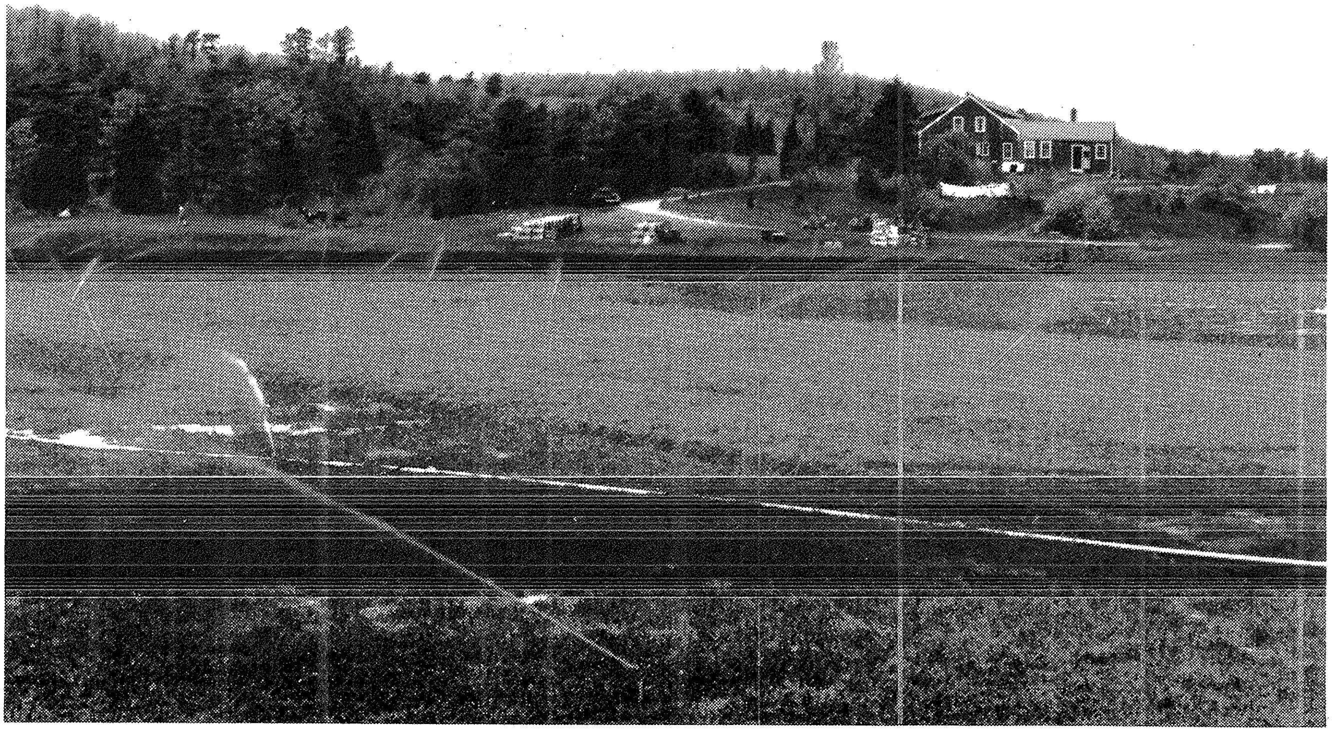
Geohydrology and Simulated Ground-Water Flow, Plymouth-Carver Aquifer, Southeastern Massachusetts

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 90-4204



Prepared in cooperation with the
MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL MANAGEMENT,
OFFICE OF WATER RESOURCES and the
TOWN OF PLYMOUTH

GEOHYDROLOGY AND SIMULATED GROUND-WATER FLOW, PLYMOUTH-CARVER AQUIFER, SOUTHEASTERN MASSACHUSETTS

By Bruce P. Hansen and Wayne W. Lapham

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CONTENTS

Page

CONTENTS (Continued)

PLATES

[Plates are located in map jacket]

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

TABLES (Continued)

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	by	To obtain
	Length	
inch (in.)	25.4	millimeter
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.09290	meter squared per day
	Volume	
gallon (gal)	3.785	liter
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
gallon per minute (gal/min)	0.06309	liter per second
inch per year (in/yr)	2.54	centimeter per year
million gallons per day (Mgal/d)	0.04381	cubic meters per second
	Area	
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

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

Chemical concentrations are given as International System Units,
in milligrams per liter (mg/L).

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

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ABSTRACT

The Plymouth-Carver aquifer underlies an area of 140 square miles and is the second largest aquifer in areal extent in Massachusetts. It is composed primarily of saturated glacial sand and gravel. The water-table and bedrock surface were mapped and used to determine saturated thickness of the aquifer, which ranged from less than 20 feet to greater than 200 feet. Ground water is present mainly under unconfined conditions, except in a few local areas such as beneath Plymouth Harbor. Recharge to the aquifer is derived almost entirely from precipitation and averages about 1.15 million gallons per day per square mile. Water discharges from the aquifer by pumping, evapotranspiration, direct evaporation from the water table, and seepage to streams, ponds wetlands, bogs, and the ocean. In 1985, water use was about 59.6 million gallons per day, of which 82 percent was used for cranberry production.

The Plymouth-Carver aquifer was simulated by a three-dimensional, finite-difference ground-water-flow model. Most model boundaries represent the natural hydrologic boundaries of the aquifer. The model simulates aquifer recharge, withdrawals by pumped wells, leakage through streambeds, and discharge to the ocean. The model was calibrated for steady-state and transient conditions. Model results were compared with measured values of hydraulic head and ground-water discharge. Results of simulations indicate that the modeled ground-water system closely simulates actual aquifer conditions.

Four hypothetical ground-water development alternatives were simulated to demonstrate the use of the model and to examine the effects on the ground-water system. Simulation of a 2-year period of no recharge and average pumping rates that occurred from 1980-85 resulted in water-level declines exceeding 5 feet throughout most of the aquifer and a decrease of 54 percent in average ground-water discharge to streams. In a second simulation, four wells in the northern part of the area were pumped at 10.4 million gallons per day in excess of rates simulated in the steady-state model for the four wells. This resulted in water-level declines of 2 feet or more in an area of 25 square miles and a decline in average ground-water discharge to streams of 6 percent. When this pumpage was simulated as recharge to the aquifer, water levels beneath the recharge area rose more than 40 feet, and ground-water discharge remained equal to average discharge in the calibrated steady-state model. In a third simulation, all 21 existing production wells were pumped at nearly the design capacity of 17.8 million gallons per day; this pumping rate produced water-level declines of less than 2 feet throughout most of the aquifer. When simulated pumpage was increased to 32.8 million gallons per day from existing wells and from 15 additional wells, the area where water-level declines exceeded 2 feet significantly increased. In another set of simulations, a well field close to a stream was pumped at rates of 2, 4, and 6 million gallons per day. At a pumping rate of 6 million gallons per day,

ground-water discharge to the stream decreased 34 percent during periods of normal precipitation and 56 percent during drought conditions.

INTRODUCTION

The Plymouth-Carver aquifer, the second largest aquifer in areal extent in Massachusetts, underlies a 140-mi^2 area in the southeastern part of the State (fig. 1). The area is bounded on the north and east by Cape Cod Bay, on the south by the Cape Cod Canal and Buzzards Bay, and on the southwest, west, and northwest by low hills that form the ground-water divides of the Sippican, Taunton, and Jones River basins. The aquifer consists of glacial outwash and recessional moraines pitted with several hundred kettle ponds. This water-table aquifer is slightly more than 200 ft thick in places and contains more than 500 billion gallons of freshwater (Williams and Tasker, 1974). On the average, about 168 Mgal of water flow through the aquifer and discharge to streams, ponds, wetlands, and to the ocean each day.

The kettle ponds are used extensively for recreational purposes. Many of these ponds, particularly in the central part of the study area, are the habitat of the red-bellied turtle, an endangered species. Two of the kettle ponds, Little South Pond and Great South Pond, are a primary source of water for the town of Plymouth.

Cranberry production in the area requires copious amounts of water for irrigation, frost protection, harvest, and cooling. In most cases, maintenance of a high water table under the cranberry bogs is necessary to limit the water requirements.

The Plymouth-Carver area is presently (1970-90) experiencing rapid population growth and a consequent increase in ground-water withdrawals. The town of Plymouth had a population of 38,835 in 1985, an increase of 109 percent over the 1970 population of 18,606 (Plymouth Town clerk, oral commun., 1986). Other towns in the study area are experiencing similar growth. Interest in developing the Plymouth-Carver aquifer as a regional water source has increased during the last decade because of a combination of hydrologic and political conditions. The city of Brockton, located about 20 miles northwest of the study area, and several other communities experiencing water shortages, are interested in withdrawing water from the aquifer. Periodic droughts have intensified this interest. In the early 1980s, the Massachusetts Water Resources Authority (MWRA), which serves as the water-supply agency for the Boston metropolitan area (formally a function of the Metropolitan District Commission), evaluated the potential use of the Plymouth-Carver aquifer in concert with six other sources of water. The Plymouth-Carver aquifer has been dropped from consideration because of cost-benefit and environmental reasons. Quantitative hydrologic information is needed before the effects of any future aquifer development can be fully evaluated.

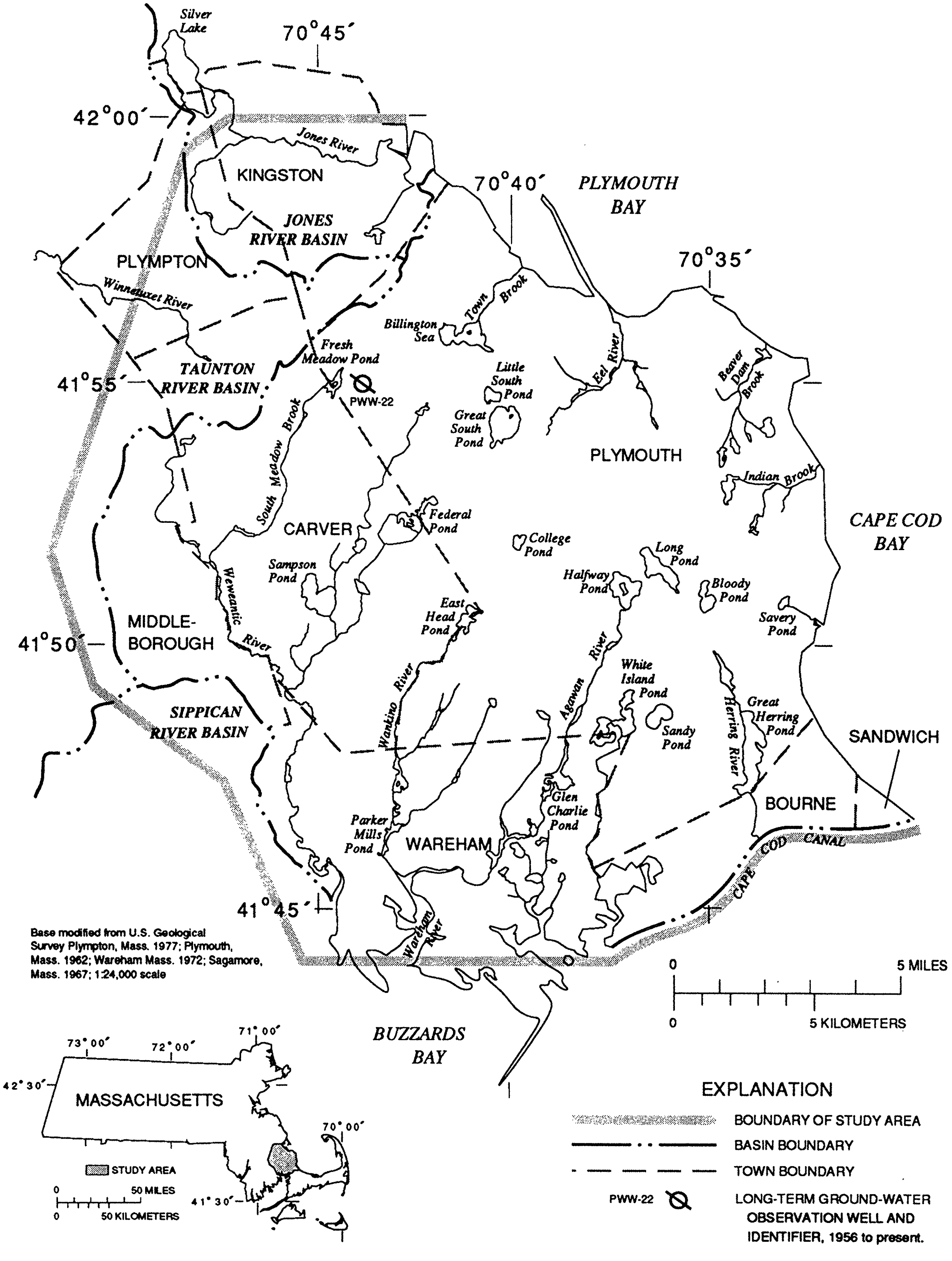
In 1982, the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Management, Office of Water Resources, and the town of Plymouth, began a study of the geohydrology of the Plymouth-Carver aquifer. This study was done under the auspices of Massachusetts Chapter 800 legislation, which provides for quantitative assessments of ground-water resources and the effects of the use of ground water on contiguous surface water in the State.

Purpose and Scope

This report presents results of a study of the geohydrology of the Plymouth-Carver aquifer. A numerical ground-water-flow model was used to simulate hydrologic response of the aquifer to stresses resulting from various hypothetical ground-water-development and wastewater-management alternatives. The description of the aquifer includes areal extent, saturated thickness, hydraulic properties, water-table configuration, direction of ground-water flow, water budget, and 1985 withdrawals. Also included is a description of the design, data input, and calibration of the numerical model and the simulated potential effects of several hypothetical ground-water-development alternatives.

Previous Investigations

The surficial geology of the Plymouth-Carver area has been described and mapped by Mather and others (1940; 1942), Mather (1952), Schafer and Hartshorn (1965), Williams and Tasker (1974), and Larson (1980). The geohydrology of the Plymouth-Carver aquifer has been described by Frimpter (1973) and Williams and Tasker (1974). The ground-water resources of the town of Plymouth have been described by IEP, Inc. (1981) and in a series of reports by Metcalf



Base modified from U.S. Geological Survey Plympton, Mass. 1977; Plymouth, Mass. 1962; Wareham Mass. 1972; Sagamore, Mass. 1967; 1:24,000 scale

Figure 1.--Location of study area underlain by the Plymouth-Carver aquifer.

and Eddy Engineering Co., Inc. (1950-87). SEA, Consultants Inc. (1983) described ground-water conditions in the town of Wareham. Ground-water, surface-water, and water-quality data collected in the Plymouth-Carver area prior to this study are summarized in Maevsky and Drake (1963) and Williams and others (1977). Unpublished data and geologic field maps compiled during this and previous studies are on file in the Massachusetts Office of the USGS (Marlborough, Mass.).

Acknowledgments

The authors thank the many private individuals and public agencies and officials who provided information and assistance during the study. The Massachusetts Department of Environmental Management, Office of Water Resources, the Massachusetts Department of Environmental Protection and the Massachusetts Water Resources Authority provided valuable information. Many consulting firms provided results of detailed geologic and hydrologic studies; these firms included Metcalf and Eddy Engineering Co., Inc.; SEA Consultants, Inc.; Whitman and Howard, Inc;, IEP, Inc;, Donald E. Reed, Consulting Geologist; Lycott Environmental Research, Inc.; Boston Survey Consultants, Inc.; C.E. Maguire, Inc.; GHR Engineering Corp.; and Geotechnical Engineers, Inc. The authors are particularly grateful to William Griffen, Paul Hannigan, John Holmes, and Jack Lenox of the town of Plymouth; Frank Mazzilli of the town of Carver; Frixon Thamilis, North Sagamore Water District; Alan Cousins and Jack Fostino, Massachusetts Department of Environmental Management; Irving DeMoranville, University of Massachusetts Cranberry Experiment Station; Marshall C. Severance, A.D. Makepeace Company; and Peter Beaton, Cranberry Growers Services, Inc.; for their continuing assistance. The Cape Cod Cranberry Growers Association and the Pilgrim Resource and Development Area Council, Inc. gave expedient support and encouragement. Finally, special appreciation is extended to the many land owners who granted the USGS permission to install and monitor observation wells and lake gages, and to conduct geophysical surveys on their property.

DESCRIPTION OF STUDY AREA

Physical Setting

The Plymouth-Carver aquifer lies within the Coastal Lowlands physiographic province of New England. Land-surface altitude ranges from sea level to higher than 250 feet above sea level on Pine Hill in the northeastern part of the study area (fig. 1). The land surface consists of flat, gently sloping sand plains pitted with kettles (depressions), and moraines with knob-and-kettle topography (many coalescing kettles with no intervening flat areas). Surface drainage is poorly developed, and extensive areas of closed drainage exist, especially in the central part of the study area. Most of the hundreds of ponds are filled kettles that intersect the water table. These kettle ponds generally have no surface-water inlets or outlets. Most streams draining the area flow either south or southwest and discharge into Buzzards Bay or the Cape Cod Canal, or flow north or northeast and discharge into Cape Cod Bay (fig. 1). The ground-water divide separating the north-draining and south-draining streams is located closer to Cape Cod Bay than to Buzzards Bay. Therefore, the south-draining streams are longer and have more gradual gradients than do the north-draining streams.

Land Use

Land use in the study area consists of woodland and brushland, agricultural land, residential land, and urban and industrial land (fig. 2). Woodland and brushland comprise 65 percent of the total area. Most of this undeveloped land is located in the central part of the study area and is sparsely populated. Agricultural land, chiefly cranberry bogs, covers 11 percent of the study area. The bogs are concentrated on the western side of the area. Residential land constitutes 19 percent of the study area, mainly along the coast and around ponds. Urban and industrial land comprise the remaining 5 percent of the study area.

Climate

The climate is characterized by warm summers and cool, wet winters. The average annual temperature is about 49.4 °F. The surrounding ocean moderates summer and winter temperatures, particularly in the

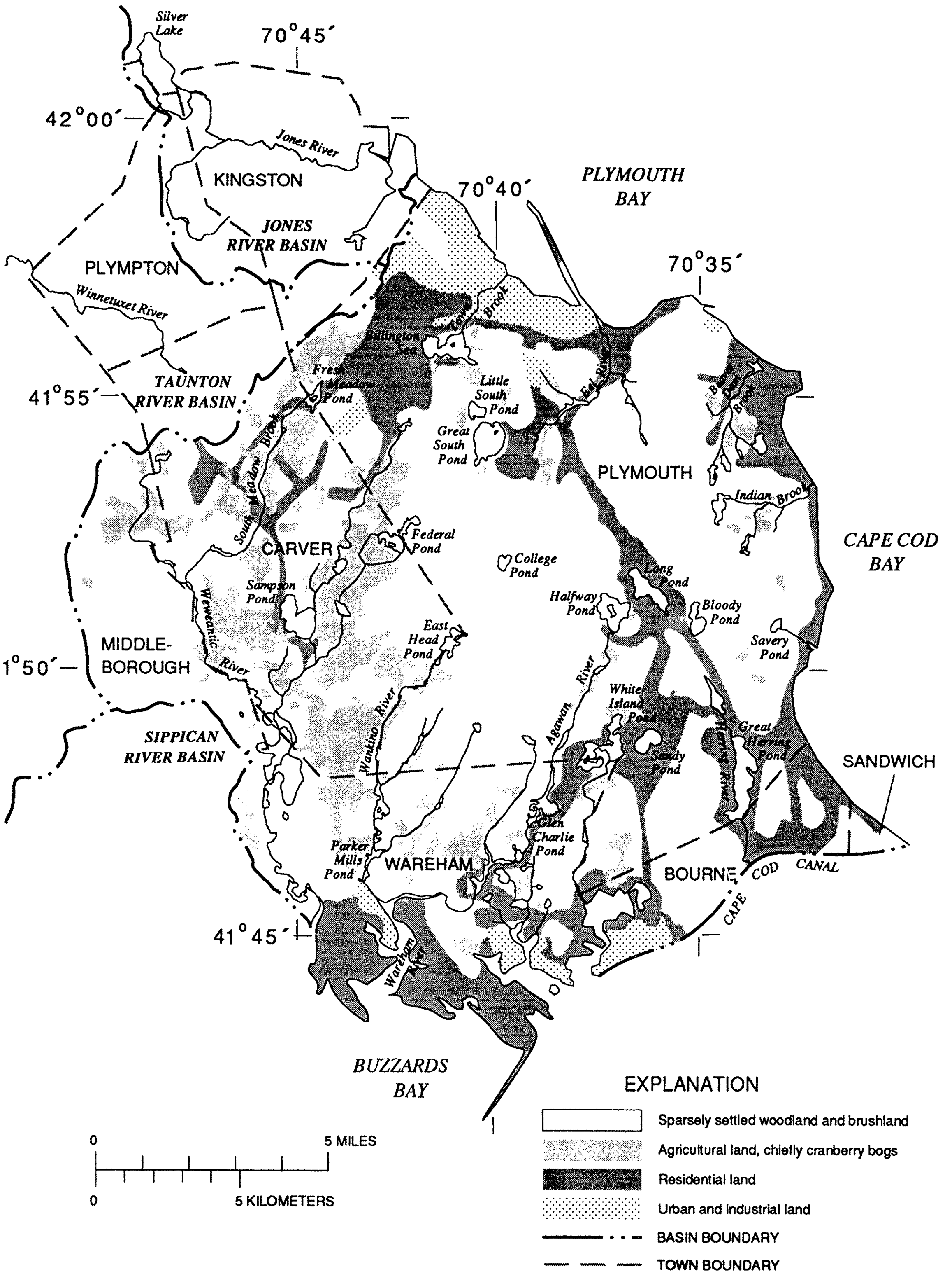


Figure 2.--Land use in study area. (Modified from Williams and Tasker, 1974.)

coastal areas. Average long-term (1951-80) annual precipitation at both East Wareham and Plymouth is 47.6 in. Precipitation averages slightly less than 3 in. during the driest months, June and July, and slightly more than 4.5 in. during the wettest months, November and December (National Oceanic and Atmospheric Administration, 1984). Free-water-surface (FWS) evaporation is approximately 28 in/yr (Farnsworth and others, 1982).

Geologic Setting

The unconsolidated surficial deposits that comprise the Plymouth-Carver aquifer were deposited in very recent geologic time. During the Pleistocene Epoch, which began about 2 million years ago, glaciers advanced from the north. Evidence indicates that at least four advances and subsequent retreats occurred. The last glacial advance reached its maximum extent about 25,000 years ago. About 15,000 years ago, this glacier began to melt and had retreated to a position

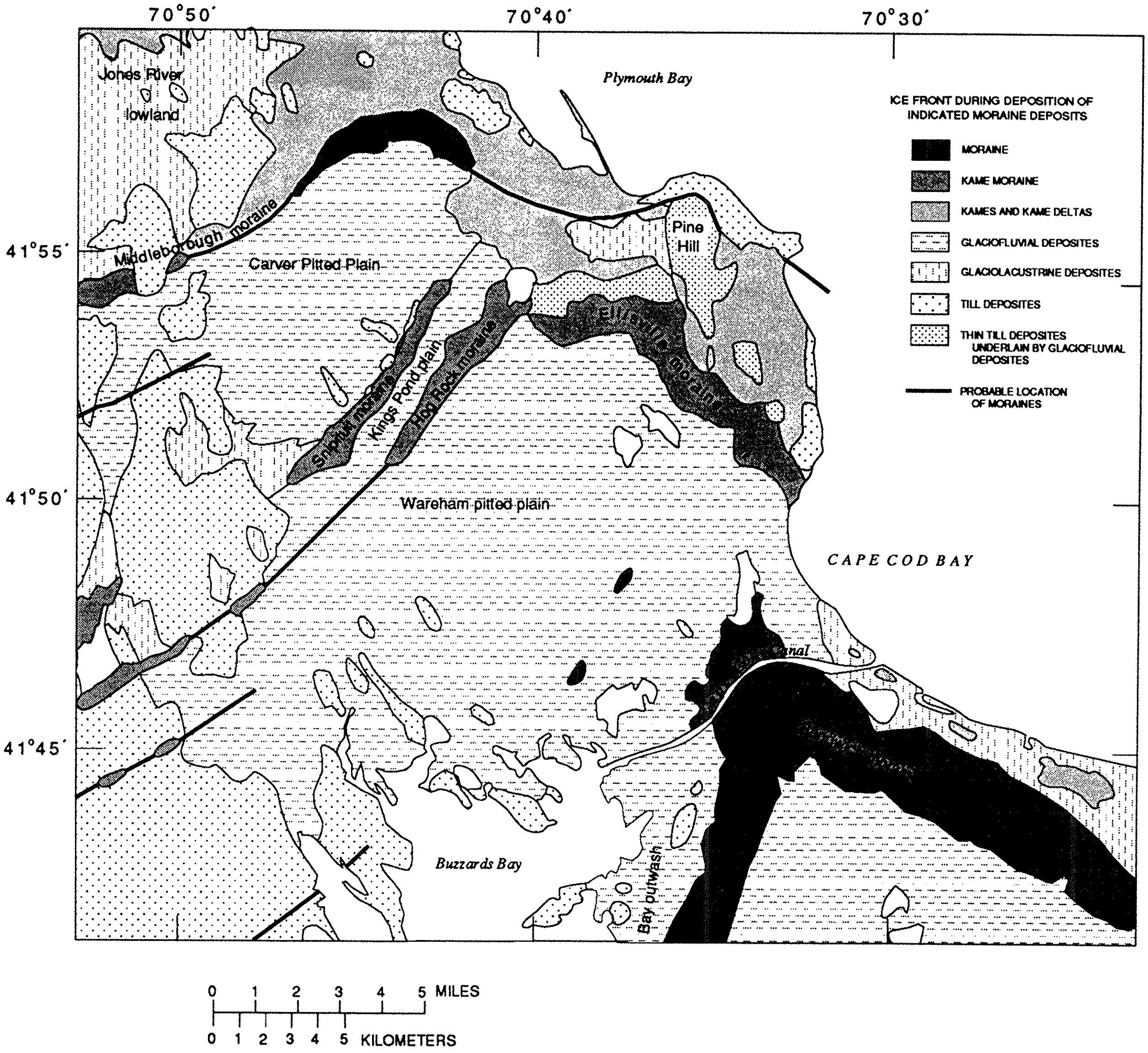


Figure 3.--Glacial deposits in Plymouth-Carver area.

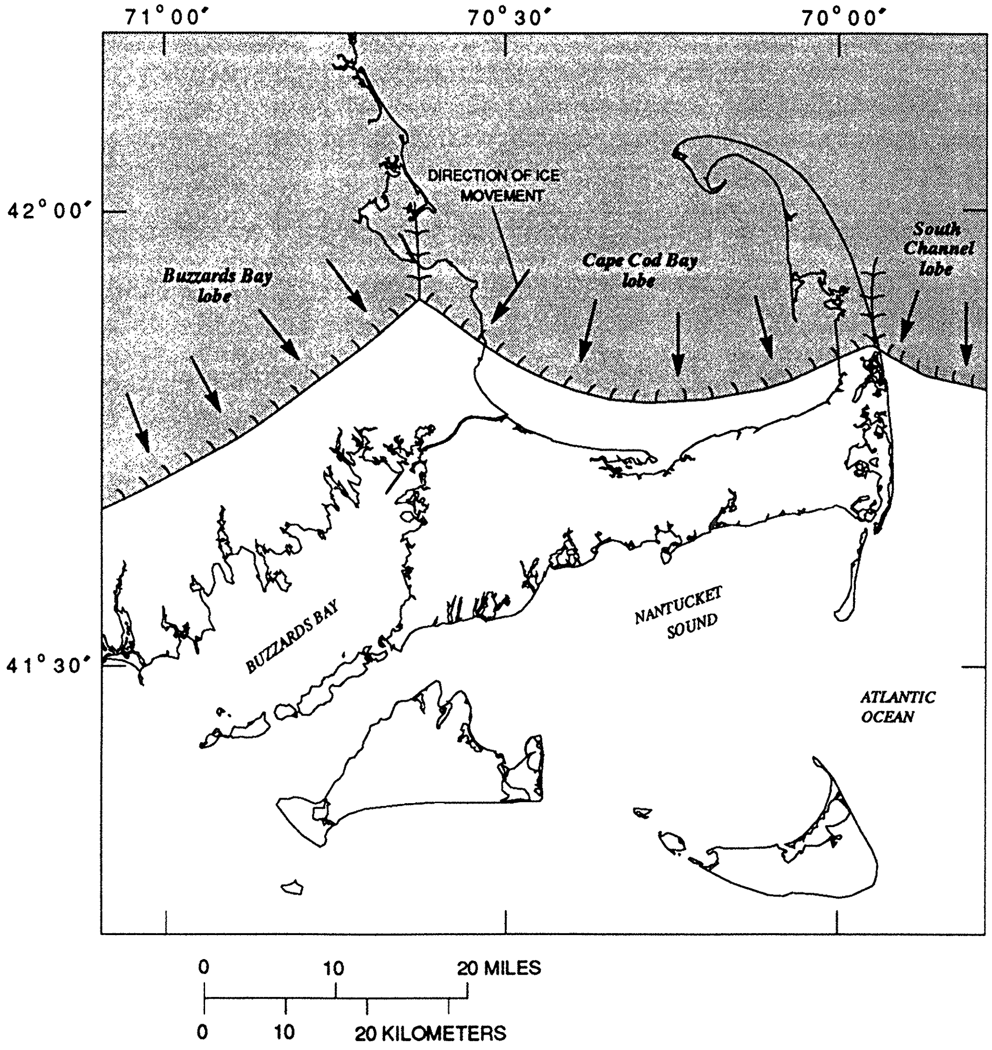


Figure 4.--Late Wisconsinan lobate glacial ice sheet in part of the study area about 14,500 years before present.

north of Boston by 14,000 years ago (Kaye and Barghoorn, 1964).

Most of the depositional and structural features shown on the surficial geology map (fig. 3) are the result of a complex series of events that occurred during the last glacial retreat. Glacial retreat from this area consisted of several major and minor retreats and readvances of two tongues or lobes of ice (Mather and others, 1940). The Buzzard Bay lobe and Cape Cod Bay lobe (fig. 4) (Woodworth and Wigglesworth, 1934) did not always retreat and advance simultaneously (Larson, 1982).

The predominant glacial features are moraines and outwash plains (fig. 3). Two southwest-trending moraines, the Hog Rock and Snipatuit moraines, mark recessional positions of the Buzzards Bay lobe. The Ellisville moraine marks a recessional position of the Cape Cod Bay lobe. The Monks Hill moraine probably was deposited at the confluence of both lobes. These morainal areas have very irregular topography consisting of hills and depressions. Records of drilling indicate that the moraines are composed mostly of stratified sand and gravel. Much of the morainal areas are covered by a thin layer of loose till composed of a poorly sorted, heterogeneous mixture of clay, silt, sand, gravel, and boulders deposited directly by and beneath the advancing ice. Geophysical logs and lithologic samples from drilling indicate that thin till layers also are present at depth.

The three outwash plains--the Wareham pitted plain, Kings Pond plain, and Carver pitted plain--slope to the south or southwest. These outwash plains are composed mostly of flat-lying to gently dipping beds of sand and gravel deposited by glacial-meltwater streams.

Kame and kame deltas north of the Ellisville moraine and along the northern coastal area are mostly stratified sand and gravel deposited by glacial meltwater atop and around stagnant blocks of ice. Subsequent melting of the ice blocks caused the very irregular, collapsed land surface.

Glaciolacustrine deposits west of Pine Hill and at the southern end of the Carver pitted plain consist of clay, silt, and fine sand layers. This material was deposited in temporary lakes that existed for short periods just after the retreat of ice from the area. At the southern end of the Carver pitted plain, outwash deposits grade into or overlie lake deposits. Much of the offshore area, and especially the northern coastal area, is underlain by fine-grained deposits that were deposited in a large glacial lake that occupied Cape Cod Bay. Other limited and unmapped areas of fine-grained deposits are present.

Compacted gray till, 1 to 3 feet thick, underlies the stratified deposits at many locations. The glacial deposits covering the area are underlain by much older granitic bedrock; the bedrock does not crop out at any location within the study area.

Mather and others (1942, p. 1153) reported that the silt content of outwash deposits generally increases with depth and distance from the source of the deposits; inspection of test-boring logs in coarse-grained outwash plains and recessional moraines indicates a fining with depth in the study area. Deposits are siltier with depth in 63 percent of the logs from outwash-plain and 55 percent of the logs from recessional-moraines. A fining of coarse grained deposits with distance from the source has not been documented in the study area. This areal trend with both depth and distance from the source is reasonable within a particular depositional environment; however, analysis of lithologic and geophysical data collected during this study indicates an overlap of several depositional environments at many locations. This overlap of depositional and erosional events probably was caused by the nonsynchronous retreat and advance of ice lobes that occurred during deglaciation of southeastern Massachusetts. Evidence for the nonsynchronous advance and retreat of ice lobes was described for Cape Cod by Mather and others (1940, 1942) and for the Plymouth-Carver area by Larson (1982). As the chronology of events that occurred during deglaciation improves, it may be possible also to improve the determination of spatial trends in grain-size distributions.

Water Use

Withdrawals of water in the study area totaled about 59.6 Mgal/d in 1985. Agricultural needs accounted for 48.8 Mgal/d, or 82 percent of the total withdrawn. Public supplies used 7.1 Mgal/d, or 12 percent. Domestic and industrial withdrawals accounted for 2.6 Mgal/d and 1.1 Mgal/d (4 and 2 percent respectively). Water is withdrawn directly from the Plymouth-Carver aquifer by pumping from wells and kettle ponds. Streams that drain the aquifer (which generally have a flow component consisting of 90 to 95 percent ground water) also are a source of water.

Agricultural Supplies

Cranberry culture is by far the largest use of water in the study area. Water needs for cranberry culture in the five major subbasins in the Plymouth-Carver area are shown in table 1. The location of the major subbasins are shown in figure 5. In 1984, the water needs for the 5,886 acres of cranberry bogs, 57 percent of

Table 1.--*Yearly cranberry-culture water needs in the Plymouth-Carver area, 1984*

[Data adapted from U.S. Department of Agriculture, 1986. Subbasin identifiers shown on figure 13. Mgal/yr, million gallons per year; Mgal/d, million gallons per day]

Subbasin identifier	Area of bog (acres)	Water need (Mgal/yr)	Average water need per acre (Mgal/yr)	Average daily water need (Mgal/d)
BB-41	1,935	5,707	2.95	15.63
BB-42	2,175	6,561	3.02	17.98
BB-43	1,209	3,777	3.12	10.35
SS-30	505	1,520	3.01	4.16
SS-31	62	225	3.63	.62
Total or average	5,886	17,790	3.02	48.74

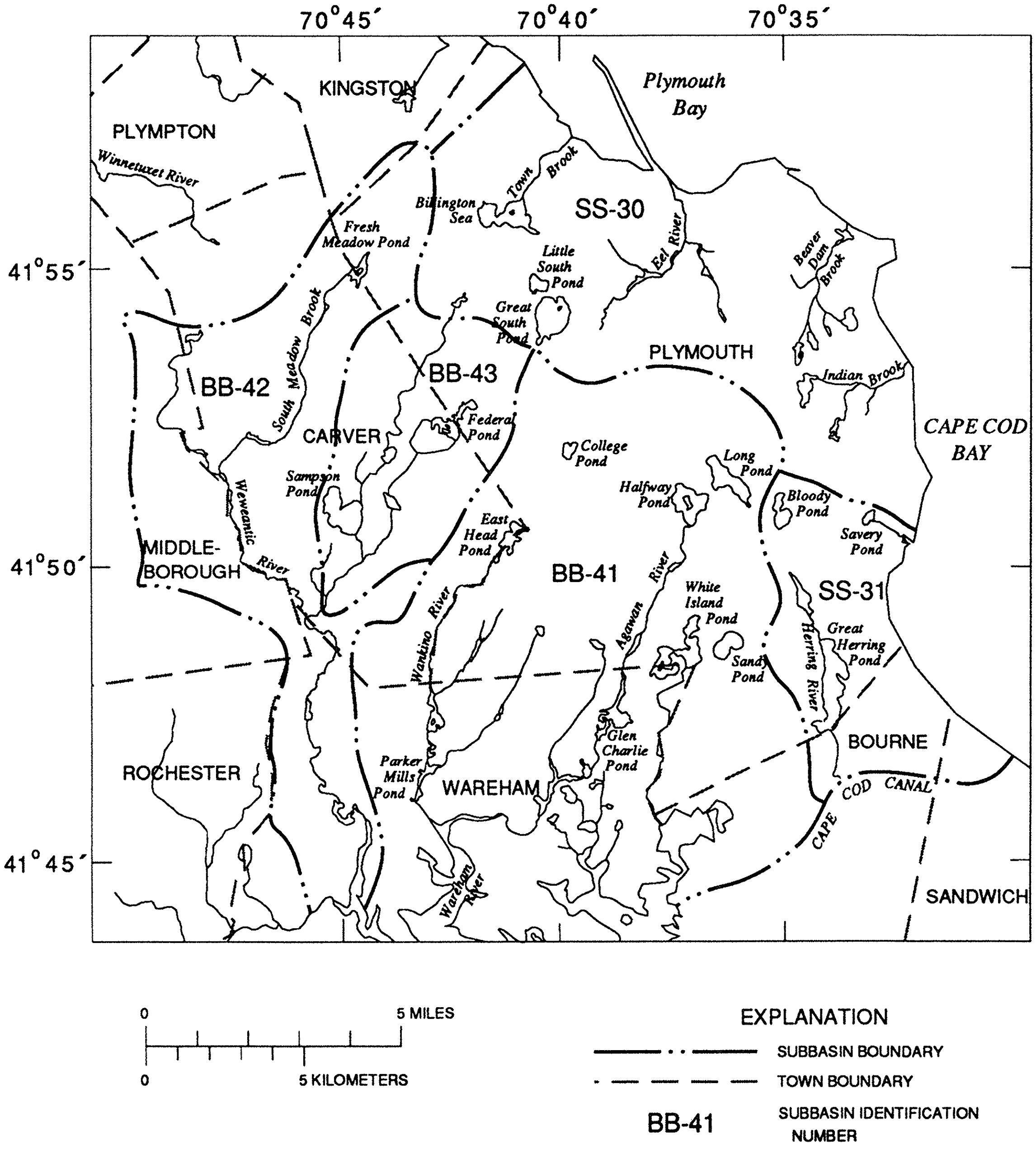


Figure 5.--Major subbasins used for tabulating cranberry-culture water needs in the Plymouth-Carver area, 1984.

which are in the Weweantic River basin (subbasins BB-42 and BB-43, fig. 13), averaged 17,789 million gallons per year (48.72 Mgal/d) (U.S. Department of Agriculture, 1986). Average yearly water need per acre of bog is 3.02 Mgal.

