Hydrogeology and Water Resources of Block Island, Rhode Island

By ANNE I. VEEGER, University of Rhode Island, Kingston, Rhode Island and HERBERT E. JOHNSTON, U.S. Geological Survey, *with a section on* Geology *By* BYRON D. STONE, U.S. Geological Survey, and LESLIE A. SIRKIN, Adelphi University, Garden City, New York

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

For additional information write to:

Subdistrict Chief
Massachusetts - Rhode Island District
U.S. Geological Survey
Water Resources Division
275 Promenade Street, Suite 150
Providence, RI 02908

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To Obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
gallon (gal)	3.785	liter
million gallons (Mgal)	28,320	cubic meters
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
gallons per day (gal/d)	90.8496	liter per second
gallons per minute per foot (gal/min/ft)	0.2070	liter per second per meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
foot squared per day (ft^2/d)[1]	0.09290	meter squared per day
foot per day (ft/d)	0.3048	meter per day

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows: $°C = 5/9 \times (°F-32)$.

VERTICAL DATUM

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATED WATER-QUALITY UNITS USED IN THIS REPORT:

Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water.

One thousand micrograms per liter is equivalent to one milligram per liter.

For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

[1]Transmissivity is cubic feet per day per foot of saturated thickness ($ft^3/d/ft$) which reduces to ft^2/d.

Hydrogeology and Water Resources of Block Island, Rhode Island

By A.I. Veeger, University of Rhode Island, Kingston, Rhode Island *and* H.E. Johnston, U.S. Geological Survey *with a section on* Geology *by* B.D. Stone, U.S. Geological Survey *and* L.A. Sirkin, Adelphi University, Garden City, New York

Abstract

Increases in the summer population of Block Island, a popular vacation area located about 10 miles south of mainland Rhode Island, have caused concern about the effect of future development on its finite supply of fresh water. Ground water is present on the island as a lens of freshwater bounded below by saltwater. The lens extends more than 300 feet below sea level in inland areas, but as little as 25 feet below sea level in low-lying coastal areas.

Yields adequate for domestic use (2-5 gallons per minute) are obtainable from wells throughout the island; yields of 25 gallons per minute or more are obtainable at many locations, particularly in the southern half of the island. Some wells reportedly yield 50 to 200 gallons per minute, but long-term withdrawals at such rates from wells screened below sea level would likely cause the water to become salty.

Annual water use on Block Island during 1990 is estimated at 53 million gallons of which about 38 million gallons, or 72 percent, is used during June-August. The Block Island Water Company delivered approximately 17 million gallons of this total from its facility at Sands Pond. Current demand by water company customers averages approximately 74,000 gallons per day from May through October. However, the sustainable yield of Sands Pond during a succession of drought years was estimated at 45,000 gallons per day. The 30,000 gallons per day deficit could be met by pumping from existing water-company wells, which yield water containing high concentrations of dissolved iron, or from nearby Fresh Pond, which yields water containing little or no dissolved iron. It is estimated that withdrawal of 30,000 to 50,000 gallons per day from Fresh Pond during drought years would produce a water-level decline of less than 1 foot.

Ground-water recharge on Block Island is estimated to average 20 inches (3.8 billion gallons) per year and is derived from infiltration of precipitation. However, the amount of fresh, potable ground water available for use on the island depends on (1) the number, location, depth and pumping rate of wells, (2) the volume and areal distribution of water returned to the ground-water-flow system through septic systems, and (3) the effect of this wastewater return flow on the quality of the ground water.

Block Island consists of a thick Pleistocene moraine deposit that includes meltwater deposits, till, sediment-flow deposits and glacially transported blocks of Cretaceous strata and pre-Late Wisconsinan glacial deposits. Horizontal hydraulic conductivities of predominantly coarse-grained sand and gravel units in which wells are screened range from 3 to 2,000 feet per day. Median hydraulic conductivity is 27 feet per day and exceeds 145 feet per day at only 10 percent of wells.

The water table on the island is a subdued reflection of the land-surface topography and is commonly only 10 to 35 feet below land surface in topographically high areas. Flow generally is from the central, topographic highs to the coast. Layers

of low hydraulic-conductivity material impede vertical flow, creating steep vertical gradients. Water levels in closely spaced shallow and deep wells can differ by 100 feet or more.

Sodium and chloride, attributed to incorporation of seaspray in recharge water, are the dominant chemical constituents in the ground water. Background concentration of chloride typically is less than 30 milligrams per liter. Dissolved-iron concentrations exceeded the 0.3 milligram per liter Federal Secondary Maximum Contaminant Level at 26 of the 77 sites sampled. High-iron concentrations were found predominantly in the eastern and northern parts of the island where concentrations as high as 10 to 27 milligrams per liter were found in some water samples. Dissolved iron occurs naturally and is attributed to the dissolution of iron-bearing minerals in the presence of organic material in the aquifer.

Sampling conducted as part of this study showed no evidence of widespread ground-water contamination. Nitrate concentrations were below the Federal Maximum Contaminant Level at each of the 83 sites sampled. No evidence of dissolved organic constituents was found at the 11 sites sampled. Ground-water samples collected near the closed Block Island landfill showed no evidence of contamination from landfill leachate. Underground fuel-storage tanks, located throughout the island, constitute a major potential source of ground-water contamination.

INTRODUCTION

The Town of New Shoreham, commonly known as Block Island, is one of Rhode Island's most valued natural areas. The island, which is approximately 10 mi south of the mainland, is a popular vacation destination. In 1984, Block Island successfully petitioned the U.S. Environmental Protection Agency (USEPA) for sole-source **aquifer**[1] status. This designation recognizes an aquifer as the "sole or principal" source of drinking water for an area (U.S. Environmental Protection Agency, 1984). The Rhode Island Department of Environmental Management has given a GAA classification to all of Block Island except for a small area that encompasses a closed landfill (Rhode Island Department of Environmental Management, written commun., 1992). A GAA classification is given to ground-water resources that warrant the highest level of protection from contamination; **ground water** in this classification is suitable for public drinking-water use without treatment.

Although the permanent population of Block Island is expected to remain stable, increases in the summer population have raised concerns about the impact of future development on the island's finite freshwater supply. To address this concern, the U.S. Geological Survey (USGS), in cooperation with the Town of New Shoreham, began a 4-year study in 1988 to evaluate the **hydrogeology** and water resources of Block Island.

Purpose and Scope

This report describes the hydrogeology and water resources of Block Island. The report includes (1) a description of the hydrogeologic framework, (2) an assessment of the chemical quality of freshwater resources, (3) documentation of temporal changes in water quality, (4) delineation of the **recharge area** of public water-supply sources, (5) identification of potential sources of ground-water contamination, and (6) a discussion on the availability of ground water and **surface water**. The report is based on data collected by the USGS from March 1988 through May 1991; data from Hansen and Schiner (1964); and unpublished data from previous investigations. A data report including all water-level, water-quality, and well-log data used in this study has been published under a separate cover (Burns, 1993).

The hydrology of Block Island is best understood in the context of the geology of the island. Because this investigation resulted in a new interpretation of the geology, a detailed description of the depositional history of the island is provided in the section titled "hydrogeology," under the subsection "geology." This section will be particularly useful for those individuals wishing to understand the three-dimensional depositional framework of the island.

[1]Boldfaced terms are defined in the glossary.

Previous Investigations

The geology and water resources of Block Island have been the focus of numerous investigations. Studies of the geology of Block Island include those by Woodworth (1934), Kaye (1960), Tuttle and others (1961), and Sirkin (1976). Studies on the hydrology of the island include those by Hansen and Schiner (1964), CE Maguire, Inc. (1984), the Block Island Water Resource Study Group (Sirkin and others, 1985a; Sirkin and others, 1985b; Sirkin and others, 1986).

Well, Spring, and Test-Hole Numbering System

Each well, spring, and test hole inventoried by the USGS on Block Island was assigned an alphanumeric code consisting of the two-letter town designator (NH), a one-letter site designator (W for well and S for spring) and a local site number. The three-letter code has been omitted from the illustrations.

Acknowledgments

The authors thank the Block Island residents who provided access to their property for purposes of data collection. Special thanks are due Norman Dahl and Barbara Burak, who were instrumental in initiating this study; Henry Dupont and Robert Downie, of the Block Island Water Company, for providing information on the town water supply and for permitting access to the company's well field; Laura Thompson, for digitizing well-location and tax-plat and lot information; and the residents who volunteered to collect **precipitation** data for this study: Elizabeth Breuer, Barbara Burak, Joseph Connolly, Norman Dahl, Ralph Derby, John Hobe, Henry Lemoine, Pam Littlefield, Sue Littlefield, Doug Michel, and Joan Salzberg. Thanks to Michael Eberle and Betty Palcsak for their editorial efforts.

STUDY AREA

Block Island, located about 10 mi south of the Rhode Island coast, has an area of approximately 11 mi^2; the island is 3.5 mi wide and 7 mi long (fig. 1). Block Island is properly called the Town of New Shoreham and lies wholly within Washington County, R.I. The island is characterized by high sea cliffs and rocky beaches along its southern and northeastern shores and by a low-lying sandy coastline along the northwestern and eastern coasts. Great Salt Pond separates the southern half of the island, where the average land-surface elevation is 100 ft above sea level, from the northern half of the island, where the average land-surface elevation is less than 50 ft above sea level.

Climate

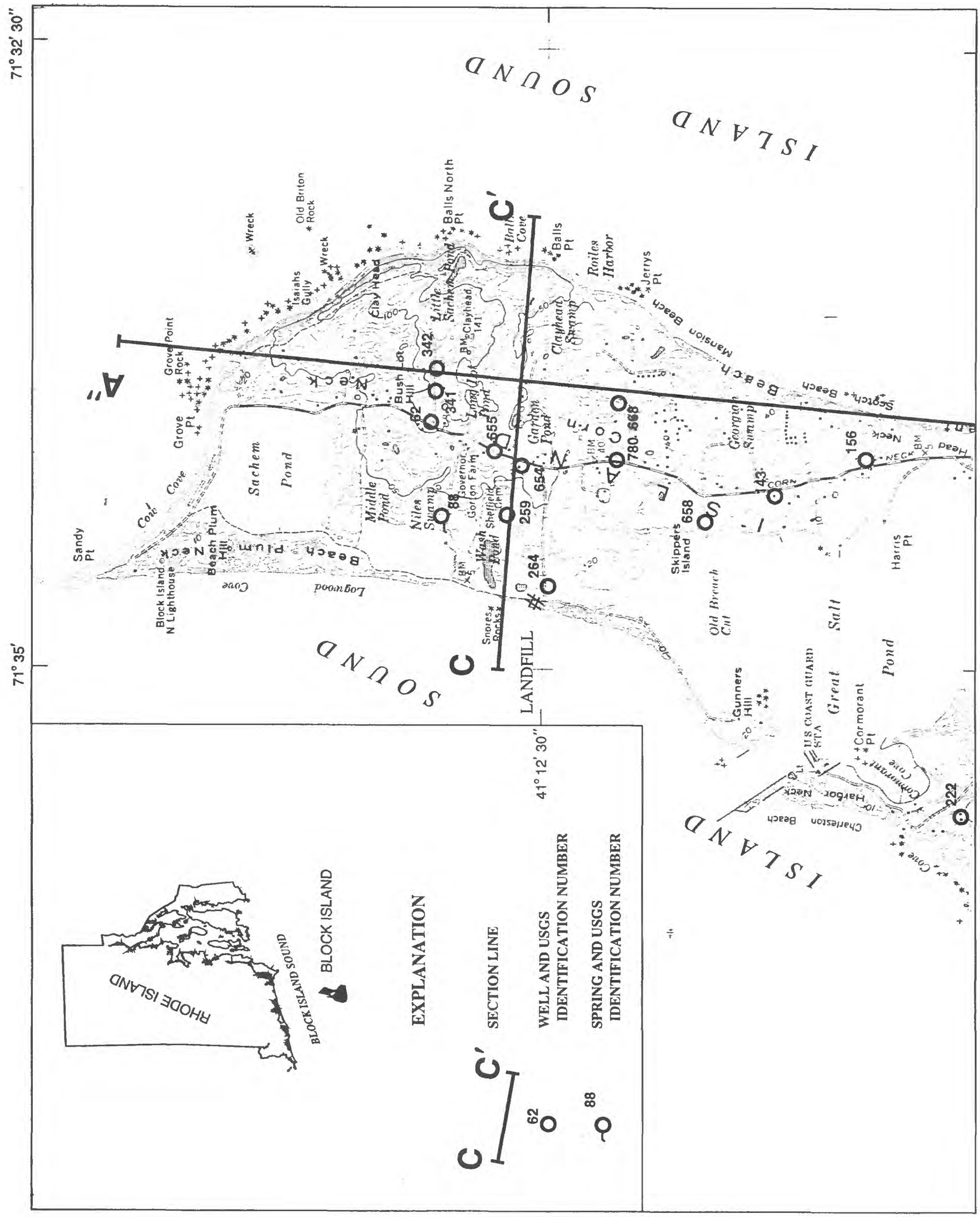
The climate of Block Island is moderated by the effects of Block Island Sound and the Atlantic Ocean. Average monthly temperatures range from a low of 31°F in February to a high of 70°F in July. Long term average annual precipitation on Block Island, as measured at the National Oceanic and Atmospheric Administration (NOAA) weather station at the airport from 1890 through 1988, was 40.2 in. Precipitation generally is evenly distributed throughout the year. In June, the driest month, the island receives an average of 2.28 in., whereas in December, the wettest month, the island receives an average of 4.34 in.

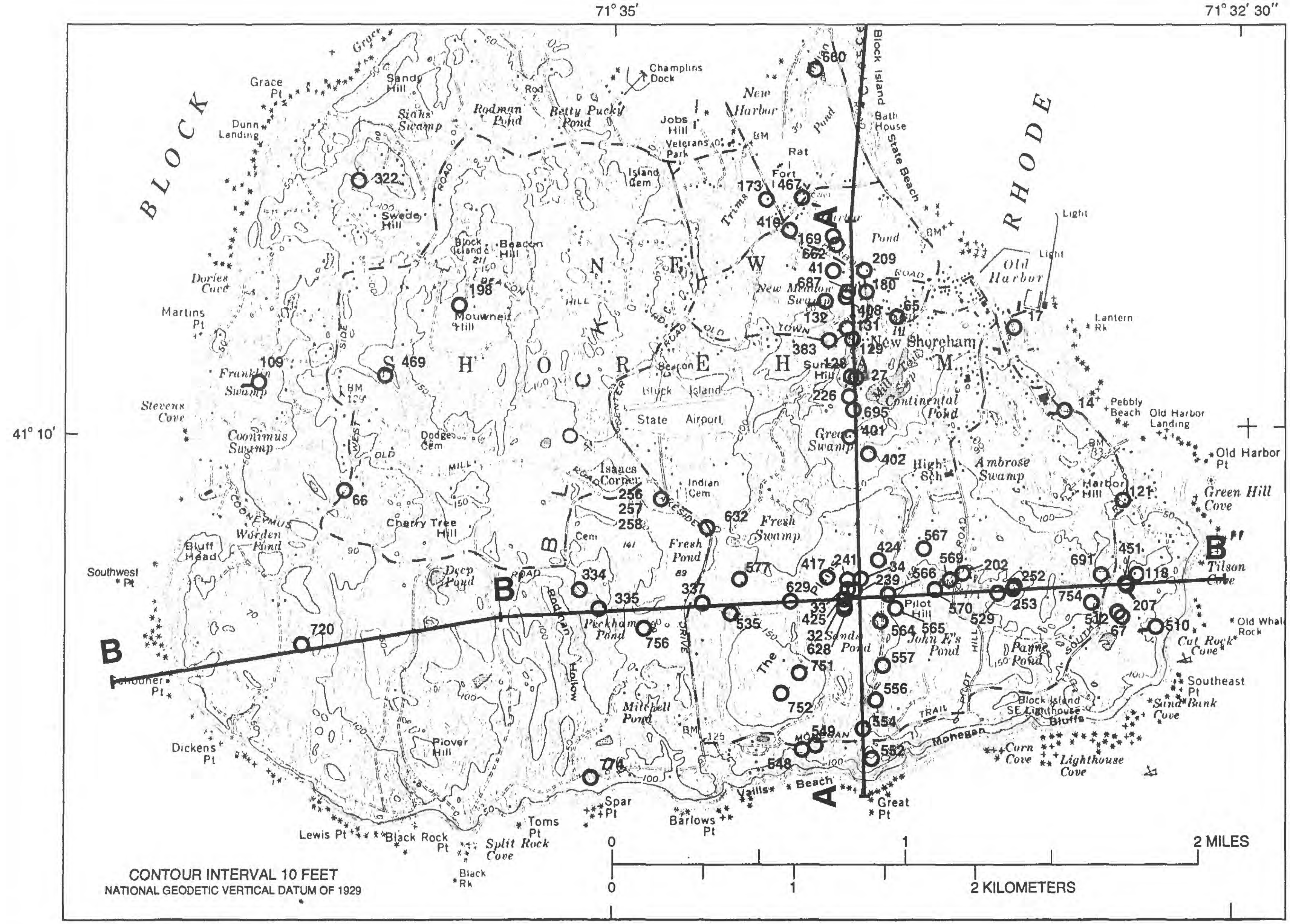
Annual precipitation[2] for 1890-1988 is shown in figure 2. A prolonged period of below-average precipitation persisted from 1906 to 1952; however, the average annual precipitation of 42.7 in. for 1951-80, the period used by NOAA during the course of this study to determine climatic norms, is greater than the long-term average.

The cumulative frequency distribution for precipitation on Block Island is shown in figure 3. Exceedance probability, shown on the x-axis, is the likelihood that a given amount of precipitation will be equaled or exceeded in any single year. In 1988, for example, Block Island received 37.13 in. of precipitation, corresponding to a 65 percent exceedance probability. Therefore, in 65 of every 100 years, annual precipitation can be expected to equal or exceed 37.13 in. In 1980 and in 1985, only about 30 in. of precipitation was recorded, corresponding to an exceedance greater than 95 percent. That is, in more than 95 of every 100 years, rainfall will be greater than 30 in.

The **median** annual precipitation has an exceedance probability of 50 percent; on Block Island this corresponds to a yearly total of 38.9 in. This median, which is not affected by extreme values, is lower than the long-term average of 40.2 in. and the NOAA norm of 42.7 in., indicating that disproportionately large annual totals, such as those in 1962, are inflating the average. The median, therefore, is the more accurate estimate of the expected annual precipitation on Block Island.

[2] 1989 and 1990 were not included in the period of record because incomplete records were collected by NOAA during those years.


71° 32' 30"
71° 35'
41° 12' 30"
ISLAND SOUND
ISLAND SOUND
A''
C
C'
LANDFILL
Sachem Pond
Great Salt Pond
Middle Pond
Little Sachem Pond
Clay Head
Clayhead Swamp
Mansion Beach
Scotch Beach
Balls Pt
Balls North Pt
Jerrys Pt
Rodes Harbor
Grove Pt
Grove Point Rock
Sandy Pt
Block Island N Lighthouse
Beach Plum Hill
Beach Plum Neck
Cow Cove
Logwood Cove
Snores Rocks
Niles Swamp
Governor Gorton Farm
Sheffield Farm
Bush Hill
Garden Pond
Georgian Swamp
Skippers Island
Harris Pt
Old Breach Cut
Gunners Hill
US COAST GUARD STA
Cormorant Pt
Cormorant Cove
Harbor Neck
Charleston Beach
Isaiahs Gully
Old Briton Rock
Wreck
62
88
156
222
259
264
341
342
654
655
658
780
668
143
EXPLANATION
SECTION LINE
WELL AND USGS IDENTIFICATION NUMBER
SPRING AND USGS IDENTIFICATION NUMBER
RHODE ISLAND
BLOCK ISLAND SOUND
BLOCK ISLAND



BASE FROM U.S. GEOLOGICAL SURVEY
BLOCK ISLAND, 1957
PHOTOREVISED 1970
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Figure 1. Topography of Block Island, Rhode Island, and locations of wells and sections.

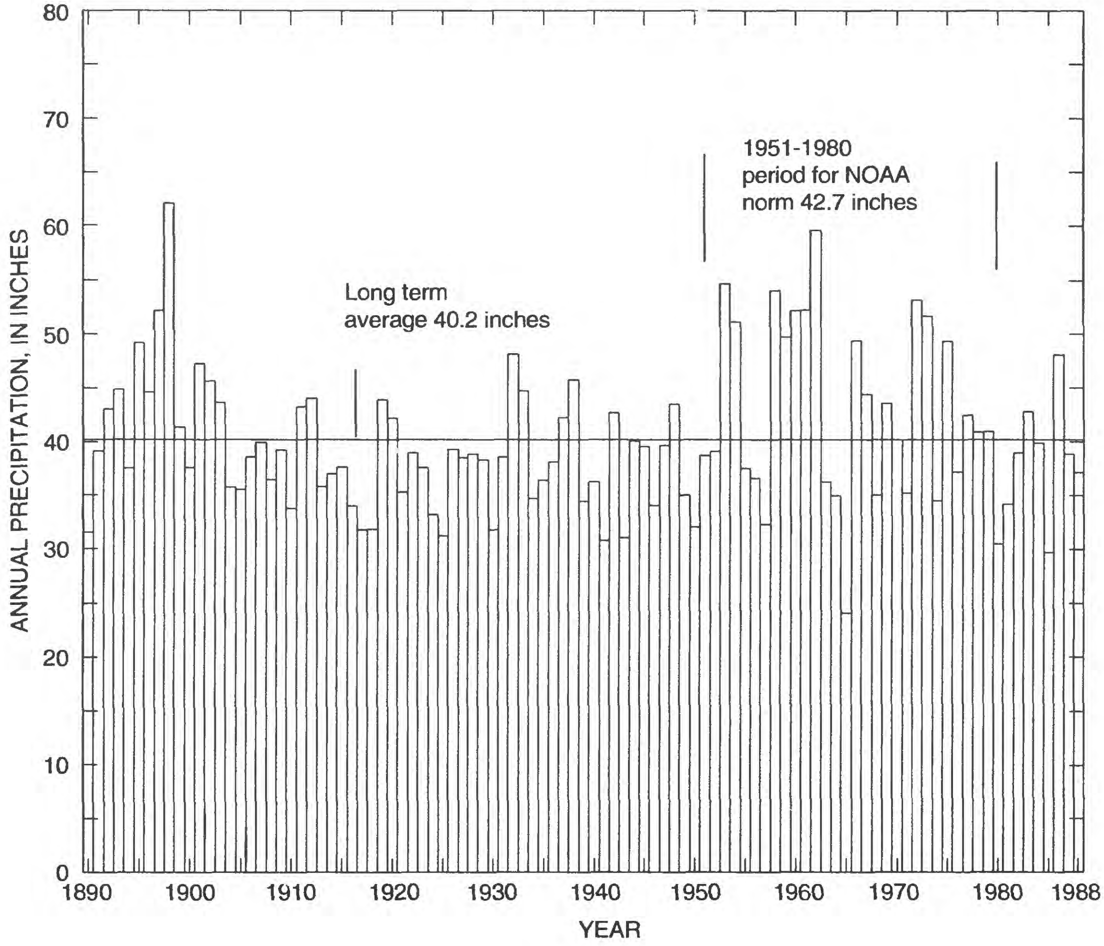


Figure 2. Annual precipitation on Block Island, 1890-1988 (National Oceanic Atmospheric Administration weather station).

Topography and Drainage

Block Island consists of two highlands joined by a sandy lowland (fig. 1). The southern highlands have an area of about 5 mi^2 and are characterized by flat to gently rolling topography in the east that grades to hummocky, high-relief topography in the west. The summit of Beacon Hill, the highest point in the southern highlands and on the island as a whole, is at an elevation of 211 ft above sea level. Numerous closed depressions are scattered among the upland flats and knolls. The depressions are circular to elongate, and their bases are commonly 10 to 30 ft below the surrounding land surface. Many of the closed depressions contain ponds, open-water wetlands, or deep marshes or swamps; however, streams are conspicuously absent throughout most of the island. Sea cliffs dominate the southern shoreline, rising from 50 ft above sea level at Southwest Point to a maximum of 150 ft at Mohegan Bluffs. Great Salt Pond and the central sandy lowland bound the highlands to the north.

The sandy lowland area is slightly more than 3 mi^2 and reaches a maximum elevation of 40 ft above sea level. Local relief is negligible, except in areas of sand dunes. A manmade breach of the lowland along the west shore of Great Salt Pond forms a navigable channel into the harbor. Brackish ponds and marshes are common and are susceptible to flooding during storms.

The northern highlands have an area of about 1 mi^2 in the northeasternmost part of the island. The land surface rises gradually to the northeast, reaching 100 ft above sea level at the eastern sea cliffs. Small ponds occupy local depressions, but streams are virtually absent. Clayhead, the highest point in the northern highlands, has an elevation of 141 ft. Sandy Point, an active sand spit, extends northward into Block Island Sound.

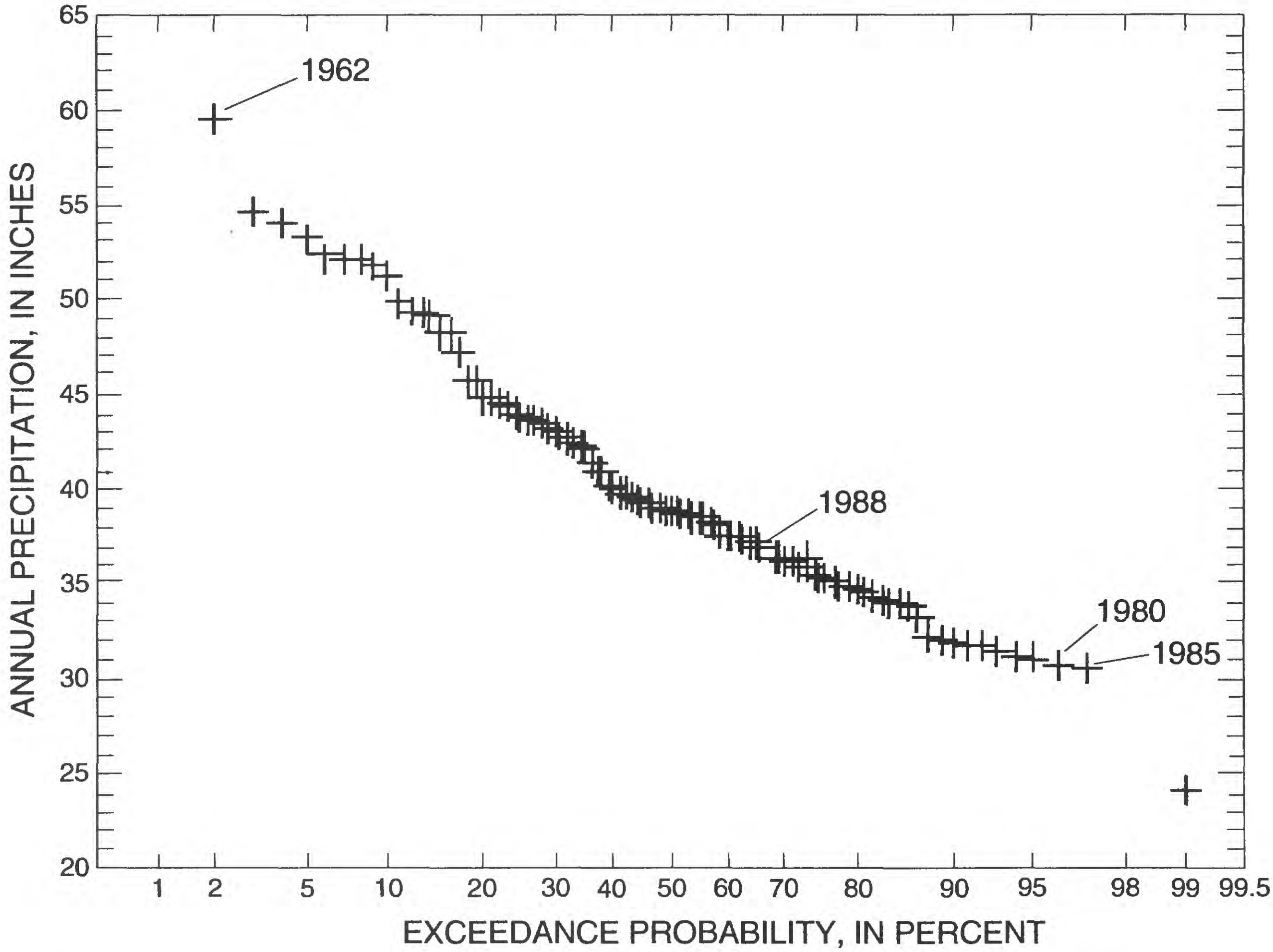


Figure 3. Frequency distribution for precipitation on Block Island, 1890-1988. (Data points for years mentioned in the text are labeled.)

The water levels in many ponds, open-water wetlands, marshes, and swamps on Block Island decline during the summer. Although perennial streams are absent in most of the island, springs are found near the base of some cliffs and in low areas around the base of hills in the southern part of the island. Seeps in cliffs are most common above fine-grained sediments.

Land Use and Population

Before the early 1900's, Block Island was a self-sustaining fishing and agricultural settlement with a permanent population of about 1,300. In the past 70 years, however, the island economy has become increasingly dependent on seasonal tourism. Residential development is now the dominant land use on the island, and commercial development is restricted to a corridor between Old Harbor, New Harbor, and the airport. This shift was accompanied by a dramatic decline in the year-round population of the island which reached a low of about 490 persons in 1960, and an increase in the summer population which averages 6,000 persons, but may reach 12,000 on peak holiday weekends. Since 1970, however, the year-round population has increased steadily, reaching 620 in 1980 and 836 in 1990—a 58 percent increase in 20 years (U.S. Census, 1972, 1982, 1992). Despite this recent trend, a population growth rate of less than 1 percent has been projected through the year 2020 (Rhode Island Department of Administration, Division of Planning, 1990).

Water Use

Approximately 93 percent of Block Island's residences depend on private wells or springs for their water supply. The remaining users, residential, commercial and municipal, are concentrated in the Old Harbor area and are supplied by the Block Island Water Company (BIWC) (Henry Dupont, Block Island Water Company, oral commun., 1990). The water company has a well field and treatment plant at the north end of Sands Pond and uses the pond as its primary water source. During periods of peak demand, **discharge** from well NHW 425 is pumped into the pond to augment supply.

In 1990, the water company delivered a total of 17.4 Mgal to 154 users (61 commercial, 86 residential, and 7 municipal). More than 55 percent of this total was produced during the height of the tourist season, June-August, to satisfy an average daily demand of 107,000 gal and a peak daily demand estimated at 150,000 gal (Henry Dupont, Block Island Water Company, written commun., 1991). Residential water use averaged 266 gal/d per household served by the BIWC during June-August. Total commercial water use during the same period averaged 77,000 gal/d.

Average daily water use for the entire island (BIWC customers and self-supplied), based on these figures and an estimated 1,250 households (Block Island Planning Board, oral commun., 1991), is 410,000 gal/d during the summer months, with self-supplied residences accounting for approximately 75 percent of the total water use (fig. 4). The resulting per capita water use, based on an average summer population of 6,000 persons (James Collins, Block Island Planning Board, written commun., 1991), is 68 gal/d, which is slightly less than the State per capita average of 70 gal/d (Johnston and Baer, 1987).

Annual water use on Block Island is estimated at 53 Mgal; this was calculated on the basis of an off-season (September-May) population of 836 (U.S. Census, 1992), a summer population of 6,000, and a per capita water use of 68 gal/d. Approximately 60 percent of this total, or 31.8 Mgal, is treated at the Block Island Wastewater Treatment Facility and released into the ocean (Mark Johnson, Block Island Wastewater Treatment Facility, written commun., 1991). Of the remaining 40 percent, or 21.2 Mgal, a small fraction, estimated at 2-3 Mgal on the basis of studies on Long Island and Cape Cod (J.P. Masterson, U.S. Geological Survey, written commun., 1993), is lost to consumptive use and the balance (18-19 Mgal) is returned to the ground-water system through leaching from septic tanks.

