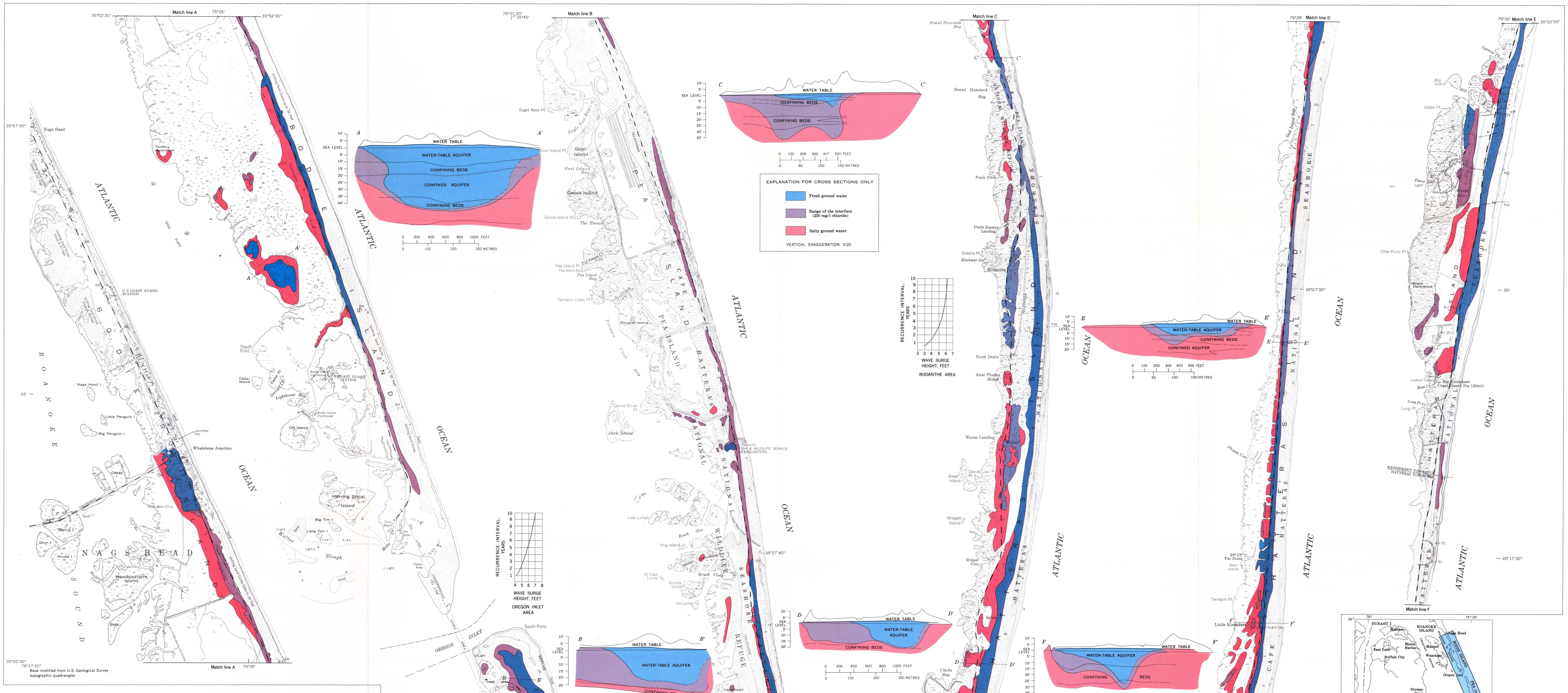
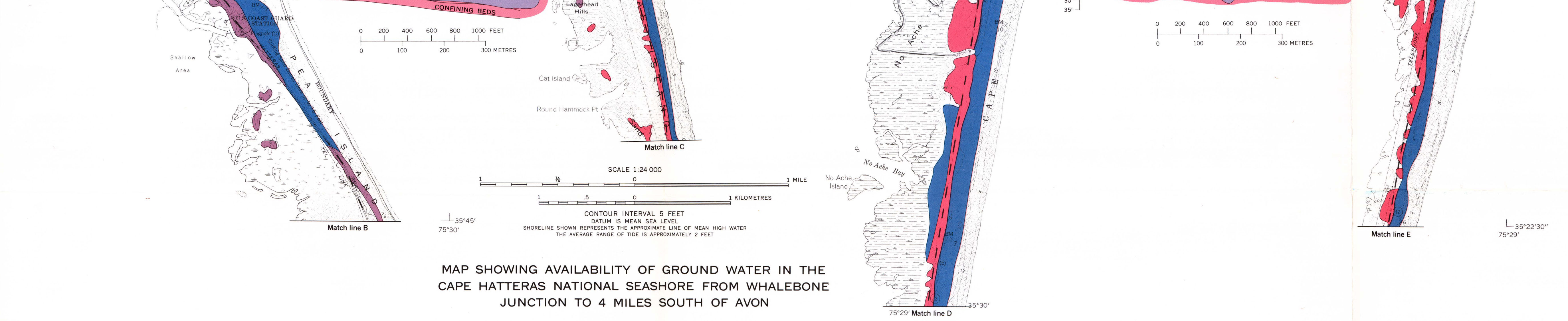
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