The U.S. Soil Conservation Service recently completed a comprehensive study of the water needs for cranberry culture in southeastern Massachusetts (U.S. Department of Agriculture, 1986, p. 7). Water needs, as defined in that study and used in this report, are "the volume of water necessary to adequately provide for cranberry raising as practiced by the average prudent grower." Water needs are based on long-term averages and fluctuate from year to year because of climatic conditions.

Large supplies of water are used nearly year round to optimize production. Water is required for frost protection of the cranberry buds and berries in the spring and fall, and for cooling during the summer. Most growers harvest by flooding the cranberry bogs and floating the berries for collection. The cranberry bogs are flooded during the winter to protect the vines from "winter kill." Flood waters may be removed, and flooding may later be repeated two or more times in most winters, depending on weather conditions. The seasonal distribution of water use is shown in table 2. The water used in a particular bog is affected by many combinations of bog physical features and water-management practices.

Most of the water used in cranberry culture is not consumed and is returned to the basin with very little loss. Nonconsumptive uses include frost protection, harvesting, and winter flooding. Some growers, or groups of growers, plan and sequence their water harvest or floods from upstream to downstream, resulting in multiple reuse of water. Water used for irrigation, frost protection, and winter floods, however, is withdrawn simultaneously with little opportunity for reuse. Water used for irrigation and cooling is mostly consumptive due to evapotranspiration.

Water for bog operation comes from streams, reservoirs, ponds, wells, and, rarely, municipal supply. Ponds or reservoirs comprise all or part of the supply for 84 percent of the bogs. Wells are the total source at only 1 percent of the bogs and a partial source at only 16 percent.

The hydrologic effects of cranberry production in the study area are to:

Table 2.--*Water-management practices and seasonal water needs for cranberry growing*

[Table adapted from U.S. Department of Agriculture, 1986. Mgal, million gallons; acre-ft, acre-foot]

		Yearly water need per acre			
		Minimum[1]		Maximum[2]	
Water-management practice	Time period	acre-ft	Mgal	acre-ft	Mgal
Frost protection	April-May	0.62	0.20	4.97	1.62
Growing season (irrigation)	June-Sept.	.83	.27	5.00	1.63
Growing season (cooling)	June-Sept.	.62	.20	0	0
Frost protection	Sept.-Oct.	.62	.20	4.97	1.62
Water harvest	Sept.-Nov.	.87	.28	4.00	1.30
Winter flood	December	2.00	.65	6.00	1.96
2nd winter flood (contingency)	Jan.-Feb	1.00	.33	2.00	.65
Total		6.56	2.13	26.94	8.78

[1] Water need for a level bog, with good water-holding characteristics, a sprinkler system, and tailwater recovery.
[2] Water need for a bog 2 feet out of level, poor water-holding characteristics, no sprinkler system, and no tailwater recovery.
[3] Tailwater-recovery indicates that water is recovered after use and pumped to a pond or reservoir where it is available for reuse.

1. Alter the streamflow regime as a result of diversion, storage, and subsequent release of water in accordance with management practices (fig. 11),
2. Decrease streamflow in an amount equal to consumptive use, and
3. Increase ground-water storage in the vicinity of impounded reservoirs and some bogs.

Public and Industrial Supplies

Ground water is the only source of water for the eight public-supply systems in Bourne, Carver, Plymouth, and Wareham. These systems withdraw water from 25 large-capacity wells, 1 well field, and 2 kettle ponds (table 3, fig. 6). The 1985 pumpage by these systems totaled 7.2 Mgal/d, which was 31 percent of the 22.9 Mgal/d combined pumping capacity of these systems. The public-supply systems provide about 72 percent of the study-area population with drinking water.

Most of the remaining 28 percent of the population obtains water from small-diameter on-site private wells. These wells generally supply single residences. This category includes a few small private water-supply systems for which withdrawal data are unavailable. Most private wells pump from the Plymouth-Carver aquifer; however, some private wells pump from bedrock, particularly in the southwestern part of the study area in Carver and Middleborough, where the aquifer is thin or absent. Three industrial water supplies (CDW-135, PWW-188, PWW-318), which account for 2 percent of the withdrawals, also are listed in table 3. These supplies obtain water from large-capacity wells developed in sand and gravel.

METHODS OF INVESTIGATION

Hydrologic-data-collection activities were designed to obtain information on the geohydrologic characteristics of the aquifer and to provide the data necessary for the design, development, and calibration of a numerical ground-water flow model of the aquifer. Data-collection efforts were concentrated in areas where data were sparse or unavailable.

Data on current and historical municipal and agricultural water-use, land-use, and recreational activities were collected and compiled. Weather records were collected and compiled to determine the effects of annual and long-term variations in precipitation on aquifer recharge. A map of the long-term average water-level altitude of the aquifer was compiled with data from 194 observation wells. Deep and shallow piezometers were installed at 15 sites to determine vertical potentiometric gradients. The land-surface altitudes at 107 wells with reference to sea level were determined by leveling. Leveled altitudes at most of the remaining observation wells were available from previous investigations. A network of 20 lake-level gages also was established and leveled. The lake-level gages and 69 wells were measured monthly from April 1984 through November 1985. Water levels at all observation wells and lake gages were simultaneously measured twice to provide "snapshots" of water levels in the aquifer. Water-level altitudes of 107 lakes and ponds were determined on November 28 and 30, 1984 using the USGS's Aerial Profiling of Terrain System (APTS), during a period when ground-water levels in the aquifer were close to their long-term average. The APTS system is described by Brown and others (1987).

The lithology and saturated thickness of the aquifer were mapped using drilling logs, geophysical logs, and seismic refraction and reflection surveys. The altitude of the bedrock surface also was mapped. All well and water-level data collected during this study were entered into the USGS's Ground-Water Site Inventory database. Sixty test holes were drilled by auger, wash-and-drive, and cable-tool drilling methods. Core and wash samples were collected, and geophysical logs of the test holes were recorded. Seismic-refraction surveys were conducted at 91 sites to provide water-level, saturated-thickness, and depth-to-bedrock information. Saturated-thickness, depth-to-bedrock, and lithologic data were obtained from seismic-reflection surveys of 18 ponds and Plymouth Harbor.

To approximate the average rate of ground-water discharge to streams, discharges of all streams draining the aquifer were measured on July 21-22, 1986, a period of near-average ground-water levels. Discharge was measured at various locations along the reach of several streams to determine gains and losses of streamflow. Average recharge to the Plymouth-Carver aquifer was estimated from water-level and pumpage data collected during this study and stream-discharge data collected during previous investigations.

Table 3.--*Major public and industrial water-supply sources*

[Mgal/d, million gallons per day; Mgal, million gallons; ---, not determined]

TOWN Water-supply system	Well number (fig. 14)	Installed pump capacity (Mgal/d)	1985 average pumpage (Mgal/d)
BOURNE			
Buzzards Bay Water District			
Head of the bay road well Sta. 1	BHW-200	0.46	0.18
Bournedale road well Sta. 2	BHW-205	.57	.16
Sta. 3[5]	BHW-305	.88	---
Sta. 4[5]	BHW-306	.60	---
North Sagamore Water District			
Well field 1	BHW- 12	.32	0
Sagamore Beach Well Well No. 1	BHW- 13	.69	.02
Black Pond Well Well No. 2	BHW-291	1.08	.18
CARVER			
Cranberry Village			
Supply well No 1	CDW-146	.26	---
Supply well No 2	CDW-147	.31	---
Oceanspray Cranberries, Inc.			
Supply Well	CDW-135	.43	[3].03
PLYMOUTH			
Plymouth Water Department			
Little and Great South Ponds		2.88	1.64
Warner Pond Well (Wannos Pond Well)	PWW- 3	1.00	.21
Lout Pond Well	PWW- 15	1.01	.03
Ship Pond Well	PWW- 58	.94	.26
Federal Furnace Well	PWW-541	.79	.37
Bradford Well	PWW-411	2.88	.93
Ellisville Well [2]	PWW-275	1.04	.36
North Plymouth Well	PWW-422	1.59	.93
White Cliff Development			
Well No. 1	PWW-317	.46	[3].06
Mayflower Seafood Company			
Supply Well	PWW-188	.22	[3].54
Oceanspray Cranberries, Inc.			
Supply Well	PWW-318	.64	[3].54
Pond Properties			
Well No. 1[6]	PWW-591	.52	---
WAREHAM			
Onset Fire District			
Sand Pond		.40	.26
Sand Pond Well[4]	WFW- 37	1.44	0
Red Brook Well No. 3	WFW- 98	.72	.15
Red Brook Well No. 4	WFW-252	.72	.08

Table 3.--*Major public and industrial water-supply sources*--Continued

TOWN **Water-supply system**	**Well number (fig. 14)**	**Installed pump capacity (Mgal/d)**	**1985 average pumpage (Mgal/d)**
WAREHAM--Continued			
Wareham Fire District			
Maple Spring Well 1S GP Well 1	WFW- 34	0.70	0.32
Maple Spring Well 2N GP Well 2	WFW- 33	.70	.13
Maple Spring Well 3NW GP Well 3	WFW- 35	.70	.10
Maple Spring Well 4W GP Well 4	WFW- 89	.70	.26
Seward Springs Well GP Well 6	WFW-323	1.08	.53
Totals		26.73	8.27

[1] Auxiliary supply.
[2] Capacity can be increased to 2.01 million gallons per day.
[3] Estimated.
[4] Emergency use only (large manganese concentrations).
[5] Put into service in 1988.
[6] Installed in 1988.

To evaluate possible future ground-water-development alternatives, a three-dimensional ground-water-flow model of the aquifer was constructed, calibrated for steady-state and transient conditions, and tested for transient conditions. Several hypothetical ground-water-development alternatives were simulated to demonstrate the use of the model.

GEOHYDROLOGY

The Plymouth-Carver aquifer is composed of unconsolidated, stratified glacial deposits that are saturated with water. The source of almost all the water in the aquifer is direct infiltration of precipitation (recharge). The aquifer is, for the most part, unconfined; however, the aquifer is confined locally. In the unconfined part of the aquifer, the water table is at atmospheric pressure and is free to rise and fall in response to changes in recharge and discharge. In the confined parts of the aquifer, the vertical movement of water is restricted by overlying deposits of low vertical and horizontal hydraulic conductivity.

Water in the aquifer moves in response to gravity from areas of high to areas of low water-table altitude. The configuration of the water table indicates the direction of ground-water flow. Ground-water flow generally is towards streams, ponds, and the ocean, where it discharges.

Aquifer Characteristics

The occurrence and movement of water in an aquifer is determined by a set of complex and interactive aquifer characteristics. These include, but are not limited to, the configuration of the water table and the bedrock surface, saturated thickness, hydraulic conductivity, specific yield, and presence of confining units.

Configuration of Water Table and Bedrock Surface

The altitude and configuration of the water table in the Plymouth-Carver aquifer for the period November 30 through December 2, 1984, ranged from near sea level along the coast to slightly more than 125 ft above sea level on the interior ground-water high that forms the divide between the study area and the Jones River basin to the north (pl. 1). During this period, water levels in the aquifer approximated their long-term average (1951-80 calendar years). The contours in plate 1 that define the altitude of the water-table map were primarily constructed by use of (1) water-level altitudes of 69 wells and 20 lakes measured from November 30 through December 2, 1984; (2) water-level altitudes of 107 ponds measured from November 30 through December 2, 1984 using the USGS's APTS; (3) concurrent water-level altitudes at 125 observation wells that were either measured intermittently from

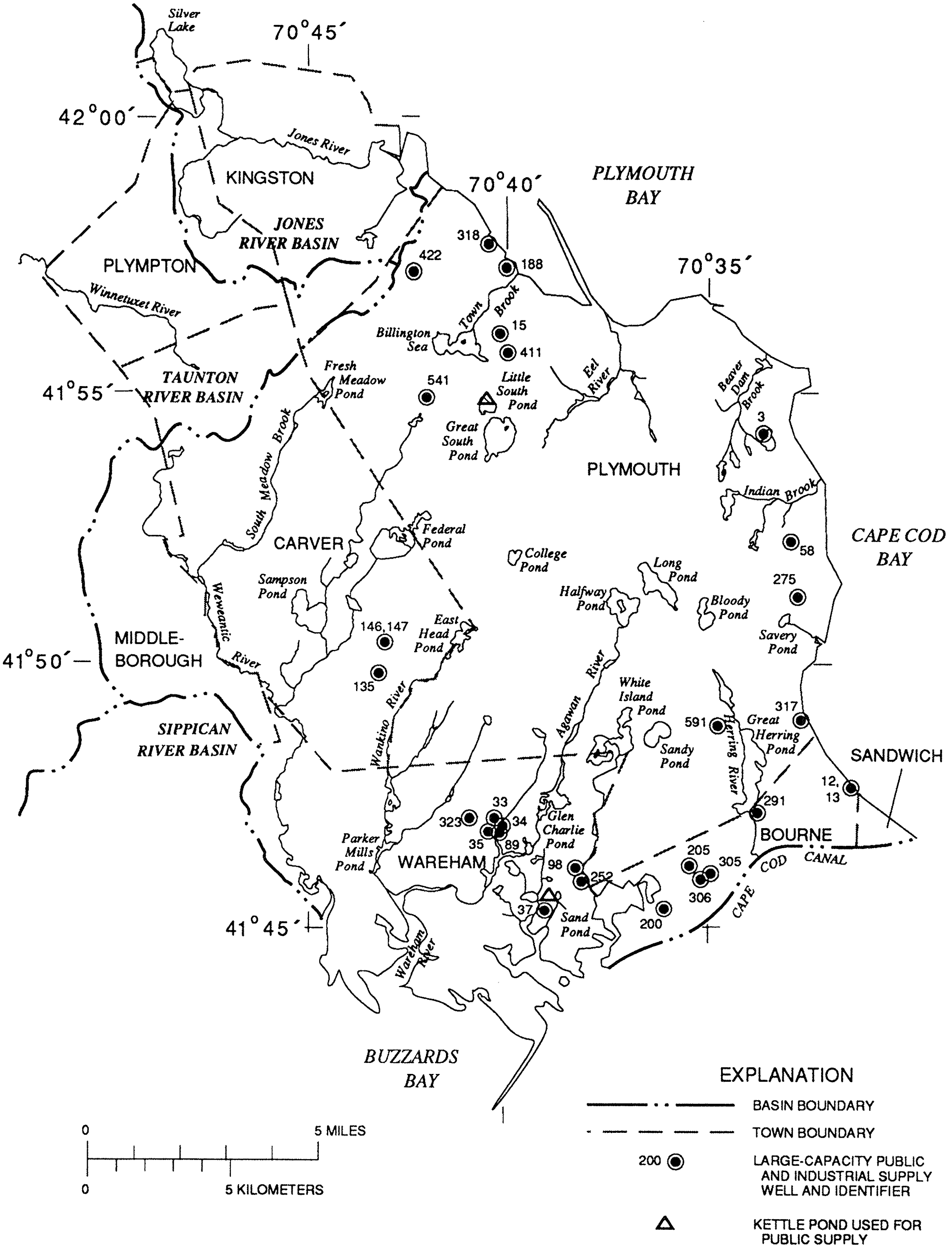


Figure 6.--Location of large-capacity, public-and industrial-supply wells and kettle ponds used for public supply.

1984 through 1986 or estimated by their relation to long-term observation well PWW-22 (fig. 1); and (4) supplemental water-surface-elevation determinations of rivers and streams from topographic maps, and a large number of water levels reported by drillers.

The altitude of the bedrock surface (pl. 2) was determined from previous studies (Williams and Tasker, 1974a and 1974b; Williams and Willey, 1973; and Williams and others, 1977), from drilling records collected, and seismic surveys and drilling conducted during this study. In general, the bedrock surface ranges from a high of about 100 ft above sea level in the southwestern corner of the study area to about 200 ft below sea level along the eastern coast. In the eastern half of the study area, the bedrock surface is bisected by a deep, narrow, southeast-trending bedrock valley. This valley probably continues eastward beneath Cape Cod Bay about 1 mi north of the Cape Cod Canal (pl. 2).

Saturated Thickness

The saturated thickness of Plymouth-Carver aquifer is the distance from the water table to the bedrock surface. The saturated thickness of the aquifer at any location can be calculated by subtracting the water-table altitude at that location from the bedrock altitude at that location by use of plates 1 and 2. The saturated thickness of the Plymouth-Carver aquifer is shown in figure 7. Saturated thickness is generally greatest in the eastern part of the study area, where bedrock altitudes are lowest. Maximum saturated thickness, slightly greater than 200 ft in some locations, is along the buried bedrock valley and its tributaries. Saturated thickness decreases to the southwest and is less than 20 ft beneath bedrock highs and till hills along the southwestern boundary of the study area.

Hydraulic Conductivity

Hydraulic conductivity is a measure of the ability of the aquifer material to transmit water. Horizontal hydraulic conductivities were estimated from aquifer thickness and transmissivity data obtained from 33 aquifer tests conducted for public and industrial supplies, and from lithologic data collected at USGS and public test-well sites. Values of horizontal hydraulic conductivity were estimated from lithologic data based on the method used by Brackley and Hansen (1977). Table 4 shows the horizontal hydraulic conductivities of various lithologic types.

Average horizontal hydraulic conductivity of stratified sand and gravel deposits, calculated from aquifer-test data, ranges from 55 to 313 ft/d ; the mean is 188 ft/d. These values are consistent with results of aquifer tests in similar deposits on nearby Cape Cod (Palmer, 1977 p. 21-45; Guswa and LeBlanc, 1985, p. 5) and the Mattapoisett River Valley (Olimpio and de Lima, 1984), a small river basin located about 8 miles southwest of the study area. Williams and Tasker (1974) found that horizontal hydraulic conductivities of outwash and moraine deposits in the study area which are composed of fine-to-coarse gravel, range from 100 to 150 ft/d; of fine-to-medium sand, from about 40 to 100 ft/d; and of fine sand containing some silt and clay, from about 10 to 40 ft/d.

Some evidence suggests that, in general, grain size and, thus, hydraulic conductivity decreases with depth in the study area. As definition of the chronology of events that occurred during deglaciation improves, it may be possible to define trends in grain-size distributions and, thus, hydraulic conductivity.

Hydraulic conductivity is commonly anisotropic (directionally variable) in glaciofluvial deposits. Anisotropic hydraulic conductivity is caused by lithologic and textural differences. In glaciofluvial deposits, these differences are commonly separated by bedding planes. The hydraulic conductivity tends to be greater in a horizontal direction than in a vertical direction because of the horizontal or near-horizontal beddings. Guswa and LeBlanc (1985) found that the ratio of horizontal-to-vertical hydraulic conductivity of coarse-grained deposits was approximately 10:1; in fine-grained deposits, it could be as large as 1,000:1.

Specific Yield

Specific yield is the ratio of the volume of water that a porous saturated medium will yield by gravity to the volume of the porous medium. Specific yields calculated on the basis of 22 aquifer tests in the unconfined aquifer ranged from 0.02 to 0.35; the mean was 0.16. These specific yields were calculated by J.R. Williams (U.S. Geological Survey, written commun., 1972) and by various engineering firms. Much smaller specific yields at several sites are indicative of semiconfined or leaky artesian conditions. These confined conditions are discussed later in the report.

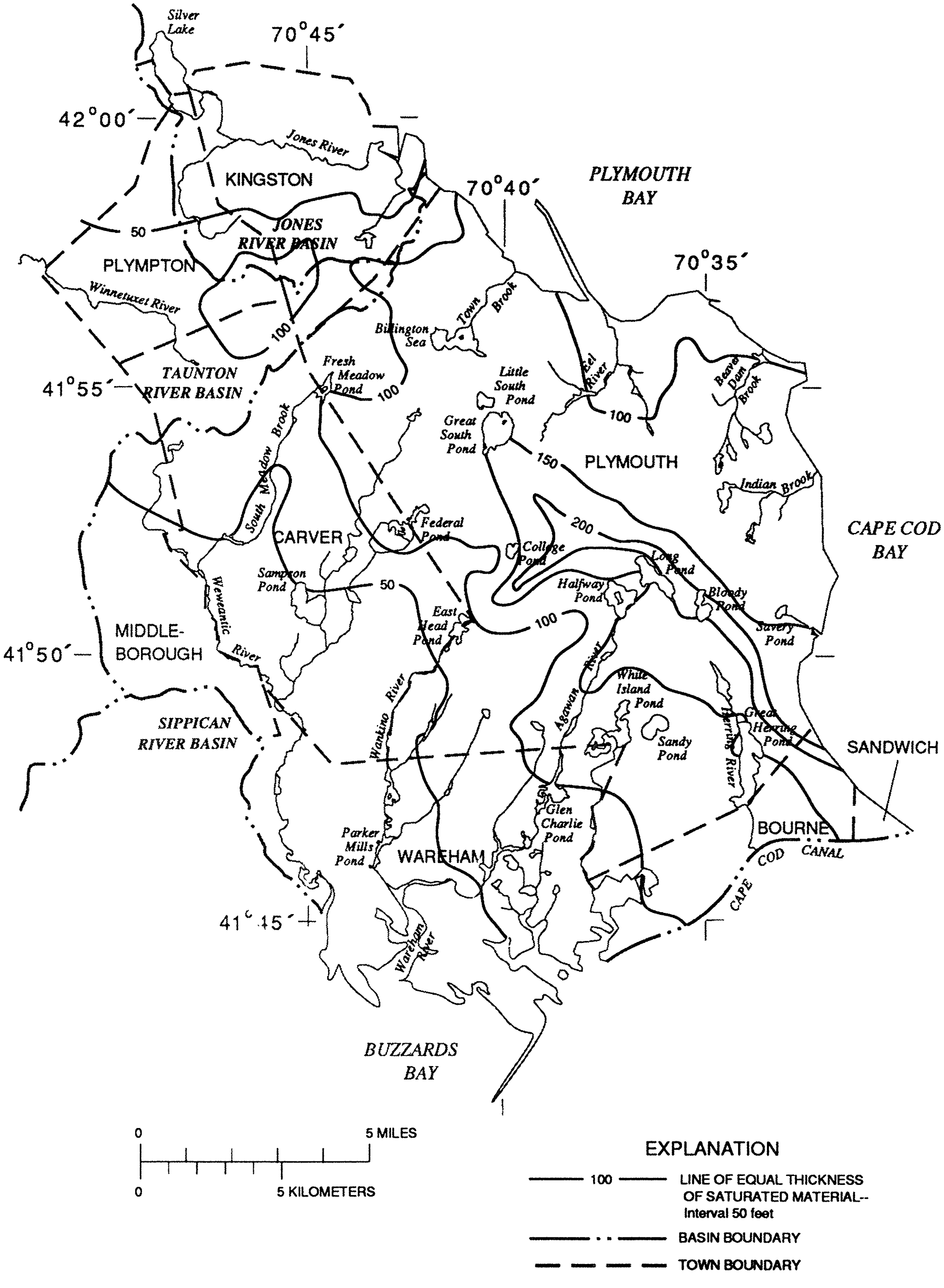


Figure 7.--Saturated thickness of the Plymouth-Carver aquifer, November 30-December 2, 1984.

Table 4.--*Horizontal hydraulic conductivities of various lithologies*

[Adapted from Brackley and Hansen, 1977. ft/d, feet per day]

Lithology	Horizontal hydraulic conductivity[1] (ft/d)
Gravel:	
Coarse	300-700
Medium	200-300
Fine	150-200
Fine to coarse	150-475
Sand and gravel	40-250
Sand:	
Coarse	90-150
Medium	40-100
Fine	20- 40
Fine to coarse	40-150
Fine to medium	40-100
Silt and clay	1- 10
Till:	
Sandy, loose	less than 100
Basal, compact	less than 10

[1] Within range shown, larger values are used when lithologic log indicates that the material is clean and well-graded and or that it yields water readily when pumped.

Confining Units

The vertical flow of water in the predominantly sand-and-gravel aquifer underlying the Plymouth-Carver area is restricted locally by layers or units of silt, clay, or till which have low vertical and horizontal conductivity. An aquifer overlain by such units is termed a confined aquifer. In the coastal area between the Eel River and Kingston, water in the Plymouth-Carver aquifer is confined locally by overlying glaciolacustrine silt, and clay and underlying bedrock (fig. 8) (Williams and Tasker, 1974). The presence and extent of the fine-grained confining units is supported by seismic-reflection and lithologic data collected during this study. The confining units in this area extend inland only to about the 20-to 25-foot land-surface topographic contour and extend seaward under Plymouth Harbor to Plymouth Beach, beyond which their extent is unknown. The confining units may be the cause of the steep water-table gradients along the north coastal area (pl. 1). Static water levels in wells completed in the confined sand and gravel are above the land surface (fig. 8). Water in the confined sand and gravel is under artesian pressure; artesian conditions also are responsible for the many springs in coastal areas, notably along the lower reaches of Town Brook.

The Manomet area of Plymouth is underlain by a thick sequence of very fine sand, silt, and clay capped by a thin unit of sand and gravel; the area includes two areas of water-table highs (pl. 1). This thick deposit probably resulted from a minor glacial readvance that "bulldozed" some of the lacustrine material from the previous retreat into a mound. Subsequent meltwater runoff deposited the sand-and-gravel cap. Hydraulic conditions at depth in this area are unknown; however, data from nearby wells indicate that this area is underlain at depth by aquifer material.

Recent drilling at the northern end of Pine Hills (Metcalf and Eddy Engineering Co., Inc., 1986) has identified a confining unit of relatively low vertical and horizontal hydraulic conductivity that probably was deposited in a small, ice-contact glacial lake. This low-hydraulic-conductivity unit underlies a perched water table of limited extent (pl. 1). One test well (Well W573) in this area penetrated unsaturated deposits beneath the confining unit (fig. 9). Water levels above and below the confining unit differ in wells screened at various intervals in this area.

Another area where confining units of silt and clay are present is north and northeast of Church Lane near the Sagamore traffic circle in Bourne (pl. 1). These materials were deposited in a glacial lake and subsequently covered by deltaic sand and gravel. Water levels in observation wells indicate that the water table above and below the confining unit is seasonally perched in this area. The levels of several ponds, including Long Swamp (pl. 1) are above the regional water table, probably because they are underlain by the confining unit.

Till layers, interbedded with sand and gravel, are present at some locations in the Plymouth-Carver aquifer. Based on lithologic and geophysical logs, these layers seem to be more numerous and composed of material with lower hydraulic conductivity in the area north of the Ellisville Moraine and west of the Pine Hills (fig. 3) than in the rest of the study area. These confining units restrict the vertical movement of ground water, especially when the ground-water system is stressed, as during large withdrawals. For

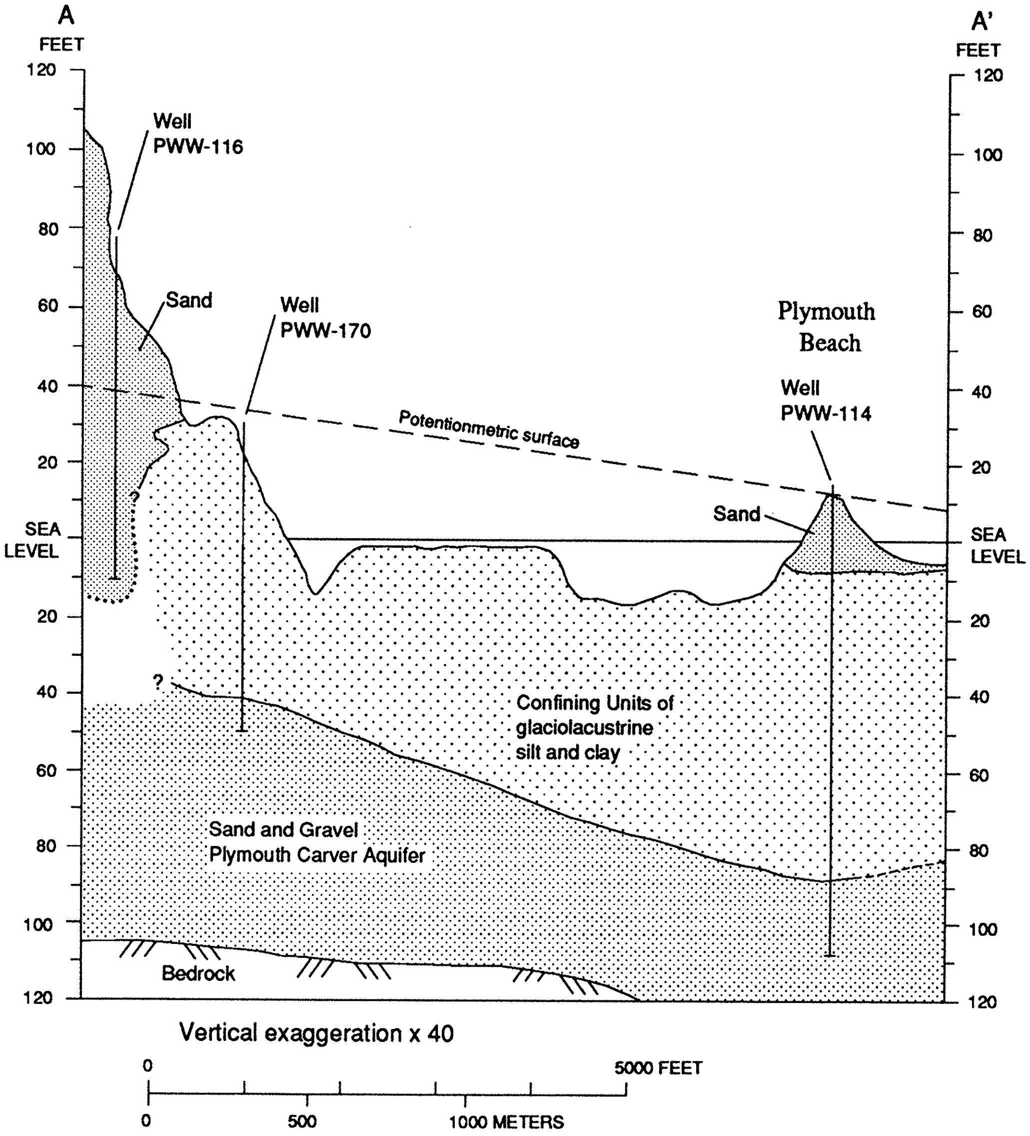


Figure 8.--Confining conditions under Plymouth Harbor.

example, figure 10 shows water-level declines in observation wells screened in sand deposits above and below a till deposit as a result of pumping a nearby large-capacity public-supply well screened below the till. Water-level declines in the shallow observation well screened above the till layer are much smaller than those in the deep observation well screened below the till deposit, indicating that the till is restricting the vertical flow of water in the aquifer at that location. Other localized confining layers probably occur in the aquifer and may have a noticeable effect on the ground-water-flow system, especially under stress conditions.