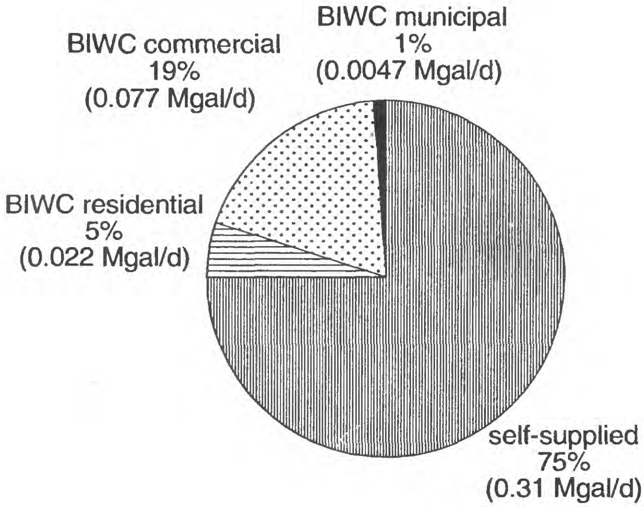


Figure 4. Water use on Block Island during June-August, 1990. (BIWC, Block Island Water Company. Mgal/d, million gallons per day.)

HYDROGEOLOGY

All freshwater on Block Island is derived from precipitation. About half of this supply is eventually returned to the atmosphere by **evapotranspiration** (the combined processes of evaporation and transpiration). The remainder is returned to the ocean through the surface-water and ground-water systems. The surface-water system includes the streams, ponds, swamps, and other bodies of open water in which water is stored or flows on the land surface. The ground-water system includes the network of **intergranular** openings below land surface in which water is stored and through which infiltrating precipitation flows from points of entry to points of discharge. The surface- and ground-water systems of Block Island are best understood within the context of the geology of the island.

Geology

By Byron D. Stone and Leslie A. Sirkin

Block Island preserves unique **interlobate moraine** deposits, which contain gravel, sand, and interbedded fine-grained units and which differ from other glacial deposits in the coastal moraine zone of the region. For example, moraines on Long Island (Sirkin, 1982), Nantucket Island, Martha's Vineyard, and Cape Cod (Oldale, 1982) contain complex, glacially deformed sediments which locally overlie gravel and sand deposits at the heads of large promorainal outwash plains. Early studies of Block Island recognized its glacial origin (Dana, 1875) and interlobate position (Upham, 1899, Woodworth, 1934). Woodworth and subsequent workers (Hansen and Schiner, 1964, Schafer and Hartshorn, 1965, Sirkin, 1976) concluded that sandy **till** of the last glaciation forms a surface unit over deposits from older glaciations. An alternative interpretation of the deposits exposed in the southern cliffs was suggested by Kaye (1960). He described thick sequences of layered, poorly sorted sediments that he termed "**stratified tills**," which are not compact till deposited directly by ice but products of mudflows that flowed off the edge of the ice sheet and accumulated in stream and pond deposits. Sirkin (1981, 1982) related these and other surficial deposits and associated ice-margin positions to late Wisconsinan glaciation.

The following overview of the stratigraphy and origin of the moraine is a general discussion that is necessary for understanding the hydrogeology of the island. Subsequent sections provide additional results of the present study, which support the newly interpreted stratigraphy and mode of deposition of the morainal deposits, consistent with previous work of Kaye (1960) and Sirkin (1982).

Overview of the Stratigraphy and Origin of the Moraine on Block Island

Block Island is underlain by thick, sandy moraine deposits that rise more than 300 ft above the surrounding ocean floor. The surficial deposits derive from the last (late Wisconsin) glaciation, but older glacial sediments and glacially transported sediments of Cretaceous age are present in the lower part of the moraine. The moraine was deposited over a high area of Cretaceous strata in an interlobate zone 3 to 5 mi north of the late Wisconsinan **terminal moraine** (fig. 5). Glacially deepened valleys, incised more than 300 ft in the Cretaceous sediments on both sides of the island, extend to lowland basins northeast and northwest of the island. Lobes of the Late Wisconsinan Laurentide ice sheet that filled these basins were the Narragansett Bay-Buzzards Bay lobe (Schafer and Hartshorn, 1965) on the east, and a lobe of ice related to the eastern edge of the Hudson-Champlain lobe (Stone and Borns, 1986) on the west.

The moraine consists of upper and lower zones. Materials in the lower moraine zone, generally below sea level, include discontinuous large blocks of glacially deformed and upwardly displaced Cretaceous strata, Pleistocene **stratified** sediments (both exposed above sea level at Balls Point), and compact till. The upper moraine zone contains sorted and stratified glacial meltwater deposits, nonsorted **sediment-flow deposits**, and till. **Granite** boulders transported from the mainland and offshore areas by the ice sheets are scattered in the upper moraine. The stratified meltwater sediments in the upper moraine zone were laid down in ice channels and ponds in a wide zone of stagnant and melting ice in front of the retreating ice sheet. **Kettle** depressions, some of which contain surface water in the present landscape, show the locations and size of large ice blocks. In cliff exposures, the relative ages of overlapping, shingle-stacked meltwater deposits and sediment-flow deposits indicate systematic recession of the ice margins to the northeast and northwest from the interlobate zone.

Sediments in the high Beacon Hill area of the southern part of the island are the oldest meltwater deposits. As the ice margins retreated, ponds formed where exposed blocks of ice melted rapidly. Meltwater flowing into in these ponds deposited silt, clay, and fine sand laminated sediments. Present outcrops and well logs reveal that these fine-grained sediments commonly are as much as 30 ft thick and may extend a few hundred feet laterally; multiple deposits place similar fine-grained deposits side by side over distances of many hundreds of feet. Following deposition and slump deformation of the fine-grained deposits, sandy foreset

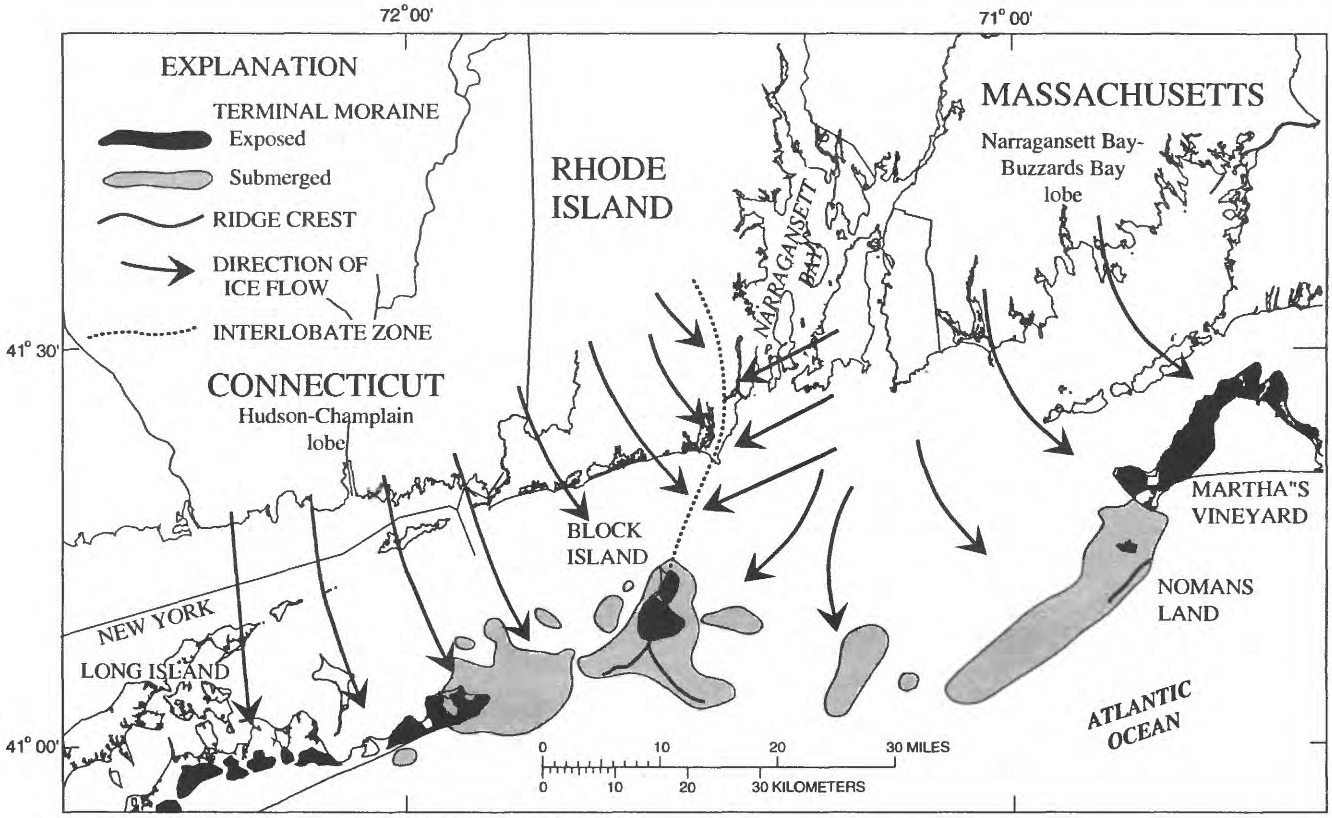


Figure 5. Location of Block Island in relation to the terminal moraine of late Wisconsin glaciation of southeastern New England. (Modified from Schafer, 1961; Kaye, 1964; Schafer and Hartshorn, 1965; Sirkin, 1982; Stone and Borns, 1986.)

strata prograded into the ponds. As divides around ponds lowered by **downwasting** of underlying ice, the ponds drained and muddy sediment-flow deposits, derived from adjacent slopes, filled the basins.

Further retreat of the ice margins on either side of Beacon Hill impounded a series of ice-dammed ponds. East of Beacon Hill, deltaic sand and gravel deposits prograded into lakes at present altitudes of about 120 to 80 ft. West of Beacon Hill, deltaic deposits accumulated in a series of long, narrow lakes at present altitudes of about 120 to 70 ft. Glacial-lake silt and clay sediments accumulated in an ice-dammed lake in the Indian Head Neck area. Recession of the ice margins to the Corn Neck area produced thin surficial sediment-flow deposits and minor stream deposits. Deltaic beds at Balls Point North accumulated in an ice-marginal lake dammed by the older materials to the south. Postglacial erosion associated with rising sea level has eroded the southern coastline more than 3 mi back to the north.

Regional Geologic Setting

Block Island is 3 to 5 mi north of the Late Wisconsinan terminal moraine (fig. 5), which, on adjacent islands, is characterized by transverse ridges and hummocky areas with few kettles, underlain by compact till, poorly sorted silty sand, and some stratified sediments (Woodworth, 1934; Schafer and Hartshorn, 1965; Oldale, 1982; Sirkin, 1982). In offshore areas, the terminal moraine forms knobs, linear ridges, and aligned areas of coarse, bouldery bottom sediments on the sea floor (Schafer, 1961). The terminal moraine forms an interlobate reentrant south of Block Island. It extends southwesterly from the reentrant toward areas south of Montauk Point (Sirkin, 1982; Needell and Lewis, 1984; Stone and Borns, 1986). It extends southeasterly as a boulder-covered platform (McMaster and Garrison, 1966), thence east and northeasterly to Nomans Land and Martha's Vineyard.

Stratigraphy

The surficial deposits of Block Island consist of morainal sediments in an upper and lower moraine zone. Sediments of the upper moraine zone are chiefly stratified deposits in glacial ice-contact landforms. The sediments also include stratified but poorly sorted, sandy, sediment-flow deposits. The lower morainal zone consists of discontinuous blocks of Cretaceous sediments, older Pleistocene sediments, and till. The lower moraine zone overlies **unconsolidated** Cretaceous sediments, which overlie **bedrock**.

Subsurface Materials

The stratigraphy of subsurface materials (fig. 6) is inferred from well records, seismic stratigraphy, and correlation with the Cretaceous section of Long Island (Sirkin, 1986; Smolensky and others, 1989). **Contacts** bounding the moraine zones are based on structure-contour maps of the top of the Cretaceous unconsolidated zone, the top of blocks of Cretaceous sediments in the lower moraine zone, and the top of the lower moraine zone, which was identified by reported **hardpan** or other disconformable materials beneath the upper moraine zone.

Bedrock

Seismic-refraction studies at Corn Neck detected the bedrock surface 1,140 ft below sea level (Tuttle and others, 1961). The bedrock seismic velocity of 19,700 ft/s indicates that the rock is dense, nonweathered igneous or metamorphic rock. Based on the regional slope of the bedrock surface (Smolensky and others, 1989), the rock surface beneath the island is inferred to dip south-southeasterly from an altitude of about -1,120 ft at the north to about -1,440 ft at the south (fig. 6). No well has penetrated bedrock on Block Island.

Cretaceous Sediments

Cretaceous sediments that **unconformably** overlie bedrock comprise a lower semiconsolidated zone and an upper unconsolidated zone (fig. 6). The semiconsolidated zone is 700 to 800 ft thick and is inferred to consist of partially cemented sandstone and conglomerate, and compact (consolidated) clay and silt, based on a seismic velocity of 12,200 ft/s (Tuttle and others, 1961; Needell and Lewis, 1984; Beres, 1991). A continuous reflector marks the top of the semiconsolidated zone in seismic-reflection profiles (Beres, 1991), and its projected position is close to the depth of change of velocity (fig. 6). Pollen from some exposed, glacially transported lignitic clays (Christopher, 1967) is of Late Cretaceous (Turonian) age (Sirkin, 1986). The clays are inferred to have been derived from the lower semiconsolidated zone, which is correlated presently with the upper part of the Raritan Formation of Long Island (Sirkin, 1986). Cretaceous sediments in the upper unconsolidated zone have a seismic velocity of 6,460 ft/s (Tuttle and others, 1961). The zone is 180 to 500 ft thick and has indistinct subhorizontal seismic reflectors (Beres, 1991). Sediments are inferred to be noncompact quartzose sand, clayey in part, containing lignite, pyrite, and iron encrusted **concretions**, similar to the Late Cretaceous Magothy Formation of Long Island with which they are correlated (Sirkin, 1986). In adjacent offshore areas, the top of the Cretaceous sequence is expressed as a weak, laterally discontinuous reflector at altitudes of -100 to -160 ft (Brown and others, 1961; Needell and Lewis, 1984; Beres, 1991). Beneath the island, the altitude of the top of the Cretaceous sediments increases from about -230 ft in the north to -160 ft (fig. 6) at the south. The Cretaceous section is incised by deep, glacially eroded valleys that extend to altitudes below -500 ft on either side of Block Island. Seismic-reflection profiles around the island and in Great Salt Pond (Beres, 1991) indicate that no deep valleys in Cretaceous strata extend beneath the island.

On Block Island, numerous wells have penetrated Cretaceous sediments that are present as discrete blocks within morainal materials in the lower moraine zone (fig. 7). Cretaceous sediments are identified in well drillers' records as "white sand," "red clay," "kaolinite," "quartz sand and gravel," "sand, gray quartz," and "clay, white-gray" (see Burns, 1993, for logs of wells NHW 62, NHW 341, NHW 342, NHW 425, NHW 451, NHW 654, and NHW 655). Such sand units reportedly are 4 to 43 ft thick; clay units are 20 to 70 ft thick. The altitudes of the tops of these blocks commonly are -50 to -100 ft, but wells have penetrated Cretaceous sediments above sea level beneath Bush Lot Hill, north of Cherry Tree Hill, beneath the Airport, north of Sands Pond, and west of Tillson Cove (fig. 1). Only one well on the island is inferred to have penetrated in-place Cretaceous sediments. Well NHW 754 (fig. 6) extends to an altitude of -235 ft, which is 85 ft below the projected top of the Cretaceous section. Well NHW 62 penetrated 170 ft of red and white clay, but the well is interpreted to have ended in gravelly materials in the lower moraine zone.

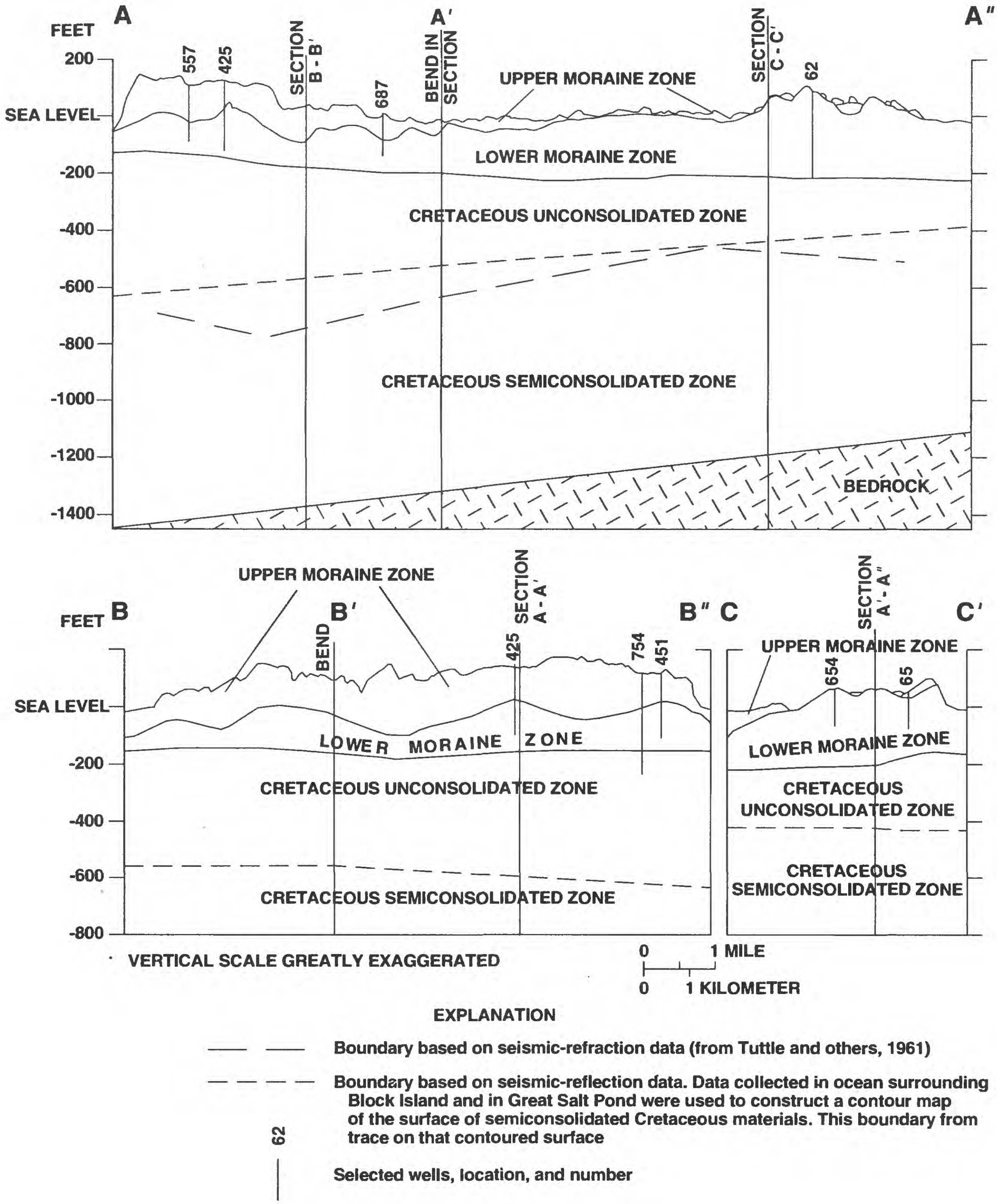


Figure 6. Generalized geologic sections showing principal lithologic and seismic units beneath Block Island. (Modified from Tuttle and others, 1961. Locations of sections shown in figure 8.)

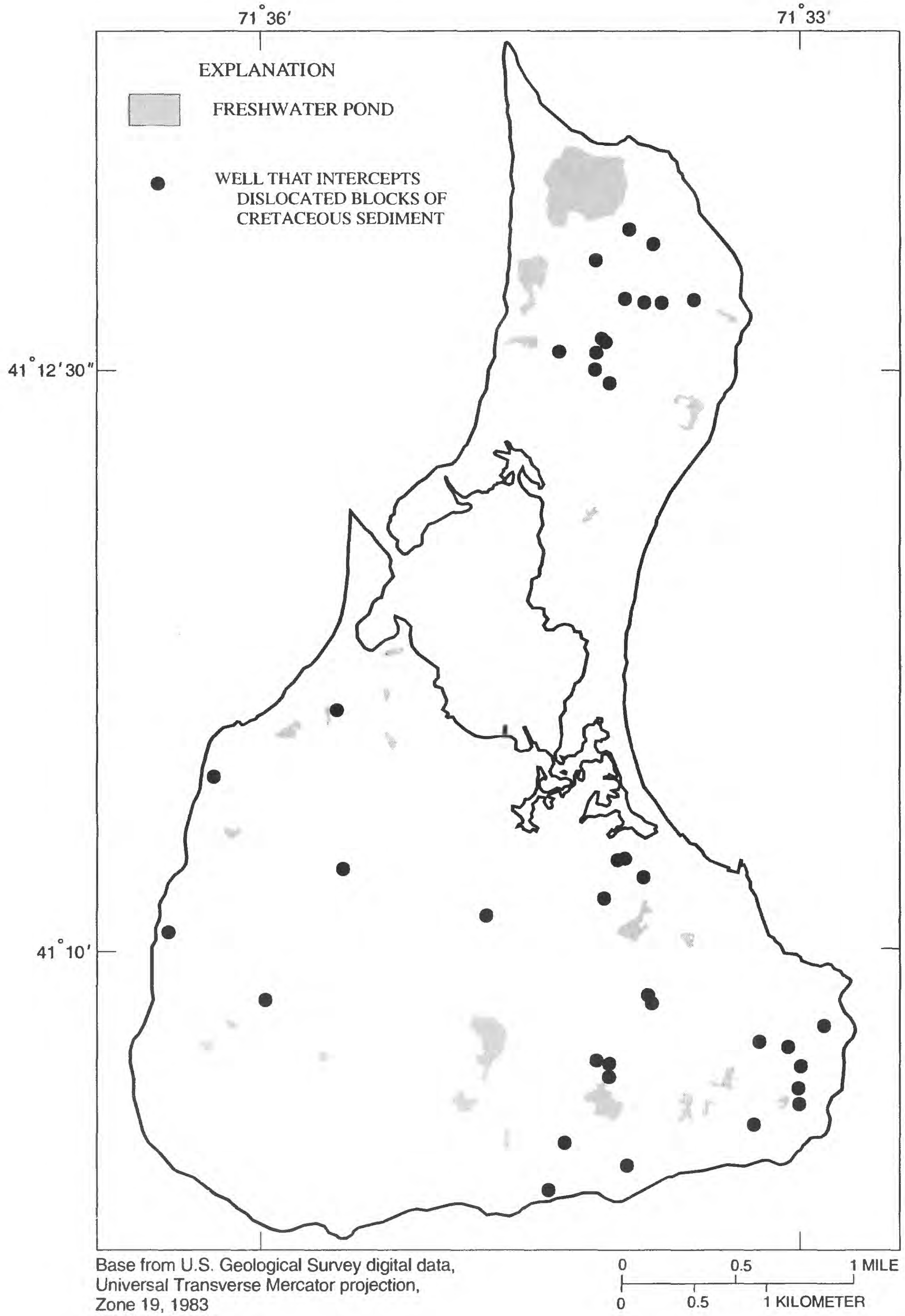


Figure 7. Locations of wells on Block Island that intercept blocks of Cretaceous sediment.

Surficial Materials

The surface distribution of morainal materials on Block Island is shown in figure 8. **Diamict** sediments, which are poorly sorted gravelly materials that contain a sand, silt and clay matrix (Flint, 1975; Lawson, 1979), underlie large areas of moderate relief in the southern and northern parts of the island. Stratified sand and gravel, and sand underlie ice-contact landforms in the southern part of the island and sandy diamict sediments in some cliff sections. Fine-grained sediments on the surface locally overlie coarser materials. At Balls Point, glacially transported blocks of Cretaceous sand and clay form a cliff face about 500 ft long and 50 ft high. Sand and gravel in **modern** beaches and **eolian** sand dune deposits rim the island. Pond, marsh, and swamp sediments, including peat as much as 40 ft thick (Boothroyd and others, 1979) underlie the floors of many kettle depressions.

Pleistocene (pre-Late Wisconsinan) Sediments

Pleistocene sediments of probable pre-Late Wisconsinan age are contained as blocks or lenses in the lower moraine zone. These sediments are brown, gray, and red gravel, sand, silt, and clay. Deformed and eroded gravel overlying Cretaceous sand at Balls Point contains rounded **clasts** of granitic and sedimentary rocks, and iron-encrusted nodules. The coarse sandy matrix in the gravel is cemented by dark red iron oxide. Sand grain minerals include quartz, feldspar, a large suite of heavy minerals, and mica. Sand grains are subangular to subrounded and are locally iron-cemented. The older Pleistocene sediments and the Late Wisconsinan glacial sediments reportedly are "brown" in well drillers' descriptions (Tuttle and others, 1961, Burns, 1993), and are differentiated from Cretaceous sediments by color.

Pleistocene (Late Wisconsinan) Sediments, Lower Moraine Zone

The lower moraine zone disconformably overlies the Cretaceous section, and averages about 200 ft thick (fig. 6). The zone underlies much of the surface on Corn Neck and is generally below sea level in the southern part of the island. The lower moraine zone consists of discontinuous blocks or lenses of deformed Cretaceous and Pleistocene sediments, minor stratified sediments, and probable basal till (some "hardpan" units in well drillers' descriptions). Subsurface data from closely spaced wells show that these diverse units are discontinuous laterally and vertically. At Balls Point, the Cretaceous and disconformable Pleistocene sediments are folded (Woodworth, 1934) and are truncated by thrust faults or erosional contacts. Many wells that are more than 100 ft deep penetrate the compact gravelly and sandy materials of the lower moraine zone (fig. 9).

Pleistocene (Late Wisconsinan) Sediments, Upper Moraine Zone

The upper moraine zone underlies the surface of the southern part of the island, where it is as much as 250 ft thick (fig. 9, section *B-B"*). It disconformably overlies compact and(or) gravelly sediments of the lower moraine zone. Stratified sediments in the upper zone are in two types of deposits: 1) glacial-stream and glacial-lake deposits composed of sorted gravel, sand, silt, and clay, and 2) sedimentary sequences composed of sand, silt, and clay, that are capped by stratified, poorly sorted diamict sediments at the surface. Sand and gravel in all deposits contain chiefly nonweathered gravel clasts and sand grains. Silt and clay sediments are dark gray and are soft and plastic in subsurface samples. Sand and gravel glacial-stream sediments, consisting of interbedded strata of **massive** or **cross-bedded** gravel and coarse sand, and thinly bedded and ripple-laminated fine sand are exposed in the gravel pit north of Swede Hill and locally in the cliff section east of Southeast Light.

Glacial-lake sediments, composed of thinly bedded and ripple-laminated sand in dipping **foreset beds** and in flat-lying **bottomset beds** are exposed in bluffs at Southwest Point and Balls Point North. Fine-grained, laminated silt and clay lake sediments are in sedimentary sequences in Southwest Point, Mohegan Bluffs, and Balls Point. Ground-penetrating radar reflection profiles reveal continuous reflectors within some of the stratified deposits. In core samples and in places where the deposits were exposed in excavations, the reflectors are known to be related to stratification; that is, contrasts from bed to bed in grain size, **porosity**, water content, or composition (Beres and Haeni, 1991; Beres, 1991). Reflectors have highest amplitudes and show greatest lateral continuity in laminated fine sand and silt (sections A, B; fig. 10). Prominent reflectors have been recorded locally in sand and gravel deposits, but are less continuous than in fine sand and silt.

Stratified sediments of the upper moraine zone in southern Block Island are contained in glacial landforms known as **morphosequences** (Koteff and Pessl, 1981). A morphosequence is a "package" of contemporaneously deposited **stratified drift** that grades from coarse grained near the glacier margin to fine grained in areas farther from the ice.

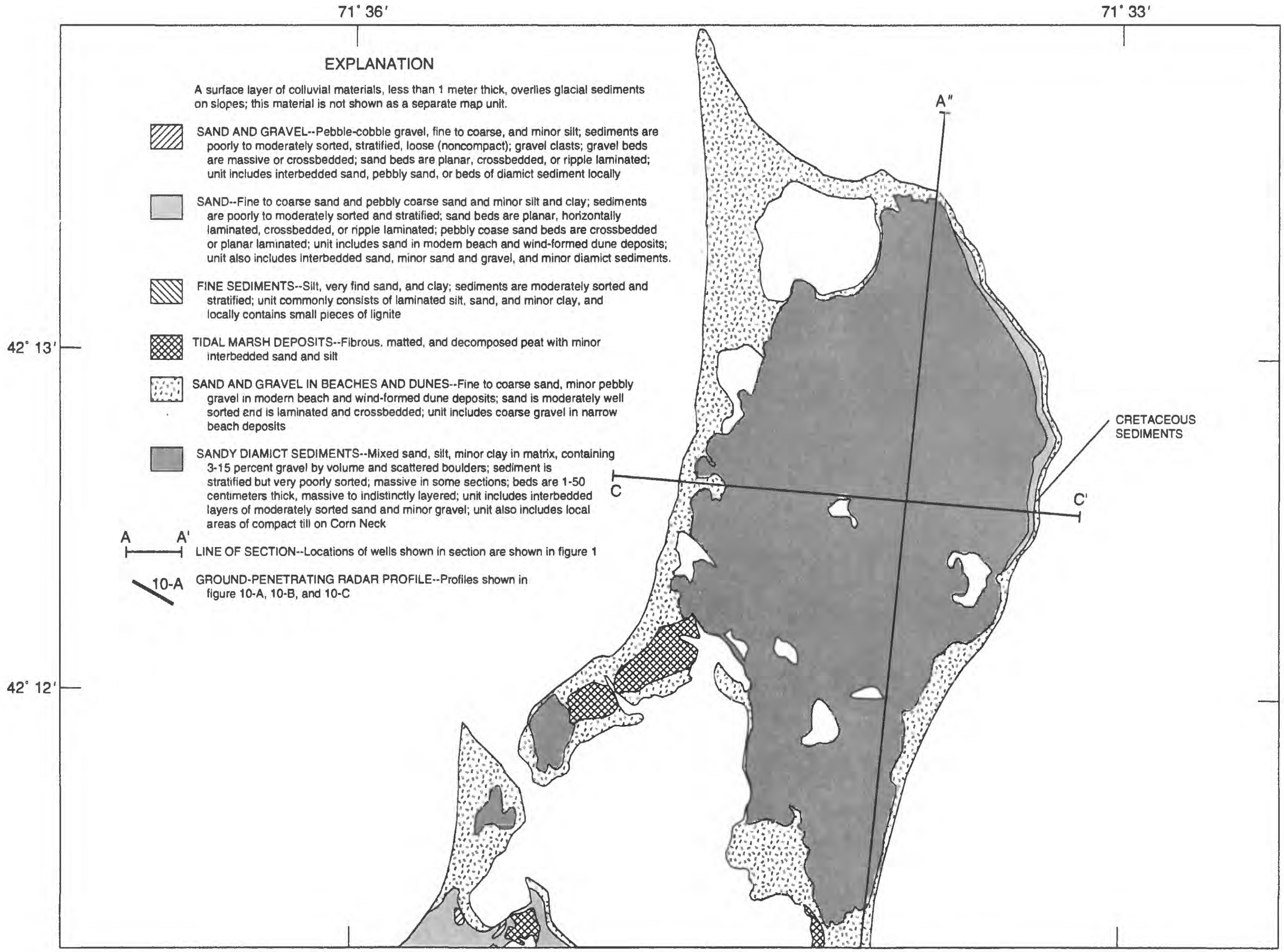
The landforms display ice-contact slopes at the glacier-proximal end of the deposit and depositional slopes at the **distal** end. Sediments grade from coarse gravel at the head to fine gravel and sand in distal areas. The distribution of sand and gravel deposits on the surficial materials map (sand and gravel, fig. 8) indicates the locations of several ice-marginal morphosequences in the southern part of the island, such as the ice-channel ridge and associated flat-topped deltaic deposit beneath Cherry Tree Hill. The interpreted distribution of sediments and bedding features in deposits in the north part of section A-A', figure 9, shows the size and shape of individual deltaic morphosequences.