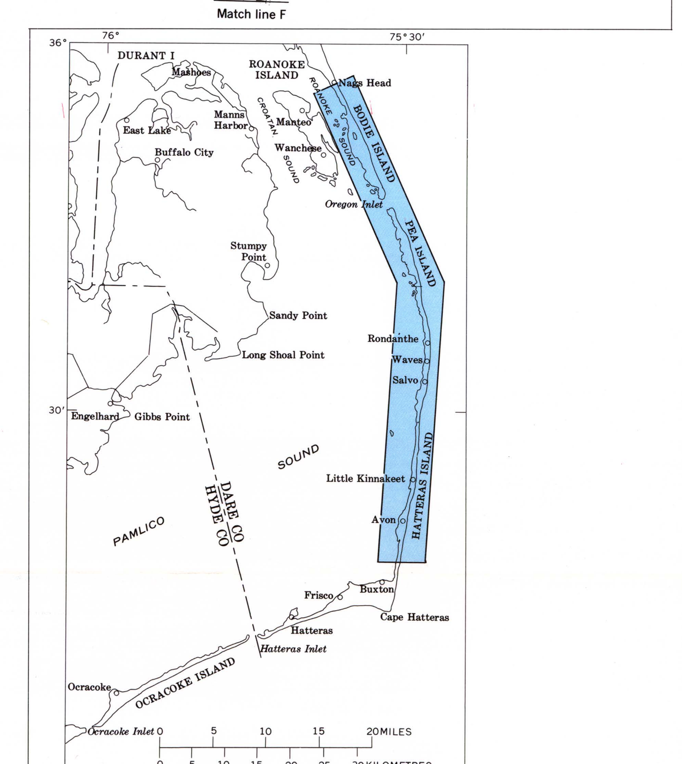
PREPARED IN COOPERATION WITH THE
U.S. NATIONAL PARK SERVICE

HYDROLOGIC INVESTIGATIONS
ATLAS HA-540 (SHEET 1 OF 2)





MAP SHOWING AVAILABILITY OF GROUND WATER IN THE CAPE HATTERAS NATIONAL SEASHORE FROM WHALEBONE JUNCTION TO 4 MILES SOUTH OF AVON



PROJECT AREA ON THIS MAP

INTRODUCTION

The Cape Hatteras National Seashore is located on a chain of barrier islands, known locally as the Outer Banks, that extend from the Virginia State line southward for about 175 miles to include the Bogue Banks (Powell, 1968). The seashore section extends from Whalebone Junction, 3½ miles south of Nags Head, southward to include Ocracoke Island The total area of this section is approximately 100 square miles, of which about 45 square miles comprises the national seashore.

The National Park Service has constructed extensive recreational facilities, including campgrounds, visitor centers, day-use facilities, and nature trails. An increasing popularity of the seashore has put a burden on these facilities. One of the major factors in the optimal use of the facilities is the availability of potable ground water. Specifically, the Park Service requires knowledge of (1) areas in which fresh ground-water supplies can be developed, (2) reliable estimates of ground-water yields in these areas, and (3) methods to conserve or enhance existing supplies.

PHYSICAL SETTING

In general aspect, the barrier islands are long, narrow islands standing only a few feet above sea level. In the national seashore section, the islands vary in width from about 600 feet near the village of Hatteras to nearly 3 miles at Cape Hatteras, and are separated from the mainland by shallow sounds as much as 28 miles wide.