Occurrence and Flow of Ground Water

The amount of water in storage in the Plymouth-Carver aquifer fluctuates seasonally and over the long term, as illustrated by the hydrograph of Plymouth well PWW-22 (fig. 11). Well PWW-22 is a 42-foot-deep well screened in glacial outwash and located just north of the Plymouth Municipal Airport (fig. 1 and pl. 1). When PWW-22 is at its long-term average water level of 24.28 ft below land surface, it is assumed that water levels throughout the rest of the aquifer are also at their long-term average levels. Aquifer

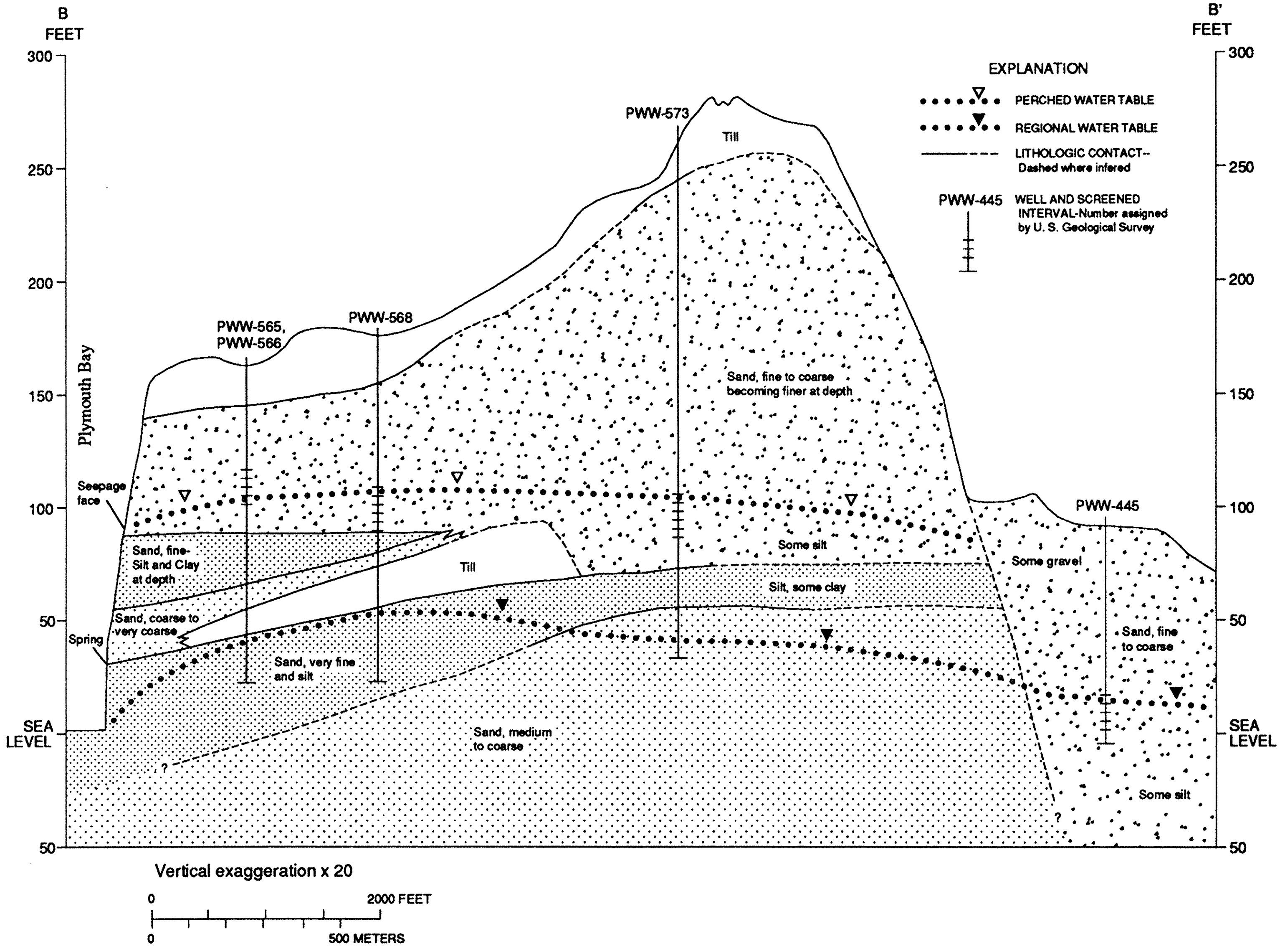
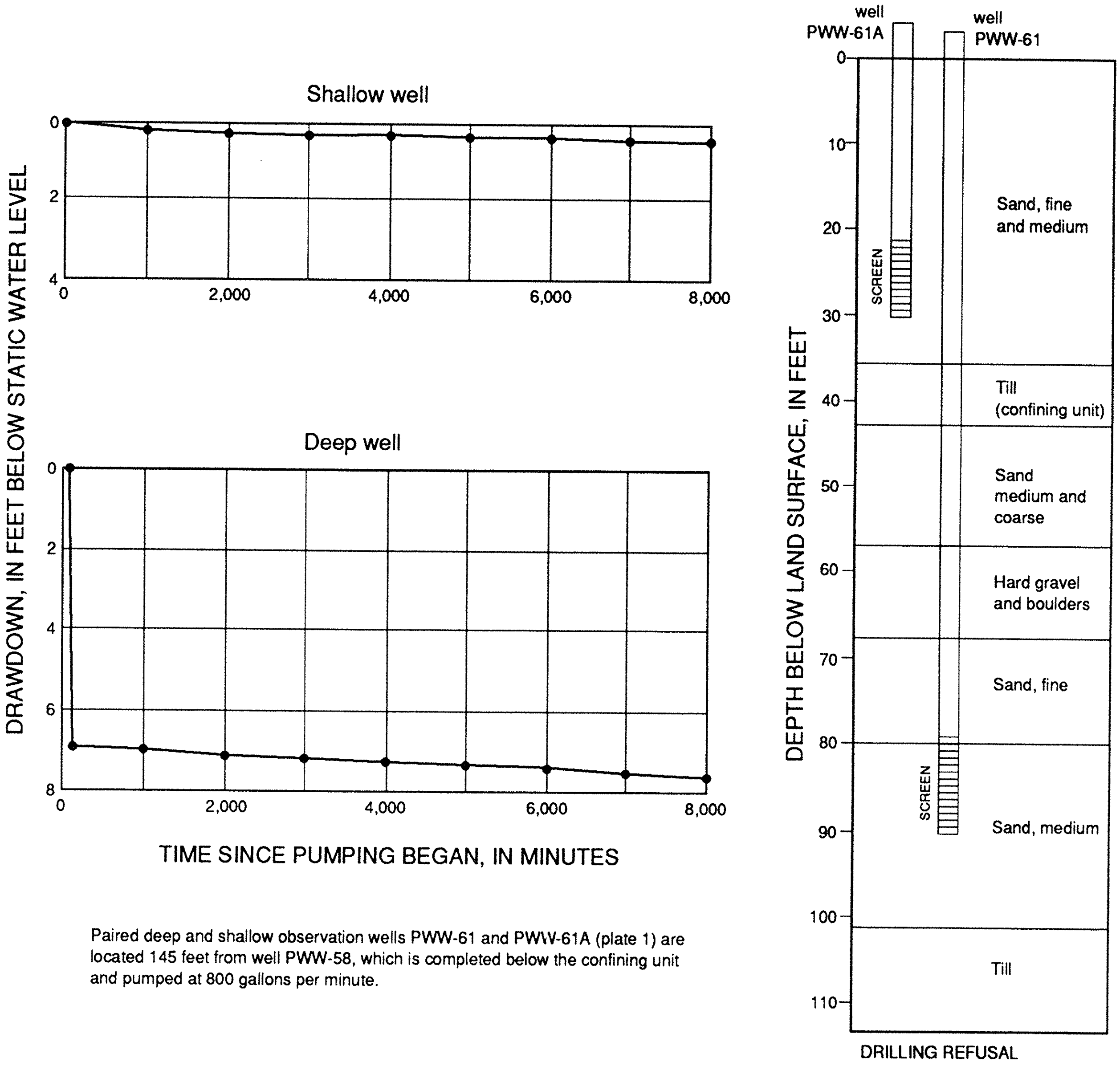


Figure 9.---Lithology and perched water-table conditions at Pine Hills.



Paired deep and shallow observation wells PWW-61 and PWW-61A (plate 1) are located 145 feet from well PWW-58, which is completed below the confining unit and pumped at 800 gallons per minute.

Figure 10.--Drawdown in observation wells screened above and below a confining unit and lithologic log of well site.

storage is usually greatest in late winter and early spring when recharge exceeds discharge. Increased rates of evapotransporation and slightly reduced rates of precipitation during the growing season decrease net recharge and aquifer storage. During late fall and early winter, when precipitation increases and evapotransporation decreases, recharge is equal to or slightly greater than discharge.

Two periods of abnormally low water levels are shown on the hydrograph of well PWW-22. Minor precipitation deficiencies measured at the Plymouth airport weather station in 1961-63 (National Oceanic and Atmospheric Administration, 1961-82), combined with major deficiencies of 10.5 and 22 inches in 1964 and 1965, respectively, caused a major depletion of ground-water storage during 1964-65. The period of low water levels during 1980-81 was caused by a major precipitation deficiency of 11 inches in 1980. Water levels, and hence storage, did not recover until a period of above normal precipitation and subsequent recharge in late 1981 and early 1982.

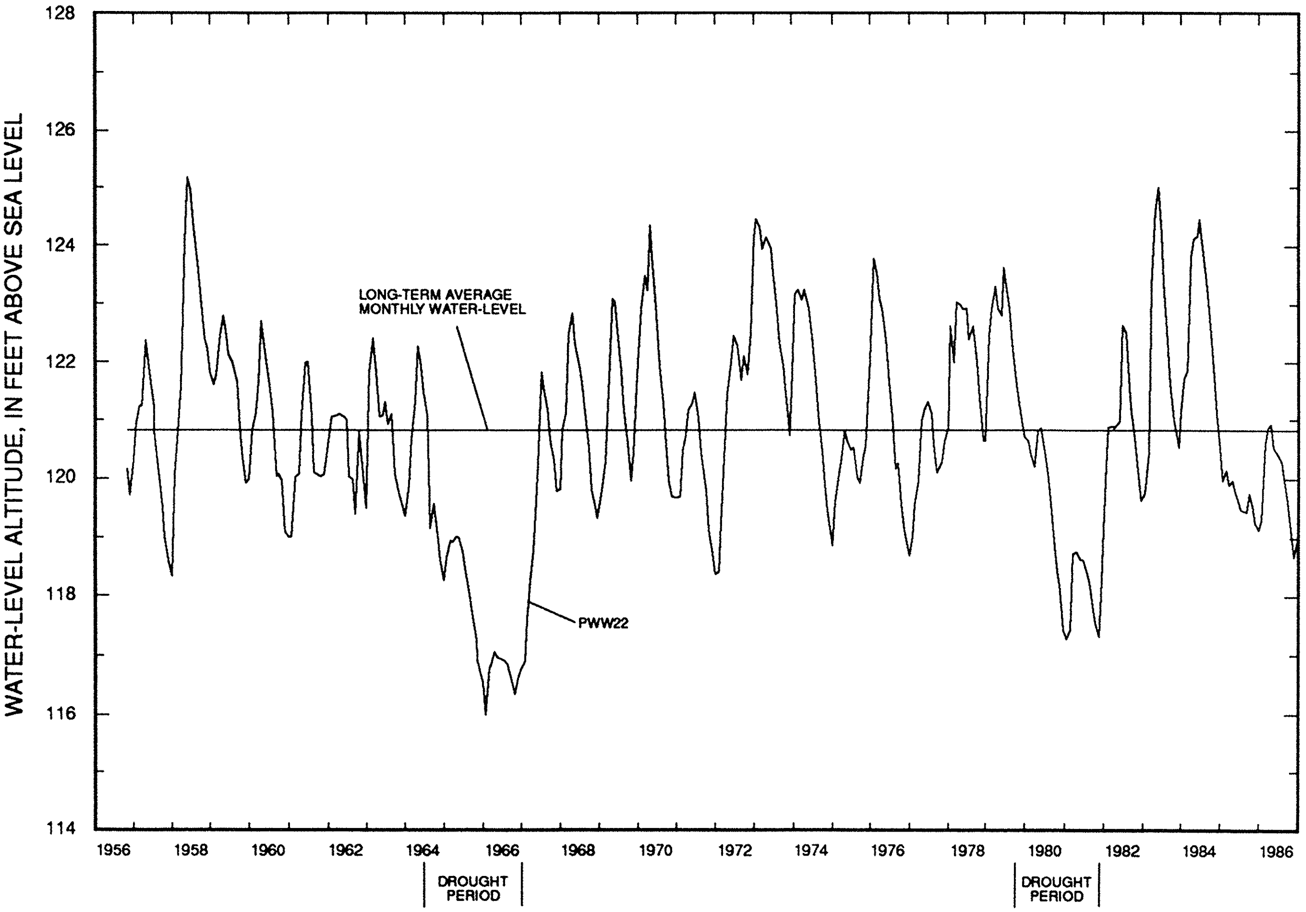


Figure 11.--Water-level fluctuations in observation well PWW-22, 1956-86.

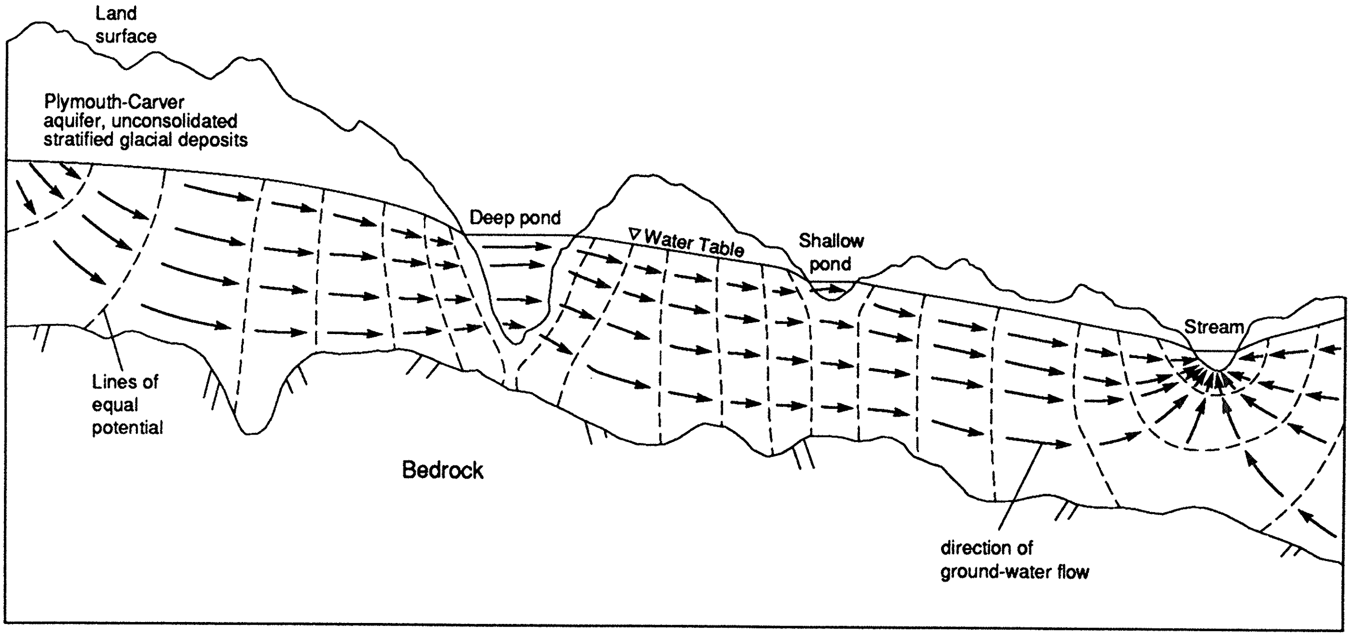
Direction of Flow

The general direction of ground-water flow in the Plymouth-Carver aquifer can be determined from the configuration of the water table. As indicated by the arrows on the water-table-altitude map (pl. 1), the primary flow pattern radiates from the ground-water highs, which underlie the upland area in the north-central and central part of the study area, toward points of ground-water discharge. Many localized ground-water highs also are present, two examples of which are in the Pine Hills and Manomet areas of Plymouth (pl. 1). Streams greatly affect the configuration of the water table. The water table slopes toward and wraps around streams that drain the aquifer.

Of note is the pronounced distortion of this generalized flow pattern caused by large, deep ponds, such as Long Pond. These ponds act as zones of high hydraulic conductivity within the aquifer. Ground-water discharges into the ponds at their upgradient ends and re-enters the aquifer at their downgradient ends. This flow pattern also occurs at the many small ponds and reservoirs in the study area but on a correspondingly smaller scale.

Plate 1 shows only the horizontal direction of ground-water flow in the Plymouth-Carver aquifer. However, actual flow in the aquifer is three-dimensional, as shown by the idealized diagram in figure 12. Flow is not only horizontal but also downward in recharge areas (water-table highs) and upward in discharge areas, such as streams, ponds, and the ocean.

Water-table gradients in the study area range from about 5 to 75 ft/mi. In general, water-table gradients are gradual on water-table highs and steeper near discharge points. Gradients tend to be more gradual in areas underlain by very conductive material than in areas underlain by slightly conductive material. A good example of the relation between gradient and conductivity is the steep gradient in the Manomet



NOT TO SCALE

Figure 12.--Idealized ground-water flow in the Plymouth-Carver aquifer.

section of Plymouth, which is underlain by a fairly extensive area of silt and clay. In comparison, the gradient is relatively flat in the Pine Hills area, which is underlain by coarse sand and gravel. Confining conditions cause noticeably steeper gradients along the northeast coast (pl. 1).

Recharge

Recharge to the Plymouth-Carver aquifer is primarily from infiltrating precipitation on the stratified glacial deposits and, to a small extent, from infiltration of precipitation runoff from adjacent till deposits in upland areas and recharge from kettle ponds. Knowledge of the rate at which water is added (recharged) to the aquifer on a yearly basis is necessary for any accurate simulation of the aquifer.

The rate of recharge to the stratified deposits can be determined by assuming that average ground-water recharge results in average ground-water discharge. Stream base flow during periods of average ground-water storage can be used to estimate recharge. To determine the average rate of recharge, the method of Rasmussen and Andreasen (1959) was used to estimate recharge on the basis of base flow, to one area that is typical of the entire aquifer.

The Eel River basin, which is underlain entirely by stratified glacial deposits, is in the north-central part of the study area. Like most of the study area, it has undulating topography and large areas with closed surface drainage. The very permeable soils in the basin allow rapid infiltration of precipitation and very little surface runoff. Therefore, almost all flow in the Eel River is ground-water discharge. The ground-water drainage divide of this basin was delineated on the basis of the water-table contours and is shown on plate 1.

The effective ground-water discharge is the amount of ground water leaving the basin as streamflow. Continuous discharge records from December 1969 to September 1971 and several instantaneous discharge measurements from other periods indicate that the effective ground-water discharge in the Ell River basin, when average ground-water-storage conditions occurred, ranged from 19 to 23.2 ft^3/s, and averaged 22.2 ft^3/s. Total ground-water discharge was approximately 24.2 ft^3/s; this was determined by adjusting the effective discharge to account for natural and human induced reductions to flow in the basin. These reductions include the evapotranspiration and pumpage listed in table 5.

The average rate of recharge to stratified deposits from precipitation is approximately 1.78 $(ft^3/s)/mi^2$, (or 24.18 inches per year) and was determined by the following calculations:

Recharge to Stratified Deposits=

$$\frac{\text{Total ground–water discharge (cubic feet per second)}}{\text{Area of deposits receiving recharge (square miles)}} \qquad (1)$$

where

Total ground-water discharge=

+22.18	(average of measured stream discharge)
+.43	(evapotransporation from drained ponds)
+.05	(evapotransporation from wetlands)
+.14	(evapotransporation from bogs)
+2.83	(pumped and diverted ground-water)
1.37	(recharge from kettle ponds) (precipitation minus evaporation)

= 24.26 ft^3/s

Area of stratified deposits receiving recharge=

+15.1	(total area)
- .21	(area of drained ponds)
- .11	(area of wetlands)
-.21	(area of bogs)
- .95	(area of kettle ponds)

13.62 mi^2

$$\text{Recharge to Stratified Deposits}= \frac{24.26\ ft^3/s}{13.62\ mi^2} \qquad (2)$$

$=1.78\ (ft3/s)/mi^2$
$=1.15\ (Mgal/d)/mi^2$
$=24.18$ in/yr

Recharge from kettle ponds and their area was subtracted from the preceding calculations because recharge to the stratified deposits from these ponds can be estimated as precipitation minus free-water-surface evaporation.

Table 5.--*Characteristics of the Eel River basin*

[ET represents evapotranspiration, $(ft^3/s)/mi^2$, cubic feet per second per square mile; ft^3/s, cubic feet per second; mi^2, square miles]

Basin characteristic	**Area (mi^2)**	**Rate of ET ($(ft^3/s)/mi^2$)**	**Total ET or diversion ($(ft^3/s)^2$)**	**Rate of recharge ($(ft3/s)/mi^2$)**	**Total recharge (ft^3/s)**
Total basin	15.1				
Kettle ponds[1]	.95	[3]2.06	1.96	[4]1.44	1.37
Drained ponds[2]	.21	[3]2.06	.43	[5]0	0
Swamps	.11	[6].45	.05	[5]0	0
Bogs	.21	[7].65	.14	[5]0	0
Stratified deposits:					
Coarse-grained	13.93				
Fine-grained	1.17				
Total	15.10			1.78	26.88
Area receiving recharge	13.62				
Water pumped and diverted			82.83		

[1] Ponds with no functioning surface-water outlet.
[2] Ponds with a functioning surface-water outlet.
[3] Free water-surface evaporation, (Farnsworth and others, 1982).
[4] Average annual precipitation minus free water-surface evaporation.
[5] Zero recharge to stratified glacial deposits assumed in areas of drained ponds, swamps, and bogs, which are ground-water discharge areas.
[6] Estimated ground-water evapotransporation (Meinzer and Stearns, 1929).
[7] Estimated ground-water evapotransporation plus consumptive water used by irrigation.
[8] Average 1965-70 pumpage from Lout Pond Well (well 15 on pl. 1) and Little and Great South Ponds (pl. 1) (John Holmes, Town of Plymouth, oral commun., 1985).

The actual areal-recharge rate is probably greater than that estimated due to the net effect of a number of factors not considered in the calculations. For example, some ground water does not discharge to a stream before leaving the basin but leaves as ground-water underflow. This underflow is not accounted for by streamflow measurements. Also, some water is lost due to evapotranspiration of ground water where the water table is less than 10 ft below land surface. This occurs only in a very small percentage of the Eel River basin, mainly adjacent to lakes, streams, and wetlands.

In the preceding calculations, it was assumed that the rate of recharge to all of the stratified glacial deposits was equal. The rate of recharge to the fine-grained deposits may be less than the rate of recharge to the coarse-grained deposits. If this is true, then the rate of recharge to the coarse-grained moraine and outwash deposits typical of a large percentage of the Plymouth-Carver aquifer area is slightly greater than estimated by the calculations. The actual rate of ground-water recharge to coarse-grained deposits probably ranges from about 26 to 28 in/yr.

No data were collected during this study on the rate of recharge to glacial till areas and few data are available for Massachusetts or New England. A study by Morrissey (1983) indicates that the recharge rate to glacial till is approximately 6.8 in/yr [0.5 $(ft^3/s)/mi^2$].

Discharge

Ground water in the Plymouth-Carver aquifer discharges to the many rivers and streams that drain the aquifer, to ponds, wetlands, and bogs, and directly to the ocean along the coast. Average ground-water discharge to rivers and streams is about 139 ft^3/s, as determined from discharge measurements of all rivers and streams draining the aquifer during a period of average ground-water levels in July 1986 (table 6). Table 6 includes some discharge measurements made along individual streams reaches to determine gains and loses along the streams. All stream-measurement sites are shown on plate 1. Some stream reaches discharge into the aquifer (recharge); for example, the Herring River between Great Herring Pond and Bournedale loses 0.93 ft^3/s (station 8a to 8, table 6).

Streambed hydraulic conductivity affects the ease with which water moves from the aquifer into streams. Stream width and depth and streambed lithology were noted during onsite field inspections. At most locations, the streams flow directly on sand-and-gravel aquifer material. A vertical conductivity of 5 ft/d is a reasonable estimate for streambed material composed of sand and mixed sand and gravel in New England (Rosenshein and others, 1968; Gonthier and others, 1974; Haeni, 1978).

Much of the ground water that discharges to wetlands and bogs is lost through evapotranspiration and from the bogs through consumptive water use by agriculture. These loses are most notable in the Weweantic River basin, which has a large percentage of its area occupied by wetlands and cranberry bogs and no municipal pumping or other diversions that would affect streamflow. Hydrographs of daily mean discharge of the Weweantic and Eel Rivers for January 1970 through September 1971 (fig. 13) illustrate the effects of evapotranspiration and consumptive water use. A very small percentage of the Eel River basin is covered by wetland and bogs, unlike the Weweantic River basin. The reduced daily mean discharge in the Weweantic River during the growing season (from April through October) is the result of increased evapotranspiration and consumptive water use.

The rate of direct ground-water discharge to the ocean is difficult to measure. Ocean discharge can be estimated by means of a ground-water-flow model, which calculates fluxes into and out of the aquifer; this is addressed later in this report.

Freshwater-Saltwater Interface

Freshwater in the Plymouth-Carver aquifer is bounded by saltwater in the coastal areas (fig. 14). Freshwater in the aquifer normally contains less than 25 mg/L of chloride, whereas seawater contains about 18,000 mg/L of chloride. Because the density of freshwater is slightly less than the density of saltwater, freshwater floats on top of the saltwater. The approximate depth below sea level to the freshwater-saltwater interface at any location is described by the steady-state equation (Hubbert, 1940)

$$z = \frac{P_f}{P_s - P_f} h ,$$

where z is the depth of the freshwater-saltwater interface, in feet below sea level;

P_f is the density of freshwater (1.0 grams per cubic centimeter);

P_s is the density of saltwater (1.025 grams per cubic centimeter); and

Table 6.--*Stream discharge in the Plymouth-Carver area, July 1986*

[Stream measurement identifiers shown in plate 1; ft^3/s, cubic feet per second]

Stream-measurement identifier	Description	Date of measurement (month-day-year)	Discharge ft^3/s
1	Stone Pond outlet at North Plymouth	07-21-86	[1]1.45
1a	Diversion of Stone Pond outlet through Cordage	07-21-86	[1]1.45
2	Town Brook at Plymouth (01015874)[2]	07-21-86	14.6
		07-22-86	[1]15.3
2a	Town Brook near Plymouth	07-22-86	10.4
3	Holmes Point Brook	07-21-86	[1]1.06
4	Eel River near Plymouth (01105876)[2]	07-21-86	[1]23.2
4a	Eel River at Sandwich Road near Plymouth	07-22-86	14.9
4b	Eel River tributary near Plymouth	07-22-86	7.87
5	Beaver Brook at White Horse Beach (01105878)[2]	07-21-86	12.7
		07-22-86	[1]11.8
6	Indian Brook at Manomet Beach	07-21-86	[1]1.18
7	Savery Pond outlet at Ellisville	07-08-86	[1]dry
8	Herring River at Bournedale	07-21-86	[1]6.35
8a	Herring River near Bournedale, Great Herring Pond outlet	07-21-86	7.28
		07-22-86	7.11
8b	Herring River at Cedarville, Great Herring Pond inlet	07-22-86	10.0
9	Ellis Pond outlet, Head of Bay Road	07-07-86	[1]dry
10	Mare Pond outlet near Bourne	07-21-86	[1].80
11	Little Long Pond outlet, inlet to Long Pond	07-21-86	4.50
12	Agawam River near Ellisville	07-21-86	12.0
13	Red Brook near Buzzards Bay	07-21-86	[1]6.13
14	Gibbs Brook at East Wareham	07-21-86	[1]4.49
15	Diversion on SR 28 near Union Pond	07-08-86	[1]no flow
16	Agawam River at East Wareham	07-21-86	[1]33.5
17	Diversion on SR28, east of trailer park	07-21-86	[1].02
18	Diversion on SR28, Stone Village Motel	07-21-86	[1]1.02
19	Diversion on SR28, near Drive-in Theater	07-21-86	[1].89
20	Diversion on SR28, east of Suzuki Dealership	07-21-86	[1].16
21	Wankinco River at East Wareham	07-21-86	[1]18.6
22	Weweantic River at South Wareham	07-21-86	81.2
		07-22-86	[1]11.9
	Total stream discharge to Ocean		139.3

[1] Site used to compute total streamflow leaving the Plymouth-Carver aquifer.

[2] USGS streamflow-gaging station number. Additional discharge and quality data for these sites are available from the USGS (Marlborough, Mass.).

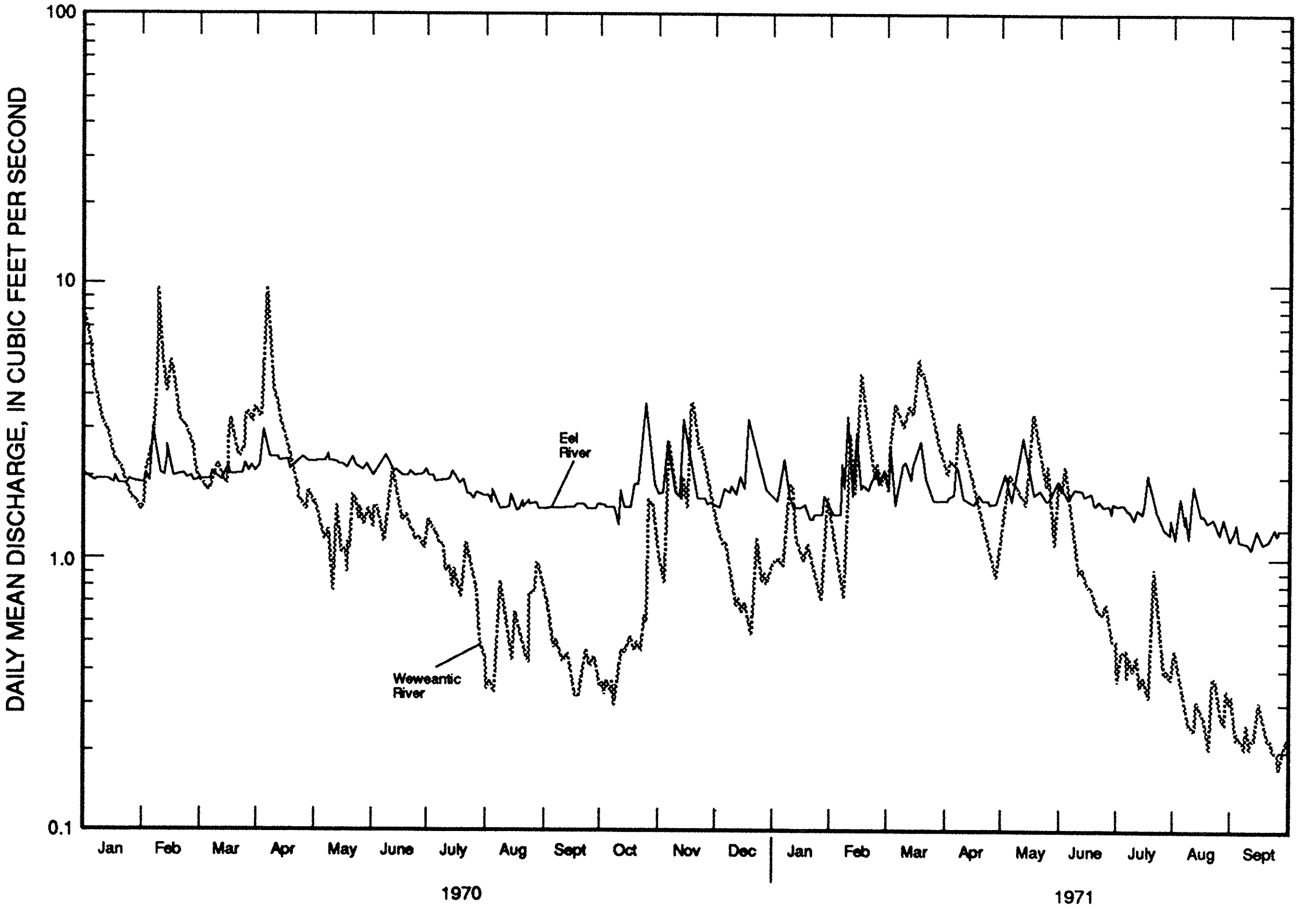
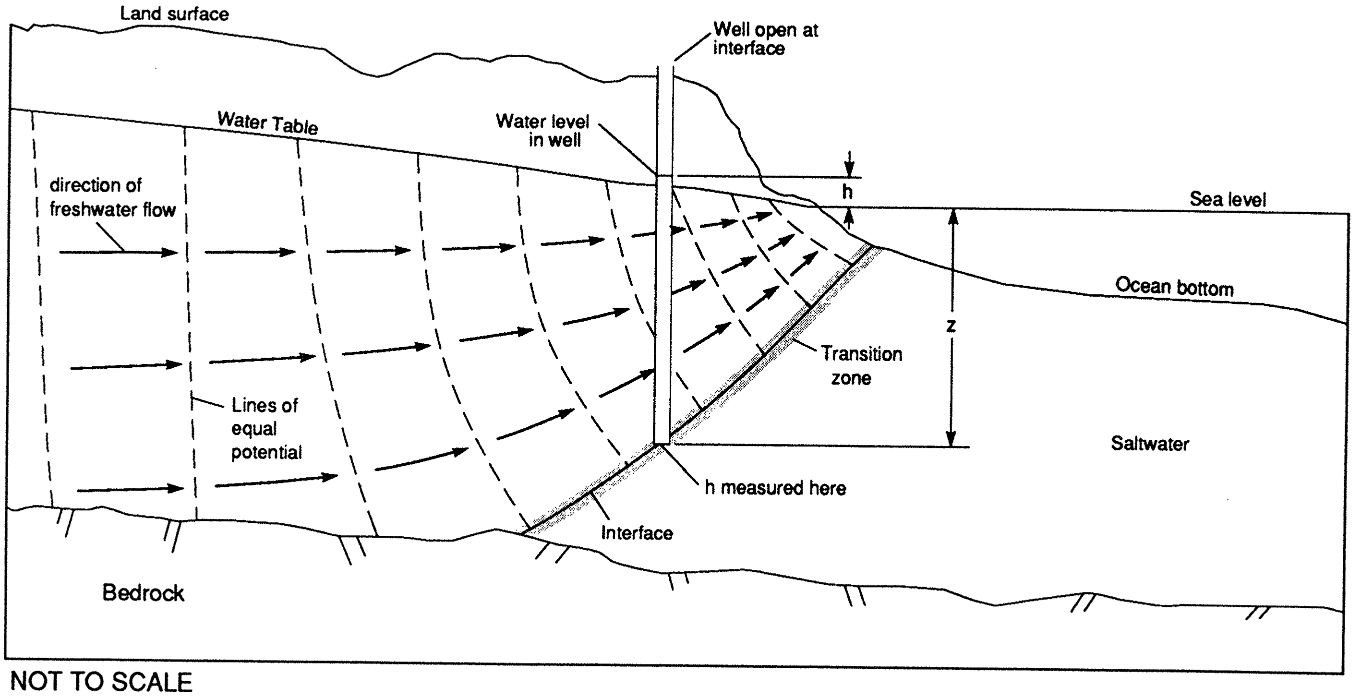


Figure 13.--Daily mean discharge of the Weweantic and Ell Rivers, January 1970 through September 1971.

h is the hydraulic head of freshwater, in feet above sea level at a given point on the interface (fig. 14).

The interface is not a sharp boundary but a transition zone where chloride concentrations range from 25 to 18,000 mg/L. This zone is created by diffusion and dispersion of the two miscible liquids. The extent of dispersion and, therefore, the thickness of the zone, is determined by the hydrologic characteristics of the aquifer and the fluctuating hydraulic conditions caused by variations in freshwater hydraulic head and tidal oscillations in the ocean. Water in the transition zone flows toward and discharges seaward of the coastline.

The position of freshwater-saltwater interface is determined by a dynamic balance in which the seaward-flowing freshwater prevents saltwater from intruding landward. A primary factor affecting the position of the boundary is the altitude of the underlying bedrock surface, generally less than 200 ft below sea level in coastal areas (pl. 2). A conservative estimate of the interface position, based on water-table altitudes near the coast, indicates that the interface is truncated at depth by relatively impermeable bedrock. Because of this truncation, the interface is considerably seaward of the position it would occupy if the bedrock were at much greater depth, as it is in the outer part of Cape Cod (LeBlanc and others, 1986). Another factor affecting the position of the interface is the amount of ground water that discharges to the coastal areas. Decreased ground-water discharge and lowered water levels, caused by pumping near the coast, may cause the interface to move landward. Conversely, increased ground-water discharge and increased ground-water levels, caused by recharge of treated sewage effluent, may result in a seaward shift of the interface.



NOT TO SCALE

$$z = \frac{P_f}{P_s - P_f} h$$

z is the depth of the freshwater-saltwater interface, in feet below sea level;

P_f is the density of freshwater (1.0 grams per cubic centimeter);

P_s is the density of saltwater (1.025 grams per cubic centimeter);

h is the hydraulic head of freshwater, in feet above sea level at a given point on the interface (fig. 12).

EXAMPLE:

If the water level in a well screened at interface is 5 feet above sea level then:

$$z = \frac{P_f}{P_s - P_f} h;$$

$$= \frac{1}{1.025 - 1} \times 5$$

$$= 40 \times 5$$

$$= 200 \text{ feet}$$

Figure 14.--Relation between freshwater and saltwater for steady-state ground-water discharge to ocean.

Available data indicate that under present (1988) conditions, the freshwater-saltwater interface in the Plymouth-Carver aquifer is nearly vertical and is located very near the coastline or just offshore. Records of wells drilled in the study area, including a large-capacity public-supply well located only 800 ft from the ocean in Bourne, indicate that only a few shallow wells drilled at Plymouth Beach have yielded brackish water or saltwater.

SIMULATION OF GROUND-WATER FLOW IN PLYMOUTH-CARVER AQUIFER

A ground-water-flow model of the Plymouth-Carver aquifer was developed to simulate the three-dimensional flow in the aquifer. The areal extent, thickness, and hydraulic properties of the aquifer, location and characteristics of streams, rates of recharge from precipitation, and location and rates of pumping were specified in the model. Model output consisted of the distribution of hydraulic-head in the aquifer, discharge to streams, and ground-water-flow rates across model boundaries.

During a series of simulations, geohydrologic variables such as horizontal and vertical hydraulic conductivity, recharge, and streambed conductance were changed in the model within reasonable limits until hydraulic heads and rates of ground-water discharge to streams simulated by the model matched on-site measurements. Once the match between simulated and measured hydraulic heads and discharge rates was acceptable, the model was considered calibrated. After calibration, the model was used to simulate the responses of hydraulic head and streamflow to natural and human-induced stress conditions.

Conceptual Model

Before construction of the ground-water-flow model, a conceptual model of the aquifer was formulated. The conceptual model is a simplified geohydrologic representation of the aquifer. Important geohydrologic features considered when formulating the conceptual model include (1) areal variation in saturated thickness (2) horizontal and vertical variations in hydraulic conductivity (3) location and types of hydraulic boundaries (4) location and hydraulic characteristics of streams; and (5) location of wells and their pumping rates. Simplified features of the Plymouth-Carver aquifer conceptual model are shown in figure 15 and are described below:

1. Simulation of three-dimensional ground-water flow was achieved by dividing the total saturated thickness of the aquifer into layers; horizontal flow in each layer and vertical leakage between layers are simulated.

