EVALUATION OF DATA AVAILABILITY AND EXAMPLES OF MODELING FOR GROUND-WATER MANAGEMENT ON CAPE COD, MASSACHUSETTS

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS 16-75

PREPARED IN COOPERATION WITH THE
COMMONWEALTH OF MASSACHUSETTS
WATER RESOURCES COMMISSION

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle EVALUATION OF DATA AVAILABILITY AND EXAMPLES OF MODELING FOR GROUND-WATER MANAGEMENT ON CAPE COD, MASSACHUSETTS			5. Report Date Published December 1975 6.
7. Author(s) Alan W. Burns, Michael H. Frimpter, and Richard E. Willey			8. Performing Organization Rept. No. USGS/WRI 16-75
9. Performing Organization Name and Address U.S. Geological Survey Water Resources Division 150 Causeway Street, Suite 1001 Boston, MA 02114			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U.S. Geological Survey Water Resources Division 150 Causeway Street, Suite 1001 Boston, MA 02114			13. Type of Report & Period Covered Final 14.

15. Supplementary Notes Prepared in cooperation with Massachusetts Water Resources Commission
100 Cambridge Street
Boston, MA 02202

16. Abstracts

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17. Key Words and Document Analysis. 17a. Descriptors

Ground water; Massachusetts; saline-water/fresh-water interfaces; hydrologic cycle; computer models

17b. Identifiers/Open-Ended Terms

Cape Cod

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
No restriction on distribution	UNCLASSIFIED	
	20. Security Class (This Page) UNCLASSIFIED	22. Price

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Commonwealth of Massachusetts
Water Resources Commission

1975

UNITED STATES DEPARTMENT OF THE INTERIOR

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Multiply English units	By	To obtain SI units
feet (ft)	0.3048	metres (m)
feet per day (ft/d)	$.3527 \times 10^{-5}$	metres per second (m/s)
feet squared per day (ft^2/d)	$.1075 \times 10^{-5}$	metres squared per second (m^2/s)
miles (mi)	1.609	kilometres (km)
square miles (mi^2)	2.590	kilometres square (km^2)
inches per year (in/yr)	$.8054 \times 10^{-9}$	metres per second (m/s)
cubic feet per second (ft^3/s)	.02832	cubic metres per second (m^3/s)

DEFINITIONS OF SELECTED GROUND-WATER TERMS
(Adapted from Sammel, et. al., 1966, Lohman and others, 1972, and U.S. Water Resources Council, 1973.)

Aquifer--A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. See Ground-water reservoir.

Aquifer test--A test involving the withdrawal of measured quantities of water from, or addition of water to, a well (or wells) and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition.

Artificial recharge--Recharge at a rate greater than natural, resulting from deliberate or incidental actions of man.

Bedrock--The consolidated rock of the earth's crust.

Discharge, ground-water--Removal of water from an aquifer by evapotranspiration, by natural flow to streams, or by pumping.

Equipotential line--A line along which the total energy of the fluid, or head, of a body of ground water is the same.

Evapotranspiration--Combined discharge of water to the air by direct evaporation and plant transpiration.

Flow line--The path which a particle of water follows in its movement through saturated, permeable rocks.

Geologic unit--A group of rocks having common or closely related characteristics.

Ground water--Water in rock materials beneath the surface of the earth. Ground water is distinguished from soil moisture in this report.

Ground-water reservoir--All rocks in the zone of saturation. See Aquifer.

Hydraulic conductivity--The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area of a porous medium that is isotropic and the fluid is homogeneous, measured at right angles to the direction of flow.

Hydraulic gradient--The change in static head per unit of distance in a given direction.

Hydraulic head--The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. In ground water, where velocities are small, the velocity head is negligible and the total head is the sum of the elevation head and the pressure head. In a nonflowing well, the head is measured as the elevation of the water level referenced to an established datum; in a flowing well, it is the elevation to which water will rise in a pipe extended high enough to prevent the well from flowing, also referenced to an established datum.

Interface--In hydrology, the contact plane between two different fluids.

Potentiometric surface--An imaginary surface representing the static head of ground water.

Recharge--The processes of addition of water to the zone of saturation, that zone beneath the water table.

Specific yield--The quantity of water that a fully saturated rock will yield by gravity drainage; expressed as a percentage which is the ratio of (1) the volume of water yielded to (2) the volume of the rock.

Storage coefficient--The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Transmissivity--The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unsaturated zone--A subsurface zone containing water under pressure less than that of the atmosphere, including water held by capillarity; and, containing air or gases generally under atmospheric pressure. Limited above by the land surface and below by the water table.

Water budget--An accounting of the inflow to, outflow from, and storage changes in a hydrologic unit.

Water table--The surface in an unconfined aquifer at which the pressure is atmospheric. It is the level at which water stands in wells that just penetrate the upper part of the aquifer.

Zone of saturation--A subsurface zone in which all the interstices are filled with water under pressure greater than atmospheric. The upper surface of the zone of saturation is the water table.

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ABSTRACT

Ground water is the major source of water for public and private supplies on Cape Cod, Massachusetts. A peninsula in the Atlantic Ocean, Cape Cod is underlain by unconsolidated earth materials that contain a lenslike reservoir of fresh water "floating" on salty ground water.

Areal and cross sectional computer simulation models based on solutions to the ground-water flow equation demonstrate the interdependence of water-table altitude, recharge, withdrawal, spatial variations and anisotropy of hydraulic conductivity, spatial variations of specific yield, position of the fresh-water/salt-water zone of diffusion, and other boundaries. Currently available (1974) descriptions of these parameters, however, are insufficient to calibrate the models to adequately predict future hydrologic conditions for resource planning and management.

INTRODUCTION

Cape Cod is a seashore resort area of national reknown. It is a hook-shaped peninsula which extends 40 mi (65 km) into the Atlantic Ocean and is separated from the mainland by Cape Cod Canal, a salt-water channel connecting Buzzards Bay and Cape Cod Bay (fig. 1). It is 440 mi^2 (1,040 km^2) in area and is underlain by unconsolidated earth materials that contain a lenslike reservoir of fresh ground water "floating" on salty ground water.

The fresh ground-water reservoir is the principal source of supply for the rapidly growing population of Cape Cod. Because of increasing resident population and increasing numbers of summer vacationers, there is local and State concern for problems of meeting increased water demands, deterioration of water quality, changes of water table and pond levels, and changes in ecology owing to changes in salinity of water in brackish-water bodies.

