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The Hydrogeology of Nags Head Woods, Dare County, North Carolina

Janet Salyer Emry
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THE HYDROGEOLOGY OF NAGS HEAD WOODS,
DARE COUNTY, NORTH CAROLINA

by

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B.S. in Geology, 1983
James Madison University

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

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OLD DOMINION UNIVERSITY
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ABSTRACT

Nags Head Woods, a coastal maritime forest located on a barrier island in eastern North Carolina, stabilizes a back-barrier dune system bordering a tidal marsh. Numerous spring-fed ponds between the dunes provide unique ecological habitats. The purpose of this study is to provide basic information about the groundwater geology in Nags Head Woods and to predict the effects upon water levels due to municipal pumping of Fresh Pond, a large lake near the center of the island.

Clean, fine-to-medium sands dominate the top of the surficial (water table) aquifer, underlain by silty fine-to-coarse sands at -4 m elevation. A silty clay bed of very low permeability is present at -12 m to -21 m elevation. Pumping tests indicate a hydraulic conductivity of 10^{-4} m/s for the uppermost clean sands and 10^{-5} m/s to 10^{-7} m/s for the lower silty sands.

The natural water table across the island forms an elongate dome which crests east and northeast of Fresh Pond; groundwater moves away from this divide towards the Atlantic Ocean to the east and Albemarle Sound to the west. Between May, 1985, and September, 1986, the crest of the water table ranged from 2.58 m to 3.21 m elevation.

Municipal pumpage of Fresh Pond, typically 2000 m³/day during the period of study, lowers lake water levels by 1.5 m to 2.0 m. The cone of depression around the lake is asymmetric with notably steeper gradients east of Fresh Pond.

A finite-difference model (PLASM) was used to predict the effects of pumping from Fresh Pond. Simulations were run for pumping rates between 946 m³/day (0.25 mgd) and 5678 m³/day (1.5 mgd) and for periods of "typical" and "dry" summer conditions. According to the model, during both "typical" and "dry" summer conditions Fresh Pond will drop approximately 0.65 m for each 0.5 mgd increase in pumpage. At 1892 m³/day (0.5 mgd) pumpage, the cone of depression will be nearly 500 m wide; at 5678 m³/day (1.5 mgd), approximately 800 m wide.

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CHAPTER 1: INTRODUCTION

1.1 Purpose

Nags Head Woods is a coastal maritime forest located on Bodie Island, an active barrier island, in the towns of Kill Devil Hills and Nags Head, North Carolina. The purpose of this study is to provide basic information about the groundwater geology of Nags Head Woods (Figure 1). This information includes (1) the shape of the water table and the location of any groundwater divides, (2) natural seasonal water level changes, (3) aquifer transmissivities and storativities, and (4) the horizontal and vertical extent of hydrostratigraphic units.

With these data, a finite-difference model may be constructed to show the effect of municipal pumpage from a nearby lake, Fresh Pond, on water levels in Nags Head Woods, based upon available rainfall and variable rates of pumpage.

1.2 Location and Geologic Setting

Barrier islands are elongate bodies of sand that are separated from the mainland by a lagoon or bay. These barriers occur in areas where tidal ranges, wave energies,

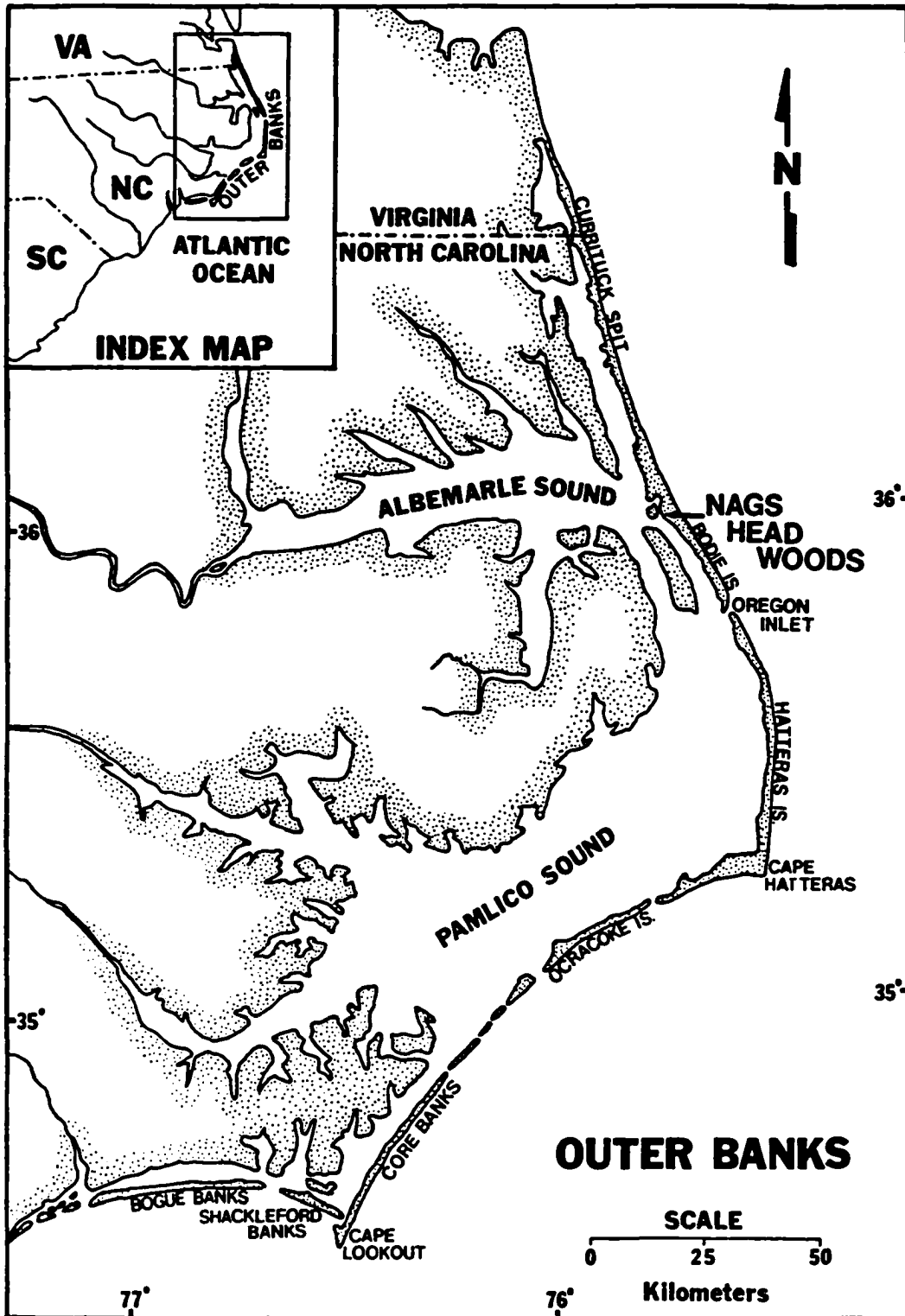


Figure 1. Map showing the location of Nags Head Woods and major islands of the Outer Banks barrier island chain, North Carolina.

and offshore gradients are relatively low. Barrier systems consist of island chains segmented by tidal inlets; these inlets develop when the barrier is breached during strong storm conditions. The islands are often surmounted by a pronounced dune system with elevations considerably above sea level (Ritter, 1978).

The Outer Banks of North Carolina, including Bodie Island, are classic examples of microtidal, transgressive barrier islands, or "washover barriers" (Leatherman, 1982). This type of barrier island occurs along wave-dominated sandy coasts where the tidal range is less than 2 m. These islands are long and narrow with few active inlets; they exhibit relatively rapid shoreline retreat due to a net sand deficiency, and, as a result of their low-lying topography, are vulnerable to washover. The Outer Banks are one of the most extensively overwashed regions of the U.S. Atlantic Coast (Leatherman, 1982).

Bodie Island can be considered a typical barrier island, although at the present time no inlets are active between Virginia Beach, Virginia and Oregon Inlet, North Carolina. Because the "island" is continuous and presently connected to the mainland, it is also known as Currituck Spit. In the past, various inlets have opened and closed along this length (Fisher, 1962; Otte et al., 1984). One prehistoric inlet, shown in Figure 2, is believed to have been located immediately north of the Nags Head Woods; geomorphic evidence for this inlet

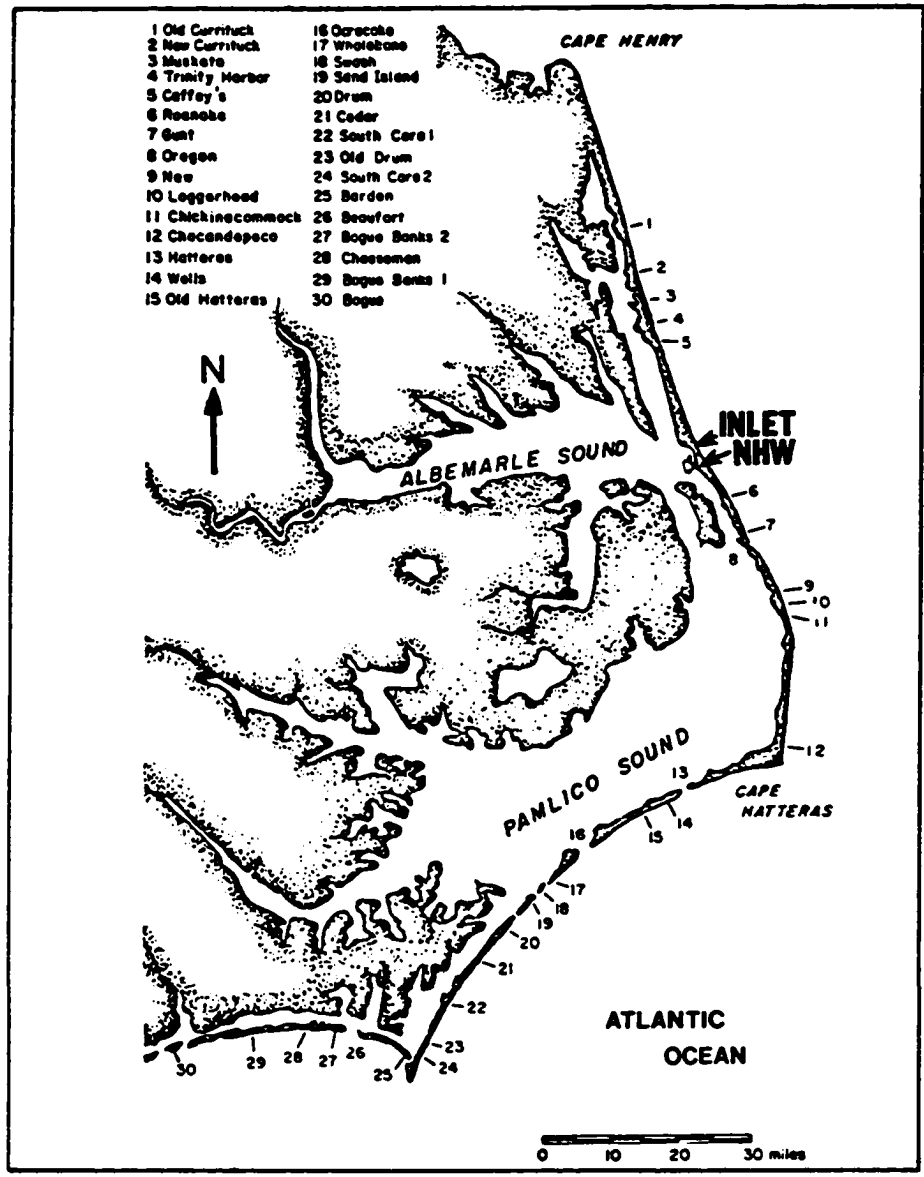


Figure 2. Location of historical inlets along the Outer Banks of North Carolina (from Fisher, 1962). NHW: Nags Head Woods; INLET: a prehistoric inlet near the study area.

includes a series of beach ridges north and south of the former inlet channel. Such a ridge pattern is also seen around modern inlets (Leatherman, 1982).

Bodie Island, oriented northwest-southeast, is elongate and varies greatly in width. The island has a very irregular, low-energy sound-side shoreline and an almost linear, high-energy ocean-side beach. The widest parts of the island are associated with either large washover fans or with back-barrier tidal deltas associated with closed inlets. The portion of the island where Nags Head Woods is located ranges from 2100 m to 3200 m wide. North of Nags Head Woods, at the location of the prehistoric tidal delta sequence, the island is up to 6400 m wide; south of the woods, the island narrows to a width of about 900 m (Otte et al., 1984).

The southern portion of Bodie Island supports several eolian dune systems. Immediately south of Nags Head Woods is Jockey's Ridge, the highest active dune (34 m elevation) in the eastern United States. Dune crests in this system shift in response to seasonal wind patterns, but do not migrate in any specific direction. Run Hill, at the northern end of the woods, is an active transverse dune with elevations up to 18 m. As Run Hill migrates southward, it slowly buries portions of Nags Head Woods (Otte et al., 1984).

Dunes between Jockey's Ridge and Run Hill, stabilized by the Nags Head Woods vegetation, consist of two systems

of smaller dunes separated by a large complex star dune. North of this star dune are three elongate, north-south trending transverse dunes with crests ranging from 6 m to 18 m elevation. South of the star dune are numerous elongate transverse dunes oriented northwest-southeast. Most of these dunes range in elevation from 6 m to 12 m; some isolated crests along the eastern and western termini of the dunes reach elevations of 21 m (Otte et al., 1984).

On Bodie Island, dune sands form part of the fresh water reservoir, which consists of both a water table aquifer extending from just below the land surface to the first confining beds of silt and clay, and several of the confined or semiconfined aquifers below these confining beds. Because of the highly porous nature of the sediment in the island, rainfall not intercepted or transpired by vegetation infiltrates directly into the water table aquifer with almost no surface runoff. Several ponds occur on the island where the water table is above the land surface; however, some of these ponds are absent during dry periods (Bolyard et al., 1979).

1.3 Nags Head Woods and Surrounding Area

Maritime forests such as Nags Head Woods are an important part of the barrier island ecosystem. These forests develop on barrier flats in the lee of protective dunes or on back-barrier secondary dunes; Nags Head Woods forms a continuous band of forested terrain on the west

side of Bodie Island on one such stabilized back-barrier dune field. These dunes protect the forest from salt-laden storm winds and hot, dry summer breezes. Major environments within the Nags Head Woods complex include forested dunes, forested interdunal flats, bay forest, open water ponds, tidal marsh, and open sands (Otte et al., 1985).

Nags Head Woods covers approximately 6 km² on the lagoonal side of Bodie Island, bordered to the west by the tidal marsh of the Albemarle Sound, to the east by the easternmost dune slope, and to the north and south by Run Hill and Jockey's Ridge (Figure 3). The Nature Conservancy owns the northern portion of the Woods, and manages the southern portion for the town of Nags Head; these areas are maintained as an ecological preserve. Some areas in the southern portion of the Woods are privately owned.

Fresh Pond, a 109,000 m² to 142,000 m² spring-fed freshwater lake, lies along the eastern edge of the Woods, halfway between the ocean and the sound and bisected by the boundary between Nags Head and Kill Devil Hills (Figure 3). Fresh Pond was enlarged and deepened by dredging in the late 1970s (J. Richeson, personal communication, 1985).

Between the dunes throughout Nags Head Woods are swampy interdunal flats and over 50 freshwater ponds. The size and shape of these permanent open-water ponds depends

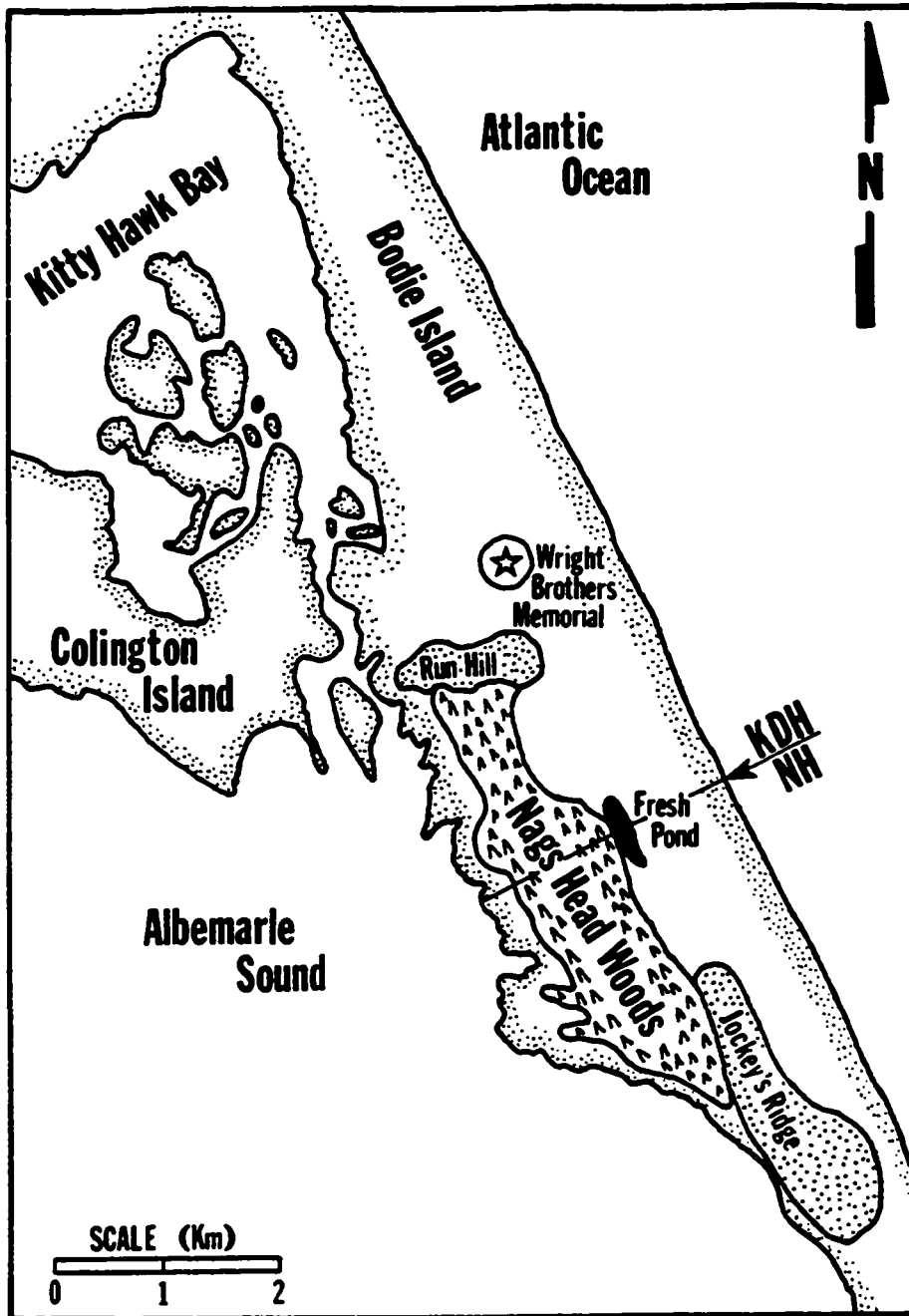


Figure 3. Location of Nags Head Woods on Bodie Island (from Otte et al., 1984).

on the configuration of the surrounding dunes and the elevation of the water table. The ponds vary in size from 400 m² to 10,000 m². Water depth in the ponds is from 1.2 m to 1.5 m, with seasonal fluctuations of 0.3 m to 0.9 m (Otte et al., 1984). Water levels in all ponds in the study area directly reflect the water table in the surficial aquifer (Otte et al., 1985). Many of the more shallow ponds are now filled with organic-rich sediment and peat (Otte et al., 1987).

During the late 1960s and again in the late 1970s and early 1980s, Fresh Pond was pumped to supply municipal water for the towns of Nags Head and Kill Devil Hills. Water was pumped at rates ranging from 500 m³/day (0.13 mgd) in winter months up to 3785 m³/day (1 mgd) in the summer. Before pumping began, the water level of Fresh Pond averaged 3 m above mean sea level; during pumping, lake levels averaged 1.2 m, and reached a minimum of 0.1 m above mean sea level in August, 1977 (J. Richeson, personal communication, 1985). While Fresh Pond was being pumped, the local water table dropped significantly, the nearby ponds experienced marked but unmeasured declines in water levels (H. List, personal communication, 1985), and some ponds in the southern section of the Woods nearly dried out (Otte et al., 1985). If low water levels in the swamps and ponds were maintained for sufficiently long periods of time (few years to tens of years), some wetlands in Nags Head Woods

would have been in serious jeopardy as ecological entities (Otte et al., 1984).

Pumping from Fresh Pond was expected to begin again during the summer of 1985 to supplement the municipal water now supplied by Dare County from wells on Roanoke Island. The towns of Nags Head and Kill Devil Hills began to pump up to 1100 m³/day (0.3 mgd) during the early months of 1986, and increased average pumping to 1900 m³/day to 2300 m³/day (0.5 to 0.6 mgd) during the summer of 1986. Present plans are to pump between 1900 m³/day and 2800 m³/day on a year-round basis (J. Richeson, personal communication, 1986).

1.4 Research Objectives

In December, 1984, the Nature Conservancy contacted the Department of Geological Sciences of Old Dominion University to study the groundwater geology of the Nags Head Woods area. This study was made to determine how renewed pumping from Fresh Pond would affect groundwater and pond water levels throughout the Woods, thus allowing the Nature Conservancy staff to implement appropriate wetland management plans. In order to evaluate the hydrogeologic framework of the area, the following objectives were established:

- (1) To determine the shape of the water table under natural conditions, and the location of any groundwater divides;

- (2) To determine natural seasonal variations in the water table;
- (3) To determine the thickness, texture, and lateral and vertical variability of the surficial aquifer and its confining beds;
- (4) To determine aquifer transmissivity and storage characteristics.

Once this information is gathered, various techniques may be used to model the water table in Nags Head Woods, simulating both natural conditions and pumping effects caused by municipal water withdrawal from Fresh Pond. For this study, a finite-difference computer model developed by Prickett and Lonquist (1971) was applied to determine expected water levels in Nags Head Woods. In addition, stratigraphic data from this study was placed into a regional context in order to determine the depositional history and likely extent of critical hydrostratigraphic units.

CHAPTER 2: REGIONAL STRATIGRAPHY AND GEOLOGIC HISTORY

2.1 Introduction

The texture and extent of hydrostratigraphic units are governed by the environments of deposition and the sequence of geologic events in the study area. The stratigraphy and depositional history of portions of the Outer Banks were studied by Pierce and Colquhoun (1970), Mixon and Pilkey (1976), Moslow and Heron (1978, 1979), and Susman and Heron (1979). These studies indicate that Pleistocene facies overlie "basement" Tertiary formations. The complex Pleistocene deposits reflect coastal plain environments subjected to a series of transgressive and regressive episodes associated with glacio-eustatic fluctuations (Shideler, 1973). Over the Pleistocene deposits lies the Holocene barrier complex, dominated by back-barrier, barrier, and inlet facies (Moslow and Heron, 1979; Susman and Heron, 1979). Support for these stratigraphic studies comes from seismic profiling along the continental shelf (Shideler and Swift, 1972) and textural analysis of modern shoreface sediments (Swift et al., 1971).

2.2 Pliocene Deposits

The "basement" stratum for Pleistocene aquifers in North Carolina is the Yorktown Formation, a well sorted, very fine to fine grained, gray-green clayey quartz sand which was deposited in a nearshore marine or shallow shelf environment during the early Pliocene transgression. This deposit is locally phosphatic and mottled with thin gray-green bands of silt and clay (Moslow and Heron, 1979; Susman and Heron, 1979). The Yorktown is found at -20 m to -25 m elevation along Core Banks and Shackleford Banks. Regional emergence of the North Carolina coastal plain in the Pliocene resulted in erosion of the Yorktown beds and diagenetic cementation of the upper 2.4 m to 3.1 m of the remaining Yorktown sediments (Moslow and Heron, 1979). The resulting limestone cap consists of a friable shell-moldic biosparrodite (Susman and Heron, 1979).

The unconformity between the limestone cap of the Yorktown Formation and overlying beds marks a major stratigraphic break representing all of late Pliocene to late Pleistocene time (over 4 million years). This unconformity shows up as a prominent reflector surface (R1) on seismic profiles from the continental shelf along the Outer Banks (Shideler and Swift, 1972). A structural contour map of reflector R1 indicates that a re-entrant may exist east of the mouth of the Albemarle Sound, suggesting the presence of an ancestral Albemarle fluvial channel at this location (Figure 4).

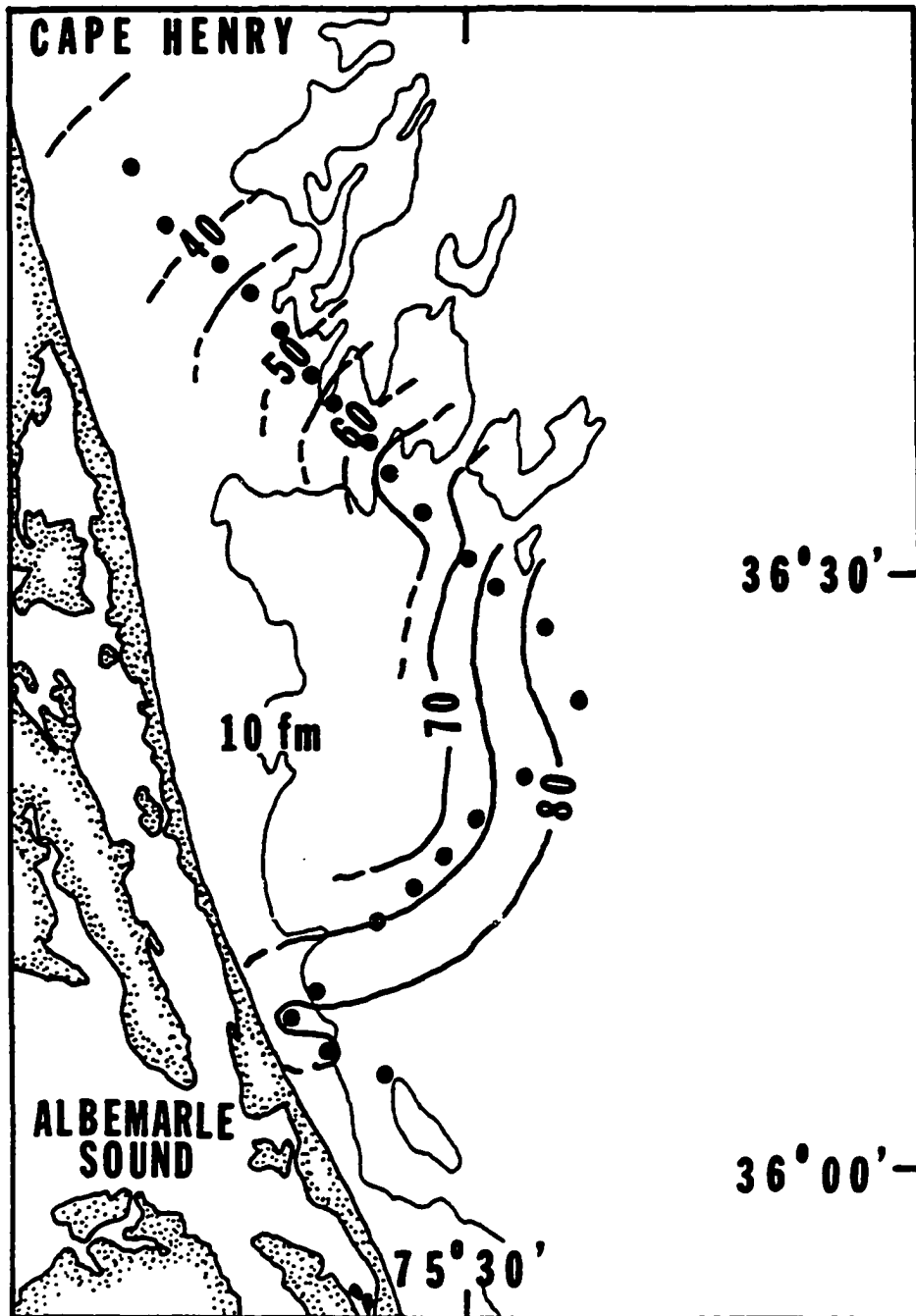


Figure 4. Structural contour map of seismic reflector surface R1 (inferred Miocene/post-Miocene boundary) on the continental shelf. Contours are presented as meters below sea level (from Shideler and Swift, 1972).

2.3 Pleistocene Deposits

2.3.1 Core Creek Sand

With the late Sangamon transgression, a lithologically varied unit of nearshore marine and tidal delta sediments was deposited. This unit, the Core Creek Sand, is a silty and clayey, fine to coarse grained quartz sand with abundant shells and shell fragments (Moslow and Heron, 1979; Susman and Heron, 1979). The Core Creek Sand corresponds to Unit B on Shideler and Swift's (1972) seismic profiles. Near the mouth of the Albemarle Sound, Unit B exhibits pronounced lenticularity, suggesting extensive fluvial cut-and-fill structures. These findings further support the presence of a prominent eastward-draining ancestral Albemarle fluvial channel in this area (Shideler and Swift, 1972). The Core Creek Sand may correlate to the Sandbridge or Tabb Formation in Virginia (Shideler and Swift, 1972; Susman and Heron, 1979; Johnson et al., 1987).