The stratified sediments of the upper moraine zone are reported as "gravel," "sand," "silt," "clay," and modified similar terms in well-log descriptions (Burns, 1993). Reported mixed gravel and clay units are generally less than 10 ft thick, and are termed "hardpan" in some logs. Logs of wells NHW 322 and NHW 335 (fig. 11) characterize the vertical sequences of stratified sediments that underlie the highest stratified deposits of the southern part of the island (section B'-B", fig. 9). On the west side, well NHW 720 penetrated the surface sand deposit (depth 0-38 ft), the coarse-to-fine-grained deposits that underlie Plover Hill (depth 38-172 ft), and the disconformable "very hard hardpan" and basal gravel sediments of the lower moraine zone. On the western side of Mouwneit Hill, well NHW 469 (fig. 11) penetrated surface **colluvium** (depth 0-4 ft) overlying the surface deposit of medium sand (depths 4 to 94 ft), and encountered the coarse sand and clay of the deposit that underlies Mouwneit Hill. The log from well NHW 322 shows the sequence of stratified sediments that underlie the surface sand deposit north of Swede Hill.

Bluff sections of the upper moraine zone along the southern shore of Block Island expose unique sedimentary sequences of stratified sand, silt, and clay at the base, overlain by very poorly sorted, stratified diamict sediments (the "stratified till" of Kaye, 1960). Measured vertical sections at Schooner Point and southeast Light are shown in figure 12. The diamict sediments consist of a silty sand matrix that supports scattered gravel clasts and few large boulders. Sediments are horizontally layered in 0.3 to 1.3 foot-thick beds. Contacts between beds are marked by changes in silt content or lines of cobbles or boulders. Sediment within each bed is moderately compact and homogeneous, or indistinctly layered in laminations less than 0.4 in. thick. Diamict sediments are commonly 5 to 10 ft thick at Schooner Point and locally in Mohegan Bluffs. At Lewis Point, a diamict sequence stands in a vertical cliff about 90 ft high. Beneath Southeast Light, the material is generally 25 ft thick. Boulders produce characteristic convex-upward hyperbolic reflectors in ground-penetrating radar profiles (section C, fig. 10).

In the lower parts of these sequences, the thin bedded fine sand, silt, and clay units are deformed spectacularly in soft-sediment folds and faults. These fine-grained units are overlain by sandy foreset-bedded sediments, the basal contacts of which truncate the folded beds beneath. In some sequences, sandy sediments pass upward by way of intertonguing into layered diamict sediments. Tongues of diamict units pinch out between sand beds. No thrust faults, shear zones, or fractures related to glacial advance (Banham, 1975, Stone and Koteff, 1979, Kaye, 1979) deform the diamict sediments, which extend to the land surface. No surface deposit of compact basal till overlies the beds. The stratified diamict sediments are similar to poorly sorted, muddy, sediment-flow deposits that are accumulating in subaerial slump and colluvial deposits along the fronts of modern glaciers (Lawson, 1979).

Descriptions of materials from wells that penetrate the diamict sequences include numerous zones of "hardpan," "clay sand," and "gravel sand and clay" that refer to poor sorting, relatively high degree of compaction, or resistance to drilling. These zones generally are more than 10 ft thick, and are the near-surface materials in areas underlain by diamict sediments (fig. 8). Logs of wells that penetrated surface diamict sediments describe sequences of upward-coarsening stratified materials, capped by the diamict sediments, similar to the bluff sections. Typical well logs in these materials are from wells NHW 557, NHW 424, NHW 687 (section A-A', fig. 9), and wells NHW 337, NHW 529 (section B'-B", fig. 9).


71° 36′
71° 33′
42° 13′
42° 12′
EXPLANATION
A surface layer of colluvial materials, less than 1 meter thick, overlies glacial sediments on slopes; this material is not shown as a separate map unit.
SAND AND GRAVEL--Pebble-cobble gravel, fine to coarse, and minor silt; sediments are poorly to moderately sorted, stratified, loose (noncompact); gravel clasts; gravel beds are massive or crossbedded; sand beds are planar, crossbedded, or ripple laminated; unit includes interbedded sand, pebbly sand, or beds of diamict sediment locally
SAND--Fine to coarse sand and pebbly coarse sand and minor silt and clay; sediments are poorly to moderately sorted and stratified; sand beds are planar, horizontally laminated, crossbedded, or ripple laminated; pebbly coase sand beds are crossbedded or planar laminated; unit includes sand in modern beach and wind-formed dune deposits; unit also includes interbedded sand, minor sand and gravel, and minor diamict sediments.
FINE SEDIMENTS--Silt, very find sand, and clay; sediments are moderately sorted and stratified; unit commonly consists of laminated silt, sand, and minor clay, and locally contains small pieces of lignite
TIDAL MARSH DEPOSITS--Fibrous, matted, and decomposed peat with minor interbedded sand and silt
SAND AND GRAVEL IN BEACHES AND DUNES--Fine to coarse sand, minor pebbly gravel in modern beach and wind-formed dune deposits; sand is moderately well sorted and is laminated and crossbedded; unit includes coarse gravel in narrow beach deposits
SANDY DIAMICT SEDIMENTS--Mixed sand, silt, minor clay in matrix, containing 3-15 percent gravel by volume and scattered boulders; sediment is stratified but very poorly sorted; massive in some sections; beds are 1-50 centimeters thick, massive to indistinctly layered; unit includes interbedded layers of moderately sorted sand and minor gravel; unit also includes local areas of compact till on Corn Neck
A A′ LINE OF SECTION--Locations of wells shown in section are shown in figure 1
10-A GROUND-PENETRATING RADAR PROFILE--Profiles shown in figure 10-A, 10-B, and 10-C
A″
C
C′
CRETACEOUS SEDIMENTS

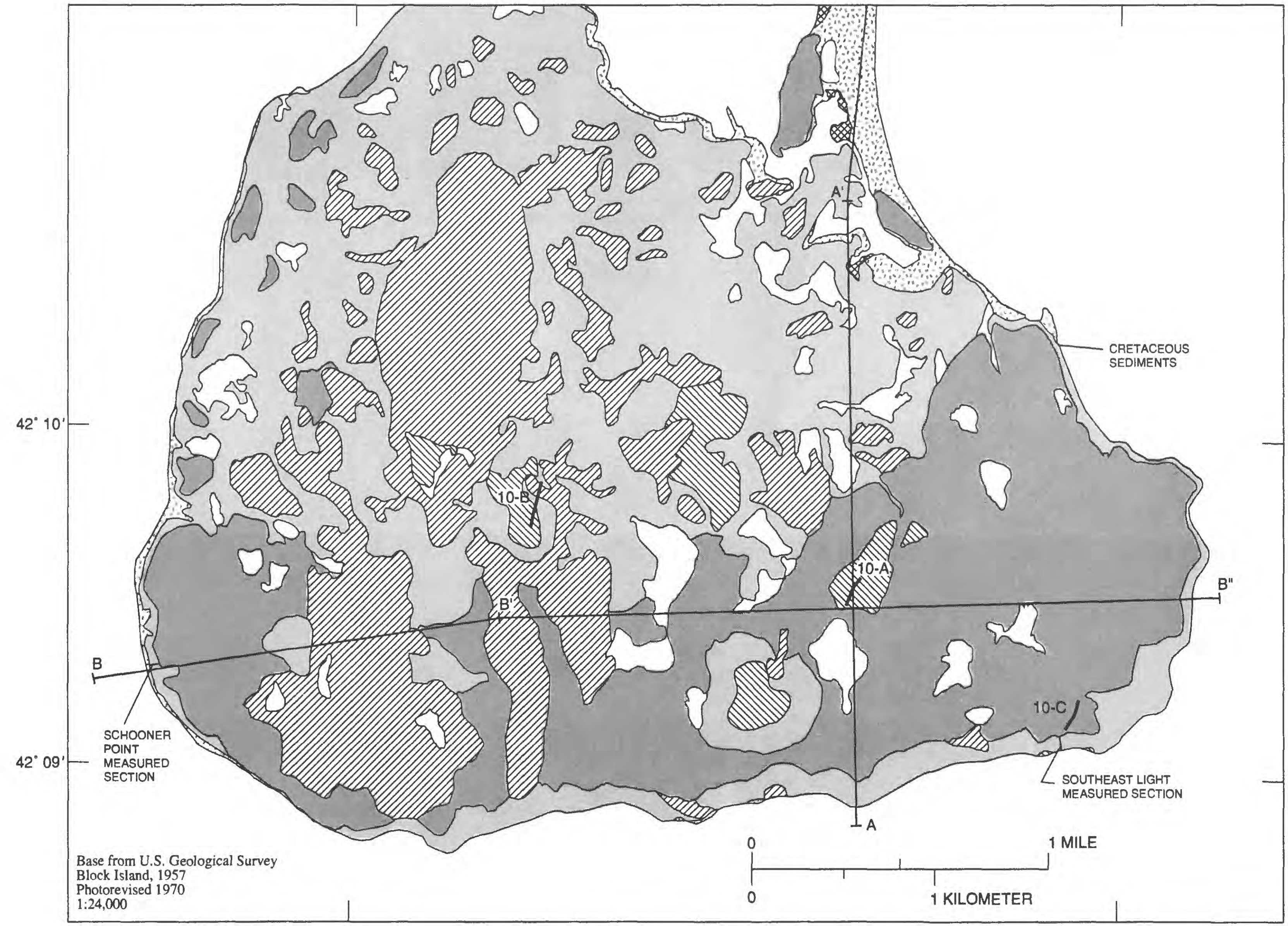


Figure 8. Distribution of surficial materials of Block Island and locations of sections.

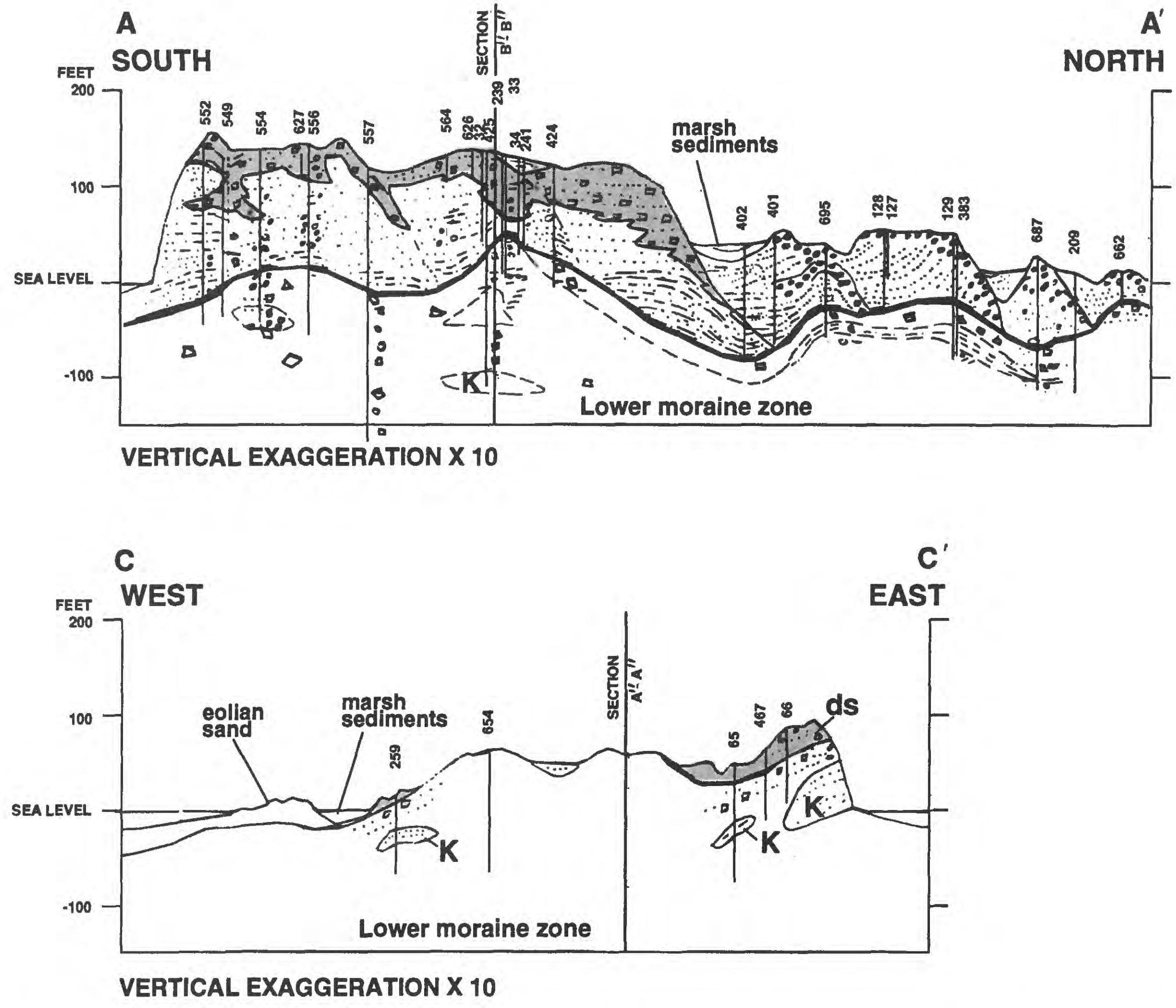


Figure 9. Interpretive geologic sections showing stratigraphic relations of sedimentary units in the upper and lower zones of the moraine on Block Island. (Subsurface relations are based on morphologic features and the distribution of surficial materials shown in figure 8; subsurface extension of ice-contact slopes; inferred deformation styles, shown schematically; and well data in Burns, 1993.)

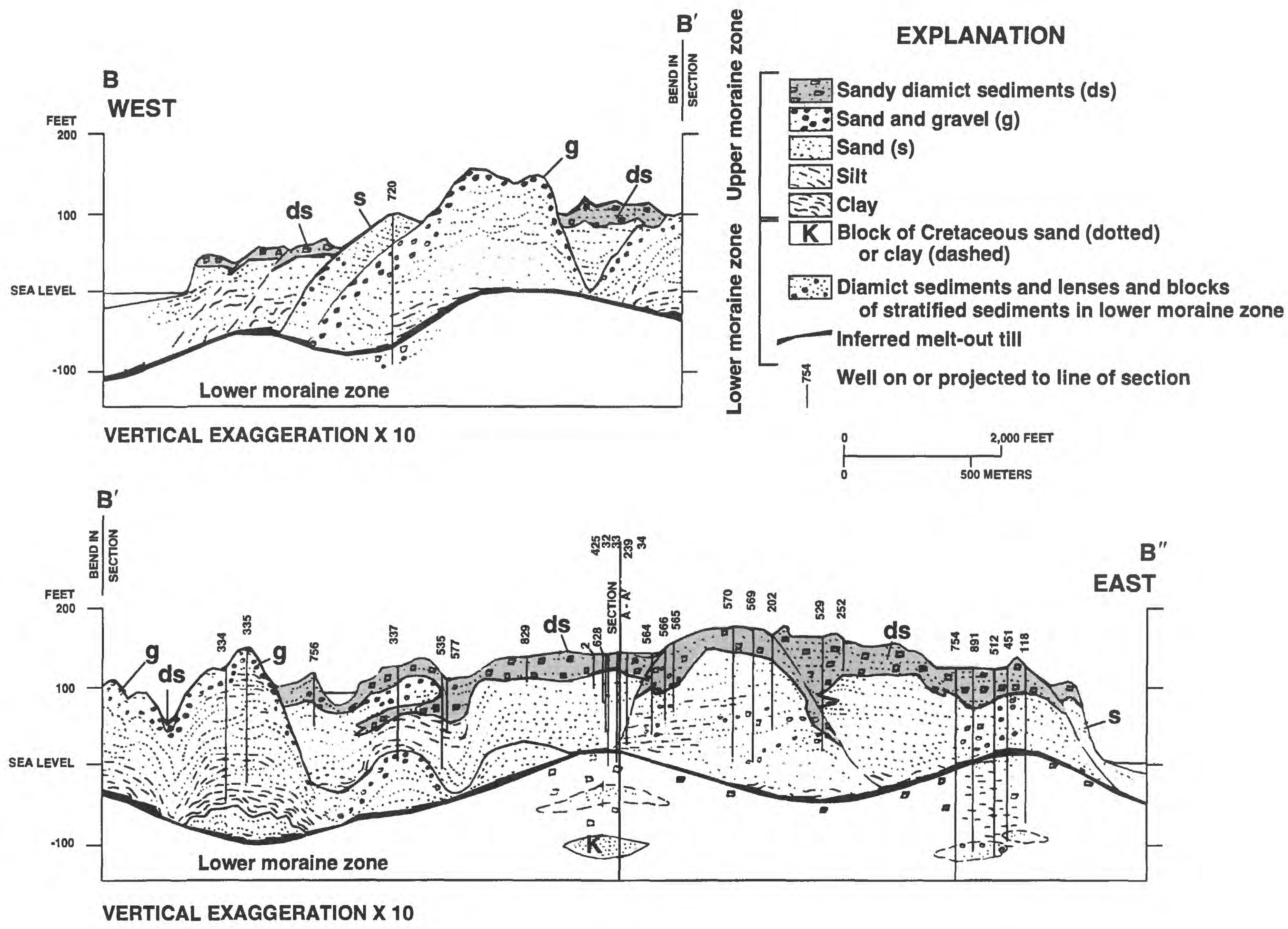


Figure 9. Interpretive geologic sections showing stratigraphic relations of sedimentary units in the upper and lower zones of the moraine on Block Island—*Continued*

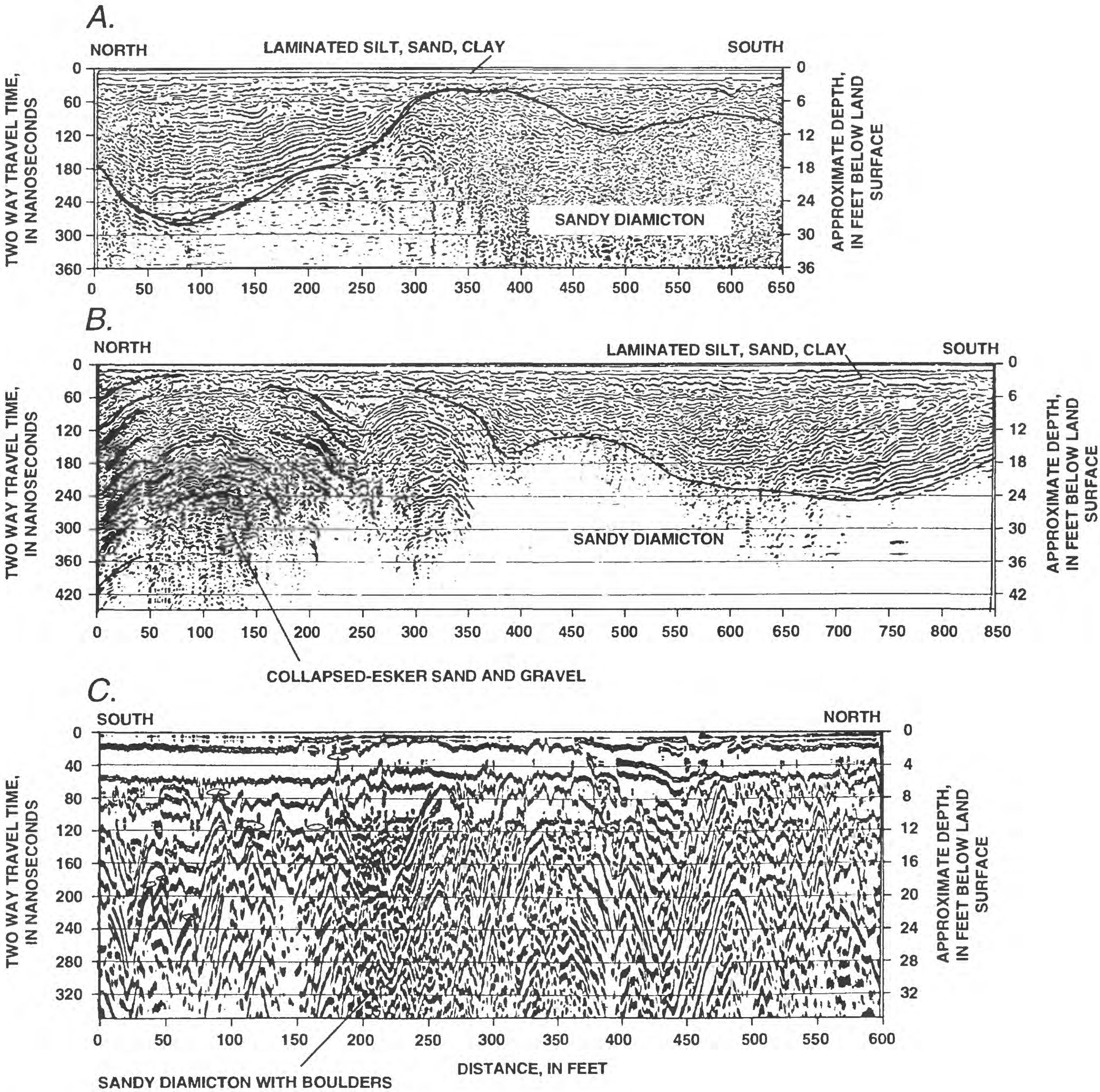


Figure 10. Ground-penetrating-radar record of stratified sediments on Block Island: (*A*) profile over surface deposit of laminated silt, sand, and clay overlying sandy diamicton; (*B*) profile over surface deposit of laminated silt, sand, and clay, which overlies sandy diamicton, and collapsed sand and gravel; and (*C*) profile over bouldery, sandy diamicton sediment at Southeast Light. (Location of profile lines shown in figure 8.) Lithology determined from selected lithologic logs in Burns (1993).

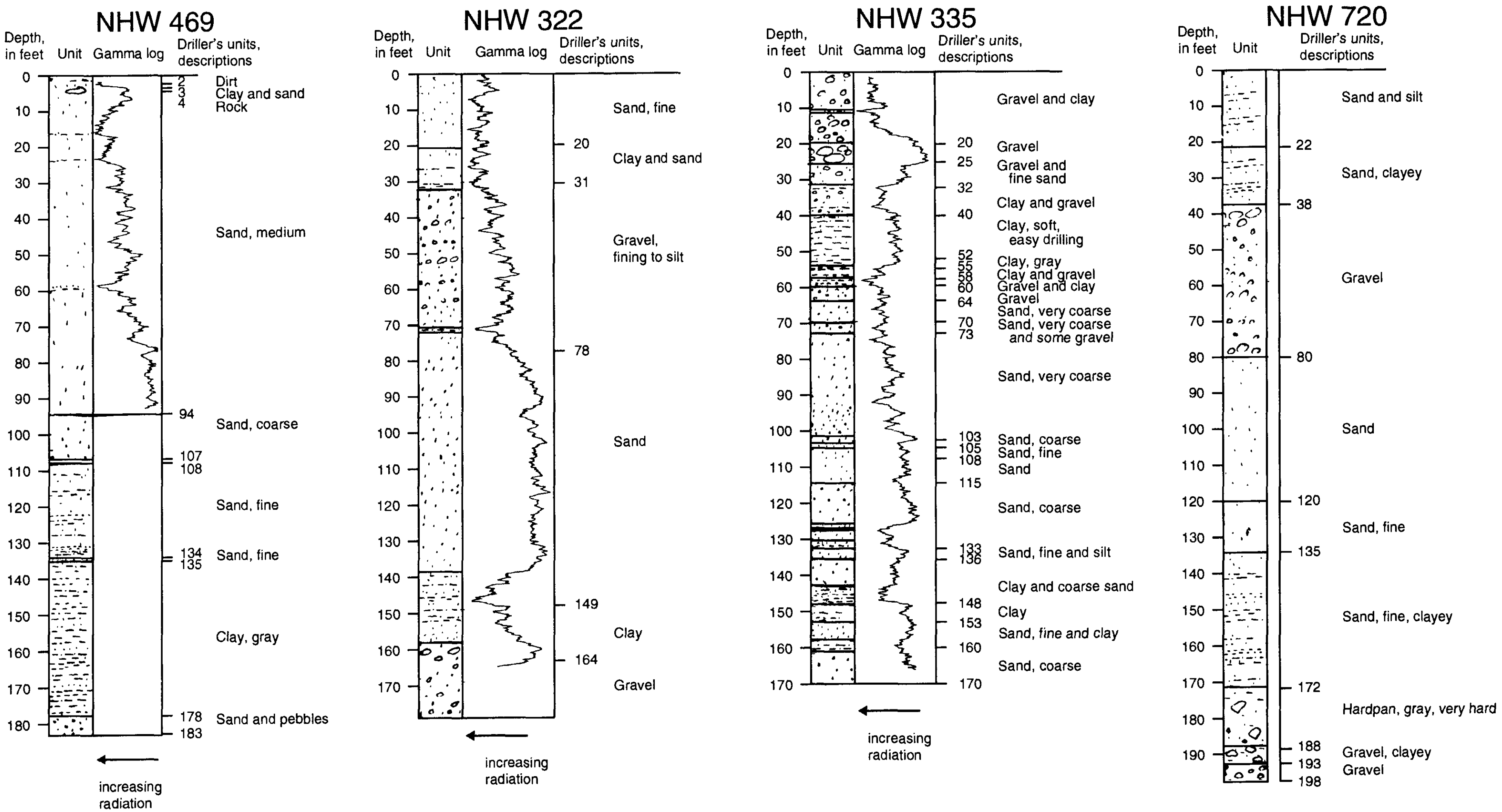
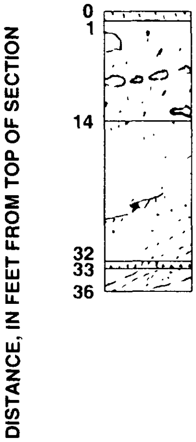


Figure 11. Graphic well logs interpreted from natural-gamma radiation logs and drillers' descriptions of materials for selected wells in stratified sediments of the upper moraine zone on Block Island. (Location of wells shown in figure 1.)

Schooner Point section Unit Description



Fine to medium, buff sand, massive; eolian mantle

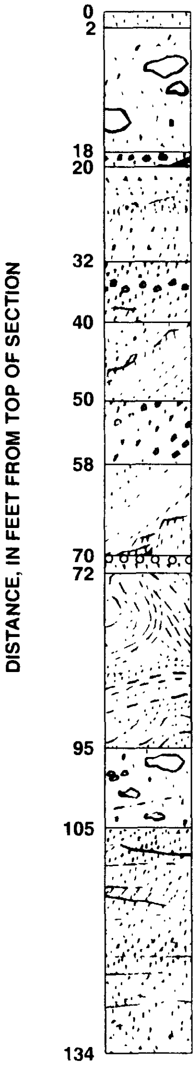
Sandy diamict sediment, stratified, containing subangular to subrounded pebbles and cobbles; layers 1-8 in. thick; bases of layers marked by stone lines; loose to compact; unit contains lenses of laminated coarse to very coarse sand; interbedded coarse sand and diamict sediments at the base of unit conformably overlies sand of underlying unit

Coarse sand in planar foreset beds that dip 10° to the south; beds are parallel, planar, 0.2-1.2 in. thick; some beds are graded; minor beds of pebbly coarse sand and ripple-laminated medium sand are interbedded

Fine to medium sand, parallel laminated; unconformable and overlapping underlying silt-clay unit

Silt, fine sand, and minor clay; thin bedded in parallel planar beds and laminations; fine sand beds are laminated and locally ripple laminated; silt layers are massive or microlaminated; clay laminae are generally 0.4 in. thick, but are as much as 3 in. thick in deformed zones; unit dips 30° to the northwest and is internally deformed by slump and load folds and decollements

Southeast Light section



Fine to medium, buff sand, massive; containing scattered pebbles and small cobbles, eolian sand mantle

Sandy diamict sediment containing scattered cobbles and few large boulders; loose to moderately compact; stratified; diamict layers 4-12 in. thick; internally massive or indistinctly layered; bases of diamict layers marked by scattered cobbles; unit contains lenses of sorted sand and gravel, less than 12 in. thick; unit is continuous laterally but appears massive in some cliff sections

Pebble and small cobble gravel with coarse sand matrix; clasts subrounded to well rounded; beds are planar, indistinctly layered; unit is lens-shaped and pinches out laterally

Medium to very coarse sand, planar bedded, local planar-tabular crossbeds are in sets as much as 8 in. thick; minor ripple-laminated fine sand is interbedded in unit

Coarse pebbly sand, planar-tabular crossbeds and interbedded planar beds of pebble gravel to coarse granular sand

Medium to coarse sand in foreset beds; parallel laminated, and minor ripple laminated fine to medium sand; beds dip 15° toward south-southwest

Coarse pebbly sand in foreset beds; iron-stained grains are orange; parallel bedded, beds dip southwesterly

Medium to coarse sand in foreset beds; parallel laminated; includes laminated and ripple-laminated fine sand and some silt

Pebbly coarse sand and pebble gravel; planar bedded; unit is lens shaped and pinches out laterally

Silt, fine sand, and medium to coarse sand; chiefly parallel bedded; beds are deformed in recumbent isoclinal folds but can be traced laterally across cliff face

Sandy diamict sediments, in massive thin beds, containing scattered pebbles, cobbles, and few small boulders; includes lenses of planar bedded pebble-cobble gravel and interbedded thin beds of massive gray silt; basal diamict unit erosionally truncates underlying sand beds of unit below

Coarse sand, pebbly sand, pebble gravel; planar tabular crossbedded, beds dip southwesterly

Figure 12. Measured sections of stratified diamict-sediment sequences of the upper moraine at Schooner Point and Southeast Light. (Locations of sections shown in figure 8.)

Age, Deposition, and Postglacial Modification of the Moraine

The nonweathered character of the surface deposits, incipient soil development, and preservation of steep-sided ridges and kettles indicate that the moraine deposits of Block Island are of Late Wisconsinan age. The island lies north of the terminal moraine, which was deposited about 21,000 years before the present, based on regional radiocarbon ages of preglacial and overlying, postglacial materials (Sirkin, 1982, Stone and Borns, 1986). The oldest date from postglacial bog sediments on the island, 12,080±200 years B.P. (sample number W-255, Davis, 1965), was obtained from wood near the base of bog sediments in southern Block Island.

The Narragansett Bay-Buzzards Bay lobe and the eastern edge of the Hudson-Champlain lobe of the last ice sheet converged on the Block Island area about 21,000 years ago (fig. 5). The glacial lobes eroded deeply into the Cretaceous strata on either side of the island, incorporating blocks of Cretaceous and Pleistocene sediments, and till in the lower moraine zone. Subglacial processes, such as (1) shear failure along contacts between clay and sand units, (2) glacial loading and elevated pore pressures in the bed materials (Clayton and Moran, 1974), and (3) freezing of blocks of sediments to the base of the ice sheet (Kaye, 1964) contributed to the depth of glacial erosion and the size of the transported blocks. The ice lobes incorporated deposits from previous glaciations, similar to parts of the moraine on Martha's Vineyard (Kaye, 1964).

As the margins of the ice lobes melted back from the interlobate area of Block Island, stratified meltwater sediments were laid down in ice channels and ponds in a glacier-marginal zone of stagnant and melting ice. Sediments beneath Mouwneit and Plover Hills in the southern part of the island initially filled ice-walled basins between the ice lobes. With continued ice-margin retreat, ponds formed where exposed blocks of ice melted rapidly. Meltwater deposited laminated silt, clay, and fine sand sediments in the ponds. Slump deformation of the unstable fine-grained sediments was followed by deposition of sandy foreset strata in the ponds. As the divides around ponds lowered by downwasting of underlying ice, the ponds drained. Muddy sediment-flow deposits, derived from adjacent slopes, filled the basins. Further retreat of the ice margins on either side of Beacon Hill impounded a series of ponds which drained over the older deposits. Deltaic sand and gravel deposits prograded into a series of successively lower lakes at present altitudes of about 120 to 70 ft on either side of Beacon Hill. Continued ice retreat was accompanied by deposition of silt and clay lacustrine sediments in the Indian Head Neck area. Recession of the ice margins to the Corn Neck area produced thin surface sediment-flow deposits and minor stream deposits. Deltaic beds at Ball Point North accumulated in an ice-marginal lake dammed by the older materials to the south. Modification of the morainal materials in the Block Island area continued in the harsh climate that accompanied deglaciation of the region, which was characterized by lack of tree cover (Davis, 1965, Sirkin, 1976), and probable extensive seasonal ground ice or permafrost (Schafer and Hartshorn, 1965, Stone and Ashley, 1990). Final collapse of surface sediments related to melting of buried ice blocks occurred after deposition of the thick sequences of sediment-flow deposits. Unstable slopes continued to shed materials which accumulated in layered colluvial slope deposits. A mantle of wind-blown sand accumulated on the surface. Warming of the postglacial climate about 13,000 years ago was accompanied by growth of a tree cover, organic deposition in marshes, and development of soils. Sea-cliff erosion along the southern end of the island produced about 3 mi of shoreline retreat during sea-level rise of 100 ft over the last 9,000 years (Oldale and O'Hara, 1980). Beach and spit deposits joined the island segments, probably in the last few thousand years. Development of the modern hydrologic regime of Block Island, which determines the position of the surface of the ground-water mound and depth of the fresh-water lens beneath the island, accompanied the latest sea-level rise.