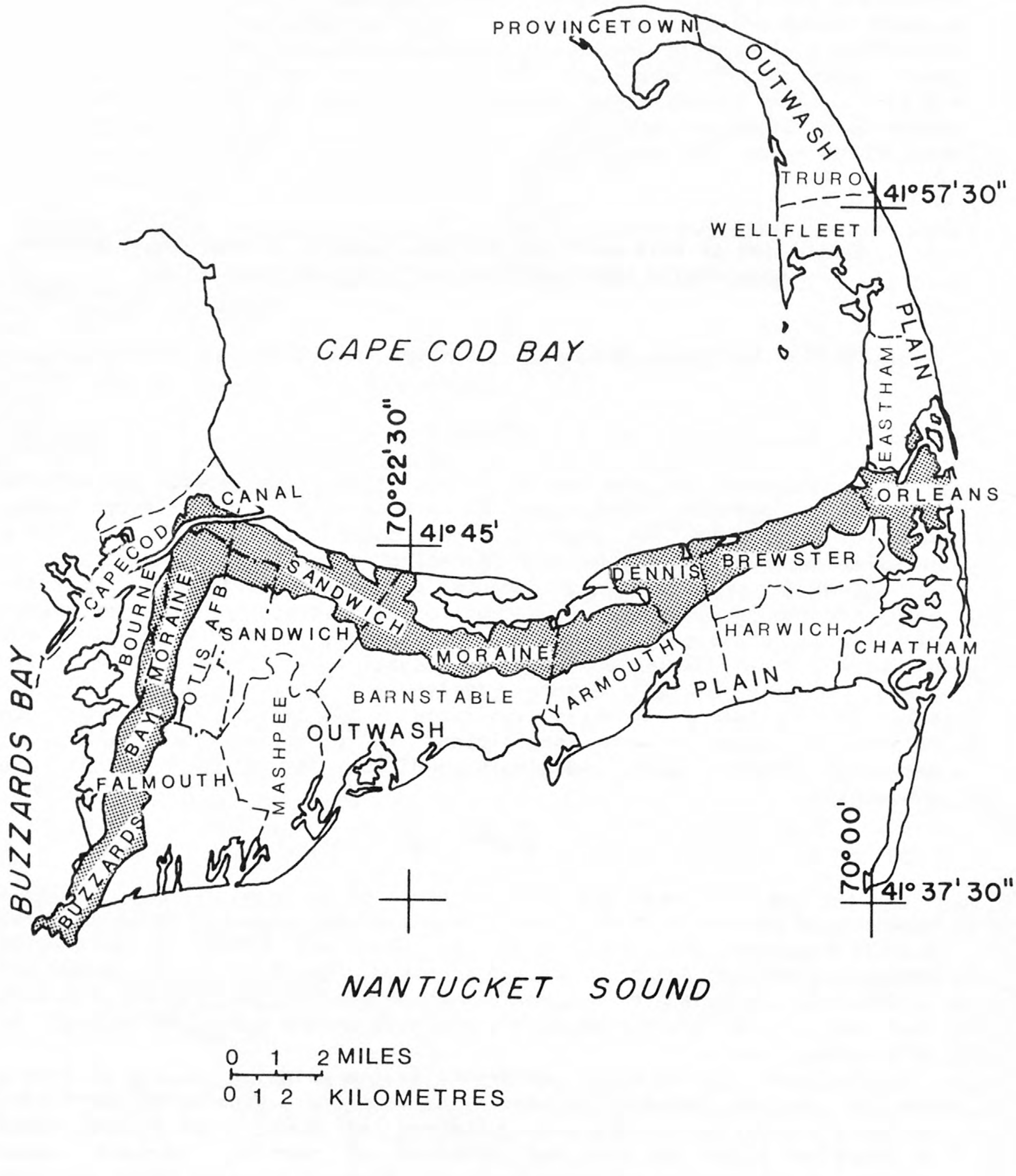


FIGURE 1 -- PHYSICAL FEATURES OF CAPE COD

The principal objectives of this report, prepared in cooperation with the Massachusetts Water Resources Commission, Division of Water Pollution Control and Division of Water Resources, are (1) to summarize existing data on Cape Cod's ground-water quantity and quality, (2) to identify the needs for data for monitoring and managing the ground-water system, (3) to produce a preliminary simulation model of the ground-water system (insofar as existing data permit), and (4) to show by examples how such a model might be used as part of the decision-making process in planning development and predicting effects of development on the ground-water system.

Data for this study were made available by D.L. Maher Co., North Reading, Mass., R.E. Chapman Co., Oakdale, Mass., and Layne-New England Co., Arlington, Mass., all well drillers, and Whitman and Howard, Inc., consulting engineers, who furnished records of municipal test and production wells, chemical analyses, and engineering reports. Superintendents of the municipal water systems furnished well locations and data on production capacities of supply wells.

HYDROLOGIC SYSTEM

Cape Cod is composed of unconsolidated sand, gravel, silt, clay, and till deposits that rest on a bedrock surface, which ranges in altitude from 80 ft (24 m) below sea level near the Cape Cod Canal to more than 900 ft (275 m) below sea level near Provincetown (Oldale, 1969b).

Till mixed with stratified sand, gravel, and silt forms the Buzzards Bay and Sandwich Moraines (fig. 1). These are broad north and east trending ridges having moderately rugged topography of hills and depressions (kettle holes). East and south of the moraines, an outwash plain slopes gently southward to Nantucket Sound. The plain is composed of stratified sand and gravel and is also pitted with kettle holes, many of which intersect the water table and contain ponds. The outer Cape from Orleans to Truro is also an outwash plain, which is composed predominantly of stratified sand and gravel and slopes gently westward from a wave-cut cliff along most of the Atlantic shoreline to the shore of Cape Cod Bay.

Fresh ground-water is contained in the upper part of these unconsolidated deposits on the outer Cape and in both unconsolidated deposits and bedrock on the inner Cape. This fresh ground water is bounded by salt water in the Atlantic Ocean, Buzzards Bay, and Cape Cod Bay and by salty ground water at depth; it is sustained entirely by infiltration of precipitation on the land surface.

There is practically no surface runoff from Cape Cod, as indicated by the low density of surface drainage channels. Rapid rises of stream stage due to precipitation are several times smaller at the U.S. Geological Survey Herring River gaging station in Harwich (fig. 2) than in comparable streams draining areas of low permeability soils in New England, further indicating that surface runoff is negligible. Of the precipitation on the Cape, some is evaporated directly from the land surface, some is evaporated or transpired from the soil, and the remainder seeps through the soil to the water table and recharges the ground-water reservoir. Water in the reservoir moves from points of high

