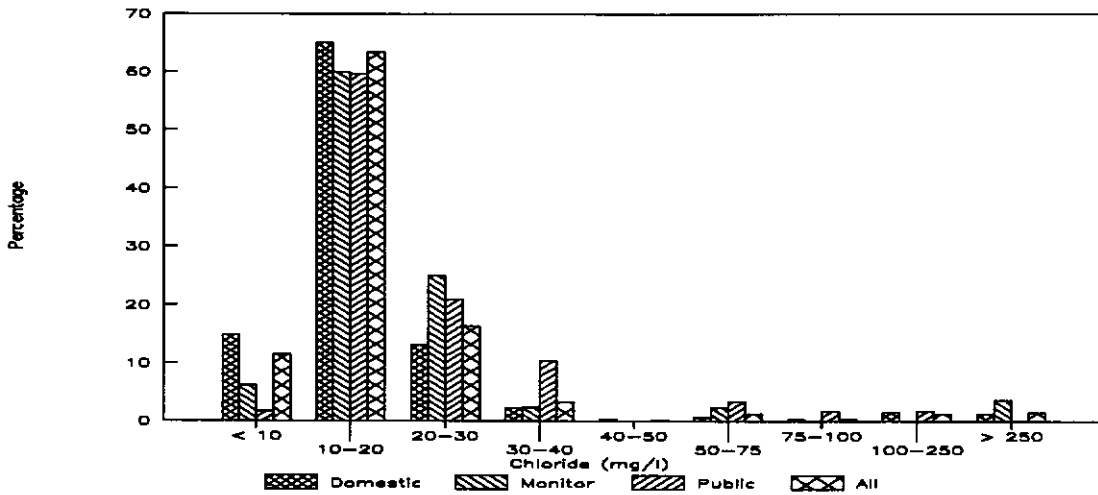


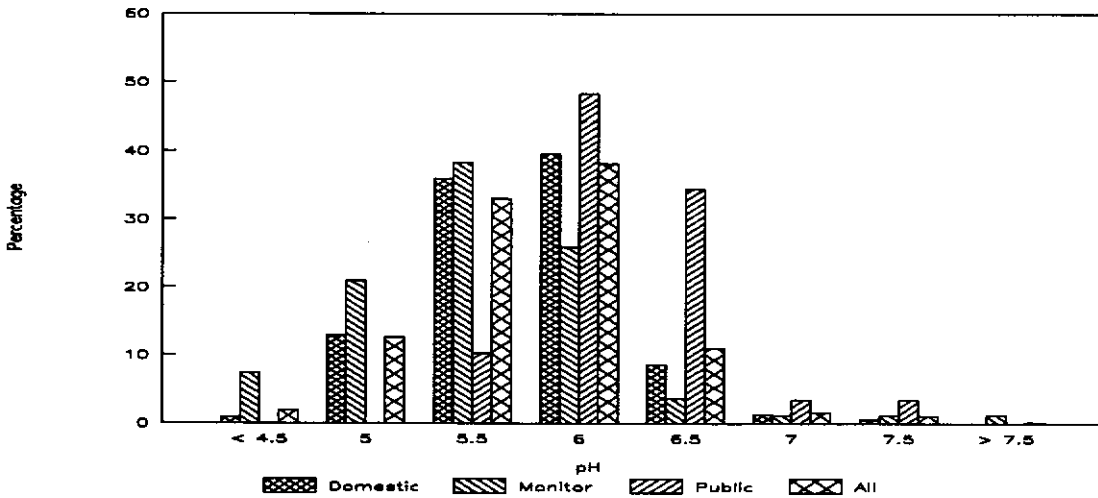
Figure 10. Total iron and dissolved solids frequency distributions.

Chloride Distribution by Well Type



	Domestic	Monitor	Public	All
Number of Wells	295	80	57	432
Minimum	1	7	10	1
Maximum	7000	2496	101	9875
Mean	48.96	79.03	24.68	57.83
Median	15	18	20	16
Variance	332134.2	126615.7	322.5	251104.4

pH Distribution by Well Type



	Domestic	Monitor	Public	All
Number of Wells	303	81	58	442
Minimum	4.23	4.10	5.20	4.10
Maximum	7.37	7.51	7.30	7.51
Mean	5.48	5.32	6.02	5.52
Median	5.51	5.22	5.95	5.53
Variance	0.200742	0.358278	0.156296	0.514958

Figure 11. Chloride and pH frequency distributions by well type.

Figure 12 is a Piper diagram (Piper, 1944), a type of discriminate plot, showing the range in major-ion composition of water. Most of the samples plot in three groupings (water types) that do not correspond to the groupings listed above (i.e., low nitrate, salty, and moderate nitrate). The remainder of the samples fall outside of the groups and may represent mixtures of different water types, or indicate anthropogenic influence.

Water type I is a calcium and magnesium (plus iron) bicarbonate type water. It usually contains iron concentrations in excess of 1 mg/l, less than 0.5 mg/l of dissolved oxygen, hydrogen sulfide gas, and dissolved solids greater than 200 mg/l. Water type I is most commonly found in the southernmost third of the study area where the aquifer is confined by the Omar Formation. In this area the Omar is usually greater than 30 ft thick; contains visible organic material (plant remains and shell material); is colored dark shades of gray, green, and blue; and has a noticeable hydrogen sulfide odor indicating reducing conditions. The combination of less than 0.5 mg/l of dissolved oxygen and hydrogen sulfide indicates bacterial reduction of organic material in the aquifer (Drever, 1982). Type I water is similar in content and genesis to anoxic water as described by Denver (1986) and to high iron water as described by Robertson (1977).

Water type II is a sodium potassium chloride (plus bicarbonate) type water. It usually occurs where the aquifer is

unconfined and is the most common natural water type in the Columbia aquifer over most of the study area. Where water type II occurs, the Omar Formation is usually less than 30 ft thick; visible organic material is uncommon; and it is colored shades of light gray, yellow, and orange indicating oxidizing conditions. The water is similar in content and genesis to oxic water described by Denver (1986). It usually is acidic and contains less than 100 mg/l dissolved solids, has measurable dissolved oxygen, and iron concentrations less than 0.2 mg/l. Samples of salty water also plot as type II water.

Type III water is a sodium potassium sulfate chloride type water, found only in monitoring wells screened in fine-grained sediments (usually the Omar Formation) where dissolved oxygen is present. It is likely that the sulfate is the result of the oxidation of organic matter in the rocks. Most of the samples characterized as moderate nitrate waters also plot as, or near, type III water indicating that type III water can result from agricultural addition of dolomite or sulfate (Denver, 1986, p. 28).

Nitrate

Sources, Production, and Depletion of Nitrate

Nitrate enters the Columbia aquifer in a number of ways. Small quantities of nitrate may enter the aquifer directly through the infiltration of acid rain (Denver, 1986, 1989).