2. The till and crystalline rock underlying the Plymouth-Carver aquifer are assumed to be impermeable; therefore, no leakage occurs between the drift and the till and bedrock. Except for locations where the bedrock is highly fractured, the hydraulic conductivity of the bedrock probably is much lower than that of the overlying Plymouth-Carver aquifer. Consequently, the leakage rate between the aquifer and bedrock probably is low. Even so, if leakage occurs over a large area, the ground-water flux to or from the bedrock could contribute substantially to the water budget of the aquifer. Because no data are available to determine the magnitude of this flux, net leakage to and from the bedrock was assumed to be zero.

3. Recharge is distributed nonuniformly over the modeled area and the rates simulated are aver-

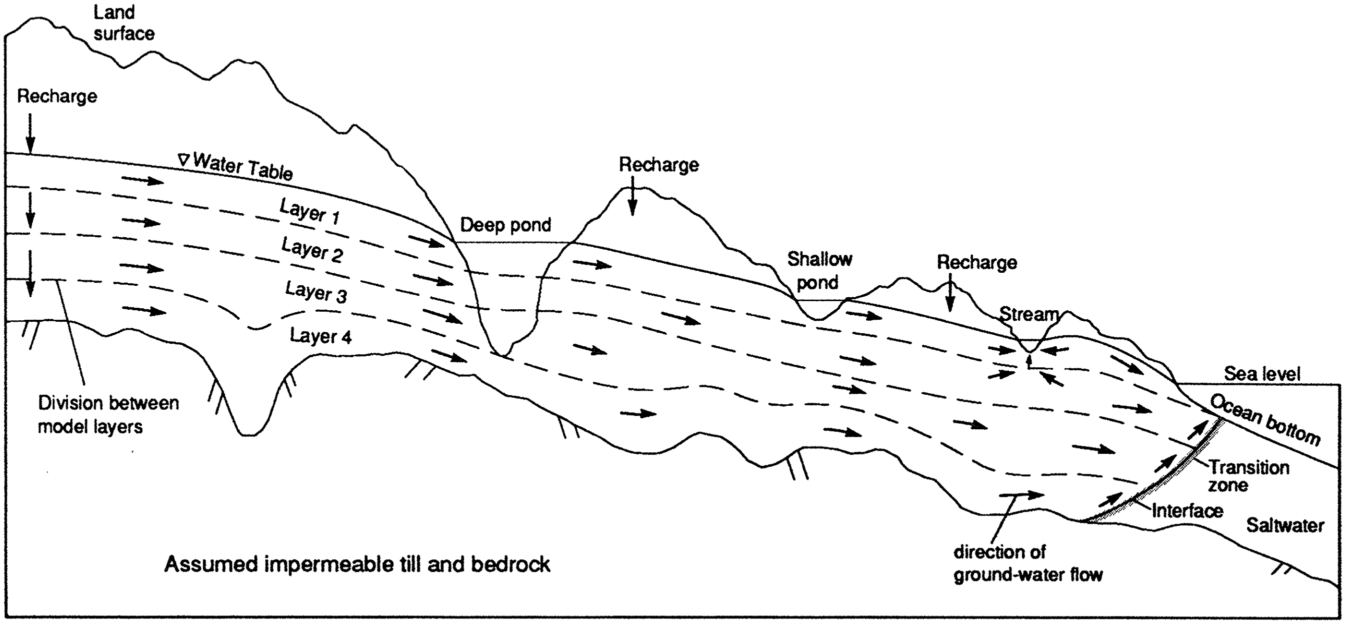


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Figure 15.--Features of conceptual model of Plymouth-Carver aquifer.

age annual recharge rates. Average annual precipitation does not vary appreciably from location to location in the study area. However, recharge rates vary areally because of differences in sediment lithologies and hydrologic settings. The average recharge rate at any location was determined on the basis of the geohydrologic conditions at that location. Four geohydrologic were identified that receive different rates of recharge: (1) Outwash-plain, moraine, and kame deposits; (2) till and lake deposits; (3) wetlands; and (4) cranberry bogs.

4. Ground-water discharge from the aquifer to streams and the ocean. Ground water discharges to streams through leaky streambeds. Streambeds are assumed to have constant thicknesses but variable widths. Also, they are assumed to be composed of sediments with vertical hydraulic conductivities that are less than or equal to that of the underlying aquifer. Stream stage is assumed to remain constant over time at the approximate stage of the stream that represents 85- to 90-percent flow duration.

   In most coastal areas, ground water discharges to the ocean along a narrow zone off the coast (fig. 14). As illustrated in figure 14, saltwater underlies freshwater at depth beneath the land surface near the coast. Only the freshwater is simulated in the model; therefore, the freshwater-saltwater interface is assumed to be sharp, and movement of that interface, for example because of pumping, is not simulated.

5. Many of the lakes and ponds in the study area are kettle ponds. These ponds are water-filled depressions in the aquifer; most ponds have no surface inflow or outflow. Kettle ponds are simulated as areas that have a specific yield equal to 1 and a hydraulic conductivity two orders of magnitude larger than the surrounding aquifer material. The other lakes and ponds are parts of river systems that drain the aquifer. Most of these lakes and ponds are from 10 to 25 ft deep, extending down into the upper part of the aquifer. Several ponds (Gallows Pond, Long Pond, Bloody Pond, near Halfway Pond in Plymouth, and Little Pond, north of Billington Sea) extend more than 40 ft into the aquifer. These lakes and ponds were simulated in the same manner as the kettle ponds.

Description of Flow Model

A finite-difference model (McDonald and Harbaugh, 1988) was used to simulate ground-water flow in the Plymouth-Carver aquifer. The aquifer was divided into a rectangular, finite-difference grid (fig. 16). The grid, which covers an area of about 350 mi^2, has 85 rows and 115 columns. Each grid block is 1,000 ft by 1,000 ft. The grid has a uniform horizontal (x-y) spacing.

The active area of the model grid, which covers 208 mi^2 (about 60 percent of the area covered by the entire grid), is outlined in figure 17. The physical boundaries of the modeled area are the coast along Plymouth Harbor and Cape Cod Bay; Cape Cod Canal; the coast along Buzzards Bay; the surface-water divide west of the Weweantic River in the town of Rochester; the surface-water divide between the Taunton River basin and the Buzzards Bay basin in Middleborough and Plympton; tributaries of the Winnetuxet River in the Taunton River basin; and Jones River Brook, which is tributary to the Jones River and the Jones River (fig. 17). The modeled area includes areas of glacial deposits on the west and northwest in the Taunton and Jones River basins so that the natural ground-water divides in these areas could be simulated.

The aquifer was divided vertically into four layers, numbered from top to bottom (fig. 15). The purpose of the layering was to enable simulation of (1) Vertical flow in the aquifer; (2) vertical variation in horizontal hydraulic conductivity; (3) local confining units (variations in vertical hydraulic conductivity); and (4) pumping from partly penetrating wells.

The following criteria were used for the layering. In most of the area, saturated thickness of the aquifer exceeds 50 ft. In these areas, layers 1 and 4 were assigned thicknesses of 25 ft, and layers 2 and 3 were assigned thicknesses equal to one-half of the remaining thickness. This method of layering (1) ensured that, in most of the modeled area, the bottom of layer 1 was far enough beneath the water table to prevent layer 1 from going artificially dry during simulations; (2) provided a 25-ft-thick aquifer layer directly on top of the bedrock for simulation of pumping of large-capacity wells screened at the bottom of the aquifer (which is the most common method of constructing municipal wells in the area); and (3) allowed for simulation of relatively gradual areal variations in the thicknesses of layers 2 and 3. In several areas where the saturated thickness of the aquifer was equal to or

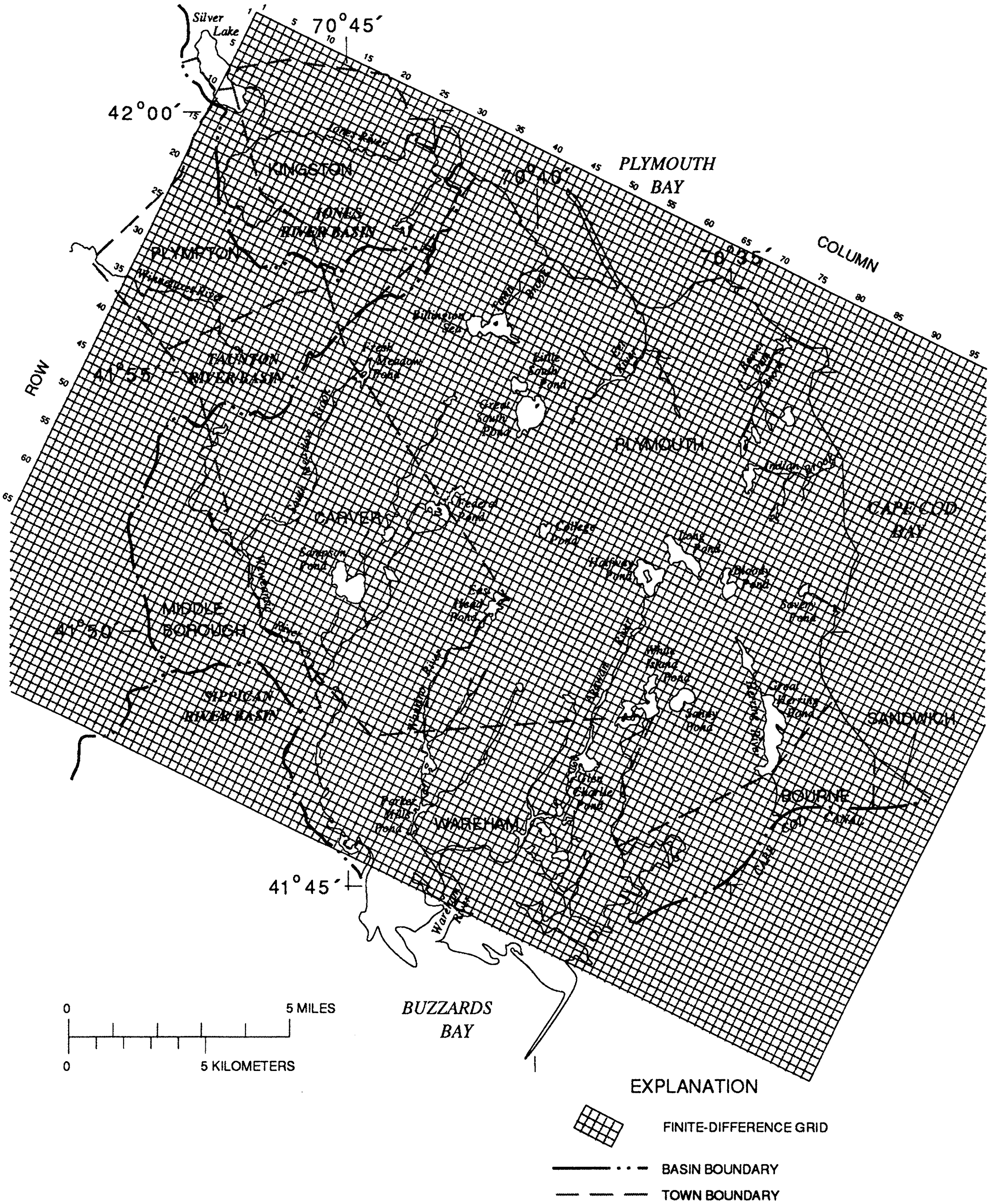

Figure 16.--Finite-difference grid for model of Plymouth-Carver aquifer.

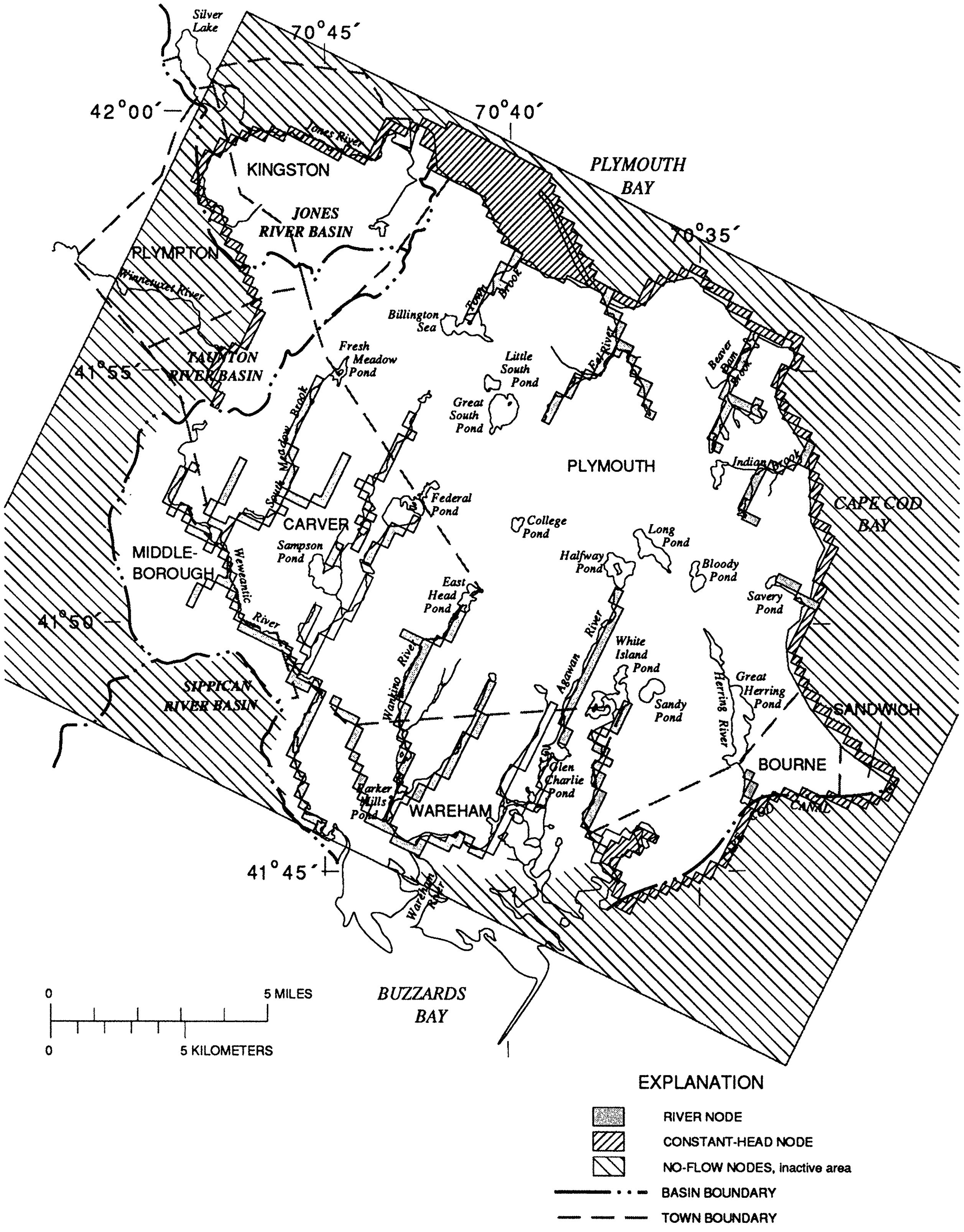

Figure 17.-- Boundary of the modeled area, location of constant head and river nodes, and no-flow boundaries on finite-difference grid.

less than 50 ft, each layer was assigned a thickness equal to one-fourth of the saturated thickness.

Layer 1 was modeled as an unconfined unit. Transmissivity at each node in layer 1 was calculated as the saturated thickness at the node multiplied by the assigned hydraulic conductivity. Therefore, the transmissivity of the layer could change over time as the water-table altitude in the layer changed.

Layers 2 and 3 were modeled as changeable between either confined or unconfined conditions (McDonald and Harbaugh, p. 5-26, 1988). Transmissivities of layers 2 and 3 were calculated as the saturated thickness times the hydraulic conductivity at each node. If the hydraulic head at a node in layers 2 or 3 dropped below the top of that layer, transmissivity was recalculated to account for the change in saturated thickness. In addition, either a storage coefficient representative of confined conditions or a specific yield representative of unconfined conditions could be simulated depending on whether the hydraulic head at the node was above or below the altitude of the top of the layer.

Layer 4 was modeled as a confined unit. Transmissivity and storage coefficient at each node were held constant during the entire simulation.

Boundary Conditions

Boundary conditions were specified around the perimeter of the active area of the model for each layer. Constant-head nodes and inactive (no-flow) nodes were used as boundaries (fig. 17).

Under natural conditions, ground water discharges to the ocean along a narrow strip at the coast. To model this discharge, constant-head values equal to sea level were assigned to all nodes in layer 1 along the coast and along the Cape Cod Canal. Constant-head values equal to sea level also were assigned in Buttermilk Bay, and in Plymouth Harbor as far north and northeast as Plymouth Beach. Plymouth Harbor is underlain by lacustrine silts and clays (simulated in layer 1), which, in turn, are underlain by coarse-grained sediments (simulated in layers 2 through 4). Freshwater flows in these sediments beneath Plymouth Harbor at least as far north and northwest as Plymouth Beach, as indicated by freshwater from deep wells on Plymouth Beach. Discharge of freshwater probably occurs to the harbor and to the ocean north of the beach. In the model, nodes in layer 1 in the Plymouth Harbor and north of the Plymouth Beach were assigned constant-head values equal to sea level.

Constant heads also were assigned to layer 1 nodes along tributaries of the Winnetuxet River in the Taunton River basin, and along Jones River Brook and the Jones River in the Jones River basin. The values assigned at each location was the approximate stage of the stream or the approximate altitude of the water table along the constant-head boundary. The reason for placing these constant-head boundary conditions in the Taunton and Jones River basins was to permit simulation of the ground-water divides in the Plymouth-Carver aquifer and these two basins and movement of these divides in response to pumping.

Constant heads also were specified in layer 2 along the Cape Cod Canal because the canal extends down into layer 2 in the model. All other boundary nodes in layers 1, 2, 3, and 4 were specified as inactive (no-flow). A no-flow boundary was simulated at the bottom of the Plymouth-Carver aquifer at the contact between the stratified glacial deposits and the till-covered bedrock.

Hydraulic Properties

As noted previously in the section on "Geologic Setting", there is some evidence that outwash-plain and morainal deposits generally become more silty with depth. The increase in silt content with depth produces progressively smaller horizontal hydraulic conductivity with depth and, probably, an increasing ratio of horizontal-to-vertical hydraulic conductivity with depth. These hydraulic properties were simulated in the model by assigning progressively smaller values of horizontal hydraulic conductivity to layers 1 through 4, and progressively larger ratios of horizontal- to- vertical hydraulic conductivity between layers 1 and 2, 2 and 3, and 3 and 4.

The following hydraulic properties were used in the final calibrated model: (1) a horizontal hydraulic conductivity of 250 ft/d was assigned to layer 1 for the outwash-plain, morainal, and kame deposits (fig. 3); (2) a value of 150 ft/d was assigned to layer 2; and (3) values of 50 ft/d were assigned to layers 3 and 4. A horizontal-to-vertical hydraulic-conductivity ratio of 10:1 initially was assigned to all layers; however, the match of measured and simulated hydraulic heads improved when progressively larger ratios were used for deep model layers. The ratios of horizontal-to-vertical conductivity became 10:1 for layers 1 and 2, 50:1 for layer 3, and 100:1 for layer 4.

Glaciolacustrine and till deposits occupy small areas throughout the Plymouth-Carver aquifer (fig. 3). Values of hydraulic conductivity were assigned to these deposits on the basis of information presented in Williams and Tasker (1974). The glaciolacustrine deposits were assigned a value of 25 ft/d in all four layers, and the till deposits were assigned a value of 10 ft/d in all four layers. The ratio of vertical-to-horizontal hydraulic conductivity for both types of deposits was assumed to be 1:100.

Recharge and Pumpage

Rates of average annual recharge used in the model are listed in table 7. The recharge rate of 27 in/yr applied to the outwash-plain, morainal, and kame deposits is somewhat larger than the estimate of about 24 in/yr that was based on continuous stream-discharge data in the Eel River basin (table 5). However, as discussed in the section on "Recharge", 24 in/yr is probably somewhat less than the actual recharge rate to the stratified glacial deposits of the Plymouth-Carver aquifer for several reasons; two of these reasons are that some ground-water probably discharges as underflow and as evapotranspiration where the water table is near land surface. The rate of 27 in/yr was used because it produced the best match between measured and simulated hydraulic heads and ground-water discharge to streams.

Table 7.--*Average annual recharge rates used in model of Plymouth Carver aquifer*

[$(ft^3/s) / mi^2$, cubic foot per second per square mile; in/yr, inches per year]

Hydrologic setting	Average annual recharge rate	
	$(ft^3/s)/mi^2$	in/yr
Outwash plain, moraines, and kames	2.0	27
Till and glaciolacustrine deposits	.5	6.8
Wetlands	0	0
Cranberry bogs	-1.3	-17

The recharge rate to till was based on the findings of Morrissey (1983), in which mean annual ground-water runoff from till was calculated to be approximately 0.5 $(ft^3/s)/mi^2$ of drainage area, or 6.8 in/yr. Both till and glaciolacustrine deposits consist primarily of fine-grained material; therefore, recharge to the glaciolacustrine deposits also is assumed to be 6.8 in/yr.

Wetlands in the modeled area are ground-water-discharge areas; therefore, net recharge to wetlands is zero. Water use in cranberry bogs results in a net consumption of about 17 in/yr (table 2). Therefore, recharge to cranberry bogs was simulated as a negative rate of -17 in/yr. Long-term average water-management activities associated with the operation of cranberry bogs is included implicitly in the model by simulating a negative rate of recharge.

Nineteen large-capacity public and industrial supply wells and 2 ponds that are public supplies (fig. 6, table 3) were simulated as wells in the model. Average pumping rates from 1980 to 1985 (table 8) were used. Pumping from several wells shown in figure 6 was not simulated in the model. Bourne wells 12, 305, and 306, Plymouth well 591, and Wareham well 37 were not in use during 1980-85, and no pumping data were available for Plymouth wells 317 and 318, and Carver wells 146 and 147. The model layer from which water was withdrawn depended on the screened interval and aquifer thickness at each well. If a pumped well was located on or near the boundary of two nodes, the pumpage was distributed between the two nodes.

Steady-State Model Calibration

The model was calibrated to hydrologic conditions that existed both in late November to early December 1984 and mid-to-late July 1986; conditions during the two periods were assumed to represent long-term, average hydrologic conditions in the modeled area. An extensive set of water-level measurements from 66 wells and 35 ponds were made during late November to early December 1984 (pl. 1). Gain-loss measurements to determine rates of ground-water discharge to streams were made during July 1986. During the gain-loss measurements, a representative set of water-level measurements were made throughout the study area to verify that water levels were similar during December 1984 and July 1986.

Table 8.--*Average annual pumping rates from public and industrial supplies simulated as wells in the Plymouth-Carver aquifer model, 1980-85*

[ft^3/s, cubic feet per second]

TOWN Supply identifier (fig. 14)	Pumping rate (ft3/s)	Model layer
PLYMOUTH		
PWW-3	0.35	3
PWW-15	.04	4
PWW-58	.38	4
PWW-188	.18	4
PWW-275	.53	4
PWW-411	1.33	4
PWW-422	1.50	4
PWW-541	.50	3
Little South Pond (LSP)	2.68	1
BOURNE		
BHW-13	.03	2
BHW-200	.29	1
BHW-205	.28	1
BHW-291	.26	2
WAREHAM		
WFW-33, 34, 35, 89	1.54	4
WFW-98, 252	.33	1
WHW-323	.55	4
Sand Pond (SP)	.42	4
Total	11.19	

The hydrograph of observation well PWW-22 (fig. 11) demonstrates that hydrologic conditions in the Plymouth-Carver aquifer during late November to early December 1984 were about equal to those during mid-to-late July 1986, and that, during these two periods, water levels were about equal to long-term average conditions. The long-term average water-level altitude in PWW-22 is 120.8 ft. The water-level altitude in well PWW-22 on December 1, 1984, and July 24, 1986, was 121.0 ft and 120.3 ft, respectively.

Three following statistical measures were used to evaluate the match between measured and simulated hydraulic heads (water levels) and ground-water discharge to and from streams during calibration: (1) The absolute value of the mean of the residuals between measured and simulated water levels and ground-water discharge, (2) the mean of the absolute value of the residuals between measured and simulated water levels and ground-water discharge, and (3) the standard deviation of the residuals between measured and simulated water levels and ground-water discharge. These three statistical measures emphasize different aspects of the distribution of residuals; therefore, analysis using all three statistical measures may provide more insight into the sensitivity of the model than using only one statistical measure. The absolute value of the mean of the residuals allows for compensating errors between the measured and simulated parameter. For example, if the simulated water level is 35 ft higher than the measured water level at one location, and the simulated water level is 35 ft lower than the measured water level at another location, the absolute value of the mean of the water-level residual is zero. A zero value for the absolute value of the mean of the residuals does not imply the model is well calibrated because compensating differences between the measured and simulated values may still be large. The mean of the absolute values of the residuals does not allow compensating errors, but it also does not emphasize the larger residuals. The standard deviation of the residuals emphasizes the larger residuals and avoids compensating errors.

The simulated steady-state water-table altitude in the aquifer is shown in figure 18. Also shown are the 101 water levels measured from late November to early December 1984. Differences between the measured and simulated water levels are summarized in table 9. The match between measured and simulated water levels ranged from a simulated water level in Beaver Pond (node 20,75) that was 13.63 ft too high to a simulated water level in observation well BHW-126 (node 51,40) that was 11.97 ft too low. Simulated water levels were within 1 ft of measured water levels at 18 of the 101 sites, within 2 ft at 41 sites, and within 5 ft at 78 sites. The absolute value of the mean of the water-level residuals at the 101 sites was 0.15 ft, the mean of the absolute values of the water-level residuals was 3.46 ft, and the standard deviation of the water-level residuals was 4.42 ft.

One possible objective criterion with which to evaluate the overall match between measured and simulated water levels is the ratio of the residual to the total relief in the water table in the modeled area. The maximum measured water-level altitude in the study area, in the northwestern part of the area, is about 125 ft (pl. 1). As the minimum water-level altitude is at sea level, relief of the water table is about 125 ft. Consequently, the mean of the absolute value of the water-level residuals for the calibrated model is about

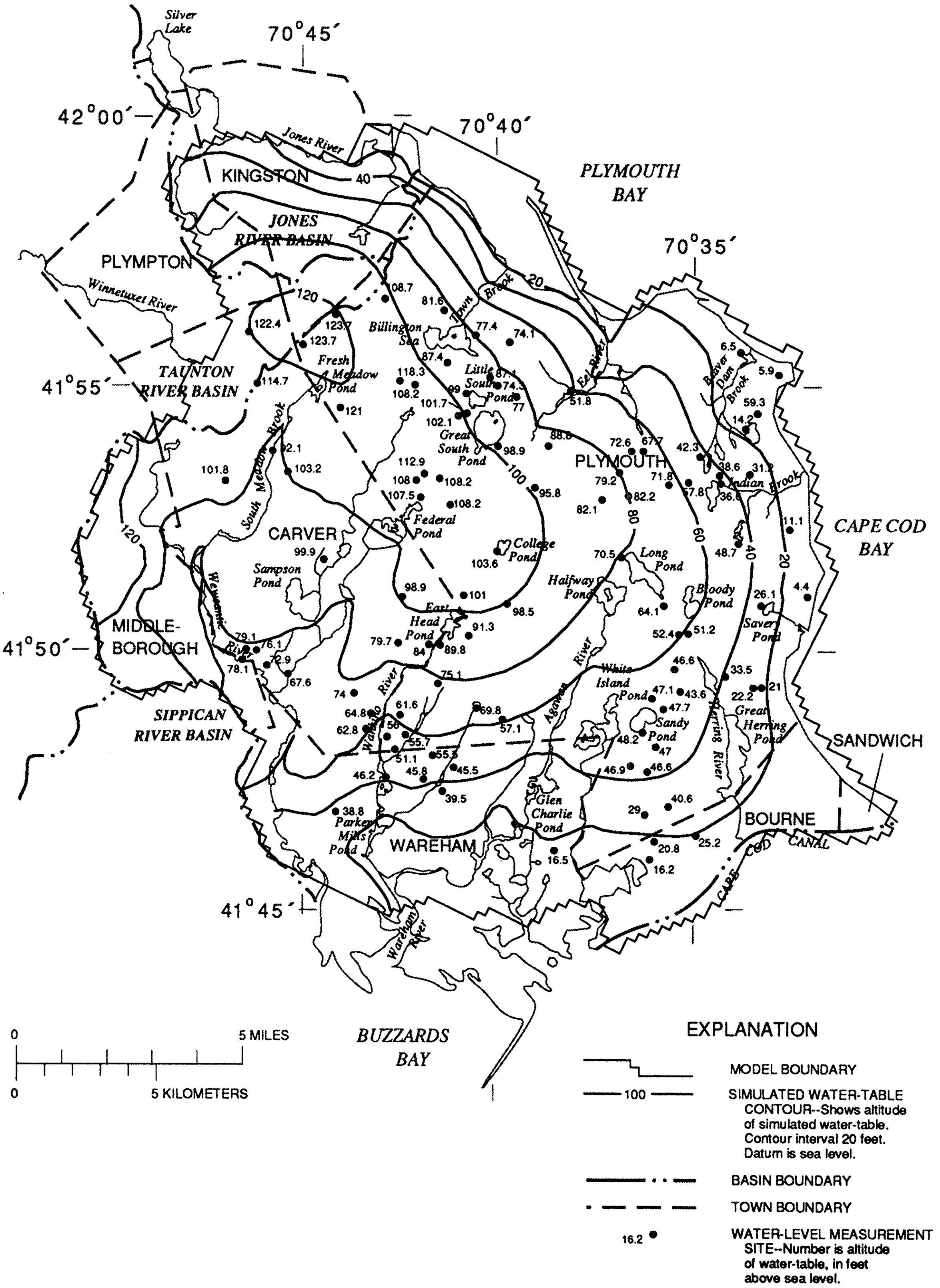

Figure 18.--Simulated steady-state water-table altitude in Plymouth-Carver aquifer, and measured water levels, December 1984.

Table 9.--*Measured and simulated water levels in observation wells and ponds in Plymouth-Carver aquifer, December 1984.*

Model			Well or pond (fig. 18)	Water level, in feet		
Row	Column	Layer		Measured	Simulated	Residual
8	78	1	PWW-501	5.88	0.97	4.91
19	40	1	PWW-502	81.63	81.86	- .23
19	48	1	PWW-261	74.05	70.30	3.75
20	44	1	PWW-503	77.41	76.09	1.32
22	77	1	PWW-313	38.59	39.25	- .66
23	67	1	PWW-241	67.73	64.29	3.44
23	77	1	PWW-285	36.60	41.49	-4.89
24	49	1	PWW-215	81.90	84.14	-2.24
24	52	1	PWW-516	77.03	81.38	-4.35
24	66	1	PWW-242	72.59	67.56	5.03
24	73	1	PWW-245	57.79	55.66	2.13
25	28	1	PWW-413	123.73	119.03	4.70
25	72	1	PWW-240	71.78	63.91	7.87
26	46	1	PWW-504	99.03	90.99	8.04
27	66	1	PWW-243	79.20	77.59	1.61
28	38	1	PWW-505	118.30	110.40	7.90
28	47	1	PWW-306	101.66	97.65	4.01
28	68	1	PWW-244	87.20	78.93	8.27
29	46	1	PWW-305	102.07	98.99	3.08
30	26	1	PWW-517	123.73	122.93	.80
30	52	1	PWW-506	98.88	97.77	1.11
30	66	1	PWW-379	82.05	85.35	-3.30
34	34	1	PWW-22	120.98	119.18	1.80
34	53	1	PWW-315	102.71	103.69	- .98
35	71	1	PWW-509	70.45	78.82	-8.37
36	24	1	CDW-119	114.70	115.84	-1.14
37	46	1	PWW-507	112.95	112.74	.21
38	78	1	PWW-414	64.07	68.56	-4.49
39	50	1	PWW-416	108.18	111.75	-3.57
40	82	1	PWW-518	52.39	56.53	-4.14
41	92	1	PWW-319	21.04	19.23	1.81
42	29	1	CDW-120	92.60	98.53	-5.93
42	92	1	PWW-418	22.16	22.54	- .38
44	31	1	CDW-121	103.23	102.31	.92
44	82	1	PWW-253	46.59	54.62	-8.03
46	61	1	PWW-510	98.53	99.92	-1.39
46	84	1	PWW-251	43.60	49.10	-5.50
47	56	1	PWW-511	101.01	104.38	-3.37
49	83	1	PWW-513	47.75	50.76	-3.01
51	40	1	BHW-126	99.95	87.98	11.97
51	50	1	CDW-99	98.92	103.27	4.35
51	59	1	PWW-415	91.34	96.06	-4.72
53	82	1	PWW-514	48.22	49.64	-1.42
53	84	1	PWW-520	47.02	46.88	.14
54	55	1	CDW-123	83.97	89.90	-5.93
54	56	1	PWW-521	89.77	88.64	1.13
56	52	1	CDW-125	79.66	89.74	-10.08
57	84	1	PWW-519	46.61	42.69	3.92
58	58	1	PWW-431	75.15	80.19	-5.04
59	63	1	PWW-512	69.78	69.07	.71

Table 9.--*Measured and simulated water levels in observation wells and ponds in Plymouth-Carver aquifer, December 1984*--Continued.

Model			Well or pond (fig. 18)	Water level, in feet		
Row	Column	Layer		Measured	Simulated	Residual
61	87	1	PWW-368	28.98	30.64	-1.66
61	93	1	BHW-293	25.22	19.65	5.57
63	56	1	PWW-430	61.56	66.69	-5.13
64	37	1	CDW-122	76.10	80.67	-4.57
64	53	1	CDW-86	64.80	66.41	-1.61
65	36	1	CDW-201	78.14	76.65	1.49
65	57	1	PWW-236	55.71	60.72	-5.01
66	53	1	CDW-85	62.84	62.02	.82
66	55	1	PWW-369	56.02	56.13	- .11
66	61	1	PWW-238	55.51	54.20	1.31
66	64	1	WFW-296	45.48	45.55	- .07
68	57	1	PWW-237	51.09	52.64	-1.55
69	61	1	WFW-295	45.81	44.37	1.44
69	64	1	WFW-297	39.49	38.75	.74
70	57	1	WFW-245	46.21	44.75	1.46
70	79	1	WFW-211	16.49	18.25	-1.76
8	73	1	BARTLETT POND	6.53	3.13	3.40
16	78	1	FRESH POND	14.24	14.81	- .57
20	75	1	BEAVER POND	20.66	34.29	13.63
20	81	1	SHALLOW POND	31.19	23.79	7.40
21	33	1	LITTLE MUDDY POND	108.70	101.29	7.41
21	57	1	RUSSELL MILL POND	51.79	58.32	-6.53
21	74	1	ISLAND POND	42.28	40.03	2.25
24	43	1	BRIGGS RESERVOIR	87.41	90.35	-2.94
24	48	1	COOKS POND	87.08	86.24	.84
24	87	1	LILLY POND	11.09	11.33	- .24
28	41	1	MICAJAH POND	108.20	105.30	2.90
28	58	1	ISLAND POND	88.79	89.47	- .68
28	83	1	MOREY POND	48.74	41.67	7.07
30	93	1	BLACK POND	4.43	0	4.43
31	20	1	UNAMED POND WEST OF CEDAR SWAMP	122.44	120.25	2.19
33	59	1	CROOKED POND	95.78	98.32	-2.54
34	89	1	SAVERY POND	26.08	24.22	1.86
37	48	1	WIDGEON POND	108.17	111.79	-3.62
38	46	1	CURLEW POND	108.00	112.84	-4.84
39	47	1	ROCKY POND	107.52	112.43	-4.91
40	82	1	GRASSY POND, PWW-518	51.16	56.18	-5.02
41	58	1	COLLEGE POND	103.58	106.49	-2.91
42	88	1	HODGES POND	33.52	36.52	-3.00
48	26	1	VAUGHN POND	101.81	102.97	-1.16
49	83	1	LITTLE DUCK POND	47.07	50.76	-3.69
57	83	1	LITTLE ROCKY POND	46.87	43.38	3.49
59	67	1	UNAMED POND SOUTH-EAST OF CHARGE POND	57.07	60.25	-3.18
59	89	1	HORSE POND	40.64	30.93	9.71
64	50	1	GOLDEN FIELD POND	74.04	75.49	-1.45

Table 9.--*Measured and simulated water levels in observation wells and ponds in Plymouth-Carver aquifer, December 1984*--Continued.