In the seashore the beach on the ocean side is bordered by an almost continuous dune ridge, the crest of which is as much as 20 feet above sea level. These dunes, which serve to prevent overwash of the banks from the ocean during storms, are partly of natural origin, having been formed by storm waves and wind, and are partly man made. The remainder of the islands generally consist of sand flats as much as 1,000 feet wide that slope gently toward the sounds. The altitude of these flats ranges from about 3 or 4 feet to about 10 feet above sea level. Along the sounds the islands are bordered almost continuously by salt marshes a few hundred feet wide. The marshes and the sand flats are subject to periodic storm surge overwash from the sound, particularly those areas that are less than 5 feet above mean sea level. Scattered along the banks, adjacent to the salt marshes, are isolated, irregular sand ridges, some of which reach altitudes of as much as 15 feet.

The three islands on which the seashore is located (Bodie, Hatteras, and Ocracoke) are separated by inlets which permit exchange of water between the ocean and sound. Inlets, like the islands, are subject to considerable change during major storms. New inlets may be formed and old ones closed. During more tranquil periods, inlets tend to migrate southward under the influence of the currents moving parallel to the shore.

The sediments composing the Outer Banks were deposited in a coastal environment. Sand is the dominant sediment composing the barrier islands and is the chief aquifer-forming material. Less permeable silts and clays, which act as confining beds, are generally interlayered between the sands. Silt and clay may also be mixed with the sand forming a heterogeneous bed of low permeability. (See geohydrologic sections on sheets 1 and 2.)

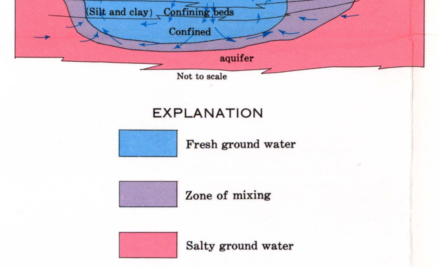
HYDROLOGIC SETTING

The fresh ground-water reservoir in the seashore consists of a water-table aquifer which extends from the land surface to the first confining beds of silt and clay, and confined or semi-confined aquifers beneath and between the silt and clay beds. (See geohydrologic sections on sheets 1 and 2.) The water-table aquifer ranges in thickness from 10 to 50 feet and averages about 15 feet. The altitude of the water table averages 3 feet above mean sea level along the narrow parts of the seashore, and is as high as 10 feet at Cape Hatteras.

Rainfall is responsible for the occurrence and maintenance of the fresh ground-water reservoir on the Outer Banks, and most rain water enters directly into the water-table aquifer with little or no surface runoff. In some instances after the ground has become saturated during very heavy rainstorms, some runoff is detected in roadside ditches and in drainage canals. Small amounts of fresh water occur in a few ponds at Cape Hatteras where the water table is above land surface in depressions; however, many of the ponds usually disappear during dry periods.

The deeper confined aquifers are as much as 30 feet thick and are below the first confining beds whose thickness ranges from about 5 to 20 feet. Exact limits of confined aquifers are difficult to define because of the gradational nature of the sediments below the water-table aquifer.

Fresh ground water on the Outer Banks may be visualized as a lens-shaped mass floating on top of denser salty water. (See idealized section and geohydrologic sections.) The size of the fresh-water lens is continually changing, owing to the rates of recharge and discharge. At the boundary between the fresh and salty water, a zone of diffusion occurs due to the mixing effect of the fresh water circulation and the tides in the adjoining ocean and sound.



Idealized section of a barrier island of the Outer Banks showing the relationship between ground-water flow and the maintenance of a fresh-water lens in the aquifer system.

Movement of fresh ground water through the system is away from the central part of the island toward the ocean and the sound at an average rate of about 1 foot per day. The confining beds of silt and clay underlying the water-table aquifer generally restrict the major part of the circulation of fresh water to this aquifer. However, in the higher and wider island areas, such as at Cape Hatteras and the southern part of Bodie Island, there is sufficient head to enable fresh water to circulate downward through the confining beds into the deeper confined aquifers. Test drilling by the North Carolina Office of Water and Air Resources in late 1972 in the Manteo-Nags Head area has shown that fresh ground water moving in confined aquifers from mainland recharge areas may extend as far east as Bodie Island. The maximum depth to which fresh water occurs in the seashore is about 120 feet below land surface in the central part of Hatteras Island at Cape Hatteras. Below this depth the confined aquifer grades into silt and clay, restricting deeper circulation of fresh water.