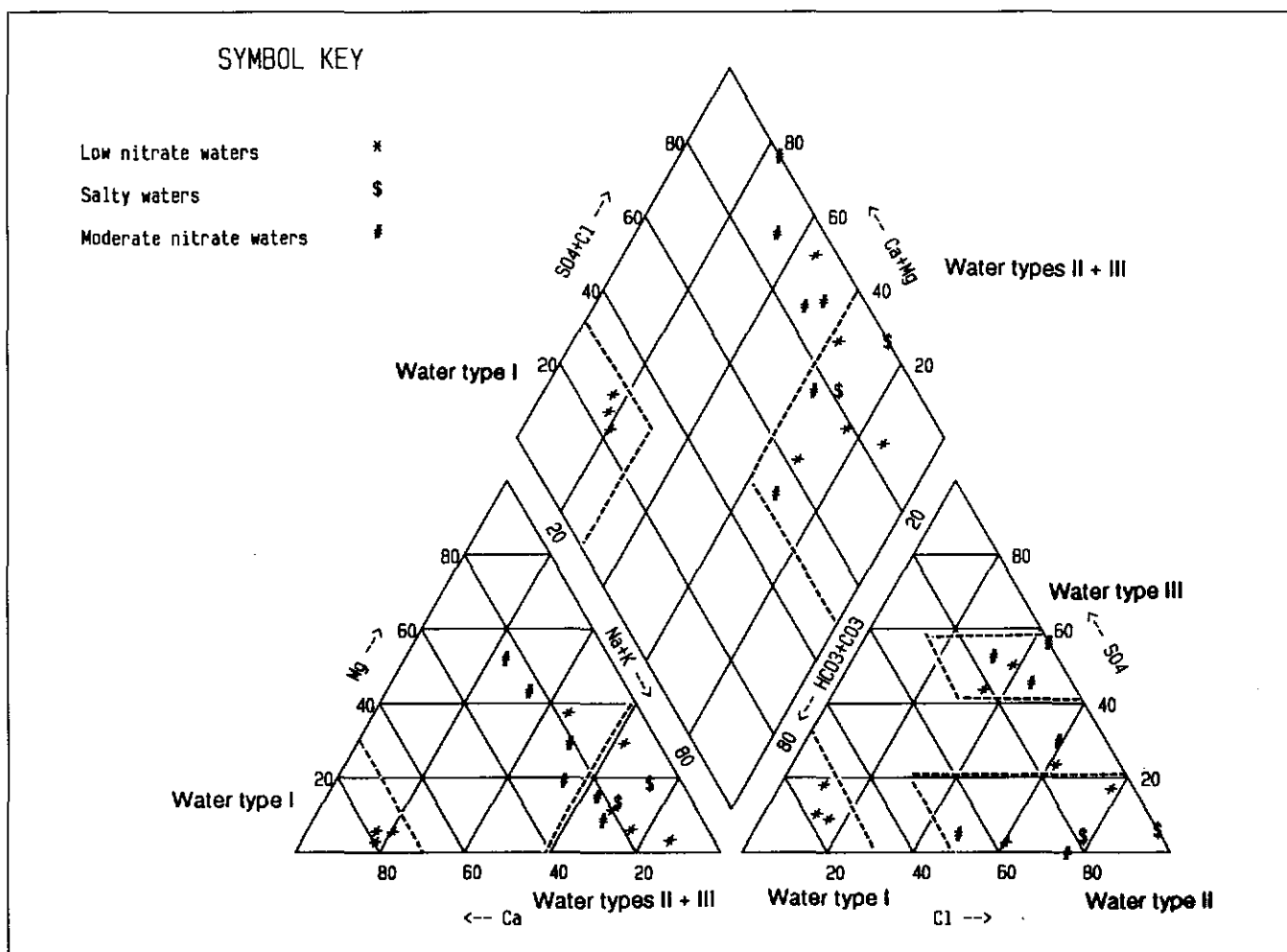
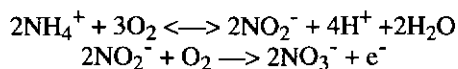


Figure 12. Comparison of major ion composition of waters with less than 2 mg/l nitrate-nitrogen. See text for discussion of water types.

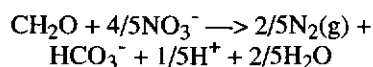
Other forms of nitrogen, most commonly ammonium compounds (from chemical fertilizers, manure, and sewage) and organic nitrogen (from manure, decay of natural organic material, and sewage), can be converted to nitrate in the soil zone and leached into the aquifer with infiltrating precipitation.

Oxidation-reduction reactions control nitrate in ground water. In chemical terms, nitrate production is an oxidation type reaction. Organic nitrogen is first converted to ammonium (NH_4^+) through the ammonification process; ammonium is then oxidized to nitrate (NO_3^-) in the presence of nitrifying bacteria by a two-step process known as nitrification:



The ammonification and nitrification processes are dependent on factors that affect the soil biota, namely, oxygen concentration, temperature, moisture, amounts and forms of nitrogen and carbon, and presence of other ions. Nitrate is only produced under oxidizing conditions. The presence of hydrogen sulfide gas and a high iron concentration in ground water indicate reducing conditions.

Denitrification, a reduction reaction, can deplete nitrate in the soil zone and, possibly, in the aquifer:



Denitrification is also dependent on factors that affect the biota of the soil and rocks. It only occurs under reducing conditions.

Distribution of Nitrate in the Columbia Aquifer

Nitrate is a common pollutant in the Columbia aquifer, occurring at concentrations exceeding the primary maximum contaminant level for drinking water in nearly 23 percent of all wells sampled and in almost all areas. Figures 13 through 16 show distributions of well depth and nitrate concentration by several different groupings of geographic areas and well type. These plots and tables can be used to assess the occurrence of nitrate contamination for particular areas, the variability in nitrate concentration between areas, the relation between well depth and nitrate concentration, and many other relations. For example, figures 14 and 15 can be used to evaluate east-west and north-south trends respectively. Nitrate contamination occurs in all types of wells sampled, although the incidence and maximum concentration of contamination is lower in public wells than in domestic or monitoring wells (Fig. 16). This is due to the fact that public wells as a group are deeper than domestic, agricultural, and monitoring wells.

In the analysis of the relationship between nitrate and well depth, depth of the midpoint of the screened interval was used. This was done because public supply and agricultural wells generally have longer screened intervals (20 to 40 ft) than monitor and domestic wells (5 to 10 ft), and it is likely that the entire screened interval contributes to the flow of water from a well.

Nitrate concentrations and variance generally decrease with depth in the aquifer (Fig. 17). The data demonstrate,

however, that contamination occurs at all depths in the aquifer, although less frequently at greater depths (Fig. 17). Linear regression analyses on data from all areas (Fig. 18) and from the southern area alone shows that there is a statistically significant ($\alpha = 0.05$) decrease in nitrate concentration with increasing well depth, but only when mean nitrate concentrations from depth range classes are used in the calculations. Linear regression on all of the data, on mean nitrate concentration by well depth class from the northern area alone, and on median nitrate concentrations from depth classes do not show a statistically significant ($\alpha = 0.05$) decrease in nitrate concentration with increasing well depth. Bachman (1984) and Robertson (1977, 1979) report a statistically significant decrease in nitrate concentration with depth using non-parametric correlation ($\alpha = 0.05$) and linear regression ($\alpha = 0.01$) techniques, respectively.