Surface-Water System

More than 200 bodies of surface water occupy kettles and other depressions on Block Island, but most are small and are only a few feet deep. The largest bodies of open freshwater are Fresh, Sands, Middle, and Sachem Ponds. The deepest are Fresh Pond (about 25 ft) and Sands Pond (about 12 ft). Some shallow surface-water bodies dry up during extended periods of little or no precipitation.

Most of the surface-water bodies are underlain by silt, clay, or other materials of low **hydraulic conductivity** that impede vertical leakage through the pond bottom. Many surface-water bodies have formed in small closed depressions so that discharge from them occurs only by evaporation and by leakage through their sides and bottoms. Water levels in most bodies of surface water appear to be expressions of the **water table**; water levels in shallow wells near ponds are generally slightly higher or lower than pond levels, indicating ground-water flow into and out of the ponds.

A few ponds overflow periodically; Fresh Pond and Peckham Pond are examples. Ground water and a small amount of overland **runoff** enter Fresh Pond and Peckham Pond from the north, east, and west. Peckham Pond also receives a small amount of surface inflow from an intermittent stream that enters the pond from the east. When the elevation of water levels in these two adjacent ponds is above 89.9 ft above sea level, overflow from Fresh Pond drains through a drainage pipe to Peckham Pond and from Peckham Pond, through a drainage pipe, into a small intermittent stream that drains southward into a closed depression. The depression, which is bounded by a 70-ft topographic contour, contains two small ponds, the northernmost of which is Mitchell Pond.

Surface drainage is poorly developed, as is evident from the lack of well-developed stream channels. Only a few small streams can be found on the island, and nearly all of their reaches are intermittent. Water in some stream reaches infiltrates to underlying sediments. The intermittent stream that discharges from Peckham Pond, for example, loses much of its water before reaching Mitchell Pond. The discharge of this stream on April 20, 1989, increased from 170 gal/min at Peckham Pond to 202 gal/min about 500 ft downstream, but then decreased to 144 gal/min about 1,000 ft downstream (50 ft upstream from Mitchell Pond). The initial increase in flow over the first 500 ft of stream channel occurs where poorly permeable sediments that apparently underlie the stream at relatively shallow depth restrict downward movement of shallow ground water. This shallow ground water discharges to the stream. Flow decreases farther downstream, eventually to zero within the closed depression, where underlying sediments are moderately permeable and downward flow of ground water is significant.

Ground-Water System

Pleistocene glacial deposits beneath Block Island are a **heterogeneous** mixture of interfingering permeable and poorly permeable materials that function as a strongly **anisotropic** aquifer system. The deposits consist of discontinuous bodies of moderately permeable sand and gravel, that generally have small thickness and areal extent. These are separated by discontinuous, poorly permeable **confining units** consisting of lenses of clay, silt, and till (sometimes referred to as hardpan by drillers), that generally have small to moderate thickness and areal extent. The confining units impede ground-water flow, particularly in the vertical direction, but do not greatly affect continuity of the regional hydraulic system. The lower part of the aquifer system appears to include underlying Cretaceous sediments. However, because only one well (NHW 754) is inferred to penetrate Cretaceous sediments that have not been displaced by glacial transport, little is known about the character of the ground-water flow system in Cretaceous formations. Consequently, the ground-water system described in this report applies only to the Pleistocene sediments. Furthermore, although upper and lower zones of the Pleistocene moraine have been identified, mapping of the contact between these zones has not been completed. Accordingly, few conclusions can be drawn about differences in hydraulic characteristics and water yielding properties of these two zones.

Freshwater in the unconsolidated sediments that underlie Block Island forms a lens-shaped body that "floats" on saltwater, because its density is less than that of the saltwater. Saltwater occurs in formations below the freshwater lens and below the ocean floor surrounding the island. The lens is thinnest near the perimeter and thickest near central parts of the island. The depth to the bottom of the freshwater lens near the central areas of the northern and southern parts of the island has not been determined. In the southeastern part of the island, well NHW-754, screened from about 225-235 ft below sea level, yields freshwater. Near the seashore, depth to saltwater may be 25 ft below sea level or less. A well 600 ft southeast of Cormorant Cove reportedly produced saltwater at a depth of 25 ft below sea level. At the south end of the island, a well drilled about 300 ft north of Spar Point is reported to have produced saltwater at a depth of about 35 ft below sea level. The thickness of the freshwater lens is estimated to range from a few tens of feet near the perimeter of the island, to more than 350 ft in the south-central part of the island.

In most places, water at shallow depths (about 35 ft or so below land surface) is unconfined; that is, it is under water-table conditions. As water moves downward beneath discontinuous lenses of clay, silt, and hardpan, however, it becomes locally confined. Because in most places drilled wells on Block Island penetrate one or more poorly permeable layers, water at depths of more than 35 ft is inferred to be confined. The ground-water-flow system includes local, shallow subsystems that are superimposed on a deeper regional-flow system. The shallow subsystems form where near-surface lenses of poorly permeable sediments impede downward flow and cause a lateral component of flow to nearby streams, springs, and seeps. The regional-flow system includes the vertical components of flow that carry freshwater below sea level in central parts of the island and then upward into salt water near the perimeter of the island.

Hydraulic Characteristics

The hydraulic characteristics of the aquifers that underlie Block Island determine their capacity to store and transmit water. Characteristics of principal interest to this study are **storage coefficient**, hydraulic conductivity, and **transmissivity**. These properties are important in determining ground-water yield and availability for the town of New Shoreham.

Storage coefficient, *S*, is a measure of the capacity of an aquifer to take water into and release it from storage. Under water-table conditions, the storage coefficient is effectively equal to **specific yield**, *Sy*, which is the capacity of an aquifer to yield water by gravity drainage. Specific yield is expressed as a fraction of a unit volume of saturated material. The typical range of specific yield for granular materials is 0.1 to 0.3 (Lohman, 1972, p. 53). In other words, saturated sediments will yield, by long-term gravity drainage, an amount of water that is equivalent to 10 to 30 percent of the sediment volume. Laboratory measurements of the specific yield of six disturbed samples of till from southern Rhode Island ranged from 0.04 to 0.21 and averaged 0.11 (Melvin and others, 1992). These values may be somewhat high, however, because the specific yield of disturbed sediments is generally higher than that of undisturbed sediments. Aquifer-test analyses and laboratory determinations have shown that 0.2 is a reasonable average for specific yield of stratified drift in southern Rhode Island. (Johnston and Dickerman, 1985, p. 31). The specific yield of silts and clays are assumed to be negligible. These sediments have high porosity, but, because the pores are not well connected, they do not readily yield water by gravity drainage. Reasonable estimates of specific yield of shallow water-yielding sediments on Block Island are 0.10 for loose, unsorted silty sands and gravels (diamict sediments), and 0.20 for sorted, stratified sands and gravels (stratified drift).

The percentage distribution of materials having relatively high specific yield (unsorted and sorted sands and gravels) and negligible specific yield (clays and silts) is not known. Cursory inspection of several hundred **lithologic logs** suggests that lenses of clay and silt may make up at least 25 percent of the total sediment volume and that most of the remainder is composed of unsorted sand and gravel.

Hydraulic conductivity, *K*, is a measure of the rate at which water will flow through a unit thickness of aquifer under unit **hydraulic gradient**. A measure of the ability of the entire **saturated thickness** of an aquifer to transmit water under a unit hydraulic gradient is termed transmissivity, *T*, which is the product of the average hydraulic conductivity of an aquifer and its saturated thickness, *b*; that is, $T = Kb$. In this report, hydraulic conductivity is reported in feet per day (ft/d), and transmissivity is reported in feet squared per day (ft^2/d) which is the reduced form of cubic feet per day per foot of saturated thickness [$(ft^3/d)/ft$].

Estimates of horizontal hydraulic conductivity were obtained for selected lithologies by first determining *T* of the water-yielding unit in which a well was screened and by then dividing *T* by saturated thickness of the unit; that is, $K = T/b$. In most instances, saturated thickness of an aquifer was assumed to be the distance from the bottom of the well screen to the bottom of the first overlying confining unit (clay, silt, hardpan). In a few instances, saturated thickness was determined as the distance between confining units above and below the screen. In 114 wells for which both screen length and type of material screened were reported, saturated aquifer thickness ranged from 2 to about 60 ft; in half of the wells, saturated aquifer thickness was 10 ft or more. About three-fourths of the 114 wells were reportedly screened in gravel or sand and gravel. Most of the remaining wells were screened in materials described as fine to coarse sand. Because the wells probably were screened in the most permeable units penetrated by the well, reported values of *K* can be considered representative of the most permeable sediments that underlie the island.

The transmissivity of aquifer materials in the upper and lower moraine zones was determined at 156 sites from specific-capacity data reported by well drillers. Specific capacity, reported in gallons per minute per foot of **drawdown** ((gal/min)/ft), is the value obtained by dividing well discharge (in gallons per minute), by the water-level drawdown (in feet) in the well resulting from pumping. Specific capacities reported by drillers range from 0.08 to 35 (gal/min)/ft. The median, however, is only 0.65, and 90 percent of the specific capacities are less than 3 (gal/min)/ft. Because head loss results from partial penetration of an aquifer by the well screen and from turbulent flow of water into and within a pumped well, reported specific capacities are commonly lower than maximum values obtainable. These factors were evaluated and reported specific capacities were adjusted, where data permitted, to obtain the most accurate estimates possible of transmissivity.

By use of the following equation (Lohman, 1979, p. 52), transmissivity of an aquifer can be estimated from the specific capacity of a 100-percent-efficient well that fully penetrates the aquifer :

$$\frac{Q}{s_w} = \frac{4\pi T}{2.30 \log_{10} 2.25T\,t/r_w^{\,2}S} , \qquad (1)$$

where

Q is pumping rate, in cubic feet per day;
T is transmissivity, in square feet per day;
s_w is drawdown, in feet;
t is duration of pumping, in days;
r_w is radius of well, in feet; and
S is storage coefficient, dimensionless.

Because T is in the numerator and the denominator of the equation, solutions must be obtained graphically. A solution was obtained for t=0.042 days (60 min.), r_w=0.25 ft, and S = 0.0001. A storage coefficient of 0.0001 is assumed reasonable for confined aquifers on Block Island. Storage coefficients for confined aquifers generally range from 0.005 to 0.00005 (Freeze and Cherry, 1979, p. 60).

The pumping period for the specific-capacity tests was reported for only one well. Because about 85 percent of the wells were drilled for domestic use and such wells are generally pumped for a least one hour upon completion or upon installation of the pump, a pumping period of 1 hour was assumed for all tests. Even though wells may have been pumped slightly longer, specific capacity, which decreases gradually during pumping, would not be greatly different. The nominal inside diameter of most of the wells tested is 6 in. The nominal inside diameter of eight of the wells is 4 in. and of one is 8 in.

Most wells on Block Island only partially penetrate the formation from which water is obtained. In about half of the wells for which specific-capacity data are available, screens are exposed to less than 30 percent of the aquifer thickness. The specific capacities of 110 partially penetrating wells were adjusted to those of fully penetrating wells by use of an equation given in Walton (1970, p. 319). Adjustments could not be made in 46 wells for which either screen length or formation thickness could not be determined.

The specific capacity of a well can also be reduced by well loss. Well loss is a component of drawdown that can occur in a well pumped at rates sufficient to cause the flow of water through the well screen and within the well bore to become turbulent. Theoretical calculations of drawdown due to well loss were made for wells on Block Island (for assumed conditions of minimal development and efficiency) by use of an equation given in Walton (1970, p. 313). Results of these computations indicate that drawdown due to well loss would have been negligible for the rates of pumping (4-90 gal/min) used to obtain specific capacity values. Transmissivities determined from specific-capacity data and adjusted where possible for the effects of partial penetration range from 15 to 17,500 ft^2/d. Median transmissivity, however, is 200 ft^2/d. Transmissivity exceeds 1,900 ft^2/d at only 10 percent of the wells. These transmissivities are indicative of the low overall water-transmitting capacity of the sediments underlying Block Island.

Hydraulic conductivity of the materials in which the wells are screened was estimated for 114 wells. The values range from 3 to 2,100 ft/d; however, the median value is 27 ft/d and only 25 percent of the values equal or exceed 43 ft/d. About 10 percent of the water-bearing materials for which estimates were made have hydraulic conductivities of 145 ft/d or more; these materials are either sorted, stratified drift or Cretaceous sediments described by drillers as quartz sand or quartz sand and gravel. The range and median values of hydraulic conductivity within lithologic types described by drillers are given in table 1. The hydraulic conductivities determined are considered to be maximums, because, in most cases, the depth to the bottom of the aquifers (and thus total aquifer thickness) is not known. Surficial mapping and examination of lithologic logs of wells indicate that the hydraulic conductivity of sediments in the upper zone of the Pleistocene moraine may be somewhat greater than sediments in the lower zone. This hypothesis could not be tested, however, because of uncertainty in identifying which zone was screened in some of the wells. Data for wells screened within selected altitude horizons (table 2) does indicate that median hydraulic conductivity of sediments decreases with depth, but only slightly.

Transmissivities and hydraulic conductivities presented herein are estimates. Nevertheless, the values are useful for comparative purposes and are probably in the correct order of magnitude.

Water Levels

Water levels in wells on Block Island are affected by topographic position, well depth, and the steep vertical hydraulic gradients that prevail throughout the island. Depth to water in wells ranges from about 1 ft to as much as 179 ft below land surface. In hilly areas, depth to water generally increases markedly with increasing well depth. For example, a cluster of three test wells (NHW 256, NHW 257, and NHW 258) were drilled to different depths about 500 ft north of Fresh Pond at a land surface elevation of 122 ft above sea level. Depths of the wells, each with 3 ft of screen exposed at the bottom, are 84, 38, and 19 ft, respectively. Depths to water in these wells on September 21, 1990 were 78.20, 24.86, and 12.52 ft, respectively. The vertical hydraulic gradient between the shallowest and deepest well was 1.01 ft/ft.

The altitude of water levels in wells ranges from about 1 ft to more than 160 ft above sea level. Precise water-level altitudes in wells were determined at 43 sites by surveying methods. Because the altitude of the water level in a well is a measure of **hydraulic head** at its screened interval, these data were used to determine the vertical distribution of head in selected areas. These data were then used to determine the approximate direction of ground water flow in the vertical dimension. Results of these determinations are described in the section on flow.

Table 1. Estimated hydraulic conductivity of materials in which wells are screened

Driller's description	Number of wells	Hydraulic conductivity, in feet per day		
		Minimum	Median	Maximum
Gravel	25	6	25	545
Sand and gravel	52	3	35	583
Sand	17	3	27	200
Quartz sands and gravels (displaced Cretaceous sediment)	6	6	115	2,100
Clayey sand, and gravels and hardpan	9	3	22	42

Table 2. Hydraulic conductivity of sediments at selected altitudes

Altitude of bottom of well screen above or below(-) sea level	Number of wells	Hydraulic conductivity, in feet per day		
		Minimum	Median	Maximum
0 to 88	10	5	36	115
-1 to -50	50	3	33	583
-51 to -100	41	3	22	[1]2,100
-101 to -169	13	3	26	145

[1]Next lowest value is 545.

The low average water-transmitting capacity of the sediments composing Block Island results in slow drainage of the precipitation that infiltrates the predominantly sandy surficial deposits (fig. 8). As a consequence, water saturated sediments are encountered relatively close to the surface throughout the island, even in topographically high areas. Hansen and Schiner (1964, p. 14) considered most of the saturated material above sea level to be **perched**. They refer to upper perched water bodies and to at least two large bodies of perched water collectively termed the "lower perched water zone." Although small bodies of perched water may occur locally near the surface, examination of their data and data obtained during this investigation, revealed no evidence of the existence of aerially extensive bodies of saturated material underlain by unsaturated material. Accordingly, the concept of a lower perched water zone was abandoned.

Available evidence points to the existence of one main zone of saturation on Block Island and thus one main water table. A map of the water-table surface (fig. 13) was prepared using control points that include (1) altitudes of water levels in 96 dug wells and 21 drilled wells that were equal to or less than 35 ft deep, (2) altitudes of springs, ponds, and swamps estimated from the topographic map, and (3) altitudes of bottoms of dry depressions, which indicate maximum potential altitude of the water table.

Water levels in wells used to contour the water table were measured chiefly during June-September 1962. Many of these wells have been destroyed since 1962 or were otherwise inaccessible to measurement during the current study. Also used were water-level measurements made in wells during March-August 1988-90, at sites where no measurements were obtained in 1962. Use of water levels from different years in contouring the water table surface is justified because (1) water levels in a USGS observation well 13 mi north of Block Island show that water levels fluctuated over nearly the same range in 1962 as they did in 1988-90, and (2) water levels measured in eight of nine key wells on Block Island at about the same time of year in 1962 as in 1988-90 differed by less than 2 ft. The key wells are located in areas where annual fluctuations of 3 to 10 ft may be expected.

Water-level fluctuations were monitored by means of float-driven digital recorders installed in five unused wells (fig. 14). Four of the wells (NHW 17, NHW 75, NHW 157, and NHW 418) are large-diameter dug wells, 6 to 17 ft deep, whose bottoms are about 18, 23, 0, and 28 ft above sea level, respectively. Well NHW 417 is a 247-foot deep drilled well in which screen is exposed 116-119 ft below sea level.

Water-level fluctuations recorded in the shallow dug wells represent fluctuations in water-table altitude that result from changes in the rates of **recharge** to, and discharge from, the ground-water system. The water table rises when the rate of recharge exceeds the rate of discharge and falls when these conditions are reversed. Although precipitation is distributed rather uniformly throughout the year, the rate of recharge from infiltrating precipitation is normally reduced during the growing season (May-October) because of increased rates of evaporation and transpiration. Consequently, there is usually a net decline in the water table during the growing season followed by a net rise during the non-growth months (November-April).

Because precipitation was substantially below average during 1988 and substantially above average in 1989, the range in water table fluctuations (2-10 ft) recorded in these four wells probably is representative of the range to be expected in them most of the time. However, somewhat larger declines may be expected during successive years of drought.

Water-level fluctuations shown in the **hydrograph** for well NHW 417 were caused primarily by the effects of ocean tides, which are more readily discernible if the record is viewed in the expanded scale shown in figure 15. The sinusoidal shape of the hydrograph in figure 15 reflects the rise and fall of the freshwater lens in response to rising and falling ocean tides. This continuous oscillation of the freshwater lens contributes to the mixing of freshwater and saltwater in a zone of brackish water that separates freshwater and saltwater beneath the island.

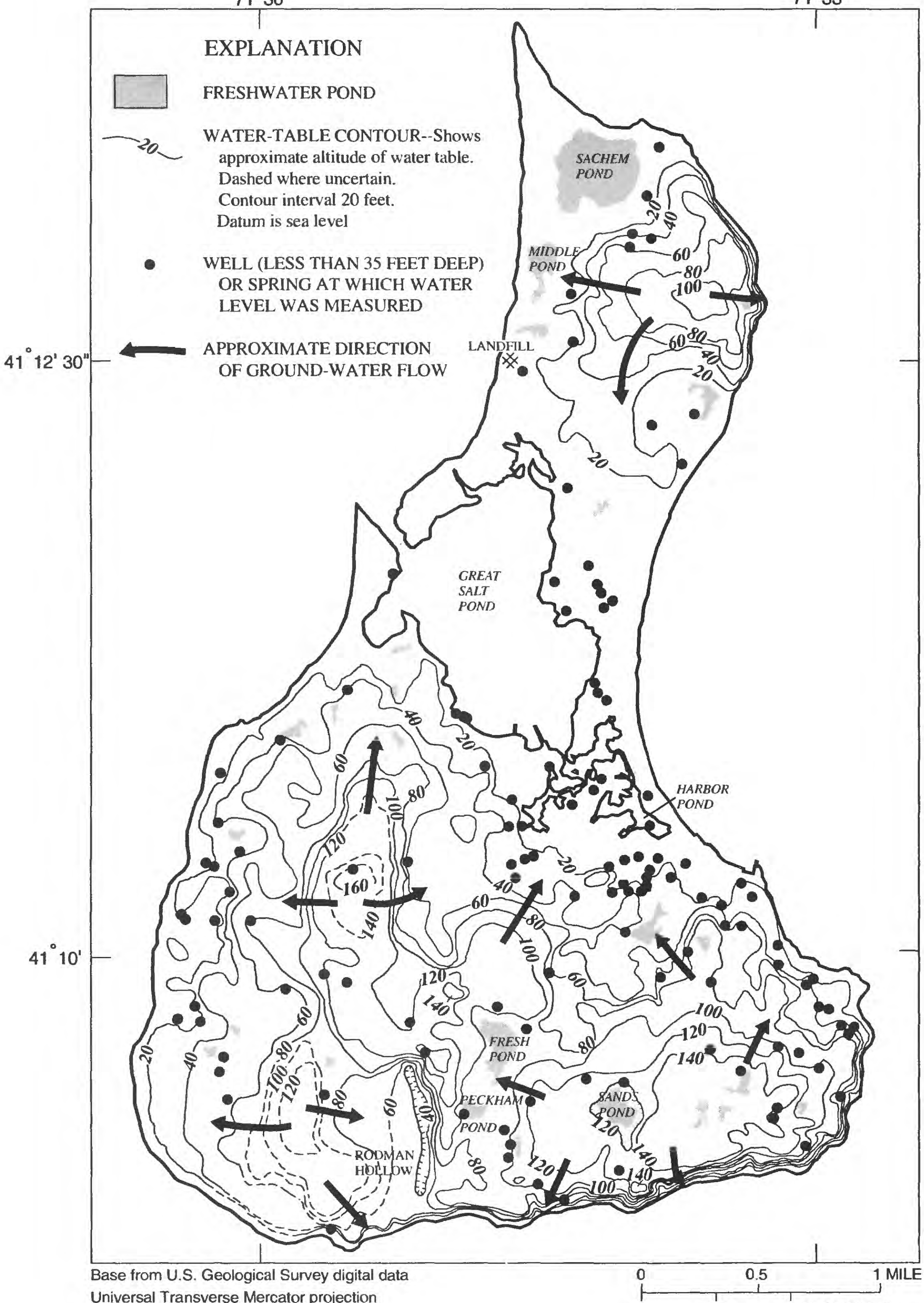


Figure 13. Generalized altitude and configuration of the water table on Block Island. (Modified from Johnston and Veeger, 1994.)

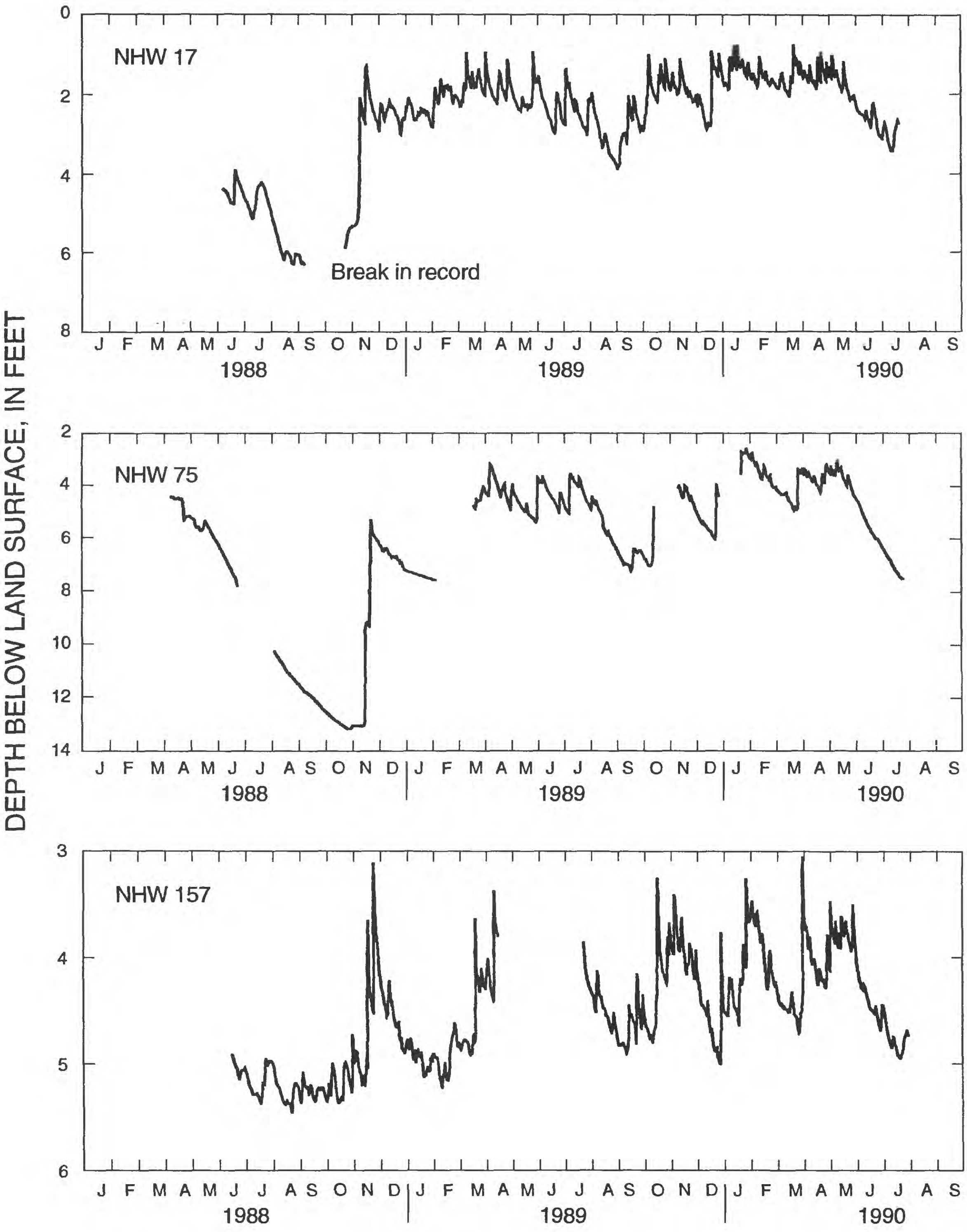


Figure 14. Water-level fluctuations in selected wells on Block Island.

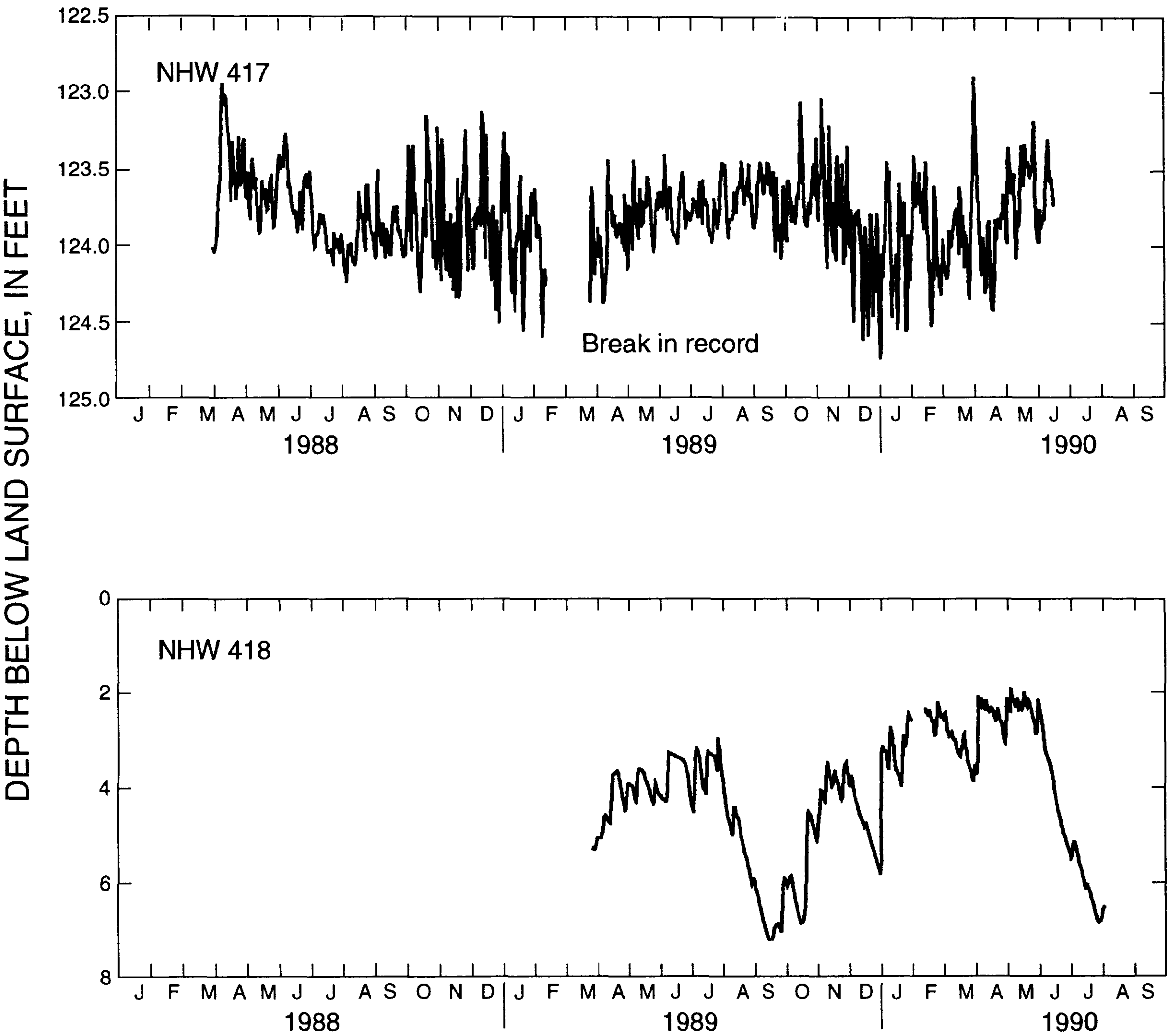


Figure 14. Water-level fluctuations in selected wells on Block Island—*Continued.*

Pumping from BIWC supply well NHW 425, which is located 580 ft to the southeast of well NHW 417 and screened from 104 to 109 ft below sea level, was observed to produce drawdown in well NHW 417. However, the effect was small and largely obscured by tidal effects. Intermittent pumping from NHW 425 at an estimated rate of 35 gal/min obviously produced drawdowns of less than 2 ft in well NHW 417 during the 27-month monitoring period, because its water level fluctuated less than 2 ft during that period.

Water levels were measured at staff gages installed in 12 ponds, including Sands Pond and Fresh Pond, about every other week between summer 1988 and summer 1990. Pond level fluctuations during this period ranged from 1.6 to 3.3 ft. Because ground-water levels in shallow wells near some ponds were at about the same altitude as pond levels, water levels in ponds were assumed to coincide with the water table.

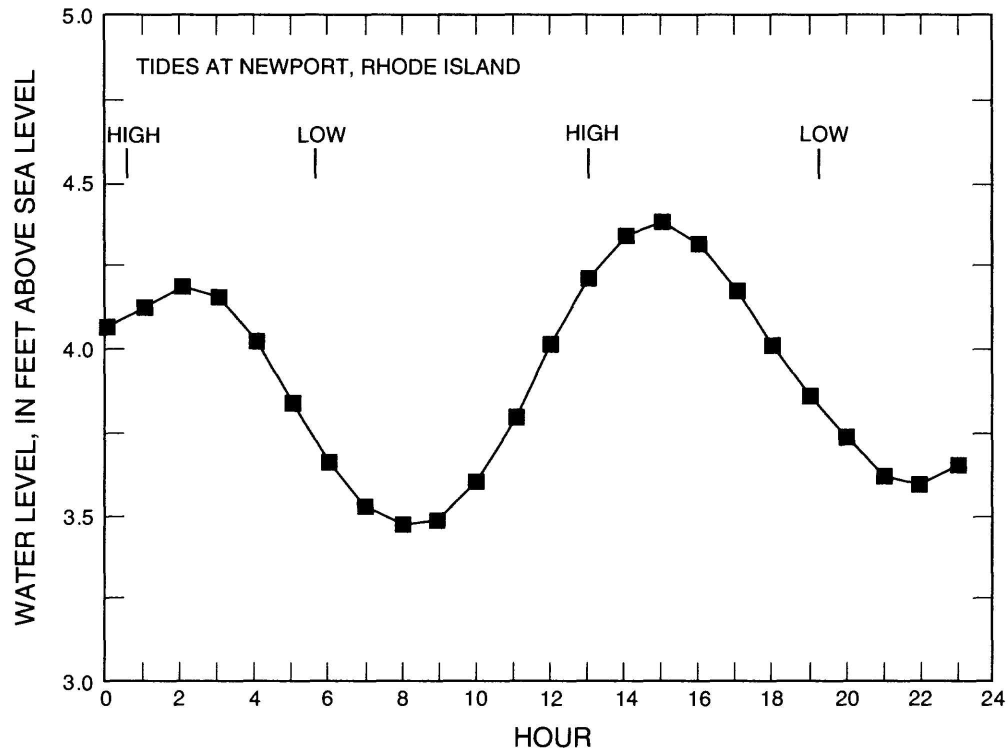


Figure 15. Effect of ocean tides on water-level fluctuations in a Block Island Water Company supply well (NHW 417), screened 116-119 feet below sea level, on October 1, 1988.