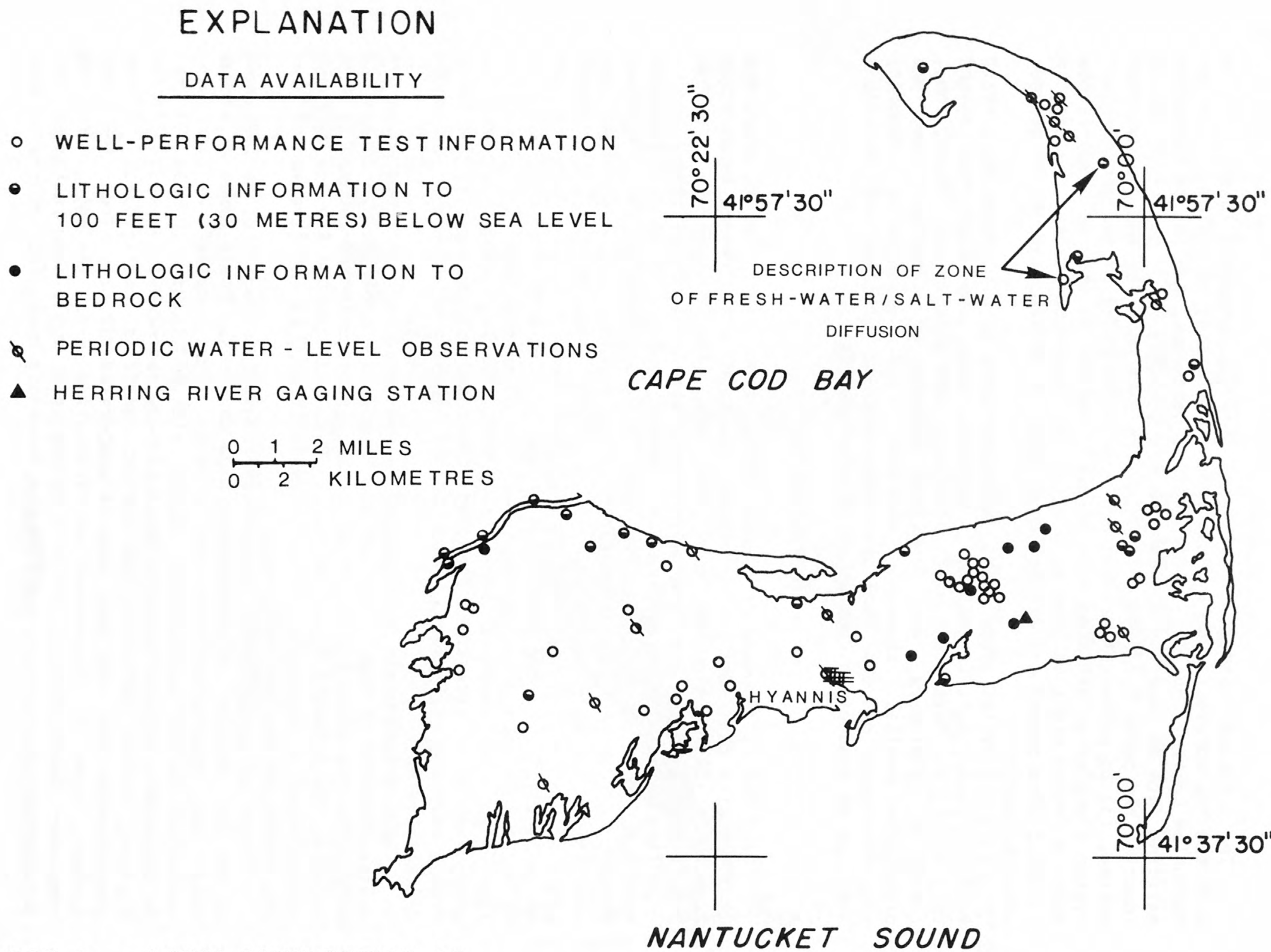


FIGURE 2. -- AREAL DISTRIBUTION OF HYDROLOGIC DATA FOR CAPE COD

head (high altitudes of the water table) toward points of lower head (lower altitudes of the water table) and ultimately is discharged to the ocean as ground-water outflow. Enroute to the ocean, some ground water is discharged naturally to the atmosphere by evapotranspiration (evaporation plus transpiration), and some is discharged artificially by pumping wells; some of this pumpage returns to the ground-water reservoir through septic systems.

Fresh ground water is slightly less dense than salt water and, therefore, "floats" as a lens-shaped body upon underlying salt water in the ground-water reservoir. The upper boundary of the fresh-water lens, the water table, has a low dome shape estimated to reach a maximum altitude of a little over 70 ft (21 m) in Sandwich, where the Cape is widest, and is at sea level at the shoreline. The lower boundary of the fresh-water lens is called the fresh-water/salt-water interface. The interface is not a sharp boundary but is a zone of mixing or diffusion of fresh and salt water.

Ground water occurs under dynamic conditions in which fresh water is constantly moving toward and discharging from the edge of the lens. Hydraulic conductivity, saturated thickness, and specific yield are physical properties that determine the capacity of the ground-water reservoir to transmit and store water. These properties, together with rates and distribution of recharge and discharge, govern the shape of the fresh-water lens, the altitude of the water table, and the depth below sea level to a point on the fresh-water/salt-water interface.

Because of horizontal layering of aquifer materials, hydraulic conductivity is commonly less in the vertical direction than in the horizontal. This anisotropy, has the effect of distorting the shape of the fresh-water lens, so that it is flatter than it would be if the aquifer were isotropic (fig. 7).

Ground-water quality on Cape Cod is generally good. The water is soft and is low in dissolved-solids concentration, but it is slightly acid. Some wells yield water containing objectionable concentrations of iron, but the occurrence of manganese is not as prevalent as in the water supplies of the rest of southeastern New England. Sodium and chloride concentrations are generally low except where sea-water intrusion, sea-water spray, sewage effluent, or highway salting have affected water quality. Provincetown has had a long history of problems with sea-water intrusion of its ground-water supplies at one of its pumping stations in North Truro.

AVAILABILITY AND ADEQUACY OF EXISTING DATA FOR GROUND-WATER MANAGEMENT

Four major elements of hydrologic data are necessary for planning the development and management of ground water on Cape Cod. These are:

(1) Ground-water recharge and discharge

(2) Hydraulic properties of the ground-water reservoir

(3) Position and description of hydrologic boundaries

(4) Water quality.

These data are necessary (1) to describe historic and present conditions as base-line data, from which future changes may be evaluated; (2) to monitor the hydrologic system to provide awareness and description of natural and man-caused changes; (3) for development and application of analytical techniques as tools for use by decision makers in predicting effects of management decisions on the hydrologic system. Most techniques involve simulating the ground-water system through solutions to some form of the mathematical equation describing ground-water flow; one technique utilizing a digital computer model is discussed later in this report.

Most of the existing geohydrologic data for Cape Cod is available from exploration and testing done during development of public water-supply wells (fig. 2). The information from this work and records of private domestic and commercial wells and highway test borings include lithologic logs, water-level measurements, well-performance test data, and chemical analyses of water.

Ground-Water Recharge and Discharge

Ground-water recharge on Cape Cod results from infiltration of precipitation downward through the zone of aeration to the water table. Recharge has been estimated as about 17 in (432 mm) per year at Provincetown and 18 in (457 mm) per year at Hyannis by Strahler (1972) and estimated as about 18 in (457 mm) per year at North Truro by Delaney and Cotton (1972a). These estimates are based on water-budget analysis using the Thornthwaite method (Thornthwaite and Mather, 1957) for computing evapotranspiration, using climatic data and assumptions concerning vegetal cover. These figures for recharge assume no overland runoff of precipitation, so the remainder of precipitation after soil moisture requirements are met is assumed available for recharge. These estimates derived by this method of water-budget analysis may be subject to large errors. Strahler (1972, p. 11), for example, points out that the recharge might be as low as 12 in (305 mm) per year on the outer Cape.

Ground-water recharge that is not lost to evapotranspiration moves as part of the ground-water flow system and on Cape Cod is ultimately discharged as ground-water outflow to the ocean. The amount of ground-water outflow is governed by the hydraulic conductivity and thickness of the aquifer, the hydraulic gradient, and the width of the section through which water is flowing. Because these parameters are generally unknown, direct calculation of the outflow is not possible at present.

Ground water is discharged artificially by pumping wells. Pumpage from public water-supply wells can be determined from records of the water companies and municipalities; pumpage from privately owned domestic and commercial wells is not recorded but can be estimated from a selective inventory of water use and an estimate of the population served by privately owned wells. The amount of this pumpage lost to the ocean could be estimated from records of sewage treatment plants. The amount of pumpage that is not discharged directly to the ocean through sewage treatment plants is assumed to be discharged through septic systems and cesspools. If the discharge of these cesspools and septic tanks is assumed to be returned in full to the aquifer as recharge, the pumpage discharged to these facilities need not be considered part of the effective withdrawal. It is possible, however, that the existence of the cesspools and septic tanks may tend to increase total evapotranspiration. Part of the discharge to cesspools and septic tanks must then be included in the effective withdrawal. Further research is necessary to provide accurate estimates of the fraction of cesspool and septic tank effluent which reaches the aquifer as recharge.