2.3.2 Atlantic Sand

Overlying the Core Creek Sand in some locations is a very fine to coarse grained, well sorted, clean quartz sand, deposited during an early to mid-Wisconsinan transgression. This unit, the Atlantic Sand, is part of a transgressing Pleistocene barrier complex that bordered the open ocean (Shideler and Swift, 1972; Moslow and Heron, 1979). The northwest-southeast alignment of these

deposits fits the configuration of a postulated Pleistocene barrier island chain (Pierce and Colquhoun, 1970).

2.3.3 Diamond City Clay

A prominent widespread unconformity, shown as an irregular eastward dipping surface (R2) on seismic profiles, separates the Core Creek and Atlantic sands from the overlying late Wisconsinan deposits (Shideler and Swift, 1972; Susman and Heron, 1979). With the late Wisconsinan regression, the lagoonal Diamond City Clay was deposited. The Diamond City Clay consists of alternating beds of virtually unfossiliferous gray silty or sandy clay and beds of shell hash in a sandy clay matrix, containing fauna indicative of a back-barrier environment (Susman and Heron, 1979).

The Diamond City Clay was subsequently exposed during a late Wisconsinan regression, producing a widespread unconformity (Moslow and Heron, 1979; Susman and Heron, 1979). This unconformity is a compound erosional surface produced by both subaerial erosion and subsequent shoreface erosion during the following Holocene transgression. This locally irregular surface (R3) appears nearly horizontal on seismic profiles, with a slight eastward dip of about 0.34 m/km (Shideler and Swift, 1972). This unconformity, the Holocene/Pleistocene boundary, is found at -9 m elevation near Core Banks and Shackelford Banks, and between -19 m and -39 m along the

shelf from Cape Henry to Cape Hatteras (Shideler and Swift, 1972; Moslow and Heron, 1979; Susman and Heron, 1979).

2.4 Holocene Deposits

Holocene barrier deposits overlie the Pleistocene Diamond City lagoonal deposits, a sequence which is expected beneath a barrier undergoing retrogression (Pierce and Colquhoun, 1970). Modern barrier sediments occur in one of three depositional complexes shown in Table 1--barrier, back-barrier, and migrating inlet environments. In North Carolina, these Holocene sediments, informally called the Outer Banks Sands by Mixon and Pilkey (1976), were deposited by the post-glacial transgression. Commonly Holocene back-barrier fine silty sands and salt marsh peats overlie the Pleistocene units (Figure 5). In some areas, however, inlet-fill deposits have replaced the back-barrier sands. These relict inlets are typically represented by a thin (0.5 m) coarse lag inlet floor deposit, a thick (up to 14 m) wedge of poorly sorted medium to coarse main channel deposits, and a thin (1.5 m to 3.0 m) cap of well sorted fine sand inlet margin or spit platform deposit. The back-barrier and inlet-fill deposits are both overlain by thin sheets of medium to coarse washover sands and fine, well sorted dune sands (Moslow and Heron, 1979; Susman and Heron, 1979). These barrier complex deposits merge

HOLOCENE DEPOSITIONAL ENVIRONMENTS ON CORE BANKS, N.C.

	DEPOSITIONAL SUB- ENVIRONMENTS	MEAN GRAIN SIZE	SORTING	ADDITIONAL SEDIMENTARY FEATURES
B A R R I E R	Overwash	Coarse to medium sand	Poorly sorted	Heavy mineral laminae, graded bedding
	Barrier flat	Medium sand	Well sorted	Soil material, humic stained sand
	Shoreface	Fine sand	Very well sorted	Burrowing, sand-sized shell material
	Recurved spit	Coarse sand	Moderately sorted	Small scale trough cross- bedding
	Dune	Fine to medium sand	Well sorted	Crossbedding, fine laminae, shell material
B A C K B A R R I E R	Flood tidal delta	Coarse sand	Moderately to poorly sorted	Fine- to very coarse-grained
	Back-barrier lagoon and intertidal flats	Fine to medium sand	Well sorted	Gray, very fine- to medium-grained silty sand
	Intertidal salt marsh	Fine sand	Well sorted	Dark brown sand, silt, and clay; some peat
I N L E T	Inlet margin	Fine sand	Moderately well sorted	Clean sand; fine- to medium-grained
	Channel	Medium to coarse sand	Moderately to poorly sorted	Small pebbles; abraded shell material
	Inlet floor	Coarse sand	Poorly sorted	Coarse shell and pebble lag

Table 1. (after Moslow and Heron, 1978; Susman and Heron, 1979).

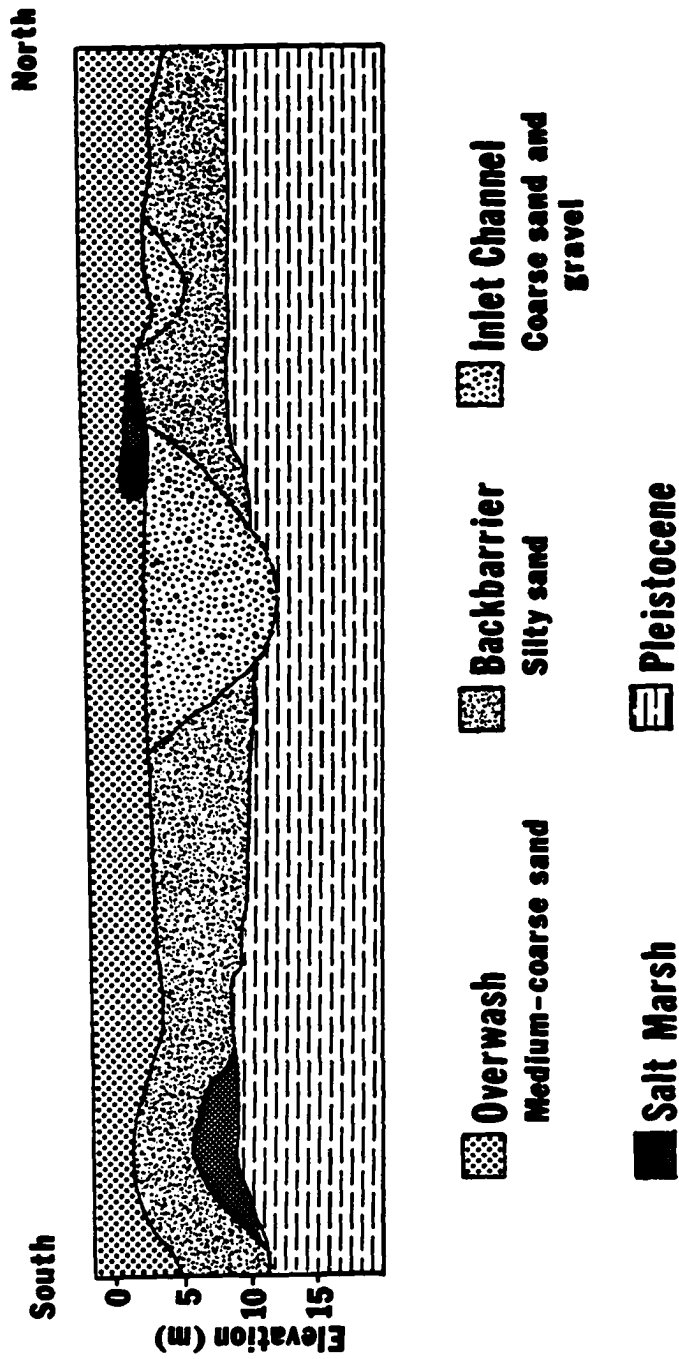


Figure 5. Stratigraphic cross-section across Core Banks, North Carolina (from Moslow and Heron, 1979).

seaward into modern shoreface deposits and landward into modern sound deposits (Moslow and Heron, 1979; Susman and Heron, 1979).

Textural analysis of the modern shoreface along the North Carolina islands indicate that these deposits are derived from Pleistocene substrata. According to Swift et al. (1971), a pronounced coarse textural anomaly exists in the Nags Head area of Currituck Spit, near the site of a prehistoric inlet (Fisher, 1962) and opposite the mouth of the Albemarle Sound. The sediments that filled this closed inlet probably were excavated from the immediate substrate, presumably the gravelly channel of the former Albemarle River. The inlet, therefore, may have originated as a detached river mouth, and Currituck Spit as a detached mainland beach (Swift et al., 1971)

CHAPTER 3: PREVIOUS HYDROGEOLOGIC STUDIES

3.1 Introduction

Previous groundwater studies in the Nags Head Woods area include those done by Kimrey (1961), the engineering firm of Moore, Gardner, and Associates (1969, 1984), Floyd (1971, 1979), and the U. S. Environmental Protection Agency (1985). These studies indicate that fresh water on Bodie Island occurs as a lens which floats upon the denser salt water around it. The uppermost aquifer in the Nags Head Woods area consists predominantly of fine, clean sands which are underlain by fine silty-sands and clays. Additional groundwater studies of the Cape Hatteras National Recreational Area, which extends some 125 km from the southern tip of Bodie Island to Ocracoke Inlet, indicate similar conditions exist on many of the Outer Banks islands.

3.2 Water Table

The earliest groundwater study in the Nags Head Woods area (Kimrey, 1961) did not include water level data or information on the natural shape of the water table. A report by Moore, Gardner, and Associates (1969) asserts that Nags Head Woods, being topographically higher than

Fresh Pond, serves as a catchment area for the lake. Rainfall was reported to recharge Fresh Pond in the form of groundwater flowing out of the Woods; other areas were suggested to contribute little recharge except when the water level in the lake is lowered considerably from its normal elevation. Supposedly, groundwater levels in the lower elevations to the north, east, and southeast of Fresh Pond were the same as water levels in the pond, and fluctuated as the water level in the pond varied (Moore, Gardner, and Associates, 1969).

More accurate data concerning the natural water table came from a series of eight water table monitoring wells installed by the U.S. Environmental Protection Agency (1985) across the island north of Nags Head Woods in the locations shown in Figure 6a. The EPA monitored these wells monthly from July, 1984 through April, 1985; these readings indicate that the water table rises from just above sea level near the Albemarle Sound, to over 3 m elevation very near the center of the island, and then decreases to sea level at the Atlantic Ocean (Figure 6b).

According to Otte et al. (1985), the water table slopes westward under Nags Head Woods, averaging 3.0 m elevation on the eastern edge of the Woods, 1.5 m in the central portion, and 0.6 m along the western edge of the dune field. This trend in water table slope indicates that the shallow aquifer underlying Nags Head Woods drains westward, into the bay forest and marsh. However, because

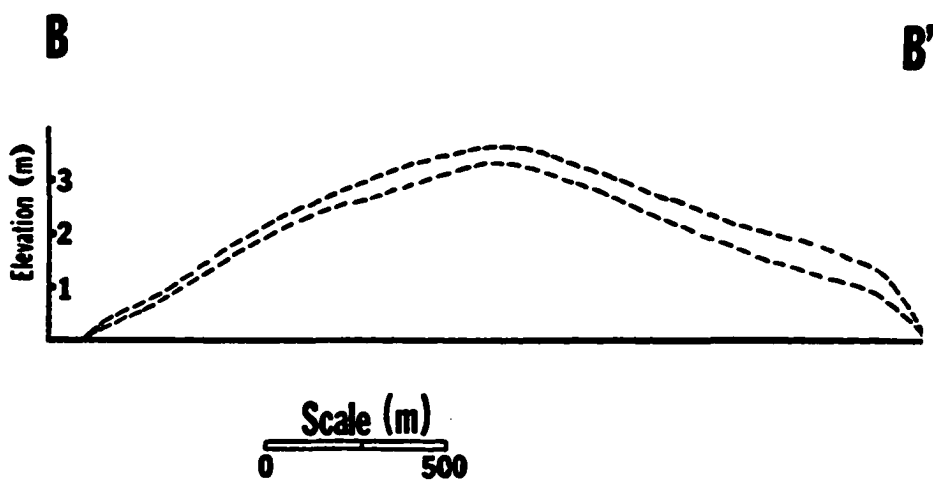
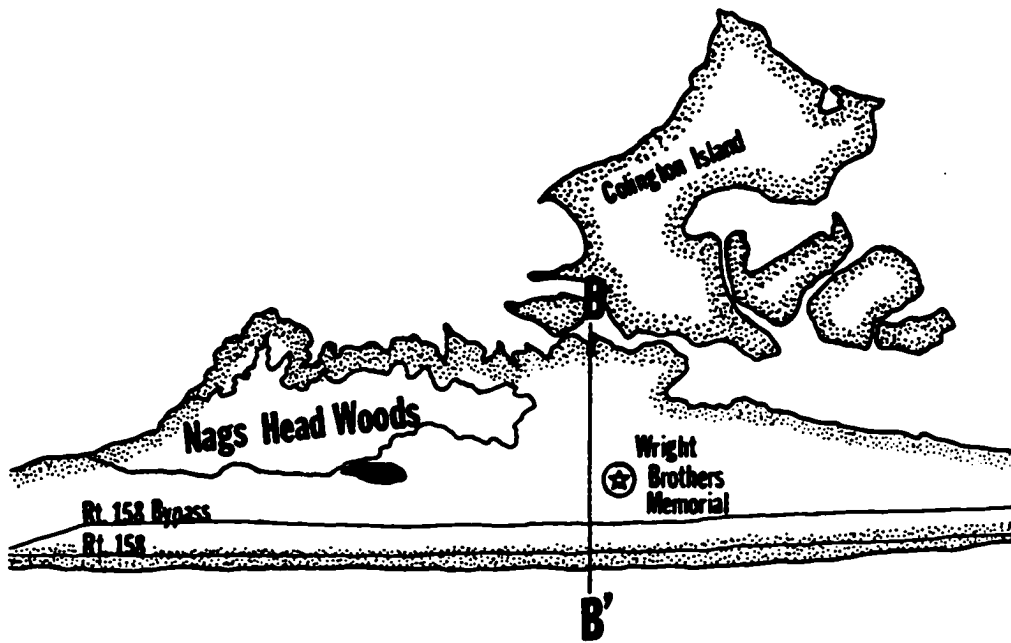


Figure 6. (a) Location of U.S. Environmental Protection Agency transect north of Nags Head Woods. (b) Maximum and minimum water table profiles along EPA transect.

water tables commonly mimic large topographic features, a groundwater divide was believed to exist beneath the large dunes between Fresh Pond and the Nature Conservancy Visitor Center, dividing the Woods into different hydraulic units (Otte et al., 1984).

In Nags Head Woods, the elevation of the water table varies seasonally with rainfall and evapotranspiration. The Nature Conservancy staff installed several wells within the Preserve when the property was acquired in 1981. Readings taken in 1982 and 1983 indicate that the elevation of the water table varied by 0.68 m in a well near the eastern edge of the Woods (well #3, Figure 10), from a minimum of 2.71 m in September, 1982 to a maximum of 3.39 m in March, 1983. Monthly readings from the eight EPA wells north of Nags Head Woods indicate that water levels near the center of the island ranged from a maximum of 3.54 m in September, 1984, to a minimum of 2.95 m in January, 1985, a change of 0.59 m (Figure 6b).

In 1979, the Dare County Department of Health requested E.O. Floyd of Moore, Gardner, and Associates to investigate groundwater conditions at Fresh Pond to determine the minimum distance from the pond that septic tank effluent could be safely discharged. At this time, Fresh Pond was being used as a municipal water source. Water levels in 20 observation wells were measured periodically to determine the elevation of the water table in the vicinity of Fresh Pond. Pumping from Fresh Pond

averaged 760 m³/day during this period, ranging from 1400 m³/day in October to 640 m³/day in February. Seasonal low water levels occurred during October, 1978, and seasonal high water levels during February, 1979. At the low water stage, water level in the lake was 0.37 m, and the height of the island's groundwater divide (eastern edge of the cone of depression) was 1.85 m. At the high water stage, lake water level was 1.23 m and the height of the eastern divide was 2.10 m. Floyd (1979) determined that when water is withdrawn from Fresh Pond by both pumping and evaporation, the lake functions somewhat as a large-diameter well with a large cone of depression forming around it (Figure 7a). Groundwater within the cone flows toward the lake, and water outside the cone flows away from the lake toward the ocean or sound; therefore, the edge of the cone of depression is a groundwater divide. Floyd concluded that the areal position of this divide remains at a distance of 330 m from the eastern edge of Fresh Pond throughout the year, unaffected by seasonal water level changes and minor variations in pumping rate (Figure 7b). Thus, the area of influence around the lake should remain relatively constant throughout the year (Floyd, 1979).

3.3 Test Borings: Nags Head Woods Area

For Kimrey's (1961) study on the groundwater supply for the Dare Beaches Sanitary District, 96 test wells were

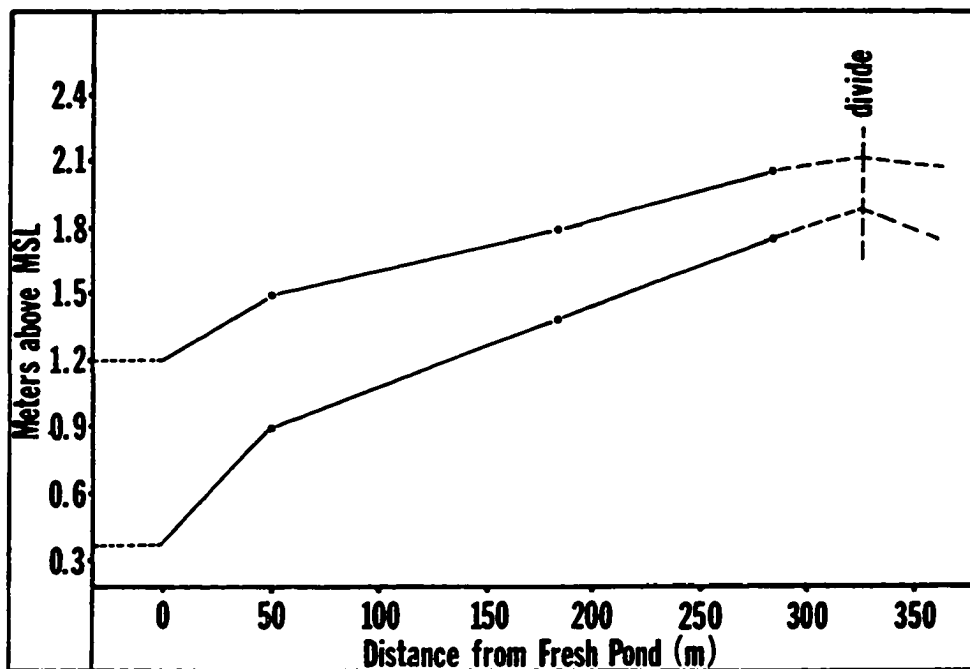
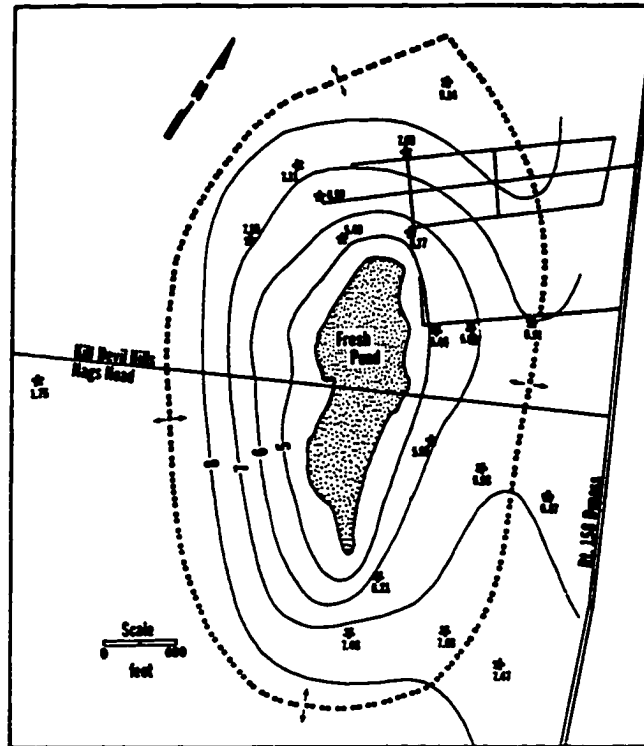


Figure 7. (a) Contoured water table elevations in the vicinity of Fresh Pond on February 22, 1979. Contour interval is one foot. (b) Water table profiles along Fresh Pond Drive. Maximum levels were recorded on February 22, 1979, minimum levels on October 23, 1978 (from Floyd, 1979).

constructed along Bodie Island. Sixty-seven of these wells were drilled along 13 east-west transects about 2 km apart; these ranged in depth from 32 m to 42 m. Twenty-nine additional test wells, ranging in depth from 20 m to 32 m, were constructed in the area containing the best potential aquifer sands. Sediment samples were taken at 1.5 m intervals during the drilling of each well.

According to Kimrey (1961), the surficial deposits consist of two units: an upper clean sand unit and a lower silty sand unit. The upper unit is a medium to fine clean sand which changes from tan to light-gray in color at depths of 3 m to 4.6 m below the land surface. At approximately 15 m depth, the upper unit grades into a dark-gray, medium to fine silty sand containing disseminated shell fragments and some clean sand lenses. Silt content generally increases downward, grading into clay with depth. A coarser third unit consisting of rounded shell fragments and gravel in a medium to fine sand matrix interfingers with the medium to fine sand, averaging 1.5 m thick near its western limit through the center of Nags Head Woods. This coarse unit thickens to a maximum of 9 m beneath the ocean beach (Figure 8).

Kimrey (1961) found confining clay layers, ranging in thickness from 0.6 m to 2.7 m, at depths of 18 m to 30 m below the land surface in four borings from the Woods. Clay layers over 0.6 m thick were not found in the upper 30 m of the surficial aquifer in 92 borings in areas

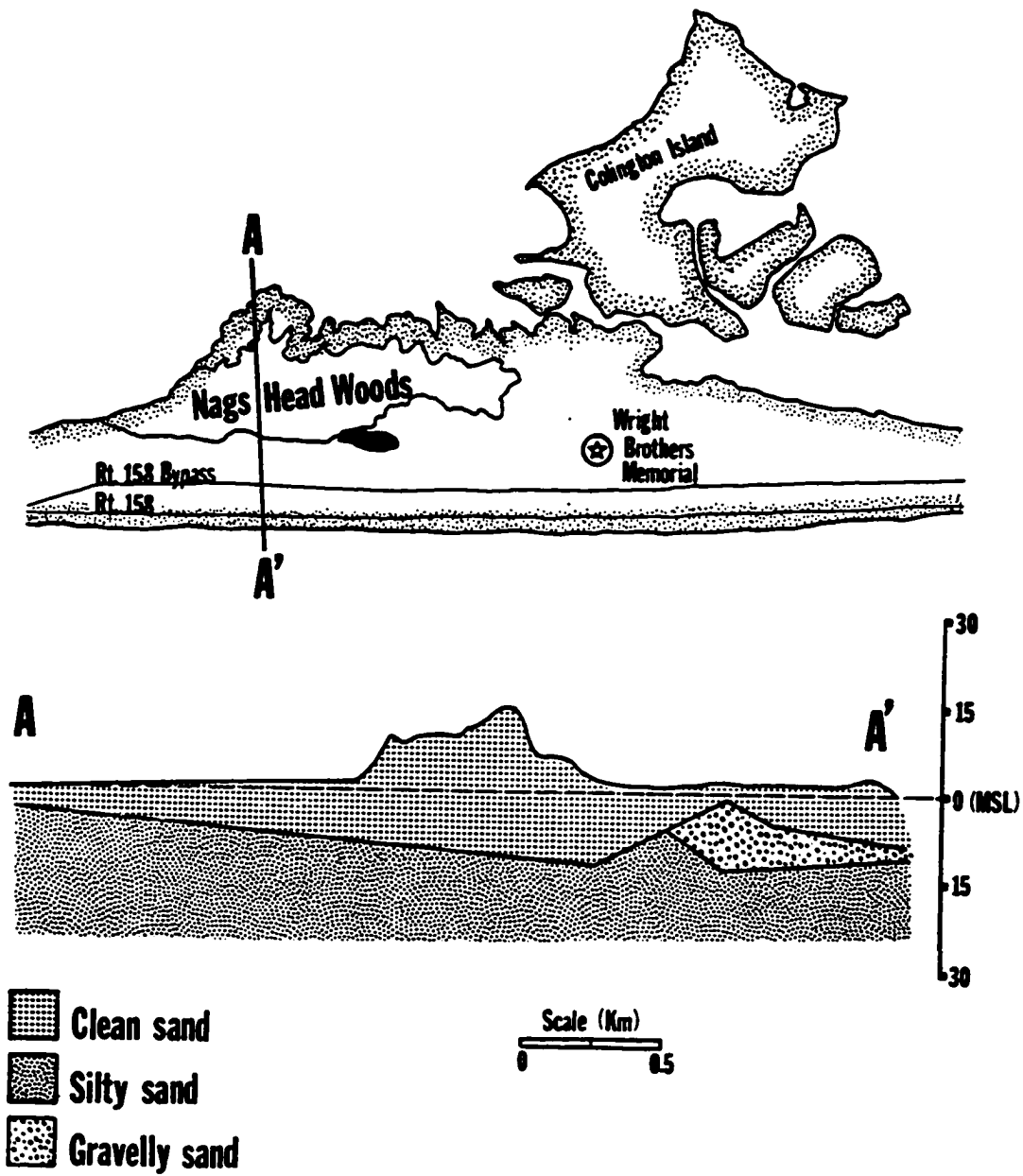


Figure 8. (a) Location of transect A-A' through Nags Head Woods. (b) Geologic cross-section along transect A-A' (from Kimrey, 1961).

surrounding Nags Head Woods (Kimrey, 1961).

In six test borings from the southern portion of the Woods, Floyd (1971) identified two lithologic units: an upper clean sand unit and a lower silty sand unit. The upper unit consists of light-gray, fine-to-medium clean quartz sand which is tan in color in its upper 3 m to 4 m, and contains scattered shell fragments in its lower 3 m. This unit extends to -11 m to -12 m elevation. The lower units consists of dark-gray, silty, fine-to-medium quartz sand, interbedded with streaks of silt and clay. This unit contains a thick, discontinuous clay lens beginning at -27 m elevation. Between the upper and lower sand units is a 6 m thick stratum of sticky gray clay.

A study by Peek et al. (1972) on potential groundwater supplies for Roanoke Island and the Dare County beaches included one 150 m-deep exploratory drill hole just north of Nags Head Woods. At that location, the upper unit consists primarily of medium-grained sands with some interbedded silts and clays, extending to a depth of 18 m. The upper aquifer is separated from the underlying aquifer by a 11 m to 30 m thick unit of clay and interbedded clay and sand, which may allow transmission of water in a vertical direction.

Logs from three test borings made by Soil and Material Engineers, Inc. on the site of a proposed elevated water tank just east of Fresh Pond indicate that the clean fine sand at the surface grades into a gravelly fine-to-coarse

silty sand unit which occurs from -3 to -6 m elevation; these are underlain by a silty fine-to-medium sand to -20 m, where the borings were terminated. Some clay seams are present at -16 m (Soil and Material Engineers, 1978).

In 1984, the U.S. Environmental Protection Agency installed a series of wells along a transect 800 m north of Nags Head Woods. Drilling logs from these wells indicate that the surficial deposit consists of fine sands and is underlain by a medium-to-coarse sand unit at -16 m. A clayey silt layer occurs from -20 m to -25 m depth (Figure 9).

3.4 Hydraulic Characteristics of Surficial Aquifers

Prior to the present study, two pumping tests were performed on the surficial aquifer in the vicinity of Nags Head Woods. Kimrey (1961) performed a pumping test approximately 1 km south of Fresh Pond on the eastern edge of the Woods in 19 m of clean, fine-to-medium sand. Kimrey obtained a transmissivity value of $2.1 \times 10^{-3} \text{ m}^2/\text{s}$, which equates to a hydraulic conductivity of $1.1 \times 10^{-4} \text{ m/s}$, assuming an aquifer thickness of 19 m. Kimrey, however, incorrectly assumed that the silty sand unit, below the 19 m of clean sand, was not hydraulically interconnected with the clean sand; hence his value is probably too large to apply to the total aquifer thickness.