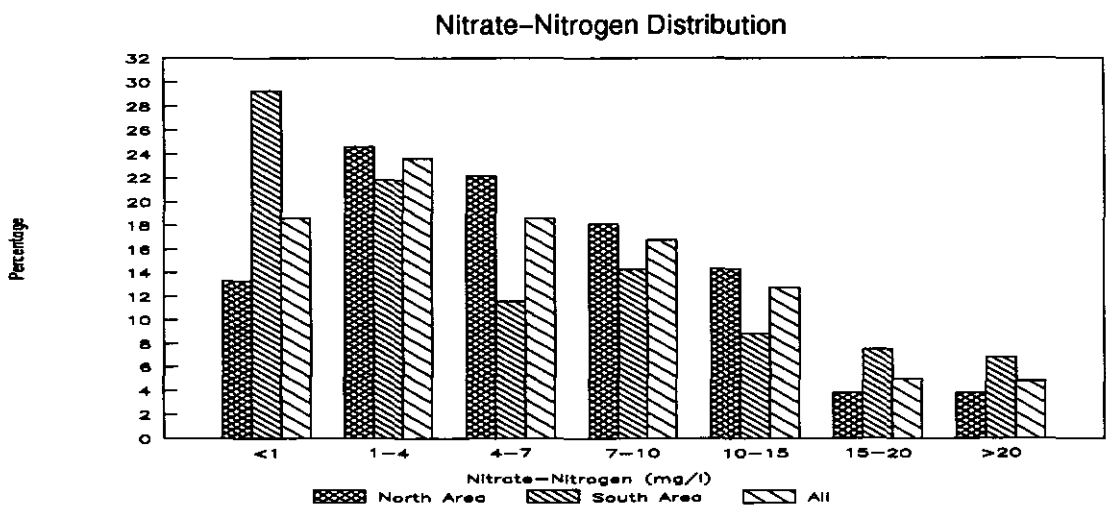
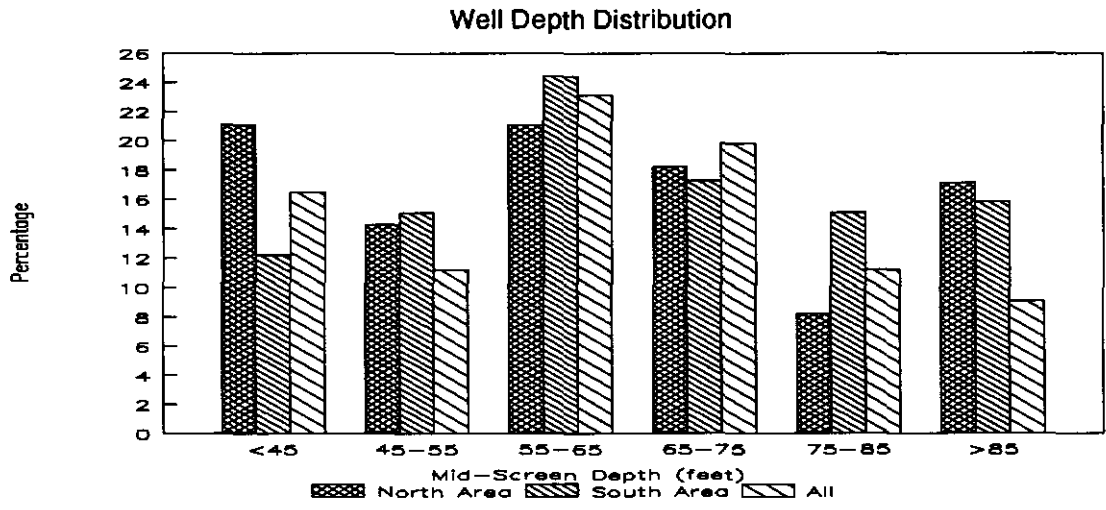
Geology, Ground-Water Flow, Land Use, and Nitrate

Figure 19 is a Piper diagram showing samples with nitrate-nitrogen concentrations greater than 2 mg/l. Most of these samples plot within or near the fields of types II and III waters. Recall that types II and III waters generally are acidic, have low dissolved solids content, iron concentrations less than 0.2 mg/l, and measurable dissolved oxygen. Not one of the samples plots as type I water, and some samples plot between types I and II, or types II and III waters. This could be due to mixing of water types I and II or II and III. However, the presence of nitrate-containing type III water may only be the result of the addition of nitrate and sulfate to type II waters, as discussed previously.

Nitrate contaminated waters always plot as either type II or type III waters. In almost all of the areas with high nitrate concentrations, the Omar Formation is relatively thin, usually less than 30 ft thick, and sandy.

In type I water, nitrate, if present, occurs at concentrations below 0.5 mg/l. A large portion of the land having type I water is under intensive agricultural use (both field crops and poultry) so that sources of nitrogen are present. As nitrate contamination is very rare, it is likely that either nitrification never occurs in the unsaturated zone, or denitrification occurs in the soil zone or as water moves through the aquifer.

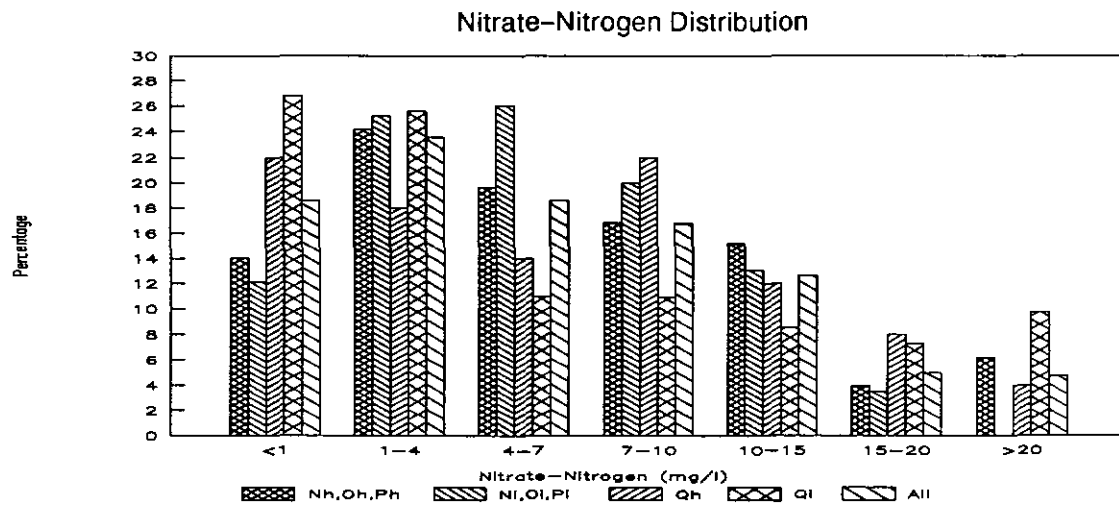
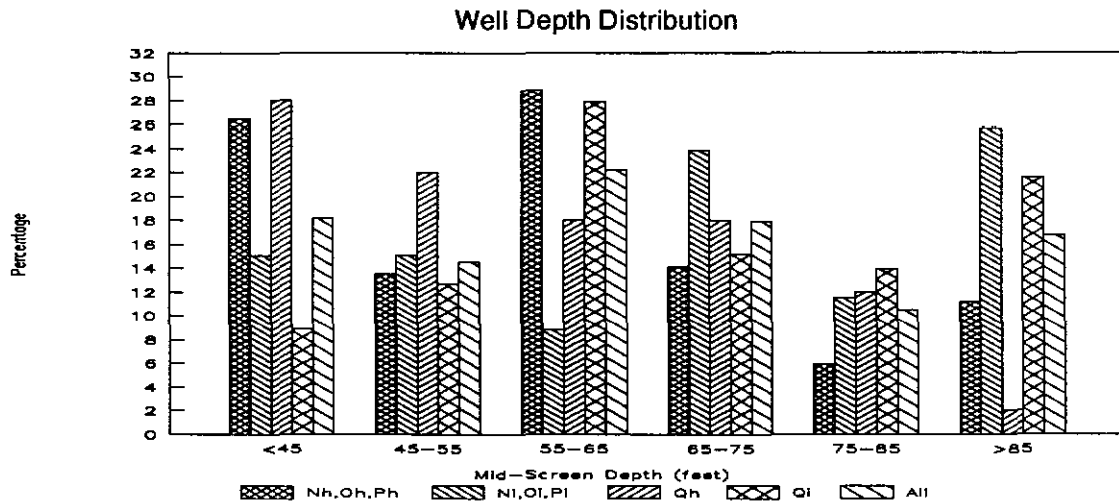
The relation between dissolved solids, specific conductance, and nitrate is another indicator of the influence of nitrate on overall chemical composition of ground water. Regression analysis indicates that specific conductance is a useful field measure for estimating dissolved solids and that nitrate has a significant influence on overall ground-water chemistry. The regression equation for specific conductance and dissolved solids produces a highly significant ($\alpha = 0.05$) and good fitting line (Fig. 20). The regression equations for nitrate and specific conductance are statistically significant ($\alpha = 0.05$), but fit the nitrate data poorly when using data from all areas (Fig. 21). Note that this equation is for samples where nitrate-nitrogen concentration was greater than or equal to 3 mg/l. This suggests that when nitrification occurs, it has a significant, but not controlling, influence on overall chemical composition of ground water.