AVAILABILITY OF FRESH GROUND WATER

RAINFALL AND GROUND-WATER RECHARGE

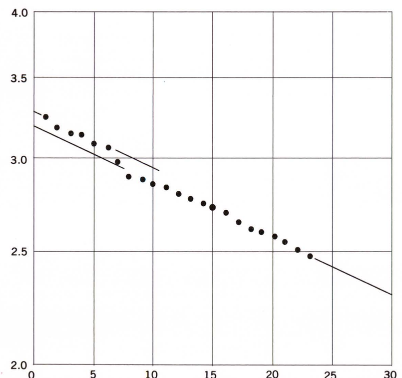
To evaluate the availability of fresh ground water on the Outer Banks, it is necessary first to assess that part of rainfall which enters the ground-water system. The yearly average rainfall ranges between 50 inches in the north to 55 inches in the southern part of the seashore.

A monthly water balance study at Cape Hatteras showed that May, June, and July are water-deficit months at the seashore, that is, there is insufficient rainfall or soil moisture to satisfy the potential evapotranspiration. These water-deficit months are also the peak demand period for water supplies in the various campgrounds operated by the Park Service. Rainfall during August and the early part of September restores soil moisture losses of the previous months, and the rainfall occurring from then until the following May is in excess of the evapotranspiration losses during that period, resulting in a water surplus ranging between 17 inches at Bodie Island and 20 inches at Cape Hatteras. Because runoff is negligible, all of the surplus water is available to recharge the ground-water system. The annual recharge ranges from 290 million gallons per square mile at Bodie Island to 350 million gallons per square mile at Cape Hatteras.

NATURAL GROUND-WATER DISCHARGE

Natural ground-water discharge occurs in two ways. First, through lateral movement toward the sounds and the ocean (see idealized section), and second, through direct evaporation from the soil zone and from plant transpiration. The evaporative processes are usually referred to collectively as evapotranspiration and account for the return to the atmosphere of 33 to 35 inches of the yearly rainfall on the Outer Banks.

To maintain equilibrium of the fresh-water system over any significant period of time such as a year, the amount of recharge to the system must equal the amount of discharge. That part of the natural discharge occurring in the ocean and sound may be measured by use of recession curves, which are a plot of the decline of ground-water levels with time during periods of no rainfall. A recession curve for a well near the Little Kinnakeet Coast Guard station (abandoned) about 6 miles north of Cape Hatteras is shown below. The data are for a winter dry period when the effects of evaporation were small and transpiration from plants was negligible, and thus represent conditions when the principal loss of water from the ground-water reservoir was by discharge into the sound and ocean.



Natural recession curve shows daily head loss in the water-table aquifer during the winter due primarily to ground-water discharge to the ocean and sound.

During the 24-day recession, the head loss from the water-table aquifer averaged 0.03 foot per day. Because the mean water level in the aquifer during the recession (2.86 feet above mean sea level) was close to the average annual water level (2.68 feet), this head loss was attributed chiefly to lateral movement of ground water to the sound and ocean. Using a specific yield of 15 percent obtained from aquifer-test data for the water-table aquifer, then the annual discharge from the ground-water system would be about 343 million gallons per square mile in this area. This calculation is in close agreement with 338 million gallons per square mile annual surplus rainfall estimated by the water balance study for the Little Kinnakeet area.

THE SALT WATER-FRESH WATER BOUNDARY

The size of the fresh-water lens is obviously a controlling factor in the availability of fresh ground water on the Outer Banks. It influences the decision of how deep to complete a well, and the maximum rate at which the well can be pumped without causing salty water to enter the well. Factors that determine the size of the fresh-water lens are the rates of recharge and discharge, and the horizontal and vertical hydraulic conductivities of the sediments.