Floyd (1971) performed a 73-hour pumping test 800 m

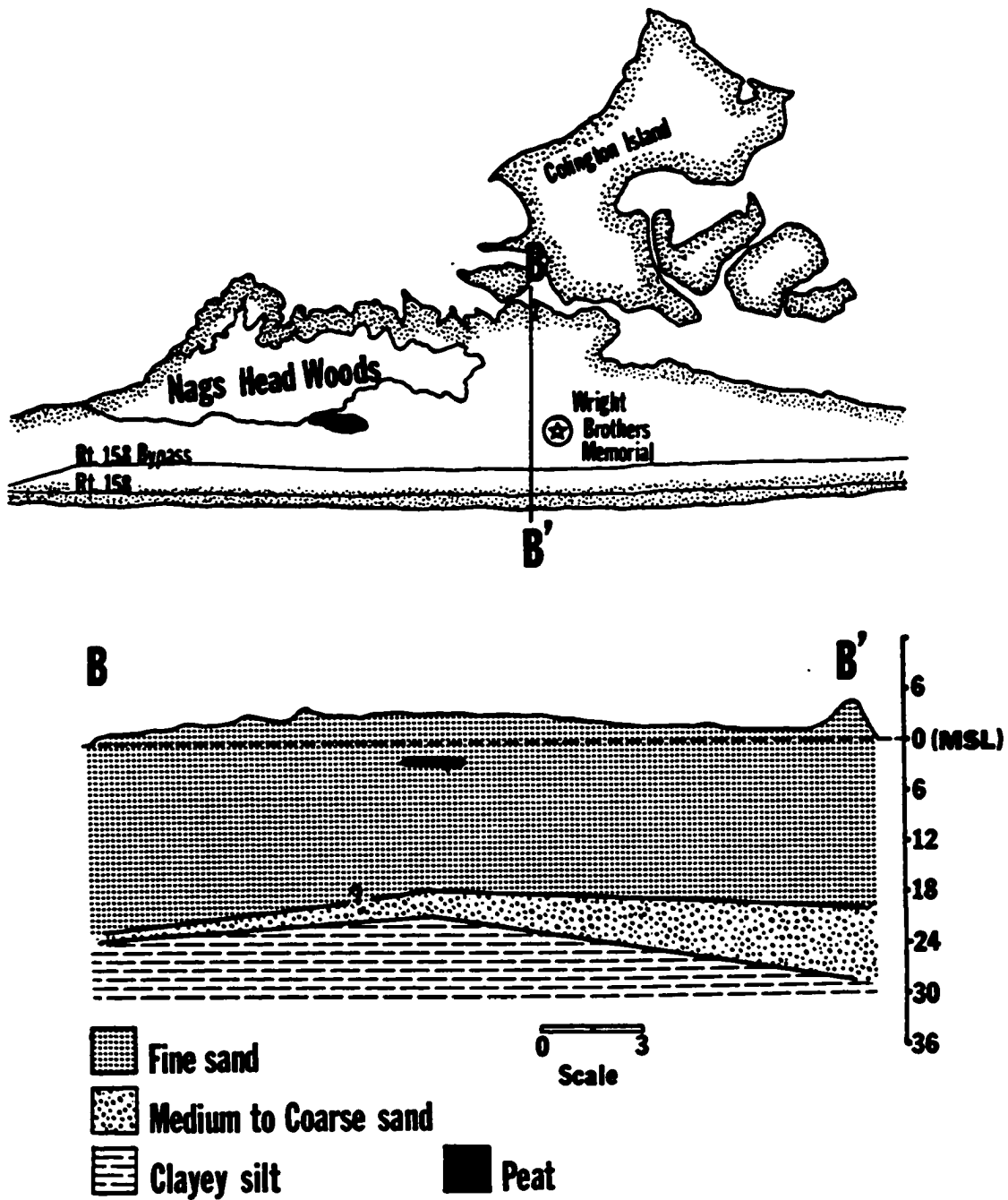


Figure 9. (a) Location of transect B-B' north of Nags Head Woods. (b) Geologic cross-section along transect B-B' (from U.S. EPA, 1985).

west of Fresh Pond, near the intersection of the Virginia Power right-of-way and the Nags Head-Kill Devil Hills town limits. At this location, according to Floyd, 11 m of fine-to-medium clean sands are underlain by 10 m of relatively impermeable gray clay. Floyd obtained a transmissivity value of $1.4 \times 10^{-3} \text{ m}^2/\text{s}$, which equates to a hydraulic conductivity of $1.3 \times 10^{-4} \text{ m/s}$, a value indicative of a clean sand aquifer (Fetter, 1980). Both Kimrey and Floyd obtained a storativity value of 0.3.

Pumping tests from test wells on nearby Roanoke Island indicated that the hydraulic conductivity of the surficial aquifer ranges from $6.6 \times 10^{-5} \text{ m/s}$ to $9.4 \times 10^{-5} \text{ m/s}$ (Moore, Gardner, and Associates, 1984). Pumping tests on the upper aquifer in other locations along the Outer Banks indicate that hydraulic conductivities fall within the 10^{-4} m/s to 10^{-5} m/s range (Brown, 1960; Harris and Wilder, 1964; Kimrey, 1960; Lloyd and Dean, 1968; Wyrick and Dean, 1968).

CHAPTER 4: RESEARCH PROCEDURES

4.1 Introduction

In order to determine the natural shape and variability of the water table in Nags Head Woods, it was necessary to install a network of monitoring wells throughout the area and to check water levels in the wells periodically. With these data the natural shape of the water table may be determined and seasonal variation documented. Water level readings also record the drawdown around Fresh Pond during municipal pumpage.

The texture and lateral and vertical extent of the surficial aquifer through Nags Head Woods were determined by drilling test borings in the area. This information can be correlated regionally, and also be incorporated into numerical models for the area. Hydraulic parameters (transmissivity, hydraulic conductivity, and storativity) were determined by conducting a pumping test on the aquifer; these data were also necessary to construct groundwater models for Nags Head Woods.

4.2 Field Work

The first stage of field work consisted of the installation of water table observation wells throughout

Nags Head Woods. This 38-well network (Figure 10) included 16 wells which already existed in the area, plus 22 wells installed for this study. Four of the previously existing wells were installed for Floyd's (1979) study, four were observation wells emplaced by the Nature Conservancy staff, and eight were unused wells which originally supplied water to the town of Nags Head. Of the wells installed for this study, four were 3.2 cm diameter galvanized steel pipe, hand-driven to a depth of over 4 m. Three wells were hand-augered to a depth of 1.5 m, and the rest were emplaced in 4 m to 15 m-deep holes augered with the Old Dominion University drill rig. These wells were constructed of 3.2 cm diameter Schedule 40 PVC pipe with a 1.0 m to 1.5 m point of slotted 3.2 cm PVC pipe.

The elevation of the top of each well used in this study was surveyed with a tripod-mounted level and stadia rod. Benchmark information was provided by the Nature Conservancy staff and by C.P. Lewis, a local surveyor. Resurveying and closed-loop checking indicates the elevations obtained are accurate to within ± 0.02 m, accuracy sufficient to illustrate the shape of the water table in this area. Water table elevations were calculated by subtracting the measured depth to the water table from the known elevation of each well top. Depth-to-water measurements were made with a 100-foot steel tape with a lead weight attached to the bottom. For

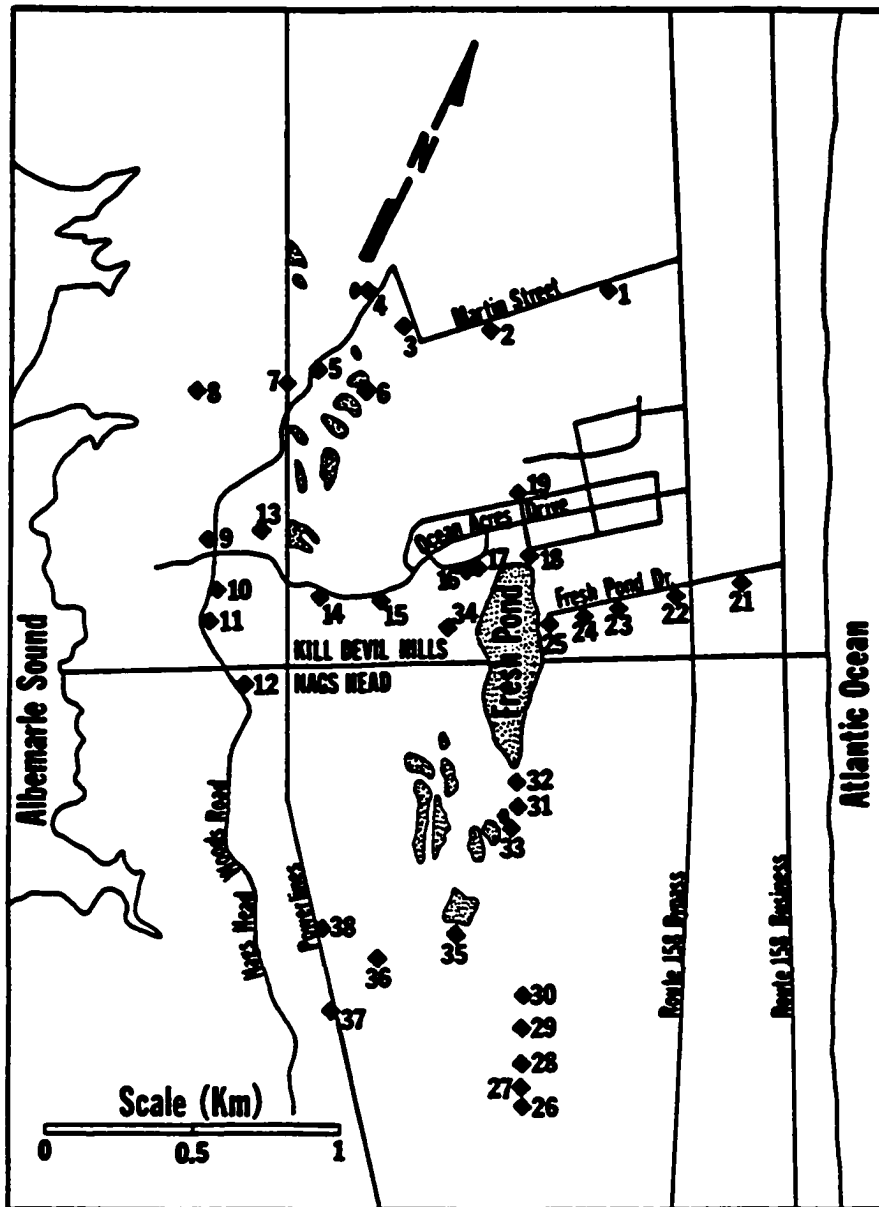


Figure 10. Locations of monitoring wells, major roads, and fresh water ponds (stippled).

each measurement, the lower foot was wiped dry and coated with carpenter's chalk. The tape was let down into a well until part of the chalked section was below water, and one of the foot marks was held exactly at the top of the casing. After withdrawal, the wetted line on the tape was read to a hundredth of a foot. These measurements were later converted to meters. A disadvantage of this method is that the approximate depth to water must be known so that a portion of the chalked section will be submerged to produce a wetted line. The accuracy of this method, however, exceeds that of most other measurement devices (Driscoll, 1986).

Water levels in the wells were monitored every other week for a year, from May, 1985, to May, 1986, and then monthly through September, 1986. Water level measurements taken before large-volume pumping from Fresh Pond began in March, 1986, record the natural shape and seasonal variation of the water table; measurements taken since then also illustrate the drawdown effect around Fresh Pond. Minimum natural levels were recorded on September 13, 1985; maximum levels, on November 7, 1985, soon after heavy rains from Hurricane Gloria.

Daily rainfall data were collected from two stations near Nags Head Woods--the U.S. Weather Station at the Manteo, N.C. Airport, and the Kill Devil Hills Water Plant next to Fresh Pond (after June, 1986). Monthly data were also collected from the U.S. Corps of Engineers Coastal

Engineering Research Center at Duck, N.C.

Stratigraphic information for Nags Head Woods was obtained from borings taken with the Old Dominion University CME-45B drill rig. Six 15 m to 30 m borings were made in Nags Head Woods at the locations shown in Figure 11. Samples were taken at 1.5 m intervals throughout each boring. The color, texture, and sorting of each sample were described in the field, and logged according to depth from the land surface. Borings #1, #2, #5, and #6 were made with 4-inch solid-stem augers, pulling the augers up after each 1.5 m flight to obtain a sample; borings #3 and #4 were made with 6-inch (outer diameter) hollow-stem augers, taking a split-spoon sample every 1.5 m. Close agreement in lithology between holes #2 and #4, located about 150 m apart, indicate that both of these sampling schemes were effective (Figure 12). Since these borings were made to delineate the extent of the surficial aquifer, each was terminated once a thick, compact clay unit was encountered. In the laboratory, the sediment samples were again described according to color, texture, and sorting; these data were then compiled into logs and cross-sections, and incorporated in the finite-difference technique used to model the water table in Nags Head Woods.

The last stage of field work was the installation of a pumping well and several observation wells and completion of a 48-hour pumping test on December 14-16, 1985.

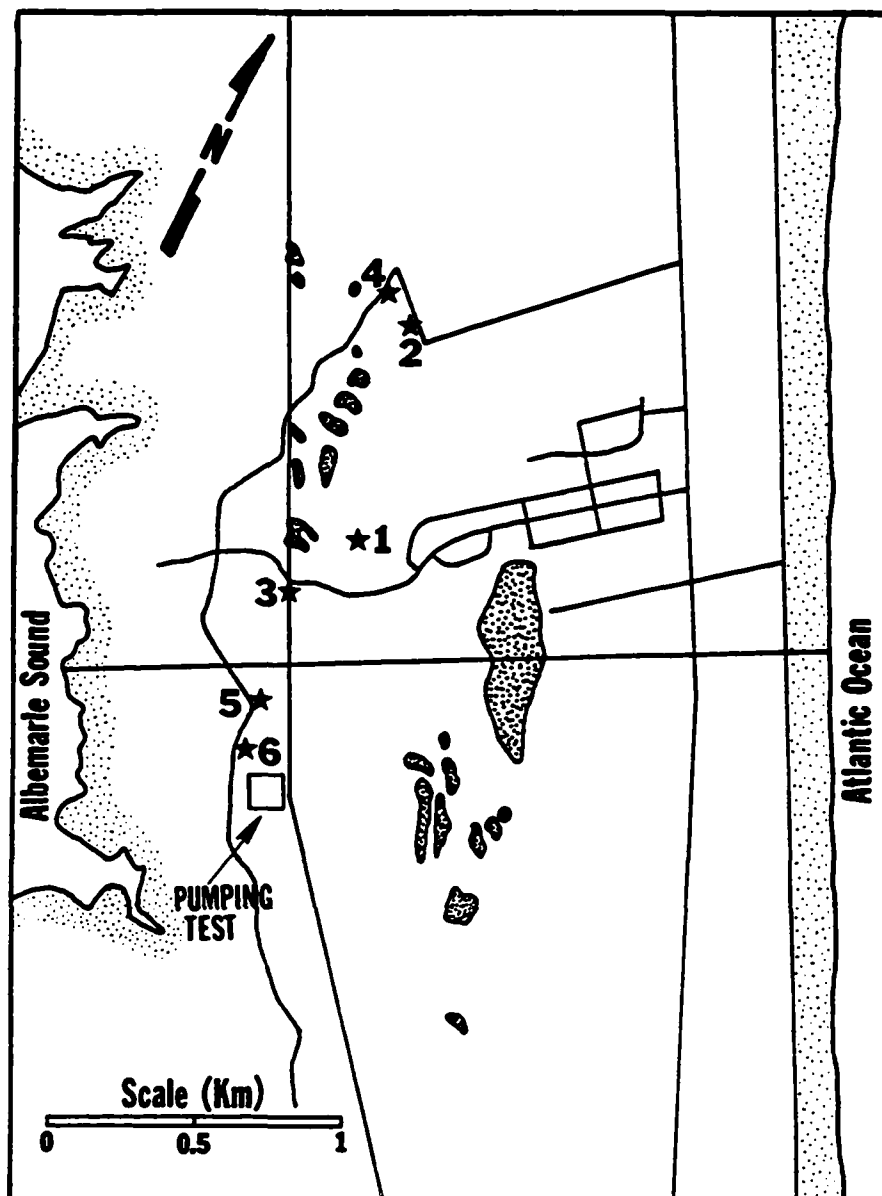


Figure 11. Locations of stratigraphic test borings and pumping test site.

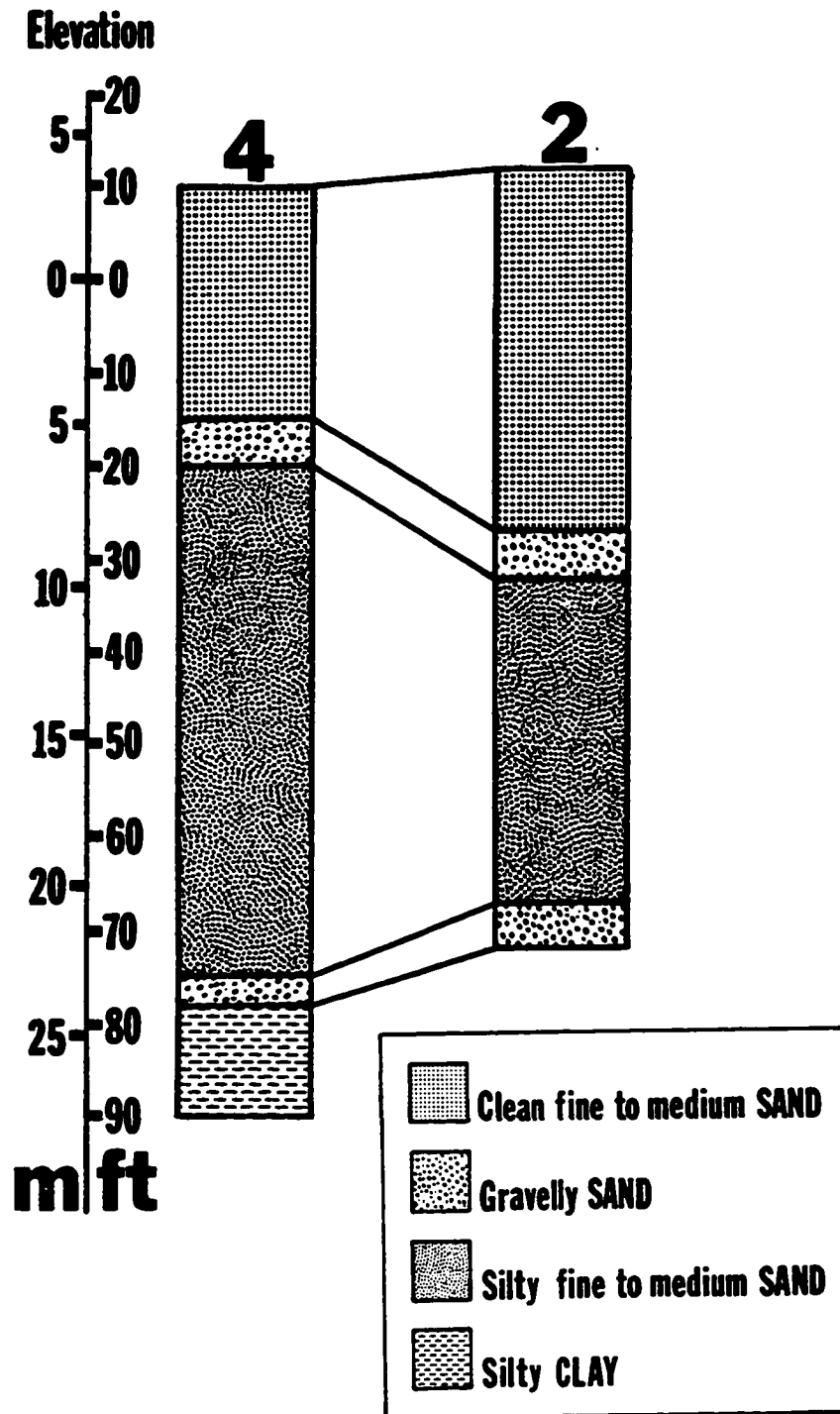


Figure 12. Stratigraphic logs of test borings #2 and #4, located 150 m apart. Boring #2 made with solid stem augers and #4 made with hollow-stem augers and split-spoon sampler.

Pumping tests are conducted to determine the hydraulic parameters of the aquifer; these parameters can then be used to predict (1) the effect of new withdrawals on existing wells, (2) the drawdowns in a well at future times, and (3) the radius of the cone of influence for individual or multiple wells (Driscoll, 1986).

Measurements required for a constant-rate pumping test are (1) time since pump started, (2) pumping rate, (3) pre-pumping water level, and (4) water levels at various intervals during the pumping period. The pumping rate was determined by observing the time required to fill container of known volume; this simple and accurate method is practical for measuring relatively low pumping rates. Depth-to-water measurements were made using the steel tape method previously described. Although this method provides accurate results in observation wells for depths to 30 m, the number of measurements that can be taken over a short period of time is limited. This constraint can be significant during the first ten minutes of a pumping test when as many measurements as possible are required (Driscoll, 1986). Lack of sufficient data points during the first few minutes of a pumping test can cause calculated transmissivity values to be in error by as much as 100% (Wyrick and Floyd, 1961).

The pumping test was performed at a house construction site near the southern end of the study area, in a flat area between high dunes (Figure 11). The pumping well was

26 m deep and screened throughout its length. Three observation wells were positioned at the sites shown in Figure 13. Water level readings were measured in the casing of the pumping well and in each observation well during the time of pumping. The accuracy of data taken from the pumping well, however, is usually less reliable because of turbulence created by the pump (Driscoll, 1986). Recovery data were also gathered from the pumping well for three hours after the pumping ceased; these data are valuable in verifying the aquifer coefficients calculated during the pumping phase of the test (Driscoll, 1986). Pump discharge was checked hourly, and averaged a relatively steady $2.6 \times 10^{-4} \text{ m}^3/\text{s}$ (4.1 gpm). Hoses led water to a pond 150 m away, far beyond the cone of depression formed by the pumping well.

4.3 Data Manipulation

Pumping tests offer the most powerful method for analyzing the hydrogeologic character of an aquifer. Measurements made during an aquifer test provide values for some of the terms in the Theis (1935) equation, permitting calculation of the transmissivity and storage capacity of the aquifer (Driscoll, 1986). In analyzing pumping test data from unconfined aquifers, however, one finds that the drawdowns differ from those predicted by the Theis (1935) equation, designed for confined aquifers. When unconfined drawdowns are plotted versus

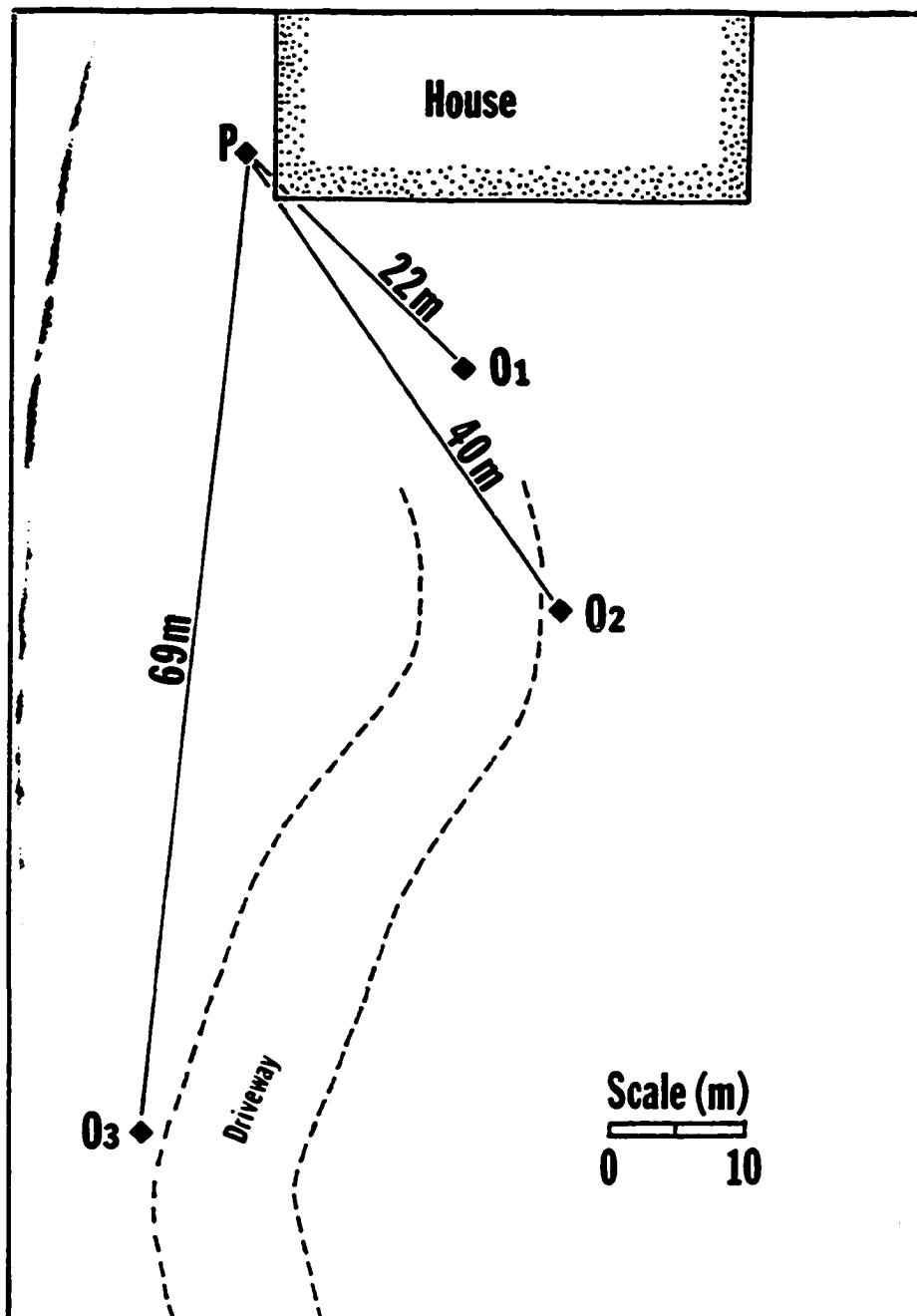


Figure 13. Map showing locations of pumping well (P) and observation wells (O₁, O₂, and O₃) during pumping test on December 14-16, 1985.

time on logarithmic paper, they usually delineate an S-shaped curve consisting of a steep segment at early times, a flat segment at intermediate times, and a somewhat steeper segment at later times. The physical phenomenon that causes this behavior is a delayed response of water draining from the previously saturated zone by gravity (Neuman, 1975).

The two types of curves that are used in this type of analysis are shown in Figure 14. Type-A (Theis) curves are used for the analysis of early drawdown data, when instantaneous release of water from storage is occurring. As time elapses, the effects of gravity drainage and vertical flow cause deviations from the theoretical Theis curve. Low-angle Type-B curves are used for the intermediate drawdown data, when vertical, gravity-fed dewatering of the aquifer is occurring. Type-B curves steepen and end on a second Type-A (Theis) curve (Fetter, 1980).

Drawdown data for the pumping well and three observation wells and recovery data for the pumping well were plotted versus time on logarithmic (log-log) paper, and matched with the type curves calculated by Neuman (1975) for fully penetrating wells in an unconfined aquifer. As explained in Neuman (1975), the late time-drawdown data are superimposed on the Type-B curves, keeping the vertical and horizontal axes of both graphs parallel to each other and matching the data to the

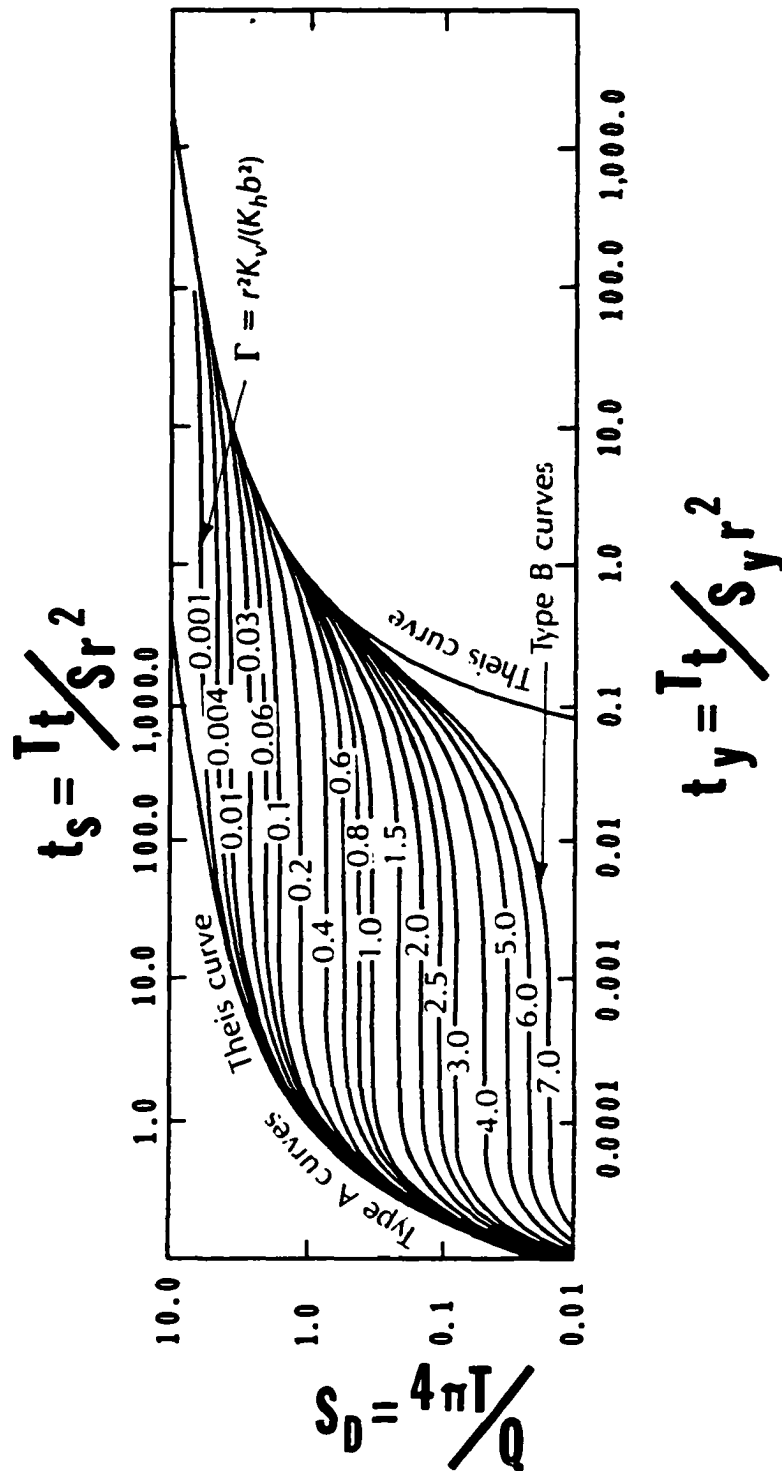


Figure 14. Type curves for drawdown in an anisotropic, heterogeneous, unconfined aquifer (from Neuman, 1975).