Model Row	Model Column	Model Layer	Well or pond (fig. 18)	Water level, in feet Measured	Water level, in feet Simulated	Water level, in feet Residual
64	90	1	GOAT PASTURE POND	20.76	16.78	3.98
65	36	1	BATES POND	79.08	78.54	.54
65	39	1	POND NEAR HUCKLEBERRY CORNER	72.91	74.48	-1.57
65	42	1	POND ON CRANE BROOK	67.63	68.65	-1.02
65	89	1	ELLIS POND	16.17	13.80	2.37
77	54	1	UNAMED POND AT INTERSECTION OF I-195 AND I-25	38.83	34.93	3.90

Absolute value of the mean of the water-level residuals, in feet 0.15

Mean of the absolute values of the water-level residuals, in feet 3.46

Standard deviation of the water-level residuals, in feet 4.42

Total number of observations = 101.

2.8 percent (3.46 ft/125 ft) of the total relief of the water table. A value less than about 5 percent is considered to indicate excellent overall agreement between measured and simulated water levels, and a value less than about 10 percent is considered acceptable. The overall agreement for this calibrated model is considered excellent.

Comparison of stream base-flow to simulated ground-water discharge measured in July 1986 is shown in table 10. A measure of the match between measured and simulated discharge to streams can be obtained by comparing the ratio of the residual to the total ground-water discharge measured in the modeled area. Total stream discharge from the modeled area on July 21-22, 1986, was about 139 ft^3/s (table 10). The mean of the absolute value of the discharge residuals for the calibrated model is about 1.6 percent (2.2 $ft^3/s \div 139 ft^3/s$) of the total stream discharge. A value less than about 5 percent is considered to indicate excellent overall agreement between measured and simulated discharges, and a value less than about 10 percent is considered acceptable. The value of 1.6 percent indicates that the overall match between measured and simulated discharge is excellent.

The steady-state ground-water budget (table 11) indicates that, under long-term average conditions, ground water flows into and out of the modeled area at a rate of 331 ft^3/s. About 95 percent of the inflow is recharge from precipitation. About 51 percent of the outflow is discharge to streams and ponds; 44 percent is discharge to the ocean and to constant-head boundaries in the modeled areas of the Taunton River and Jones River basins, 3.3 percent is public-supply and industrial pumping, and 1.7 percent is loss from cranberry-bog operations.

Transient Model Calibration and Validation

Transient calibration of the ground-water-flow model was achieved by matching measured to simulated water-level changes in observation well PWW-22 during the drought from 1964-66 (fig. 11). Validation that the model correctly simulates aquifer response was achieved by comparing measured and simulated water-level changes from April 1984 through October 1985. No data were available regarding the regional effects of large-scale pumping for transient calibration or valification. Individual wells were pumped from 1980 through 1985 at rates small enough that, in general, drawdown only exceeded 10 ft in the immediate vicinity of the wells.

Table 10.--*Measured and simulated ground-water discharge to streams in the Plymouth-Carver aquifer, July 21-22, 1986*

[---, no data available; ft^3, cubic foot per second]

Stream-measurement site (plate 1)	Date of measurement (month-day-year)	Discharge[1] (ft3/s)		
		Measured	Simulated	Residual
Town Brook at Plymouth upstream of site 2 (01105874)	07-21-86	14.6	---	---
	07-22-86	15.3	9.0	6.3
Eel River near Plymouth upstream of site 4 (01105876)	07-21-86	23.2	22.7	.5
Eel River at Sandwich Road near Plymouth upstream of site 4a	07-22-86	14.9	13.4	1.5
Eel River tributary near Plymouth upstream of site 4b	07-22-86	7.87	3.4	4.47
Beaver Brook at White Horse Beach upstream of site 5 (01105878)	07-21-86	12.7	---	---
	07-22-86	11.8	14.7	[1]-2.9
Indian Brook at Manomet Beach upstream of site 6	07-21-86	1.18	[1]-.72	1.9
Herring River between outlet from Great Herring Pond and Cape Cod Canal between site 8a and 8	07-21-86	[1]-.93	[1]-.91	[1]-.02
Red Brook near Buzzards Bay upstream of site 13	07-21-86	6.13	5.9	.23
Agawam River at East Wareham upstream of site 16	07-21-86	33.5	30.7	2.8
Wankinco River at East Wareham upstream of site 21	07-21-86	18.6	18.7	[1]-.1
Weweantic River at South Wareham upstream of site 22	07-21-86	81.2	---	---
	07-22-86	11.9	---	---
	(Average)	46.5	51.0	[1]-4.5
Agawan River between site 16 and the confluence of the Agawam and Wankinco Rivers	07-21-86	2.1	5.4	[1]-3.3
Agawam River just upstream of the confluence with Wankinco River, Wareham	07-21-86	35.6	36.1	[1]-.5
Absolute value of the mean of the water-level residuals, in ft				0.5
Mean of the absolute values of the water-level residuals, in ft				2.2
Standard deviation of the water-level residuals, in ft				3.0

[1] Negative discharge means that water moves from the stream into the underlying aquifer.

Table 11.--*Simulated steady-state ground-water budget of the Plymouth-Carver aquifer*

[ft^3/s, cubic foot per second]

Inflow	**Rate (ft^3/s)**	**Outflow**	**Rate (ft^3/s)**
Effective recharge[1]	315.6	Ground-water discharge to the ocean and to constant-head boundaries on west and northwest edge of modeled area	145
Leakage from streams and ponds into the aquifer	7.7	Ground-water discharge to streams	169.1
Flow into the aquifer from constant-head boundaries	7.7	Pumpage	11.2
		Loss from cranberry bogs	5.8
Total inflow	331.0	Total outflow	331.1

[1] Effective recharge = Precipitation - Evapotranspiration.

Determination of Specific Yield

Estimates of storage coefficient and specific yield of the Plymouth-Carver aquifer were needed for transient calibration of the model. The value for the storage coefficient was assigned on the basis of model results for another aquifer in Massachusetts (de Lima and Olimpio, 1989). As discussed previously, values of specific yield calculated from aquifer tests ranged from 0.02 to 0.35. From within this range of values, a single value for the specific yield was assigned in the model on the basis of hydrograph analysis, as explained later in this section.

Sensitivity testing of a model of a small aquifer near Woburn, Mass., about 50 miles north of the study area, resulted in virtually no difference in the response of the aquifer to pumping for storage coefficients ranging from 10^{-2} to 10^{-4} (de Lima, U.S. Geological Survey, oral commun., 1988). Consequently, a value of 5×10^{-3} was chosen for the storage coefficient for model layers 2, 3, and 4 for simulation of those layers under fully saturated conditions.

The specific yield of the aquifer was estimated from measured water-level altitudes in observation well PWW-22 (fig. 19) and the average annual rate of recharge (27 in.) used for the calibrated steady-state model. The hydrograph of observation well PWW-22 shows that, except for a short period in early 1965, water levels declined continuously from 1964 through 1966. During the 8 months from May through December 1964, the water level in PWW-22 declined about 4.2 ft. This 8-month decline extrapolates to an annual decline of about 6.3 ft (76 in.). Specific yield can be calculated by dividing the average annual recharge to the aquifer (27 in/yr from the calibrated steady-state model) by the total water-level decline during a year of no recharge. Therefore, the calculated specific yield of the Plymouth-Carver aquifer near observation well PWW-22 is 0.35. Additional calculations of aquifer specific yield near well PWW-22 were made using hydrograph recessions measured during two other periods of no recharge--from June through November 1983, and from June through December 1984 (fig. 20). During the 6 months from June through November 1983, the water level in well PWW-22 declined 4.5 ft. This 6-month decline, extrapolated for an additional 6 months of decline would result in an annual decline of about 9.0 ft or 108 in. Therefore, the specific yield of the aquifer near observation well PWW-22 was calculated as 0.25. During the 7 months from June through December 1984, the water level in PWW-22 declined 4.6 ft. This 7-month decline, extrapolated for an additional 5 months of decline would result in an annual decline of about 7.9 ft or 94.8 in. Therefore, the specific yield of the aquifer near observation well PWW-22 was calculated as 0.28. Results of these calculations of specific yield of the Plymouth-Carver aquifer near observation well PWW-22 are summarized in table 12.

The average of the three specific-yield values for sediments near well PWW-22 is 0.29. The method of calculating the specific yield assumes that no recharge occurred during the periods of hydrograph recession. Probably some recharge did occur during each of the

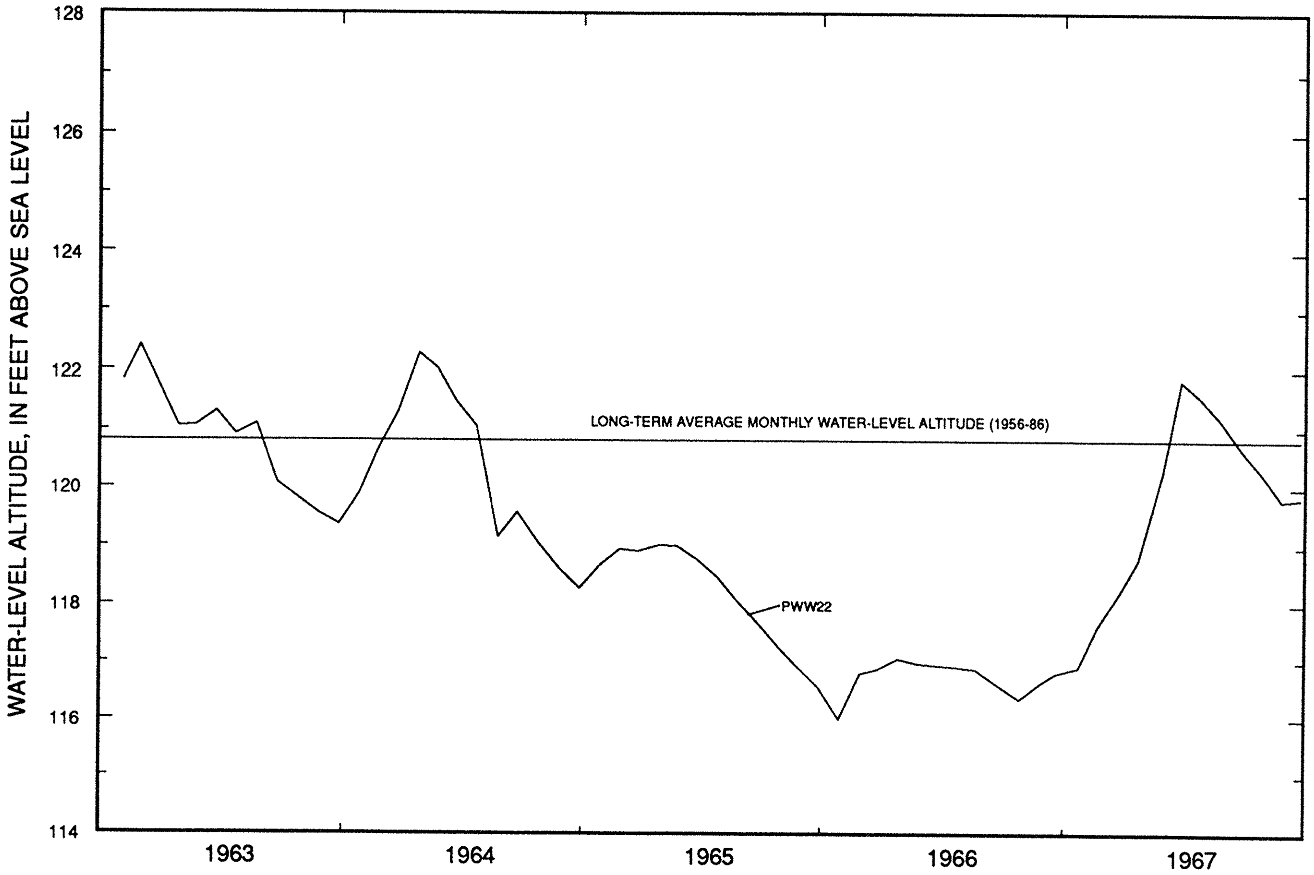

Figure 19.--Water-level altitude in observation well PWW-22, 1963-67.

three periods shown. Therefore, the actual value of specific yield of the aquifer near well PWW-22 probably is slightly less than 0.29; a value of 0.28 was chosen for specific yield of the aquifer for transient calibration of the model.

Calibration and Validation

The model was first calibrated to transient conditions on the basis of the water-level decline measured in one well during 1964-66. After the model was calibrated to transient conditions, the model's ability to simulate transient conditions was further tested by simulating hydrologic conditions that occurred during the early 1980s by comparing simulated declines to measured declines in water levels in 11 observation wells distributed throughout the modeled area.

The model was calibrated for transient conditions by testing how accurately it predicted water-level declines at well PWW-22 during the 1964-66 drought (fig. 21). The "assumed hydrograph recession" in figure 21 shows the expected water-level decline if recharge during January 1965 had not occurred. The water-level decline in well PWW-22 from August 1964, when water levels were at their average steady-state level, through the 2-year no-recharge period was simulated in the model. Though the simulated water levels are several feet lower than the measured water levels, the simulated recession closely parallels both the measured decline from August 1964 to January 1965, and the assumed recession that would have occurred after January 1965. The match between measured and simulated water-level declines in well PWW-22 indicates that, at least in the vicinity of observation well PWW-22, the calibrated model closely simulates transient water-level response in the aquifer.

The model's ability to simulate transient conditions was further tested after transient calibration by comparing measured and simulated water levels in 11 observation wells located throughout the basin from December 1983 to January 1985. As indicated on the hydrograph of well PWW-22 (fig. 20), recharge caused

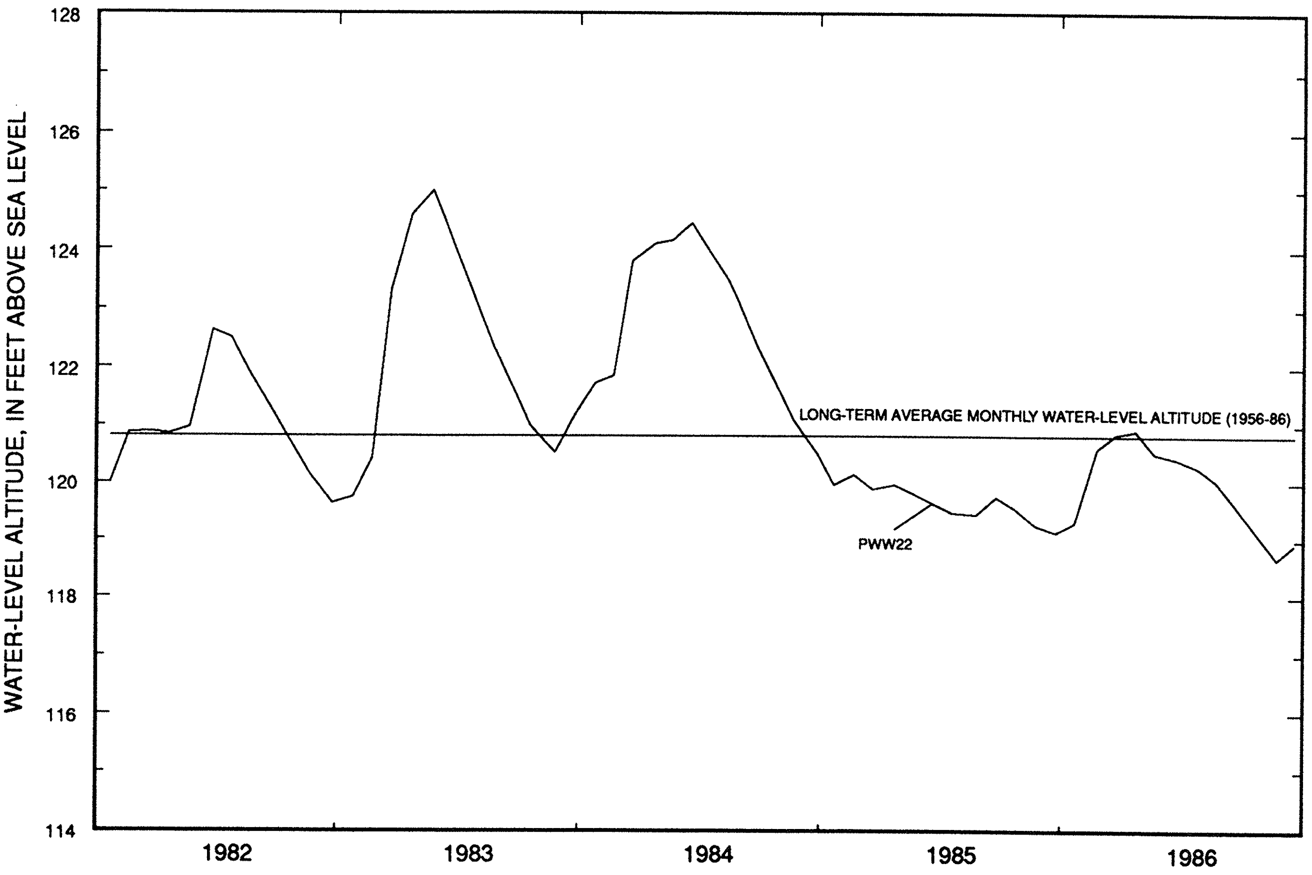

Figure 20.--Water-level altitude in observation well PWW-22, 1982-87.

Table 12.--*Calculated values of specific yield of Plymouth-Carver aquifer near observation well PWW-22*

Period of hydrograph recession	Water-level decline (ft)	Extrapolated decline during 1 year		Specific yield
		Feet	Inches	
May - December 1964	4.2	6.3	76	0.35
June - November 1983	4.5	9.0	108	.25
June - December 1984	4.6	7.9	94.8	.28

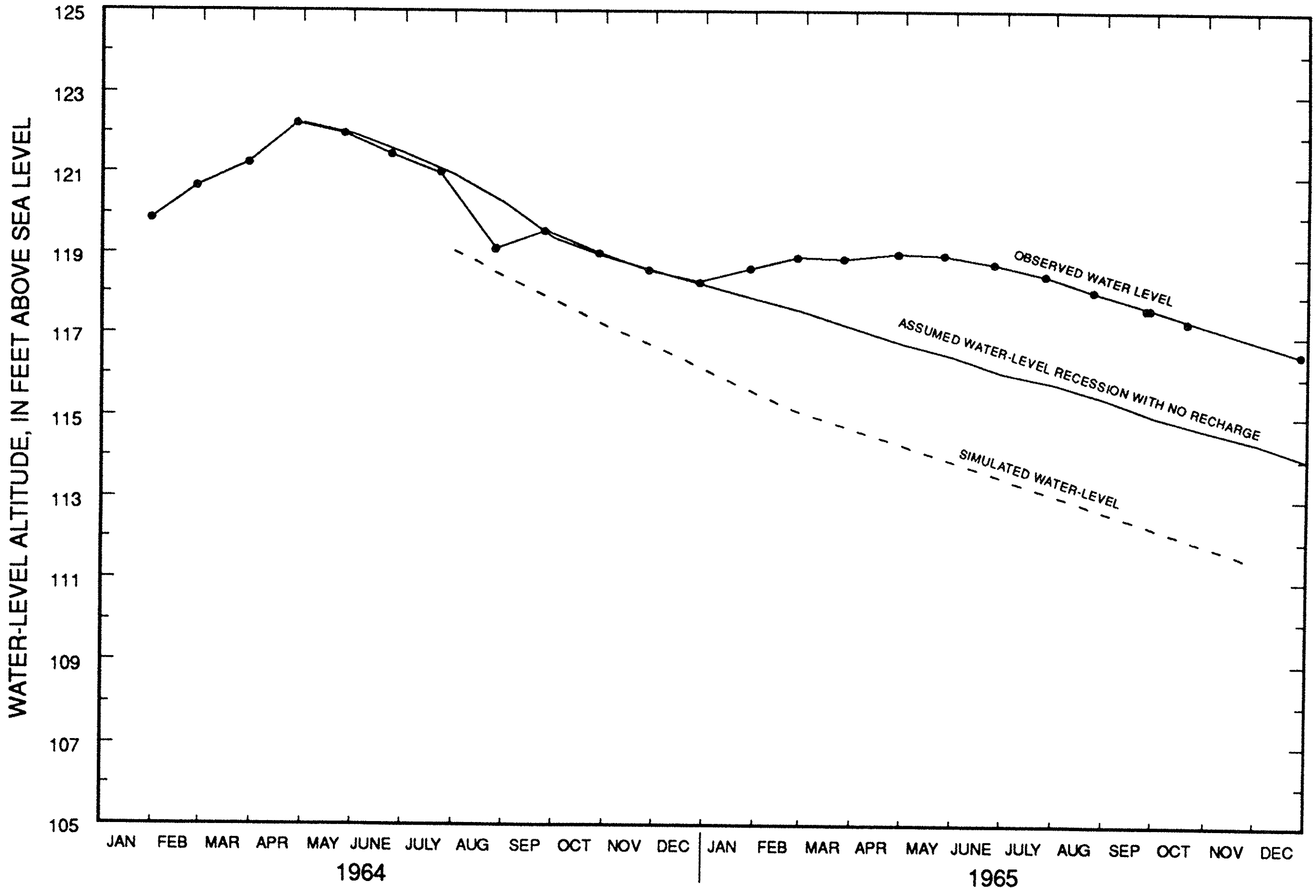

Figure 21.--Measured and simulated water levels in observation well PWW-22 during 1964-66 drought.

water levels in PWW-22 to rise from December 1983 through June 1984. During early July 1984, water levels in well PWW-22 were near the maximum attained during the 30 years of record (fig. 11). From July 1984 through January 1985, virtually no recharge occurred, and water levels in the well declined steadily. Other observation wells show a similar pattern of water-level fluctuation.

The water level in well PWW-22 in December 1983 was close to the long-term average water level in that well. As indicated on the hydrograph (fig. 20), the water level in PWW-22 rose about 3.6 ft from December 1983 through July 1984. Using this rise of 3.6 ft and the specific yield of 0.28 determined previously, the calculated recharge rate above the long-term average rate of 27 in/yr simulated in the calibrated model during those 7 months was 12.8 in. or 21.9 in/yr. Therefore, raising the water level 3.6 ft above the long-term average level requires simulation of the 27 in/yr of average recharge necessary to sustain long-term average conditions plus simulation of an additional 22 in/yr for those 7 months (for a total of 49 in/yr of recharge for 7 months). Following the 7-month recharge period, a 1-year period of no recharge was simulated. Measured and simulated water levels in 11 observation wells located throughout the basin are shown in figure 22. The generally good agreement between measured and simulated water levels indicates that the model closely simulates response to natural variation in recharge throughout the aquifer.

It is preferable to calibrate a model that is designed to simulate the effects of large-scale development of an aquifer with data collected during pumping of large-capacity wells or from large-scale pumping tests, because the stress on the aquifer during the pumping is similar to that which will be simulated. Because there is no large-scale pumping of the Plymouth-Carver aquifer, no data of this type are available to aid in calibration. Therefore, it is uncertain how well the model will simulate the effects of large-scale development of the aquifer.

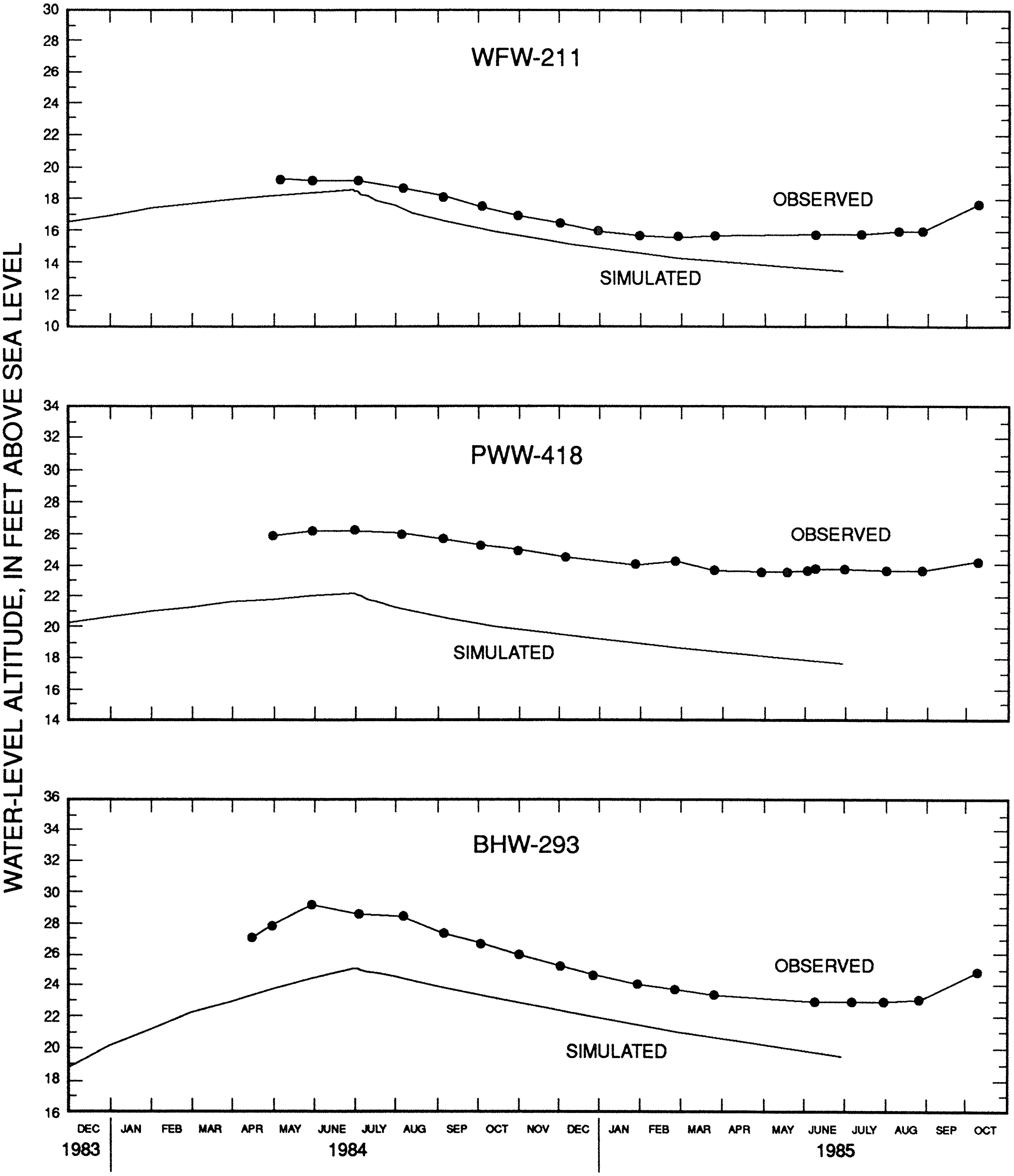

Figure 22.--Measured and simulated water-level altitudes in 11 observation wells screened in Plymouth-Carver aquifer, December 1983 through January 1986.

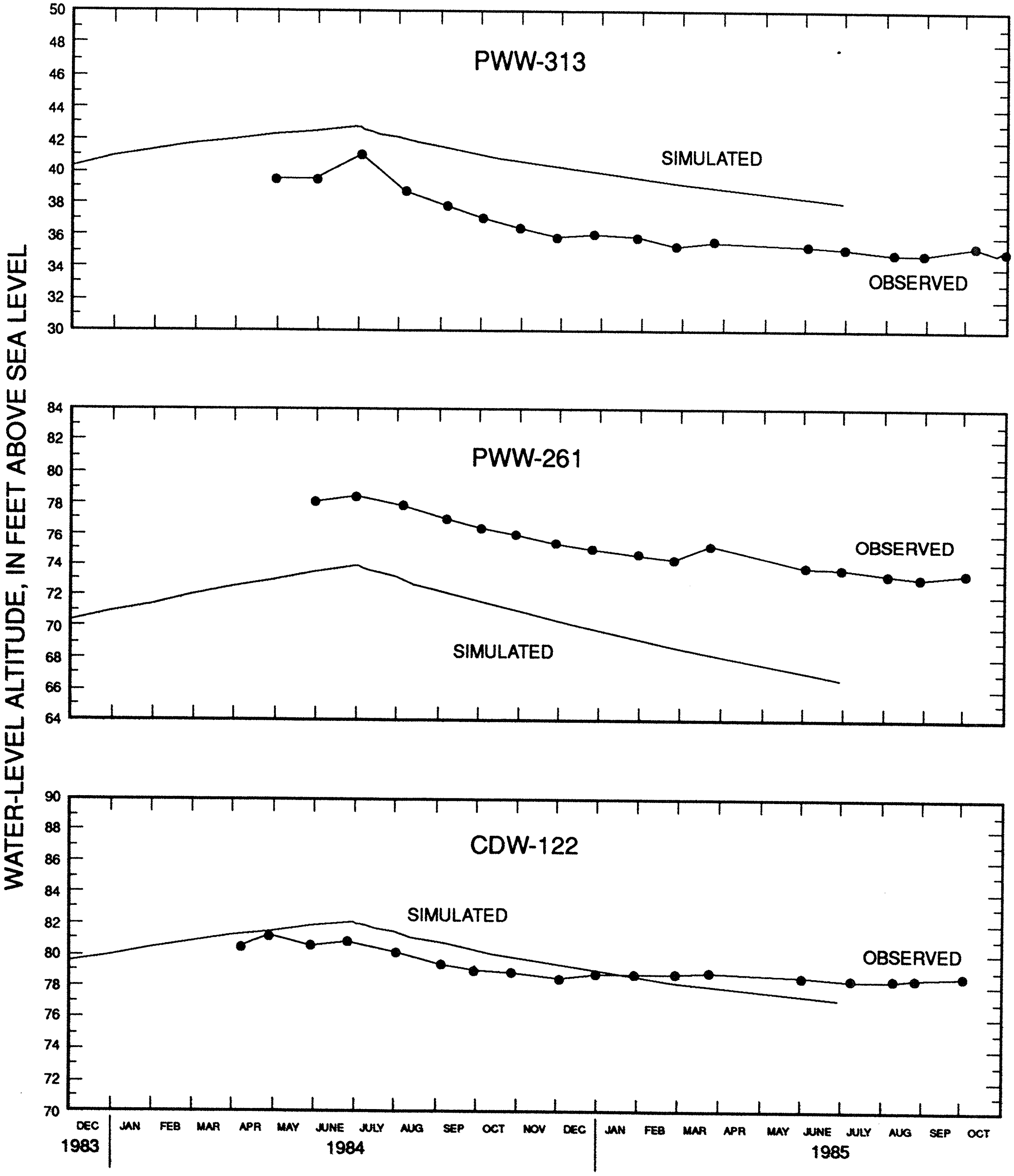

Figure 22.--Measured and simulated water-level altitudes in 11 observation wells screened in Plymouth-Carver aquifer, December 1983 through January 1986--Continued.

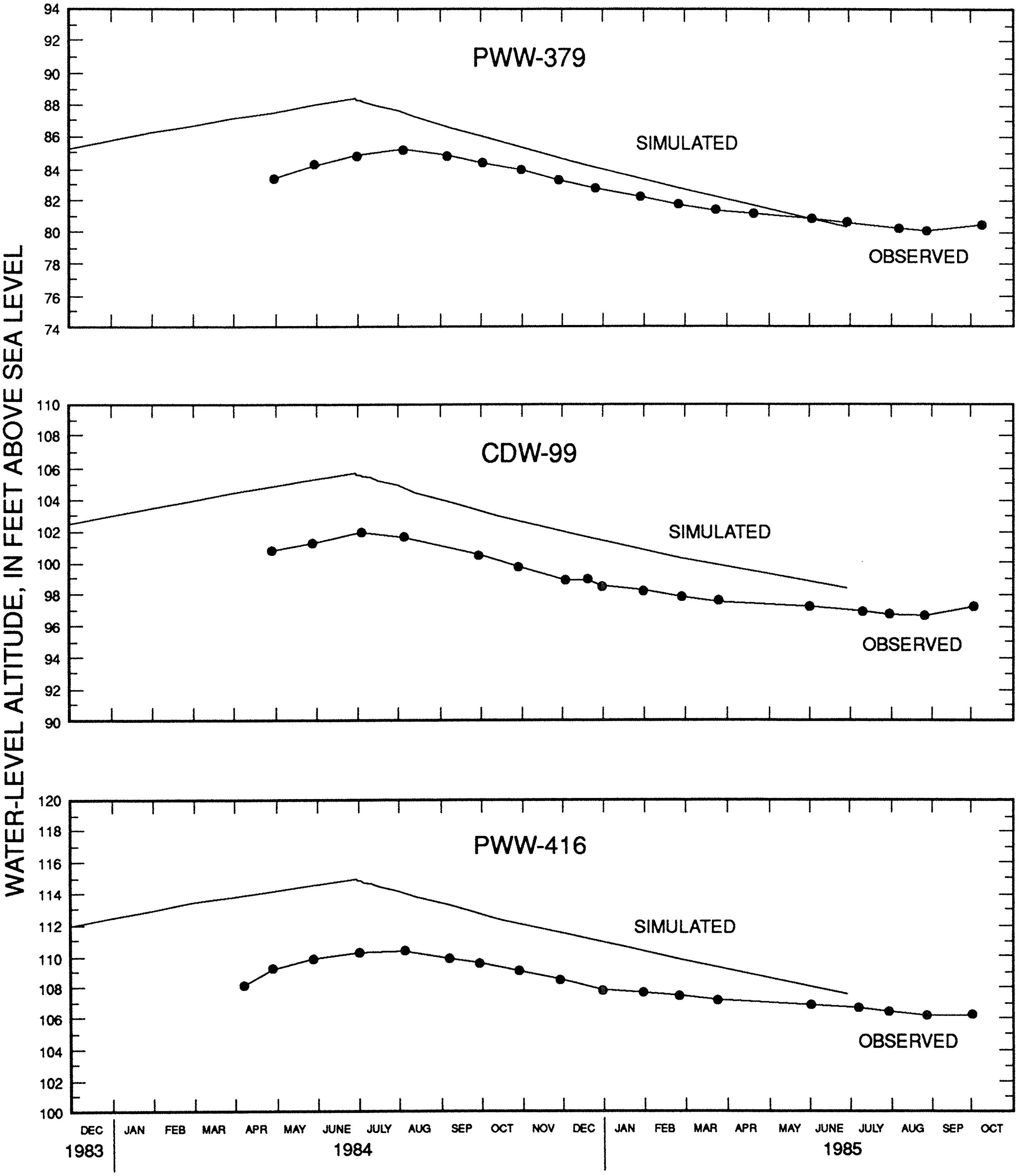

Figure 22.--Measured and simulated water-level altitudes in 11 observation wells screened in Plymouth-Carver aquifer, December 1983 through January 1986--Continued.