More accurate estimates of recharge and discharge are required for managing ground-water resources. Although no known method is highly accurate, suggested methods for improving on available estimates are:

(1) Estimating ground-water discharge and change in storage through analyses of water-level data from observation wells installed in five-point arrays. These analyses are based on finite-difference approximations of the differential equation describing ground-water flow (Urie, 1971; Weeks and Sorey, 1973).

(2) Estimating ground-water outflow through systematic collection of data on hydraulic gradients, hydraulic conductivity, and thickness of aquifer materials.

(3) Utilizing the transfer value of recharge data from other areas of analogous hydrogeologic setting.

Position and Description of Hydrologic Boundaries

The hydrologic boundaries of the fresh-water lens are the water table (the top, normally above sea level), the surface boundaries (the edges, normally at sea level), and either the bedrock surface (or other low-permeability material) or the fresh-water/salt-water interface (the bottom). The surface boundaries and the bottom boundaries, where defined by bedrock or other low-permeability material, are fixed and unmoving; whereas, the water table and the fresh-water/salt-water interface are in a hydrodynamic balance with the entire system and, thus, are constantly shifting.

Description and monitoring of the water table, its seasonal variations, and long-term trends provide base-line data for evaluation and prediction of future water-table and pond-level changes. The U.S. Geological Survey, in cooperation with the Massachusetts Department of Public Works and the Massachusetts Water Resources Commission, maintains a network of 15 water-level observation wells on Cape Cod (fig. 2). Monthly measurements have been collected at these wells for periods ranging from 8 to 24 years for the purpose of describing seasonal and long-term changes in water-table altitudes. The U.S. Geological Survey also maintains a network of 103 sites for measurement of water levels in wells, streams, and ponds in North Truro in cooperation with the National Park Service; 55 sites are measured monthly, and 48 sites are measured semi-annually.

Woods Hole Oceanographic Institution maintains nine observation wells at Otis Air Force Base as part of its study of waste-water spray irrigation. The Association for the Preservation of Cape Cod measures water-level fluctuations of 35 ponds.

A water-table map of inner Cape Cod based on altitudes of ponds, bogs, and streams taken from U.S. Geological Survey topographic maps has been prepared by Alfred C. Redfield (in Strahler, 1972); and a water-table map of North Truro based on water-level measurements (fig. 3) has been prepared by Delaney and Cotton (1972b).

Although existing data are adequate to indicate the general shape, altitude (head), and nature of fluctuations of the water table, precise measurement of its altitude at additional sites will be required, particularly where the water table is nearly flat and only a few feet above mean sea level.

Modern U.S. Geological Survey 7-1/2-minute topographic quadrangle maps are available for all of Cape Cod, and these are generally adequate for delineating the ocean shoreline and tidal streams. However, some onsite investigation of tidal lagoons and streams will be required to refine definition of the surface boundaries.

The bedrock surface, for all practical purposes, forms an impervious lower boundary of the ground-water reservoir. The depth of the bedrock surface has been mapped, and some data on the thickness of the basal till layer are available. Based on logs for 10 test holes that reach bedrock (fig. 2) and on seismic surveys (Oldale and Tuttle, 1964; Oldale, 1969b; and Oldale, Uchupi, and Prada, 1973), the bedrock surface is 80 ft (24 m) below sea level near Cape Cod Canal and more than 900 ft (275 m) below sea level near Provincetown.

The available data are adequate to indicate the general position of bedrock in the central part of Cape Cod (Yarmouth, Dennis, and Brewster). However, additional information from test holes in the inner and outer Cape areas will be necessary to verify results obtained from geophysical surveys. This information is necessary to determine the saturated thickness of the aquifer; lithologic logs and water samples obtained during drilling would also furnish the information needed to map variations in hydraulic conductivity and the location of the fresh-water/salt-water interface.

Location, description, and monitoring of the fresh-water/salt-water interface provide data required for evaluating and predicting salt-water encroachment into the aquifer. There are only two sites (fig. 2) on Cape Cod where the position of the fresh-water/salt-water interface has been determined by measuring the quality (chloride concentration) of ground water at progressively greater depths in the aquifer; more information is required to determine the position of this boundary. Where the interface is above bedrock or some other major lithologic unit of low permeability, it forms the lower boundary of the fresh-water flow system. The position of this boundary, and that of the water table, responds to stresses on the hydrodynamic system.

Hydraulic Conductivity and Specific Yield

Values of hydraulic conductivity and specific yield of the aquifer are required to analyze and predict responses due to development. These properties can be measured indirectly by analysis of water-level changes in the aquifer in response to a stress, such as pumping.

Well performance tests designed to evaluate well capacity and to meet State Health Department regulations are available for many sites (fig. 2) on Cape Cod. The analysis of data from such tests may provide further estimates of values of hydraulic conductivity and specific yield.

Hydraulic conductivity can be estimated from lithologic logs of wells and test holes. These estimates are based on the relationship between hydraulic conductivity and grain size and sorting of aquifer material. Estimated values of hydraulic conductivity range from 11 to 118 ft/d (3.4 to 36 m/d) in the North Truro area.

Available data are inadequate to construct maps showing the variation of hydraulic conductivity and specific yield. The sites for which estimates can be made are widely scattered. Furthermore, wells and test holes for which hydrologic and lithologic data are available commonly describe no more than the upper 100 ft (30 m) of the saturated material; lithologic logs are available for only 10 holes that penetrate the full thickness of the aquifer (fig. 2).

Water Quality

In planning for the development and management of water resources, great emphasis is placed on the quantity of water that is available. The quality of available water, however, determines its usefulness, and more and more attention is being paid to techniques of water-quality management. This aspect of water-resources planning is of special concern to decision makers of Cape Cod, where the disposal of increasing volumes of domestic wastes, and salt-water intrusion due to increased pumping, can degrade water quality.

The Massachusetts Department of Public Health monitors the quality of all public water supplies, and the U.S. Geological Survey analyzes the chemical quality of water supplies at military installations on the Cape. In addition, water quality on Cape Cod is under study by Dr. Karl H. Deubert of the Massachusetts Agricultural Experiment Station under grants from the Office of Water Research and Technology, U.S. Department of the Interior.

The data from these studies have not been fully evaluated. Preliminary analyses indicate that the results would provide good base-line data on water quality and would provide the basis for designing a network of water-quality monitoring stations.

GROUND-WATER SIMULATION MODELS

A base-line description and the continuous monitoring of the hydrologic system are essential to the development and management of the water resources of Cape Cod. In addition, however, the data, ideally would be analyzed and interpreted to evaluate the effects of alternative development schemes. One such analytical technique, useful to decision makers in planning, is a digital computer simulation model.

Digital computer models have been developed that simulate the ground-water system and have been used to recreate and predict changes in the system that result from man's activities. Most models used to simulate ground-water systems are solutions to some form of the differential equation of ground-water flow:

$$\frac{\partial h}{\partial t} = \frac{T}{S} \left[\frac{\partial h^2}{\partial x^2} + \frac{\partial h^2}{\partial y^2} \right] + W \qquad (1)$$

where h, hydraulic head

t, time

T, transmissivity of the aquifer

S, storage coefficient of the aquifer

x, lateral distance

y, longitudinal distance

W, flux of an external source or sink

Analytic solutions exist for differential equations describing one-dimensional radial flow and two-dimensional cross-sectional flow in an aquifer bounded on both sides by fully penetrating constant head sources. For other situations, the solution to the differential equations must be approximated.