Type-B curve with the best fit. At any match point, the values of s , s_D , t , and t_y are determined:

where s is drawdown (from field data),
 s_D is drawdown (from type curve),
 t is time (from field data), and
 t_y is a dimensionless time parameter (from type curve).

Transmissivity is then calculated from the following equation:

$$T = 0.0796 (Q (s_D/s)), \quad (1)$$

and the specific yield from

$$S_y = Tt/r^2t_y. \quad (2)$$

The early drawdown data are then superimposed on the Type-A (Theis) curve for the B-value of the previously matched Type-B curve. A new set of match points are determined, and the transmissivity calculated again by the above equation (1). Storativity is calculated from

$$S = Tt/r^2t_s, \quad (3)$$

where t_s is another dimensionless time parameter, having a different scale than t_y . After determining the transmissivity (T) of the aquifer, the hydraulic

conductivity (K) can be calculated from the following equation:

$$K = T/b, \quad (4)$$

where b is the thickness of the aquifer (Neuman, 1975).

CHAPTER 5: RESULTS

5.1 Introduction

Water level data from the Nags Head Woods monitoring wells indicate that the water table across Bodie Island assumes the shape of an elongated dome which is unaffected by the dunes or other minor topographic features of the area; this shape is maintained through seasonal water level variations. Episodes of rainfall are directly reflected by water levels in the wells. When water is withdrawn from Fresh Pond, a cone of depression forms around it, as shown by lowered water levels in wells near the lake.

The water table aquifer is composed of clean and silty sands underlain by a thick clay unit which may be regional in extent. Hydraulic conductivities derived from pumping test drawdown data indicate that the aquifer is composed predominantly of silty sands at that location.

5.2 Water Table -- Natural Conditions

Contour maps and profiles of water level data indicate that the natural shape of the water table on Bodie Island is an elongated dome which crests about 140 m east of Fresh Pond and slopes to sea level on both sides of the

island. As shown by the water table profile in Figure 15, the sand-dune topography of the area does not affect this shape. The water table maintains its elongated dome shape even while it rises and falls due to varying rates of precipitation and evapotranspiration (Figures 16 through 18). The elevation of the water table at the crest varied as much as 0.63 m during this study, reaching a maximum of 3.21 m in November, 1985, and a minimum of 2.58 m in September, 1985. During most of the year the crest of the water table wrapped around the north and east sides of Fresh Pond, indicating that water moved through Fresh Pond from the north and east and drained to the west (Figures 16 and 17), probably as a result of evaporation from the lake. On November 7, 1985, within a week after passage of a hurricane, the groundwater crest was linear, 140 m east of Fresh Pond (Figure 18). In the small ponds of Nags Head Woods, west of the water table divide, groundwater enters from the east and exits to the west.

Figure 19 shows a graph of rainfall data from May, 1985, to May, 1986, and graphs of water table elevations for selected wells for the same period of time. These graphs illustrate that water levels in Nags Head Woods directly reflect the amount of rainfall received. Groundwater levels in most wells rebound quickly following periods of heavy rains. However, variations in rainfall extent and intensity can produce irregular effects on the water table. Some wells show little

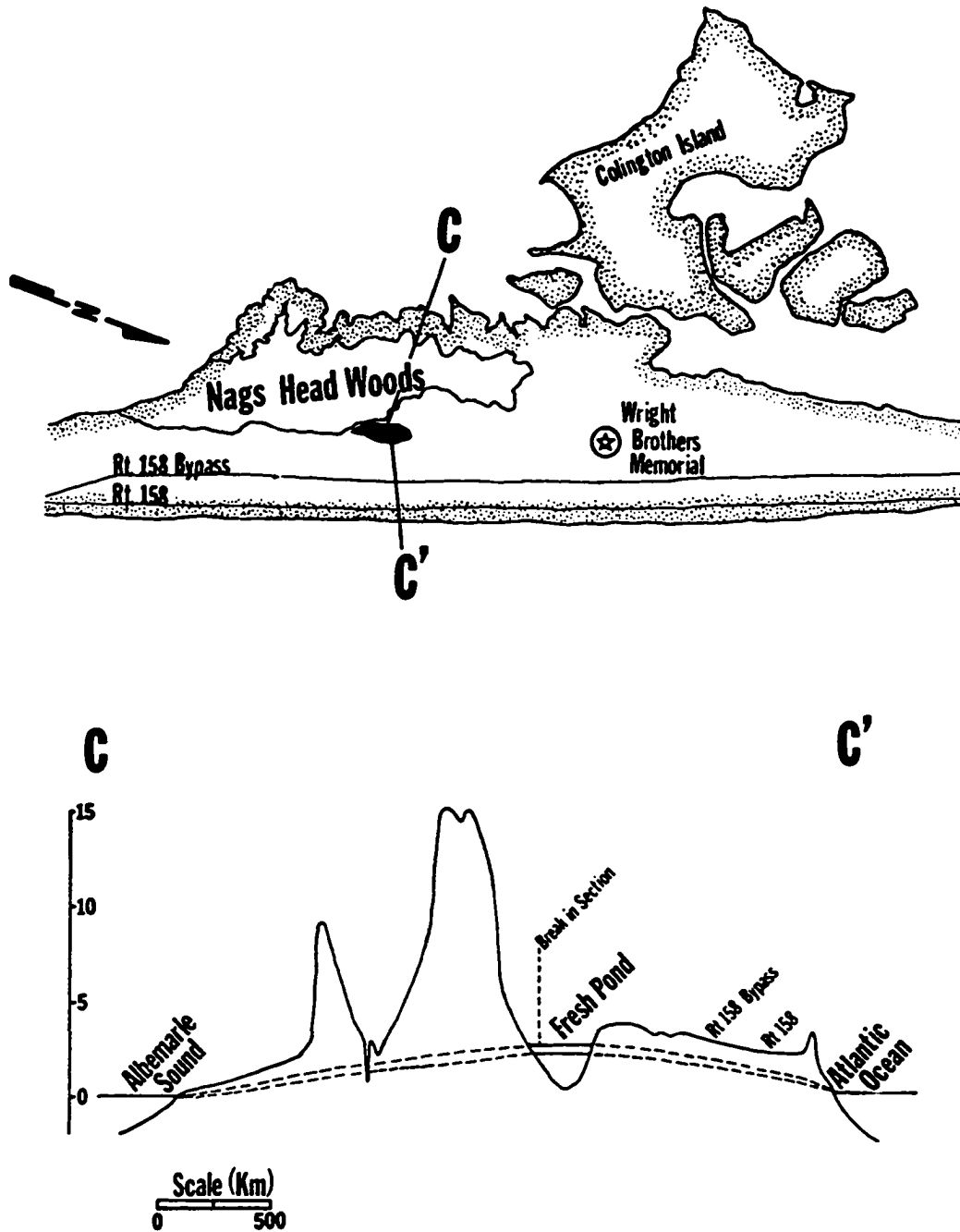


Figure 15. (a) Location of transect C to C' across Bodie Island. (b) Water table profile along transect C to C'. Maximum water levels recorded November 7, 1985; minimum levels on September 13, 1985. Vertical exaggeration is 70X.

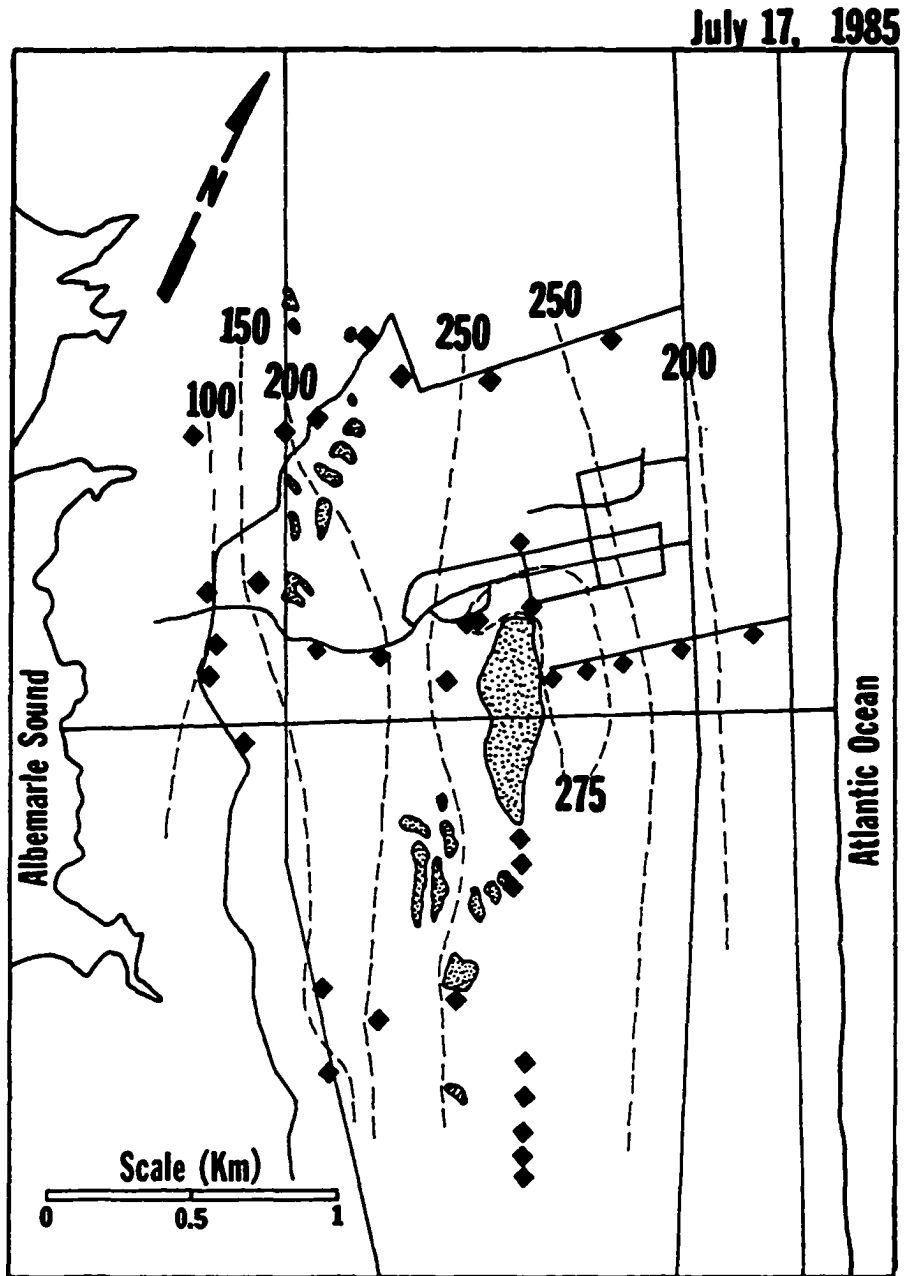


Figure 16. Water table contour map for July 17, 1985. Contours are in centimeters elevation.

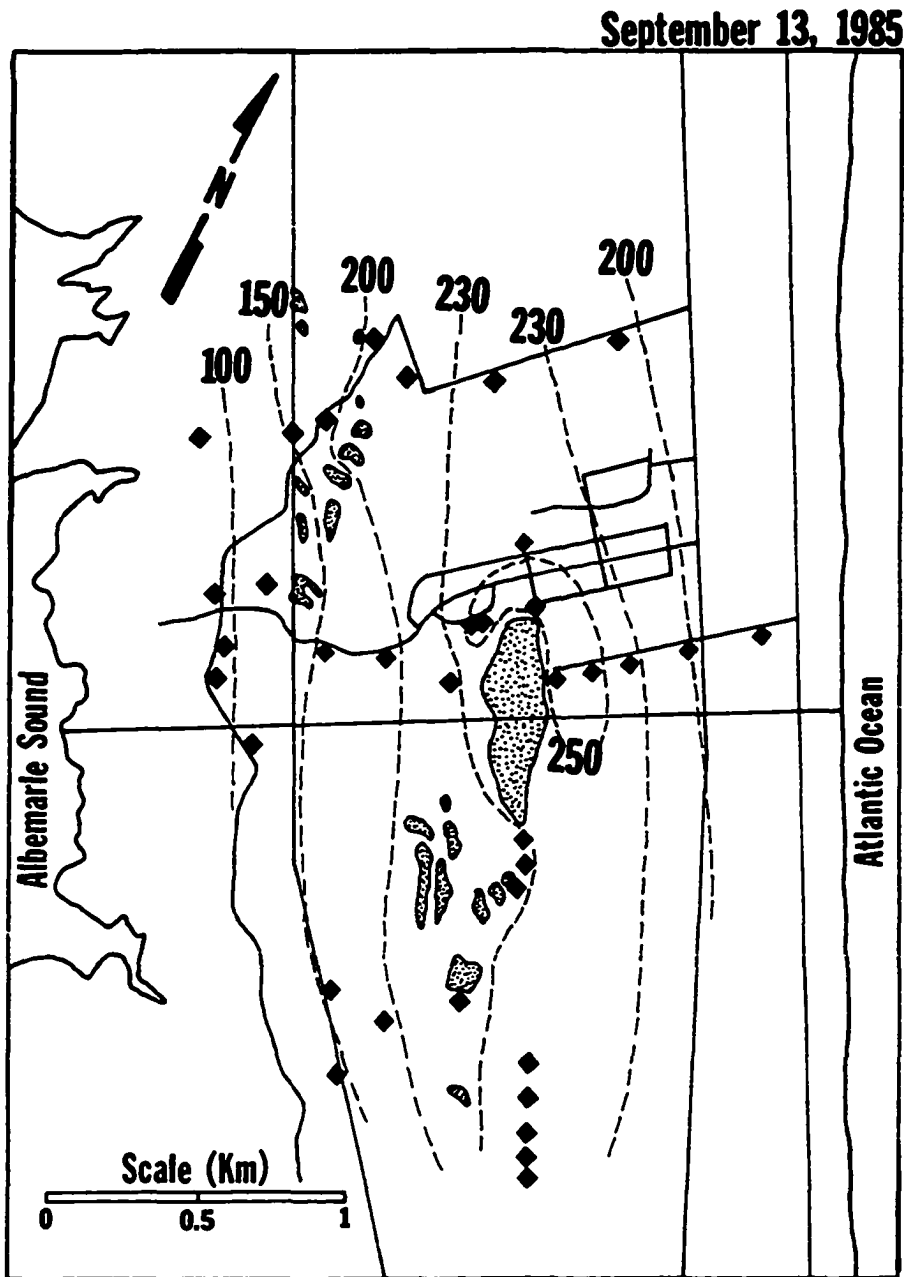


Figure 17. Water table contour map for September 13, 1985. Contours are in centimeters elevation.

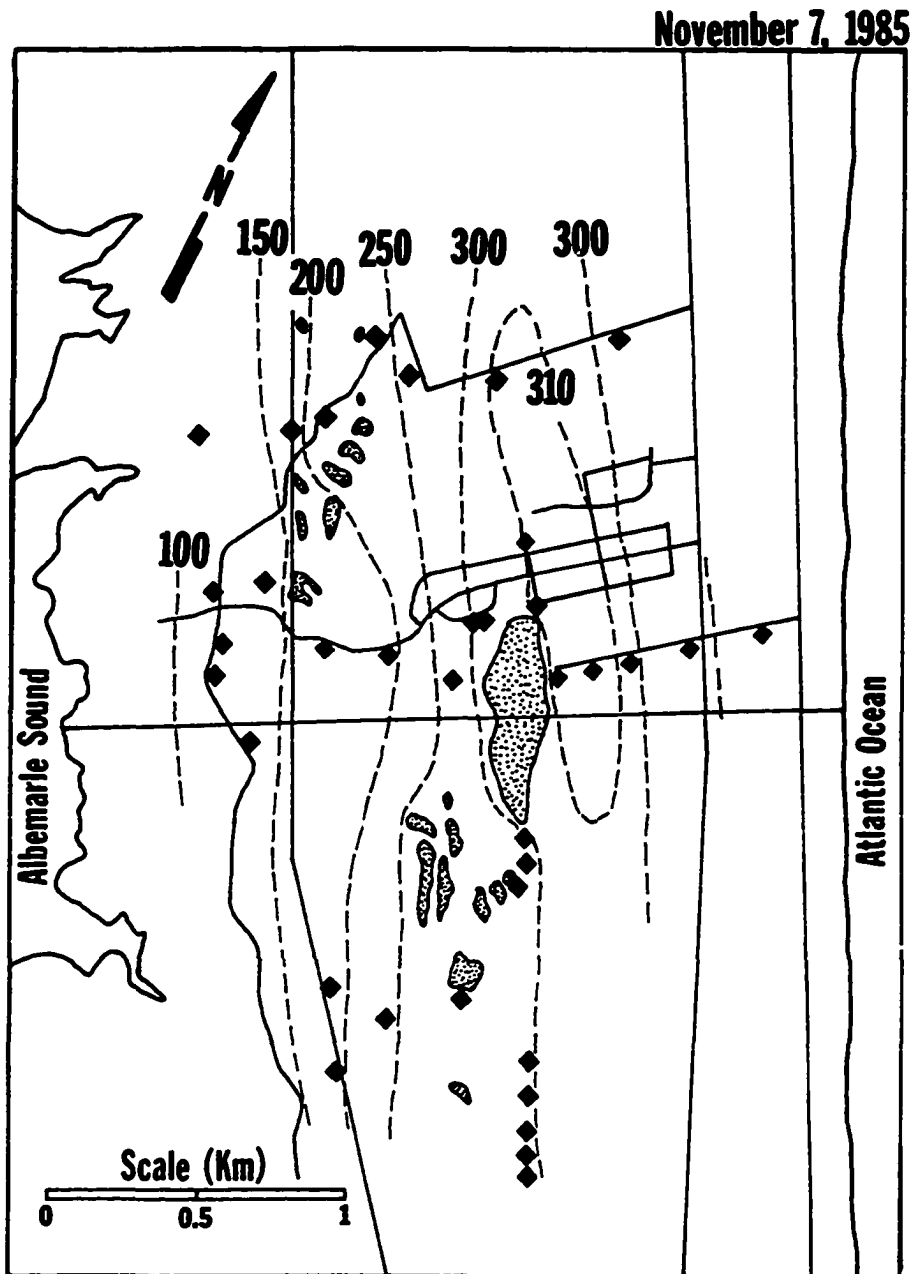


Figure 18. Water table contour map for November 7, 1985. Contours are in centimeters elevation.

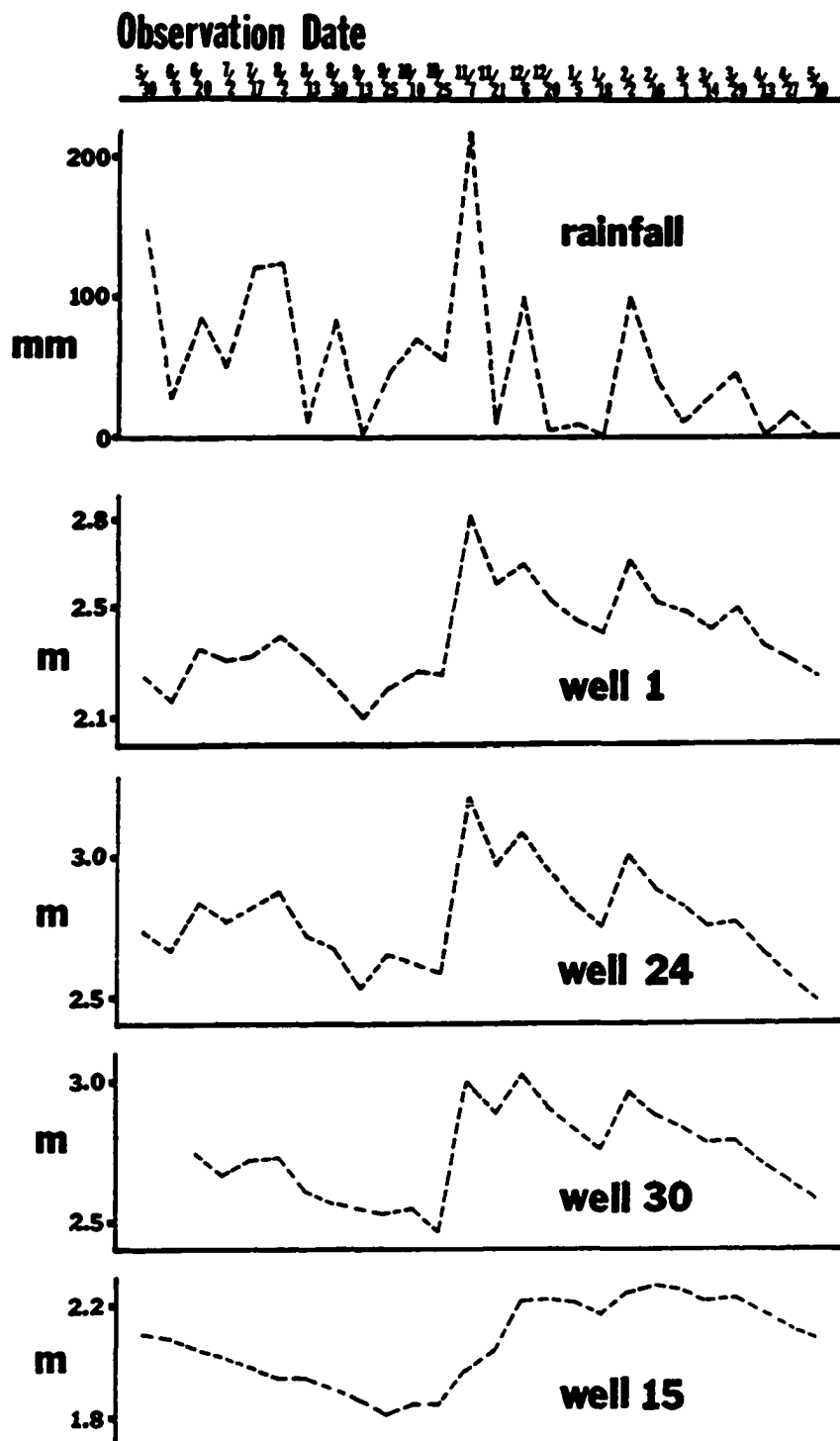


Figure 19. Graphs of rainfall (in millimeters) and well water levels (in meters elevation) for the observation dates shown above.

change, some increase, and others decrease during the same period, probably as a result of variations in precipitation over the study area. In some particularly deep wells, water levels fluctuate less rapidly and show a more muted response to rainfall than in the shallower wells. Water levels in well #15, located on a high dune crest where the unsaturated zone is approximately 13.5 m thick, respond more slowly to rainfall than water levels in the other wells. Note that the peak on November 7, 1985 in Wells #1, #24, and #30 does not appear until November 21 in Well #15, when levels in the other wells have already declined. Because distance to the water table is greater in this well, the infiltrating water does not reach the water table for many days after a rainfall (Dunne and Leopold, 1978).

Due to high evapotranspiration rates during summer months, rainfall may not reach the water table at all. Note that the two weeks of rainfall prior to August 30, 1985, made very little impact on water table levels (Figure 19).

5.3 Water Table -- Pumping Conditions

Preliminary testing of the Nags Head and Kill Devil Hills water treatment facilities at Fresh Pond resulted in occasional pumping from the lake beginning in mid-November, 1985, and continuing through March, 1986. This pumping averaged $960 \text{ m}^3/\text{day}$ (0.25 mgd) on 7 to 15

days out of each month. By April, pumpage had increased to 2100 m³/day (0.55 mgd) on 25 days out of the month. From May through September, 1986, pumping occurred daily at a relatively constant rate of 2000 m³/day (0.53 mgd) (J. Richeson, personal communication, 1986). Wells near Fresh Pond showed measurable declines in water levels by the beginning of May as a significant cone of depression began forming around the lake. A water level gauge, installed in Fresh Pond by Nags Head Water Plant personnel on June 25, 1986, provided additional detail on the shape of the cone of depression. From June 25 through September, 1986, lake water elevation averaged 1.05 m. with a variation of ± 0.14 m. Minor changes in pumping rate and variations in rainfall do not markedly affect the lake water level (in Figure 20). Water table contour maps show that the cone of depression around Fresh Pond deepened and expanded during June, but then did not significantly change as pumping continued from July to September (Figures 21, 22, and 23). Throughout this period, the eastern edge of the cone of depression (groundwater divide) remained at an average distance of 306 m from Fresh Pond. The western edge of the cone of depression varied from 120 m to 186 m from the lake, moving towards the west during drier months and towards Fresh Pond in wetter months.

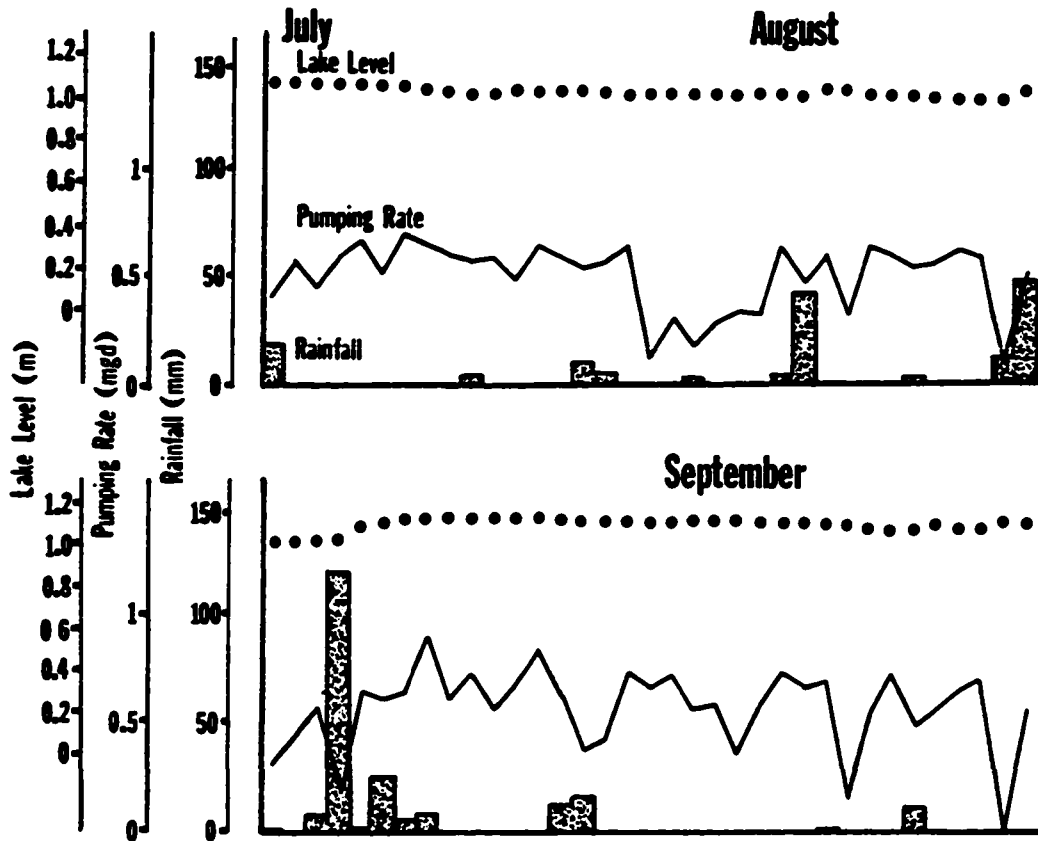


Figure 20. Graph comparing water level at Fresh Pond, pumping rates, and precipitation daily from July 10, 1986 to September 13, 1986.