Area	Mean NO ₃ -N (mg/l)	Median	Maximum	Number of Wells	Variance	Mean Depth (ft)
North	6.74	5.85	33	293	34.22983	62.47
South	6.81	4.80	34	148	59.56176	65.58
All	6.76	5.60	34	441	42.77779	63.76

Note: Minimum concentration is < 0.5 mg/l for all classes.

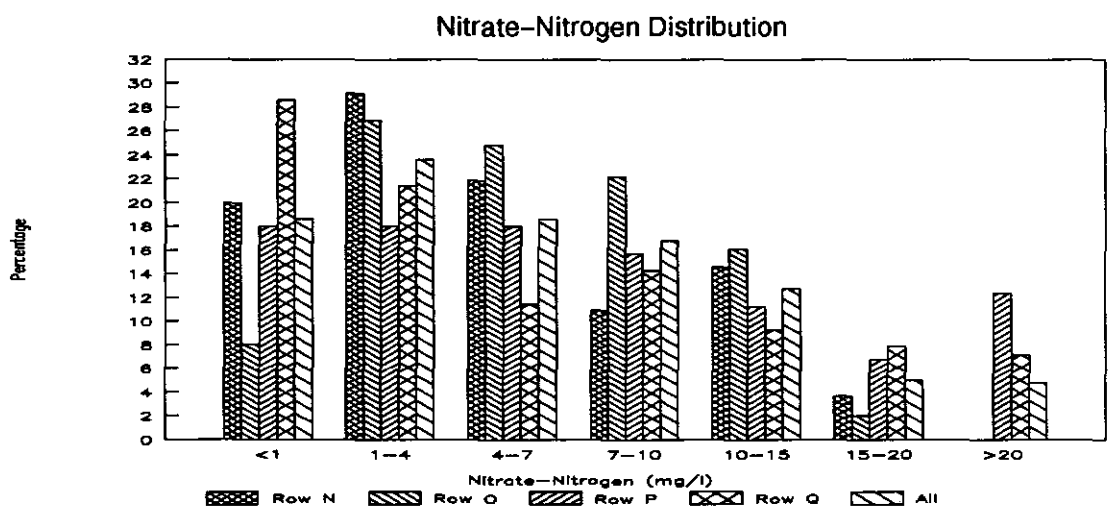
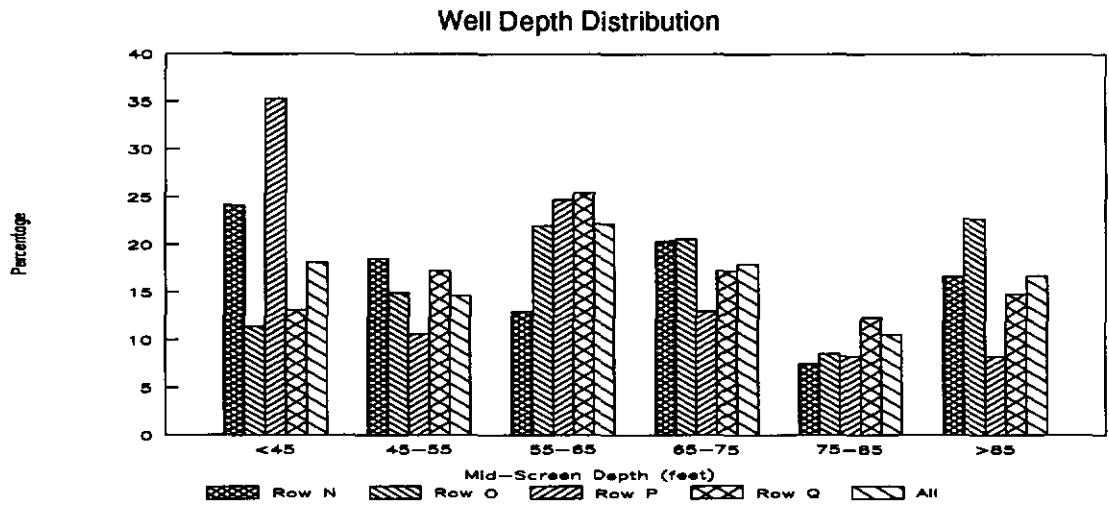
Figure 13. Frequency distributions of well depth and nitrate for areas north and south of Indian River Bay.



Column	Mean NO ₃ -N (mg/l)	Median	Maximum	Number of Wells	Variance	Mean Depth (ft)
(N,O,P) h	7.24	6.00	33	178	44.63096	57.48
(N,O,P) i	5.95	5.85	17.6	115	17.11913	70.29
Qh	6.83	6.40	27	50	40.08608	51.87
Qi	7.55	4.00	34	83	74.32922	68.76
All	6.76	5.60	34	441	42.77779	63.76

Note: Minimum concentration is < 0.5 mg/l for all classes.

Figure 14. Frequency distributions of well depth and nitrate by five-minute grid columns (Fig. 3), and between columns located north and south of Indian River Bay.