The simulation model described here is a digital model developed to approximate the solution of equation (1). It uses the iterative alternating direction implicit procedure for solving a set of finite difference equations. It is a modification of a model developed by Pinder and Bredehoeft (1968) and similar to a model developed by Prickett and Lonnquist (1971).

To construct the model, a grid system of the area to be modeled is selected. Values of head, hydraulic conductivity, and thickness of the saturated zone are needed for every grid point. For non-steady state problems, specific yield is also needed. All boundary conditions and sources or sinks must be specified.

Input data required for construction of a simulation model of the ground-water system of Cape Cod include:

(1) a map of the initial water table (head)
(2) a description of surface boundaries of the aquifer
(3) a description of the areal variation of hydraulic conductivity
(4) a map of depth to the lower boundary (lithologic or fresh-water/salt-water interface)
(5) a description of the hydrologic stresses (components of recharge and discharge)
(6) a description of the areal variation of specific yield (for use in non-steady state modeling).

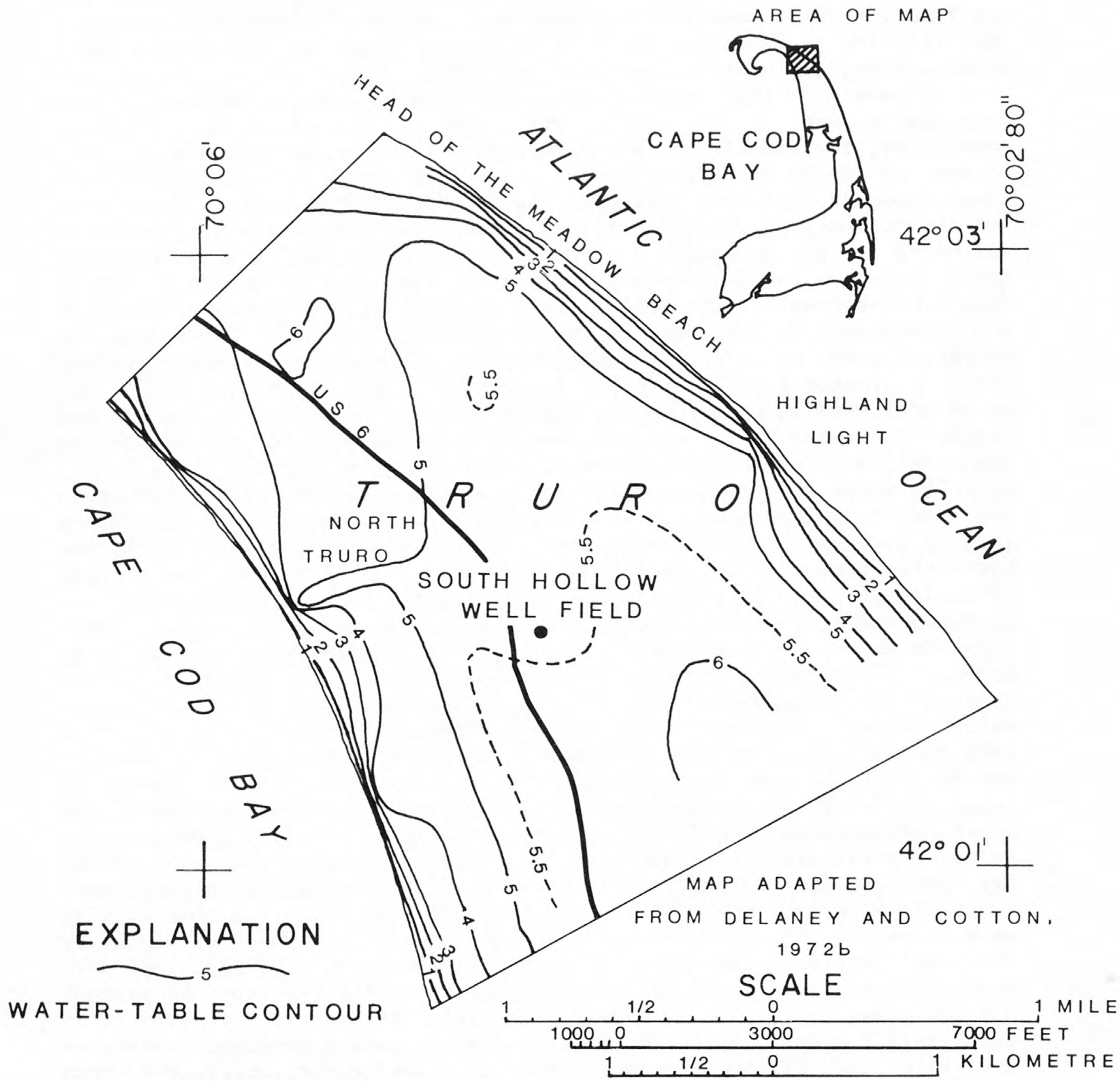
Calibration of the model consists of matching known responses to historical stresses, such as pumping. Management decisions for the future could then be based on the use of the verified model to predict effects on the system due to probable future stresses.

Existing hydrogeologic data are inadequate for the construction and verification of a model of the hydrologic system of Cape Cod. However, data relating to a small area in Truro can be used to illustrate model construction, calibration, and selected uses.

In terms of the above-listed data requirements, a reasonably good water-table map is available, and the only significant surface boundaries, the shorelines, are adequately shown on the topographic map. A map of depth to bedrock is not needed for the Truro area because the lower boundary of the system is the fresh-water/salt-water interface. For the purposes of this report, the fresh-water/salt-water interface is estimated to be at a depth equal to 40 times the altitude of the water table, based on the Ghyben-Herzberg theory. Pumping records are available from Provincetown's South Hollow well field, the only pumping center of any consequence in the area to be modeled. Data are inadequate to construct a map of hydraulic conductivity: Values of hydraulic conductivity estimated from lithologic logs range from 11 to 118 ft/d (3.4 to 36 m/d), and these values are used as guides in construction of the model. Published estimates (see page 6) of recharge that can be used in the model construction range from 12 to 18.4 in (467 mm) per year.