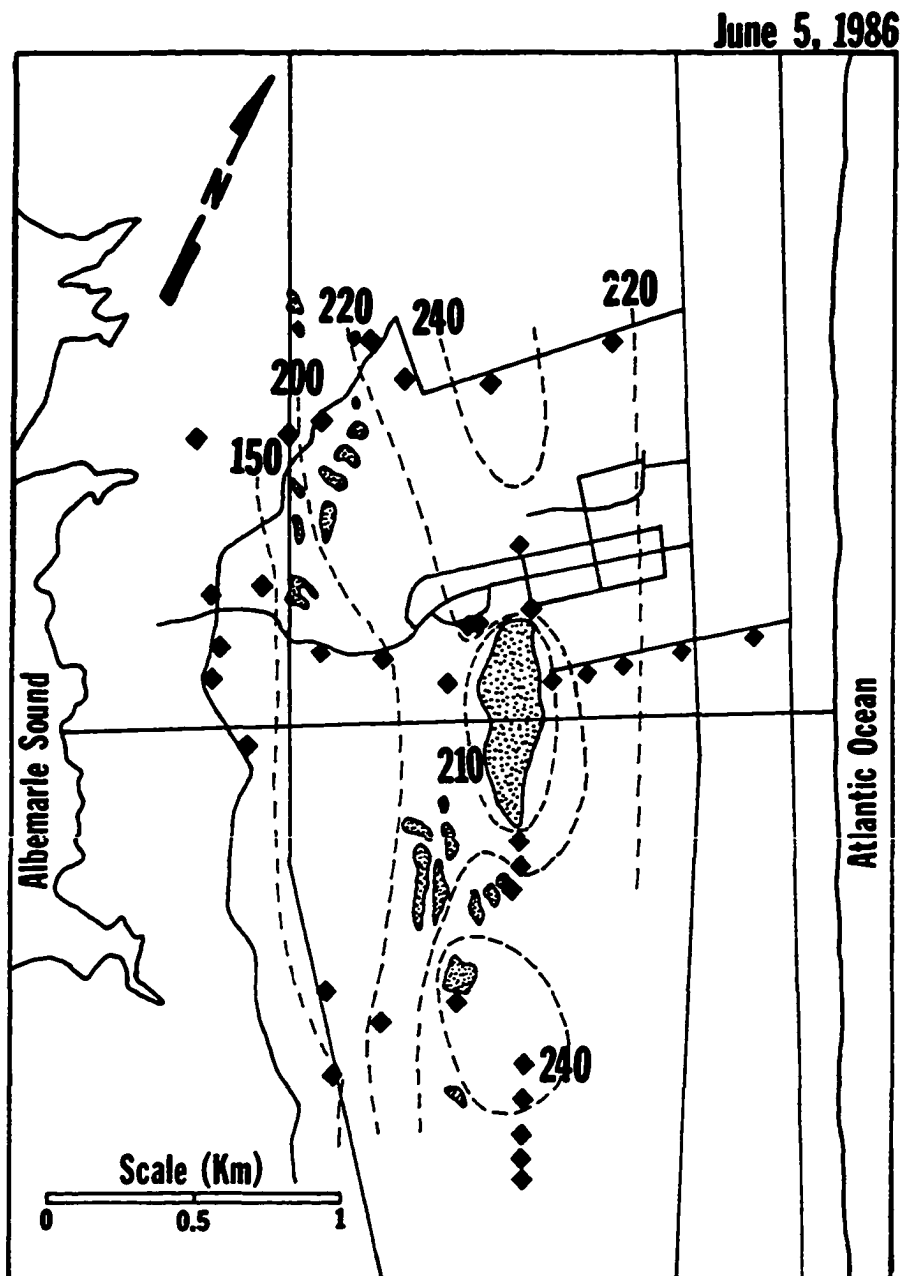


Figure 21. Water table contour map for June 5, 1986. Contours are in centimeters elevation.

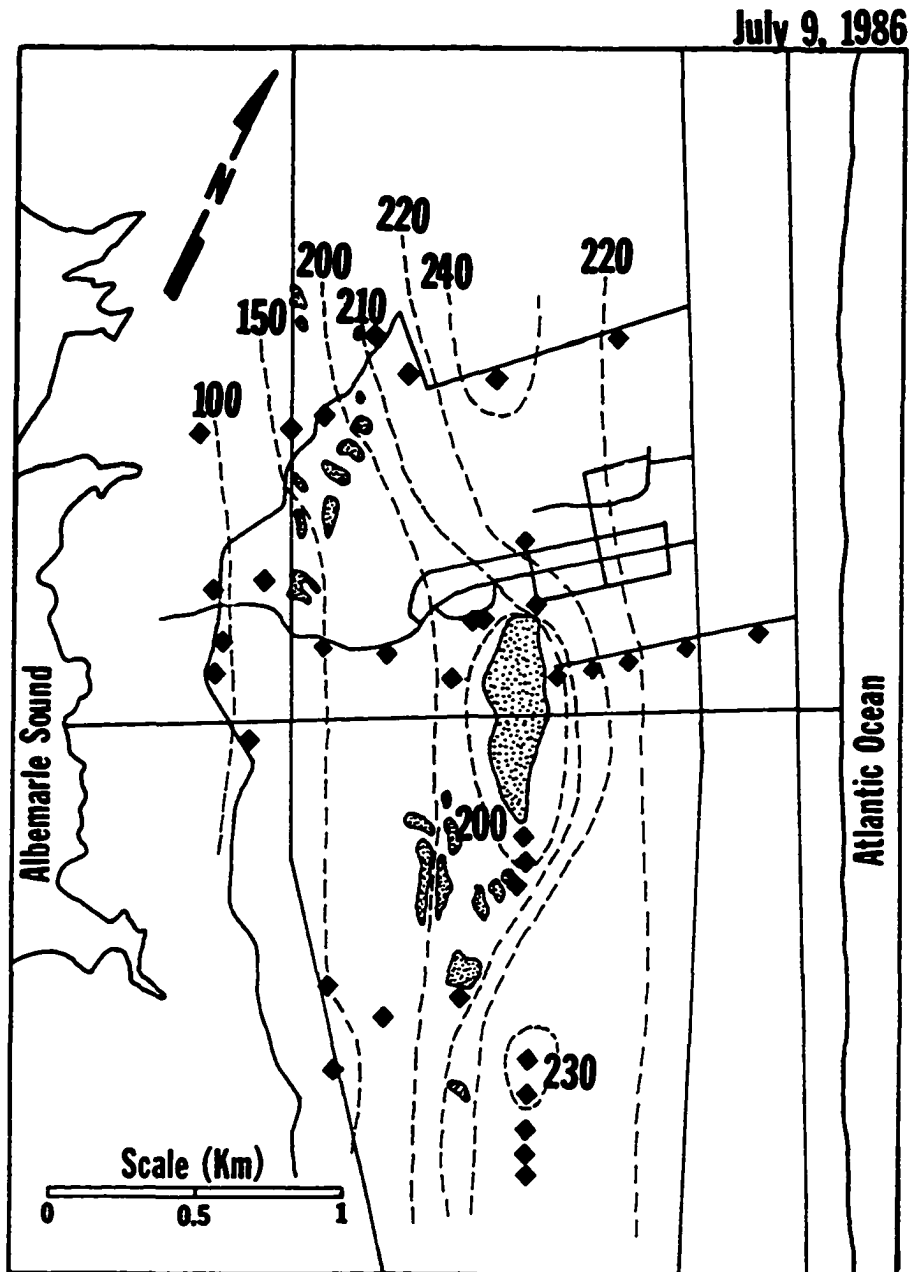


Figure 22. Water table contour map for July 9, 1986. Contours are in centimeters elevation.

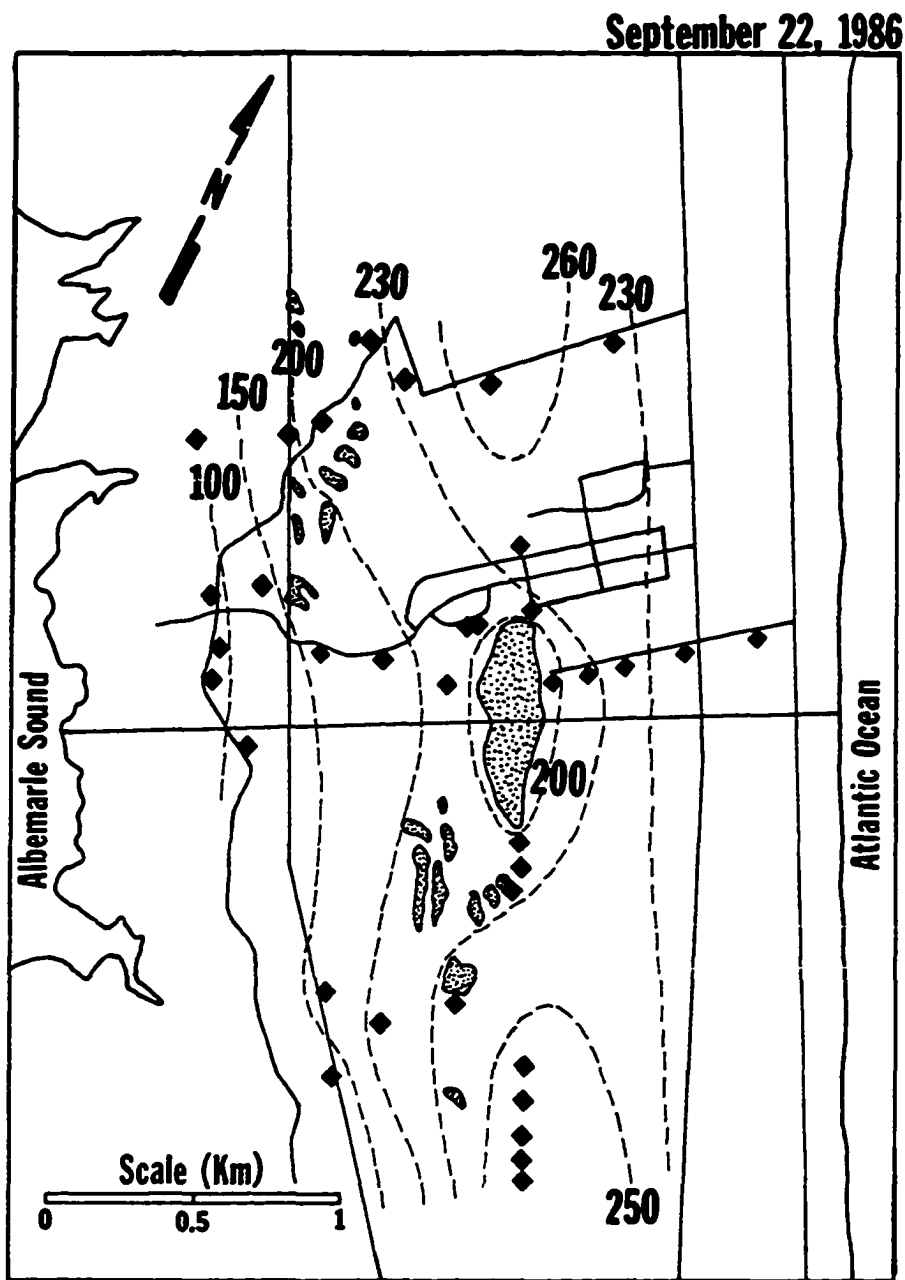


Figure 23. Water table contour map for September 22, 1986. Contours are in centimeters elevation.

5.4 Stratigraphy

The stratigraphic data gathered from the six test borings taken in Nags Head Woods for this study (Figure 24) indicate that the surficial aquifer is not uniformly thick or equally porous everywhere. Throughout the northern portion of the Woods, the surficial aquifer consists of a well-sorted, well-rounded, fine-to-medium sand at the surface which changes in color from tan to gray at depths of 3 m to 5 m. At elevations varying from -5 m to -8 m, these clean sands grade into a poorly-sorted, fine-to-gravelly sand approximately 2 m thick. Underlying this coarse unit are fine-to-medium silty sands containing zones of abundant shell fragments, some small pebbles, and some thin interbedded clayey silts. The base of the aquifer is marked by a dark-green compact clay layer at elevations varying from -11 m to -24 m.

In the southern half of the study area, the stratigraphy is slightly more complex. At -4 m to -5 m elevation, the fine-to-medium clean sands grade into fine-to-coarse silty sands containing shell fragments. Within this silty sand unit is an interbedded, discontinuous 2 m to 3 m thick clayey silt layer which occurs at elevations ranging from -6 m to -7 m. Underlying the silty sands at -18 m is a dark-green compact clay unit.

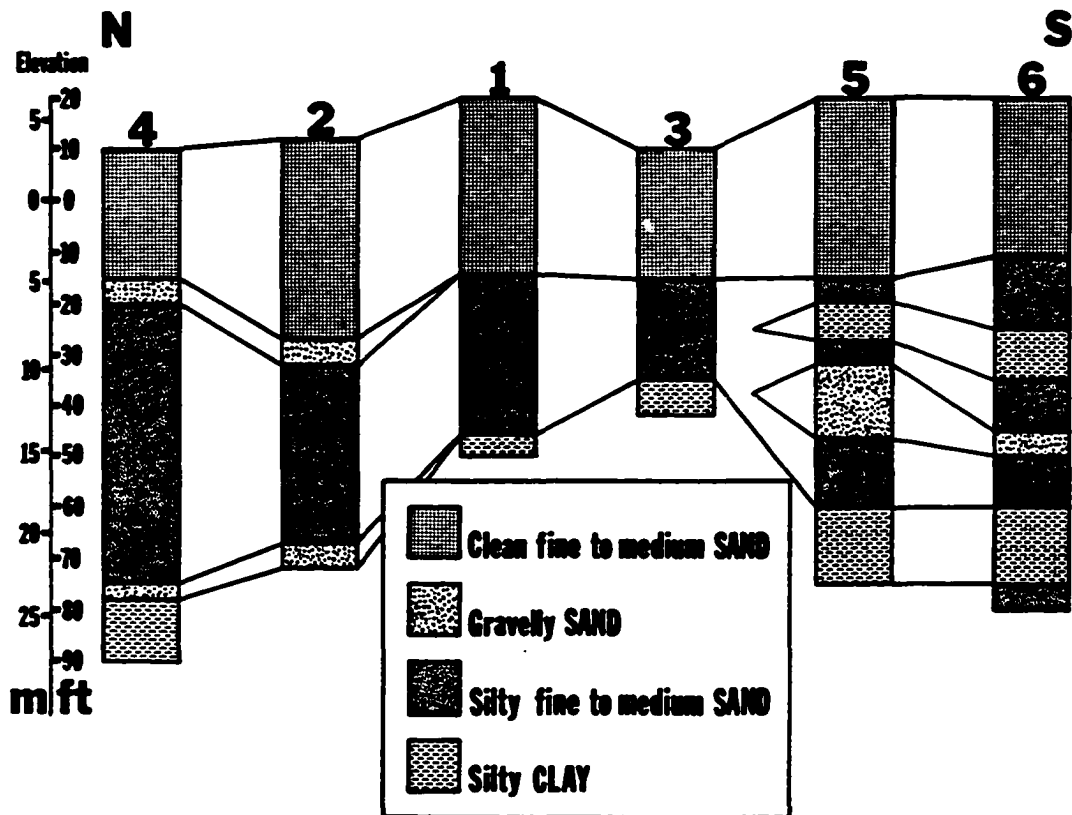


Figure 24. Stratigraphic correlation of boring logs (from north to south) through Nags Head Woods.

5.5 Hydraulic Characteristics

Table 2 shows the results of the pumping test calculations. Calculated transmissivity values range from $2.8 \times 10^{-6} \text{ m}^2/\text{s}$ to $1.5 \times 10^{-4} \text{ m}^2/\text{s}$, and hydraulic conductivity values from $1.4 \times 10^{-7} \text{ m/s}$ to $2.2 \times 10^{-5} \text{ m/s}$, based on an average aquifer thickness of 20 m. Because the pumping test was conducted in an interdunal flat area, where only a few meters of clean sand overlies the silty sand unit, the resulting hydraulic conductivities are indicative of a predominately silty sand aquifer rather than a clean sand aquifer (Fetter, 1980). Most of the variability between these hydraulic conductivity values arises from the ambiguities in the curve-fitting analysis. The storativity values calculated from the pumping test data range from 0.01 for observation well O₃ to 0.03 for observation wells O₁ and O₂; storativity cannot be determined using drawdown data from the pumping well, as distance to the observation well is a factor in the computations.

VALUES OF TRANSMISSIVITY (T), HYDRAULIC CONDUCTIVITY (K),
AND STORATIVITY DERIVED FROM PUMPING TEST DATA

DATA SET	T (m ² /s)	K (m/s)	Storativity
Observation well #1—drawdown	7.4×10^{-5}	3.7×10^{-6}	0.03
Observation well #2—drawdown	4.4×10^{-4}	2.2×10^{-5}	0.03
Observation well #3—drawdown	1.5×10^{-4}	7.4×10^{-6}	0.01
Pumping well—drawdown	2.8×10^{-6}	1.4×10^{-7}	—
Pumping well—recovery	3.4×10^{-6}	1.7×10^{-7}	—

Table 2. The pumping test was conducted December 14-16, 1985, at a house construction site in southern Nags Head Woods.

CHAPTER 6: COMPUTER MODELING

6.1 Introduction

Models of aquifers are used to determine the actual or predicted behavior of the aquifer under different sets of conditions. Mathematical models of aquifer systems can be solved by two independent procedures: analytical methods and numerical methods. Analytical models are based upon formal equations derived from physical theory, while numerical models approximate flow equations by finite-difference or finite-element techniques.

6.2 Analytical Models

Analytical models are based upon mathematical equations derived from classical theory, including the equations of Theim (1906), Theis (1935), Polubarinova-Kochina (1962), and Toth (1962). An analytical model was developed by Whittecar (Whittecar and Salyer, 1986), based upon an equation by Fetter (1980). This equation (5) predicts the level of water tables on infinite-strip islands or peninsulas, and thus should be applicable to Bodie Island. Water table elevation (h_x) at any point (x) on an island of width (L) can be related to the elevation of the surrounding water (h_1 and h_2), the

hydraulic conductivity (K), and the rate of recharge into the aquifer (W):

$$h_x^2 = h_1^2 - (x(h_1^2 - h_2^2))/L + x((W/K)(L-x)) \quad (5)$$

Because the ocean and lagoon waters are at sea level around a barrier island, $h_1 = h_2 = 0$ and Equation 5 reduces to:

$$h_x^2 = x((W/k)(L-x)) \quad (6)$$

Whittecar's model uses this equation to predict the natural water table shape through the Nags Head Woods area. Theim's (1906) equation describing steady-state radial flow for an unconfined aquifer is then used to calculate the effect of pumpage from Fresh Pond and subtract that drawdown from the predicted natural water table:

$$h_2^2 = ((Q/3.1416K)(\ln(r_2/r_1))) - h_1^2 \quad (7)$$

where Q = discharge from Fresh Pond,
 K = hydraulic conductivity,
 r_1 = effective radius of Fresh Pond,
 r_2 = distance from lake to node,
 h_1 = elevation of Fresh Pond during pumping, and
 h_2 = groundwater level at node.

As shown in Figure 25, this analytical model closely predicted water levels through Nags Head Woods on July 9, 1986. A "total error" value for this simulation (the

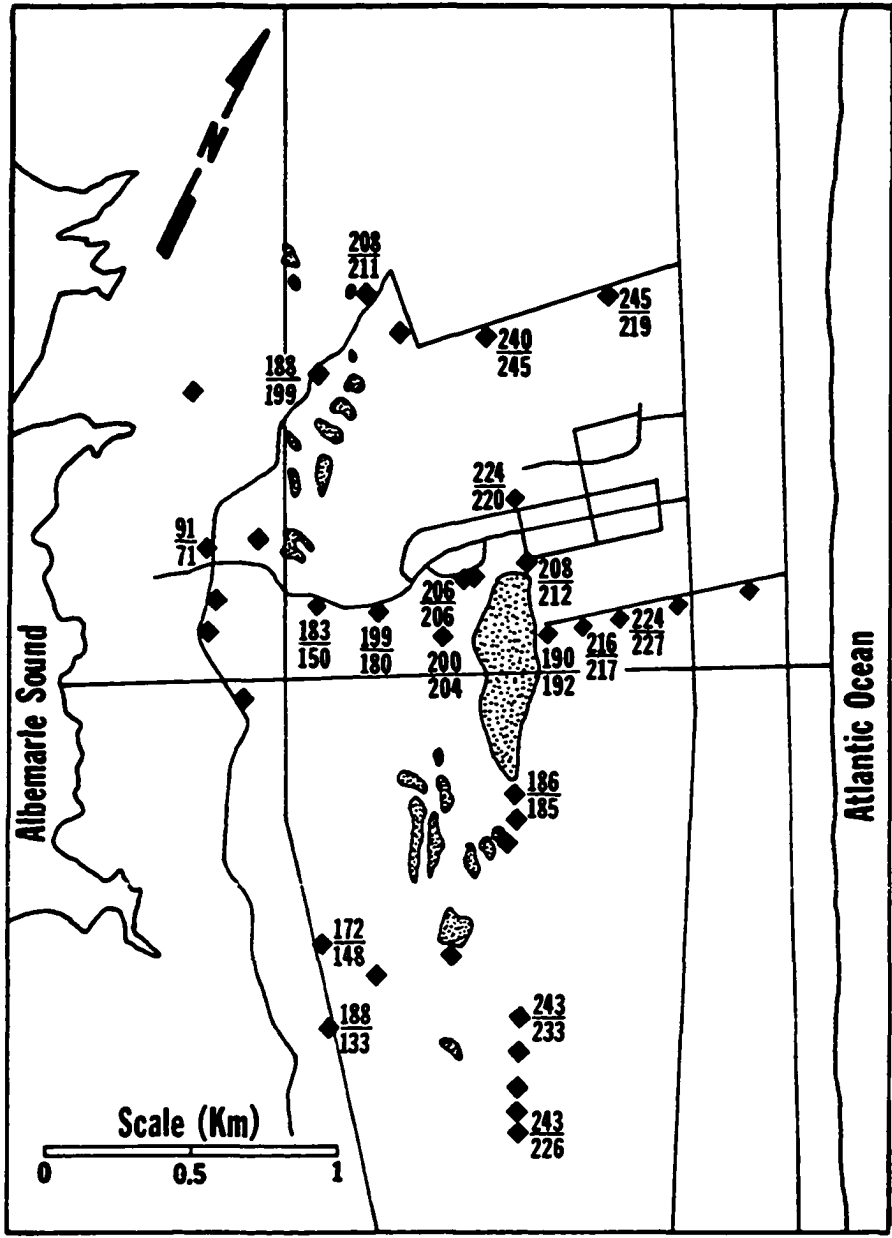


Figure 25. Results of analytical modeling (from Whittecar and Salyer, 1986).

average difference between predicted and actual water levels for all wells) is 12.6 cm/well. Analytical models such as this suffer from severe limitations, however, including restriction to two dimensions, restriction to homogeneous or layered cases, and restriction to steady-state conditions. Numerical models were developed to overcome these limitations.

6.3 Finite-difference Models

In contrast to analytical models, most finite-difference models solve the partial differential equation governing the nonsteady-state, two-dimensional flow of groundwater in a continuous artesian, nonhomogeneous, and isotropic aquifer:

$$d/dx(T_x dh/dx) + d/dy(T_y dh/dy) = S dh/dt + Q(x,y,t) \quad (8)$$

where T = transmissivity,
 h = head,
 t = time,
 S = storativity,
 Q = net groundwater withdrawal rate, and
 x,y = rectilinear coordinates.

Although there is no general solution for this equation, a numerical solution can be obtained through a finite-difference approximation made by replacing the derivatives in Equation 8 with differences taken between nodal points (Wang and Anderson, 1982). A continuous aquifer is represented by a grid of points (nodes) in

square or rectangular spacings, so that these points are a small, but finite, distance apart and the spatial changes in head are approximately linear (Fetter, 1980). The equations governing the flow of groundwater in the discretized model are then written in finite-difference form, and the resulting set of finite-difference equations is solved numerically with the aid of a digital computer (Prickett and Lonquist, 1971). The finite-difference form of Equation 8 at the point (i,j) is:

$$\begin{aligned}
 & T_{i-1,j,2} (h_{i-1,j} - h_{i,j}) / \Delta x^2 + \\
 & T_{i,j,2} (h_{i+1,j} - h_{i,j}) / \Delta x^2 + \\
 & T_{i,j,1} (h_{i,j+1} - h_{i,j}) / \Delta y^2 + \\
 & T_{i,j-1,1} (h_{i,j-1} - h_{i,j}) / \Delta y^2 = \\
 & S(h_{i,j} - h_{\emptyset i,j}) / \Delta t + Q_{i,j} / \Delta x \Delta y
 \end{aligned}
 \tag{9}$$

where $h_{\emptyset i,j}$ is the calculated head at the end of the previous time increment Δt , and $T_{i-1,j,2}$, $T_{i,j,2}$, $T_{i,j,1}$, and $T_{i,j-1,1}$ are aquifer transmissivity within the vector volume between node i,j, and nodes i-1,j; i+1,j; i,j+1; and i,j-1 (Figure 26).

Since there is an equation of the same form as Equation 9 for every node of the digital model, a large set of simultaneous equations must be solved for the unknown variable, $h_{i,j}$ (Prickett and Lonquist, 1971). A solution is obtained by solving sets of equations for nodes along the columns or rows of the grid starting at one boundary of the model and progressing sideways or downward to another boundary. This iterative procedure is

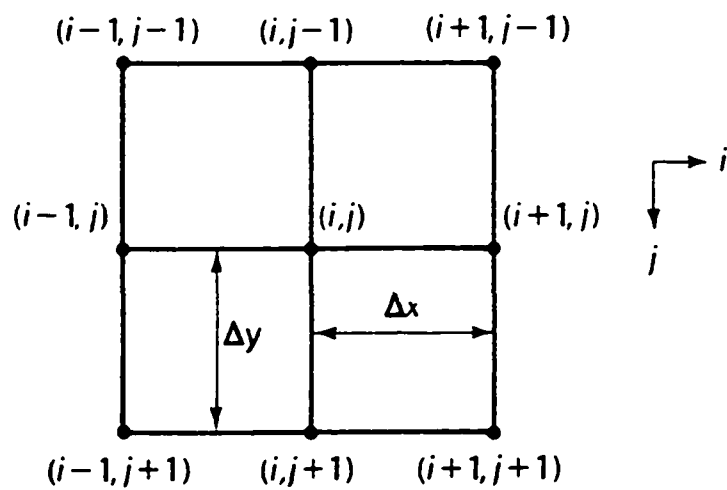
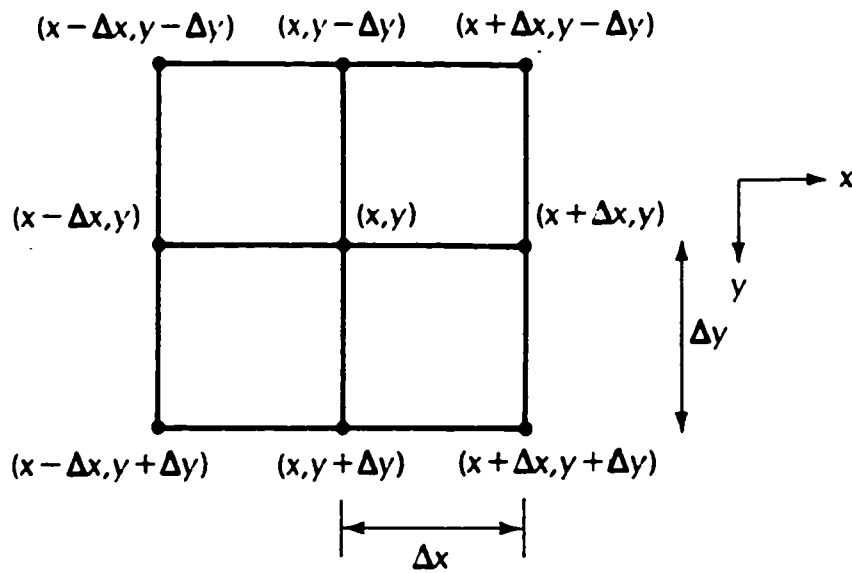


Figure 26. Computer notation for finite difference grid (from Fetter, 1980).

repeated until convergence is achieved (Wang and Anderson, 1982).

Although Equations 8 and 9 are strictly valid only for confined aquifers, they can also be used for unconfined aquifers by allowing T (transmissivity) to vary with time as the saturated thickness changes (Wang and Anderson, 1982). Transmissivity is recalculated during each iteration by subtracting the aquifer bottom elevation from the newly-calculated head elevations to obtain a new aquifer thickness; this new aquifer thickness is then multiplied by a given hydraulic conductivity value (Prickett and Lonquist, 1971).