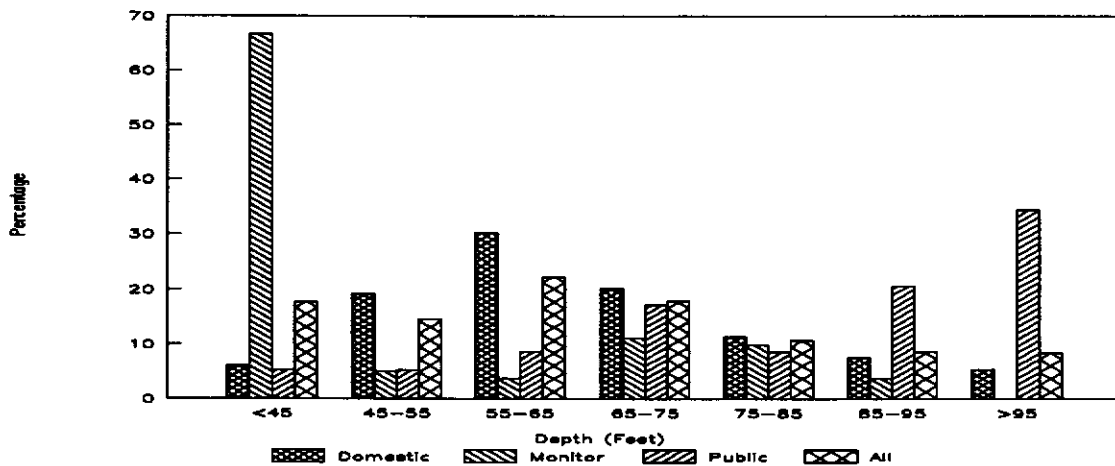


Row	Mean NO ₃ -N (mg/l)	Median	Maximum	Number of Wells	Variance	Mean Depth (ft)
N	5.29	4.20	17	55	19.69164	60.71
O	6.18	6.20	18	149	15.17503	67.78
P	8.58	6.90	33	89	69.86726	54.76
Q	7.00	4.00	34	141	61.54168	64.25
All	6.76	5.60	34	441	42.77779	63.76

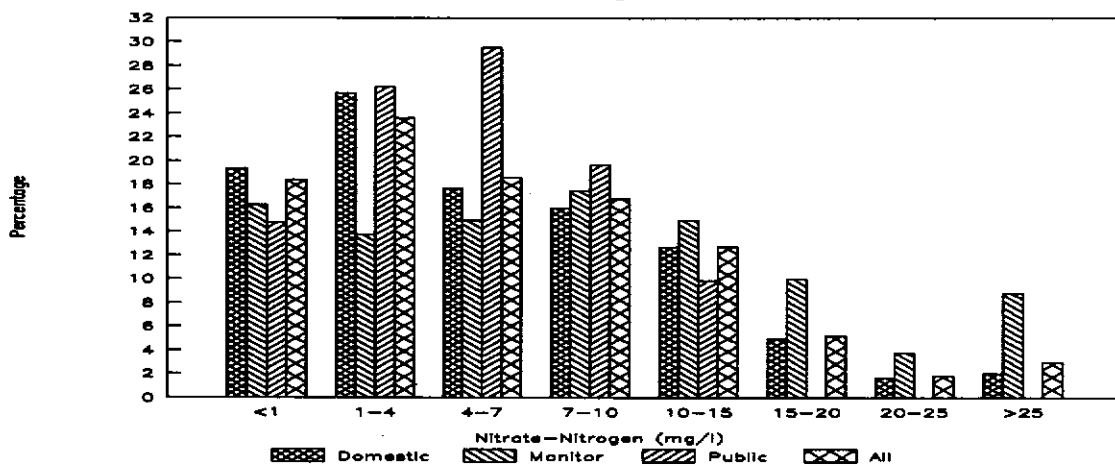
Note: Minimum concentration is < 0.5 mg/l for all classes.

Figure 15. Frequency distributions of well depth and nitrate by five-minute grid rows (Fig. 3).

Well Depth Distribution



Nitrate-Nitrogen Distribution

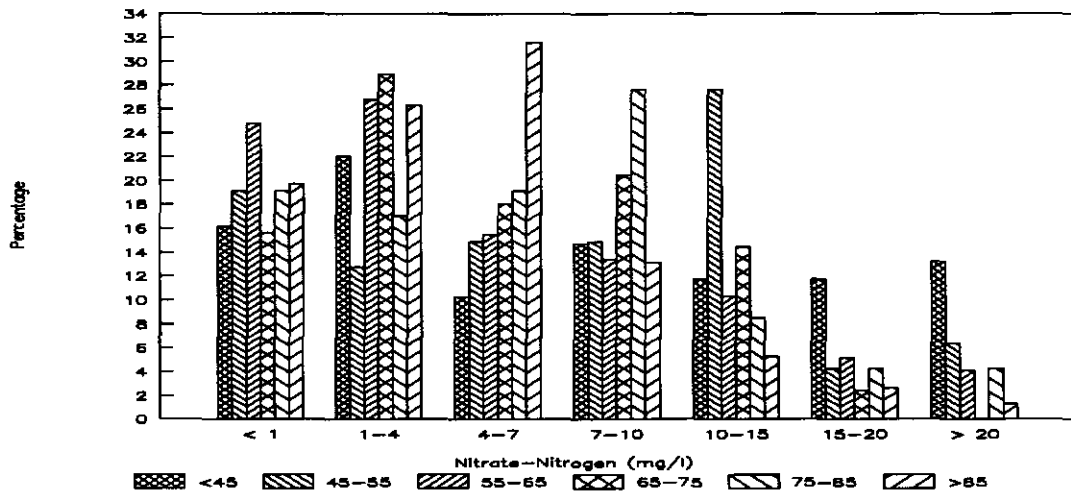


	Mean NO ₃ -N (mg/l)	Median	Maximum	Number of Wells	Variance	Mean Depth (ft)
Domestic	6.33	4.80	34	300	36.78274	66.50
Monitor	9.71	7.60	33	80	76.51734	39.74
Public	5.10	5.65	14	61	12.21882	84.40
All	6.76	5.65	34	441	42.77779	63.68

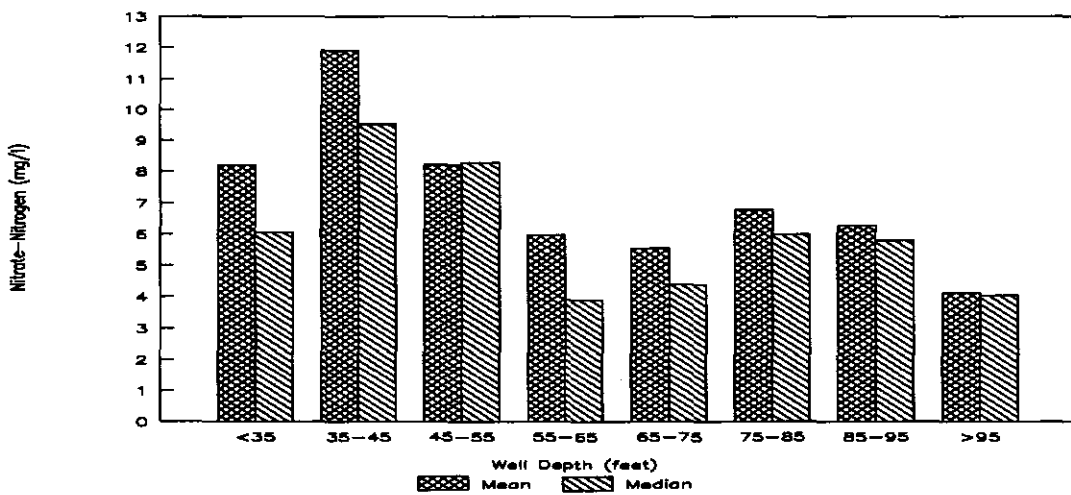
Note: Minimum concentration is < 0.5 mg/l for all classes.