The depth of the fresh-water lens, according to the Ghyben-Herzberg principle, is a function only of the height of fresh water above sea level and theoretically extends about 40 feet below mean sea level for each foot of fresh-water head above mean sea level. Thus, for a 3-foot head of fresh water, the theoretical depth to the salt water-fresh water interface would be about 120 feet below mean sea level. However, this principle considers only the balance of a static immiscible liquid system and does not apply to a dynamic diffusive system such as that on the Outer Banks.

The boundary between the fresh-water lens and the underlying salty water is not a sharply defined line, but is a zone of mixing or diffusion wherein the saline ground water mixes with the fresh water. This zone, which may be as much as several hundred feet wide and tens of feet thick, is due primarily to the effects of tidal fluctuations alternately moving salty water back and forth within the aquifer. This action would ultimately destroy the fresh-water lens if it were not for the movement of fresh water recharge downward and outward in the lens.

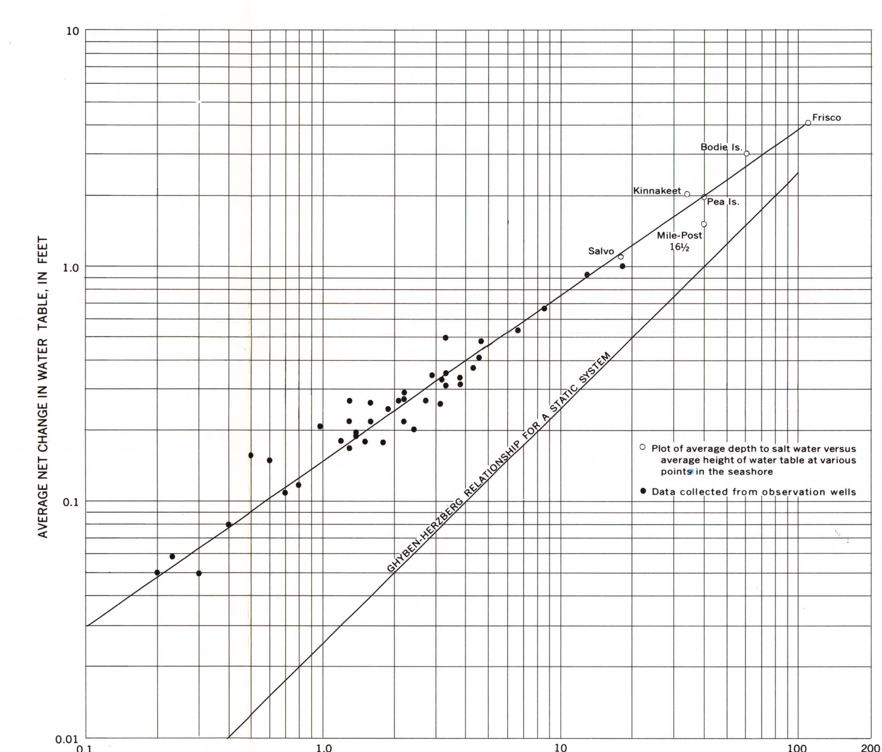
Vertical fluctuations in the diffusion zone are caused by the response of the system to rainfall and subsequent decline in fresh-water head due to natural discharge. An inverse relationship exists between the fluctuations in the fresh-water head and a corresponding rise or fall of the zone of diffusion. A decline in the water level is accompanied by a rise in the zone of diffusion and vice versa.

For purposes of describing the fluctuations of the salt water-fresh water boundary, the 250-mg/1 (milligrams per liter) chloride line is chosen to represent an "interface" between salty water and fresh water, since it is the recommended upper limit for chloride in drinking water (U.S. Public Health Service, 1962). Differences in the size of the fresh-water lens at the 250 mg/1 chloride level in different parts of the seashore are shown on the various geohydrologic sections on the maps.

With a head change imposed upon a static system, the interface between salty and fresh water would change according to the Ghyben-Herzberg ratio of 40:1 when reaching equilibrium. A similar relationship likewise occurs in a dynamic ground-water system, except that the motion of the water itself plus the differences in vertical and horizontal hydraulic conductivities of the sediments will influence both the amount and the rate of change in the depth of the interface for a given head change in the water table. Thus, it is probable that the ratio between head change and depth to interface would be less than the Ghyben-Herzberg ratio.