6.4 The Nags Head Woods Model

One of the most widely used and well-documented finite-difference models is the groundwater program developed by Prickett and Lonquist (1971). This extremely versatile model consists of a basic aquifer simulation program which can be adapted to many different aquifer situations by adding various subprograms. These modifications may include (1) one-, two-, or three-dimensional problems, (2) water table, nonleaky artesian, or leaky artesian conditions, (3) steady-state or transient conditions, (4) differing boundary conditions, and (5) specialized types of printout.

The Prickett and Lonquist model for water table conditions is written with dimensions of NR, the number of

rows of width ΔY , and NC, the number of columns of width ΔX . In order to prepare the Nags Head Woods model, a map of the aquifer system was overlain by the finite-difference grid of 28 columns and 30 rows shown in Figure 27. The grid was prepared so that ΔX and ΔY are equal to 100 m. Column #2 represents the western boundary of the aquifer, the freshwater-saltwater interface which lies within the tidal marsh, and column #27 represents the eastern boundary which lies near the ocean beach. Head values for these columns, therefore, were set at mean sea level. Head values for columns #1 and #28 (outside the actual aquifer boundaries) were also set to sea level to produce western and eastern no-flow boundaries (Wang and Anderson, 1982).

A datum plane was set to 30 m below sea level, so that head (H) and aquifer bottom (BOT) elevations are input as positive values above that plane. Calculated head values are also output as positive values above the datum plane.

Default values which are written into the program include:

```

NR,NC---the size of the grid
TT-----an average transmissivity value
SF-----the storage factor
HH-----an average initial head value
QQ-----the withdrawal rate for each node
PP-----average aquifer permeability
BOTT----the elevation of the bottom of the
          aquifer

```

These values are sufficient to describe an aquifer system which has an NC-by-NR rectangular shape, is homogeneous

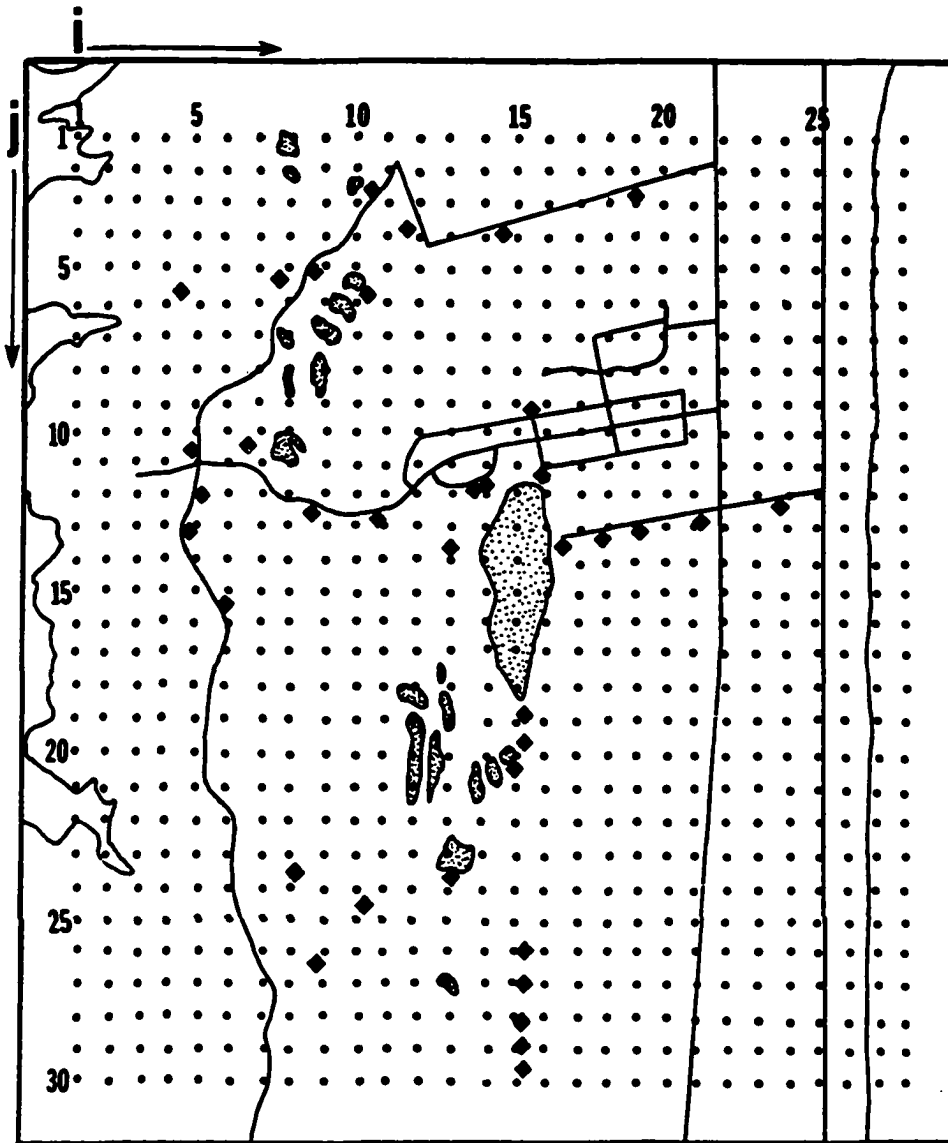


Figure 27. Map of study area showing finite-difference grid used in modeling water table elevations.

and isotropic, has the same initial head values at each node, and the same net withdrawal rate at each node. These conditions are very restrictive; thus this model would not be very useful unless it could be modified. Modifications are made by reading in values for each node having properties different from the specified default value (Fetter, 1980).

Because the water table across Bodie Island is domed, rather than flat, initial head values must be stated for each node in the finite-difference grid. Initial head values, in matrix form, are contained in data files which are called up at the beginning of each run of the Nags Head Woods model. Likewise, predicted head values are output in matrix form and stored in data files at the end of each computer run.

The Prickett and Lonquist model uses an alternating direction implicit method in combination with Gauss-Seidel iteration as the numerical solution procedure. Within each time step, the solution iterates alternately along columns and rows until the heads converge within a specified error tolerance (Wang and Anderson, 1982). An initial time step (DELTA), the number of time steps (NSTEPS), and the error tolerance value (ERROR) are parameter values which must be input into the program. An initial small value for DELTA is chosen for the first time step (or increment) when water levels are fluctuating rapidly. Thereafter, DELTA is increased between time

steps, using progressively larger time increments to increase efficiency as water levels fluctuate more slowly (Prickett and Lonquist, 1971).

6.5 Determination of Effective Recharge

The Prickett and Lonquist (1971) model requires a constant recharge rate (QQ) per unit area (ΔX by ΔY). Rainfall, however, is always sporadic over time and area, making determination of a suitable recharge value to input into the model difficult. This problem was solved by using a subprogram which estimates "effective" monthly recharge and incorporates it into the Prickett and Lonquist model. This subprogram, developed by Whittecar (Whittecar and Salyer, 1986; Whittecar and Emry, 1987), determines average monthly recharge by subtracting the effects of interception and evapotranspiration from the amount of total rainfall:

$$W_{mo} = (R_{mo} \times I_{mo}) - ET_{mo} \quad (10)$$

where W_{mo} is the average recharge per month,
 R_{mo} is monthly rainfall (from Manteo, N.C.),
 I_{mo} is a monthly interception factor, and
 ET_{mo} is monthly evapotranspiration loss.

Interception is that rain water which is caught by leaves, limbs, and grass and evaporates, never reaching the water table. Conifer forests intercept 22-28% of gross rainfall, while deciduous forests intercept 13-20%

(Dunne and Leopold, 1978). Since Nags Head Woods is approximately half conifer and half deciduous (H. List, personal communication, 1986), this model reduces total monthly rainfall by 20% from October through April. From May through September, no interception effect is calculated, as nearly all of the interception that occurs during these months lessens evaporation from the leaves by the same amount (Dunne and Leopold, 1978).

Evapotranspiration includes both evaporation of moisture from exposed surfaces and the transpiration of moisture by vegetation. The Thornthwaite method of calculating potential evapotranspiration (Dunne and Leopold, 1978), which is based primarily on air temperature, was used to estimate average monthly evapotranspiration values using temperature records from the Manteo, N.C. airport. These values for monthly evapotranspiration (ET_{mo}) are subtracted from the quantity of monthly rainfall that escapes interception. In the event that evapotranspiration (ET_{mo}) exceeds rainfall (R_{mo}), recharge for that month is figured as zero, not as negative recharge.

The average monthly rainfall values (W_{mo}) obtained from these calculations are not sufficient to represent actual aquifer recharge; rainfall from previous months must also be considered. Previous studies indicate that under conditions of no recharge, water levels decline exponentially--dropping quickly at first, but less rapidly

with time (Fetter, 1980; Heath and Trainer, 1981). Whittecar's subprogram (Whittecar and Salyer, 1986) weights each month's rainfall for a year, assuming that the amount of water that fell last month is more important than rain from earlier months. The larger the decay factor, the greater significance given to antecedent rainfall. This method allows the effects of especially dry or wet periods to be averaged into a long-term recharge rate. Effective monthly recharge (W_{em}) is estimated by:

$$W_{em} = W_s/d \quad (11)$$

where
$$W_s = \sum_{a=0}^{11} (W_{mo} \times D^a) \quad (12)$$

$$d = \sum_{b=0}^{11} (D^b) \quad (13)$$

where a and b are equal to the number of months prior to the previous month, and D is a decay factor (less than 1). Based upon comparisons of measured water levels, taken at the water table divide, and predicted heads, Whittecar determined that a recharge-decay (D) value of 0.95 adequately described recharge conditions in the Nags Head Woods area (Whittecar and Salyer, 1986).

For the model used in the present study, Whittecar's

recharge subprogram was modified to consider any number of months of rainfall, rather than an arbitrary 12 months. This modification was made in hopes of even more accurately determining a suitable recharge value to input into the Nags Head Woods model. Monthly rainfall data (in mm) from the U.S. Weather Station at the Manteo, N.C. Airport were input into the subprogram to calculate an effective monthly recharge (W_{em}) value in millimeters per month. This recharge value was then converted to meters per day for use in the rest of the program. Figure 28 shows the effective recharge rates which were calculated for various numbers of months of antecedent rainfall. As this graph indicates, recharge values may be much too large or too small unless enough antecedent rainfall is considered. Calculated recharge values actually stabilize after at least 18 months of antecedent rainfall have been considered, indicating that present water levels may be affected by rainfall from up to 1.5 years ago.

Once an effective recharge rate considering 18 months of antecedent rainfall has been determined for the date which will be modeled, the rest of the Nags Head Woods program can be run.

6.6 Procedure

The Prickett and Lonquist (1971) aquifer simulation program, modified to model the water table aquifer in Nags

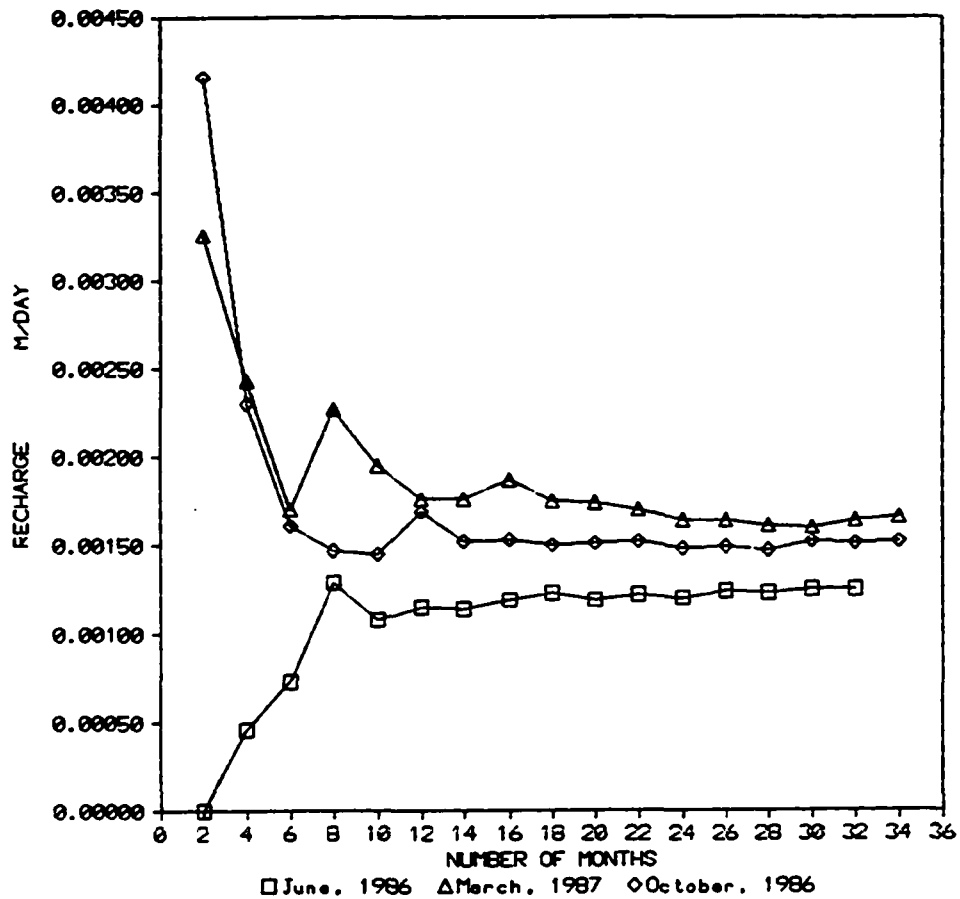


Figure 28. Effective recharge (in meters per day) determined for the months of June and October, 1986, and March, 1987, considering an increasing number of months of antecedent rainfall.

Head Woods (Appendix B), was run on an IBM PC-AT computer. For these simulations, metric units (meters, meters per day, and cubic meters per day) were used, although the program will work with any consistent system of units.

The first phase of computer modeling was an attempt to generate a natural water table, unaffected by pumping from Fresh Pond. For this simulation, initial head values across the island were set to mean sea level (+30 m) and recharge applied until a mounded water table was generated; a water table mound approximating natural levels occurred after almost a year at recharge rates of 82 mm/month to 88 mm/month. In order to simulate the asymmetrical nature of the natural water table, the bottom of the aquifer was set at +4.1 m (25.9 m below MSL) for the western two-thirds of the island and at +11.75 m (18.25 m below MSL) for the eastern third of the island (Figure 29). This change in aquifer bottom elevation, although unrealistic, was necessary to produce a simulated groundwater crest at column #18, which corresponds to the natural groundwater crest just east of Fresh Pond. These simulated water tables corresponded fairly well with the natural water table, as shown in Figure 30. After considerable trial and error, a hydraulic conductivity value of 4.0×10^{-4} m/s was found to yield the best results for this phase of modeling.

Phase two of computer modeling was to take an initial

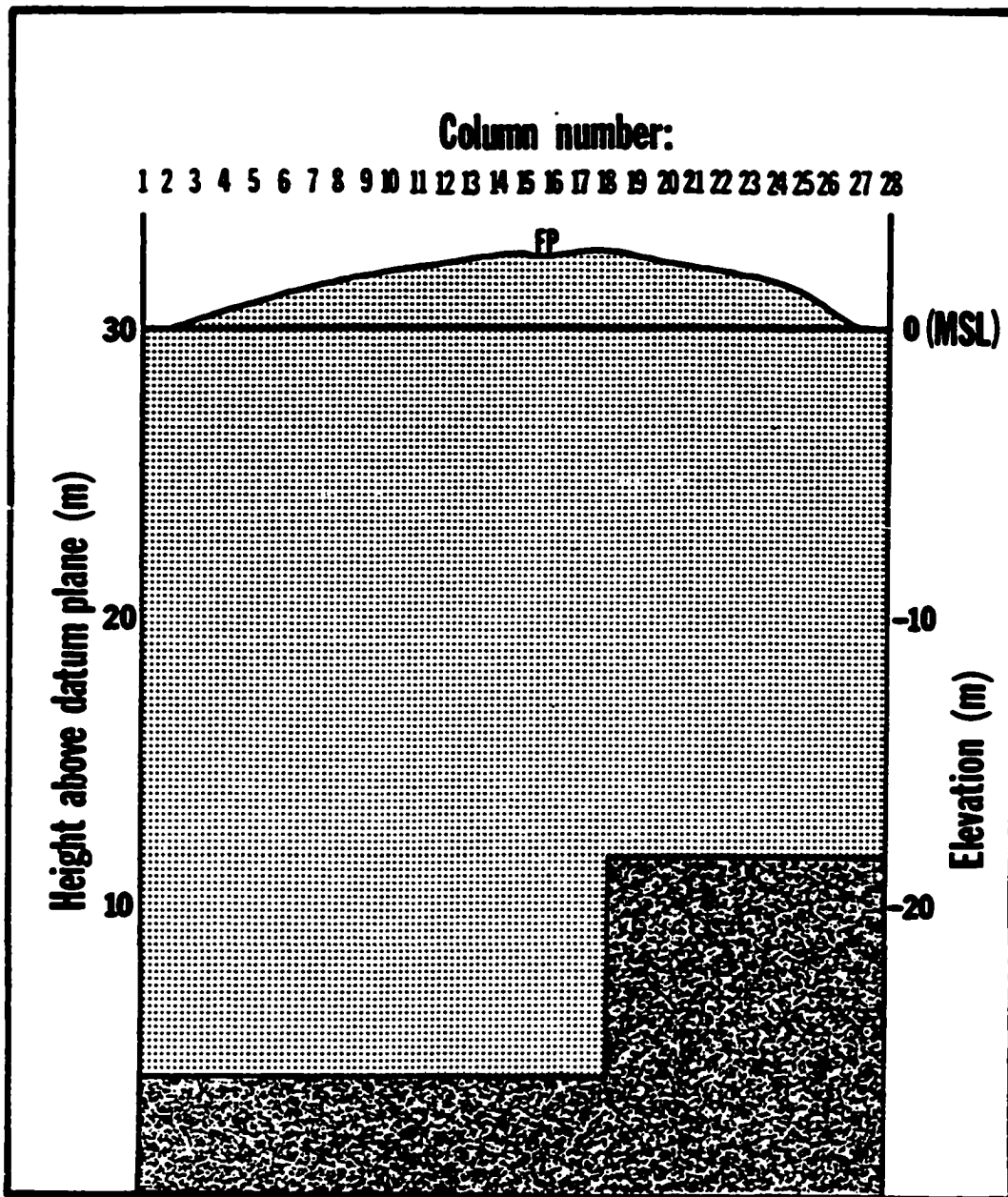


Figure 29. Model cross-section across Bodie Island through Fresh Pond (FP) for the first phase of computer modeling.

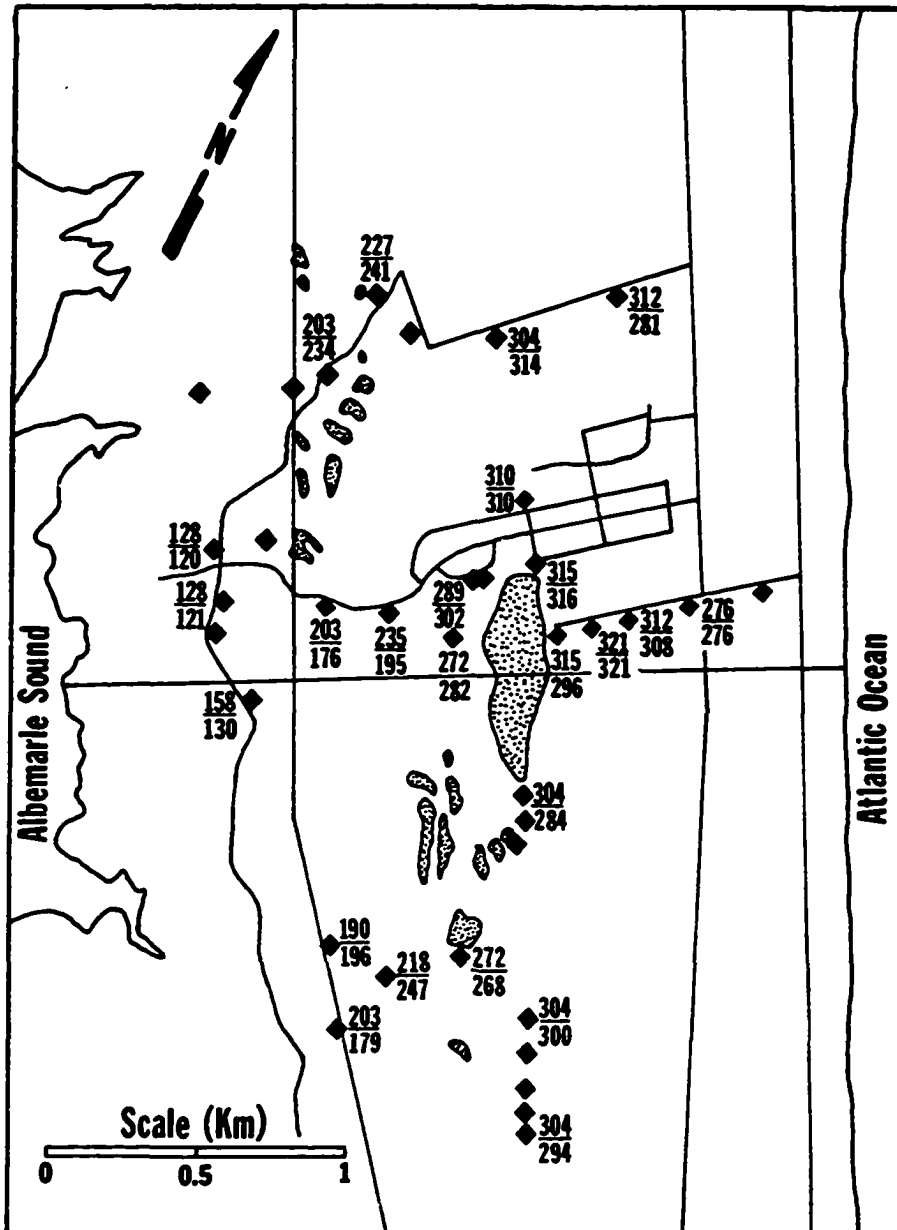


Figure 30. Results of phase one computer modeling for November 7, 1985. Hydraulic conductivity (K) is 4×10^{-4} m/s. Total error is 14.8 cm/well.

water table, either actual data or data previously generated by the computer, and, given known recharge and pumpage, to predict the configuration of the water table at a later date. An average pumping rate (2000 m³/day--0.53 mgd) was divided among the ten nodes covered by Fresh Pond; the withdrawal rate for each of these nodes, therefore, was 200 m³/day. If no pumping was occurring, these ten nodes received the same amount of recharge as the rest of the grid.

For this part of the simulation, a flat aquifer bottom was necessary to obtain accurate results. Aquifer bottom elevation was set at +4.1 m (25.9 m below MSL) for the entire island, as shown in Figure 31. This aquifer bottom elevation is an average value obtained from stratigraphic data from the present study and previous studies of the Nags Head Woods area.

Because the actual cone of depression around Fresh Pond showed little change over the measurement period, relatively steady-state conditions were assumed. Steady-state conditions were simulated by using a large initial time step and modeling only six time steps (NSTEPS) rather than many time steps for the number of days between the initial water table and the date being modeled. At least six time steps are required before drawdowns fall on the theoretical curves, irrespective of the DELTA value (Prickett and Lonquist, 1971).

Figure 32 shows the computer-generated water table for

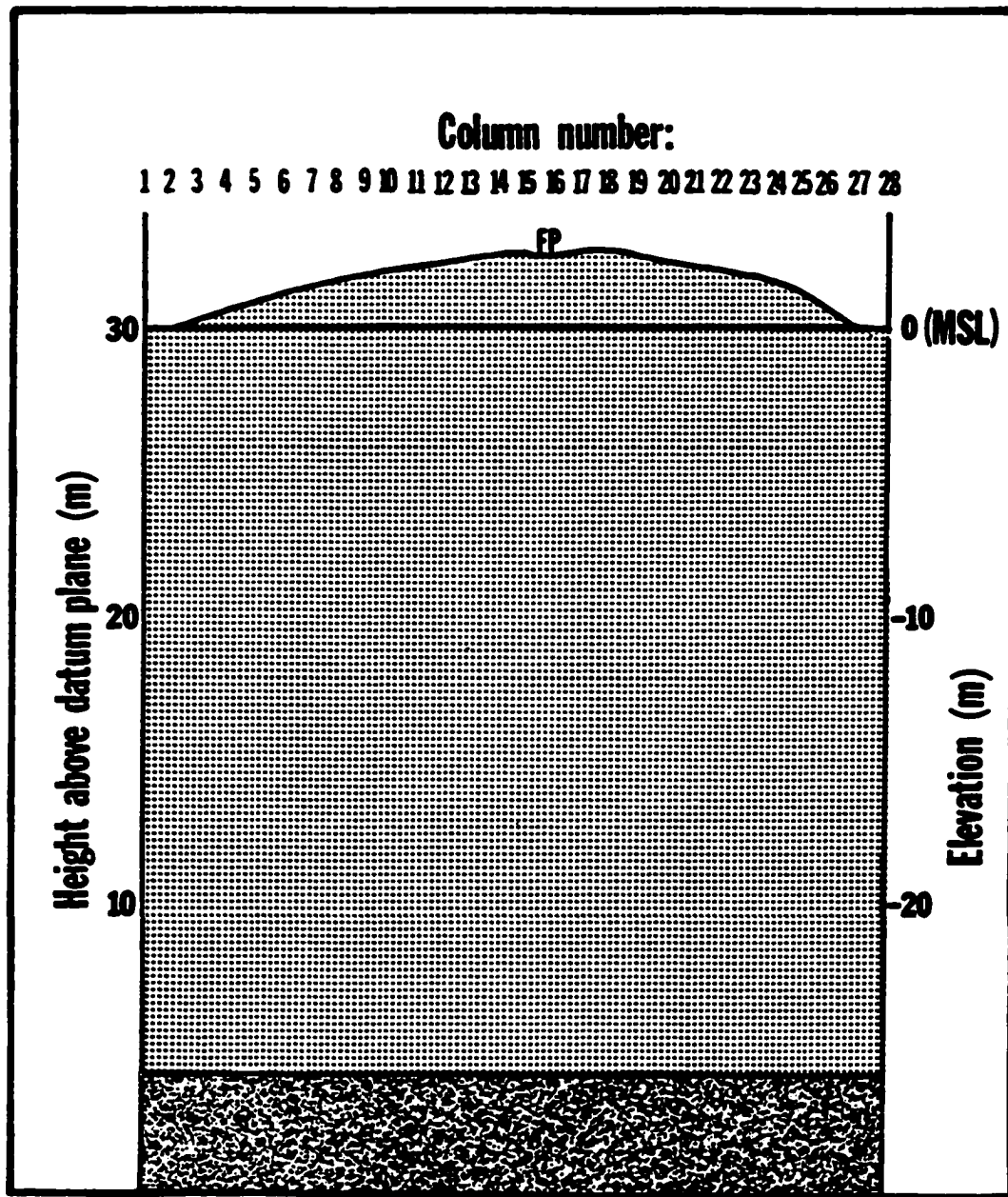


Figure 31. Model cross-section across Bodie Island through Fresh Pond (FP) for the second phase of computer modeling.