Figure 16. Frequency distributions of well depth and nitrate by well type.

Nitrate-Nitrogen Classes vs. Well Depth Classes



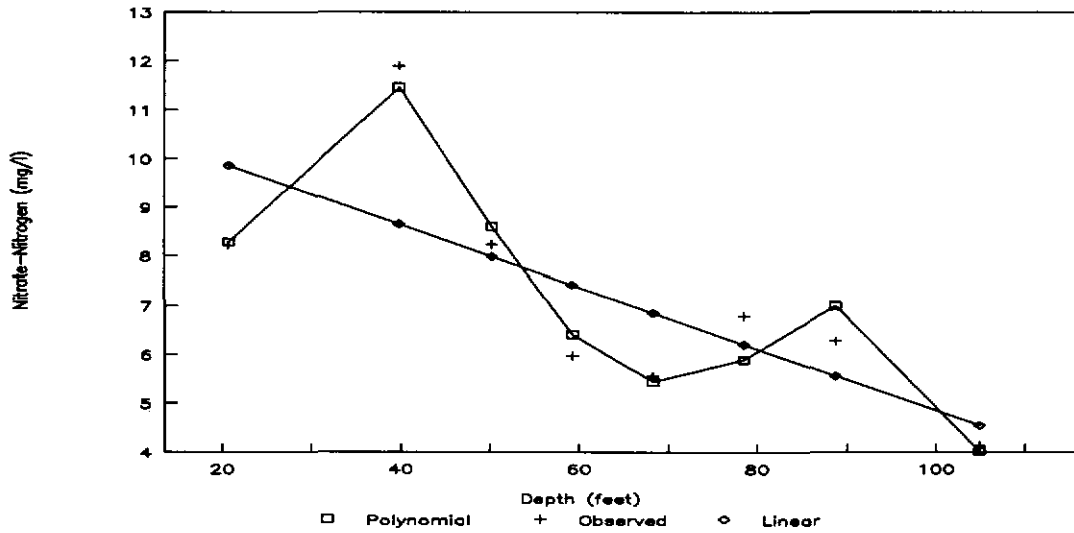
Nitrate-Nitrogen Concentration vs. Well Depth Classes



Depth Range (feet)	Mean NO ₃ -N (mg/l)	Median	Maximum	Number of Samples	Variance	Mean Depth (feet)
< 35	8.21	6.05	33	48	67.87125	20.75
35-45	11.91	9.53	33	20	108.9959	39.80
45-55	8.23	8.30	27	47	43.97144	50.24
55-65	5.98	3.90	33	97	41.53903	59.24
65-75	5.56	4.40	18	83	19.18724	68.20
75-85	6.79	6.00	34	47	43.27396	78.46
85-95	6.28	5.80	30	38	34.93427	88.71
> 95	4.13	4.05	13	38	9.792910	104.84

Figure 17. Nitrate frequency distribution by well depth.

Well Depth Classes versus Mean Nitrate-Nitrogen



Regression equation 1 (Polynomial): All data

$$y = -37.3748 + 4.052701x - 0.11316x^2 + 1.251e-3x^3 - 4.8124e-6x^4$$

r squared = 0.951971 – Significant at alpha = 0.05, but not a significant improvement over linear regression (eqn. 2).

Regression equation 2 (Linear): All data

$$y = 11.16753 - 0.06321x$$

r squared = 0.532599 – Significant at alpha = 0.05

Regression equation 3: North area data (not shown)

$$y = 10.76854 - 0.05351x$$

r squared = 0.381619 – Not significant at alpha = 0.05

Regression equation 4: South area data (not shown)

$$y = 11.97237 - 0.08366x$$

r squared = 0.612938 – Significant at alpha = 0.05

y = mean nitrate – nitrogen concentration (mg/l) per depth class

x = mean depth (feet) within depth class

Nitrate Versus Well Depth

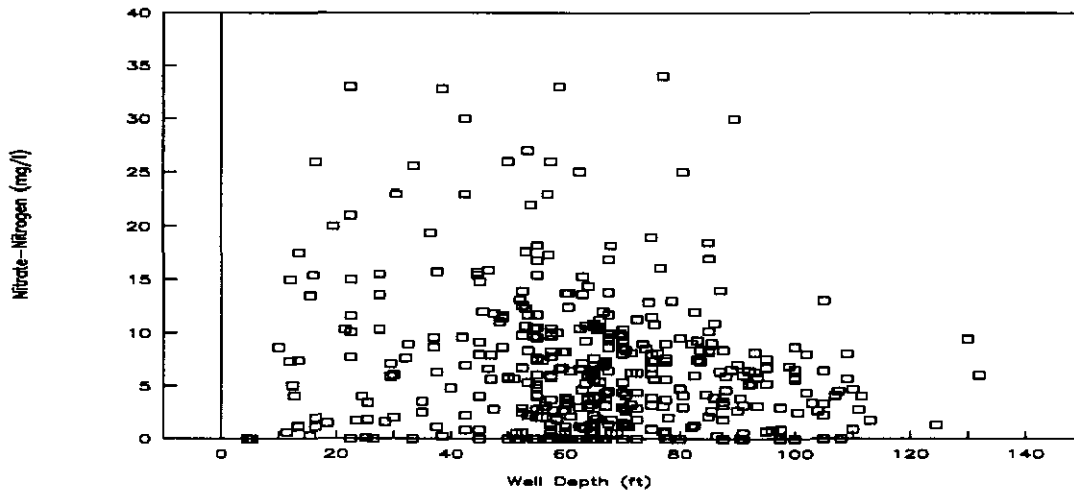


Figure 18. Relation between nitrate and well depth. The upper graph shows the results of regression analyses. The lower graph is a scatter plot of all data. Linear regression on all data is not significant at alpha = 0.05.