Recharge and Discharge

Ground-water recharge is the fraction of precipitation that percolates through soils to the water table after losses to overland runoff and evapotranspiration. To determine ground-water recharge, measured precipitation must be reduced by the amount of water lost to evapotranspiration and overland runoff according to the following equation:

$$R = P - (E + O) , \qquad (2)$$

where

R is ground-water recharge;
P is precipitation;
E is evapotranspiration; and
O is overland flow.

Because precipitation has been measured on Block Island and because evapotranspiration and overland runoff can be estimated with some confidence, estimates of average annual discharge (and, therefore, recharge) can be obtained by substituting appropriate values for these items into the equation.

As mentioned previously, average annual precipitation on Block Island during 1890-1988 was 40.2 in., and the median annual precipitation during 1890-1990 was 38.9 in. During 1951-80, the period used by the National Weather Service during the course of this study to compute normal precipitation, average precipitation was 42.7 in.

Hansen and Schiner (1964) estimated that average annual evapotranspiration on Block Island during 1887-1961 was 25 in. (or 61 percent of average annual precipitation) by use of a method by Thornthwaite and Mather (1957). Estimates of evapotranspiration determined by subtracting long-term (1930-49) runoff from long-term precipitation compiled by Knox and Nordenson (1955) indicate that evapotranspiration ranges from 43 percent of precipitation in southern Rhode Island to 50 percent of precipitation in northern Rhode Island and averages about 47 percent. Johnston and Dickerman (1985, p. 10) also calculated evapotranspiration to be the difference between precipitation and runoff and determined evapotranspiration in the 100-mi^2 **drainage area** upstream from Wood River Junction in southern Rhode Island to average about 43 percent of precipitation during 1941-78. Direct measurement of recharge on Nantucket Island during 1964-83, by means of a method involving measurement of tritium in ground water, indicates that average annual evapotranspiration in that area is only 29 percent of average annual precipitation (Knott and Olimpio, 1986). A value of 50 percent was chosen for the analysis on Block Island because it is a conservative estimate that is within the range of values.

Overland runoff on Block Island was considered by Hansen and Schiner (1964, p. 13) to be a small fraction of average annual precipitation because of the permeable sandy soils that cover most of the island; the presence of numerous closed depressions, particularly in the southwestern part of the island; and the absence of visible runoff during most storms. This assumption is supported by results of numerous field studies in humid, vegetated areas (Freeze and Cherry, 1979, p. 219). Studies on Long Island, N.Y. (Cohen and others, 1968, p. 40), indicate that overland runoff is probably no more than 2 percent of average annual precipitation. Other investigators (Nemickas and Koszalka, 1982; Knott and Olimpio, 1986) have estimated overland runoff in areas of south coastal New England and New York to be from less than 1 to about 2 percent of average annual precipitation.

For purposes of estimating average annual ground-water recharge for Block Island, it was assumed that average annual evapotranspiration and overland runoff are equivalent to 50 percent and 2 percent of average annual precipitation, respectively. Substitution of these values into the equation and use of median annual precipitation of 38.9 inches for 1890-1988 gives the following estimate of average annual recharge:

$$R = 38.9 \text{ in.} - (19.5 \text{ in.} + 0.8 \text{ in.}) = 18.6 \text{ in.}$$

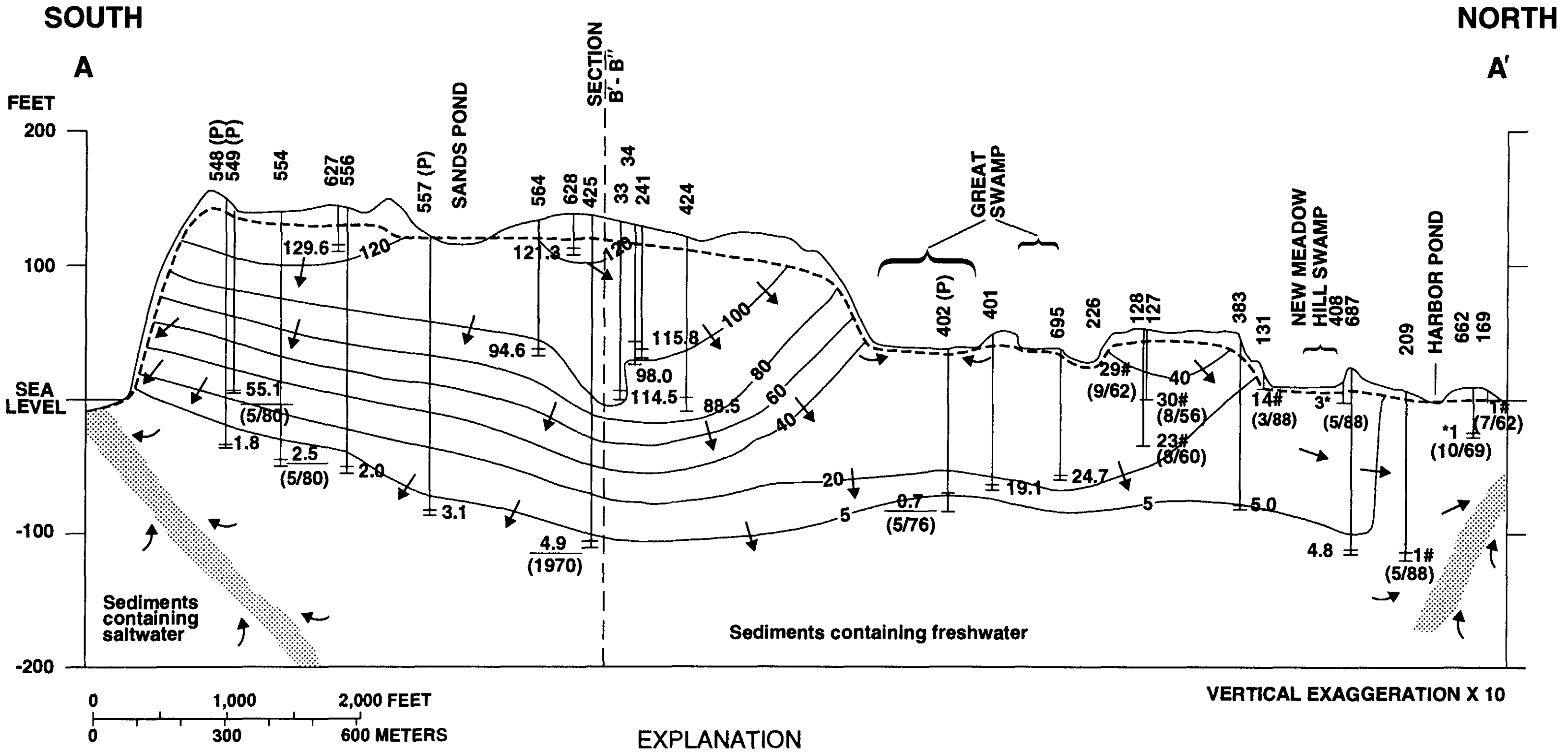
Average annual recharge of 18.6 inches over the 11 mi^2 area of Block Island is equivalent to average annual recharge to Block Island of 9.8 Mgal/d.

Fresh ground water discharges naturally to saltwater by way of streams, shoreline springs and seeps, and upward flow directly to the ocean and saltwater ponds. Measurements and estimates of **ground-water discharge** to streams, springs, and seeps indicate that less than 2 Mgal/d of the average annual ground-water discharge of about 10 Mgal/d discharges to these sites and that most of the balance discharges directly to the ocean and saltwater ponds.

During April 1989, flows of four streams that discharge to saltwater were measured near their mouths, and discharges of 31 small streams, springs, and seeps that discharge to saltwater were estimated. The measured discharges (1.3 Mgal/d) and estimated discharges (1.0 Mgal/d) total 2.3 Mgal/d. Because the measurements and estimates were made during a year of above-average precipitation at a time of year when the water table was near its maximum altitude, it is reasonable to assume that the combined average annual discharge from these sites would be significantly less than 2.3 Mgal/d (assuming estimated discharges to be reasonably correct). Thus, average annual discharge of ground water by upward flow directly to the ocean near the perimeter of the island and by upward flow directly to saltwater ponds may exceed 8 Mgal/d.

Flow

Ground-water flow on Block Island is three dimensional; there are vertical as well as lateral components of flow. The approximate direction of flow can be determined by contouring hydraulic-head measurements made in wells screened at different depths below land surface. As is shown in the map of the water-table contours (fig. 13) and sectional views (figs. 16 and 17), ground water flows from areas of high hydraulic head to areas of low hydraulic head. Precipitation that percolates to the water table flows from points of entry to points of discharge along paths that are approximately perpendicular to these contours. (Arrows depicting flow direction in figures 16 and 17 may not be perpendicular to contours of hydraulic head because of the exaggeration of the vertical scale and because hydraulic conductivity of the aquifer system is neither homogeneous nor isotropic.)



EXPLANATION

FRESHWATER-SALTWATER BOUNDARY--Estimated position

548 (P)
1.8

WELL--Well number is at top; most wells are projected 100 to 400 feet to line of section; (P) indicates that the well is projected more than 400 feet. Horizontal lines indicate screened interval and number is hydraulic head, in feet above sea level. Heads were measured during June-July 1989, unless date is given in parentheses; underscored value indicates head determined from driller's record. Heads were determined from leveled measuring points, except those annotated by # (measured by altimeter survey) or * (estimated from topographic map)

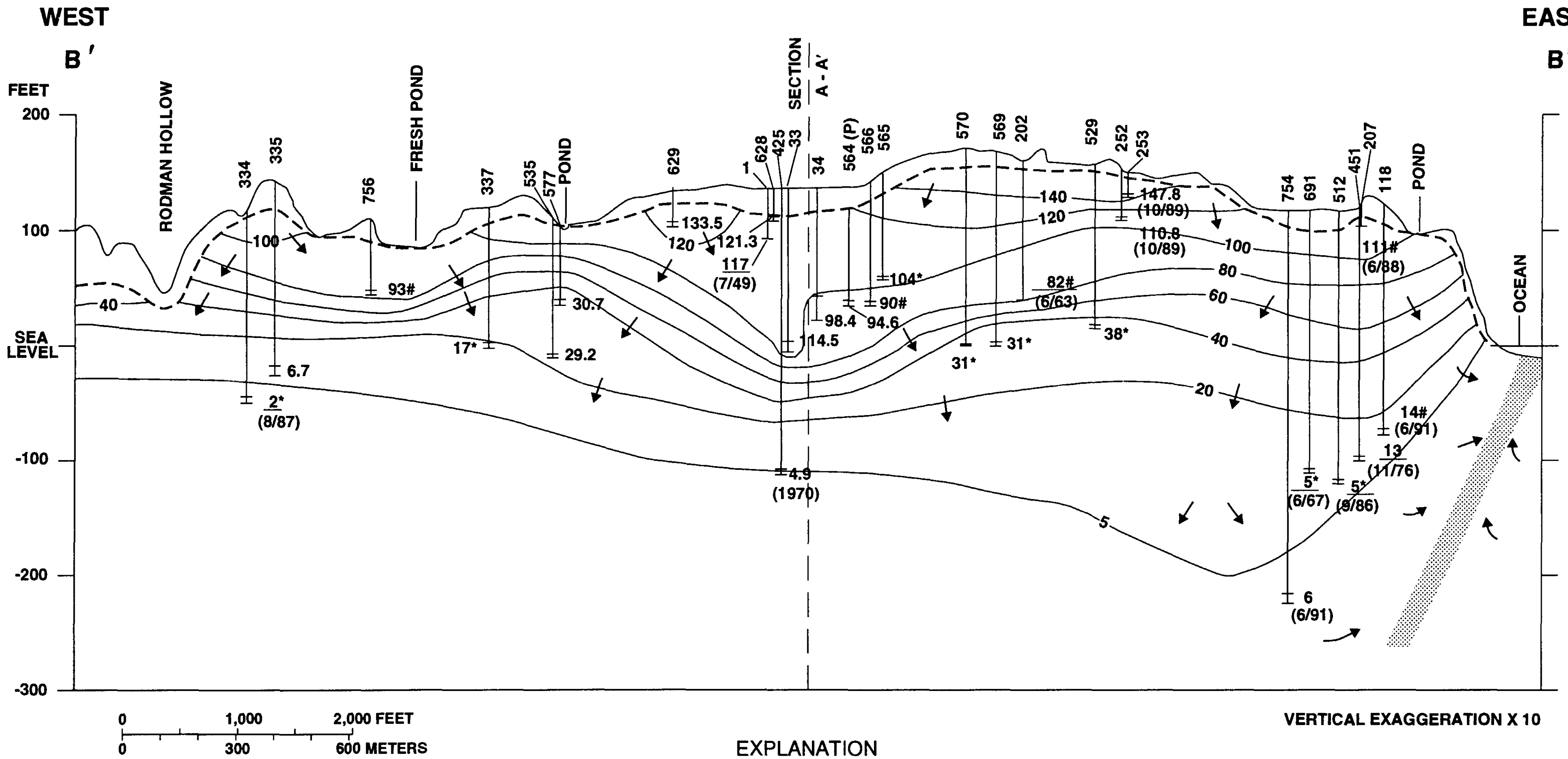
60

EQUIPOTENTIAL CONTOUR-- Shows line of approximate altitude at which water level would stand in a tightly cased well screened at that depth in June-July 1989. Intervals are 5 and 20 feet. Datum is sea level

WATER TABLE-- Position inferred in areas between wells in which water levels were measured

APPROXIMATE DIRECTION OF GROUND-WATER FLOW

Figure 16. North-south hydrologic section through Sands Pond well field showing vertical distribution of hydraulic head and approximate direction of ground-water flow June - July 1989. (Location of section and wells shown in figure 1.)



EXPLANATION

FRESHWATER-SALTWATER BOUNDARY--Estimated position

564 (P) 94.6 WELL--Well number is at top; most wells are projected 100 to 400 feet to line of section; (P) indicates that the well is projected more than 400 feet. Horizontal lines indicate screened interval and number is hydraulic head, in feet above sea level. Heads were measured during June 1989, unless date is given in parentheses; underscored value indicates head determined from driller's record. Heads were determined from leveled measuring points, except those annotated by # (measured by altimeter survey) or * (estimated from topographic map)

20 EQUIPOTENTIAL CONTOUR-- Shows line of approximate altitude at which water level would stand in a tightly cased well screened at that depth in June 1989. Intervals are 5 and 20 feet. Datum is sea level

WATER TABLE--Position inferred in areas between wells in which water levels were measured

APPROXIMATE DIRECTION OF GROUND-WATER FLOW

Figure 17. East-west hydrologic section through the Sands Pond well field showing vertical distribution of hydraulic head and approximate direction of ground-water flow, June 1989. (Location of section and wells shown in figure 1.)

The water-table map (fig. 13) shows the approximate two-dimensional directions of shallow ground-water flow. In general, the water table slopes away from topographically high areas, producing more or less radial flow from these areas toward the ocean. A notable exception is the ground-water drainage area of about 0.36 mi^2 that includes Fresh and Peckham Ponds. Most of the shallow ground-water flows towards Rodman Hollow, as is indicated by the arrows pointing toward the 40-foot depression contour on the water table. From there, flow is southward into the ocean. Some of the shallow ground water in the Fresh Pond drainage area flows from the eastern side of Fresh Pond into Fresh Swamp, eventually discharging into Harbor Pond or Great Salt Pond. Another notable exception is the 120-foot depression contour that encloses Sands Pond; this depression is caused by withdrawals from the pond for public water supply. Occasionally, the pond elevation is higher than ground-water level at the northern end of the pond. On these occasions, some shallow ground water flows northward from the pond toward Great Swamp.

The slope, or gradient, of the water table is steep in most areas because the lenses of low hydraulic conductivity underlying much of the island impede the downward flow of water. Gradients are steepest where the sediments are least permeable, such as along the northeastern and southeastern edges of the island. In these areas, the gradients cause seepage to occur at the surface. The steep vertical gradients shown in figures 16 and 17 (sections A-A′ and B′-B″), also attest to the presence of the many lenses of silt and clay that impede vertical flow.

WATER RESOURCES

The development potential of a water resource is a function of both its quality and abundance. These characteristics and their relationship to the development potential of the Block Island ground-water reservoir are discussed in the following sections.

Water Quality

The suitability of a water supply for public use largely depends on its quality, or chemical composition. The USEPA is required, under the 1986 Amendments to the Safe Drinking Water Act, to establish drinking-water regulations and health advisories for constituents in drinking water that may have an adverse effect on health. **Maximum Contaminant Levels** (MCL's), which are Federally enforceable, establish the maximum permissible level of chemical constituents in water delivered to any user of a public water system. Secondary Maximum Contaminant Levels (SMCL's), which are not Federally enforceable, establish limits for chemical constituents that may affect the aesthetic quality of the water. In addition, States may establish maximum contaminant levels that meet or exceed the water-quality requirements of the USEPA. A summary of MCL's, SMCL's, and Rhode Island maximum contaminant levels for inorganic constituents reported in this study are presented in table 3 (U.S. Environmental Protection Agency, 1987a, 1987b; Rhode Island Department of Health, written commun., 1991).

Precipitation

Precipitation samples were collected for chemical analysis from a rain gage at the northern end of Sands Pond (Burns, 1993). Sodium and chloride are the dominant constituents, and the ratio of sodium to chloride is consistent with a seawater source. Sulfate is present in concentrations greater than those expected from a marine source as a result of anthropogenic inputs (burning of fossil fuels). Precipitation falling on Block Island is slightly acidic; the median **pH** of samples collected during the course of this study was 4.7. Precipitation is, however, naturally acidic because carbon dioxide gas, present in the atmosphere, dissolves in rainwater and produces carbonic acid. The resulting pH is theoretically near 5.6. The median pH of 4.7 for precipitation on Block Island indicates additional acidification by pollutants in the atmosphere.

The **specific conductance** (a measure of ionic concentration) of these samples ranged from 11 to 85 μS/cm, with a median of 35. This range is reflective of the variable concentrations of sodium, chloride, and sulfate—0.75 to 7.8, 1.6 to 14, and 0.7 to 7 mg/L, respectively. Variability in the chemical composition of precipitation is a function of storm track, intensity, and duration. Therefore, it is not possible to define an average composition for precipitation on Block Island.

Table 3. Federal maximum contaminant levels and secondary maximum contaminant levels and Rhode Island maximum contaminant levels for inorganic chemicals, and pH of drinking water

[MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; RI, Rhode Island; --, no data available]

Constituent	Contaminant levels, in milligrams per liter		
	MCL	SMCL	RI
Barium	2.0	--	1.0
Cadmium	.005	--	.005
Chloride	--	250	--
Chromium	.1	--	.05
Copper	1.3	1	--
Fluoride	4.0	2	4.0
Iron	--	.3	--
Lead	.015	--	.015
Manganese	--	.05	--
Nickel	.1	--	--
Nitrate (as N)	10.0	--	10.0
pH	--	6.5 to7.5	--
Silver	--	.10	.05
Sulfate	--	250	--
Zinc	--	5	--

Surface Water

Surface-water bodies (ponds, streams, and fresh-water wetlands) on Block Island receive input from precipitation, ground-water discharge, and, in some cases, storm washovers of saltwater. In addition, their chemical composition can be affected by sea spray and human activities. The chemical composition of these surface-water bodies, therefore, varies both spatially and temporally in response to these factors.

Specific conductance ranged from 56 to 447 µS/cm in 36 ponds and streams sampled during 1989 as part of this study. Because dissolved ions contribute to the electrical conductivity of a solution, specific conductance can be used as an indirect measure of the concentration of dissolved constituents. On Block Island, specific conductance is largely controlled by the concentration of sodium and chloride from sea salt. As the concentration of the ions increases, so does the specific conductance. Surface-water sites where specific conductances were less than 100 µS/cm receive most of their input from precipitation, and specific conductances of the water are in the range of those for precipitation on Block Island. These sites are generally inland, and water levels at these sites fluctuate significantly as a result of rainfall. Sites where specific conductances exceeded 100 µS/cm may receive most of their input from ground water or, in coastal areas, they may receive significant amounts of salt from sea spray or storm washovers. Fresh and Sands ponds, the largest ponds in the southern highlands, are surface expressions of the water table. As such, their composition is similar to that of the shallow ground water (discussed in the following section). Sands Pond, however, is currently used for public water supply, and, since 1985, discharge from BIWC supply well #5 (NHW 425) is pumped into the pond during periods of peak demand to maintain pond levels above the water company's intake. This well is 246 ft deep and is screened at about 110 ft below sea level. The chemical composition of water from this well varies as a function of pumping duration; the **dissolved solids** concentration increases as pumping continues. During 1977-86, concentrations of total dissolved solids in water from this well ranged from 82 to 603 mg/L and total iron from 1.1 to 14.5 mg/L (Burns, 1993). The chemical composition of Sands Pond has changed as a result of input from this well. Periodic testing by the Rhode Island Department of Health has shown that chloride concentrations in the pond have fluctuated from a low of 26 mg/L during the 1984-1985 monitoring period to a high of 89 mg/L during the 1986-87 monitoring period (Burns, 1993).

Direct influxes of seawater also have a substantial effect on water quality in coastal ponds. Middle and Sachem ponds, for example, were inundated by storm surges during the 1956 hurricane (Guthrie and Stolgitis, 1977). In 1962, the chloride concentration in Sachem Pond was 2,100 mg/L (Hansen and Schiner, 1964), considerably higher than the 25 to 35 mg/L background concentrations in ground water. By 1988, at the time of this study, chloride concentrations in the pond had declined to 110 mg/L as a result of flushing of ground water and dilution by precipitation.

Because of the variability in the chemical quality of surface-water bodies on Block Island, it is not possible to make generalizations regarding ambient water quality for the island as a whole. Surface-water bodies in the interior of the island are expected to have chemical compositions reflecting a mixture of precipitation and local, shallow ground water—the higher the specific conductance, the greater the ground-water contribution. In coastal areas, sea spray can contribute a significant quantity of solutes to the pond and can produce elevated[3] sodium and chloride concentrations. Low-lying coastal ponds and marshes, particularly those along the western shore of Corn Neck, are susceptible to storm washovers and may exhibit dramatic changes in chemical composition over a short period of time.

[3]In this report the term elevated concentration refers to a concentration higher than the background level.

Ground Water

Determinations of physical properties and concentrations of common constituents in water from 78 wells and 6 springs were used to characterize the quality of ground water on Block Island. A summary of selected physical properties and concentrations of major constituents is given in table 4.

As expected, ground-water quality on Block Island is strongly affected by sea salt, and sodium and chloride account for 40 to 80 percent of the **anion** and **cation** concentrations, in **milliequivalents per liter**. Complete chemical analyses of major cations and anions were done on water samples from 20 wells (Burns, 1993). The average chemical composition of these samples is illustrated in figure 18.

Physical Properties and Major Chemical Constituents

A complete listing of selected physical properties and concentrations of major and trace constituents in ground water at the 92 sites sampled by the USGS is published under separate cover in Burns (1993). Below is a summary of those data.

Table 4. Summary statistics for selected properties and constituents of ground water on Block Island, R.I.

[Data are in milligrams per liter except as indicated; ND, constituent concentration was less than the analytical detection limit (0.01 for nitrate, 0.003 for iron, 0.01 for manganese, 1.0 for sulfate); see table 3 for limit description; µS/cm, microsiemen per centimeter at 25°C; °C, degrees Celsius; --, no data available]

Constituent or property	Number of analyses	Minimum	Median	Maximum	Limit
pH	90	4.4	6.4	8.2	6.5 to 7.5
Specific conductance (µS/cm)	92	88	203	1,890	--
Sodium	25	9	20	170	--
Chloride	92	8	28	540	250
Nitrate (as N)	83	ND	.84	7.5	10
Iron	76	ND	.07	27	.3
Manganese	76	ND	.05	3.1	.05
Alkalinity (as $CaCO_3$)	42	9	21.5	65	--
Calcium	25	2.7	5.8	19	--
Magnesium	25	3.0	4.5	15	--
Potassium	33	1.0	2	5.3	--
Sulfate	33	ND	15	48	250
Silica	25	9.6	14	24	--

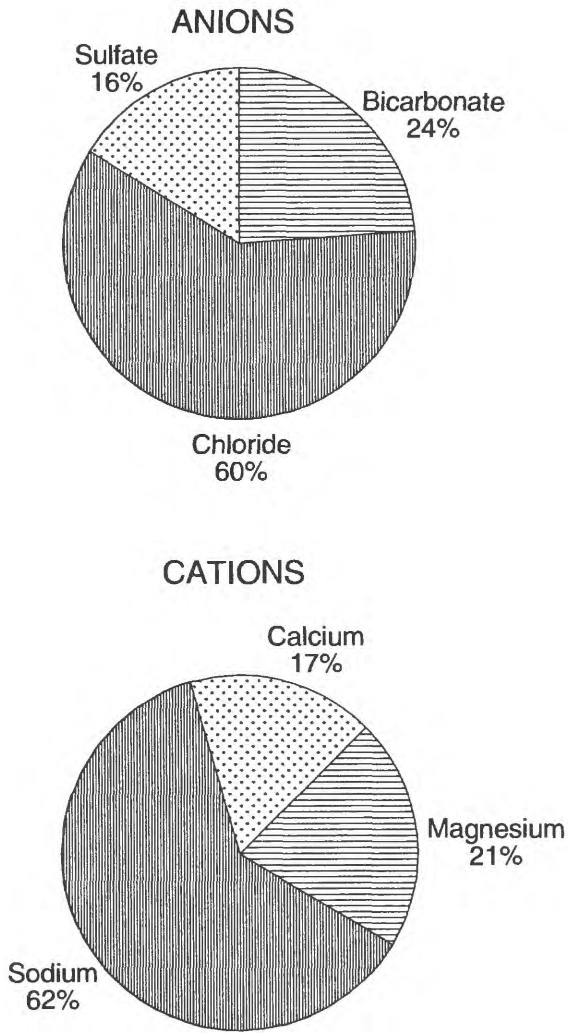


Figure 18. Average chemical composition of ground water on Block Island expressed in percentage of milliequivalents.

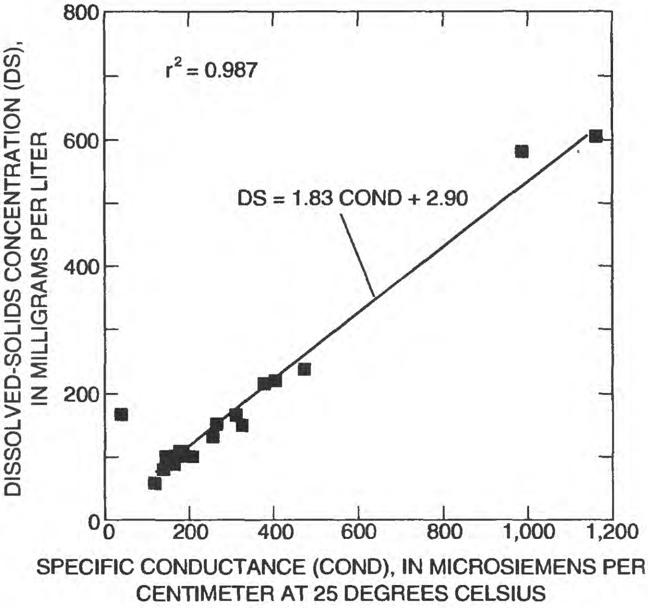


Figure 19. Relation between specific conductance and dissolved-solids concentration in ground water on Block Island.

pH

The pH of ground water sampled ranged from 4.4 to 8.2, and the median was 6.4. The pH of most waters was 6 to 7. Values of pH exceeded 7 at only 6 of the 90 sites sampled. At pH of less than 7, water is mildly corrosive and can dissolve lead, copper, and zinc from metal plumbing and solder. For example, blue-green staining on porcelain fixtures is evidence of copper pipe corrosion.

Specific Conductance

Specific conductance among the 92 sites sampled ranged from 88 to 1,890 μS/cm, and the median was 203. Specific conductance is an indirect measure of dissolved solids because dissolved solids contribute to the ionic concentration, which in turn contributes to the electrical conductance of the solution. Measurements of specific conductance and dissolved solids in water from 23 wells and springs on Block Island show that the dissolved solids (DS) concentration is related to specific conductance (Cond) as follows (fig. 19):

$$DS = 1.83 \times Cond + 2.90, \qquad (3)$$

where

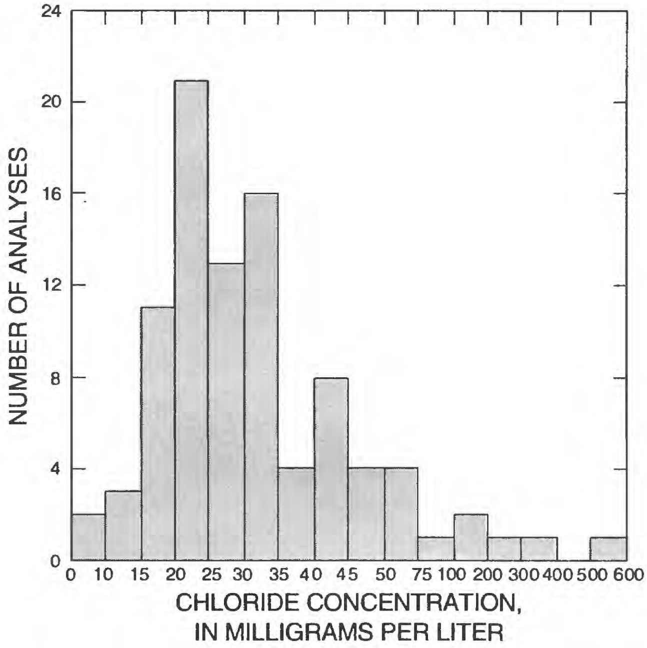
DS is in milligrams per liter, and
Cond is in μS/cm.

Elevated specific conductances on the island are generally attributable to increases in sodium and chloride concentrations. For example, water from well NHW 70 has a specific conductance of 176 μS/cm and a chloride concentration of 23 mg/L, whereas waters from wells NHW 85 and NHW 369 have specific conductances of 470 and 1,890 μS/cm, respectively, and chloride concentrations of 100 and 540 mg/L, respectively. In some cases, however, elevated specific conductance indicates the presence of increased concentrations of other constituents. For example, water from well NHW 153 has a specific conductance of 404 μS/cm but a chloride concentration of only 9 mg/L. In this well, high concentrations of nitrate (7.5 mg/L as N) are partly responsible for the elevated specific conductance.

Sodium and Chloride

Ground water on Block Island is strongly affected by the salts in sea water. Sodium and chloride, which are common in sea salts, on average account for more than half of the ions in ground water on Block Island (fig. 18). The range and median chloride and sodium concentrations are given in table 4. Frequency distributions for sodium and chloride in ground water sampled on the island during the course of this investigation are shown in figure 20. Background chloride concentration is 30 mg/L or less; background sodium concentration is 20 mg/L or less. Although this concentration is higher than that observed in precipitation on the island, dissolution of dry fallout (composed predominantly of sea salt) during recharge can produce higher salt concentrations in ground water than in precipitation. Sodium and chloride contribution from human activities, such as road salting and use of septic tanks, probably do not affect ground water quality because road salt is not used on the island, and nitrate, an indicator of contamination of ground water by septic tanks, is found at low concentrations in the water sampled.