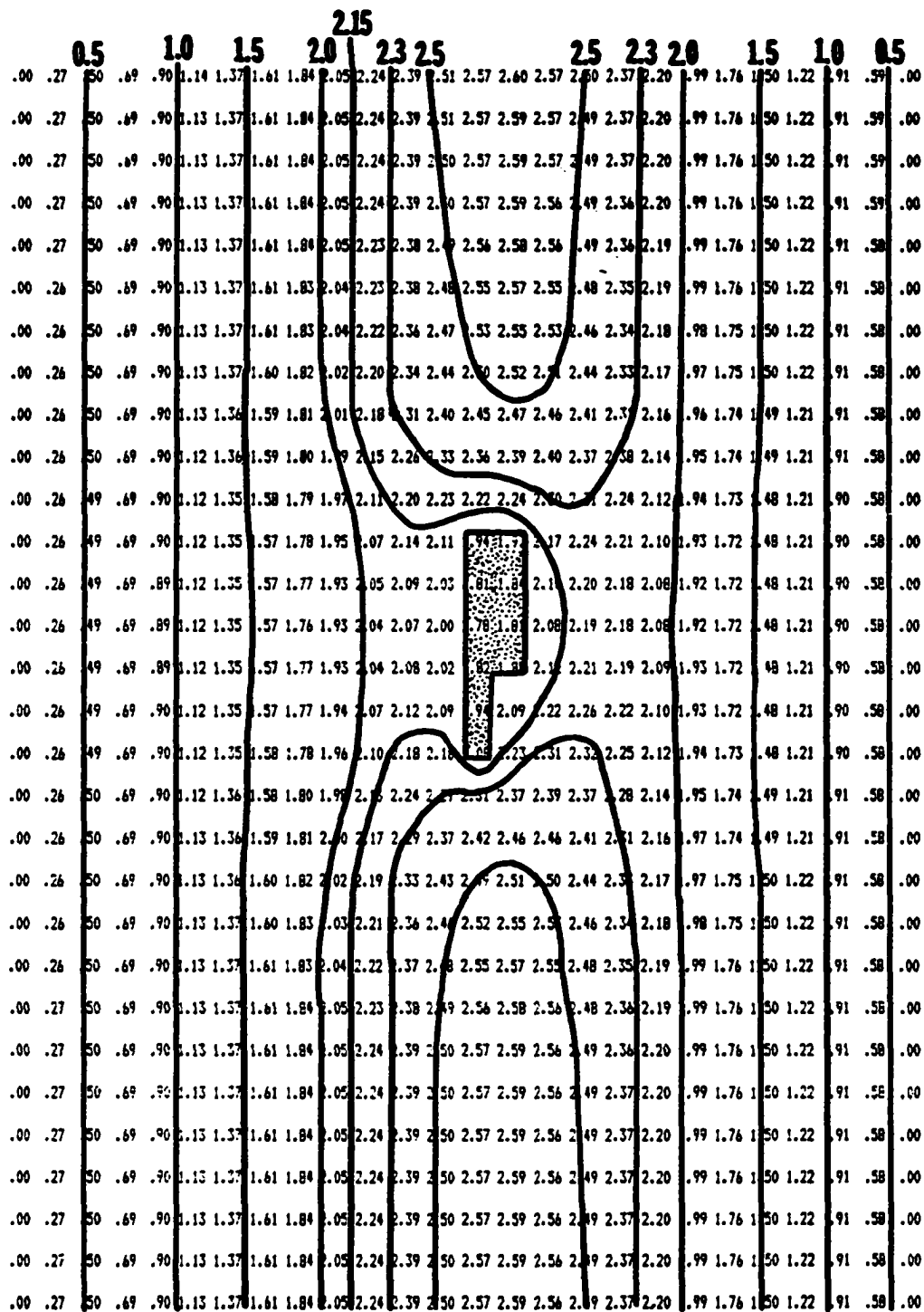


Figure 32. Contoured computer printout of predicted water table elevations for July 9, 1986. Hydraulic conductivity is 2×10^{-4} m/s. Pumpage (Q) from Fresh Pond is $2000 \text{ m}^3/\text{day}$. Contours are in meters.

July 9, 1986, an typical summer day preceeded by average rainfall. Figure 33 shows the predicted and actual water level for each well for July 9, 1986. The hydraulic conductivities that best simulate the natural water table range from 2.0×10^{-4} m/s to 3.5×10^{-4} m/s. These values agree well with those used in the first phase of computer modeling (4×10^{-4} m/s). Total error ranged from 14.8 cm/well to 16.4 cm/well for both phases of modeling.

6.7 Model Predictions

Models of aquifers are used to determine the actual or predicted behavior of the aquifer under different sets of conditions. Because models can predict future aquifer behavior, they are very useful in developing groundwater management plans. The information gained from the Nags Head Woods model will allow the Nature Conservancy staff to develop and implement appropriate wetland management plans for the Nags Head Woods Preserve, in response to the municipal pumpage of Fresh Pond.

Once the Nags Head Woods model was calibrated to the July data, it was used to predict the drawdown surrounding Fresh Pond for pumping rates varying from 946 m³/day to 5678 m³/day (0.25 to 1.5 mgd) under both "average" and "dry" summer conditions (Tables 3 and 4). Table 3 shows the effects of municipal pumpage assuming water levels were initially at elevations typical of summertime

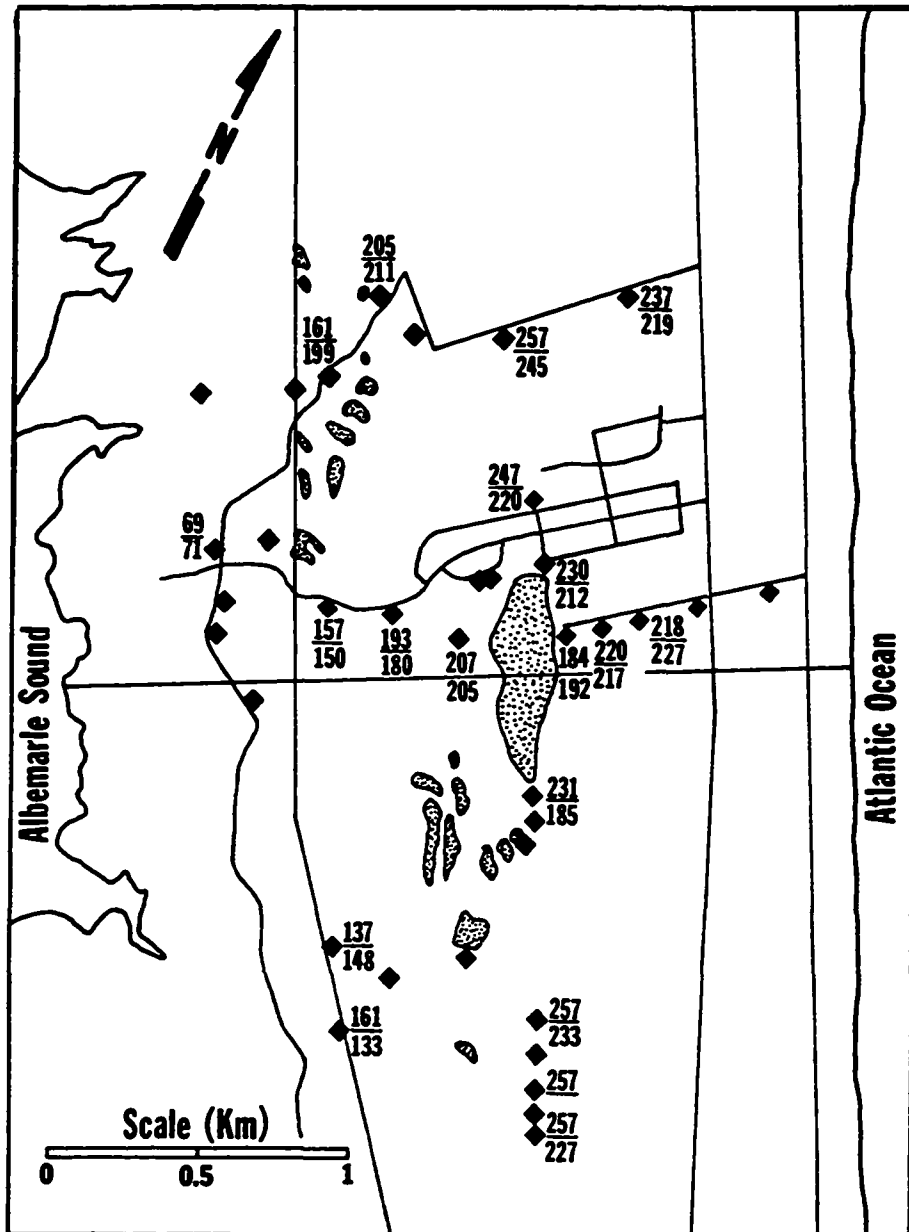


Figure 33. Results of phase two computer modeling for July 9, 1986. Hydraulic conductivity (K) is 2×10^{-4} m/s. Total error is 16.4 m/well.

EFFECTS OF PUMPING FRESH POND IN "TYPICAL" PERIODS

PUMPAGE in m ³ /day (mgd)	ELEVATION OF LAKE (m)	HEIGHT OF EASTERN GROUNDWATER DIVIDE (m)	APPROXIMATE DISTANCE (m) FROM LAKE TO GROUNDWATER DIVIDE	
			(east)	(west)
946 (0.25)	2.09	2.20	150	117
1892 (0.5)	1.80	2.06	210	175
2839 (0.75)	1.46	1.97	240	205
3785 (1.0)	1.14	1.86	270	230
4731 (1.25)	0.81	1.79	305	270
5678 (1.5)	0.48	1.74	340	310

Table 3. Effects on water table from pumping of Fresh Pond for various pumping rates, under "typical" summer conditions preceded by average rainfall. Water table elevations on July 9, 1986, were used as "initial conditions".

EFFECTS OF PUMPING FRESH POND IN "DRY" PERIODS

PUMPAGE in m ³ /day (mgd)	ELEVATION OF LAKE (m)	HEIGHT OF EASTERN GROUNDWATER DIVIDE (m)	APPROXIMATE DISTANCE (m) FROM LAKE TO GROUNDWATER DIVIDE	
			(east)	(west)
946 (0.25)	1.71	1.80	170	160
1892 (0.5)	1.39	1.67	220	210
2839 (0.75)	1.05	1.56	280	270
3785 (1.0)	0.72	1.45	310	300
4731 (1.25)	0.36	1.41	360	350
5678 (1.5)	0.04	1.34	380	350

Table 4. Effects on water table from pumping of Fresh Pond for various pumping rates, under "dry" summer conditions preceded by below-average rainfall. Water levels on September 13, 1985 were used as "initial conditions".

conditions (July 9, 1986). Table 4 shows the effect of drawdown around Fresh Pond for varying pumping rates under dry summer conditions, using the driest water levels recorded during the study (on September 13, 1985) as initial conditions. Lake water levels were obtained by averaging the predicted water levels for the ten nodes which comprise Fresh Pond in the model.

Both Table 3 and 4 indicate that at low pumping rates ($946 \text{ m}^3/\text{day}$) lake water levels begin to decline, dropping from approximately 3.0 m elevation to 2.09 m during "typical" summer conditions and from approximately 2.5 m elevation to 1.71 m during drier periods. At this pumping rate, drawdown around the lake extends from 150 m to 170 m from the eastern lake edge and from 120 m and 160 m from the western edge. At a pumping rate of $2839 \text{ m}^3/\text{day}$, the lake water level drops to 1.05 m elevation under dry conditions and to 1.46 under average conditions. Drawdown around the lake extends from 240 m to 280 m from the eastern lake edge and from 205 m to 270 m from the western edge. With heavy pumpage from Fresh Pond ($4731 \text{ m}^3/\text{day}$ to $5678 \text{ m}^3/\text{day}$), lake level drops to 0.81 m and 0.48 m, respectively, under average conditions. Under dry conditions, lake water level drops to 0.36 m elevation at $4731 \text{ m}^3/\text{day}$ and to 0.04 m at $5678 \text{ m}^3/\text{day}$. Under these conditions, drawdown around the lake extends hundreds of meters from the lake edge (Figure 34).

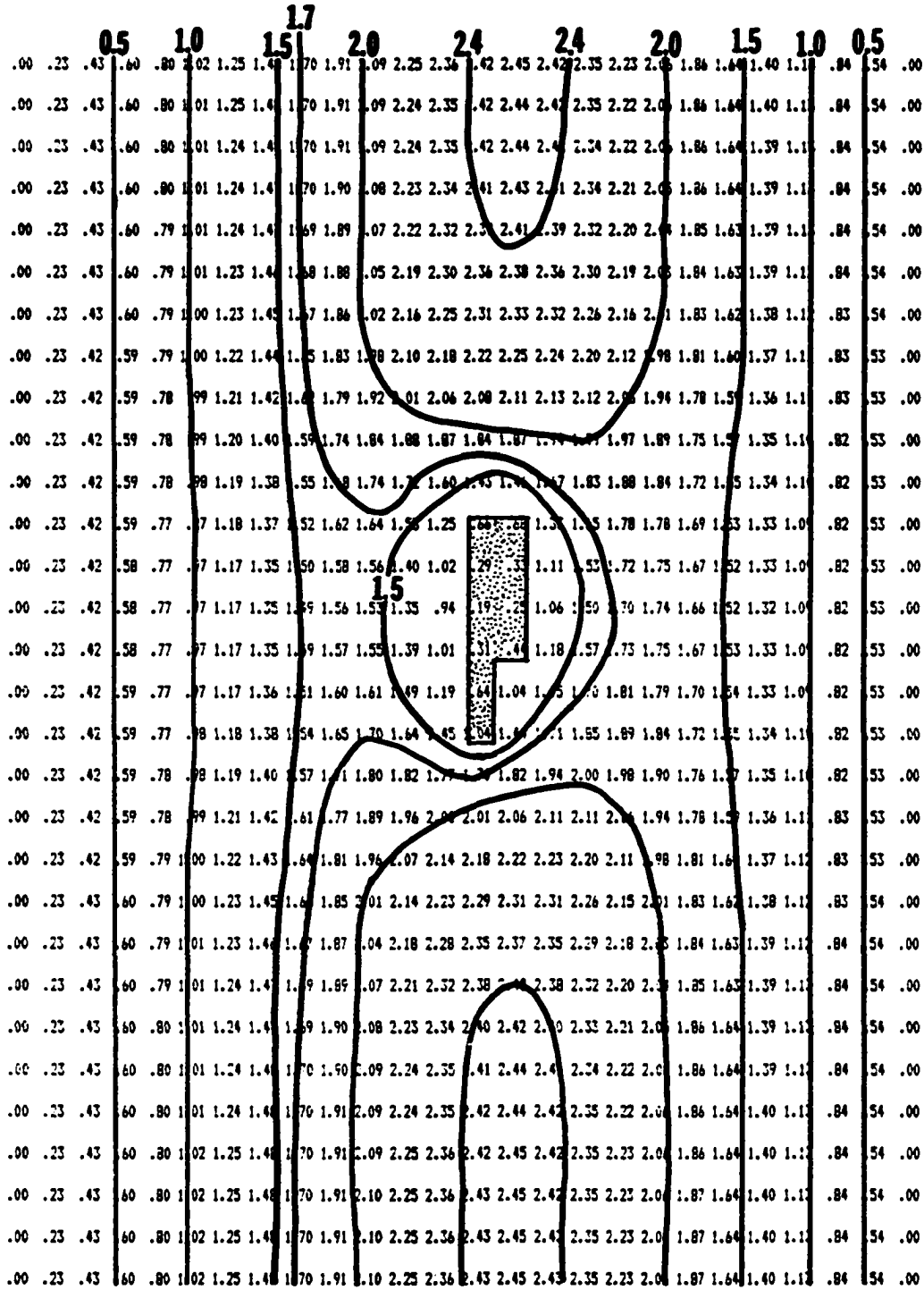


Figure 34. Contoured computer printout of predicted water table elevations with pumpage from Fresh Pond increased to 5678 m³/day (1.5 mgd).

CHAPTER 7: DISCUSSION AND CONCLUSIONS

7.1 Depositional History of Hydrostratigraphic Units

The surficial aquifer in the vicinity of Nags Head Woods is composed of two stratigraphic units--an upper clean sand unit and a lower silty sand unit. The surficial clean sand unit is part of the "Holocene barrier complex" described by Moslow and Heron (1979) and Susman and Heron (1979) and is informally named the Outer Banks Sands (Mixon and Pilkey, 1976; Susman and Heron, 1979). Based on both sedimentary and geomorphic evidence, these sands are interpreted as beach ridge sands which have been reworked somewhat by eolian processes. These beach ridges were deposited by progradation around an active inlet which once occupied the Kitty Hawk Bay area (Fisher, 1967). Likewise, the gravelly sand lenses at the base of the clean surficial sands are interpreted as inlet channel lag deposits. Buried peat beds, common beneath many retrograding barrier islands (Leatherman, 1982), are absent beneath the study area. This absence may also indicate that inlet scouring and infilling dominated this area more recently than island migration.

The thick beds of shelly, silty sands which underlie the clean sands and gravelly sands are interpreted as

back-barrier bar, channel, and lagoonal sediments, deposited before the barrier island retrograded to its present position. These sediments may correlate to the Diamond City Clay, which is late Pleistocene in age.

The dense, gray-green clay which underlies the silty sand unit was deposited in a very quiet water back-barrier environment, and is possibly Pliocene in age. The irregularity of the top surface of this unit presumably reflects scouring by fluvial streams formed during subsequent low sea level stands.

Other hydrogeologic studies along the Outer Banks indicate that a similar stratigraphic sequence exists beneath many of the barrier islands. Commonly back-barrier silty sands overlies older low-energy deposits. The silty sands are overlain by clean, barrier island sediments, including washover, beach ridge, and dune deposits (Brown, 1960; Harris and Wilder, 1964; Lloyd and Dean, 1968; Moslow and Heron, 1979; Susman and Heron, 1979). This sequence is disrupted by inlet fills at many locations along the islands; inlet fill sediments typically account for a large percentage of island sediments (Moslow and Heron, 1978; Susman and Heron, 1979). Because these types of sediments are found beneath most of the Outer Banks islands, hydrologic conditions on the islands should also be similar.

7.2 Water Table -- Natural Conditions

The water table across Bodie Island is an elongate dome which intersects sea level at each coastline. This groundwater ridge, however, is not symmetrical; the crest of the water table usually lies 140 m east of Fresh Pond, about two-thirds of the way across the island. From this divide, groundwater either flows eastward to the Atlantic Ocean or westward to the Albemarle Sound. Since Fresh Pond and Nags Head Woods lie west of the divide, groundwater flows underneath the forest and through the ponds from east to west, to eventually discharge into the Albemarle Sound (Otte et al., 1984). North of the study area, at the location of the EPA transect, the water table is fairly symmetrical (Figure 6b). The asymmetry of the groundwater crest in the Nags Head Woods area, therefore, may be only a local effect, caused by surface evaporation from the many ponds contained within Nags Head Woods, and especially from Fresh Pond. Evaporation from the surface of Fresh Pond alone can amount to 760 mm to 1000 mm per year (Floyd, 1979). Interception of rainfall and transpiration of soil moisture by the thick forest on the western side of the island reduce recharge in that area and contribute to the asymmetry of the water table. Other factors which may influence the water table shape are (1) variations in subsurface lithology/texture, (2) variations in rainfall over the study area, and (3) differences in salinity between sound and ocean waters.

7.3 Seasonal Water Table Variation

The water table varied by 0.63 m at its crest over the measurement period which began in May of 1985 and concluded in September of 1986. Water level data supplied by the Nature Conservancy staff indicate a variation of 0.68 m in 1982 and 1983, while data from the EPA wells north of Nags Head Woods indicate a variation of 0.59 m in 1984 and 1985. From this limited data, normal yearly variation in water table elevation seems to be at least 0.6 m to 0.7 m. During summer months, water levels decline during periods of only minor amounts of rainfall, as a result of increased evapotranspiration. Only after major storms (over 100 mm of rainfall?) do water levels increase in the summer. Lowest levels generally occur in early fall and highest levels in mid-winter to early spring. Heavy rains from hurricanes, however, may significantly alter this pattern, as these storms occur in late summer and fall. For example, highest water levels recorded during the present study occurred on November 7, 1985, just after the area received 216 mm of rain from Hurricane Gloria.

7.4 Water Table -- Pumping Conditions

When water is withdrawn from Fresh Pond by both pumping and evaporation, the lake functions somewhat like a large-diameter well. A large cone of depression forms around Fresh Pond and water within this cone flows toward

the lake, while water outside the cone flows to the ocean or sound. The edge of the cone of depression, therefore, is a groundwater divide. Floyd (1979) reported that the eastern divide remained at a distance of 330 m from the lake edge, despite seasonal water level variation and minor changes in pumping rate. During the present study, the eastern edge of the divide also remained relatively stationary at a distance of 306 m from the lake. However, the location of the western divide varied from 120 m to 186 m from the lake, moving towards the west during drier months and towards Fresh Pond in wetter months. This asymmetry between the eastern and western location of the groundwater divide occurs because the water table naturally sloped westward from its crest 140 m east of Fresh Pond, and pumping merely moved this natural divide further east. As a result of this water table slope, more water flows into Fresh Pond from the east than from the west under pumping conditions.

7.5 Hydraulic Characteristics

Table 4 shows the range of values for hydraulic conductivity commonly found for various unconsolidated sediments. Based on this information, the hydraulic conductivity values of 1.1×10^{-4} m/s and 1.3×10^{-4} m/s derived by Kimrey (1961) and Floyd (1971) indicate that well sorted sands are the predominant aquifer material. The hydraulic conductivity values determined

VALUES OF HYDRAULIC CONDUCTIVITY FOR VARIOUS
UNCONSOLIDATED SEDIMENTS

MATERIAL	HYDRAULIC CONDUCTIVITY (m/s)
Clay	10^{-11} to 10^{-8}
Silt, Sandy silts, Clayey sands, Till	10^{-8} to 10^{-6}
Silty sands, Fine sands	10^{-7} to 10^{-5}
Well sorted sands, Glacial outwash	10^{-5} to 10^{-3}
Well sorted gravel	10^{-4} to 10^{-2}

Table 4. (after Fetter, 1980).

during the present study range from 1.4×10^{-7} m/s to 2.2×10^{-5} m/s, indicating that silty sands or fine sands predominate the aquifer material at the pumping test site. Major factors which can influence the hydraulic conductivity of the surficial aquifer at Nags Head Woods are variation in texture of sandy aquifer materials (e.g. mean grain size, sorting), and the potential presence of clay-rich strata which decreases the vertical permeability of the total aquifer material. Because of these geologic variations, hydraulic conductivities in seemingly "uniform" aquifers can differ by factors of 10 to 100 (Freeze and Cherry, 1979). The lower values of hydraulic conductivity obtained by this study, therefore, reflect a significant change in aquifer material from the previous studies. Kimrey (1961) and Floyd (1971) only tested the upper stratigraphic unit of clean, fine to medium sands; the present study, however, mainly tested the lower silty sand unit, as the pumping test was performed in an interdunal flat area where only a few meters of clean sand overlies the silty sand.

The coefficient of storage, or storativity, is the amount of water released from storage per unit change in hydraulic head per unit area. For unconfined aquifers, storativity may range from 0.01 to 0.3 (Heath and Trainer, 1981; Driscoll, 1986). A storage coefficient of 0.3, obtained by Kimrey (1961) and Floyd (1971) in the Nags Head Woods area, indicates that 30% of the water contained

in storage within the aquifer pore space drains by gravity when the water table surface declines. The storage coefficients of 0.01 and 0.03 determined in this study, however, indicate only a 1% to 3% release from storage. The discrepancy between these storativity values also suggests that the aquifer material tested in the present study is more poorly sorted than strata sediments tested in the previous studies.

7.6 Computer Modeling

The finite-difference computer modeling technique used in this study predicts water levels across Bodie Island in the vicinity of Nags Head Woods. The model is not particularly sensitive to minor anomalies in water table shape because of the averaging nature of the technique; however, it simulates the general water table geometry very well and can be used to predict the drawdown around Fresh Pond resulting from municipal pumpage of the lake.

According to the model, if heavy pumpage (over 3785 m³/day or 1.0 mgd) were maintained for a sufficiently long period of time, ponds and wetlands in Nags Head Woods would dry out and a new ecological balance might be established, especially in the eastern portion of the Woods near Fresh Pond. Additionally, if water levels in Fresh Pond remained below sea level for an extended period of time, saltwater might intrude beneath the fresh water of Nags Head Woods and rise up into Fresh Pond. At the

same time, the saltwater-freshwater interface along the western edge of Nags Head Woods could migrate tens of meters inland.

The greatest flow of groundwater apparently occurs through the shallow strata of higher permeability. Several observations support this conclusion. The hydraulic conductivity values which best simulated the natural water table, from 2.0×10^{-4} m/s to 4.0×10^{-4} m/s, suggest an aquifer composed of well sorted sands. These hydraulic conductivities, although too high to describe conditions through the entire aquifer thickness, agree very well with values obtained by Kimrey (1961) and Floyd (1971) for the upper clean sand unit. Also, groundwater models of all types indicate that flow through a homogeneous aquifer is greatest in the near surface and diminishes in rate with depth (Freeze and Cherry, 1979; Wang and Anderson, 1982). The stratigraphy in the study area, with the better-sorted deposits at the surface, will accentuate the flow rate at shallow depths. The fact that Fresh Pond only penetrates the upper part of the surficial aquifer to approximately -3 m elevation further suggests that the shallow sands would carry the flow (Figure 35).

Although flow into Fresh Pond may be reduced by material blanketing the lake bottom, the effects of such a barrier are ignored in this model. Because no streams flow into Fresh Pond, no muds are likely to accumulate. Organic material, however, may form a mat or ooze that

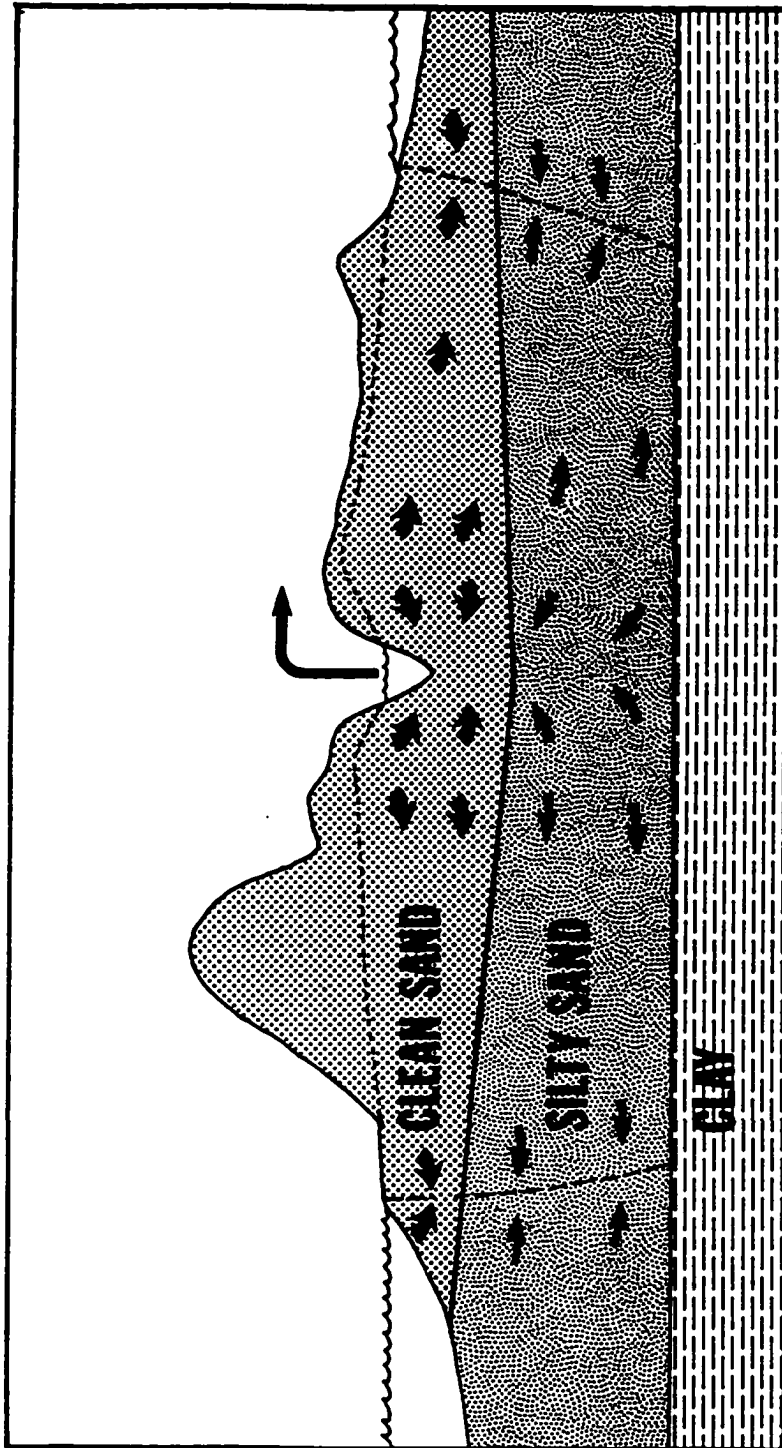


Figure 35. Sketch showing direction of groundwater flow through the surficial aquifer in Nags Head Woods. The upper clean sand unit ($K = 10^{-4}$ m/s) carries the bulk of the flow.

would restrict flow into the lake. Further research would be needed to determine the effect of such a barrier on groundwater flow.

Finite-difference computer modeling offers some potential advantages over analytical techniques, such as the ability to model in three dimensions, to analyze anisotropic, heterogeneous situations, and to consider either transient or steady-state conditions. However, comparison of the Nags Head Woods finite-difference model and Whittecar's analytical model for the same data suggests that both models yield adequate results. The simpler analytical approach may be preferable for relatively uncomplicated water table configurations.

Municipal pumpage of Fresh Pond carries with it significant implications for the Nags Head Woods Preserve. However, with cooperation between the towns of Nags Head and Kill Devil Hills and the Nature Conservancy, the present ecological balance in Nags Head Woods can be maintained. Based upon analyses of the computer model, present pumpage, which averages $2000 \text{ m}^3/\text{day}$ (0.53 mgd), should not significantly affect the water table and the many ponds in the Nags Head Woods Preserve. I suggest, however, that the water level within the lake should be monitored and pumpage managed so that lake water levels never drop below 1.0 m elevation. If lake levels remain below 1.0 m elevation for an extended period of time, saline water may begin to encroach beneath the lake and,

in time, Fresh Pond could become contaminated with salty water. Therefore, future pumpage from Fresh Pond should be limited to a maximum of 3785 m³/day (1.0 mgd).