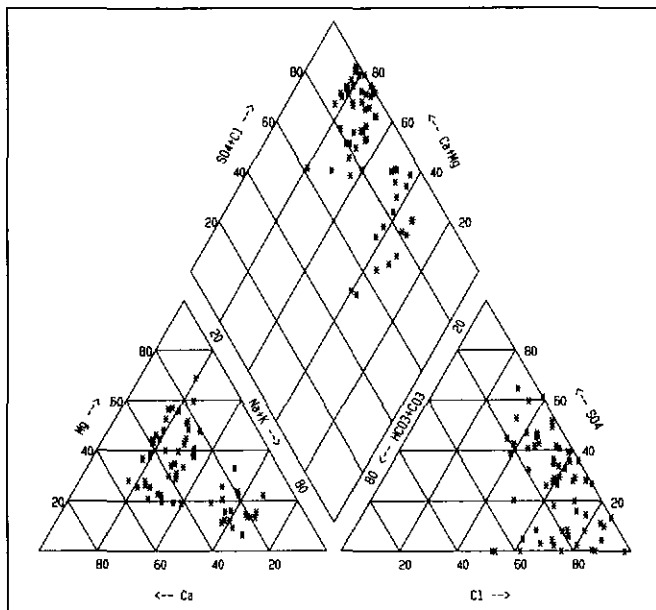


Figure 19. Comparison of major ion composition of waters with more than 2 mg/l nitrate-nitrogen.

It has long been known that both agricultural and waste disposal practices can cause nitrate contamination of ground water (Miller, 1972; Robertson, 1977; Ritter and Chirnside, 1982). Proving the source of contamination in a particular well however, may not always be possible. Agricultural practices can be identified as the source of nitrate contamination in areas where development has not been significant. It is rarely possible to find a well affected solely by septic effluent (Denver, 1989), even in developed areas, because development has occurred on former agricultural lands or immediately adjacent to agricultural lands. In addition, domestic lawn and garden maintenance practices can add nitrate to ground water (Tinker, 1991).

There appears to be a general relation between land use and nitrate contamination. The highest nitrate concentrations in wells sampled for this study (greater than 20 mg/l) were found around Route 26 (blocks Qh and Qi and row Q, Figs. 3, 14, and 15) and along Route 5 west of Route 24 (row P, Figs. 3 and 15). These areas have had intensive poultry production for at least 20 years. The occurrence of high nitrate concentrations in the Route 26 area was previously reported by Robertson (1977) and Ritter and Chirnside (1982). A few areas having significant nitrate contamination not found by Robertson (1977) are around Route 1 between Lewes and Rehoboth Beach. Land use in these areas is agricultural (cropland) or mixed agricultural and residential with on-site wastewater disposal systems.

Previous studies have suggested that nitrate concentration can be related to land use at the well (Robertson, 1977, 1979; Ritter and Chirnside, 1982, 1984; Bachman, 1984). The land use overlying a particular well, however, will not always be an accurate predictor of either the source or possibility of contamination (or a lack of contamination) because of ground-water flow patterns and chemistry. For example, in deeper portions of the aquifer where many wells obtain water, the water most likely has entered the ground hundreds to thousands of feet up-gradient of the wells, where land use might be different from that at the well head. Another com-

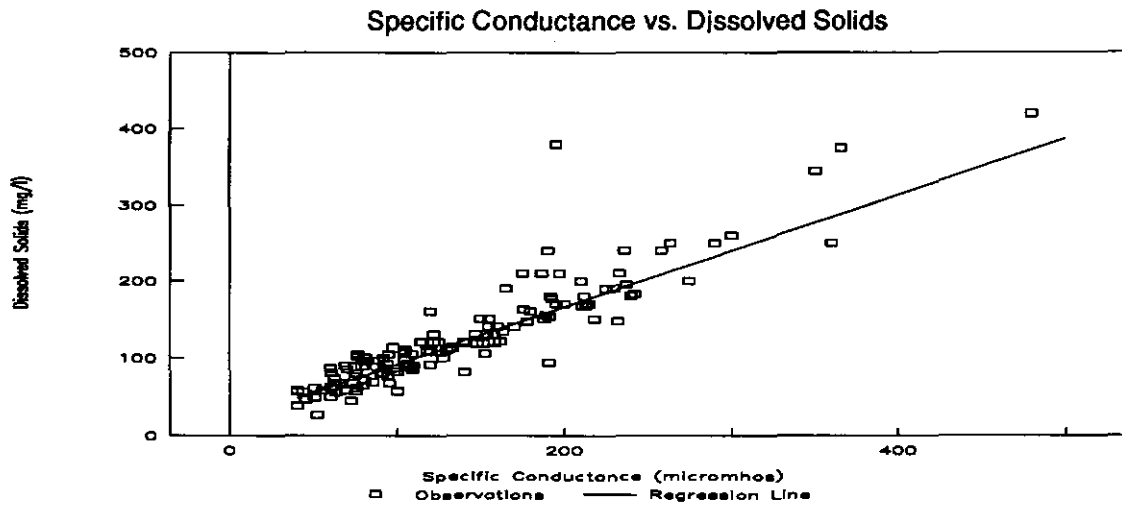
plexity is added by the slow movement of ground water; it might take ground water and nitrate ten to twenty years to move from land surface to a particular well, in which time land use may have changed. Also, geochemical processes may alter the chemical composition of the water as it moves along a flow path. Therefore, evaluations of the effects of land use on nitrate concentration in a particular water sample should consider the land-use characteristics at distances of hundreds to thousands of ft from the well head.

The interactions between geology, ground-water flow paths, and land-use practices (i.e., nitrogen input) are most evident when analyzing the distribution of nitrate with depth in the aquifer. Nitrate concentrations often vary with depth within the aquifer (Fig. 22; Andres, 1991). For example, at Oi32-01, -13, and -02, nitrate was not detectable at the water table, but the lower half of the aquifer is contaminated. In this case, water at the water table originates in a forested area, whereas waters in the lower half of the aquifer originate in cropland 3,000 to 7,000 ft away (Fig. 5). In addition, tritium concentrations in waters in the lower half of the aquifer at this site indicate that these waters are less than 20 years old. At another site, nitrate concentrations are low near the water table (Qi31-03, nitrate-nitrogen less than 5 mg/l), high in the middle third of the aquifer (Qi31-04, nitrate-nitrogen greater than 30 mg/l), and non-detectable at greater depth (Qi31-05). In this case, the wells are located approximately 500 feet from a poultry farm, so that the distribution of nitrate is either a result of past (older than 3 to 5 years) manure handling practices or of ground-water flow patterns. Water in Qi31-05 has low tritium and high iron concentrations indicating older water (greater than 35 years) of a regional flow system that has interacted with a sediment type different from that found at shallower depths.

CONCLUSIONS

The results of this investigation provide some of the data necessary to evaluate the condition of the Columbia aquifer, the primary fresh-water source of coastal Sussex County. Initial analysis of the data yields the following conclusions.