The water from some wells had chloride concentrations that exceeded background concentrations, probably as a result of saltwater intrusion (fig. 20). Wells that are screened below sea level, particularly those near to the coast, are susceptible to saltwater intrusion because the freshwater lens is thin. Wells in the interior of the island are less susceptible to saltwater intrusion because the freshwater lens thickens toward the center of the island. Wells screened as deep as 200 ft below sea level have yielded concentrations of chloride only slightly above background levels (fig. 21). Intensive pumping in these wells, however, may result in dramatic increases in salt content (see well 425, fig. 21). Shallow wells, screened above sea level, cannot be affected directly by saltwater intrusion. However, diffusion from the saltwater-freshwater interface can cause an increase in dissolved solids in shallow wells drilled near the coast. In addition, coastal areas can receive abundant seaspray and salts may leach into the aquifer producing elevated sodium and chloride concentrations in shallow ground water.



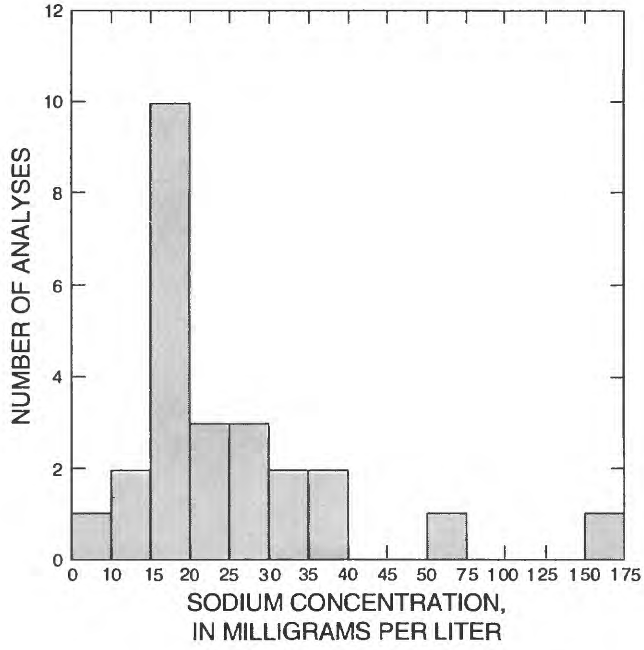


Figure 20. Frequency distributions for chloride and sodium concentrations in ground water on Block Island. (Note unequal concentration intervals.)

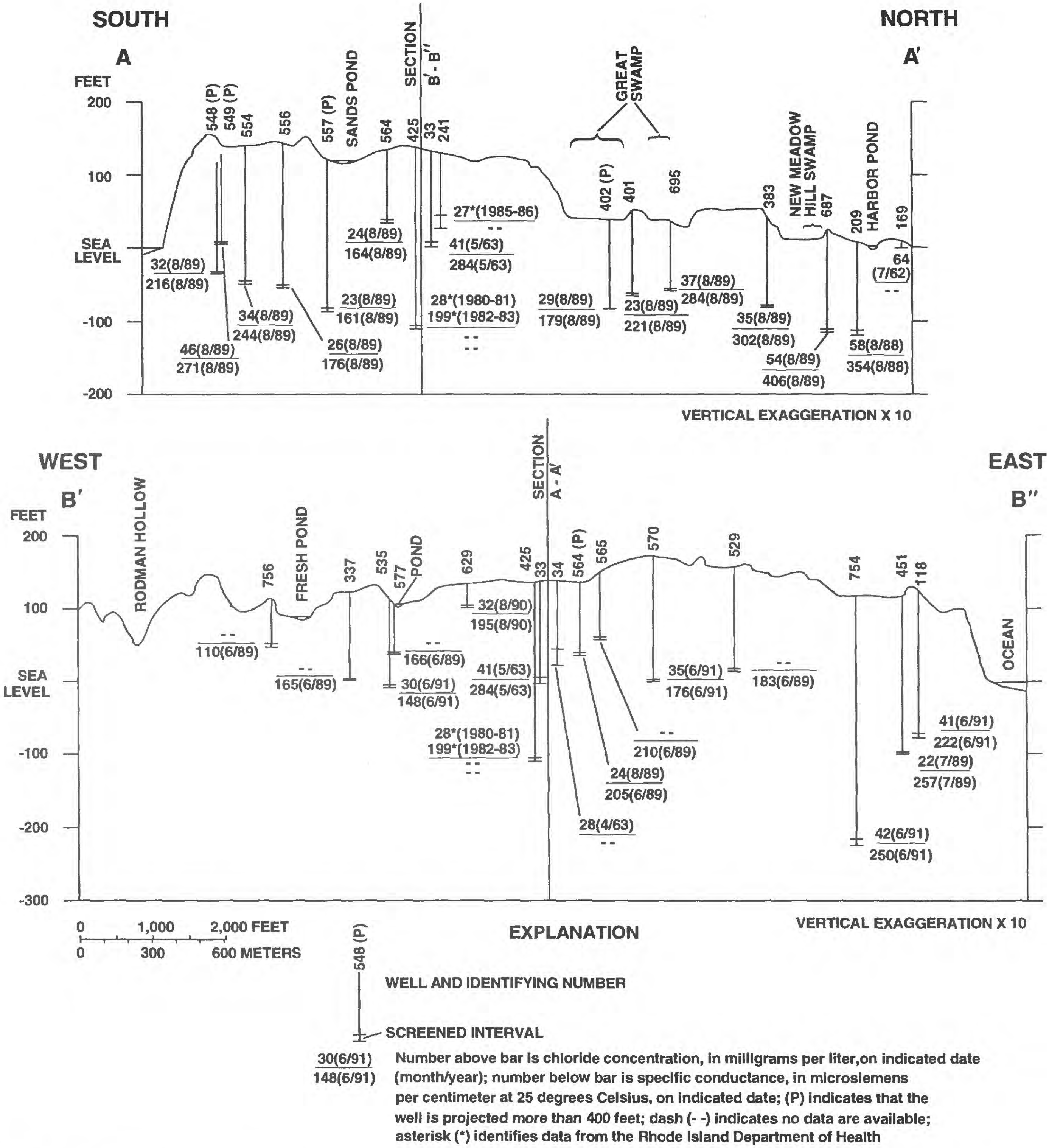


Figure 21. Hydrologic sections showing chloride concentrations and specific conductance in ground water in the southern part of Block Island on selected dates. (Location of sections shown in figure 1.)

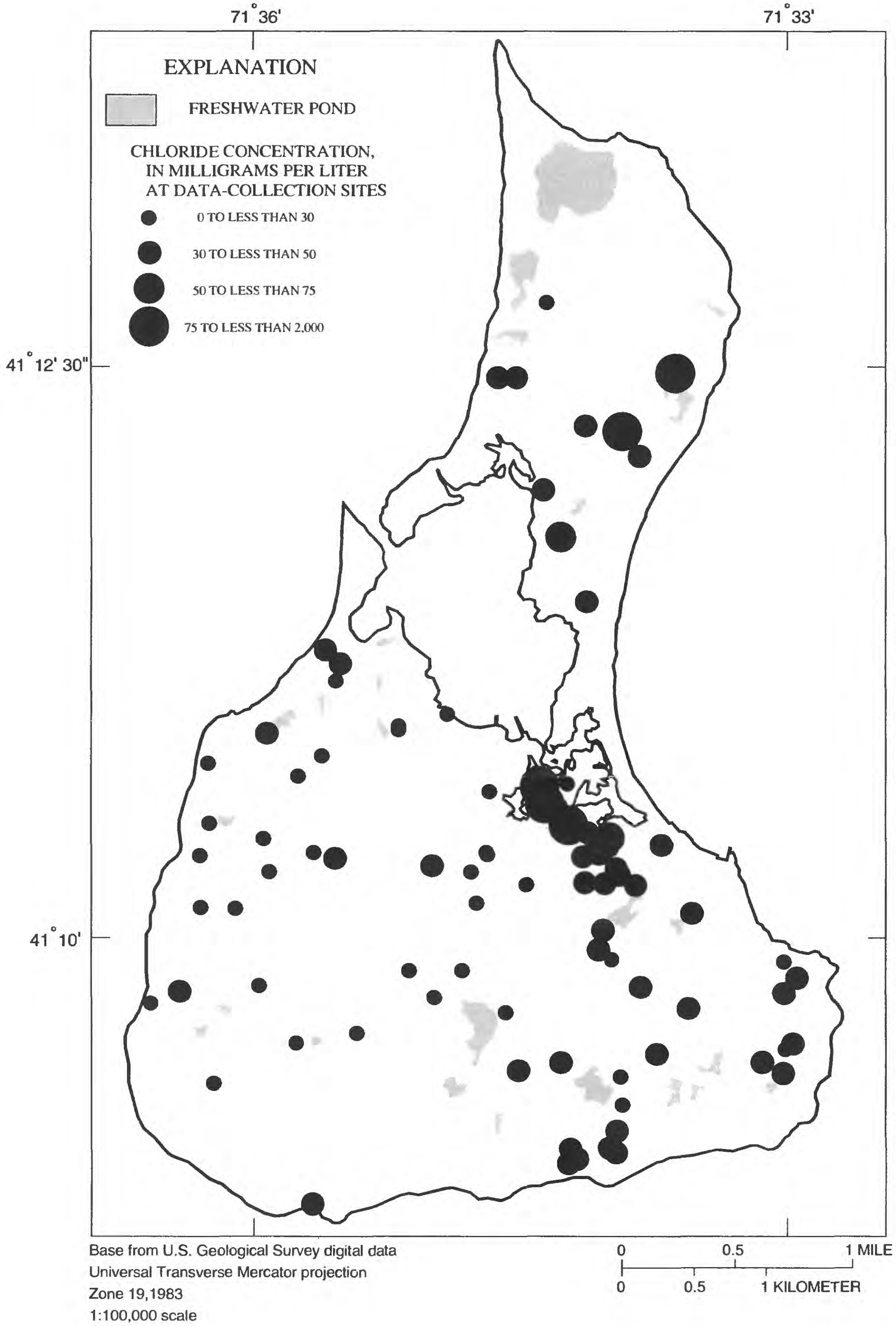


Figure 22. Areal distribution of chloride concentration in ground water on Block Island.

The spatial distribution of chloride concentrations in ground water on Block Island is shown in figures 21 and 22. Background chloride concentrations were found in water from wells as deep as 140 feet below sea level in the interior parts of the island where the freshwater lens is relatively thick. However, chloride concentrations above background were found at less than 100 feet below sea level in coastal areas where the freshwater lens is thin. Chloride concentrations clearly indicative of saltwater intrusion (greater than 75 mg/L) are found predominantly in low-lying areas of Corn Neck and the areas surrounding Old Harbor and New Harbor.

Nitrate

Nitrate concentrations among the 83 wells sampled ranged from less than 0.01 to 7.5 mg/L (as N), and the median was 0.84 mg/L. The concentration did not exceed the 10 mg/L limit established as a safe level for drinking water (U.S. Environmental Protection Agency, 1987a) at any of the sites. At more than half of the sites, nitrate concentrations were less than 1 mg/L (fig. 23).

Nitrate is a naturally occurring constituent in precipitation. Rainfall sampled on Block Island contained 0.09 to 1.2 mg/L nitrate (as N). However, most nitrate in precipitation is used by plants as the water infiltrates through the soil. Of the 83 wells sampled, 38 had nitrate concentrations greater than 1 mg/L, suggesting that it is attributable to human activity, such as septic-systems, fertilizer application, and runoff from livestock pens. Shallow wells are most susceptible to nitrate contamination because of their proximity to these potential sources; however, contamination of ground water in deep wells can occur if they are not properly sealed at the surface.

Iron and Manganese

Dissolved iron concentrations among the 77 wells and springs sampled ranged from less than 0.003 to 27 mg/L, and dissolved manganese concentrations ranged from less than 0.01 to 3.1 mg/L. Concentrations at 26 of the sites exceeded the SMCL of 0.3 mg/L for dissolved iron (fig. 24), and concentrations at 35 sites exceeded the SMCL of 0.05 mg/L for dissolved manganese. These SMCL's were established because high concentrations of iron and manganese can affect the aesthetic quality of the water.

Iron is the constituent of concern to most homeowners on Block Island because it oxidizes rapidly upon contact with oxygen creating a rust-colored precipitate that stains laundry and plumbing fixtures,

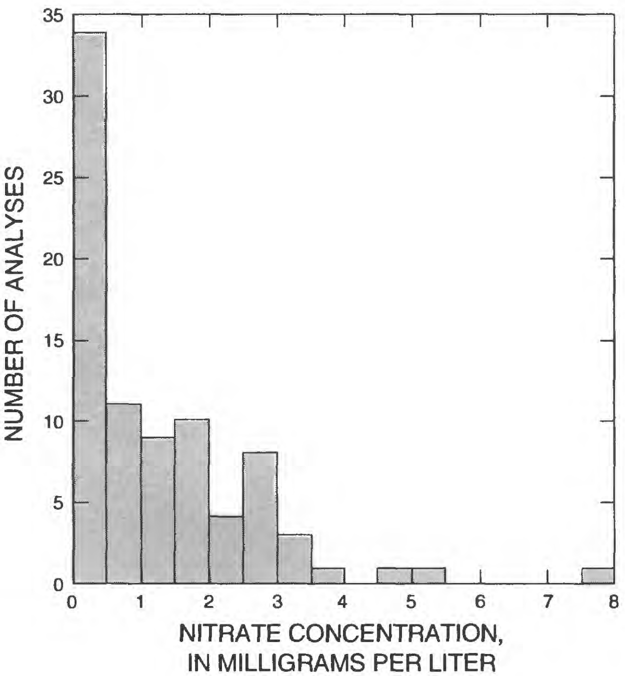


Figure 23. Frequency distribution for nitrate concentrations in ground water on Block Island.

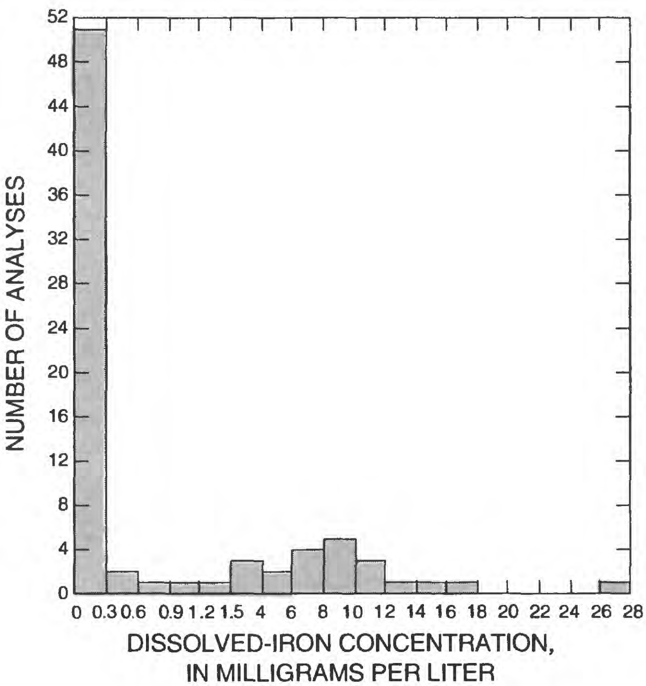


Figure 24. Frequency distribution for dissolved-iron concentrations in ground water on Block Island. (Note unequal concentration intervals.)

clogs water-filtration equipment, and makes the water unsuitable for drinking or cooking. The incidence of high iron concentrations in ground water appears to be predominantly along Corn Neck and in the eastern half of the southern highland; with lower concentrations found in the western half of the southern highland (fig. 25). In addition to the 77 ground-water samples that were analyzed for dissolved iron by the USGS, a questionnaire was distributed by the Block Island Water Resources Group (written commun., 1989) requesting information on water quality. Respondents were asked whether they had experienced problems of staining, assumably from high concentrations of iron in their water supply. A positive response was interpreted as a dissolved-iron concentration in excess of 0.3 mg/L. A comparison of the analytical and survey results reveals that discrepancies are largely confined to the southwestern part of the island were homeowners reported water-quality problems, but analytical results revealed low dissolved-iron concentrations. A number of these samples did, however, contain dissolved manganese at levels above the SMCL of 0.05 mg/L that would adversely affect the aesthetic quality of the water.

Examination of the average concentration of major constituents (excluding sodium and chloride) shows that the chemical composition of high-iron ground water is distinct from that of low-iron ground water and is characterized by higher concentrations of alkalinity, sulfate, and silica (fig. 26). High dissolved-iron ground water, common in many Atlantic Coastal Plain aquifers, has commonly been attributed to the reduction of insoluble Fe(III) in iron-oxyhydroxides to the more soluble Fe(II) (Back and Barnes, 1965; Langmuir, 1969). However, elevated sulfate concentrations, found on Block Island only in association with high concentrations of dissolved iron, suggest that the oxidation of iron-sulfide minerals (for example, pyrite) is the dominant source of iron. Chapelle and Lovley (1992) demonstrated that discrete zones of high-iron ground water can be produced where sulfate-reducing bacteria are excluded by Fe(III)-reducing bacteria. The association of high dissolved-iron concentrations with elevated silica and alkalinity concentrations suggests a link between the aquifer mineralogy and the occurrence of dissolved iron. Elevated concentrations of dissolved silica coupled with high sulfate concentrations in high dissolved-iron ground water suggest that the water-rock interactions in these waters is strongly affected by the oxidation of iron-sulfide minerals. Pyrite oxidation alone does not account for the observed increase in alkalinity. Oxidation of organic matter, however, can result in the observed higher alkalinity. Therefore, the chemical evolution of high-iron ground water is consistent with the simultaneous oxidation of pyrite and organic matter.

Geologic Controls on Iron Distribution

The spatial distribution of high-iron ground water can be explained, at least in part, by the island's depositional history. As described previously, Block Island consists of a complex interlobate moraine. Because the island consists of debris deposited by two separate ice lobes, the materials attributable to each of these lobes may be mineralogically distinct. In the source area for the Narragansett Bay-Buzzard's Bay lobe, iron sulfides are known to occur in hydrothermal deposits along the western edge of the Narragansett Basin, as accessory minerals in Narragansett Basin rocks, particularly the Rhode Island Formation (Quinn, 1971), and in Cretaceous coastal-plain sediments underlying Block Island Sound (Sirkin, 1986). In contrast, biotite and hornblende are the common iron-bearing minerals in the source area for the Hudson-Champlain sublobe that flowed across central Rhode Island. Organic matter, which is absent in the plutonic rocks of central Rhode Island, is abundant in Narragansett Basin rocks, coal accumulations are mineable in the Rhode Island Formation (Quinn and Moore, 1962). Organic matter, in the form of lignite, is also commonly reported in Cretaceous coastal-plain deposits—namely, the Magothy and Raritan Formations (Knobel and Phillips, 1988; Back and Barnes, 1965).

Well-log data (Burns, 1993) reveal that transported blocks of Cretaceous coastal-plain sediments are most commonly found in the northern and eastern parts of the island (see fig. 7). Therefore, the deposits from the Narragansett Bay-Buzzard's Bay ice lobe that derived material from Narragansett Basin and the Coastal Plain should have been rich in organic matter and iron-sulfide minerals relative to the deposits from the Hudson-Champlain ice sublobe, which derived the bulk of its sediment from the plutonic and metamorphic rocks of central Rhode Island.

The contact between deposits attributable to each of these lobes has not been mapped. However, the water chemistry provides some insight into the probable location of the margin. Because the chemistry of high-iron water requires the presence of both pyrite and organic matter, these waters are interpreted to have been in contact with deposits attributable to the Narragansett Bay-Buzzard's Bay ice lobe. The spatial distribution of high-iron water (fig. 25) suggests that these deposits are

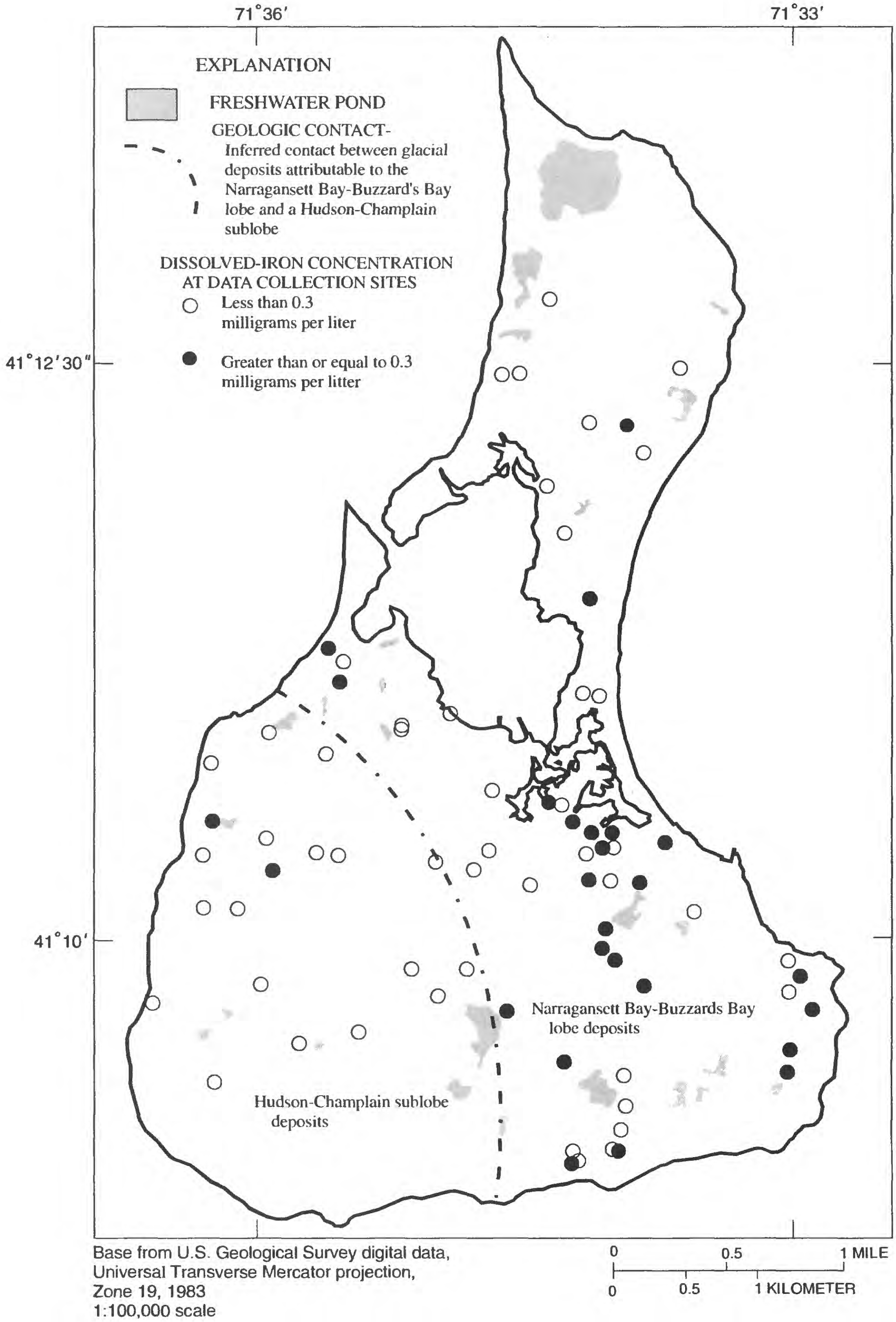


Figure 25. Areal distribution of dissolved-iron concentrations in ground water on Block Island.

largely confined to the eastern and possibly northern parts of the island. The zone of low-iron ground water in the southwestern part of the island is interpreted to be in contact with deposits from the Hudson-Champlain sublobe. These findings are consistent with the glacial origin of Block Island and suggest that the interlobate margin is reflected in the position of the hydrochemical interface in the southern half of the island along a line running from northwest to southeast approximately from Grace Cove to Barlow Point (fig. 25).

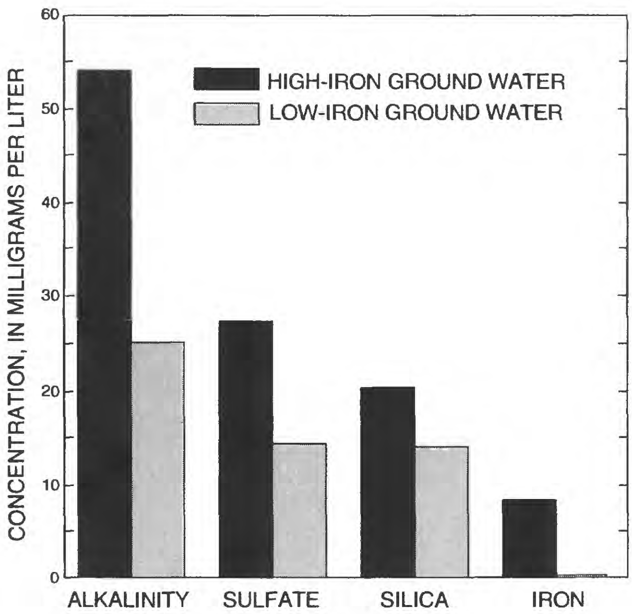


Figure 26. Average chemical compositions of high-iron and low-iron ground water on Block Island.

Trace Elements

Analysis of trace elements was performed on samples from selected wells and springs. A summary of concentrations is given in table 5; the complete chemical analyses are available in Burns (1993). None of these constituents were found at concentrations in excess of the USEPA or State drinking-water regulations.

Organic Chemicals

Eleven sites were sampled for dissolved **organic chemicals**, including four springs (NHS 14, 109, 132 and 510), three USGS wells (NHW 264, 629 and 632), and four private wells (NHW 198, 419, 658, and 780). Sample sites were chosen on the basis of proximity to buried oil tanks, as documented by the Town of New Shoreham, because leaking oil tanks would be the most likely source of organic chemicals on the island. Selected site characteristics and results of analyses are listed in table 6. No evidence of dissolved organic chemicals was found at the sites sampled.

Temporal Trends

Temporal changes in water quality were assessed by comparing the concentration of chloride in 21 wells and springs sampled as part of this study and that of Hansen and Schiner (1964). The chloride data for these sampling sites is shown in figure 27. Points plotting along the line in this graph show that the chloride concentration in 1988-89 equals the chloride concentration in 1962; therefore, no temporal change in chloride concentration has occurred. Chloride concentration was greater in 1988-89 than 1962 at only two wells, NHW

Table 5. Summary statistics for selected trace elements of ground water on Block Island, R.I.

[Data are in milligrams per liter; ND, constituent concentration was below the analytical detection limit (0.01 for copper, 0.01 for fluoride, 0.01 for lead, 0.001 for silver, 0.003 for zinc); see table 3 for limit description]

Constituent	Number of analyses	Minimum	Median	Maximum	Limit
Barium	14	0.026	0.097	0.21	1
Bromide	23	.04	.15	1.1	--
Copper	14	ND	.01	.13	1.3
Fluoride	10	ND	ND	.3	4
Lead	14	ND	ND	.01	.015
Silver	14	ND	ND	.002	.05
Stronium	14	.026	.067	.21	--
Zinc	14	ND	.027	2.0	5

Table 6. Presence of organic chemical constituents in ground water on Block Island

[Site: S, spring; W, well. GC/FID - gas chromatographic, flame ionization detection; --, no data]

Site	Well depth, in feet below land surface	Water level, in feet below land surface	GC/FID scan results
NHS 14	--	--	Negative
NHS 109	--	--	Negative
NHS 132	6	3	Negative
NHS 510	--	--	Negative
NHW 198	171	--	Negative
NHW 264	31	9	Negative
NHW 419	85	33	Negative
NHW 629	35	3.4-16.8	Negative
NHW 632	22	11.8-18.2	Negative
NHW 658	32	6	Negative
NHW 780	64	38	Negative

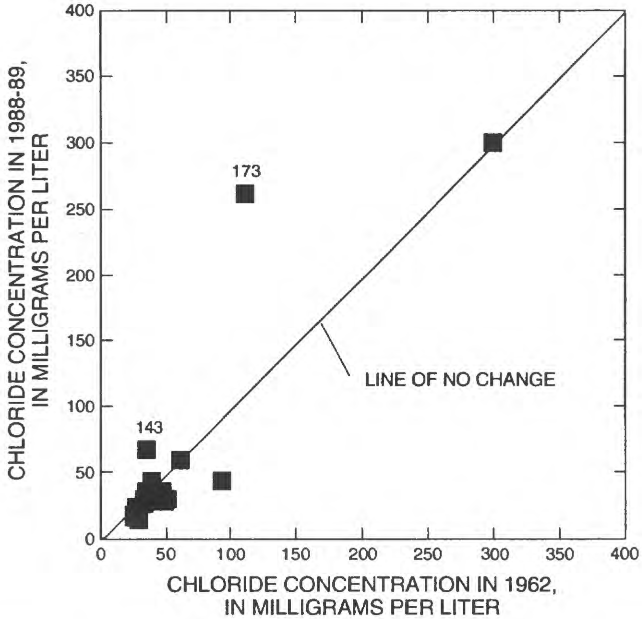


Figure 27. Change in chloride concentration in 21 wells on Block Island, 1962 and 1988-89. (Labels are well numbers.)

143 and NHW 173. These wells penetrate to 43 and 56 ft below sea level respectively and are both in low-lying areas close to the shore. Increased chloride concentrations at these sites are attributable to saltwater intrusion induced by pumping in this low-lying shoreline area where the freshwater lens is thin.

Chloride concentration declined at several wells, including wells NHW 41, 67, 121, 156, 180, and 222. The decreases observed at NHW 121, 156, and 180 probably reflect the variable contribution of sea spray to the composition of recharge water because only one of these wells, NHW 156, penetrates below sea level (to an altitude of -14 ft) and because all three sites are near the shore.

The remaining three wells, NHW 41, 67, and 222, penetrate to altitudes below -40 ft. Chloride concentrations in all three wells range from 50 to 92 mg/L in 1962. As of the late 1980's, however, water from each of these wells was found to have chloride concentrations 50 percent or less than those measured in 1962. All of these wells are near the shore, and the elevated chloride concentrations observed in 1962 are attributed to saltwater intrusion and the chemical diffusion of chloride across the freshwater-saltwater interface. During 1939-59, Block Island received below-average precipitation (fig. 2). Declining water levels in the freshwater lens would have promoted upward migration of the freshwater-saltwater interface, causing intrusion of brackish and saline water into zones previously occupied by fresh water. Although greater than normal precipitation fell during 1960-61, this short-term increase could not offset the trend of the preceding 20 years. During 1966-86, however, greater-than-average precipitation fell on Block Island. Increased storage of freshwater during this period would have prompted downward migration of the interface and an accompanying decrease in chloride concentrations.

Chloride fluctuations produced as a result of natural changes in the position of the freshwater-saltwater interface can be expected to occur over a period of years; however, upconing beneath pumped wells can result in dramatic changes in chloride concentration in just a few months.

Potential Sources of Contamination

Although no evidence of widespread ground-water contamination was found during the course of this study, potential sources of contamination exist, including saltwater intrusion, leakage from septic systems and underground storage tanks, and leachate from the closed Block Island landfill.

Saltwater Intrusion

Saltwater intrusion is the process by which the freshwater-saltwater interface migrates upward in response to a pumping-induced decline in hydraulic head. Although wells that are screened below sea level and located along the shore are most easily affected, any well screened below sea level is at risk. Chloride data clearly demonstrate the effect of pumping on the position of the interface.

Until 1980, the BIWC used multiple wells in the Sands Pond area for its water supply. Beginning in 1981, however, well NHW 425 (BIWC well #5) was used exclusively. This well penetrates to 109 ft below sea level and is pumped at about 35 gal/min during peak demand in the summer. Drawdown in the well during periods of intensive pumping in 1981 and 1982 resulted in upconing of the interface and subsequent increases in chloride concentration (figs. 21, 28). The well was not pumped during 1983-84, and chloride concentrations declined to background levels by the time the well was put back in service in 1984-85. Once back in service, however, chloride concentrations began to rise again as upconing of the interface resumed. The relation between chloride concentration and pumping shown here clearly demonstrates the susceptibility of deep wells to saltwater contamination.