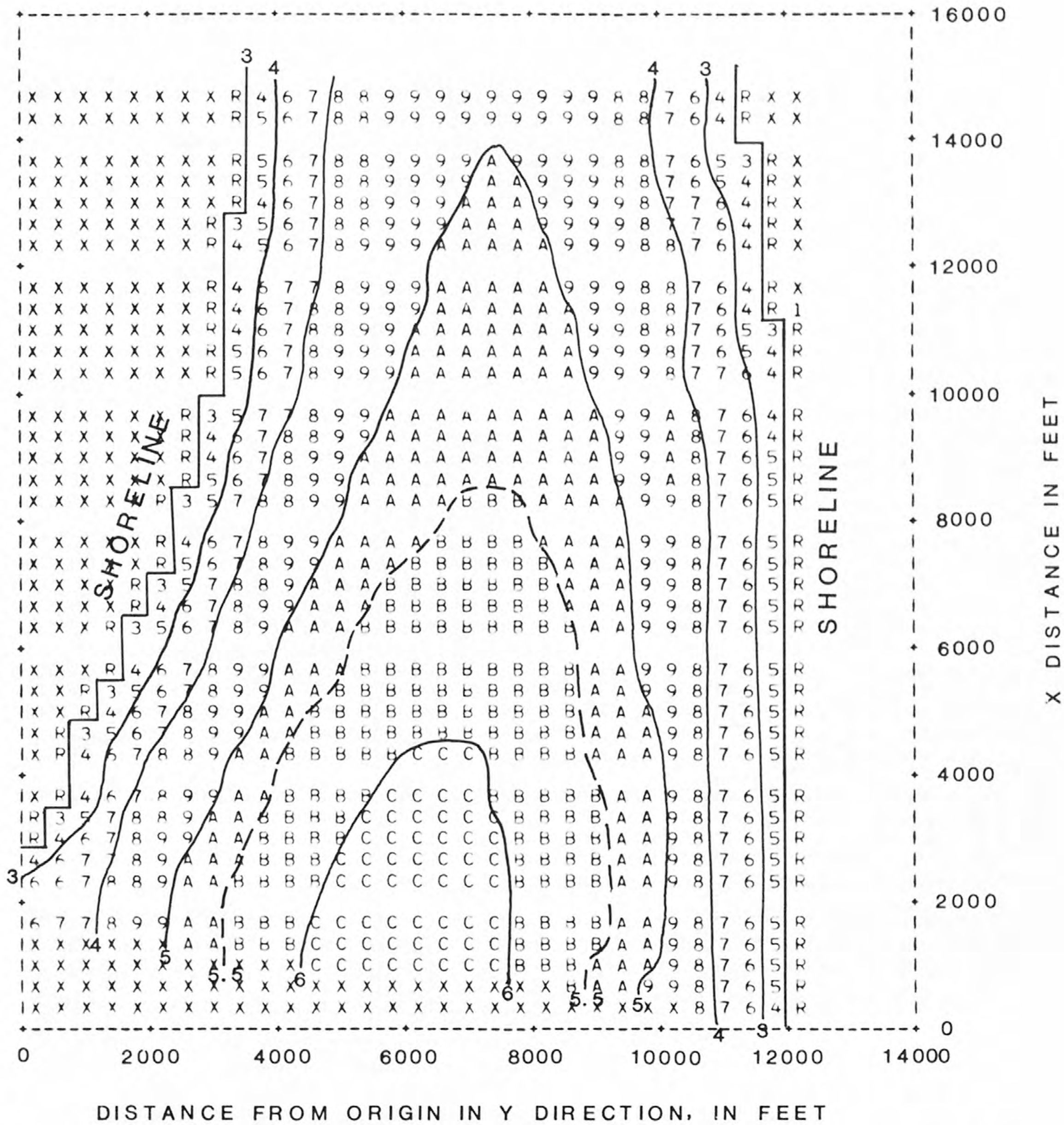
The model constructed on the basis of available data described above was used in an attempt to simulate the known water-table configuration (fig. 3). Several trials were made based on available data on recharge, hydraulic conductivity, and pumpage from South Hollow well field (fig. 3). In the first trial, uniform recharge of 18 in (457 mm) per year and uniform hydraulic conductivity of 40 ft (12.2 m) per day were input to the model, and pumpage from the well field was assumed to be zero. The water-table configuration generated by the model, based on these inputs, stood more than twice as high above sea level as the known water table. A second trial was made using uniform recharge of 18 in (457 mm) per year, uniform hydraulic conductivity of 86.4 ft (26.3 m) per day, and no pumpage; the water table simulated by the model is shown in figure 4. Although the model did not precisely duplicate the known water-table configuration (fig. 3), the results show that the values for recharge and hydraulic conductivity used in the second trial are nearly in the correct ratio. That is, if the value for recharge were halved to 9 in (229 mm) per year and the value for hydraulic conductivity were halved to 43.2 ft (13.2 m) per day, the water table simulated by the model would be the same as shown in figure 4. Other trials were made using a value of 18 in (457 mm) per year for recharge and steady pumpage from the South Hollow well field at the rate of 0.85 ft^3/s (2.41×10^{-2} m^3/s), approximately the average annual pumpage: Values of hydraulic conductivity were adjusted by trial and error until the known water-table configuration was approximated as shown in figure 5.

Although the water table simulated in the model run shown in figure 5 matches the known water table approximately, recharge, in reality, is not necessarily 18 in (457 mm) per year, nor is the value of hydraulic conductivity uniformly 86.4 ft (26.3 m) per day. However, it would appear that the relative values of recharge and hydraulic conductivity may be reasonably well approximated by use of the model. This



SHOWS ALTITUDE OF WATER TABLE.
CONTOUR INTERVAL 1 FOOT (0.30 METRE)
WITH SUPPLEMENTAL 0.5 FOOT (0.15 METRE)
CONTOUR (DASHED). DATUM IS MEAN SEA LEVEL.

FIGURE 3. -- WATER TABLE OF JUNE 5-7, 1972



LEGEND

RRRR = CONSTANT HEAD BOUNDARY

W = WELL LOCATION

XXXX = NO-FLOW BOUNDARY

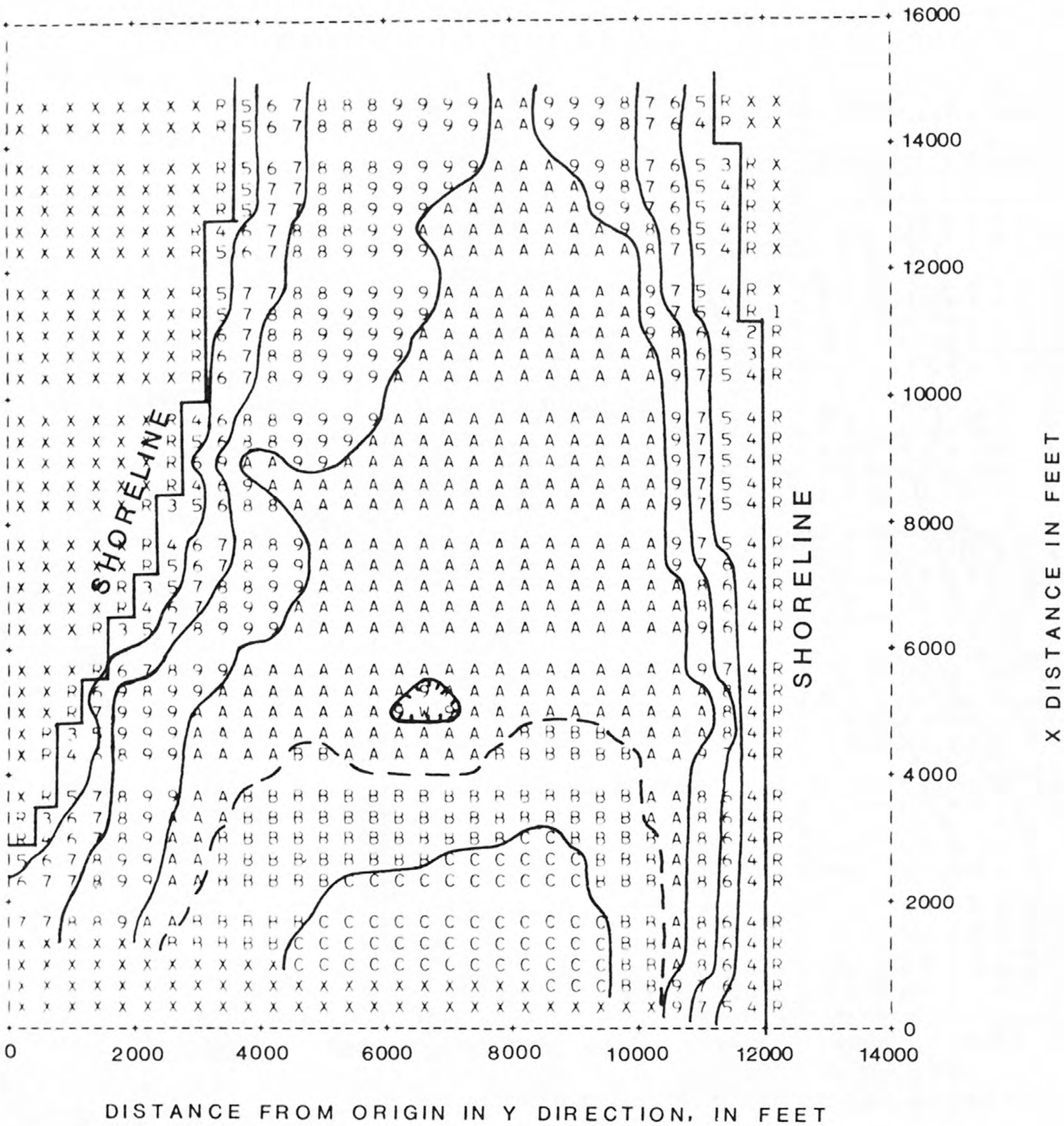
THE FOLLOWING 20 SYMBOLS ARE CYCLED: 0123456789ABC