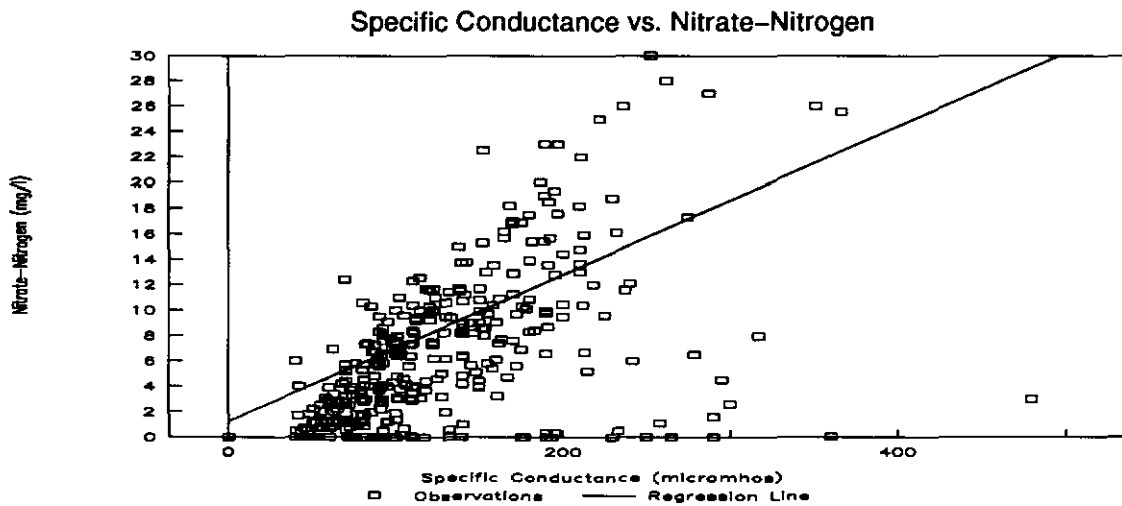
- (1) Nitrate, primarily caused by near surface agricultural and wastewater disposal practices, is a common anthropogenic contaminant in the Columbia aquifer.
- (2) Nitrate concentrations exceeding the primary maximum contaminant level for drinking water occur in nearly 23 percent of all wells sampled. These high concentrations occur over much of the area and at all depths in the Columbia aquifer.
- (3) The distribution of nitrate in ground water reflects the interaction between land use, sediment and soil type, and ground-water flow patterns. In the southern third of the study area, nitrate-nitrogen concentrations commonly are less than 0.5 mg/l because of anoxic conditions and biological activity in the soil and aquifer. Where nitrate-nitrogen concentrations exceed 0.5 mg/l, nitrate moves along ground-water flow paths that may carry the nitrate thousands of feet away from its point of origin and more than 80 ft below land surface. Under these conditions, nitrate can persist in the aquifer for decades.



Regression Equation: $y = 18.48685 + 0.736765x$
 r squared = 0.98285 – significant at $\alpha = 0.05$
 $y =$ Dissolved Solids (mg/l), $x =$ Specific Conductance (micromhos)

Note: Not all data are shown.

Figure 20. Relation between specific conductance and dissolved solids.



Regression Equation: $y = 1.213528 + 0.057973x$
 r squared = 0.389186 – Significant at $\alpha = 0.05$
 $y =$ nitrate–nitrogen (mg/l), $x =$ specific conductance (micromhos)

Figure 21. Relation between specific conductance and nitrate. Regression on data only where nitrate-nitrogen is greater than 3 mg/l.

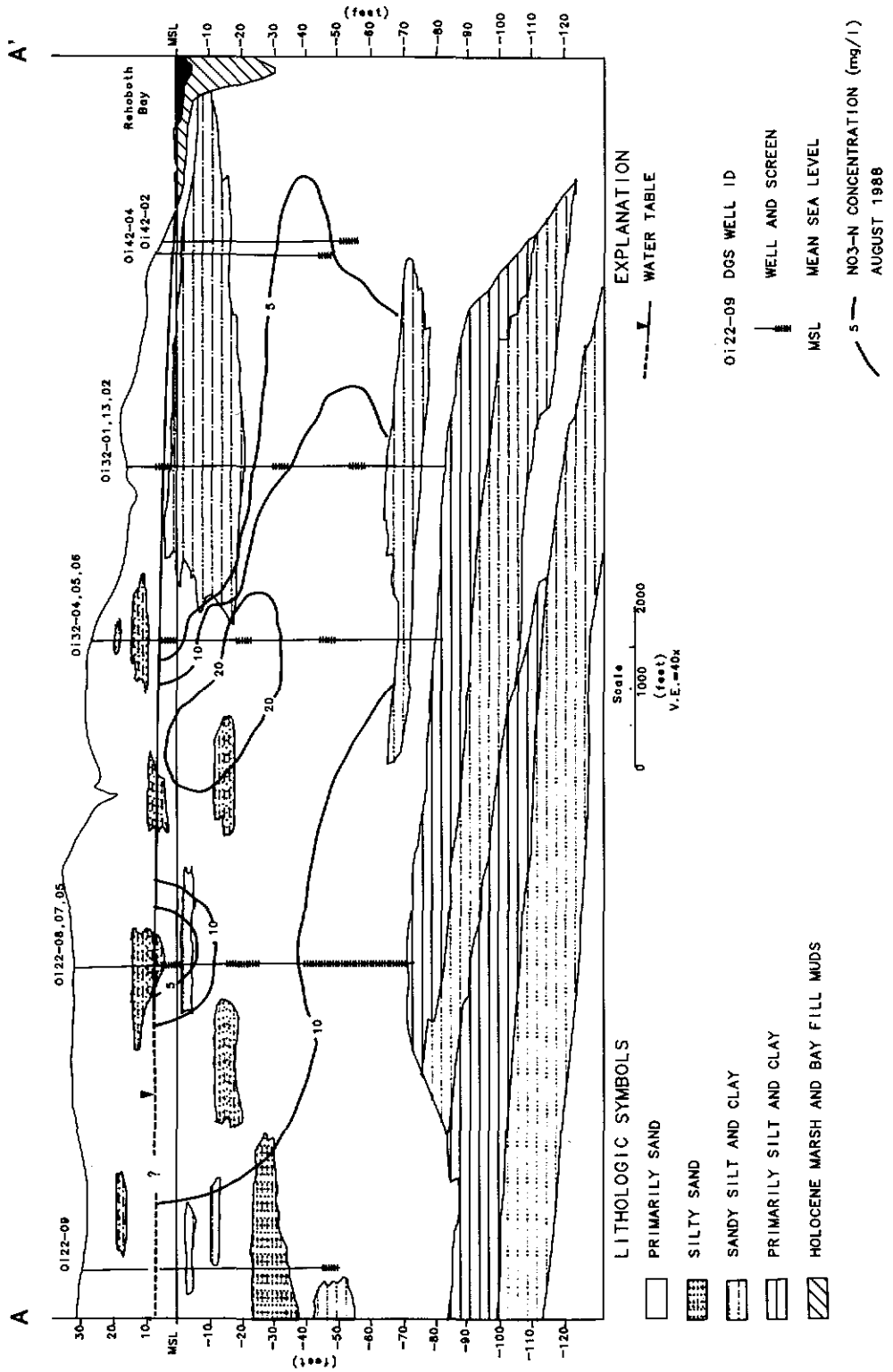


Figure 22. Nitrate distribution on August 3, 1988, cross-section A-A'.

More sophisticated statistical analyses of nitrate distribution, both in space and time, are necessary to quantify both the volume of nitrate-contaminated ground water and the land area underlain by nitrate-contaminated ground water, to analyze and predict changes in the areal distribution of nitrate contamination with time, and to develop methods to predict the nitrate content of ground water resulting from different hydrogeologic and land-use conditions. This work would be valuable for calculating the discharge of nitrate into bodies of surface water, locating and designing public water supply wells, and advising the public of potential water quality problems.

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