Septic Systems

Septic systems can produce locally high nitrate and bacteria concentrations in shallow ground water. This is of particular concern in relatively densely populated parts of the island that are not sewered. The Rhode Island Department of Environmental Management requires a 100-ft separation between a domestic-supply well and a septic leach field (Rhode Island Department of Environmental Management, written commun., 1989). This setback distance is designed to ensure adequate dilution and attenuation of contaminants before the water enters a well. The nitrate data collected as part of this study indicate that water-supply contamination due to septic systems is not widespread. Although septic systems may be partly responsible for elevated nitrate concentrations at some wells, none of the water samples collected exceeded the MCL of 10 mg/L. It should be noted, however, that most residences on the island are served by deep wells that are less susceptible to contamination from a surficial source than shallow wells are. Local contamination of shallow ground water by individual septic systems and cesspools may be present in some areas.

Underground Storage Tanks

Underground storage tanks (USTs) can be a serious threat to ground-water quality. A fuel-storage-tank survey conducted by the Town of New Shoreham indicated that of 194 underground storage tanks reported in use as of 1990, 4 tanks were reported to be more than 30 years old, 22 were 20 to 30 years old, 76 were 10 to 20 years old, and 9 were reported to be of unknown age. All UST's have a limited life expectancy; old, uncoated tanks last an average of 12 years, whereas newer, coated tanks

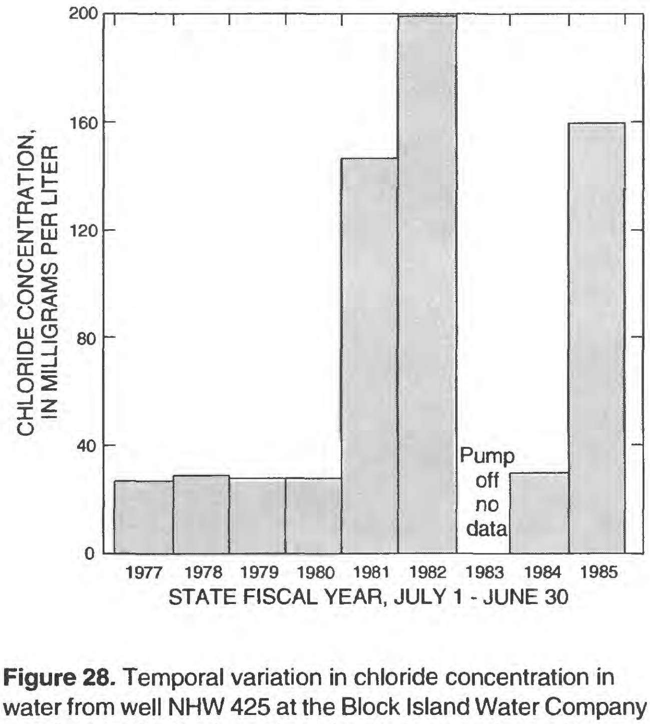


Figure 28. Temporal variation in chloride concentration in water from well NHW 425 at the Block Island Water Company well field, 1977-85. (Location of well shown in figure 35.)

are expected to last 25 years. Leakage from such storage tanks can cause serious and widespread contamination, which may not be noticed until catastrophic failure of the tank occurs or contamination is detected in an adjacent water-supply well. Cleanup of tank leakage is costly and difficult. Although the town has banned the installation of additional tanks, existing tanks are a potential source of ground-water contamination.

Landfill

Leachate from a landfill can be a serious threat to ground-water quality. Any leachate leaving the Block Island landfill will flow west, toward the ocean, under the influence of the local hydraulic gradient (fig. 13). No evidence of ground-water contamination was found in a USGS well (NHW 264) to the south of the landfill, or in a spring (NHS 88) and Middle Pond to the north of the landfill. Although leachate may be present in the unpopulated area to the west of the landfill, the results of this study indicate that ground water in populated areas to the north, south and east of the landfill has not been adversely affected.

Water Availability

Surface-water and ground-water resources have been developed for private and public water supply on Block Island. Additional supplies can be developed from both sources, however, surface-water sources are more limited than ground-water sources. Ground water can be developed from wells virtually anywhere on the island to supply domestic needs. Ground-water supplies for larger commercial and public-supply needs also can be developed at many locations provided that care is taken not to complete the wells too far below sea level or to pump them at rates likely to induce saltwater intrusion.

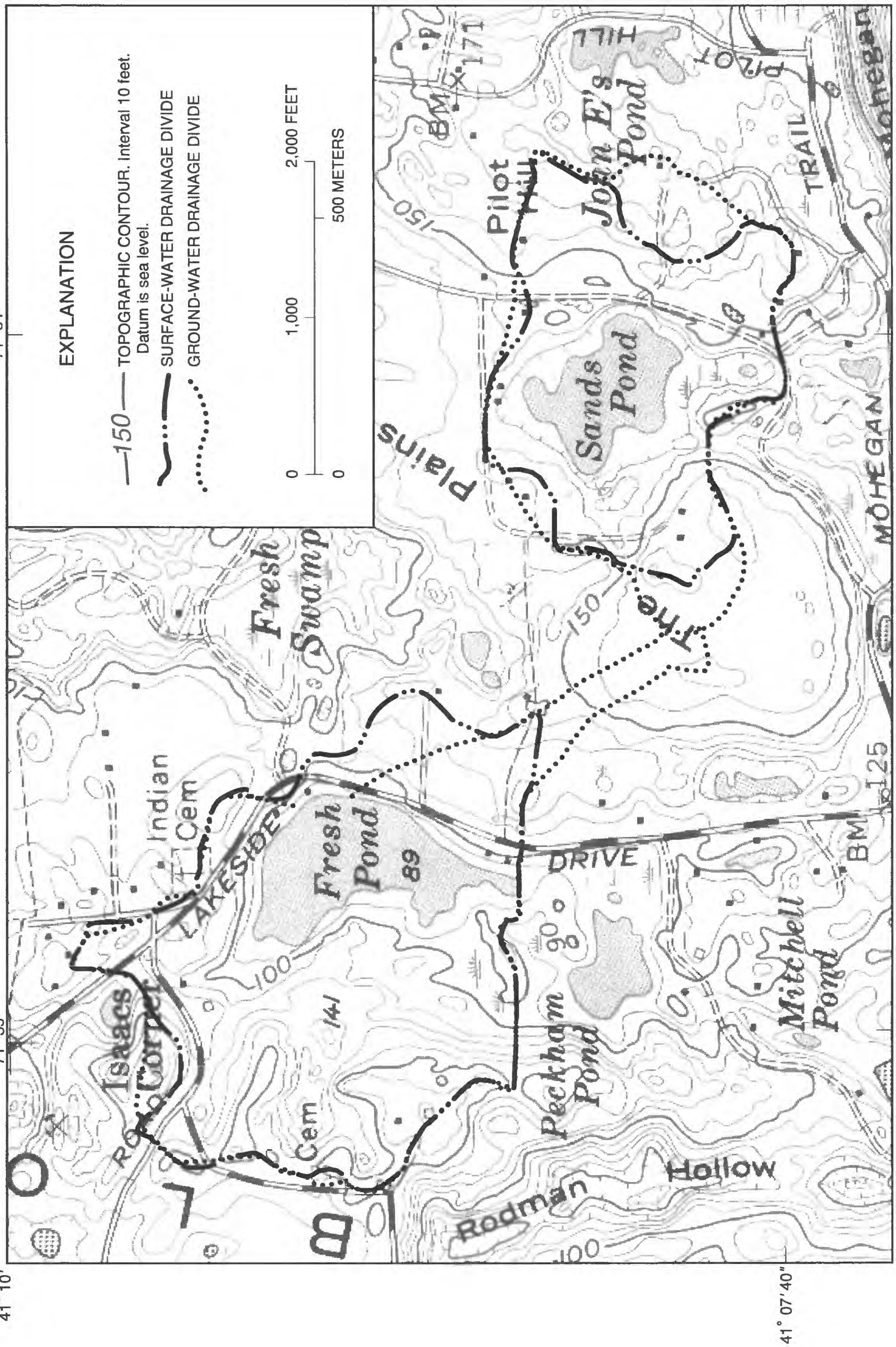
Surface Water

Only Sands Pond and Fresh Pond seem to be viable sources of public water supply. Sands Pond, which is currently (1991) the principal source of the town's public water supply, is fully developed. During some years of below-average precipitation, its yield must be augmented with water from wells to meet peak summer demands. Fresh Pond, 0.5 mi northwest of Sands Pond, has been proposed as a possible source of additional water supply (C.E. Maguire, Inc., 1984, p. C-22). This proposal is under consideration by the Town, but there is concern about how extraction of water from Fresh Pond will affect its level (Henry Dupont, Block Island Water Company, oral commun., 1991). Estimates of the effects of extracting water at rates of 30,000 and 50,000 gal/d on the level of Fresh Pond during May-October are provided as part of this investigation. Because of the need to protect water quality, the surface-water and ground-water drainage areas were delineated for these ponds (fig. 29). The surface-water drainage divides are based on land surface elevations, whereas ground-water divides are based on water-table altitudes. The surface-water and ground-water drainage divides do not always coincide.

Sands Pond

Sands Pond is in a topographic depression that extends below the water table; there is no stream inflow or outflow. The pond has a surface area of about 14.7 acres and an average depth of about 8 ft (C.E. Maguire, Inc., 1984, p. B-10); its maximum depth is about 12 ft. It has a surface-water drainage area of about 64 acres and a ground-water drainage area of about 79 acres (fig. 29). Since completion of a new water-treatment plant in 1985, annual withdrawals from Sands Pond for public supply have ranged from 14.4 Mgal in 1986 to 17.4 Mgal in 1989 and 1990 (James Collins, Block Island Water Company, written commun., 1992). More than 75 percent of these volumes were withdrawn during May-October. The average rate of withdrawal during these 6-month periods ranged from 67,000 to 74,000 gal/d.

The level of Sands pond is affected by water-table fluctuations in adjacent sediments, overland runoff into the pond from its surface drainage area, precipitation on its surface, evaporation, the addition of water pumped from a nearby well (NHW 425), and withdrawals for public supply. Fluctuation of the pond level in response to net recharge during two relatively dry years (1988 and 1990) and a relatively wet year (1989) is shown in figure 30. Net recharge is defined as monthly precipitation minus the sum of evaporation and BIWC withdrawal. Monthly evaporation data for November through April, and monthly data for well discharge to the pond, were unavailable. Because the pond is much like a large-diameter well, its level rises and falls with the general overall rise and fall of the water table as measured in observations wells (see fig. 14). Pumping from nearby supply well NHW 425 causes no water-level drawdown in the pond, because the bottom of the pond



BASE FROM U. S. GEOLOGICAL SURVEY
BLOCK ISLAND, RI, 1:24,000, 1957
PHOTOREVISED 1970

Figure 29. Surface- and ground-water drainage areas for Sands and Fresh Ponds.

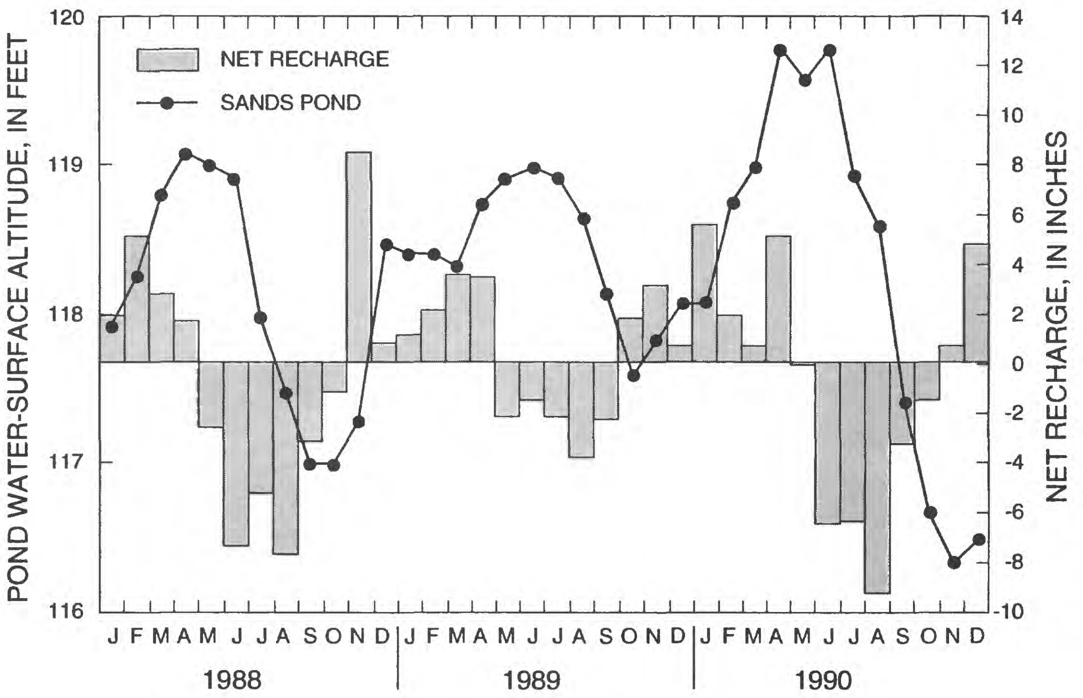


Figure 30. Altitude of the water surface of Sands Pond and net recharge to the pond, 1988-90.

and the well screen are separated by more than 200 ft of material in which average vertical hydraulic conductivity is very low.

Prior to the use of Sands Pond as a source of public water supply, ground-water flowed into it, as it does today, from its east, south, and west sides where the water table is higher than the pond level (see fig. 13), and flowed out of it into the ground along its north side where the water table was lower than the pond level. Now, however, large seasonal withdrawals for water supply combined with evaporation losses cause the pond level to be below the water table in sediments at the north end of the pond much of the time between May and October. When the gradient is reversed in this way, ground water flows into the pond here also.

Water levels measured at the northern end of the pond in well NHW 628, which is screened at an altitude 5 to 8 ft lower than that of the pond bottom, show that the ground-water level was as much as 2 ft higher than the pond during the summer of 1989 (causing ground water to flow into the pond). During the winter and spring of 1988 and 1989, on the other hand, water levels in this well were as much as 1 to 3 ft lower than the pond level (causing pond water to flow northward into the ground-water-flow system).

Water budgets were developed for Sands Ponds for 6-month periods, May through October, in each of years 1988, 1989, and 1990 (table 7). The budgets were prepared to assist in estimating a volume of water that could be withdrawn during dry summers without causing the pond to decline to an altitude of 115 ft, the approximate altitude of the BIWC intake pipe.

Inflow to the pond during the budget periods resulted from precipitation on the pond, ground-water pumpage into the pond from well NHW 425, and ground-water inflow. Inflow from overland flow from the pond's surface drainage area was assumed to occur largely during the non-growing months and was neglected in budget computations.

Ground-water inflow to the pond was estimated as the difference required to balance the water budget equation. It is recorded in table 7 as net ground-water inflow, because it is possible that additional ground-water inflow occurred that was balanced by an equal

Table 7. Estimated water budget for Sands Pond, May-October 1988-90

[Inflow = Outflow + Change in Storage]

Water-budget component	1988			1989			1990		
	Inches	Gallons × 1,000	Gallons per day × 1,000	Inches	Gallons × 1,000	Gallons per day × 1,000	Inches	Gallons × 1,000	Gallons per day × 1,000
INFLOW[1]									
Net ground-water inflow[2]	22.76	9,084	49.38	18.07	7,212	39.21	8.52	3,401	18.49
Precipitation on pond	13.01	5,193	28.2	29.8	11,902	64.68	13.66	5,452	29.63
Ground-water pumpage into pond[3]	5.26	2,100	11.41	.53	210	1.14	2.10	838	4.55
Subtotal	41.03	16,377	88.99	48.40	19,324	105.03	24.28	9,691	52.67
OUTFLOW									
Evaporation from pond[4]	27.14	10,833	58.87	28.12	11,224	61.00	27.61	11,020	59.89
Pumpage from pond	33.93	13,544	73.61	33.38	13,324	72.41	34.23	13,664	74.26
Subtotal	61.07	24,377	132.48	61.50	24,548	133.41	61.84	24,684	134.15
Change in pond storage[5]	-20.04	-8,000	-43.49	-13.10	-5,224	-28.38	-37.56	-14,993	-81.48

[1]Surface inflow to the pond was assumed to be negligible.

[2]Calculated as the value needed to balance the equation after substituting measured or estimated values for other items in the equation.

[3]Computed by use of an assumed average pumping rate of 21,000 gallons per day for 100 days in 1988, 10 days in 1989, and 40 days in 1990.

[4]Assumed to be equal to pan evaporation measured at National Oceanographic and Atmospheric Administration station at Kingston, R.I. Value for June 1988 was estimated from evaporation measured at National Oceanographic and Atmospheric Administration station in Coventry, Conn.

[5]Change in storage calculated with the assumption that area of pond is 14.7 acres between pond altitudes of 119.8 and 116.7 ft.

amount of ground-water outflow. Ground-water inflow balanced by an equal amount of outflow can be ignored in the budget.

Precipitation on the pond surface was assumed to be equal to that measured at the NOAA weather station at the Block Island airport. Pumpage into the pond from nearby well NHW-425 was estimated based on an assumed average pumping rate of 35 gal/min and pumping period of 10 hours per day.

In 1988, pumping from this well began in June and continued intermittently throughout much of the summer; a total of 100 days of pumping was assumed for May-October. In 1989, because above average precipitation caused the pond level to remain relatively high throughout the summer, only 10 days of pumping were assumed. In 1990, the well was pumped intermittently until the end of June, when pumping was discontinued for the rest of the year (James Collins, Block Island Water Company, oral commun., 1992). A total of 40 days of pumping was assumed for 1990.

Outflow from the pond during the budget period resulted from evaporation and withdrawals for water supply. Evaporation from the pond surface was assumed to be equal to pan evaporation measured at the NOAA station at Kingston, R.I., 23 mi to the north. Withdrawals for water supply were metered.

Pond-surface elevation, which ranged from 119.8 to 116.7 ft above sea level during the budget period, was measured about every 2 weeks. Changes in the volume of pond storage between the beginning of May and the end of October were computed assuming a constant pond area of 14.7 acres. The change in pond area resulting from these changes in pond level was not determined. It is assumed that any error in volumetric computation resulting from an increase in pond area at high stage is offset by error resulting from a decrease in pond area at low stage.

Sands Pond is reported to be capable of yielding 45,000 gal/d (C.E. Maguire, Inc., 1984, p. C-3)—a rate that seems reasonable. During May-October of the relatively dry years of 1988 and 1990, the pond yielded an average of 62,000 and 70,000 gal/d (not including well-water pumped into the pond), respectively. During these periods, the pond level declined to within about 2 ft of the BIWC intake pipe. During successive years of dry weather, the pond yield could approach 45,000 gal/d, leaving a water-supply demand deficit of as much as 30,000 gal/d. Successive years of dry weather are not rare. For example, over the past 98 years (1890-1988), annual precipitation has been less than that received in 1990 for two or more consecutive years on six occasions (1904-05, 1916-18, 1924-25, 1949-50, 1963-65, and 1980-81).

Fresh Pond

Fresh Pond also occupies a depression that extends below the water table. The pond has a maximum depth of about 25 ft (Guthrie and Stolgitis, 1977) and covers about 28 acres. It has a surface drainage area of about 108 acres and a ground-water drainage area of about 111 acres (fig. 29). The pond has no perennial inflowing streams, but surface outflow occurs at times at its southern end through a shallow ditch and culvert leading to Peckham Pond. A culvert at the southern end of Peckham Pond, which is at an elevation of 89.91 ft above sea level, controls surface outflow from both ponds. Ground-water inflow occurs along the western, northern, and southeastern sides of Fresh Pond where the water-table gradient slopes toward the pond (see fig. 13). Leakage from the pond into the ground occurs along its eastern side, where the water-table gradient slopes eastward, and along its southern side where the water-table gradient slopes south-southwest away from the pond.

Inflow to Fresh Pond results from overland runoff from its surface drainage area, from direct precipitation on its surface, and ground-water inflow. Outflow occurs by evaporation from the pond surface, surface outflow, and subsurface leakage. The net effect of precipitation and evaporation (available only for May-October) on the pond level during 1988-90 is shown in figure 31. Because the pond-level hydrograph includes years of unusually high and relatively low precipitation, the

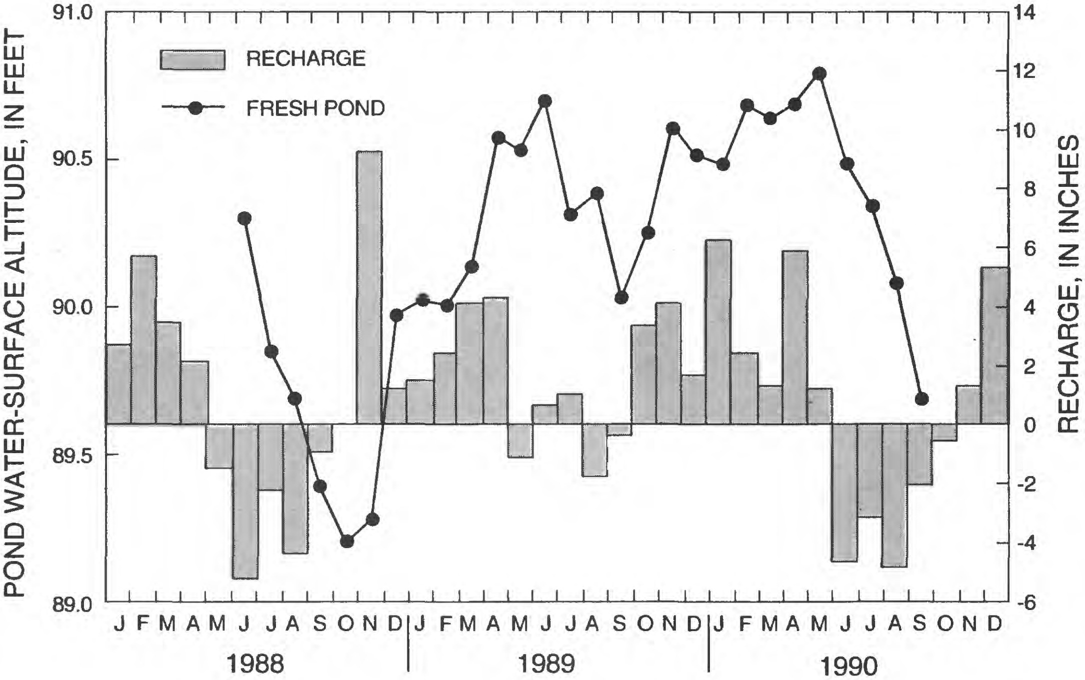


Figure 31. Altitude of the water surface of Fresh Pond and net recharge to the pond, 1988-90.

range in pond altitudes shown is probably representative of minimum and maximum levels to be expected most of the time.

The approximate maximum rate of natural water-level decline to be expected in Fresh Pond during summer periods of little or no precipitation when evaporation rates are high is shown in figure 32. This is a recession curve which was prepared by tracing the steepest segments of decline from the pond-level hydrograph for 1988-90, and then fitting them into a composite curve. The steepest rates of pond decline were recorded during intervals of virtually no precipitation when evaporation rates were at about the maximum rates to be expected during most summers. The break in slope of the curve at elevation 89.9 ft above sea level is the point at which surface outflow ceases. The curve is estimated for elevations between 89.5 and 89.0 ft above sea level, because there were few extended dry periods when the pond level was between these elevations.

The recession curve can be used to predict the natural decline in pond level for up to 60 days of little or no precipitation during periods of summer drought. For example, if the pond level were at 90.5 ft on May 1, it would be at about 89.9 ft 32 days later, or at about 89.0 ft 60 days later, if there were no precipitation. Withdrawals from the pond would result in additional decline of about 0.11 ft for each 1 Mgal withdrawn, assuming a constant pond area of 28 acres.

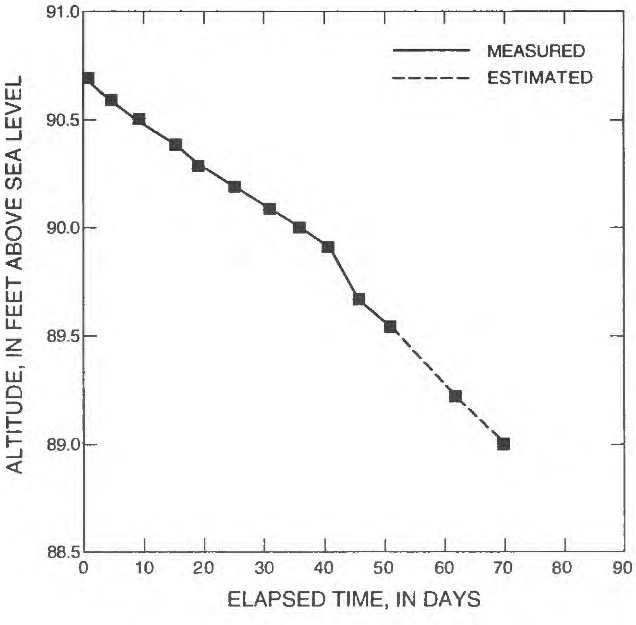


Figure 32. Approximate maximum rate of decline of the level of Fresh Pond.

During dry years, an additional 30,000 gal/d could be required by the BIWC to meet an average daily demand of 75,000 gal/d from May through October. This is equivalent to a volume of 5.5 Mgal. Withdrawal of this volume of water from Fresh Pond during periods of no rainfall, when pond level is at or below an elevation of 89.9 ft above sea level, would lower its level about 0.6 ft below its natural level. Withdrawal of 9.2 Mgal, an amount equal to a 50,000 gal/d supply for 6 months, under similar conditions would lower the pond level about 1.0 ft below its natural level. Declines would be smaller if withdrawals were made while the pond level was above an elevation of 89.9 ft above sea level, because part of the water withdrawn would be captured surface runoff.

Transfer of water from Fresh Pond to Sands Pond during late winter and early spring when the level of Fresh Pond exceeds 89.9 ft above sea level would result in minimal pond-level decline. Some of the transferred water may be lost to subsurface leakage from Sands Pond, if it is filled to a level higher than the water table at its north end. Optimum recovery of transferred water would require experimentation and maintenance of accurate records of transfer rates and pond stages. The elevation of the pond relative to that of the water table can be determined by continued monitoring pond level and the water level in well NHW 628.

Ground Water

The availability of ground water can be determined from yield or drawdown data on 28 springs and 531 wells. Springs typically discharge only a few gallons per minute, but discharges of as much as 35 gal/min have been reported. The discharge from most springs decreases during summer and fall and many cease to flow during droughts. Only 7 of the 28 springs for which information is available were used for drinking-water supplies in 1990. Most self-supplied homes and commercial establishments on Block Island are served by wells.

One hundred of the wells for which data are available are shallow, large-diameter dug wells. They range in depth from 4 to 43 ft, but most are no deeper than 15 ft. Their diameters range from 18 to 180 in. Reported yields of four dug wells range from less than 1 to 5 gal/min. Yields of other dug wells are not known but are most likely in the same range. In 1963, nearly half of the self-supplied homes and commercial establishments on Block Island were supplied from dug wells (Hansen and Schiner, 1964, p. 22). Few dug wells have been constructed since then, and only about half of those in use in 1963 were in use in 1990. It is estimated that fewer than 15 percent of the self-supplied homes and commercial establishments are now supplied from dug wells. Many dug wells have been abandoned or destroyed because they go dry during the summer.

Drillers' estimates of yield are available for 390 of the 431 drilled wells. These yields range from less than 1 to 200 gal/min. The distribution of yields available from wells screened above and below sea level is shown in figure 33. This figure shows that yields adequate for domestic and commercial uses are obtainable at some locations from wells screened above sea level where there is no risk of saltwater contamination.

About 95 percent of the wells drilled on Block Island yield 5 gal/min or more, and 50 percent yield 18 gal/min or more. Although the yields obtained are generally more than adequate for the intended use, larger yields could have been obtained at many sites by the use of longer well screens. The yield obtainable from a well in a uniformly permeable formation is roughly proportional to its screen length (Driscoll, 1986, p. 250). Because screens in many wells on Block Island are exposed to less than half of the water-yielding unit, doubling of the screen length may produce nearly double the yield obtained.

The areal distribution of wells reported to yield 25 gal/min or more from selected depth intervals is shown in figure 34. This yield is adequate for most commercial and small-scale water-supply uses. It is apparent from this figure that the ground-water reservoir will yield water at moderately high rates to wells at many locations throughout the island. It is also apparent that most of the existing relatively high yielding wells are screened below sea level (figs. 33 and 34).

Although relatively high yields can be obtained from wells screened below sea level at many locations on Block Island, continuous withdrawals at average rates of 25 gal/min or more at many sites could cause the well water to become saline within a few weeks or months. The risk of saltwater contamination of wells screened below sea level is greatest at sites within a few hundred feet of the ocean and near Great Salt Pond, where saline water has been reported at depths of 25 to 40 ft below sea level; however, saltwater contamination also can occur in wells farther inland if sustained withdrawal rates are high enough or the wells are screened far enough below sea level. Withdrawals at rates adequate for domestic use (2-5 gal/min) appear to be obtainable at any depth without risk of saltwater contamination

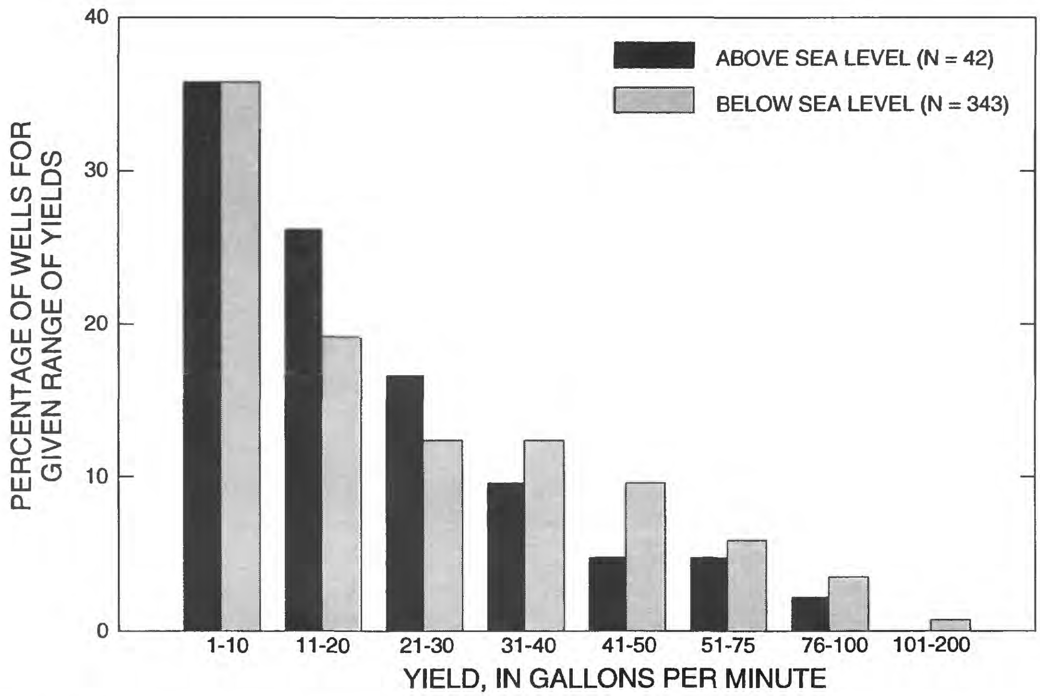


Figure 33. Yields of wells on Block Island screened above and below sea level.