EXPLANATION

WATER-TABLE CONTOUR

SHOWS ALTITUDE OF WATER TABLE. CONTOUR INTERVAL 1 FOOT (0.30 METRE) WITH SUPPLEMENTAL 0.5 FOOT (0.15 METRE) CONTOUR (DASHED). DATUM IS MEAN SEA LEVEL.

FIGURE 4. - SIMULATED WATER TABLE USING UNIFORM HYDRAULIC CONDUCTIVITY.



LEGEND

RRRR = CONSTANT HEAD BOUNDARY

W = WELL LOCATION

XXXX = NO-FLOW BOUNDARY

THE FOLLOWING 20 SYMBOLS ARE CYCLED: 0123456789ABC

EXPLANATION

5

WATER-TABLE CONTOUR

SHOWS ALTITUDE OF WATER TABLE. CONTOUR INTERVAL 1 FOOT (0.30 METRE) WITH SUPPLEMENTAL 0.5 FOOT (0.15 METRE) CONTOUR (DASHED). DATUM IS MEAN SEA LEVEL.

SHOWS A DEPRESSION

FIGURE 5. - SIMULATED WATER TABLE USING ESTIMATED DISTRIBUTION OF HYDRAULIC CONDUCTIVITY.

relationship, shown mathematically, is:

$$H \propto \frac{W \cdot A - P}{K \cdot A}$$

Head (H) is directly proportional to recharge (W) times the area modeled (A) minus pumpage (P) and inversely proportional to hydraulic conductivity (K) times the same area.

The model was used second in an attempt to duplicate known fluctuations of the water table. By averaging the water budgets of Strahler (1972, p. 32) and Delaney and Cotton (1972a, p. 20) and weighting the result to give a value for recharge of 18 in (457 mm) per year, estimates of monthly recharge were computed, which included a 4-month period from June through September when recharge is zero. A specific yield value of 0.20 was assumed, and the model was run to simulate water-table fluctuations for a 1-year period. The annual range of water-level fluctuations was modeled to be as much as 3 ft (0.9 m). This compares with historic water levels, which in 10 years of record have not fluctuated more than 2 ft (0.6 m) and have not fluctuated more than about 1 ft (0.3 m) in any one year. By trial and error, values for hydraulic conductivity can now be adjusted until the range of modeled fluctuations agrees more reasonably with the historical data.

By assuming a range of reasonable values for specific yield, the respective estimates of hydraulic conductivity could be computed. When any one of the three variables (recharge, hydraulic conductivity, or specific yield) is given, the other two may be calculated.

A third use of the model was an attempt to simulate the position of the fresh-water/salt-water interface. To model this interface, the data grid must be oriented vertically. Using the known density differences between fresh water and salt water, the fresh-water head within a body of static salt water, or on the interface between the static salt water and moving fresh water, is computed by:

$$h_f = \frac{\rho_s - \rho_f}{\rho_f} \cdot D_s$$

the equivalent fresh-water head of salt-water (h_f) is equal to the density difference of salt water and fresh water ($\rho s - \rho f$) times the depth below sea level at which the equivalent fresh-water head is being computed (D_s) divided by the density of fresh water (ρf)

The position of the fresh-water/salt-water interface can be computed by trial and error if the distribution of heads throughout the aquifer is known (fig. 6). Aquifer heads are initially computed for an assumed depth which exceeds the maximum possible depth of fresh water anywhere in the system. Along each horizontal line these heads are compared to the equivalent fresh-water head given by the above equation for that depth. The point at which the aquifer head equals the head given by the above equation is taken as the location of the interface at that depth.