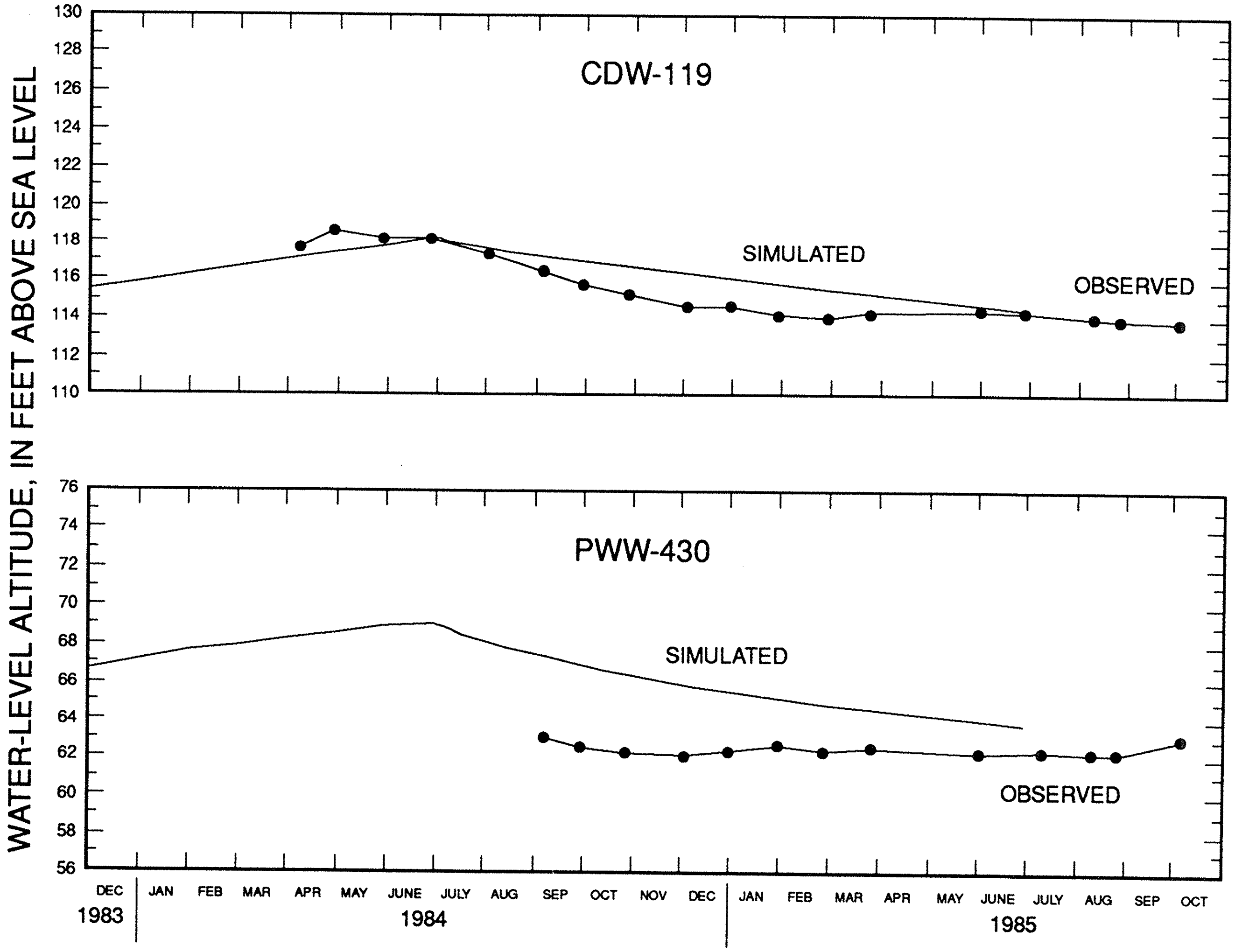

Figure 22.--Measured and simulated water-level altitudes in 11 observation wells screened in Plymouth-Carver aquifer, December 1983 through January 1986--Continued.

Table 13.--*Summary of water-level residuals for simulated recharge rates of 18, 24, 27, and 30 inches per year*

[ft, feet; in/yr, inches per year; total number of observations = 101]

	Water-level residuals (ft) for recharge rate (in/yr)			
	18	**24**	**27**	**30**
Absolute value of the mean of the water-level residuals[1], in feet	4.64	1.52	0.15	1.76
Mean of the absolute values of the water-level residuals, in feet	5.44	3.56	3.46	3.82
Standard deviation of the water-level residuals, in feet	5.03	4.52	4.42	4.54

[1] Water-level residual = Measured water level minus simulated water level.

Model Sensitivity to Variations in Input Parameters

A sensitivity analysis of the Plymouth-Carver ground-water-flow model was made determine the response of the model to changes in input parameters such as recharge rate, hydraulic conductivity and specific yield of the unconsolidated deposits, and streambed conductance. This analysis evaluated the degree to which errors in estimation of those factors affect the accuracy of the model. For example, assume that only small differences occur in simulated hydraulic heads and ground-water discharge between simulations in which the rate of recharge was 20 percent larger or smaller than that used for steady-state calibration, but that large differences occur in simulated hydraulic heads and ground-water discharge between simulations in which the recharge rate was 50 percent larger or smaller than that used for steady-state calibration. If the recharge rate used in the calibrated model is considered accurate within ± 10 percent, then the model would be insensitive to the recharge rate within this 20-percent range, and there would be no advantage to refining the recharge rate further for input to the model. However, if the recharge rate is considered accurate only within a range of ± 70 percent, the model would be sensitive to the recharge rate, and further data collection to improve definition of the recharge rate would be warranted.

Sensitivity analysis of the ground-water-flow model entailed uniformly increasing and decreasing values of input parameters and noting the response of water levels and rates of ground-water discharge to streams to the input variation. As was used during calibration, three statistical measures were used to evaluate the sensitivity of the model to changes in model inputs: (1) The absolute value of the mean of the residuals between measured and simulated water levels and ground-water discharge, (2) the mean of the absolute value of the residuals between measured and simulated water levels and ground-water discharge, and (3) the standard deviation of the residuals between measured and simulated water levels and ground-water discharge.

Average Annual Recharge

Sensitivity of the model to the average annual rate of recharge to the outwash-plain, morainal, and kame deposits was tested by simulating recharge rates of 18, 24, 27, and 30 in/yr. The rate of 27 in/yr was used for the calibrated steady-state model. The range of simulated recharge rates approximates the range of recharge rates estimated for glacial deposits in southeastern Massachusetts (Knott and Olimpio, 1986).

Results of the four simulations are summarized in tables 13, 14, and 15. Detailed information pertaining to the results summarized in tables 13 and 14 are provided in tables 23 and 24 at the end of the report. A comparison of water-level residuals for the four simulated rates of recharge is shown in table 13. Measured water levels in observation wells and ponds in the Plymouth-Carver aquifer and simulated water levels for these four recharge rates, and a comparison of the water-level residuals are shown in table 23. The

Table 14.--*Summary of ground-water-discharge residuals for simulated recharge rates of 18, 24, 27, and 30 inches per year*

[ft^3/s, cubic foot per second; in/yr, inches per year]

	Discharge residual (ft^3/s) for recharge rate (in/yr)			
	18	24	27	30
Absolute value of the mean of the discharge residuals[1], in cubic feet per second	7.3	2.8	0.5	2.0
Mean of the absolute values of the discharge residuals, in cubic feet per second	7.6	3.3	2.2	3.4
Standard deviation of the discharge residuals, in cubic feet per second	5.6	3.0	3.0	4.1

[1] Discharge residual = measured ground-water-discharge minus simulated ground-water-discharge.

absolute value of the mean of the water-level residuals (table 13), for example, for the four recharge rates are 4.64 ft for the rate of 18 in/yr, 1.52 ft for the rate of 24 in/yr, 0.15 ft for the rate of 27 in/yr, and 1.76 ft for the rate of 30 in/yr. All three statistical measures indicate that the recharge rate of 27 in/yr resulted in the best agreement between measured and simulated water levels; the most conclusive evidence is provided by the absolute value of the mean of the water level residuals.

As with the calibrated model, the ratio of the water-level residuals to the total relief in the water table (125 ft) was used to compare the significance of the differences in residuals. For example, the mean of the absolute values of the water-level residuals for the calibrated model was about 2.8 percent (3.46 ft/125 ft (table 13)) of the total relief of the water table, whereas the mean of the absolute value of the water-level residuals for the simulations with recharge rates of 18, 24, and 30 in/yr are 4.4, 2.8, and 3.1 percent of the total relief in the water table, respectively. A mean of the absolute values of the water-level residuals for the calibrated model that was less than about 5 percent of the total relief of the water table was considered to indicate excellent overall agreement between measured and simulated water levels, and a value less than about 10 percent was considered acceptable. Means of the absolute values of the water-level residuals were less than 5 percent of the total relief of the water table for all four recharge rates, indicating excellent overall agreement. Therefore, simulated water levels were insensitive to recharge rates from 18 through 30 in/yr.

Table 14 shows the ground-water-discharge residuals for the four simulated rates of recharge. Table 24 shows measured and simulated ground-water discharge to streams resulting from the four recharge rates summarized in table 14. The significance of the differences in the discharge residuals is determined by comparing the ratio of the residual to the total rate of ground-water-discharge to streams measured in the modeled area. As previously indicated total stream discharge from the modeled area on July 21-22, 1986, was about 139 ft^3/s (table 10). Consequently, the mean of the absolute value of the discharge residuals for the calibrated model was about 1.6 percent [2.2 ft^3/s ÷ 139 ft^3/s (table 10)] of the total ground-water discharge to streams in the modeled area, whereas the mean of the absolute value of the discharge residuals for the simulations with recharge rates of 18, 24, and 30 in/yr were 5.5, 2.4, and 2.4 percent of the total ground-water discharge, respectively. A value less than about 5 percent was considered to indicate excellent overall agreement between measured and simulated discharges, and a value less than about 10 percent was considered acceptable. Values for recharge rates of 24, 27, and 30 in/yr were less than 5 percent, and the value for a recharge rate of 18 in/yr was less than 10 percent, indicating excellent overall agreement for recharge rates of 24, 27, and 30 in/yr, and good agreement for a recharge rate of 18 in/yr. Therefore, the ground-water-discharge residuals indicated that ground-water discharge to streams in the model was insensitive to rates of recharge of 18 to 30 in/yr.

Comparison of the simulated ground-water budgets of the Plymouth-Carver aquifer for the four simulated recharge rates (table 15) indicates that the percentage of recharge that discharges to streams increased only from about 46 percent [((107.8 ft^3/s) ÷ (235.3 ft^3/s)) x 100] for a recharge rate of 18 in/yr to about 53 percent for a recharge rate of 30 in/yr [((192.0 ft^3/s)) ÷ (364.8 ft^3/s) x 100].

Horizontal Hydraulic Conductivity of Unconsolidated Deposits

Sensitivity of the model to the horizontal hydraulic conductivity of the outwash-plain, morainal, and kame deposits was tested by simulating the range of hydraulic-conductivity values that might prevail in the outwash plains and moraines of southeastern Massachusetts. The values tested were multiples of the values of hydraulic conductivity used for each model cell in the calibrated steady-state model. The multiples were 0.2, 0.5, 1.0, 2.0, and 5.0.

Results of the five simulations are summarized in tables 16, 17, and 18. Detailed information pertaining to the results summarized in tables 16 and 17 are provided in tables 25 and 26 at the end of the report. Table 16 shows the water-level residuals for the five simulated hydraulic-conductivity values. Simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for the multiples of hydraulic conductivity, and comparison of the water-level residuals are given in table 25. Comparison of the three statistical measures for simulations indicates that the hydraulic-conductivity values used in the calibrated steady-state simulation (multiple of 1.0) resulted in the best match of residuals. An increase or a decrease in hydraulic conductivity increased the water-level residuals. For example, the standard deviation of the water-level residuals increased from

Table 15--*Simulated ground-water budgets of the Plymouth-Carver aquifer for average annual recharge rates of 18, 24, 27, and 30 inches per year*

[ft^3/s, cubic foot per second; in/yr, inches per year]

Inflow					Outflow				
	Inflow (ft^3/s) for simulated recharge rate of					Outflow (ft^3/s) for simulated recharge rate of			
	18	24 (in/yr)	27	30		18	24 (inches per year)	27	30
Recharge from precipitation	208.5	279.9	315.6	351.3	Ground-water discharge to the ocean and to constant-head boundaries on western and northwestern edges of modeled area	113.2	134.2	145.0	155.8
Leakage from streams and ponds into the aquifer	16.0	9.4	7.7	6.4	Ground-water discharge to streams	107.8	146.7	169.1	192.0
Flow into the aquifer from constant-head boundaries	10.8	8.5	7.7	7.0	Pumpage	[1]8.5	11.2	11.2	11.2
					Loss from cranberry bogs	5.8	5.8	5.8	5.8
Total inflow	235.3	297.8	331.0	364.7	Total outflow	235.3	297.9	331.1	364.8

[1] Some pumping wells go dry during simulation; once those wells go dry, no pumping from them is simulated.

Table 16.--*Summary of water-level residuals for multiples of the horizontal hydraulic conductivity of the unconsolidated deposits used in the calibrated, steady-state model.*

[ft, feet]

	Water-level residuals (ft) for indicated multiple of hydraulic conductivity				
	0.2	0.5	1.0	2.0	5.0
Absolute value of the mean of the water-level residuals[1], in feet	31.67	10.26	0.15	7.08	14.75
Mean of the absolute values of the water-level residuals, in feet	33.08	10.84	3.46	7.80	15.12
Standard deviation of the water-level residuals, in feet	22.53	8.01	4.42	6.39	10.32

[1] Water-level residual = Measured water level - simulated water level.

4.42 for a hydraulic-conductivity multiple of 1.0 to 6.39 ft and 10.32 ft for multiples of 2.0 and 5.0 respectively, and the standard deviation increased from 4.42 to 8.01 and 22.53 for hydraulic-conductivity multiples of 0.5 and 0.2, respectively.

The comparative significance of these differences in water-level residuals can be assessed using the ratio of the residual to the total relief in the water table. The mean of the absolute value of the water-level residuals for the calibrated model (hydraulic-conductivity multiple of 1.0) was about 2.8 percent (3.46 ft/125 ft) of the total relief of the water table, whereas the means of the absolute value of the water-level residuals for multiples of 0.2, 0.5, 2.0, and 5.0 were 26.5, 8.7, 6.2, and 12.1 percent, respectively, of the total relief in the water table. The results for hydraulic-conductivity multiples of 0.2 and 5.0 exceeded the 10-percent criterion considered to indicate a good overall agreement between measured and simulated water levels. Therefore, for these two multiples, the agreement is considered poor. The results for multiples of 0.5 and 2.0 were 5 to 10 percent--a range considered to indicate a good overall agreement. Simulated water levels were considerably more sensitive to variation in hydraulic conductivity of the outwash-plain and morainal deposits than to variation in recharge within the probable ranges of values of hydraulic conductivity and recharge that would occur in the study area. Therefore, in future studies in the area, additional investigation of the variation in hydraulic conductivity of the outwash-plain and morainal deposits is warranted.

Table 17 shows the ground-water-discharge residuals for the five simulated hydraulic conductivity values.

Table 17.--*Summary of ground-water-discharge residuals for multiples of the horizontal hydraulic conductivity of unconsolidated deposits used in the calibrated, steady-state model.*

[ft^3/s, cubic foot per second]

	Discharge residuals, (ft^3/s) for indicated multiple of hydraulic conductivity				
	0.2	0.5	1.0	2.0	5.0
Absolute value of the mean of the discharge residuals[1], in cubic feet per second	3.8	1.7	0.5	3.7	10.8
Mean of the absolute values of the discharge residuals, in cubic feet per second	3.8	2.5	2.2	4.5	12.4
Standard deviation of the discharge residuals, in cubic feet per second	3.5	3.0	3.0	4.4	10.2

[1] Discharge residual = measured ground-water discharge - simulated ground-water discharge.

Table 25 compares the measured and simulated ground-water discharge to streams resulting from the five multiples of hydraulic conductivity summarized in table 17. The same comparative significance of the differences in the discharge residuals was made by comparing the ratio of the residual to the total rate of ground-water discharge to streams measured in the modeled area. The mean of the absolute value of the discharge residuals for the calibrated model (multiple of 1.0) was about 1.6 percent (2.2 $ft^3/s \div 139\ ft^3/s$) (table 17) of the total ground-water-discharge to streams in the modeled area, whereas the mean of the absolute value of the discharge residuals for the simulations using hydraulic-conductivity multiples of 0.2, 0.5, 2.0, and 5.0 were 2.7, 1.8, 3.2, and 8.9 percent of the total ground-water discharge, respectively. Given the criteria used to assess the agreement between measured and simulated ground-water discharge, hydraulic conductivity multiples of 0.2, 0.5, and 2.0 resulted in excellent agreement, and a multiple of 5.0 resulted in good agreement. Therefore, ground-water discharge to streams in the model is insensitive to hydraulic conductivity values ranging from 0.2 to 5.0 times those used in the calibrated steady-state model. The reason why discharge values are not affected significantly throughout the range of hydraulic conductivity values tested probably is because those values are fairly high and, therefore, do not significantly restrict discharge.

Comparison of the ground-water budgets of the aquifer for the five hydraulic-conductivity simulations (table 18) indicates that the total simulated outflow from the modeled area for a multiple of 0.2 was only about 4 percent smaller than that of the calibrated model, and the simulated outflow for a multiple of 2.0 was about 12 percent larger. Total outflow for the hydraulic-conductivity multiple of 5.0 was about 51 percent larger than the outflow from the calibrated model.

Streambed Conductance

Sensitivity of the model to the streambed conductance was tested by simulating the range of anticipated values of streambed conductance that probably occurs in the study area. Simulations were done with streambed conductances that were multiples of 0.1, 0.2, 1.0, 5.0, and 10.0 of the values used in the calibrated steady-state model.

Results of the five simulations are summarized in tables 19, 20, and 21. Detailed information pertaining to the results summarized in tables 19 and 20 are provided in tables 27 and 28 at the end of the report. Table 19 shows the water-level residuals for the five multiples of streambed conductance. Table 27 shows simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for these multiples of streambed conductance, and a comparison of the water-level residuals. Statistical analysis indicated that there was little difference between residuals for multiples from 1.0 through 10. However, for streambed-conductance multiples less than 1.0, the water-level residuals increased as the multiple decreased. The insensitivity of the model to streambed-conductance multiples from 1.0 through 10 occurred because the streambed conductivity is sufficiently high that it does not impede ground-water discharge.

The mean of the absolute value of the water-level residuals for the calibrated model (multiple of 1.0) was about 2.8 percent (3.46 ft/125 ft (table 19) of the total relief of the water table. The means of the absolute values of the water-level residuals for simulations with streambed-conductance multiples of 0.1, 0.2, 5.0, and 10.0, were 7.4, 4.9, 2.7, and 2.7 percent, respectively, of the total relief in the water table. The sensitivity of simulated water levels increased as the streambed conductance decreased. However, the agreement between measured and simulated water levels was excellent for streambed-conductance multiples from 0.2 through 10.

Table 20 shows the ground-water-discharge residuals for the five simulated multiples of streambed conductance. Table 28 compares the measured and simulated ground-water discharge to streams resulting from the five multiples of streambed conductance. The same comparative significance of the differences in the discharge residuals was made by comparing the ratio of the residual to the total rate of ground-water discharge to streams measured in the modeled area (table 20). The mean of the absolute value of the discharge residuals for the calibrated model (multiple of 1.0) was about 1.6 percent (2.2 $ft^3/s \div 139\ ft^3/s$) of the total ground-water discharge to streams in the modeled area, whereas the mean of the absolute value of the discharge residuals for the simulations with streambed-conductance multiples of 0.1, 0.2, 5.0, and 10.0 were 2.6, 2.2, 1.9, and 2.2 percent of the total ground-water discharge, respectively. Simulations with streambed-conductance multiples from 0.1 through 10 of the calibrated-model values resulted in excellent agreement. Ground-water budgets for the five streambed-conductance simulations (table 21) show that the total outflow from the modeled area

Table 18.--*Simulated ground-water budgets of the Plymouth-Carver aquifer for multiples of horizontal hydraulic conductivity values used in the calibrated, steady-state model*

[ft³/s, cubic foot per second]

Inflow						Outflow					
	Inflow (ft^3/s) for indicated multiple of hydraulic conductivity						Outflow (ft^3/s) for indicated multiple of hydraulic conductivity				
	0.2	0.5	1.0	2.0	5.0		0.2	0.5	1.0	2.0	5.0
Recharge from precipitation	315.6	315.6	315.6	315.6	315.6	Ground-water discharge to the ocean and to constant-head boundaries on western and northwestern edges of modeled area	95.5	116.9	145.0	194.6	320.7
Leakage from streams and ponds into the aquifer	.7	2.1	7.7	30.8	111.1	Ground-water discharge to streams	206.9	186.1	169.1	158.5	165.4
Flow into the aquifer from constant-head boundaries	.3	2.1	7.7	23.7	73.6	Pumpage	8.5	11.2	11.2	11.2	8.5
						Loss from cranberry bogs	5.8	5.8	5.8	5.8	5.8
Total inflow	316.6	319.8	331.0	370.1	500.3	Total outflow	316.7	320.0	331.1	370.1	500.4

Table 19.--*Summary of water-level residuals for multiples of streambed conductance used in the calibrated, steady-state model.*

[ft, feet]

	Water-level residuals (ft) for indicated multiple of streambed conductance				
	0.1	0.2	1.0	5.0	10.0
Absolute value of the mean of the water-level residuals[1], in feet	8.47	4.60	0.15	0.91	0.96
Mean of the absolute values of the water-level residuals, in feet	9.31	6.15	3.46	3.34	3.33
Standard deviation of the water-level residuals, in feet	7.05	5.60	4.42	4.18	4.15

[1] Water-level residual = measured water level - simulated water level.

changed by less than 5 percent throughout the range of multiples of 0.1 to 10.

Aquifer Specific Yield

Sensitivity of the model to specific yield also was tested. For this analysis, four model simulations were compared. In all four simulations, water-level declines during the 2-year period of no recharge that occurred during the 1964-66 drought were simulated. Results were compared to measured water-level declines in observation well PWW-22. The specific-yield values for the four simulations were 0.10, 0.20, 0.28 (the calibrated-model value) and 0.40. These values represent the maximum range of specific yields that would likely be found in outwash plain and morainal deposits in the study area. Results of the four simulations are shown in figure 23.

As shown in figure 23, a specific yield of 0.28 resulted in the best match between the slopes of measured and simulated water-level declines. On the basis of the calculated recession, the water-level decline in well PWW-22 would have been about 5.0 ft from August 1964 to August 1965 if no recharge had occurred (fig. 23). Simulated declines during that same period for the four values of specific yield of 0.10, 0.20, 0.28, and 0.40 were about 11.2, 7.5, 5.9, and 4.5 ft, respectively. Therefore, the model is relatively insensitive to values of specific yield ranging from about 0.20

Table 20.--*Summary of ground-water-discharge residuals for multiples of the streambed conductance used in the calibrated, steady-state model.*

[ft^3/s, cubic foot per second]

	Discharge residuals (ft^3/s) for indicated multiple of streambed conductance				
	0.1	0.2	1.0	5.0	10.0
Absolute value of the mean of the discharge residuals[1], in cubic feet per second	2.8	1.8	0.5	0.2	0.3
Mean of the absolute values of the discharge residuals, in cubic feet per second	3.6	3.0	2.2	2.7	3.0
Standard deviation of the discharge residuals, in cubic feet per second	3.8	3.5	3.0	3.4	3.8

[1] Discharge residual = measured ground-water discharge - simulated ground-water discharge.

Table 21.--*Comparison of simulated ground-water budgets of the Plymouth-Carver aquifer for multiples of streambed conductance used in the calibrated, steady-state model*

[ft^3/s, cubic foot per second]

Inflow	Inflow (ft^3/s) for indicated multiple of conductance					Outflow	Outflow (ft^3/s) for indicated multiple of conductance				
	0.1	0.2	1.0	5.0	10.0		0.1	0.2	1.0	5.0	10.0
Recharge from precipitation	315.6	315.6	315.6	315.6	315.6	Ground-water discharge to the ocean and to constant-head boundaries on western and northwestern edges of modeled area	165.6	156.2	145.0	145.3	147.4
Leakage from streams and ponds into the aquifer	0.2	0.9	7.7	21.1	27.4	Ground-water discharge to streams	139.8	150.3	169.1	182.3	186.6
Flow into the aquifer from constant-head boundaries	6.5	7.0	7.7	7.9	7.9	Pumpage	11.2	11.2	11.2	11.2	11.2
						Loss from cranberry bogs	5.8	5.8	5.8	5.8	5.8
Total inflow	322.3	323.5	331.0	344.6	350.9	Total outflow	322.4	323.5	331.1	344.6	351.0

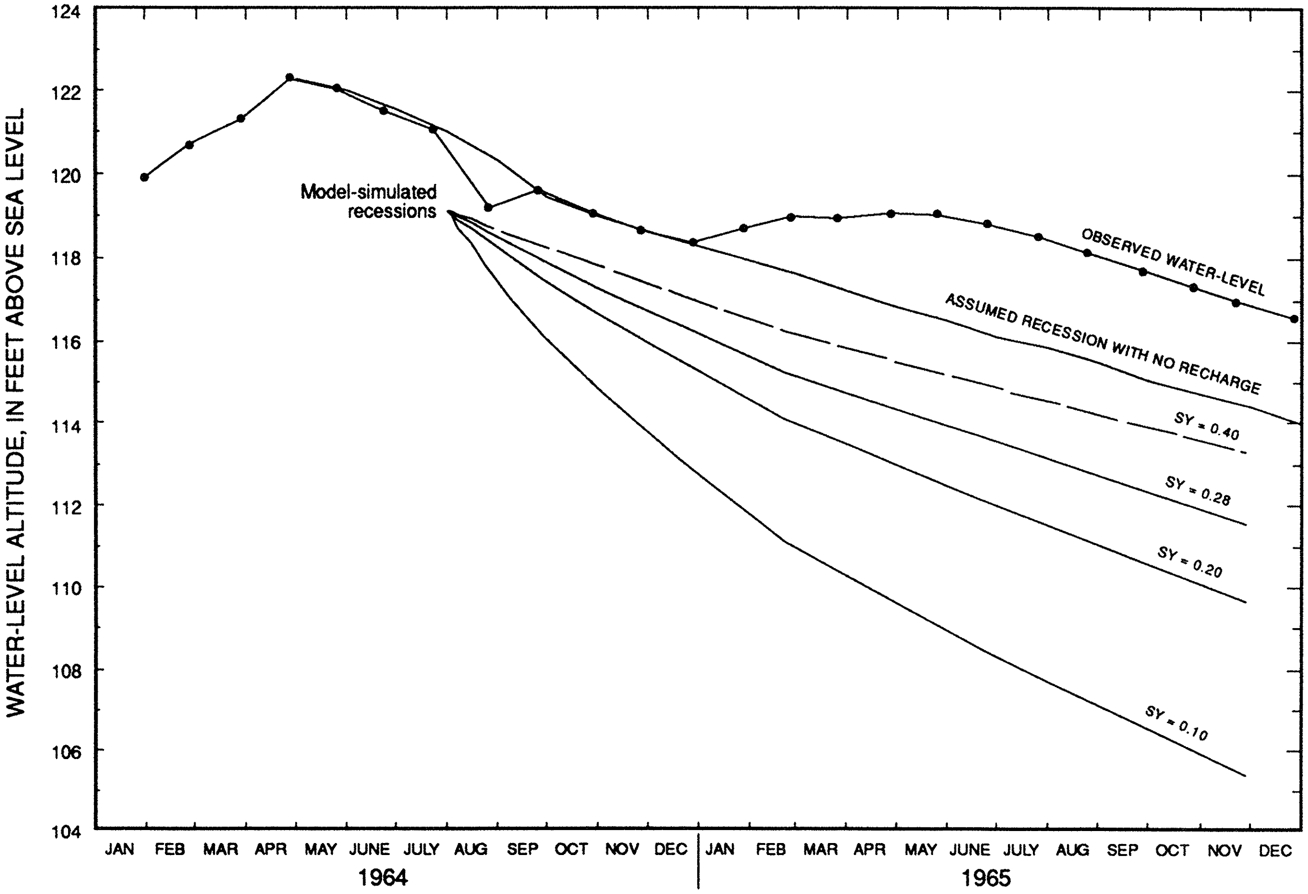

Figure 23.--Measured and simulated water-level declines in observation well PWW-22 for different values of specific yield in unconsolidated deposits.

through 0.40 in the vicinity of well PWW-22 for transient simulations of 1 year or less.

Simulation of Effects of Ground-Water Development Alternatives

Four hypothetical ground-water development alternatives were simulated with the model. The alternatives were designed to illustrate a variety of possible applications of the model as a tool for water-resource management in the study area. The alternatives discussed are only a few of the many possible alternatives for development and management of the aquifer; their inclusion in this report is not an endorsement of them. The alternatives simulate the effects of (1) Long-term drought on water levels at average 1980-85 pumping rates, (2) large-scale ground-water development in the northern part of the aquifer in which (2a) all pumping is consumptive or (2b) the water pumped is recharged artificially into the aquifer through infiltration ponds after treatment, (3) large-scale regional ground-water development, and (4) the effect of ground-water development on streamflow.

Simulation of Long-Term Drought

Beginning in about 1964, virtually no recharge occurred in the study area for 2 years. During this period, eastern Massachusetts experienced one of the worst droughts of the century (R.B. Lautzenheizer, State Climatologist, New England Climatic Service, written commun., 1988). The general effect of this period of no recharge on water levels in the Plymouth-Carver aquifer is shown on the long-term hydrograph of water-level fluctuations in observation well PWW-22 (fig. 11).

The model was used to simulate water-level declines in the Plymouth-Carver aquifer during a 2-year period of no recharge similar to that which occurred during the 1964-66 drought. The initial water levels for this simulation were the calibrated steady-state water levels, which approximated long-term average water levels in the aquifer. The pumping rate used was the average annual rate of pumping from public-supply and industrial wells during 1980-85; this was the same pumping rate that was used in the calibrated, steady-state model. Also simulated as part of the calibrated model was the long-term annual rate of loss of water attributable to cranberry-bog operations (table 7).

Simulated water-level declines at the end of the 2-year period are shown in figure 24. Water-level declines exceeded 5 ft throughout most of the aquifer and exceeded 10 ft in the central and northwestern parts of the aquifer. Total ground-water discharge to streams at the beginning of the simulation was 169.1 ft^3/s (table 11). By the end of the 2-year period of no recharge, ground-water discharge to streams had decreased by 54 percent to 77.4 ft^3/s.

Simulation of Large-Scale Pumping with and without Artificial Recharge

The effects of large-scale pumping with and without artificial recharge were evaluated by simulating two conditions: (1) All pumping is consumptive (no artificial recharge); and (2) all pumping in excess of the rate used in the calibrated steady-state model is recharged artificially after treatment back into the aquifer through infiltration ponds.

For both simulations, four arbitrarily selected wells were pumped at twice their rated capacities until steady-state conditions were achieved; these four wells were PWW-15, PWW-411, PWW-422, and PWW-541 (table 8, fig. 14). Pumping from these four wells was simulated in the calibrated steady-state model at 0.03, 0.9, 1.0, and 0.3 Mgal/d, respectively (table 8) (1 ft^3/s = 0.6462 Mgal/d). Pumping rates from these four wells, with and without artificial recharge, were 2.0, 5.8, 3.2, and 1.6 Mgal/d, (twice their rated capacities) respectively. The increases in pumping for these four wells from the rates simulated in the calibrated steady-state model were 2.0, 4.9, 2.2, and 1.3 Mgal/d, respectively. Total pumpage in the two simulations exceeded pumping in the calibrated steady-state model by 10.4 Mgal/d (16.1 ft^3/s).

Water-level declines attributable to pumping the four wells with all pumping consumptive (without artificial recharge) were 2 ft or more over an area of about 25 mi^2 (fig. 25). Water-level declines in the immediate vicinity of all four wells exceeded 8 ft. Ground-water discharge to streams in the modeled area decreased from 169.1 ft^3/s in the calibrated steady-state model to 158.4 ft^3/s.

In the pumping simulation with artificial recharge, all the water pumped in excess (10.4 Mgal/d) of that in the calibrated steady-state model was recharged artificially into a 2,000- by 2,000-ft area about 3,000 ft north of well PWW-422. The thickness of the unsaturated zone near the simulated recharge area ranges from about 40 to 65 ft. Simulated artificial recharge to the aquifer at a rate of 10.4 Mgal/d caused the water table directly beneath the recharge area to rise more than 40 ft (negative water-level declines in fig. 26). The combination of pumping and artificial recharge decreased ground-water discharge to streams by about 3.4 ft^3/s (from 169.1 ft^3/s in the calibrated steady-state model to 165.7 ft^3/s) but increased ground-water discharge to the ocean by 6 ft^3/s. Although the net withdrawal of water in this simulation was the same as that in the calibrated steady-state model, the ground-water-flow pattern in the aquifer was changed by redistributing natural ground-water discharge from the modeled area.

Simulation of Large-Scale Regional Withdrawal

Large-scale ground-water development of the aquifer was simulated for two hypothetical situations: (1) Increased pumping from 21 existing wells simulated in the calibrated steady-state model, and (2) increased pumping from 21 existing wells simulated in the calibrated steady-state model plus pumping from 15 additional wells located throughout the aquifer. Nearly every well simulated in the calibrated steady-state model was pumped at its design capacity for these simulations. Each of the 15 additional wells was pumped at a rate of 1 Mgal/d. Total pumping from wells simulated in the steady-state model was 17.8 Mgal/d, and total pumping from existing wells plus the 15 additional wells was 32.8 Mgal/d. Pumping in excess of that in the steady-state model was 10.6 Mgal/d for the simulation of increased pumping

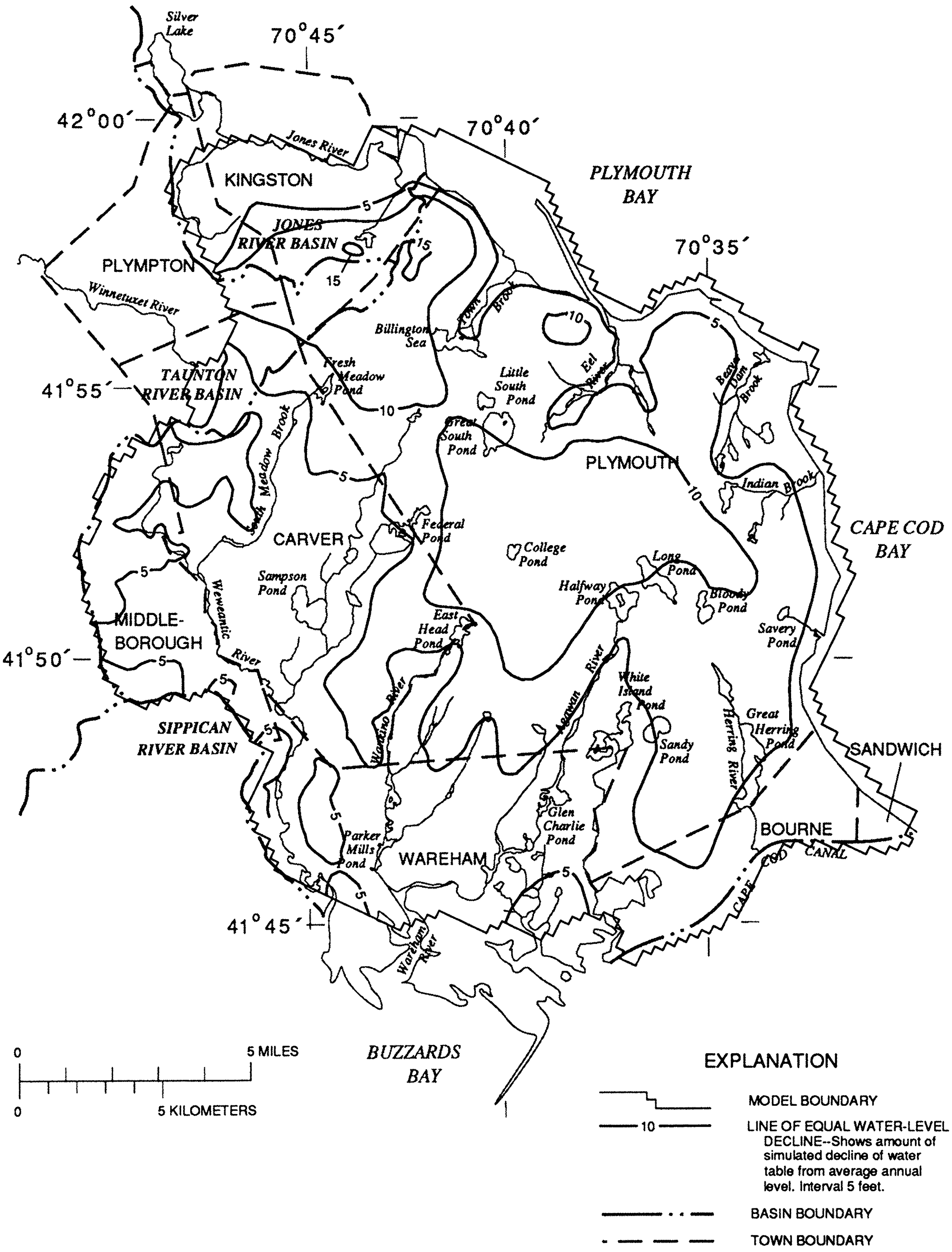

Figure 24.--Simulated water-level declines in Plymouth-Carver aquifer after 2-year period of no recharge.