Measured head changes in the water table were correlated with changes in depth to the salt-water interface at paired observation wells at several locations in the seashore (Sections *D-D′*, *E-E′*, and *F-F′*). The data collected at each site showed a similar ratio between head change and the corresponding depth change of the interface; these data were combined and are shown on the graph at the right as a non-constant ratio between head change and the change in the depth of the interface that approaches the Ghyben-Herzberg ratio toward the higher values of head. Theoretically the changing ratio for a dynamic system would become asymptotic with the Ghyben-Herzberg ratio at some point beyond the observed data.

Data points showing the average depth to salty water versus the average height of the water table for several other areas in the seashore were added to the upper end of the graph to provide a basis for the extension of the curve and to check the appropriateness of the plot. It appears that the curve could be extended through a 4- to 5-foot head change before becoming asymptotic to the Ghyben-Herzberg ratio.



Graph showing the amount of head change in the fresh-water lens causes a corresponding inverse change in the depth of the interface.

The graph, then, might be used to estimate the amount of rise in the salt-water interface caused by the lowering of the water table either naturally or by pumping at the sites where the data were collected. It is felt that because of the similarity of geologic and hydrologic conditions throughout the area, the graph could also be used elsewhere in the seashore where no significant confining beds exist between the water table and the salt-water interface.

RECOVERY OF FRESH GROUND WATER

The yield of any well or well system is related to the hydraulic conductivity of the aquifer, the thickness of the aquifer, the diameter of the well, the area of the well open to the aquifer, interference from other pumping wells, and proximity or relation to aquifer boundaries. The composite effect of these conditions are reflected by the rate and amount of head decline produced in an aquifer due to pumping from wells (drawdown); the greater the pumping rate, the greater will be the drawdown.

In the seashore, the presence of salty water at relatively shallow depths is an additional factor affecting the withdrawal of fresh ground water, because any lowering of the head in the aquifer, either naturally or by pumping, produces a rise in the interface. Therefore, drawdown is the key to the recovery of fresh water in the seashore, and fresh-water recovery will be most efficient when drawdown is minimal. One method for accomplishing this is to spread withdrawals over a larger area with a horizontal well instead of concentrating the effect at a point as in a vertical well.

Hantush and Papadopulos (1962) have provided analytical solutions for the drawdown distribution around horizontal wells, and have shown that, while the resulting drawdown is more widespread, it is not as much at any one point as the drawdown caused by vertical wells. The effects of drawdown in a vertical and a horizontal well are compared on the following diagram. For the same discharge, 10 gpm (gallons per minute), the maximum drawdowns after 1 day of pumping are computed to be 1.12 and 0.34 foot respectively. These head changes correspond to the interface rising about 17.5 and 3.5 feet. By doubling the discharge rate of the horizontal well, the maximum salty water rise is still well below the horizontal well. Thus, a horizontal well system is more efficient hydraulically in the recovery of fresh water from the thin lenses in the seashore and are less susceptible to salt-water encroachment.

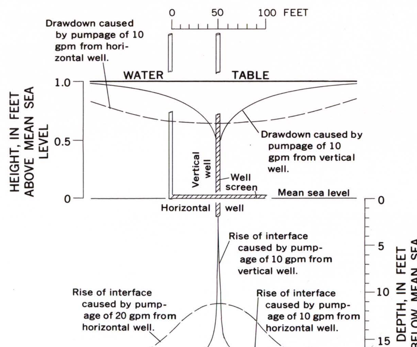


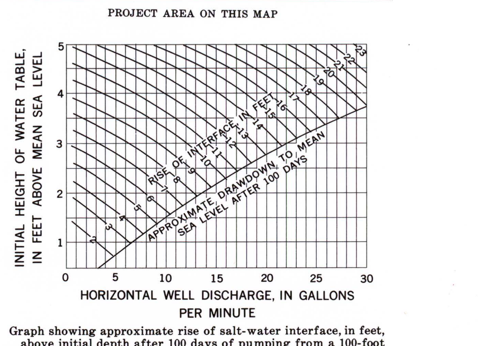
Diagram showing comparison of the effects of 1 day's pumping at 10 gallons per minute from a vertical and a horizontal well under the same conditions.