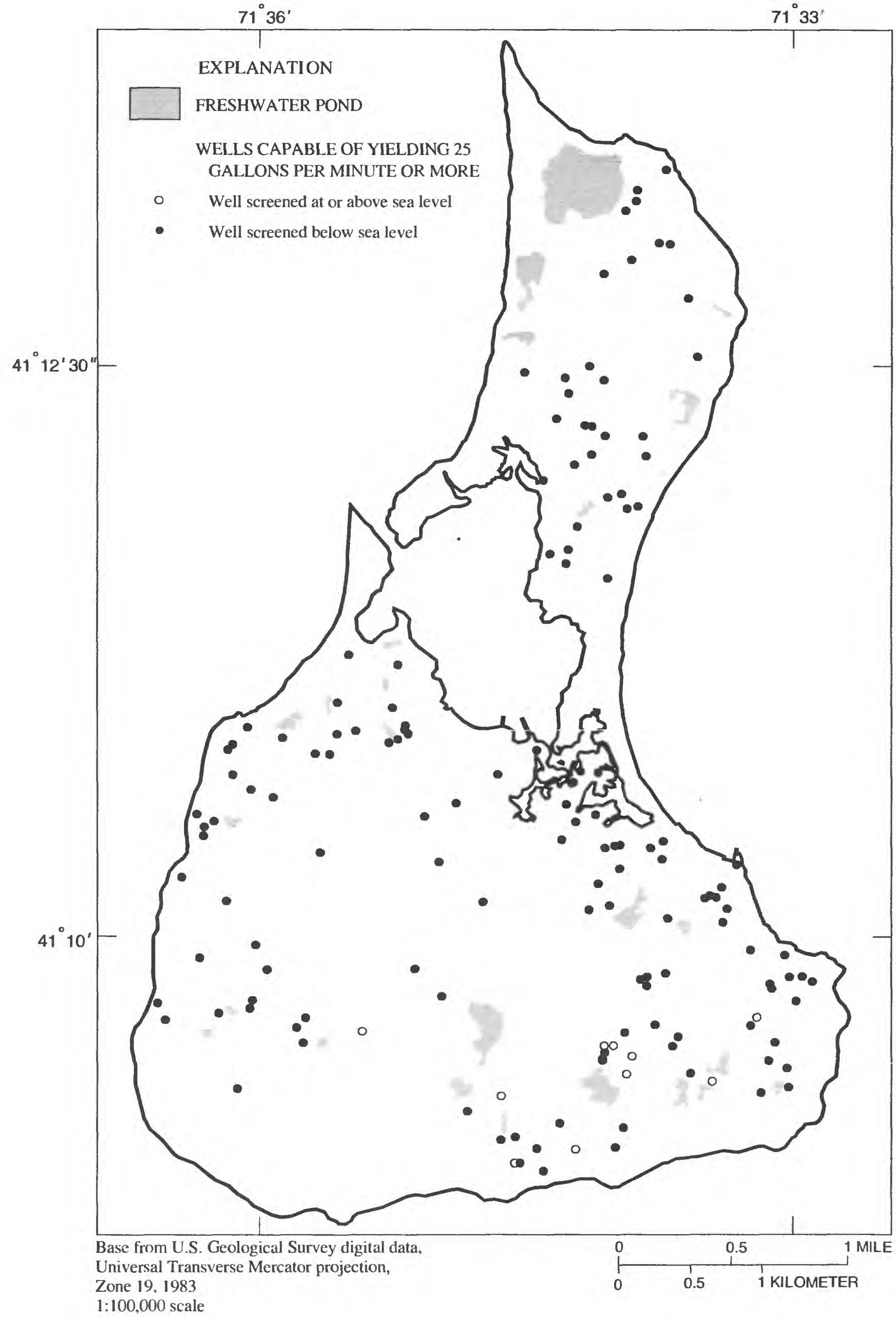


Figure 34. Location of wells on Block Island screened above or below sea level that reportedly yield 25 gallons per minute or more.

as long as the water is not initially saline. Few if any domestic wells have been abandoned due to an increase in salinity after being put into production.

The greatest potential for developing substantial yields from wells screened above sea level is in the part of the island south of Great Salt Pond. Data for wells in the BIWC well field at Sands Pond illustrate the range in yield obtainable at different horizons above and below sea level in the same general area (fig. 35; table 8). Yields ranging from 12 to 90 gal/min were measured at six wells (NHW 1, 2, 3, 32, 34, and 241) in which the bottoms of screens were 23 to 93 ft above sea level; however, dissolved iron in water from wells NHW 32, 34, and 241 greatly exceed USEPA's SMCL for drinking water (U.S. Environmental Protection Agency, 1987b). (No information is available on the pumping history of, or quality of water from, wells NHW 1, 2, and 3).

Data on the ability of wells screened above sea level on Block Island to sustain moderate to high pumping rates for periods of several months or longer is scanty. The wells in the Sands Pond well field have been pumped longest and at the highest rates, but records of withdrawals are not fully documented. In 1963, the public-supply demand of 40,000 gal/d (28 gal/min) apparently was met largely from NHW 33 and 34 (Hansen and Schiner, 1964, p. 22). The bottom of the screen in NHW 33 extends 4 ft below sea level; the bottom of the screen in NHW 34 is 23 ft above sea level. Soon after completion, NHW 33 and 34 are reported to have yielded 42 and 38 gal/min, respectively. (In July, 1979, NHW 34 reportedly produced 50 gal/min, apparently after having been redeveloped.) During the worst drought of this century, NHW 33 and 34 are reported to have yielded only 22 gal/min (in October 1965) and 7 gal/min (in August 1965), respectively. The low yields probably resulted from the combined effects of depletion of ground-water storage and a decrease in the specific capacity of the wells caused by clogging of the well screens. Pumping from the wells at maximum drawdowns during the drought could have increased the rate of sediment movement into the screens, causing gradual reduction in flow through the openings. During the peak of the drought, the wells were producing at a combined rate of 29 gal/min, which is about 36 percent of their combined initial yielding capacity of 80 gal/min.

Recharge areas for wells in the Block Island Water Company well field could not be determined. The complexity of the geology, lack of working pumps in all but one well and lack of observation wells at appropriate locations and depths precluded determination of the distribution of hydraulic head produced when these wells are pumped.

Total ground-water withdrawals of 36 Mgal from the Block Island aquifer system in 1990 were equivalent to about 1 percent of average annual recharge (about 3,575 Mgal). Net ground-water withdrawal (total withdrawal less septic-system return flow) was even smaller (about 21 Mgal). Because few problems of saltwater or septic-system contamination of well supplies have occurred, substantially larger quantities of freshwater could be withdrawn. The amount of additional freshwater that can be developed, however, is a variable quantity governed by (1) the number, location, depth, and pumping rates of wells used to withdraw water, (2) the volume of ground water discharged to the ocean by way of the municipal wastewater collection system, (3) the volume and areal distribution of return flow by way of septic systems, and (4) the effect of septic-system return flow on the quality of ground water.

Maximum recovery of freshwater would result from expansion of the existing network of widely distributed and low-producing domestic wells, keeping well screens above or only slightly below sea level wherever possible. Because net withdrawals of ground water would remain relatively small, the effect of septic-system return flow on ground-water quality would be the principal limiting control on how much more water could be withdrawn. This study indicates that the volume of wastewater currently being discharged to the ground has had little effect on ground-water quality. However, additional study would be required to determine the volume and distribution of septic-system return flow that can be absorbed without causing appreciable degradation of ground-water quality.

The volume of additional ground water available for development in the low-lying business district centered around New Harbor may be small. Ground water withdrawn in this area—as much as 18 Mgal in 1991—discharges to the ocean by way of the municipal wastewater collection and treatment system. This withdrawal, calculated as the difference between the volume of water supplied to the area from Sands Pond by the Block Island Water Company and the volume of wastewater discharged to the ocean (fig. 36), includes seepage of ground water into the sewer lines as well as pumpage from wells. Because these withdrawals are not balanced

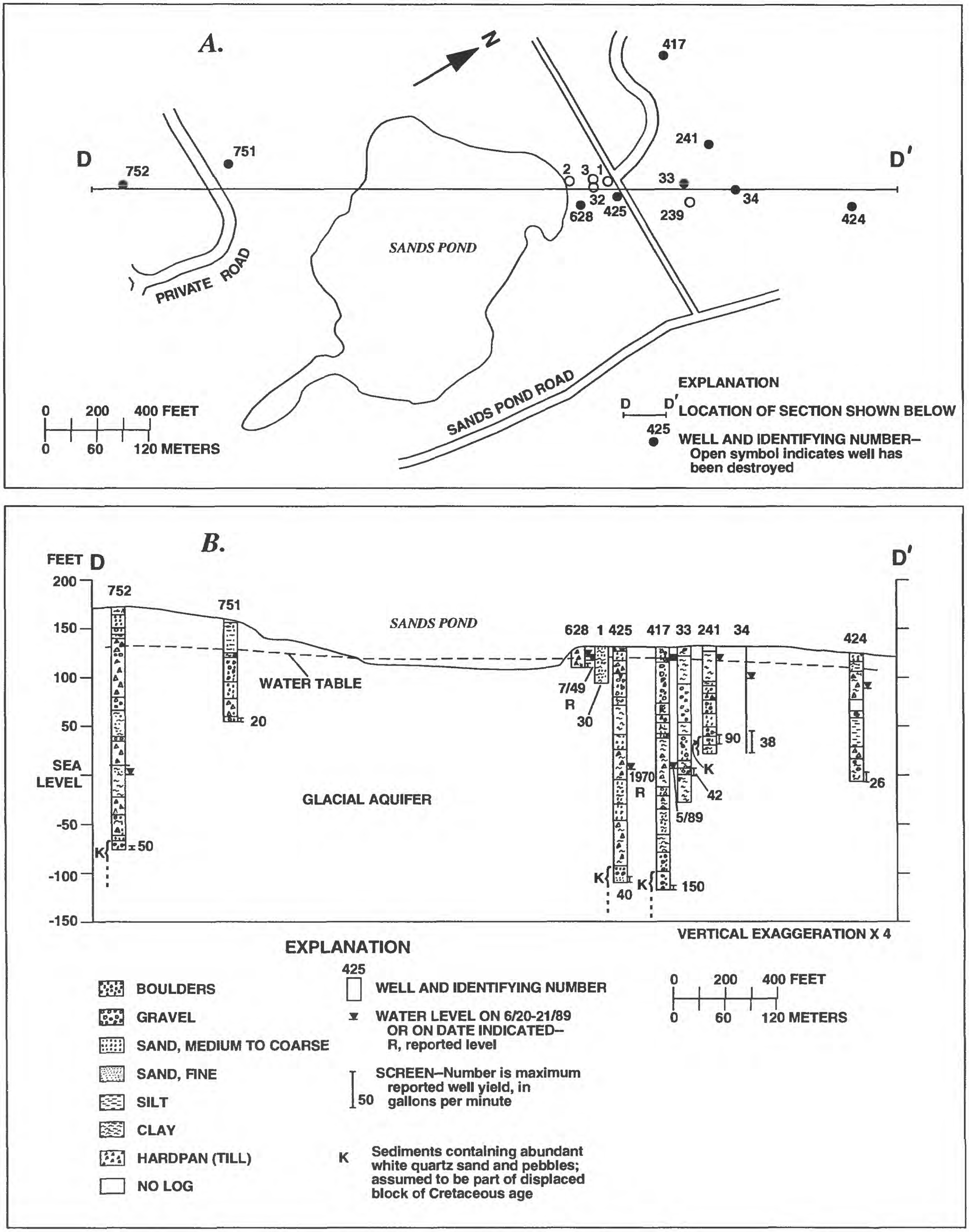


Figure 35. (*A*) Locations of selected wells in the vicinity of Sands Pond and (*B*) types of materials penetrated by, and yields of wells.

Table 8. Construction and yield data for selected Block Island Water Company wells

[USGS well No.: Locations of wells are shown in figure 35. Land-surface altitude is in feet above sea level. Well depths are given in feet below land surface. ft, foot; in., inch; gal/min, gallon per minute. do., ditto]

USGS well No. (NHW)	Town No.	Date drilled	Land surface altitude (ft)	Casing diameter (in.)	Well depth (ft)	Screen or well-bottom altitude (ft)	Yield data: Rate (gal/min)	Yield data: Drawdown (ft)	Yield data: Date	Remarks
1	--	11/35	130	2.5	37	93	30	--	11/35	Destroyed. Reason unknown.
2	--	11/35	128	2.5	34	94	12	--	11/35	Do.
3	--	11/35	130	2.5	37	93	30	--	11/35	Do.
32	--	7/50	130	6	88	60	40	--	7/50	Destroyed. High iron.
33	1	7/50	131.3	6	135	7 to -4	42	--	7/50	To be discharged to Sands. Pond in 1992. High iron.
							22		10/65	
34	2	7/51	130.3	6	107	44 to 23	38	--	7/51	Unused. High iron.
							25	--	7/64	
							7	--	8/65	
							50	77	7/79	
239	--	6/63	131	8	127	4	4	--	6/63	Destroyed. Low yield
241	3	6/63	126.4	8	106	40 to 30	40	20	6/63	Unused. High iron.
							65	--	7/63	
							90	20	8/79	
							50	--	7/82	
417	6	5/81	127.9	6	247	-116 to -119	150	--	6/81	Abandoned for legal reasons.
							130	--	7/82	
424	4	1965	121.9	6	130	2 to -8	26	--	1966	Unused. High iron.
425	5	8/65	163.8	8/6	246	-105 to -109	40	31	1970	Discharged to Sands Pond. Deepened from 169 ft in 1970.
							80		7/82	

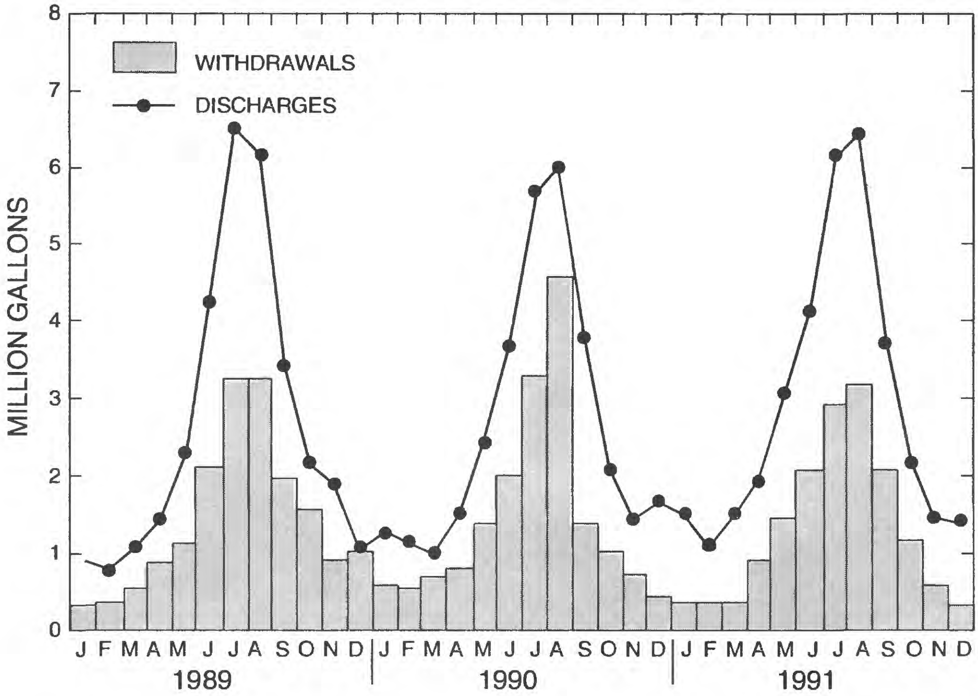


Figure 36. Water-supply withdrawals from Sands Pond and wastewater discharges to the ocean, 1989-91.

by septic-system return flow, the saltwater-freshwater contact beneath the business district can be expected to rise slowly over time. Although few saltwater encroachment problems have been reported in the business district, increased withdrawals from wells in this area during droughts may cause some of the more deeply screened wells to become saline.

Development of Future Public Water Supplies

Additional water supplies, which might be needed during droughts, could be obtained by pumping water from Fresh Pond, by reactivating wells at Sands Pond, or by drilling additional wells at other locations. Development of supplies from Fresh Pond would provide water that is low in iron. Use of the pond could save energy by reducing pumping lifts in comparison to those required to pump water from the wells at Sands Pond.

Of five supply wells available at Sands Pond, NHW 425 is active, NHW 33 is to be equipped with a windmill-driven pump that will discharge the well water into Sands Pond, and NHW 34, 241, and 424 are inactive. Water from all these wells contains high concentrations of dissolved iron that would have to be removed before the water could be distributed to the public. Currently, iron is removed by discharging water from well NHW 425 onto the shore of Sands Pond, which results in precipitation of iron on the shore or nearby pond bottom. Additional study would be required to determine the feasibility of removing iron from large volumes of well water.

The capacity of the ground-water reservoir to yield 25 gal/min or more at many sites on Block Island affords the opportunity for development of public water supplies at sites other than at Sands Pond, should this become necessary. The most favorable area for development of such supplies would be the southwestern part of the island, where high concentrations of dissolved iron in ground water seem to be less prevalent than they are elsewhere. Drilling in areas as far from the ocean as possible and screening wells above or only minimally below sea level would minimize the possibility of saltwater contamination at any new wells.

SUMMARY AND CONCLUSIONS

Freshwater is present on Block Island in ponds, a few intermittent streams, and a lens of ground water that is underlain by salt water. Small supplies of drinking water are obtainable from ponds, but ground water is the principal freshwater resource. Because of this, the unconsolidated sediments that form Block Island have been designated a sole-source aquifer by the U.S. Environmental Protection Agency, and virtually the entire island has been given a GAA ground-water classification by the Rhode Island Department of Environmental Management. A GAA classification is given to ground water resources that warrant the highest level of protection from contamination; ground water in this classification is suitable for public supply without treatment.

Annual water use on Block Island during 1990 is estimated to be 53 Mgal. Of this total, approximately 17 Mgal was pumped from Sands Pond by the Block Island Water Company for distribution to homes and commercial establishments in the business district. The remaining 36 Mgal was pumped from private wells and a few springs that supply 93 percent of the homes on Block Island. About 60 percent (31.6 Mgal) of the water used on Block Island in 1990 was discharged to the ocean through a public sewer system; the remainder (21.4 Mgal) was returned to the ground-water reservoir through septic systems.

The island is part of a glacial end-moraine deposit of Late Pleistocene age that unconformably overlies older unconsolidated sediments of Cretaceous age. The base of the glacial deposits ranges from 230 ft below sea level at the northern end of the island to 160 ft below sea level at the southern end. The glacial sediments consist of a complex mixture of sorted and stratified meltwater deposits, nonsorted sediment-flow deposits, till, and glacially transported blocks of older (pre-Late Wisconsinan) glacial and Cretaceous strata.

The freshwater lens is present chiefly in the glacial sediments but locally extends into the underlying Cretaceous sediments. South of Great Salt Pond, the bottom of the freshwater lens is estimated to be 300 ft or more below sea level; the upper surface of the lens is the water table, which is locally as high as 160 ft above sea level. In lowlying coastal areas the water table commonly is only about 1 ft or less above sea level, and wells in these areas reportedly reach salt water at depths of as little as 25 ft below sea level. Recharge to the freshwater lens by precipitation is estimated to average about 10 Mgal/d.

The complex interbedding of glacial sediments with widely differing hydraulic conductivities has produced an aquifer that is heterogeneous and strongly anisotropic. Layers of clay, silt, and other materials having very low hydraulic conductivity impede vertical flow, thereby creating locally steep vertical gradients as demonstrated by water levels in some closely spaced shallow and deep wells that differ by 100 ft or more. Because the average hydraulic conductivity of the sediments that form Block Island is low, the water table conforms closely to the topographic surface. As a consequence ground water flows radially from the central highlands to the coast.

The principal water-yielding units are discontinuous lenses of moderately to highly permeable sand and gravel, which range in thickness from 4 to 60 ft. Horizontal hydraulic conductivities of these units range from 3 to 2,100 ft/d; median hydraulic conductivity, however, is only 27 ft/d and values exceed 145 ft/d at only 10 per cent of wells.

The chemical quality of ground water on the island is strongly affected by sea salt. Sodium and chloride, attributable to incorporation of sea spray in recharge water, are dominant chemical constituents, although concentrations generally are not excessively high. The median concentration of sodium in 25 samples of ground water is 20 mg/L; the median concentration of chloride in 92 samples of ground water is 28 mg/L. Nitrate concentrations, which are affected by septic system leachate, were less than the USEPA's MCL of 10 mg/L (as N) for public drinking-water supplies at each of 83 sites sampled. Concentrations range from nondetectable (less than 0.01) to 7.5 mg/L, with a median value of 0.8 mg/L. Dissolved iron, however, exceeded the USEPA's SMCL of 0.3 mg/L for public drinking-water supplies at 26 of 77 sites sampled. Concentrations range from nondetectable (less than 0.01 mg/L) to 27 mg/L with a median of 0.07 mg/L. High concentrations of iron were detected predominantly in ground water from the eastern and northern parts of the island and are attributed to the presence of iron-bearing minerals in association with organic material.

A comparison of chloride concentrations from wells and springs sampled as part of this study and that of Hansen and Schiner (1964) indicates that concentrations in water from most wells have declined or remained constant during the past

30 years (1960-90). This may be an indication that ground-water withdrawals are not significantly affecting the position of the freshwater/saltwater interface.

The recharge areas of Sands and Fresh Ponds were delineated on the basis of surface-water and ground-water divides. Sands Pond has a surface-water drainage area of approximately 64 acres and a ground-water drainage area of approximately 79 acres. Fresh Pond has a surface-water drainage area of approximately 108 acres and a ground-water drainage area of approximately 111 acres. These recharge areas define the zone of contribution for surface- and ground-water flow to each of the ponds. Generalized ground-water flow directions can be inferred from the water-table map and geohydrologic sections. However, actual flow paths followed by recharge water are strongly affected by the presence of layers of low hydraulic conductivity material between the water table and the well intakes and may deviate significantly from generalized flow paths.

Sampling conducted as part of this study showed no evidence of widespread ground-water contamination. Ground water in some parts of the island, however, may be at risk of contamination from saltwater intrusion, leachate from septic systems, and leakage from buried fuel tanks. Saltwater contamination of well supplies can result from withdrawal at sustained rates of as little as 50,000 gal/d (35 gal/min) from wells screened 100 ft or more below sea level at sites as far as one-half mile inland. Saltwater contamination also can result from sustained pumping at even lower rates from wells drilled below sea level in lowlying coastal areas. However, withdrawals for domestic use, which typically average less than 300 gal/d, appear sustainable in wells screened at nearly any depth below sea level as long as the water is not initially saline. Potential leakage from as many as 194 buried fuel tanks located at residences throughout the island constitute the most serious threat to ground-water quality. Leachate from the closed Block Island landfill flows westward into Block Island Sound and does not constitute a threat to drinking water supplies on the island.

In 1990, the Block Island Water Company withdrew an average of about 74,000 gal/d from Sands Pond during May-October. Although this yield may be sustainable over a succession of years when precipitation is average or above average, sustainable yields may be closer to 45,000 gal/d during a succession of drier years, thereby creating a deficit of 30,000 gal/d. This deficit could be met from wells in the Block Island Water Company well field at Sands Pond, two of which reportedly produced 40,000 gal/d during the summer of 1963. However, water from these wells contains excessively high concentrations of dissolved iron. The water company has proposed the use of Fresh Pond to meet the deficit, partly because the water is iron-free and partly because the cost of pumping from Fresh Pond has been determined to be lower than that for pumping ground water. It is estimated that withdrawal of 30,000 gal/d from Fresh Pond would produce a water-level decline of less than 1 ft during dry years.

Ground water is readily available for development throughout the island. Yields adequate for domestic use (2-5 gal/min) are obtainable at most sites, and yields of 25 gal/min or more are obtainable at many locations, particularly in the part of the island south of Great Salt Pond. A small percentage of wells reportedly yield 50 to 200 gal/min. Although most wells are drilled to depths below sea level, yields of 25 gal/min or more are locally obtainable from wells with screens above sea level in the southern part of the island.

The amount of fresh, potable ground water available for use on the island depends on (1) the number, location, depth, and pumping rates of wells; (2) the volume of ground water discharged to the ocean by way of the municipal wastewater collection system; (3) the volume and areal distribution of water returned to the ground-water flow system through septic systems; and (4) the effect of septic-system return flow on the quality of the ground water. Closely spaced wells and wells pumped at high rates increase the likelihood of saltwater intrusion in wells screened below sea level. Return flow of water from septic systems helps maintain the altitude of the water table and, therefore, lessens the effect of pumping on the position of the freshwater/saltwater interface. However, leachate from septic systems depends largely on dilution to achieve acceptable water quality; therefore, close spacing of septic systems may result in unacceptable degradation of water quality.

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GLOSSARY

The following are definitions of selected technical terms as they are used in this report; they are not necessarily the only valid definitions for these terms. Terms defined in the glossary are in **bold print** where first used in the main body of this report.

Anion. An atom, group of atoms, or molecule that has a net negative charge.

Anisotropic. That condition in which all hydraulic properties vary with direction.

Aquifer. A formation, group of formations, or part of a formation that contains enough saturated permeable material to yield significant quantities of water to wells and springs.

Bedrock. The solid rock, commonly called "ledge," that underlies unconsolidated material at the Earth's surface.

Bottomset Beds. The layers of finer material carried out and deposited on the bottom of the sea or a lake in front of a delta.

Cation. An atom, group of atoms, or molecule that has a net positive charge.

Clast. An individual particle of sediment or sedimentary rock produced by the physical disintegration of a larger mass.

Colluvium. A general term applied to loose and unconsolidated deposits, usually at the foot of a slope; gravity plays the primary role in the transport of such material.

Concretion. A nodular or irregular accumulation of material in a sedimentary rock; developed by localized precipitation of material from solution.

Confining Units. A layer or strata which, because of its low permeability relative to the surrounding aquifer material, inhibits the flow of ground water.

Contact. A plane or irregular surface between two different types or ages of rocks or unconsolidated sediments.

Cross-Bedded. Characteristic of sediment or sedimentary rock; the arrangement of laminations at angles other than the primary bedding plane of the strata.

Diamict. A poorly sorted sediment, showing no evidence of transport by water.

Discharge. The volume of water that passes a given point within a given period of time.

Dissolved Solids. The residue from a clear sample of water after evaporation and drying for 1 hour at 180°C; consists primarily of dissolved mineral constituents, but may also contain organic matter and water of crystallization.

Distal. At the greatest distance from the sediment source.

Downwasting. Melting of the ice sheet, or glacier.

Drainage Area. The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide.

Drawdown. The decline of water level in a well after pumping starts. It is the difference between the water level in a well after pumping starts and the water level as it would have been if pumping had not started.

Eolian. Of, or pertaining to, the action of wind.

Evapotranspiration. Water withdrawn from a land area by evaporation from water surfaces and moist soil and plant transpiration.

Foreset Beds (Strata). The series of layers accumulated as sediment rolls down the steep frontal slope of a delta.

Granite. A coarse-grained, light colored, igneous rock.

Ground Water. Water in the ground that is in the zone of saturation, from which wells, springs, and ground-water runoff are supplied.

Ground-Water Discharge. Water that discharges from the ground-water flow system to a spring, seep, or surface-water body.

Hardpan. Drillers' term used to describe layers of unconsolidated sediment that are hard to drill through. In this report, hardpan is interpreted as till.

Heterogeneous. Synonymous with nonuniformity. A material is heterogeneous if its hydrologic properties vary with position within it.

Hydraulic Conductivity. The volume of water that will flow through a cross-sectional area under a specific gradient during a specific length of time. Hydraulic conductivity is reported herein as feet per day (ft/d).

Hydraulic Gradient. The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydraulic Head. The height of a column of water above a point of measurement in an aquifer plus the elevation of that point above or below an established datum. For this report, hydraulic head is assumed effectively equal to the altitude of the water level, in feet above or below sea level in a tightly cased well that is screened at its bottom.

Hydrogeology. The study of subsurface water (that is ground water).

Hydrograph. A graph showing stage (height), flow velocity, or other property of water with respect to time.

Intergranular. Void space between grains, or clasts, of rock or sediment.

Interlobate. At the junction of two lobes of ice.

Kettle. A roughly circular or oblong depression produced by collapse following the melting of a buried ice block.

Lithologic Log. Description of geologic material collected during sampling of test wells.

Massive. Sediment or sedimentary rock that displays little or no cross bedding.

Maximum Contaminant Level. Maximum concentration or level of a contaminant in drinking-water supplies as established by the U.S. Environmental Protection Agency. Primary maximum contaminant levels are based on health considerations and are legally enforceable. Secondary maximum contaminant levels are based on aesthetic considerations and are recommended guidelines.

Median. The middle value of a set of measurements that are ordered from lowest to highest; 50 percent of the measurements are lower than the median and 50 percent are higher.

Milliquivalents per liter. Chemical concentration unit (meq/L). A meq/L is equal to the concentration in mg/L divided by the atomic (or molecular) weight and multiplied by the charge of the ion.

Modern. Of, or pertaining to, processes that are ongoing at present.

Moraine. Sediment, deposited chiefly by direct glacial action, that accumulates at the margin of a glacier; consists of poorly sorted sediment which may range in size from clay to boulders.

Morphosequence. A "package" of contemporaneously deposited stratified drift that grades from coarse grained near the glacier margin to fine grained in areas further from the ice.

Organic Chemical. A chemical compound containing carbon. Historically, organic compounds were those derived from vegetable or animal sources. Today, many organic chemicals are synthesized in the laboratory.

Perched. Hydrologic condition refering to the superposition of two zones of saturated sediment separated by a zone of unsaturated sediment.

pH. Symbol denoting the negative logarithm of hydrogen-ion concentration in a solution to base 10. Values of pH range from 0 to 14. The lower the value, the more acidic the solution (that is, the more hydrogen ions it contains). A value of 7.0 is the neutral point. Values greater than 7.0 indicate an alkaline solution, whereas values less than 7.0 indicate an acidic solution.

Porosity. A measure of the amount of pore space in a rock or sediment; expressed as the ratio of the void volume to the total volume of the rock or sediment; commonly expressed as a percentage.

Precipitation. The discharge of water from the atmosphere, either in a liquid or solid state.

Recharge. The amount of water that is added to the saturated zone, for ground water, or that gets to a surface-water body.

Recharge Area. The area that contributes recharge to a given well, surface-water body, or aquifer.

Runoff, Total. Part of precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversion, storage, or other works of man in or on stream channels. Includes surface- and ground-water runoff.

Saturated Thickness. The thickness of an aquifer below the water table.

Sediment-Flow Deposits. Largely unstratified and unsorted material transported by a gravity flow through air or water; a landslide or submarine-landslide deposit.

Specific Conductance. A measure of the ability of water to conduct an electrical current, expressed in microsiemens per centimeter at 25 degrees Celsius. Specific conductance is related to the type and concentration of ions in solution and can be used for estimating the dissolved-solids concentration of the water. Commonly, the concentration of dissolved solids (in milligrams per liter) is about 65 percent of specific conductance (in microsiemens per centimeter at 25 degrees Celsius. This relation is not constant from stream to stream or from well to well, and it can even vary in the same source with changes in the composition of the water.

Specific Yield. Ratio of the volume of water a fully saturated rock or unconsolidated material will yield by gravity drainage, given sufficient time, to the total volume of rock or unconsolidated material; commonly expressed as percentage.

Storage Coefficient. The volume of water an aquifer releases from, or takes into, storage per unit surface area of the aquifer per unit change in head; commonly expressed as a decimal or percentage. In an unconfined aquifer, the storage coefficient is virtually equal to the specific yield.

Stratified. Exhibiting layering and lamination indicative of formation in layers or strata.

Stratified Drift. Unconsolidated sediment that has been sorted by glacial meltwater and deposited in layers, or strata.

Surface Water. Bodies of water present at the land surface, including wetlands, ponds, lakes, and rivers.

Terminal/End Moraine. Sediment, deposited chiefly by direct glacial action, that accumulates at the terminus of a glacier. An end moriane marks a stable ice-front position during the retreat of a glacier. A terminal moraine marks the maximum advance of the ice.

Till. A glacial deposit of predominantly nonsorted, nonstratified material ranging in size from boulders to clay. It is commonly so compact that it is difficult to penetrate with light drilling equipment.

Transmissivity. The hydraulic conductivity of an aquifer multiplied by the saturated thickness of the aquifer. Transmissivity is expressed herein as feet squared per day (ft^2/d).

Unconfined Aquifer (Water-table Aquifer). An aquifer in which the upper surface of the saturated zone, the water table, is at atmospheric pressure and is free to rise and fall.

Unconformable. Not succeeding the underlying strata in immediate order of age. Indicates a period of erosion between the two depositional events.

Unconsolidated. Loose granular material, lacking intergranular cement.

Water Table. The upper surface of the saturated zone.

GEOLOGIC-AGE CHART

Era	Period	Epoch	Age estimates of lower (older) boundary in million years
Cenozoic	Quaternary	Holocene	0.010
		Pleistocene	2
	Tertiary	Pliocene	5
		Miocene	24
		Oligocene	38
		Eocene	55
		Paleocene	63
Mesozoic	Cretaceous		138
	Jurassic		205
	Triassic		~240
Paleozoic	Permian		290
	Pennsylvanian		~330
	Mississippian		360
	Devonian		410
	Silurian		435
	Ordovician		500
	Cambrian		[1]~ 570

[1]Rocks older than 570 million years are termed Precambrian.

U.S. Geological Survey, Geologic Names Committee, 1983