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APPENDIX A
Water Table Elevations, 1985-1986

ELEVATION OF WATER TABLE (METERS)											
WELL NO.	WELL TOP ELEV.	1985									
		5/30	6/6	6/20	7/2	7/17	8/2	8/13	8/30	9/13	9/25
1	3.564	2.250	2.166	2.342	2.312	2.317	2.378	2.308	2.208	2.087	2.203
2	4.193	2.623	2.553	2.718	2.637	2.602	2.699	2.590	2.493	2.392	2.514
3	3.862	/	/	/	/	/	/	/	/	/	/
4	2.913	2.319	2.328	2.289	2.241	2.209	2.219	2.295	2.122	2.045	2.106
5	5.597	2.292	2.262	2.255	2.209	2.171	2.174	2.156	2.141	2.074	2.030
6	3.100	2.309	2.268	2.256	2.220	2.192	2.169	2.143	2.448	/	/
7	2.810	/	/	/	/	/	/	/	/	/	/
8	2.608	1.627	1.427	1.451	1.335	/	/	/	/	/	/
9	2.684	1.021	1.030	1.060	1.024	1.005	0.986	0.928	0.922	0.825	0.905
10	7.682	0.987	0.983	1.037	1.007	0.982	0.989	0.931	0.934	0.858	0.915
11	2.857	1.149	1.138	1.182	1.154	1.174	1.120	1.049	/	/	/
12	2.223	1.258	1.258	1.297	1.252	1.211	1.199	1.162	1.174	1.127	1.108
13	2.519	1.727	1.701	1.716	1.645	1.599	1.620	1.492	1.435	1.354	1.446
14	4.749	1.814	1.780	1.766	1.771	1.677	1.655	1.619	1.282	1.530	1.509
15	5.666	2.097	2.081	2.042	2.014	1.977	1.932	1.932	1.893	1.852	1.801
16	3.689	2.759	2.697	2.800	2.735	2.750	2.769	2.676	2.632	2.554	2.619
17	4.066	2.728	2.707	2.796	2.739	2.752	2.771	2.736	2.693	2.542	2.609
18	4.440	/	/	2.886	2.795	2.837	2.858	2.736	2.693	2.581	2.673
19	4.077	2.580	2.523	2.675	2.612	2.638	2.660	2.541	2.471	2.364	2.502
20	9.519	2.301	2.423	2.265	/	/	/	/	/	/	/
21	2.386	1.673	1.668	1.756	1.737	1.792	1.911	1.700	/	/	/
22	3.042	2.14R	2.118	2.259	2.230	2.280	2.378	2.720	2.156	2.015	2.143
23	3.491	2.492	2.470	2.628	2.604	2.644	2.763	2.528	2.470	2.324	2.472
24	4.159	2.735	2.666	2.838	2.778	/	2.873	/	2.671	2.533	2.658
25	4.110	2.735	2.681	2.784	2.730	2.766	2.793	2.684	2.648	2.547	2.592
26	4.775	/	2.570	2.650	2.609	/	/	/	2.583	2.471	2.520
27	5.040	/	2.635	2.672	2.617	2.654	2.669	2.635	2.658	2.464	2.526
28	4.302	/	2.651	2.690	2.629	2.684	2.697	2.601	2.571	2.459	2.541
29	5.399	/	2.639	2.730	2.641	2.686	2.708	2.604	2.563	2.458	2.522
30	4.362	/	/	2.741	2.669	2.709	2.724	2.611	2.569	/	2.523
31	4.996	/	2.463	2.575	2.497	2.558	2.579	2.448	2.396	2.286	2.372
32	4.362	/	2.439	2.254	2.477	2.658	2.555	2.417	2.363	2.259	2.357
33	3.462	2.514	2.471	2.487	2.449	2.569	2.465	2.407	2.344	2.240	2.271
34	5.144	/	/	2.636	2.593	2.581	2.614	2.538	2.492	2.401	2.401
35	4.032	/	/	/	/	2.507	2.560	/	2.444	2.334	2.378
36	3.545	/	/	/	/	2.165	2.265	2.128	2.073	1.953	2.058
37	2.860	/	/	/	/	1.485	1.552	1.470	1.427	1.360	1.398
38	3.079	/	/	/	/	1.604	1.732	1.631	1.582	1.503	1.539
LAKE ELEV.	/	/	/	/	/	/	/	/	/	/	/

WELL NO.		ELEVATION OF WATER TABLE (METERS)													
		1985							1986						
		10/10	10/25	11/7	11/21	12/6	12/20	1/5	1/18	2/2	2/16				
1	3.564	2.260	2.238	2.812	2.584	2.613	2.517	2.442	2.365	2.650	2.503				
2	4.193	2.546	2.474	3.143	2.928	/	/	/	/	/	/	/	/	/	
3	3.862	/	/	/	/	/	/	/	/	/	/	/	/	/	
4	2.913	2.126	2.109	2.413	2.448	2.513	2.521	2.486	2.450	2.547	2.538				
5	5.597	2.114	2.080	2.342	2.376	2.441	2.436	2.430	2.381	2.479	2.500				
6	3.100	/	/	/	/	/	/	/	/	/	/	/	/	/	
7	2.810	/	/	/	/	/	/	/	/	/	/	/	/	/	
8	2.608	/	/	1.725	/	/	/	/	/	/	/	/	/	/	
9	2.684	0.996	0.993	1.201	/	/	/	/	/	/	/	/	/	/	
10	7.682	0.947	0.955	1.208	/	/	/	/	/	/	/	/	/	/	
11	2.857	/	/	/	/	/	/	/	/	/	/	/	/	/	
12	2.223	1.123	1.138	1.304	1.767	1.894	1.871	1.851	1.815	1.927	1.930				
13	2.519	1.446	/	/	1.784	1.860	1.878	1.869	1.835	1.927	1.930				
14	4.749	1.537	1.506	1.760	2.120	2.191	2.209	2.194	2.154	2.223	2.249				
15	15.666	1.834	1.834	1.947	2.901	2.921	2.921	2.851	2.797	2.941	2.868				
16	3.689	2.601	2.569	3.013	2.900	2.999	2.914	2.838	2.805	2.997	2.910				
17	4.066	2.597	2.568	3.024	2.977	3.091	2.962	2.872	2.805	2.997	2.910				
18	4.440	2.646	2.602	3.164	2.977	3.091	2.962	2.872	2.805	2.997	2.910				
19	4.077	2.487	2.442	3.103	2.882	2.988	2.823	2.707	2.323	2.873	2.769				
20	9.519	/	/	/	/	/	/	/	/	/	/	/	/	/	
21	2.386	/	/	/	/	/	/	/	/	/	/	/	/	/	
22	3.042	2.159	2.134	2.759	2.539	2.627	2.431	2.268	2.146	2.392	2.283				
23	3.491	2.467	2.467	3.080	2.887	2.996	2.805	2.662	2.552	2.830	2.711				
24	4.159	2.623	2.592	3.210	2.970	3.089	2.937	2.827	2.751	2.995	2.882				
25	4.110	2.581	2.548	2.958	2.854	2.951	2.888	2.819	2.763	2.897	2.833				
26	4.775	2.530	2.462	2.935	2.876	2.987	2.870	2.783	2.715	2.858	2.779				
27	5.040	2.527	2.478	2.944	2.878	2.995	2.871	2.874	2.720	2.876	2.794				
28	4.302	2.533	2.473	2.968	2.800	3.007	2.891	2.798	2.737	2.902	2.820				
29	5.399	2.525	2.456	2.980	2.878	3.013	2.884	2.805	2.750	2.948	2.863				
30	4.362	2.541	2.462	2.999	2.881	3.018	2.904	2.825	2.761	2.956	2.877				
31	4.996	2.354	2.317	2.835	2.697	2.821	2.710	2.625	2.654	2.747	2.680				
32	4.362	2.338	2.300	2.821	2.673	2.821	2.684	2.597	2.533	2.716	2.652				
33	3.462	2.307	2.275	2.600	2.611	2.706	2.670	2.570	2.507	2.652	2.582				
34	5.144	2.439	2.390	2.821	2.753	2.845	2.788	2.755	2.727	2.822	2.816				
35	4.032	2.399	2.360	2.675	2.714	2.802	2.744	2.518	2.469	2.576	2.576				
36	3.545	2.040	2.055	2.474	2.459	2.556	2.544	2.469	2.411	2.511	2.445				
37	2.860	1.424	1.421	1.790	1.768	1.857	1.808	1.757	1.711	1.872	1.845				
38	3.079	1.561	1.541	1.958	1.930	2.009	1.954	1.902	1.858	2.021	1.994				
LAKE ELEV.		/	/	/	/	/	/	/	/	/	/	/	/	/	

		ELEVATION OF WATER TABLE (METERS)											
		1986											
WELL NO.	WELL TOP ELEV.	3/1	3/14	3/29	4/13	4/27	5/10	6/5	7/9	8/9	9/22		
1	3.564	2.473	2.415	2.479	2.363	2.305	2.263	2.227	2.189	2.269	2.360		
2	4.193	/	/	/	/	/	/	2.498	2.446	2.418	2.674		
3	3.862	/	/	/	/	/	/	/	/	/	/		
4	2.913	2.532	2.486	2.480	2.428	2.380	2.313	2.236	2.110	2.007	2.280		
5	5.597	2.479	2.439	2.439	2.381	2.333	2.272	2.134	1.988	1.870	2.118		
6	3.100	/	/	/	/	/	/	/	/	/	2.167		
7	2.810	/	/	/	/	/	/	/	/	/	/		
8	2.608	/	/	/	/	/	/	/	0.710	/	/		
9	2.684	/	/	/	/	/	/	/	/	/	/		
10	7.682	/	/	/	/	/	/	/	/	/	/		
11	2.857	/	/	/	/	/	/	/	/	/	/		
12	2.223	/	/	/	/	/	/	/	/	/	/		
13	2.519	/	/	/	/	/	/	/	/	/	/		
14	4.749	1.911	1.896	1.902	1.850	1.802	1.756	1.651	1.498	1.412	1.525		
15	15.666	2.243	2.212	2.221	2.169	2.124	2.078	1.989	1.801	/	1.812		
16	3.689	/	/	/	/	/	/	/	/	/	/		
17	4.066	2.844	2.758	2.746	2.633	2.515	2.399	2.219	2.058	1.920	2.089		
18	4.440	2.864	2.794	2.788	2.657	2.553	2.447	2.257	2.123	2.002	2.186		
19	4.077	2.721	2.641	2.678	2.553	2.480	2.410	2.268	2.202	2.378	2.385		
20	9.519	/	/	/	/	/	/	/	/	/	/		
21	2.386	/	/	/	/	/	/	/	/	/	/		
22	3.042	2.235	/	/	/	/	/	/	1.625	/	1.823		
23	3.491	2.638	2.549	2.607	2.485	2.421	2.348	/	2.270	2.261	2.447		
24	4.159	2.818	2.748	2.778	2.635	2.568	2.477	/	2.171	2.089	2.282		
25	4.110	2.781	2.720	2.687	2.562	2.431	2.287	2.265	2.171	1.803	1.915		
26	4.775	2.733	2.678	2.669	2.596	2.532	2.474	2.348	1.916	2.276	2.612		
27	5.040	2.742	2.693	2.681	2.602	2.541	2.480	2.355	2.265	/	2.602		
28	4.302	2.772	2.707	2.704	2.631	2.567	2.503	2.367	2.282	2.266	2.594		
29	5.399	2.811	2.756	2.753	2.680	2.616	2.558	2.405	2.318	2.249	2.588		
30	4.362	2.831	2.773	2.776	2.697	2.642	2.578	2.419	2.331	2.313	2.583		
31	4.996	2.634	2.576	2.582	2.500	2.445	2.366	2.186	2.331	2.043	2.251		
32	4.362	2.609	/	2.551	2.460	2.396	/	2.153	1.846	/	2.203		
33	3.462	/	/	/	/	/	/	/	/	/	/		
34	5.144	/	/	/	/	/	/	/	2.048	/	2.097		
35	4.032	2.798	2.767	2.770	2.709	2.676	2.590	2.439	2.048	1.882	2.097		
36	3.515	2.551	2.515	2.512	2.448	2.381	2.298	2.105	/	2.124	2.401		
37	2.860	1.815	1.766	1.760	1.702	1.653	1.592	1.459	1.332	1.811	2.087		
38	3.079	1.970	1.918	1.921	1.854	1.814	1.753	1.622	1.481	1.274	1.477		
LAKE ELEV.	/	/	/	/	/	/	/	/	1.130	0.975	1.050		

APPENDIX B
Program Listing

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1 C*****
2 C**
3 C**   FINITE DIFFERENCE COMPUTER MODEL--NAGS HEAD WOODS, N.C.   **
4 C**
5 C**           Janet Salyer Emry   **
6 C**           G. Richard Whittecar   **
7 C**
8 C**   Modified from The Illinois State Water Survey's Basic   **
9 C**   Aquifer Simulation Program with Water Table Conditions   **
10 C**
11 C**   (Prickett, T.C., and Lonquist, G.C., 1971, Selected   **
12 C**   Digital Computer Techniques for Groundwater Resource   **
13 C**   Evaluation. Illinois State Water Survey Bulletin 55.)   **
14 C**
15 C*****
16 C
17 C
18 C   DEFINITION OF VARIABLES
19 C
20 C   HO(I,J)----HEADS AT START OF TIME INCREMENT (I,J) IN METERS
21 C   H(I,J)----HEADS AT END OF TIME INCREMENT IN METERS
22 C   SF2(I,J)---STORAGE FACTOR FOR WATER TABLE CONDITIONS
23 C           IN SQUARE METERS
24 C   Q(I,J)----CONSTANT WITHDRAWAL RATES IN CUBIC METERS/DAY
25 C   T(I,J,1)---AQUIFER TRANSMISSIVITY BETWEEN I,J AND
26 C           I,J+1 IN SQUARE METERS/DAY
27 C   T(I,J,2)---AQUIFER TRANSMISSIVITY BETWEEN I,J AND
28 C           I+1,J IN SQUARE METERS/DAY
29 C   AA,BB,CC,DD---COEFFICIENTS IN WATER BALANCE EQUATIONS
30 C   NR-----NUMBER OF ROWS IN MODEL
31 C   NC-----NUMBER OF COLUMNS IN MODEL
32 C   NSTEPS----NUMBER OF TIME INCREMENTS
33 C   DELTA----TIME INCREMENTS IN DAYS
34 C   HH,S2,QQ,TT---DEFAULT VALUES
35 C   I-----MODEL COLUMN NUMBER
36 C   J-----MODEL ROW NUMBER
37 C   PERM(I,J,1)---AQUIFER PERMEABILITY BETWEEN I,J AND I,J+1
38 C           IN METERS/DAY
39 C   PERM(I,J,2)---AQUIFER PERMEABILITY BETWEEN I,J AND I+1,J
40 C           IN METERS/DAY
41 C   BOT(I,J)--ELEVATION OF THE BOTTOM OF THE AQUIFER IN METERS
42 C
43 C
44 C
45   DIMENSION H(35,40), HO(35,40), SF2(35,40), Q(35,40)
46   DIMENSION T(35,40,2), B(40), G(40), DL(35,40), BOT(35,40)
47   DIMENSION PERM(35,40,2)
48 C
49 C   READ PARAMETERS AND DEFAULT VALUES
50 C
51   NC=28
52   NR=30
53   WRITE(*,3)
54   3   FORMAT(/,1X,'Enter hydraulic conductivity (K) in',
55     11X,'meters per second')
56   READ(*,*)PP
57   WRITE(*,29)
58   29  FORMAT(/,1X,'Enter pumpage from Fresh Pond in cubic'
59     11X,'meters per day')

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60      READ(*,*)SCOTT
61      CALL RESUB(QQ)
62      WRITE(*,16)
63  16   FORMAT(/,1X,'Enter number of time increments')
64      READ(*,*)NSTEPS
65      WRITE(*,14)
66  14   FORMAT(/,1X,'Enter time increments in days')
67      READ(*,*)DELTA
68      WRITE(*,429)
69  429  FORMAT(/,1X,'Enter projected error')
70      READ(*,*)ERROR
71      WRITE(*,109)
72  109  FORMAT(/,1X,'Enter name of data file (Unit 1000) when the'
73      11X,'computer asks for file name',8X)
74      QQ=-(QQ*10000.0)
75      IF(SCOTT.EQ.0.0) SCOTT=(QQ*10.0)
76      PP=PP*86400.0
77      TT=PP*25.9
78 C
79 C      FILL ARRAYS WITH DEFAULT VALUES
80 C
81      DO 20 I=1,NC
82      DO 20 J=1,NR
83      SF2(I,J)=3000.0
84      PERM(I,J,1)=PP
85      PERM(I,J,2)=PP
86      BOT(I,J)=4.1
87      T(I,J,1)=TT
88      T(I,J,2)=TT
89      H(I,J)=32.5
90      HO(I,J)=32.5
91  20   Q(I,J)=QQ
92 C
93 C      READ NODE VALUES
94 C
95      OPEN(1000,FILE='      ')
96      DO 59 J=1,NR
97      READ(1000,40,END=100) (H(I,J),I=1,NC)
98  40   FORMAT(35F6.2)
99  59   CONTINUE
100  100  Q(15,12)=SCOTT/10.0
101      Q(15,13)=SCOTT/10.0
102      Q(15,14)=SCOTT/10.0
103      Q(15,15)=SCOTT/10.0
104      Q(15,16)=SCOTT/10.0
105      Q(15,17)=SCOTT/10.0
106      Q(16,12)=SCOTT/10.0
107      Q(16,13)=SCOTT/10.0
108      Q(16,14)=SCOTT/10.0
109      Q(16,15)=SCOTT/10.0
110 C
111      DO 457 J=1,NR
112      DO 457 I=19,NC
113      BOT(I,J)=11.75
114  457  CONTINUE
115 C
116 C      START OF SIMULATION
117 C
118      TIME=0.

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119      DO 320 ISTEP=1,NSTEPS
120      TIME=TIME+DELTA
121      WRITE(*,1111) ISTEP,TIME
122 1111  FORMAT(//,1X,'TIME INCREMENT #',I3,/,1X,'TIME EQUALS ',F10.5)
123 C
124 C      PREDICT HEADS FOR NEXT TIME INCREMENT
125 C
126      DO 70 I=1,NC
127      DO 70 J=1,NR
128      D=H(I,J)-HO(I,J)
129      HO(I,J)=H(I,J)
130      F=1.0
131      IF(DL(I,J).EQ.0.0) GO TO 60
132      IF(ISTEP.GT.2) F=D/DL(I,J)
133      IF(F.GT.5) F=5.0
134      IF(F.LT.0.0) F=0.0
135 60    DL(I,J)=D
136      H(I,J)=H(I,J)+D*F
137 70    IF(H(I,J).LE.BOT(I,J)) H(I,J)=BOT(I,J)+0.01
138 C
139 C      REFINE ESTIMATES OF HEADS BY IADI METHOD
140 C
141      ITER=0
142 80    E=0.0
143      ITER=ITER+1
144      WRITE(*,105) ITER
145 105   FORMAT(//,1X,'This is iteration',I3)
146 C
147 C      TRANSMISSIVITY CONTROL
148 C
149      DO 83 I=1,NC
150      DO 83 J=1,NR
151      IF(I.LT.NC) T(I,J,2)=PERM(I,J,2)*SQRT((H(I,J)-BOT(I,J))*
152 1(H(I+1,J)-BOT(I+1,J)))
153 83    IF(J.LT.NR) T(I,J,1)=PERM(I,J,1)*SQRT((H(I,J)-BOT(I,J))*
154 1(H(I,J+1)-BOT(I,J+1)))
155 C
156 C      COLUMN CALCULATIONS
157 C
158      DO 190 II=1,NC
159      I=II
160      IF(MOD(ISTEP+ITER,2).EQ.1) I=NC-I+1
161      DO 170 J=1,NR
162 C
163 C      CALCULATE B AND G ARRAYS
164 C
165      BB=SF2(I,J)/DELTA
166      DD=HO(I,J)*SF2(I,J)/DELTA-Q(I,J)
167      AA=0.0
168      CC=0.0
169      IF(J-1) 90,101,90
170 90    AA=-T(I,J-1,1)
171      BB=BB+T(I,J-1,1)
172 101   IF(J-NR) 110,120,110
173 110   CC=-T(I,J,1)
174      BB=BB+T(I,J,1)
175 120   IF(I-1) 130,140,130
176 130   BB=BB+T(I-1,J,2)
177      DD=DD+H(I-1,J)*T(I-1,J,2)

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178 140 IF (I-NC) 150,160,150
179 150 BB=BB+T(I,J,2)
180 DD=DD+H(I+1,J)*T(I,J,2)
181 160 W=BB-AA*B(J-1)
182 B(J)=CC/W
183 170 G(J)=(DD-AA*G(J-1))/W
184 C
185 C RE-ESTIMATE HEADS
186 C
187 DO 7001 J=1,NR
188 H(1,J)=30.0
189 H(2,J)=H(1,J)
190 H(28,J)=30.0
191 H(27,J)=H(28,J)
192 7001 CONTINUE
193 E=E+ABS(H(I,NR)-G(NR))
194 H(I,NR)=G(NR)
195 N=NR-1
196 180 HA=G(N)-B(N)*H(I,N+1)
197 E=E+ABS(HA-H(I,N))
198 H(I,N)=HA
199 N=N-1
200 IF(N.GT.0) GO TO 180
201 DO 190 N=1,NR
202 IF(H(I,N).GT.BOT(I,N)) GO TO 190
203 E=E+BOT(I,N)+0.01-H(I,N)
204 H(I,N)=BOT(I,N)+0.01
205 190 CONTINUE
206 C
207 C TRANSMISSIVITY CONTROL
208 C
209 DO 193 J=1,NR
210 DO 193 I=1,NC
211 IF(I.LT.NC)T(I,J,2)=PERM(I,J,2)*SQRT((H(I,J)-BOT(I,J))
212 1*(H(I+1,J)-BOT(I+1,J)))
213 193 IF(J.LT.NR)T(I,J,1)=PERM(I,J,1)*SQRT((H(I,J)-BOT(I,J))
214 1*(H(I,J+1)-BOT(I,J+1)))
215 C
216 C ROW CALCULATIONS
217 C
218 DO 300 JJ=1,NR
219 J=JJ
220 IF(MOD(ISTEP+ITER,2).EQ.1) J=NR-J+1
221 DO 280 I=1,NC
222 BB=SF2(I,J)/DELTA
223 DD=HD(I,J)*SF2(I,J)/DELTA-Q(I,J)
224 AA=0.0
225 CC=0.0
226 IF(J-1)200,210,200
227 200 BB=BB+T(I,J-1,1)
228 DD=DD+H(I,J-1)*T(I,J-1,1)
229 210 IF(J-NR)220,230,220
230 220 DD=DD+H(I,J+1)*T(I,J,1)
231 BB=BB+T(I,J,1)
232 230 IF(I-1)240,250,240
233 240 BB=BB+T(I-1,J,2)
234 AA=-T(I-1,J,2)
235 250 IF(I-NC)260,270,260
236 260 BB=BB+T(I,J,2)

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237      CC=-T(I,J,2)
238 270    W=BB-AA*B(I-1)
239      B(I)=CC/W
240 280    G(I)=(DD-AA*G(I-1))/W
241 C
242 C      RE-ESTIMATE HEADS
243 C
244      DO 6002 J=1,NR
245      H(1,J)=30.0
246      H(2,J)=H(1,J)
247      H(28,J)=30.0
248      H(27,J)=H(28,J)
249 6002    CONTINUE
250      E=E+ABS(H(NC,J)-G(NC))
251      H(NC,J)=G(NC)
252      N=NC-1
253 290    HA=G(N)-B(N)+H(N+1,J)
254      E=E+ABS(H(N,J)-HA)
255      H(N,J)=HA
256      N=N-1
257      IF(N.GT.0) GO TO 290
258      DO 300 N=1,NC
259      IF(H(N,J).GT.BOT(N,J)) GO TO 300
260      E=E+BOT(N,J)+0.01-H(N,J)
261      H(N,J)=BOT(N,J)+0.01
262 300    CONTINUE
263 C
264      WRITE(*,205) E,ERROR
265 205    FORMAT(/,1X,'Error is:',1X,E12.7,3X,'Projected error is:'
266      11X,E12.7,///)
267 C
268 C      PRINT RESULTS
269      IF(E.GT.ERROR) GO TO 80
270 C
271      OPEN(2000,FILE='RESULT.DAT',STATUS='NEW')
272      DO 341 J=1,NR
273 341    WRITE(2000,330) (H(I,J),I=1,NC)
274 330    FORMAT(30F6.2)
275      WRITE(2000,4100)
276 4100   FORMAT('100')
277      DELTA=DELTA*1.2
278 320    CONTINUE
279      DO 66 J=1,NR
280      DO 66 I=1,NC
281      H(I,J)=(H(I,J)-30.0)
282 66     CONTINUE
283      DO 69 J=1,NR
284 69     WRITE(*,211) (H(I,J),I=1,NC)
285 211    FORMAT(35F5.2)
286 C
287      OPEN(5000,FILE='WELL.DAT',STATUS='NEW')
288      WRITE(5000,1699) H(15,4),H(14,12),H(16,11),H(15,9),H(19,13),
289      1H(18,13),H(17,14),H(15,20),H(15,19),H(13,14)
290 1699   FORMAT(1X,'WELL #2 =',F5.2,/,1X,'WELL #17 =',F5.2,/,1X,
291      1'WELL #18 =',F5.2,/,1X,'WELL #19 =',F5.2,/,1X,'WELL #23 =',
292      1F5.2,/,1X,'WELL #24 =',F5.2,/,1X,'WELL #25 =',F5.2,/,1X,
293      1'WELL #30 =',F5.2,/,1X,'WELL #31 =',F5.2,/,1X,'WELL #34 =',
294      1F5.2)
295      WRITE(*,99)

```

```

296 99  FORMAT(1X,'The results of this computer run have been stored'
297      11X,'in files:',/,1X,'"RESULT.DAT"',/,1X,'"WELL.DAT"')
298 C
299     STOP
300     END
301 C
302 C
303 C
304 C  SUBPROGRAM TO ESTIMATE EFFECTIVE MONTHLY INFILTRATION
305     SUBROUTINE RESUB(QQ)
306     INTEGER MO,MM,REX,DAD,TREE
307     REAL K,MOM
308     DIMENSION ER(12), ET(12), R(12), RF(12)
309     ET(1)=6.1
310     ET(2)=10.5
311     ET(3)=28.4
312     ET(4)=60.4
313     ET(5)=99.7
314     ET(6)=133.6
315     ET(7)=155.3
316     ET(8)=148.4
317     ET(9)=110.5
318     ET(10)=64.5
319     ET(11)=36.8
320     ET(12)=16.8
321     RF(1)=0.8
322     RF(2)=0.8
323     RF(3)=0.8
324     RF(4)=0.8
325     RF(5)=1.0
326     RF(6)=1.0
327     RF(7)=1.0
328     RF(8)=1.0
329     RF(9)=1.0
330     RF(10)=0.8
331     RF(11)=0.8
332     RF(12)=0.8
333     K=.95
334     WRITE(*,40)
335 40  FORMAT(/,1X,'How many months of recharge do you want to'
336     11X'consider ?')
337     READ(*,*)NOMO
338     WRITE(*,1)
339 1  FORMAT(/,1X,'What month has just passed ? (input "1" for'
340     11X,'January, "2" for February, etc.)')
341     READ(*,*)MO
342     WRITE(*,2)MO
343 2  FORMAT(/,1X,'How much rain (mm) fell during',1X,I2,1X,'?')
344     READ(*,*)PPT
345     R(1)=(PPT*RF(MO))-ET(MO)
346     IF(R(1).LT.0.0) R(1)=0.0
347     MM=MO-1
348     DO 41 JSE=2,NOMO
349     TREE=JSE-1
350     WRITE(*,4)TREE,MO
351 4  FORMAT(/,1X,'How much rain (mm) fell during the month',1X,I2,
352     11X,'months before',1X,I2,1X,'?')
353     READ(*,*)PPT

```

```
354     IF (MM.LE.0) MM=MM+12
355     R(JSE)=(PPT*RF(MM))-ET(MM)
356     IF (R(JSE).LT.0.0) R(JSE)=0.0
357 41    MM=MM-1
358     SRE=R(1)
359     DO 43 REX=2,NOMO
360     SRE=SRE+(R(REX)*K**REX-1)
361 43    CONTINUE
362     MOM=1
363     DO 44 DAD=1,NOMO-1
364     MOM=MOM+K**DAD
365 44    CONTINUE
366     RCHG=SRE/MOM
367     QQ=RCHG/30400
368     WRITE(*,28)QQ
369 28    FORMAT(/,1X,'Effective daily recharge is',F7.5,1X,'meters'
370     11X,'per day')
371     RETURN
372     END
```