Two horizontal wells have been constructed in the seashore, one is being used at the Salvo campground and the other is near a proposed campground site on Ocracoke Island. These wells are 100 feet long and consist of four 5-foot lengths of 2-inch screen separated by 20-foot lengths of blank casing. The analytical solutions by Hantush and Papadopulos (1962) are based on screen for the entire length of the horizontal well; calculations show that the longer the screen length, the less the drawdown. For example, if the length of the horizontal well shown on the diagram were doubled to 200 feet while holding the pumping rate constant, the maximum drawdown would be about 0.20 foot, or roughly two-thirds that for the 100-foot screen length shown. Construction of a 100-foot horizontal well that is screened the entire length would not be any more difficult than for the above systems, and would have the advantage of a more widespread drawdown distribution.

Estimation of yields from a horizontal well system in the seashore depends upon knowledge of (1) the height of the water table above mean sea level at the beginning of pumping, (2) the length of the pumping period, (3) initial depth to the interface, (4) thickness of the water-table aquifer, and (5) the average transmissivity of the aquifer. For the narrow parts of the seashore, where the water table ranges between ½ and 5 feet above mean sea level, the use of a horizontal well system is most applicable; the water-level ranges for specific areas are given on the maps. The length of the pumping period for the Park Service facilities is about 100 days, which is roughly equivalent to the length of the camping season in the seashore. Although water systems operated by the Park Service are not pumped continuously, the estimate for the maximum possible water supply must include the contingency that the system will operate continuously throughout the season.

The depth to the interface is variable with time, with position on a given island section, and from place to place as indicated by the geohydrologic sections. Average interface depths are also estimated for certain areas on the maps, but an accurate interface depth at any proposed well site must be obtained from a test well. The average thickness of the water-table aquifer except on the widest section of the islands is about 15 feet and the average transmissivity, as determined from aquifer tests, is about 3,300 feet squared per day.

Using the preceding conditions and further assuming that during the period there is no significant recharge to the aquifer, a series of curves was prepared and are presented on the graph showing the approximate rise of the interface at various discharges from a 100-foot horizontal well for different initial heights of the water table in the seashore after 100 days of continuous pumping. The curves end approximately where the drawdown in the horizontal well reaches mean sea level after 100 days. The depth to the salt water-fresh water interface at this time can be determined by subtracting the rise in the interface, as shown on the graph, from the initial depth to the interface.



Graph showing approximate rise of salt-water interface, in feet, above initial depth after 100 days of pumping from a 100-foot horizontal well with 2-inch diameter placed at mean sea level.

EXPLANATION

AREAS FAVORABLE FOR GROUND-WATER DEVELOPMENT

Areas not likely to be affected by inundation of salty water; average water level range: 5-10 ft. above mean sea level; depth to salty water: 60-100 ft. below mean sea level potential yield: (a) water table aquifer-75,000-100,000 gallons per day per vertical well (b) confined aquifer-50,000 gallons per day per vertical well.

Areas subject to rare inundations of salty water; average water level range: 2.5-4 ft. above mean sea level; depth to salty water: 20-35 ft. below mean sea level; potential yield: 20,000-45,000 gallons per day per horizontal well.

AREAS OF LIMITED GROUND-WATER POTENTIAL

Areas rarely inundated by salty water, but relatively shallow depth of confining beds limits thickness of fresh-water lens; average water level range: 3-5 ft. above mean sea level; depth to salty water: 10 to 25 ft. below mean sea level; potential yield: 15,000-45,000 gallons per day per horizontal well.

Areas not usually inundated by salty water, but are adjacent to or surrounded by areas frequently flooded so that pumping effects may induce salt-water encroachment after the flooding; average water level range: 0.5-2.5 ft. above mean sea level; depth to salty water: 15-35 ft. below mean sea level; potential yield: 5,000-25,000 gallons per day per horizontal well.

Areas subject to frequent inundation by salty water and would require a year or more to reestablish a significant lens of fresh water; average water level range: 0.5-2.5 ft. above mean sea level; depth to salty water: 5 to 15 ft. below mean sea level; potential yield: 2,000-25,000 gallons per day per horizontal well.

Areas that are not suitable for ground-water development.

GROUND-WATER RESOURCES OF THE CAPE HATTERAS NATIONAL SEASHORE, NORTH CAROLINA

By

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1975

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For sale by U.S. Geological Survey, Reston, Virginia 22092, price $1.00 per set