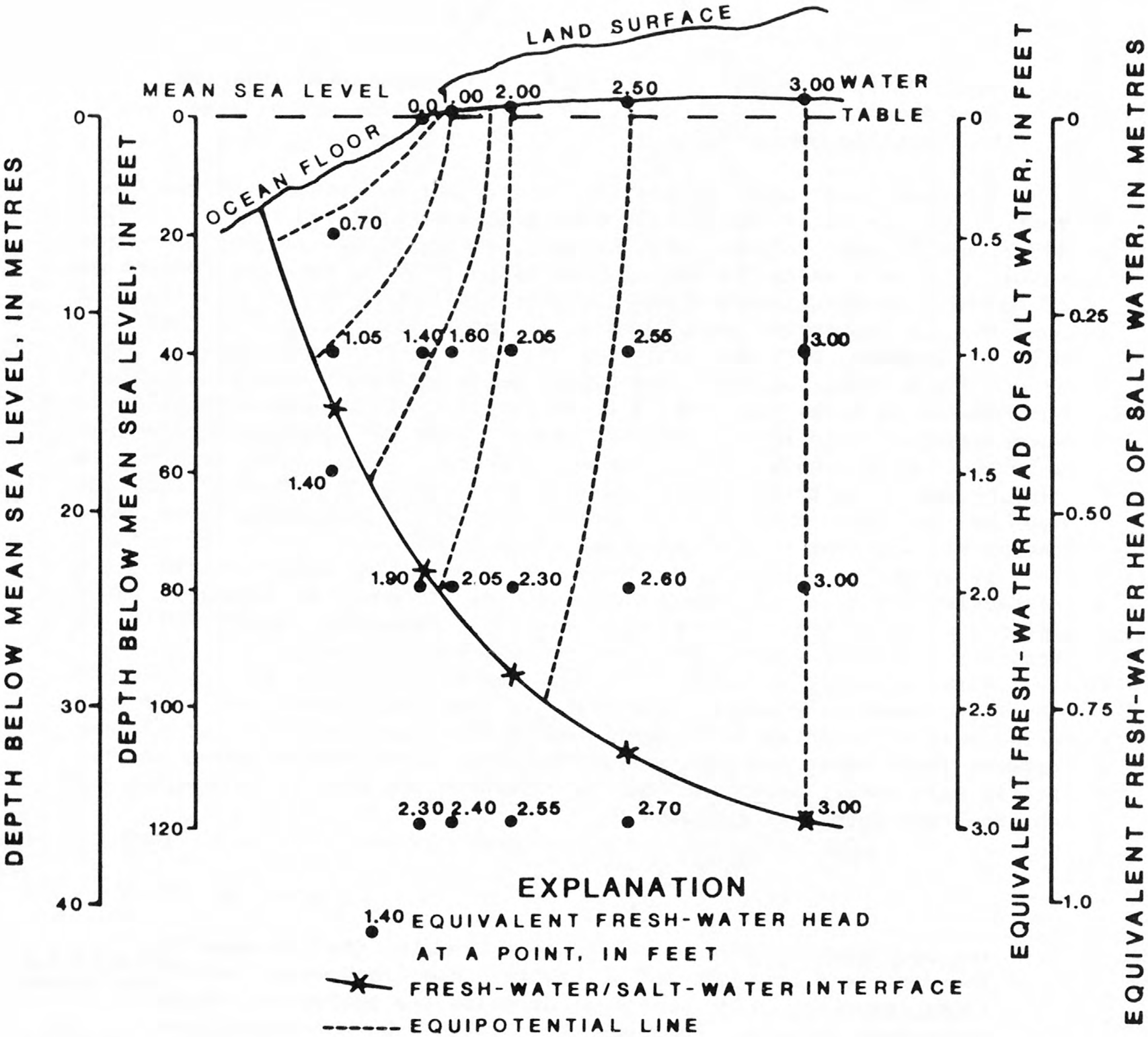


FIGURE 6. -- HYPOTHETICAL FRESH-WATER/SALT-WATER INTERFACE AND HEADS AT DEPTH.

The vertically oriented model described above can be used to describe the effects of the anisotropic distribution of hydraulic conductivity due to layering of aquifer materials. Heads at the water table are not necessarily equal to heads at the fresh-water/salt-water interface directly below, especially if the aquifer is anisotropic (fig. 6). The degree of anisotropy can have a considerable effect on the position of the fresh-water/salt-water interface. The three different positions of the interface illustrated (fig. 7) are due only to different ratios of vertical (K_v) to horizontal (K_h) hydraulic conductivity. The assumed water-table altitude was the same for each interface position. This variation of interface illustrates the dependence of interface position on anisotropy and illustrates a need to evaluate the degree of anisotropy.

CONCLUSIONS

Cape Cod depends almost entirely on ground-water resources for its water supply. Although this resource is known to be susceptible to degradation from salt-water intrusion and wastes disposed on land, data are insufficient for detecting, predicting, or evaluating changes in the ground-water quality and flow.

The ground-water simulation model described in this report is based on data relating to a small area in Truro and is designed to predict the physical effects on the ground-water system of water development and proposed management options. Although the model demonstrates the method of simulating the Cape Cod ground-water hydrologic system, it cannot be calibrated to represent specific areas accurately because (1) physical descriptions of aquifer boundaries are incomplete or must be inferred from sparse and irregularly scattered measurement sites, (2) water storage and transmissive properties of the aquifer have not been measured quantitatively, (3) the initial (present) conditions of water-table altitude are poorly defined, and (4) the few estimates of recharge rates have a large degree of error. Data collection will, therefore, constitute the major element of any future effort to improve the management of ground water on Cape Cod.

Many parameters of the Cape hydrologic system are time relative. Landward encroachment of sea water and lowering of the water table as a result of ground-water withdrawal might be expressed in feet per year, although these rates have not yet been determined on the Cape. Recharge is usually described in inches of water added to ground-water storage per year.

Owing largely to the magnitudes of these changes and the variations of precipitation from month to month and year to year, measurements over several years are more representative and more reliable for predicting future hydrologic conditions than measurements made over 1 year or less. For these reasons, a sound ground-water management program that anticipates future change on Cape Cod will require continual monitoring, refinement, and updating of these time-dependent parameters.

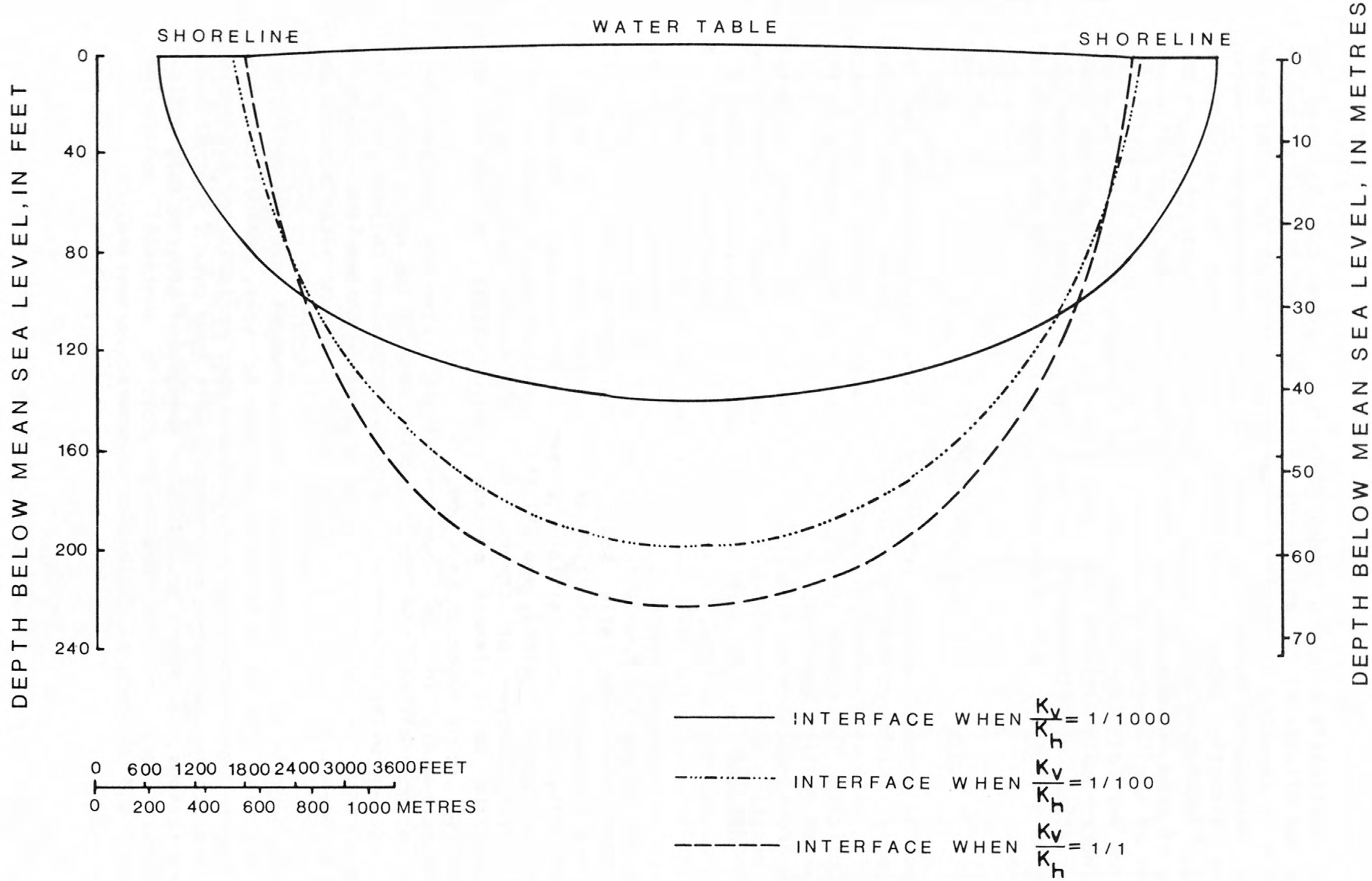


FIGURE 7.-POSITIONS OF THE FRESH-WATER/SALT-WATER INTERFACE DUE TO VARIOUS ANISOTROPIC DISTRIBUTION OF HYDRAULIC CONDUCTIVITY.

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