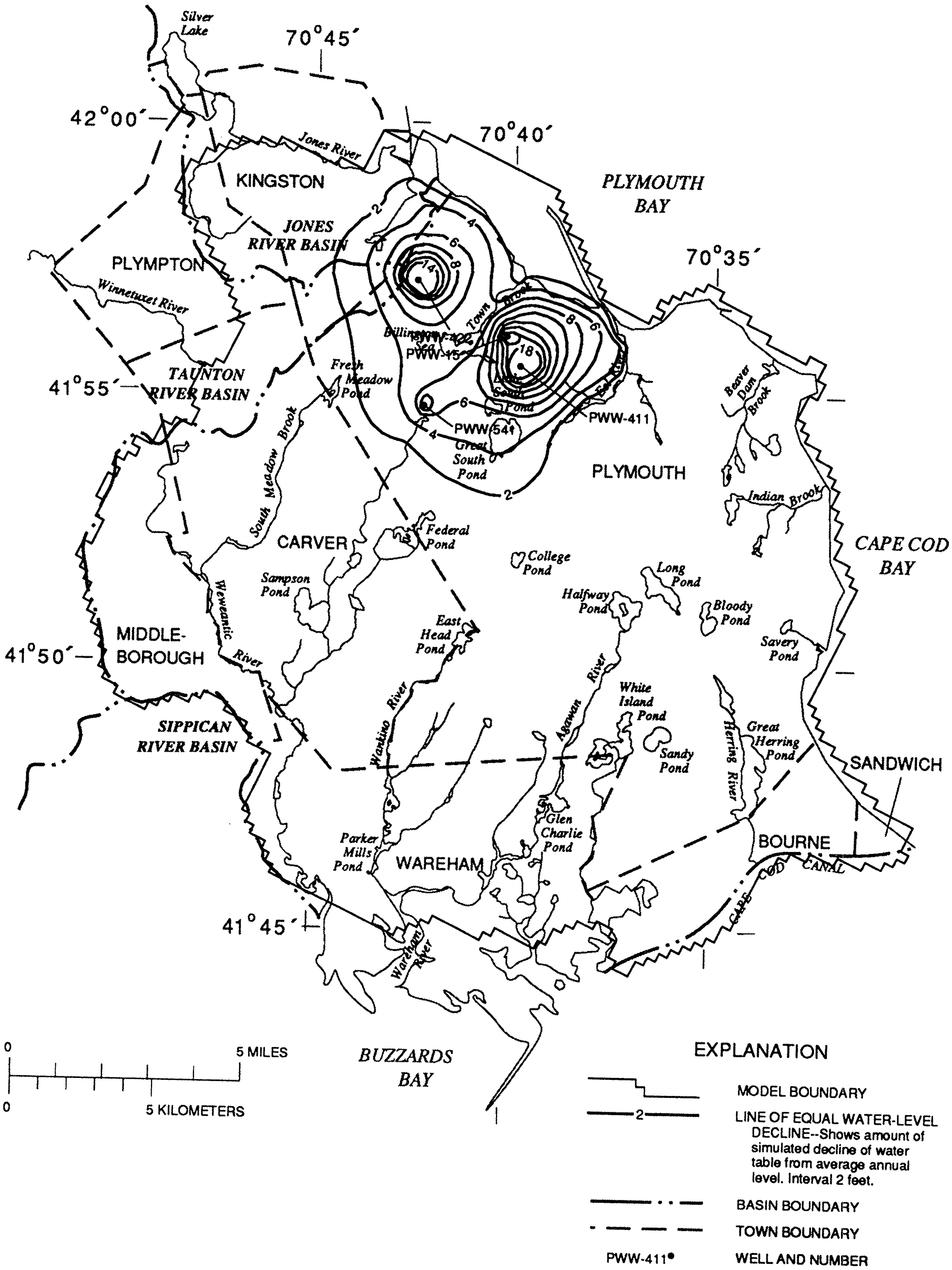

Figure 25.--Water-level declines in Plymouth-Carver aquifer for pumping simulation without artificial recharge and with twice the rated pumping capacity at four selected wells.

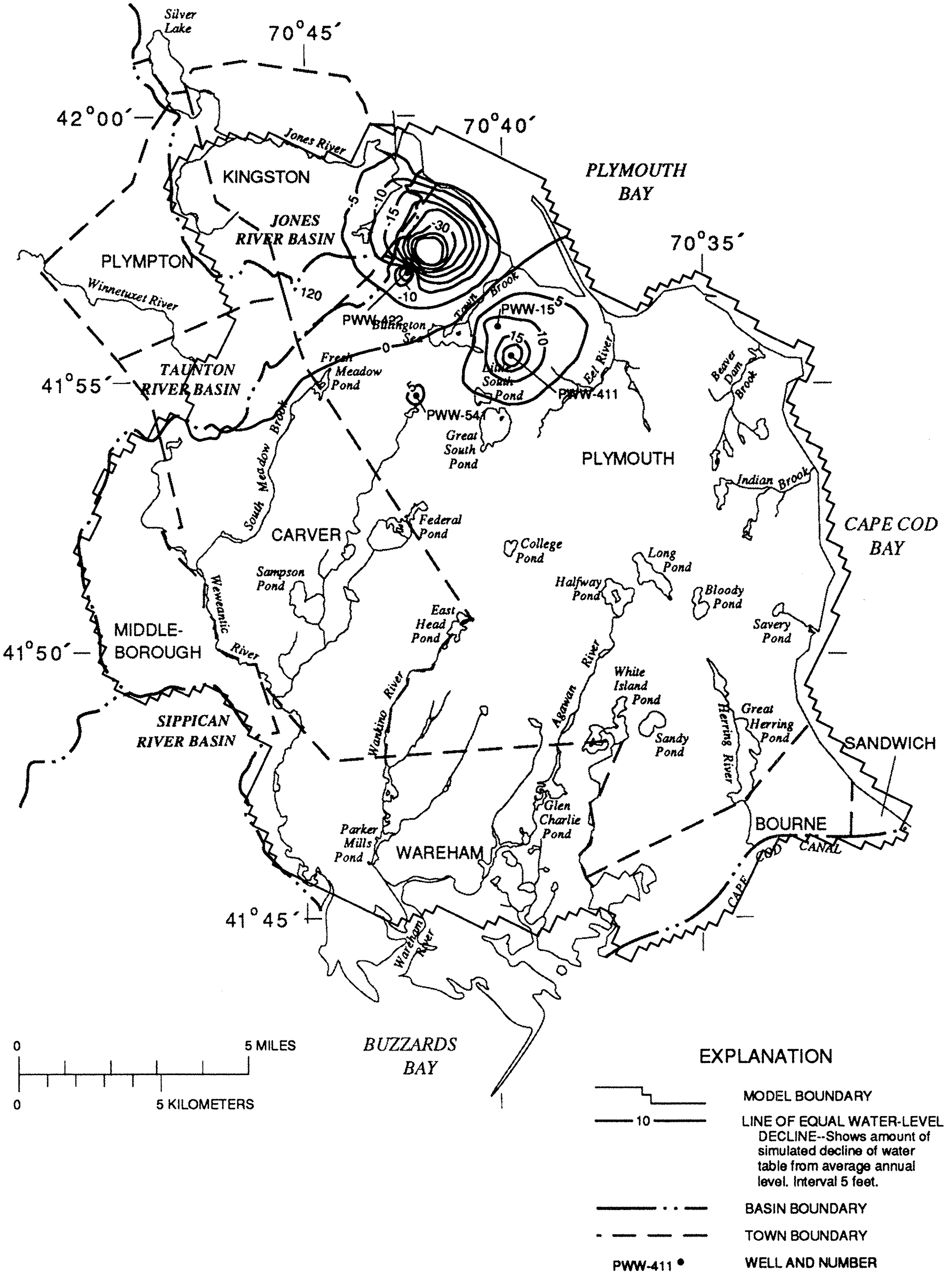

Figure 26.--Water-level declines in Plymouth-Carver aquifer for pumping simulation with artificial recharge and a pumping rate of 10.4 million gallons per day at four selected wells.

from existing wells and 25.6 Mgal/d for the simulation of increased pumping from existing wells and 15 additional wells.

Pumping the existing wells at nearly design capacity caused local water-level declines of more than 10 ft around some of the wells (fig. 27), but water-level declines were less than 2 ft throughout most of the aquifer. The additional 15 Mgal/d pumped from the 15 new wells significantly increased the area where water-level declines were more than 2 ft (fig. 28).

Simulation of Effect of Ground-Water Development on Streamflow

The model was used to simulate the effect of ground-water development on streamflow. This hypothetical situation demonstrates how the model might be used to aid agricultural water-use planning, development, and management.

A hypothetical well field is to be located in Myles Standish State Forest (fig. 2), along the eastern side of the Crane Brook basin (fig. 29). This basin contains 1,209 acres of cranberry bogs. The bog owners are concerned that withdrawals from the proposed well field may not leave enough water available for optimum cranberry production.

Maximum water demand for cranberry culture occurs in mid-December when all of the bogs are flooded simultaneously to prevent freezing of the plants. The flooding normally is completed in 5 to 10 days. On the basis of data from the U.S. Soil Conservation Service (U.S. Department of Agriculture, 1986), it was determined that 915 Mgal (183 Mgal/d for 5 days or 92 Mgal/d for 10 days) of water is required to flood the bogs in the basin. During years of normal precipitation, 95 percent of the streamflow in this basin is ground-water discharge. In some years, almost 100 percent of streamflow in December is ground-water discharge.

The model was used to simulate the effects of pumping from the proposed well field on streamflow during normal and extreme-drought conditions. Twelve wells were simulated in the well field (fig. 29). Four wells (1-4) were used to pump 2 Mgal/d; eight wells (1-8) were used to pump 4 Mgal/d, and 12 wells were used to pump 6 Mgal/d. Table 22 shows the simulated streamflow (ground-water discharge) resulting from these hypothetical situations.

During years of normal precipitation when streamflow is mainly ground-water discharge, 88 percent of the water required for a 10-day winter flood (94 percent for a 5-day flood) comes from storage in ponds, reservoirs, or ground water. During drought and well-field pumping conditions, streamflow is reduced, so more water must come from storage reservoirs. No attempt is made here to distribute the need for flood water or assess the adequacy of existing storage reservoirs to meet these demands. In general, the effects of pumping will be greatest near, and just downstream from, the well field. Figure 30 shows simulated streamflow in Crane Brook, from Federal Pond to the confluence with Sampson Brook (fig. 29), during various climatic and pumping conditions.

The model was not calibrated with any streamflow data from Sampson Brook, so the relative magnitudes of stream discharges after pumping may not be accurate. However, the simulation results provide an indication of the relative effects of several possible sets of climatic and pumping conditions on stream discharge in the subbasin.

Appraisal and Limitations of the Model

The ground-water-flow model discussed in this report simulated the three-dimensional distribution of regional water levels in the Plymouth-Carver aquifer and the distribution of regional ground-water discharge to streams and the ocean. The model was constructed using all available information on the geohydrologic characteristics of the aquifer. From a regional perspective, the model accurately simulated ground-water flow. However, measured water levels in the aquifer and ground-water discharge to streams differed somewhat from those simulated because of uncertainties regarding local aquifer geometry and hydraulic properties and because it was not possible to include all complexities of the aquifer in the model. The calibrated steady-state model simulated water levels in the aquifer and ground-water discharge to streams during periods when hydrologic conditions approximate the long-term average. Several hypothetical ground-water development and management alternatives were simulated to illustrate a variety of possible applications of the model as a tool for water-resources management in the study area. The alternatives discussed in this report are only a few of the many possible alternatives for development and management of the aquifer.

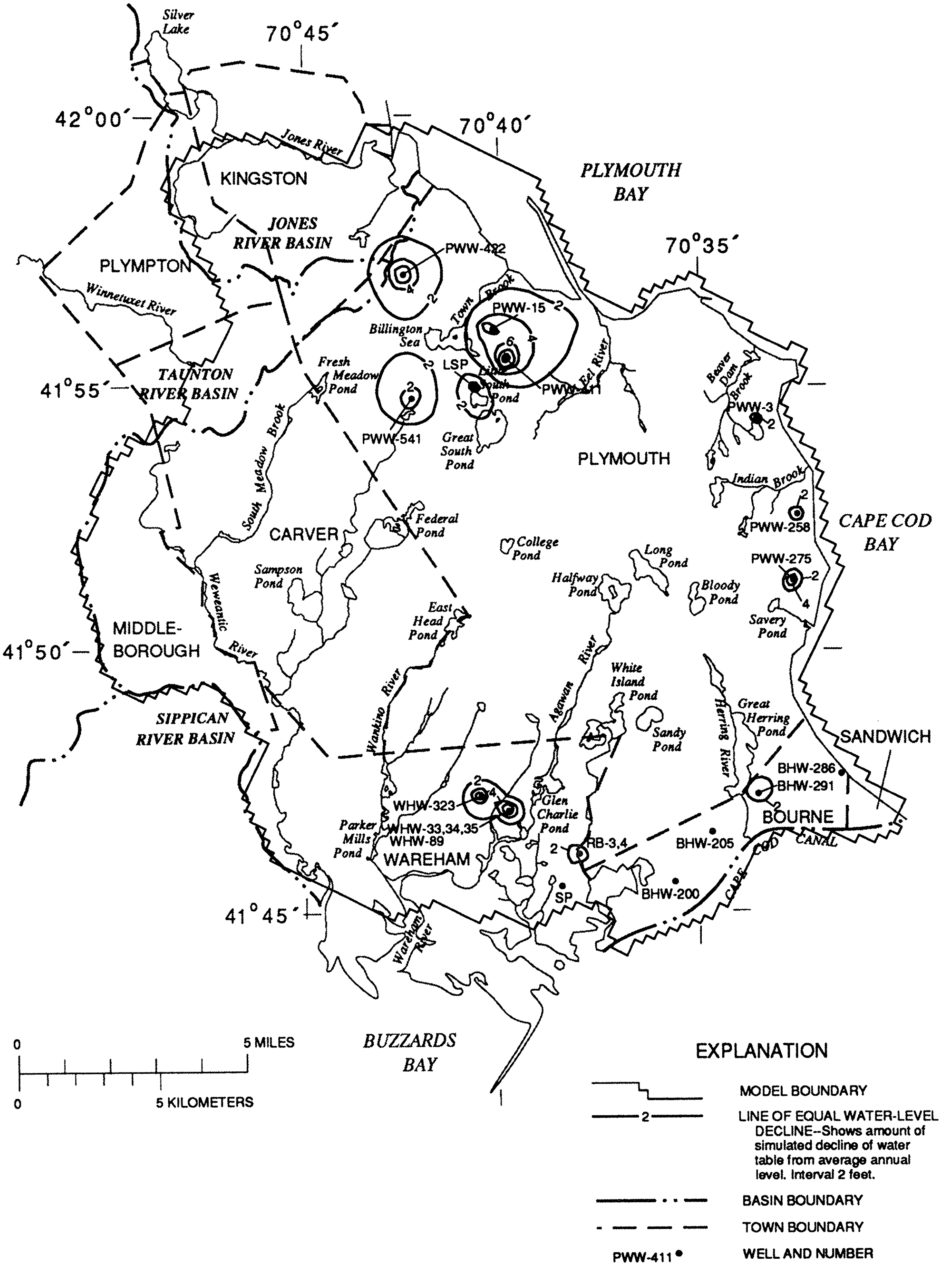

Figure 27.--Water-level declines in Plymouth-Carver aquifer for simulation of increased pumping from existing wells.

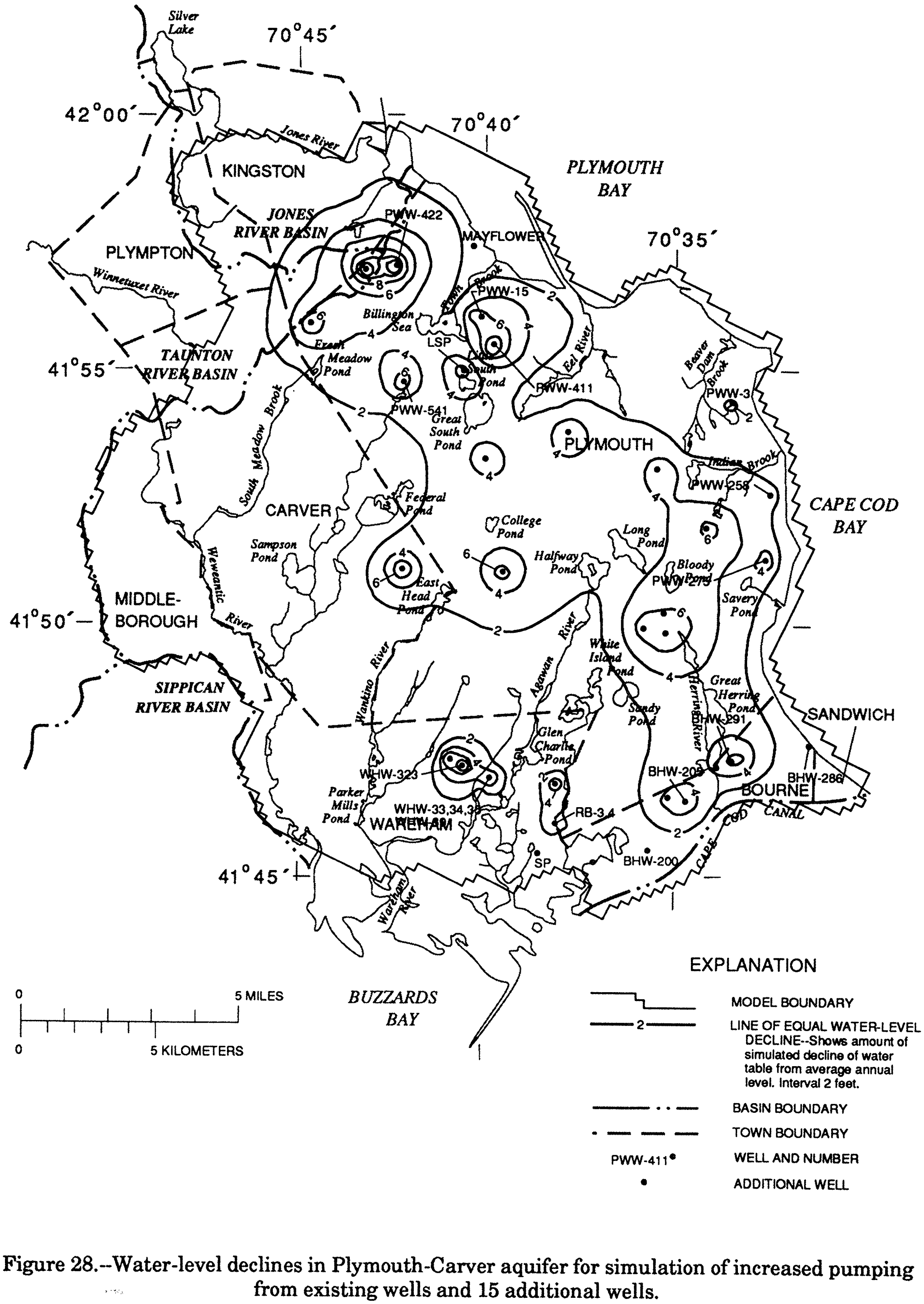

Figure 28.--Water-level declines in Plymouth-Carver aquifer for simulation of increased pumping from existing wells and 15 additional wells.

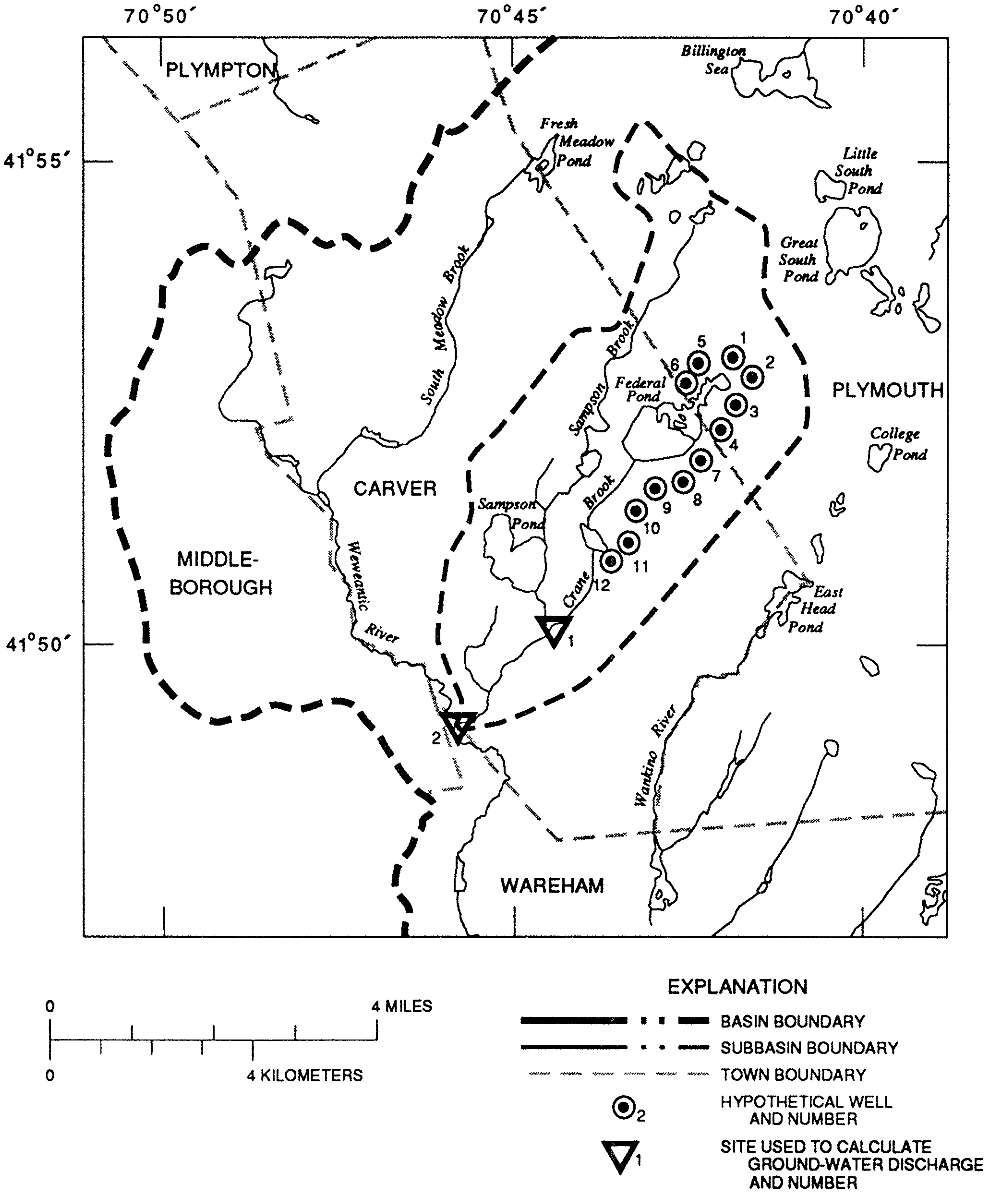

Figure 29.--Crane Brook basin, hypothetical well field, and sites used to calculate ground-water discharge.

The model was designed for use in estimating the regional effects of ground-water development on ground-water levels and streamflow. The model was not designed for precise simulation of well interference on a small scale or for well-field design. However, the model can provide information on hydraulic-boundary conditions for use in more detailed models of smaller areas within the Plymouth-Carver aquifer.

The model only approximates hydrologic conditions in the aquifer and has several limitations. One major limitation is that stream stage is held constant in the model during a simulation, even though actual stream stage changes continuously over time, and a stream may even dry up. Therefore, although an actual stream may go dry as a result of pumping, the simulated stream will continue to supply water to the wells at a rate partly dependent on the assigned stream stage. Because of this, simulated hydraulic heads in the aquifer could be higher than actual hydraulic heads, and simulated drawdowns in wells could be less than actual drawdowns.

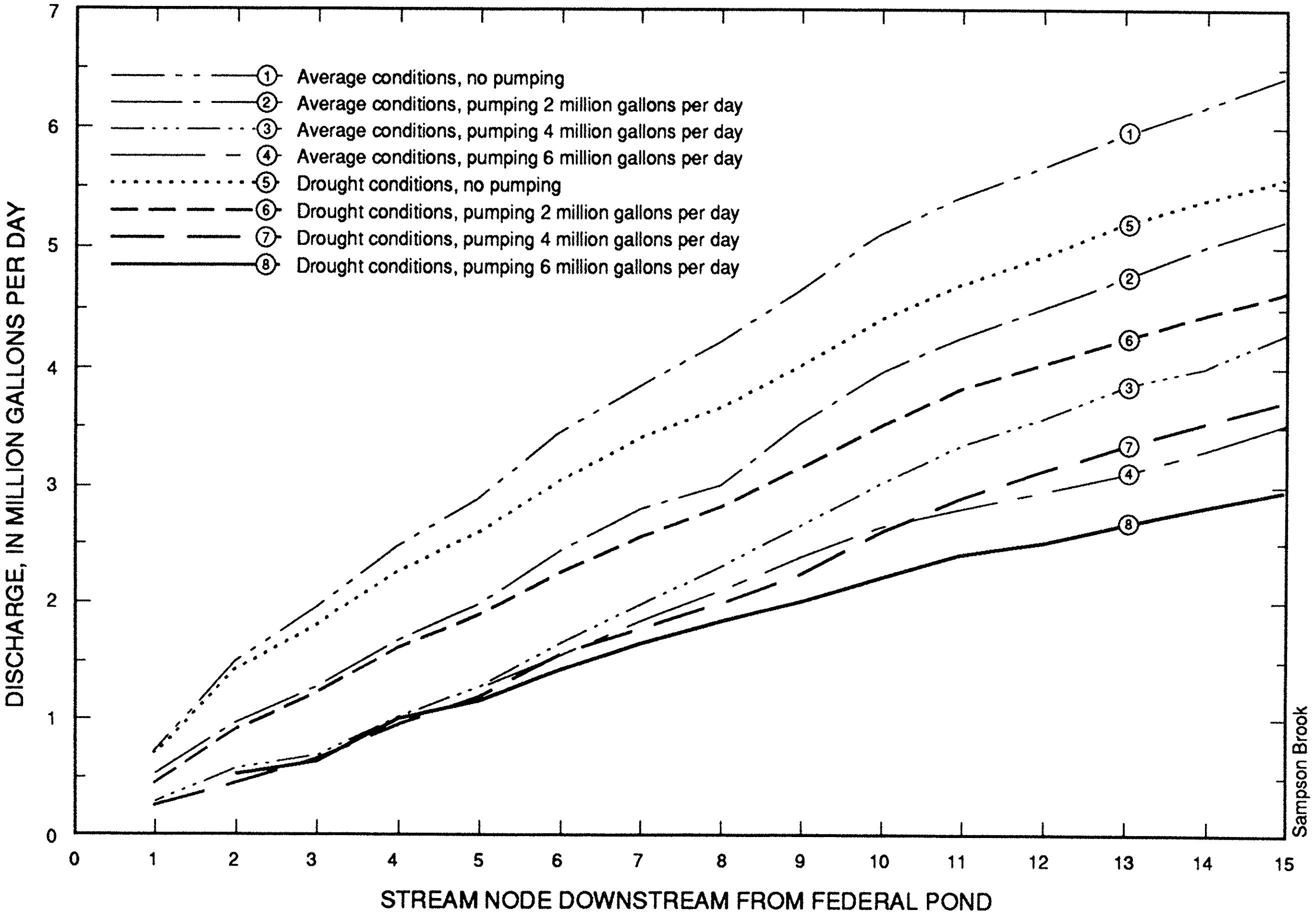

Figure 30.--Simulated streamflow in Crane Brook from Federal Pond to confluence with Sampson Brook.

A second major limitation of the model is the simplified representation of the distribution of vertical and horizontal hydraulic conductivity in the outwash-plain and morainal deposits. Lithologic logs of the aquifer suggest that these deposits become siltier with depth and that the horizontal hydraulic conductivity of these deposits, therefore, decreases with depth. This decrease was simulated in the model by assigning horizontal hydraulic conductivities for the outwash-plain and morainal deposits of 250, 150, 50, and 50 ft/d to model layers 1, 2, 3, and 4, respectively. At some locations, however, the deposits do not become siltier with depth, and the horizontal hydraulic conductivity remains high throughout the vertical section. Simulation of pumping from model layers 3 and 4 at these locations may result in overestimation of drawdown near the pumped well and underestimation of drawdown far from the pumped well. A possible refinement of the model would be to alter the horizontal hydraulic-conductivity matrices for each layer to account for areas where lithologic logs suggest that the deposits do not become siltier with depth.

Another limitation of the model is that the assigned values for the storage coefficient and specific yield are the same throughout the modeled area, although the actual values probably vary from location to location in the aquifer. Another possible refinement to the model would be to determine the areal variation in these values by field investigation and then vary values of storage coefficient and specific yield areally in the model accordingly. This would enable more accurate simulation of local transient response to variations in recharge and pumping.

A fourth limitation of the model is that it does not simulate the saltwater-freshwater interface along the coast. Therefore, the model does not provide a means of simulating the extent of saltwater intrusion due to pumping near the coast or to simulate changes in the salinity of water from the pumped wells.

Table 22.--*Simulated ground-water discharge to Crane Brook for various climatic and pumping conditions*

[Mgal/d, million gallons per day]

Climatic condition[1]	**Well field pumping rate (Mgal/d)**	**Simulated ground-water discharge (Mgal/d)**	
		S-1 (fig. 29)	**S-2 (fig. 29)**
Average	0	6.4	10.7
Average	2	5.2	9.3
Average	4	4.3	7.9
Average	6	3.5	7.1
Maximum drought	0	5.6	8.0
Maximum drought	2	4.7	6.9
Maximum drought	4	3.7	5.5
Maximum drought	6	3.0	4.7

[1] Average climatic conditions used in steady-state simulation; maximum drought used in transient simulation.
[2] Maximum drought refers to the conditions measured during 1964-66.

SUMMARY AND CONCLUSIONS

The Plymouth-Carver aquifer has an areal extent of 140 mi^2 and is composed predominantly of glacial sand and gravel. The area served by the aquifer is experiencing rapid population growth and increasing pressure to develop the aquifer as a regional source of water. Development decisions require an understanding of the regional behavior of the aquifer system.

The mostly unconfined Plymouth-Carver aquifer is underlain by granitic bedrock. The altitude of the bedrock surface ranges from 100 ft above sea level to about 200 ft below sea level. Surficial glacial deposits, mostly sand and gravel, are greater than 200 ft thick at some locations. The saturated thickness of the aquifer ranges from less than 20 to slightly greater than 200 ft. The hydraulic conductivity of sand and gravel deposits, as determined by aquifer tests, ranges from 55 to 313 ft/d. There is some evidence from lithologic logs that aquifer deposits are finer and siltier with depth. Some limited areas of artesian or perched-water-table conditions are caused by confining units.

The major source of aquifer recharge is precipitation. Recharge to the sand and gravel deposits, as determined from Eel River streamflow data, is 24.2 in/yr, but is probably somewhat higher than that. The altitude of the water table ranges from sea level to slightly higher than 125 ft above sea level. In general, groundwater flows radially from water-table highs and discharges to streams and the ocean.

In 1985, the withdrawal of water from the Plymouth-Carver aquifer averaged 59.6 Mgal/d. Agricultural use for cranberry culture accounted for 82 percent of total water use; public supplies accounted for 12 percent.

A three-dimensional, finite-difference ground-water-flow model was used to simulate regional flow in the aquifer. The model was designed to estimate the regional effects of ground-water development and should not be used for detailed analysis of hydrologic conditions in a small area. The model was calibrated to, and closely duplicates, measured water levels and groundwater discharge to streams. However, some inaccuracies are present because of uncertainties in aquifer geometry and hydraulic properties and from simplification of the modeled distribution of some hydraulic properties. The sensitivity of the model to changes in input values for recharge, hydraulic conductivity, specific yield, and streambed conductance was tested. The model was insensitive to rates of recharge of 18 to 30 in/yr. The model was more sensitive to hydraulic conductivity; simulations with horizontal hydraulic-conductivity multiples of 0.2 or less, and 5.0 or greater gave unacceptable results. Model sensitivity increased as streambed conductance decreased; however, good water-level agreement was achieved using streambed-conductance multipliers from 0.2 through 10. Specific yields of 0.20 to 0.40 provided close agreement of simulated water-level declines to the assumed decline at observation well PWW-22 during August 1965 through August 1966 if there had been no recharge during that period.

Four hypothetical ground-water development alternatives were simulated to demonstrate the use of the model. Simulation of a 2-year period of no recharge (an approximation of the maximum recorded drought) resulted in water-level declines larger than 5 ft throughout most of the study area and larger than 10 ft in the central and northwestern parts. Ground-water discharge to streams decreased 54 percent from average.

In a second simulation, four wells in the northern part of the area were pumped at 12.6 Mgal/d (10.4 Mgal/d larger than steady-state rates). When this pumping was treated as being consumptive (no artificial recharge), water levels declined 2 ft or more in an area of 25 mi^2, and ground-water discharge to streams decreased 6 percent from average. When the same amount was pumped and then recharged to the aquifer, water levels beneath a simulated infiltration pond rose more than 40 ft. Total ground-water discharge remained equal to steady-state discharge but was redistributed.

In a third simulation, all of the 21 existing production wells were pumped at nearly design capacity, a rate 10.6 Mgal/d greater than steady-state pumping. This rate then was increased to 25.6 Mgal/d greater than steady state by pumping from existing wells and from 15 additional wells distributed throughout the aquifer. Pumping from the existing wells at design capacity resulted in water-level declines of less than 2 ft throughout most of the aquifer. Increased pumping from the 15 additional wells substantially increased the area where water-level declines exceeded 2 ft.

In a final simulation, a well field close to a stream that drains the aquifer was pumped at 2, 4, and 6 Mgal/d. At a pumping rate of 6 Mgal/d, ground-water discharge to the stream decreased 34 percent during periods of normal precipitation and 56 percent during drought conditions.

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APPENDIX:
Results of Sensitivity Analyses of Ground-Water Flow Model

Table 23.--*Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for average annual recharge rates of 18, 24, 27, and 30 inches per year*

[ft, feet; in/yr, inches per year]

Model			Well or pond (fig. 18)	Water level (ft)				
Row	Column	Layer (fig. 16)		Measured	Simulated for recharge rate (in/yr)			
					18	24	27	30
8	78	1	PWW-501	5.88	0.78	0.91	0.97	1.03
19	40	1	PWW-502	81.63	77.55	80.14	81.86	83.24
19	48	1	PWW-261	74.05	64.77	67.99	70.30	72.46
20	44	1	PWW-503	77.41	71.74	76.33	76.09	77.74
22	77	1	PWW-313	38.59	35.25	39.12	39.25	40.49
23	67	1	PWW-241	67.73	57.86	63.06	64.29	66.19
23	77	1	PWW-285	36.60	37.05	43.67	41.49	42.87
24	49	1	PWW-215	81.90	78.84	83.10	84.14	86.64
24	52	1	PWW-516	77.03	76.48	79.25	81.38	83.44
24	66	1	PWW-242	72.59	60.91	67.77	67.56	69.52
24	73	1	PWW-245	57.79	49.98	53.82	55.66	57.42
25	28	1	PWW-413	123.73	109.35	117.07	119.03	122.22
25	72	1	PWW-240	71.78	56.61	58.99	63.91	66.15
26	46	1	PWW-504	99.03	88.35	83.38	90.99	94.03
27	66	1	PWW-243	79.20	69.26	76.19	77.59	80.15
28	38	1	PWW-505	118.30	102.52	107.33	110.40	113.09
28	47	1	PWW-306	101.66	91.98	94.78	97.65	100.42
28	68	1	PWW-244	87.20	69.81	74.98	78.93	81.75
29	46	1	PWW-305	102.07	93.14	97.95	98.99	101.77
30	26	1	PWW-517	123.73	115.07	120.26	122.93	125.48
30	52	1	PWW-506	98.88	90.77	94.95	97.77	100.49
30	66	1	PWW-379	82.05	75.78	82.23	85.35	88.33
34	34	1	PWW-22	120.98	111.92	116.68	119.18	121.52
34	53	1	PWW-315	102.71	94.82	100.52	103.69	106.74
35	71	1	PWW-509	70.45	69.32	75.74	78.82	81.73
36	24	1	CDW-119	114.70	111.67	114.08	115.84	117.21
37	46	1	PWW-507	112.95	105.36	110.19	112.74	115.24
38	78	1	PWW-414	64.07	59.69	64.12	68.56	71.28
39	50	1	PWW-416	108.18	103.01	109.01	111.75	114.63
40	82	1	PWW-518	52.39	48.20	53.52	56.53	59.11
41	92	1	PWW-319	21.04	15.53	16.98	19.23	20.42
42	29	1	CDW-120	92.60	97.00	99.20	98.53	99.04
42	92	1	PWW-418	22.16	18.28	19.07	22.54	23.90
44	31	1	CDW-121	103.23	99.50	100.06	102.31	103.23
44	82	1	PWW-253	46.59	47.22	52.23	54.62	56.96
46	61	1	PWW-510	98.53	90.23	96.80	99.92	102.94
46	84	1	PWW-251	43.60	42.19	46.87	49.10	51.29
47	56	1	PWW-511	101.01	95.47	102.69	104.38	107.18
49	83	1	PWW-513	47.75	44.73	48.81	50.76	52.68
51	40	1	BHW-126	99.95	87.02	87.82	87.98	88.30
51	50	1	CDW-99	98.92	96.53	100.37	103.27	105.39
51	59	1	PWW-415	91.34	88.62	93.15	96.06	98.38
53	82	1	PWW-514	48.22	45.35	48.25	49.64	51.03
53	84	1	PWW-520	47.02	41.97	45.72	46.88	48.45
54	55	1	CDW-123	83.97	86.03	90.01	89.90	91.16

Table 23.--*Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for average annual recharge rates of 18, 24, 27, and 30 inches per year*--Continued

Model			Well or pond (fig. 18)	Water level (ft)				
Row	Column	Layer (fig. 16)		Measured	Simulated for recharge rate (in/yr)			
					18	24	27	30
54	56	1	PWW-521	89.77	85.38	87.55	88.64	89.73
56	52	1	CDW-125	79.66	85.56	88.40	89.74	91.07
57	84	1	PWW-519	46.61	38.22	41.67	42.69	44.11
58	58	1	PWW-431	75.15	76.57	78.98	80.19	81.35
59	63	1	PWW-512	69.78	65.32	67.82	69.07	70.28
61	87	1	PWW-368	28.98	26.38	28.47	30.64	31.98
61	93	1	BHW-293	25.22	15.66	17.49	19.65	20.90
63	56	1	PWW-430	61.56	64.40	65.93	66.69	67.43
64	37	1	CDW-122	76.10	78.01	78.73	80.67	81.50
64	53	1	CDW-86	64.80	64.15	65.35	66.41	67.12
65	36	1	CDW-201	78.14	74.74	77.82	76.65	77.25
65	57	1	PWW-236	55.71	58.09	59.98	60.72	61.57
66	53	1	CDW-85	62.84	59.48	59.85	62.02	62.80
66	55	1	PWW-369	56.02	54.39	54.98	56.13	56.69
66	61	1	PWW-238	55.51	51.85	53.43	54.20	54.96
66	64	1	WFW-296	45.48	44.54	46.44	45.55	45.88
68	57	1	PWW-237	51.09	50.56	50.45	52.64	53.30
69	61	1	WFW-295	45.81	42.77	45.16	44.37	44.89
69	64	1	WFW-297	39.49	37.56	38.36	38.75	39.14
70	57	1	WFW-245	46.21	43.05	45.56	44.75	45.28
70	79	1	WFW-211	16.49	16.73	16.02	18.25	18.74
8	73	1	BARTLETT POND	6.53	2.89	3.05	3.13	3.21
16	78	1	FRESH POND	14.24	13.65	14.43	14.81	15.19
20	75	1	BEAVER POND	20.66	32.84	33.81	34.29	34.75
20	81	1	SHALLOW POND	31.19	20.41	22.68	23.79	24.83
21	33	1	LITTLE MUDDY POND	108.70	91.10	97.81	101.29	104.60
21	57	1	RUSSELL MILL POND	51.79	57.30	57.95	58.32	58.68
21	74	1	ISLAND POND	42.28	39.93	40.00	40.03	40.06
24	43	1	BRIGGS RESERVOIR	87.41	85.55	88.05	90.35	92.50
24	48	1	COOKS POND	87.08	81.25	83.52	86.24	88.82
24	87	1	LILLY POND	11.09	8.79	10.50	11.33	12.12
28	41	1	MICAJAH POND	108.20	98.11	102.49	105.30	107.98
28	58	1	ISLAND POND	88.79	82.25	86.97	89.47	91.88
28	83	1	MOREY POND	48.74	34.76	39.45	41.67	43.69
30	93	1	BLACK POND	4.43	0.	0.	0.	0.00
31	20	1	UNNAMED POND WEST OF CEDAR SWAMP	122.44	116.83	119.09	120.25	121.41
33	59	1	CROOKED POND	95.78	88.67	95.05	98.32	101.44
34	89	1	SAVERY POND	26.08	19.09	22.55	24.22	25.83
37	48	1	WIDGEON POND	108.17	103.73	108.98	111.79	114.52
38	46	1	CURLEW POND	108.00	105.68	110.38	112.84	115.24
39	47	1	ROCKY POND	107.52	104.98	109.88	112.43	114.90
40	82	1	GRASSY POND	51.16	47.93	53.52	56.18	58.74
41	58	1	COLLEGE POND	103.58	96.00	103.04	106.49	109.81
42	88	1	HODGES POND	33.52	30.20	34.48	36.52	38.52
48	26	1	VAUGHN POND	101.81	100.03	102.01	102.97	103.91

Table 23.--*Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for average annual recharge rates of 18, 24, 27, and 30 inches per year*--Continued

Model Row (fig. 16)	Model Column (fig. 16)	Model Layer (fig. 16)	Well or pond (fig. 18)	Water level (ft) Measured	Simulated for recharge rate (in/yr) 18	24	27	30
49	83	1	LITTLE DUCK POND	47.07	44.73	48.81	50.76	52.68
57	83	1	LITTLE ROCKY POND	46.87	39.44	42.10	43.38	44.65
59	67	1	UNNAMED POND SOUTHEAST OF CHARGE POND	57.00	56.21	58.96	60.25	61.56
59	89	1	HORSE POND	40.64	25.92	29.30	30.93	32.50
64	50	1	GOLDEN FIELD POND	74.04	71.96	74.36	75.49	76.58
64	90	1	GOAT PASTURE POND	20.76	13.47	15.69	16.78	17.82
65	36	1	BATES POND	79.08	76.29	77.82	78.54	79.23
65	39	1	POND NEAR HUCKLEBERRY CORNER	72.91	72.94	73.98	74.48	74.96
65	42	1	POND ON CRANE BROOK	67.63	68.39	68.56	68.65	68.73
65	89	1	ELLIS POND	16.17	11.17	12.93	13.80	14.63
77	54	1	UNNAMED POND AT INTERSECTION OF I-195 AND I-25	38.83	34.12	34.70	34.93	35.17

	18	24	27	30
Absolute value of the mean of the water-level residuals[1], in feet	4.64	1.52	0.15	1.76
Mean of the absolute values of the water-level residuals, in feet	5.44	3.56	3.46	3.82
Standard deviation of the water-level residuals, in feet	5.03	4.52	4.42	4.54

Total number of observations = 101.

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[1] Water-level residual = Measured water level - simulated water level.

Table 24.--*Measured and simulated ground-water discharge to streams in the Plymouth-Carver aquifer for average annual recharge rates of 18, 24, 27, and 30 inches per year*

[ft^3/s, cubic foot per second, in/yr, inches per year]

Stream-measurement site (plate 1)	Date of measurement (month-day-year)	Discharge[1] (ft^3/s) Measured	Simulated using recharge rate in/yr 18	24	27	30
Town Brook at Plymouth upstream upstream of site 2 (01105874)	07-21-86	14.6				
	07-22-86	15.3	3.4	6.8	9.0	11.3
Eel River near Plymouth upstream of site 4 (01105876)	07-21-86	23.2	14.1	19.5	22.7	25.8
Eel River at Sandwich Road near Plymouth upstream of site 4a	07-22-86	14.9	7.9	11.3	13.4	15.4
Eel River tributary near Plymouth upstream of site 4b	07-22-86	7.87	1.3	2.7	3.4	4.2
Beaver Brook at White Horse Beach upstream of site 5 (01105878)	07-21-86	12.7				
	07-22-86	11.8	9.0	12.8	14.7	16.7
Indian Brook at Manomet Beach upstream of site 6	07-21-86	1.18	-.72	-.72	-.72	-.72
Herring River between outlet from Great Herring Pond and Cape Cod Canal between site 8a and 8	07-21-86	- .93	-1.2	-1.0	-.91	-.82
Red Brook near Buzzards Bay upstream of site 13	07-21-86	6.13	1.1	4.3	5.9	7.6
Agawam River at East Wareham upstream of site 16	07-21-86	33.5	18.7	26.7	30.7	34.8
Wankinco River at East Wareham upstream of site 21	07-21-86	18.6	9.9	16.7	18.7	23.4
Weweantic River at South Wareham upstream of site 22	07-21-86	81.2				
	07-22-86	11.9	30.5	43.9	51.0	57.8
Agawam River between site 16 and the confluence of the Agawam and Wankinco Rivers	07-21-86	2.1	4.3	5.0	5.4	5.8
Agawam River just upstream of the confluence with Wankinco River, Wareham	07-21-86	35.6	23.0	31.8	36.1	40.5
Absolute value of the mean of the discharge residuals[2], in feet			7.3	2.8	0.5	2.0
Mean of the absolute values of the discharge residuals, in feet			7.6	3.3	2.2	3.4
Standard deviation of the discharge residuals, in feet			5.6	3.0	3.0	4.1

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[1] Negative discharge means that water moves from the stream into the underlying aquifer.

[2] Discharge residual = measured ground-water discharge - simulated ground-water discharge.

Table 25.--*Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for multiples of the horizontal hydraulic conductivity of unconsolidated deposits used in the calibrated, steady-state model*

[ft, feet]

Model			Well or pond	Water level (ft)					
Row	Column (fig.16)	Layer	(fig. 18)	Measured	Multiple of hydraulic conductivity				
					0.2	0.5	1.0	2.0	5.0
8	78	1	PWW-501	5.88	2.85	1.44	0.97	0.75	0.63
19	40	1	PWW-502	81.63	104.47	89.06	81.86	73.93	63.67
19	48	1	PWW-261	74.05	108.29	80.79	70.30	62.32	53.85
20	44	1	PWW-503	77.41	102.00	83.65	76.09	68.57	59.12
22	77	1	PWW-313	38.59	62.99	47.39	39.25	33.37	28.33
23	67	1	PWW-241	67.73	101.73	76.76	64.29	54.48	44.18
23	77	1	PWW-285	36.60	67.77	50.53	41.49	34.89	29.17
24	49	1	PWW-215	81.90	129.75	96.49	84.14	74.53	64.03
24	52	1	PWW-516	77.03	120.54	92.20	81.38	73.18	63.48
24	66	1	PWW-242	72.59	105.79	80.35	67.56	57.37	46.47
24	73	1	PWW-245	57.79	93.80	67.90	55.66	47.06	38.99
25	28	1	PWW-413	123.73	191.02	141.93	119.03	104.67	94.16
25	72	1	PWW-240	71.78	111.93	79.50	63.91	52.78	40.94
26	46	1	PWW-504	99.03	146.65	103.50	90.99	80.61	70.47
27	66	1	PWW-243	79.20	131.56	95.14	77.59	64.77	52.09
28	38	1	PWW-505	118.30	163.26	127.07	110.40	97.30	82.82
28	47	1	PWW-306	101.66	153.09	112.79	97.65	85.88	73.06
28	68	1	PWW-244	87.20	138.82	98.45	78.93	64.90	50.05
29	46	1	PWW-305	102.07	154.52	114.35	98.99	87.02	75.20
30	26	1	PWW-517	123.73	181.43	141.19	122.93	111.47	103.24
30	52	1	PWW-506	98.88	151.85	113.64	97.77	85.68	71.91
30	66	1	PWW-379	82.05	148.80	105.95	85.35	70.59	55.16
34	34	1	PWW-22	120.98	167.61	134.55	119.18	107.89	95.91
34	53	1	PWW-315	102.71	166.57	123.28	103.69	89.18	73.49
35	71	1	PWW-509	70.45	140.51	98.96	78.82	64.29	48.94
36	24	1	CDW-119	114.70	146.21	124.82	115.84	110.50	106.31
37	46	1	PWW-507	112.95	163.16	128.56	112.74	100.29	85.87
38	78	1	PWW-414	64.07	126.62	87.48	68.56	55.13	41.18
39	50	1	PWW-416	108.18	172.24	130.89	111.75	97.56	82.35
40	82	1	PWW-518	52.39	112.85	74.77	56.53	44.02	31.92
41	92	1	PWW-319	21.04	48.02	27.98	19.23	13.96	9.79
42	29	1	CDW-120	92.60	102.89	99.59	98.53	97.91	96.81
42	92	1	PWW-418	22.16	55.24	32.61	22.54	16.40	11.49
44	31	1	CDW-121	103.23	117.95	106.84	102.31	99.34	95.96
44	82	1	PWW-253	46.59	106.04	71.04	54.62	43.59	32.80
46	61	1	PWW-510	98.53	164.65	120.91	99.92	84.99	68.61
46	84	1	PWW-251	43.60	98.18	64.75	49.10	38.83	29.31
47	56	1	PWW-511	101.01	164.03	123.64	104.38	90.70	76.04
49	83	1	PWW-513	47.75	94.27	64.51	50.76	41.82	33.41
51	40	1	BHW-126	99.95	90.20	88.78	87.98	87.09	84.46
51	50	1	CDW-99	98.92	147.68	117.52	103.27	93.24	82.00
51	59	1	PWW-415	91.34	145.43	111.82	96.06	84.82	71.31
53	82	1	PWW-514	48.22	82.49	59.73	49.64	43.30	37.36
53	84	1	PWW-520	47.02	83.90	58.52	46.88	39.55	32.99
54	55	1	CDW-123	83.97	111.08	96.70	89.90	84.29	73.89

Table 25.--*Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for multiples of the horizontal hydraulic conductivity of unconsolidated deposits used in the calibrated, steady-state model*--Continued

Model			Well or pond	Water level (ft)					
				Measured	Multiple of hydraulic conductivity				
Row	Column (fig.16)	Layer	(fig. 18)		0.2	0.5	1.0	2.0	5.0
54	56	1	PWW-521	89.77	95.97	92.38	88.64	84.13	73.83
56	52	1	CDW-125	79.66	115.72	97.86	89.74	83.88	74.65
57	84	1	PWW-519	46.61	76.73	53.40	42.69	35.98	30.08
58	58	1	PWW-431	75.15	103.93	87.44	80.19	74.89	65.84
59	63	1	PWW-512	69.78	92.20	76.24	69.07	63.73	55.20
61	87	1	PWW-368	28.98	62.95	40.77	30.64	24.38	19.25
61	93	1	BHW-293	25.22	47.94	29.04	19.65	13.74	9.32
63	56	1	PWW-430	61.56	80.64	70.65	66.69	64.19	59.97
64	37	1	CDW-122	76.10	96.09	85.35	80.67	77.85	75.77
64	53	1	CDW-86	64.80	78.57	69.86	66.41	64.37	61.30
65	36	1	CDW-201	78.14	88.56	80.08	76.65	74.70	73.43
65	57	1	PWW-236	55.71	77.16	65.45	60.72	57.88	54.02
66	53	1	CDW-85	62.84	74.97	65.69	62.02	59.99	57.57
66	55	1	PWW-369	56.02	64.51	58.23	56.13	55.18	53.57
66	61	1	PWW-238	55.51	68.53	58.39	54.20	51.48	47.62
66	64	1	WFW-296	45.48	48.20	46.50	45.55	44.55	42.11
68	57	1	PWW-237	51.09	63.98	55.68	52.64	51.12	49.23
69	61	1	WFW-295	45.81	53.67	47.03	44.37	42.68	40.38
69	64	1	WFW-297	39.49	43.84	40.21	38.75	37.74	36.07
70	57	1	WFW-245	46.21	53.55	47.02	44.75	43.75	42.82
70	79	1	WFW-211	16.49	28.51	20.95	18.25	16.88	15.93
8	73	1	BARTLETT POND	6.53	3.65	3.38	3.13	2.90	2.71
16	78	1	FRESH POND	14.24	17.95	15.83	14.81	14.22	13.82
20	75	1	BEAVER POND	20.66	40.94	36.55	34.29	32.48	30.41
20	81	1	SHALLOW POND	31.19	41.43	30.42	23.79	18.99	15.25
21	33	1	LITTLE MUDDY POND	108.70	166.72	122.43	101.29	86.79	73.11
21	57	1	RUSSELL MILL POND	51.79	58.04	58.19	58.32	57.97	55.38
21	74	1	ISLAND POND	42.28	40.15	40.12	40.03	39.81	39.11
24	43	1	BRIGGS RESERVOIR	87.41	127.54	101.09	90.35	80.80	69.52
24	48	1	COOKS POND	87.08	133.42	98.78	86.24	76.30	65.60
24	87	1	LILLY POND	11.09	24.73	16.05	11.33	7.87	5.28
28	41	1	MICAJAH POND	108.20	156.74	121.05	105.30	92.62	78.78
28	58	1	ISLAND POND	88.79	137.02	104.28	89.47	78.54	65.86
28	83	1	MOREY POND	48.74	65.23	52.38	41.67	31.08	21.61
30	93	1	BLACK POND	4.43	0	0	0	0	0
31	20	1	UNNAMED POND WEST OF CEDAR SWAMP	122.44	151.39	129.10	120.25	115.51	112.50
33	59	1	CROOKED POND	95.78	163.74	119.21	98.32	83.18	66.91
34	89	1	SAVERY POND	26.08	60.36	35.57	24.22	16.88	10.96
37	48	1	WIDGEON POND	108.17	168.04	129.42	111.79	98.39	83.22
38	46	1	CURLEW POND	108.00	161.25	128.06	112.84	100.84	86.75
39	47	1	ROCKY POND	107.52	163.24	128.40	112.43	100.20	86.28
40	82	1	GRASSY POND	51.16	112.20	74.29	56.18	43.79	31.79
41	58	1	COLLEGE POND	103.58	176.98	129.34	106.49	90.06	72.06
42	88	1	HODGES POND	33.52	82.46	51.07	36.52	27.19	19.20
48	26	1	VAUGHN POND	101.81	118.48	107.76	102.97	99.87	97.04

Table 25.--*Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for multiples of the horizontal hydraulic conductivity of unconsolidated deposits used in the calibrated, steady-state model*--Continued

Model			Well or pond (fig. 18)	Water level (ft)					
Row	Column (fig.16)	Layer		Measured	Multiple of hydraulic conductivity				
					0.2	0.5	1.0	2.0	5.0
49	83	1	LITTLE DUCK POND	47.07	94.27	64.51	50.76	41.82	33.41
57	83	1	LITTLE ROCKY POND	46.87	74.47	52.97	43.38	37.45	32.15
59	67	1	UNNAMED POND SOUTHEAST OF CHARGE POND	57.0	85.65	67.98	60.25	55.11	48.47
59	89	1	HORSE POND	40.64	67.22	42.78	30.93	23.47	17.52
64	50	1	GOLDEN FIELD POND	74.04	97.15	82.18	75.49	71.18	66.10
64	90	1	GOAT PASTURE POND	20.76	42.15	24.62	16.78	12.08	8.59
65	36	1	BATES POND	79.08	92.34	82.63	78.54	76.14	74.51
65	39	1	POND NEAR HUCKLEBERRY CORNER	72.91	83.00	76.88	74.48	73.06	72.04
65	42	1	POND ON CRANE BROOK	67.63	68.51	68.57	68.65	68.75	68.87
65	89	1	ELLIS POND	16.17	34.69	20.12	13.80	10.08	7.33
77	54	1	UNAMED POND AT INTERSECTION OF I-195 AND I-25	38.83	36.68	35.89	34.93	33.41	28.82

	0.2	0.5	1.0	2.0	5.0
Absolute value of the mean of the water-level residuals[1], in feet	31.67	10.26	0.15	7.08	14.75
Mean of the absolute values of the water-level residuals, in feet	33.08	10.84	3.46	7.80	15.12
Standard deviation of the water-level residuals, in feet	22.53	8.01	4.42	6.39	10.32

Total number of observations = 101.

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[1] Water-level residual = Measured water level - simulated water level.

Table 26.--*Measured and simulated ground-water discharge to streams in the Plymouth-Carver aquifer for multiples of the horizontal hydraulic conductivity of unconsolidated deposits from that in the calibrated, steady-state model*

Stream-measurement site (plate 1)	Date of measurement (month-day-year)	Discharge[1] (ft^3/s) Measured	Simulated using multiple of hydraulic conductivity 0.2	0.5	1.0	2.0	5.0
Town Brook at Plymouth upstream upstream of site 2 (01105874)	07-21-86	14.6					
	07-22-86	15.3	16.8	12.9	9.0	3.8	-3.9
Eel River near Plymouth upstream of site 4 (01105876)	07-21-86	23.2	27.8	25.0	22.7	18.5	10.1
Eel River at Sandwich Road near Plymouth upstream of site 4a	07-22-86	14.9	17.1	15.3	13.4	8.7	-3.2
Eel River tributary near Plymouth upstream of site 4b	07-22-86	7.87	7.2	5.4	3.4	1.0	-2.0
Beaver Brook at White Horse Beach upstream of site 5 (01105878)	07-21-86	12.7					
	07-22-86	11.8	14.7	15.4	14.7	11.4	-3.4
Indian Brook at Manomet Beach upstream of site 6	07-21-86	1.18	4.9	1.2	-.72	-.72	-.72
Herring River between outlet from Great Herring Pond and Cape Cod Canal between site 8a and 8	07-21-86	-.93	3.9	.41	-.91	-1.1	-1.2
Red Brook near Buzzards Bay upstream of site 13	07-21-86	6.13	12.0	9.7	5.9	-1.1	-22.1
Agawam River at East Wareham upstream of site 16	07-21-86	33.5	33.8	32.9	30.7	26.5	18.2
Wankinco River at East Wareham upstream of site 21	07-21-86	18.6	27.3	24.2	18.7	13.0	0.32
Weweantic River at South Wareham upstream of site 22	07-21-86	81.2					
	07-22-86	11.9	58.4	54.6	51.0	46.6	39.3
Agawam River between site 16 and the confluence of the Agawam and Wankinco Rivers	07-21-86	2.1	3.6	4.3	5.4	7.6	13.3
Agawam River just upstream of the confluence with Wankinco River, Wareham	07-21-86	35.6	37.3	36.8	36.1	34.0	31.6
Absolute value of the mean of the discharge residuals[2], in feet			3.8	1.7	0.5	3.7	10.8
Mean of the absolute values of the discharge residuals, in feet			3.8	2.5	2.2	4.5	12.4
Standard deviation of the discharge residuals, in feet			3.5	3.0	3.0	4.4	10.2

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[1] Negative discharge means that water moves from the stream into the underlying aquifer.

[2] Discharge residual = measured ground-water discharge - simulated ground-water discharge.

Table 27.-- *Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for multiples of streambed conductance used in the calibrated steady-state model*

Model Row (fig. 16)	Model Column	Model Layer	Well or pond (fig. 18)	Water level, in feet: Measured	Multiple of streambed conductance: 0.1	0.2	1.0	5.0	10.0
8	78	1	PWW-501	5.88	1.26	1.15	0.97	0.93	0.92
19	40	1	PWW-502	81.63	90.52	86.03	81.86	81.23	81.16
19	48	1	PWW-261	74.05	81.52	76.26	70.30	68.76	68.53
20	44	1	PWW-503	77.41	86.44	81.42	76.09	74.87	74.68
22	77	1	PWW-313	38.59	43.01	41.26	39.25	39.68	40.42
23	67	1	PWW-241	67.73	72.14	68.52	64.29	63.69	63.89
23	77	1	PWW-285	36.60	45.22	43.48	41.49	41.98	42.73
24	49	1	PWW-215	81.90	95.74	90.49	84.14	82.25	81.96
24	52	1	PWW-516	77.03	94.09	88.37	81.38	79.37	79.08
24	66	1	PWW-242	72.59	75.76	71.96	67.56	66.94	67.14
24	73	1	PWW-245	57.79	60.76	58.43	55.66	55.28	55.45
25	28	1	PWW-413	123.73	123.57	121.38	119.03	118.44	118.35
25	72	1	PWW-240	71.78	69.95	67.26	63.91	63.30	63.43
26	46	1	PWW-504	99.03	102.73	97.55	90.99	88.87	88.54
27	66	1	PWW-243	79.20	85.76	82.14	77.59	76.49	76.49
28	38	1	PWW-505	118.30	118.83	114.88	110.40	109.18	109.02
28	47	1	PWW-306	101.66	108.46	103.68	97.65	95.72	95.43
28	68	1	PWW-244	87.20	86.40	83.19	78.93	77.82	77.79
29	46	1	PWW-305	102.07	109.59	104.89	98.99	97.13	96.85
30	26	1	PWW-517	123.73	128.35	125.82	122.93	122.15	122.05
30	52	1	PWW-506	98.88	109.44	104.50	97.77	95.40	95.03
30	66	1	PWW-379	82.05	93.47	90.03	85.35	83.96	83.84
34	34	1	PWW-22	120.98	128.20	124.03	119.18	117.93	117.77
34	53	1	PWW-315	102.71	114.26	109.75	103.69	101.59	101.30
35	71	1	PWW-509	70.45	86.67	83.53	78.82	77.19	77.04
36	24	1	CDW-119	114.70	123.14	119.81	115.84	114.79	114.64
37	46	1	PWW-507	112.95	122.95	118.31	112.74	111.13	110.91
38	78	1	PWW-414	64.07	75.50	72.78	68.56	67.18	67.10
39	50	1	PWW-416	108.18	121.64	117.20	111.75	110.02	109.80
40	82	1	PWW-518	52.39	61.84	59.76	56.53	55.64	55.69
41	92	1	PWW-319	21.04	20.67	20.07	19.23	19.17	19.30
42	29	1	CDW-120	92.60	117.13	108.74	98.53	96.12	95.82
42	92	1	PWW-418	22.16	24.23	23.53	22.54	22.47	22.62
44	31	1	CDW-121	103.23	118.69	110.90	102.31	100.42	100.19
44	82	1	PWW-253	46.59	60.12	58.00	54.62	53.65	53.70
46	61	1	PWW-510	98.53	109.06	105.17	99.92	98.20	97.95
46	84	1	PWW-251	43.60	53.56	51.79	49.10	48.46	48.57
47	56	1	PWW-511	101.01	113.80	109.65	104.38	102.72	102.45
49	83	1	PWW-513	47.75	55.35	53.47	50.76	50.14	50.21
51	40	1	BHW-126	99.95	102.32	94.16	87.98	87.84	87.94
51	50	1	CDW-99	98.92	113.83	108.80	103.27	101.79	101.55
51	59	1	PWW-415	91.34	106.36	101.83	96.06	94.10	93.83
53	82	1	PWW-514	48.22	53.64	51.88	49.64	49.21	49.25
53	84	1	PWW-520	47.02	50.29	48.76	46.88	46.67	46.80
54	55	1	CDW-123	83.97	102.25	96.71	89.90	87.60	87.26
54	56	1	PWW-521	89.77	102.77	97.02	88.64	84.65	83.89
56	52	1	CDW-125	79.66	100.57	95.03	89.74	88.58	88.44
57	84	1	PWW-519	46.61	45.63	44.24	42.69	42.66	42.84
58	58	1	PWW-431	75.15	91.74	86.18	80.19	78.80	78.64
59	63	1	PWW-512	69.78	81.07	75.75	69.07	67.34	67.12

Table 27.-- *Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for multiples of streambed conductance used in the calibrated steady-state model*

Model			Well or pond	Water level, in feet					
Row	Column	Layer		Measured	Multiple of streambed conductance				
(fig. 16)			(fig. 18)		0.1	0.2	1.0	5.0	10.0
61	87	1	PWW-368	28.98	32.94	31.97	30.64	30.57	30.81
61	93	1	BHW-293	25.22	20.44	20.06	19.65	20.18	20.67
63	56	1	PWW-430	61.56	80.64	73.91	66.69	65.03	64.82
64	37	1	CDW-122	76.10	91.62	85.26	80.67	79.73	79.60
64	53	1	CDW-86	64.80	80.37	73.49	66.41	64.87	64.68
65	36	1	CDW-201	78.14	87.40	81.07	76.65	75.81	75.70
65	57	1	PWW-236	55.71	74.68	68.07	60.72	59.05	58.84
66	53	1	CDW-85	62.84	76.22	69.39	62.02	60.32	60.10
66	55	1	PWW-369	56.02	72.83	65.17	56.13	53.89	53.59
66	61	1	PWW-238	55.51	66.72	60.73	54.20	52.81	52.64
66	64	1	WFW-296	45.48	57.35	51.52	45.55	44.67	44.61
68	57	1	PWW-237	51.09	68.26	61.05	52.64	50.72	50.48
69	61	1	WFW-295	45.81	56.17	50.26	44.37	43.35	43.24
69	64	1	WFW-297	39.49	49.59	44.09	38.75	37.91	37.84
70	57	1	WFW-245	46.21	59.54	52.84	44.75	42.87	42.64
70	79	1	WFW-211	16.49	22.52	20.94	18.25	17.14	16.97
8	73	1	BARTLETT POND	6.53	5.69	4.54	3.13	2.96	2.97
16	78	1	FRESH POND	14.24	22.13	19.36	14.81	13.46	13.32
20	75	1	BEAVER POND	20.66	39.74	37.36	34.29	33.67	33.73
20	81	1	SHALLOW POND	31.19	26.46	25.22	23.79	24.87	26.28
21	33	1	LITTLE MUDDY POND	108.70	107.58	104.50	101.29	100.50	100.38
21	57	1	RUSSELL MILL POND	51.79	75.81	67.83	58.32	55.73	55.37
21	74	1	ISLAND POND	42.28	41.84	40.64	40.03	40.00	40.00
24	43	1	BRIGGS RESERVOIR	87.41	100.29	95.67	90.35	88.61	88.29
24	48	1	COOKS POND	87.08	97.63	92.49	86.24	84.34	84.04
24	87	1	LILLY POND	11.09	12.15	11.74	11.33	11.93	12.47
28	41	1	MICAJAH POND	108.20	114.35	110.15	105.30	103.91	103.71
28	58	1	ISLAND POND	88.79	102.17	97.00	89.47	86.70	86.31
28	83	1	MOREY POND	48.74	44.29	42.99	41.67	43.38	44.80
30	93	1	BLACK POND	4.43	0	0	0	0	0
31	20	1	UNNAMED POND WEST OF CEDAR SWAMP	122.44	122.19	121.27	120.25	119.99	119.96
33	59	1	CROOKED POND	95.78	108.39	104.18	98.32	96.25	95.98
34	89	1	SAVERY POND	26.08	26.18	25.37	24.22	24.12	24.30
37	48	1	WIDGEON POND	108.17	121.84	117.31	111.79	110.11	109.89
38	46	1	CURLEW POND	108.00	123.25	118.51	112.84	111.19	110.97
39	47	1	ROCKY POND	107.52	122.90	118.14	112.43	110.71	110.48
40	82	1	GRASSY POND	51.16	61.50	59.43	56.18	55.28	55.33
41	58	1	COLLEGE POND	103.58	115.50	111.63	106.49	104.80	104.54
42	88	1	HODGES POND	33.52	39.51	38.30	36.52	36.21	36.36
48	26	1	VAUGHN POND	101.81	118.49	111.10	102.97	101.06	100.81
49	83	1	LITTLE DUCK POND	47.07	55.35	53.47	50.76	50.14	50.21
57	83	1	LITTLE ROCKY POND	46.87	46.44	44.98	43.38	43.32	43.45
59	67	1	UNNAMED POND SOUTHEAST OF CHARGE POND	57.0	72.25	67.42	60.25	58.07	57.83
59	89	1	HORSE POND	40.64	32.67	31.91	30.93	31.20	31.68
64	50	1	GOLDEN FIELD POND	74.04	86.02	80.37	75.49	74.57	74.45
64	90	1	GOAT PASTURE POND	20.76	17.82	17.38	16.78	16.84	17.02
65	36	1	BATES POND	79.08	89.33	82.98	78.54	77.70	77.59

Table 27.--*Measured and simulated water levels in observation wells and ponds in the Plymouth-Carver aquifer for multiples of streambed conductance used in the calibrated steady-state model*

Model (fig. 16)			Well or pond (fig. 18)	Water level, in feet					
Row	Column	Layer		Measured	Multiple of streambed conductance				
					0.1	0.2	1.0	5.0	10.0
65	39	1	POND NEAR HUCKLEBERRY CORNER	72.91	85.04	78.97	74.48	73.42	73.28
65	42	1	POND ON CRANE BROOK	67.63	78.68	72.49	68.65	68.11	68.05
65	89	1	ELLIS POND	16.17	14.80	14.39	13.80	13.77	13.89
77	54	1	UNNAMED POND AT INTERSECTION OF I-195 AND I-25	38.83	41.62	37.64	34.93	34.85	34.91
Absolute value of the mean of the water-level residuals[1], in feet					8.47	4.60	0.15	0.91	0.96
Mean of the absolute values of the water-level residuals, in feet					9.31	6.15	3.46	3.34	3.33
Standard deviation of the water-level residuals, in feet					7.05	5.60	4.42	4.18	4.15
Total number of observations = 101.									

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[1] Water-level residual = Measured water level - simulated water level.

Table 28.--*Measured and simulated ground-water discharge to streams in the Plymouth-Carver aquifer for multiples of streambed conductance from that in the calibrated steady-state model*

[ft^3, cubic foot per second]

Stream-measurement site (plate 1)	Date of measurement (month-day-year)	Discharge[1] (ft^3)					
		Measured	Multiple of streambed conductance				
			0.1	0.2	1.0	5.0	10.0
Town Brook at Plymouth upstream of site 2 (01105874)	07-21-86	14.6					
	07-22-86	15.3	6.3	7.5	9.0	9.5	9.6
Eel River near Plymouth upstream of site 4 (01105876)	07-21-86	23.2	18.0	20.3	22.7	23.2	23.2
Eel River at Sandwich Road near Plymouth upstream of site 4a	07-22-86	14.9	8.8	10.7	13.4	14.4	14.5
Eel River tributary near Plymouth upstream of site 4b	07-22-86	7.87	3.5	3.7	3.4	3.0	2.9
Beaver Brook at White Horse Beach upstream of site 5 (01105878)	07-21-86	12.7					
	07-22-86	11.8	10.6	12.1	14.7	16.2	16.7
Indian Brook at Manomet Beach upstream of site 6	07-21-86	1.18	-.21	-.44	-.72	-3.1	-5.1
Herring River between outlet from Great Herring Pond and Cape Cod Canal between site 8a and 8	07-21-86	-.93	-.09	-.19	-.91	-3.2	-4.5
Red Brook near Buzzards Bay upstream of site 13	07-21-86	6.13	7.7	7.0	5.9	5.6	5.5
Agawam River at East Wareham upstream of site 16	07-21-86	33.5	25.3	26.5	30.7	33.0	33.4
Wankinco River at East Wareham upstream of site 21	07-21-86	18.6	18.5	19.5	18.7	19.9	19.8
Weweantic River at South Wareham upstream of site 22	07-21-86	81.2					
	07-22-86	11.9	46.0	48.9	51.0	51.2	51.3

Table 28.--*Measured and simulated ground-water discharge to streams in the Plymouth-Carver aquifer for multiples of streambed conductance from that in the calibrated steady-state model*--Continued

Stream-measurement site (plate 1)	Date of measurement (month-day-year)	Discharge[1] (ft^3) Measured	Multiple of streambed conductance 0.1	0.2	1.0	5.0	10.0
Agawam River between site 16 and the confluence of the Agawam and Wankinco Rivers	07-21-86	2.1	5.1	5.4	5.4	5.4	5.3
Agawam River just upstream of the confluence with Wankinco River, Wareham	07-21-86	35.6	30.4	31.7	36.1	38.4	38.8
Absolute value of the mean of the discharge residuals[2], in feet			2.8	1.8	.5	.2	.3
Mean of the absolute values of the discharge residuals, in feet			3.6	3.0	2.2	2.7	3.0
Standard deviation of the discharge residuals, in feet			3.8	3.5	3.0	3.4	3.8

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[1] Negative discharge means that water moves from the stream into the underlying aquifer.

[2] Discharge residual = measured ground-water discharge - simulated ground-water discharge.

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