GROUND-WATER HYDROLOGY

FLOW SYSTEM

Water from precipitation recharges the aquifer, flows laterally through the sediments, and discharges mainly to the ocean. Other discharge areas include several saltwater bays, inlets, canals, and streams near sea level that extend inland from the coast. The bays and streams divide the Cape Cod ground-water flow system into six separate areas, or cells, each of which is characterized by a water-table mound (fig. 5). Under natural conditions, the cells are hydraulically independent ground-water flow systems.

Ground-water flow in each of the six cells is approximately steady because of a long-term balance between ground-water recharge and discharge. The configurations of the flow cells remain approximately the same from year to year. The total steady-state flow through the aquifer system, estimated from computer-model analyses (Guswa and LeBlanc, 1985), is 270 Mgal/d. The water-table altitude generally is highest near the centers of the cells and lowest near the coast. Ground water flows in the direction of the principal hydraulic gradient—from the centers of the cells to the ocean—as shown in figure 5 by arrows drawn perpendicular to the water-table contours.

General ground-water flow directions along two hydrologic sections through the Cape are shown in figure 6. Flow is nearly horizontal in much of the aquifer. Vertical flow occurs mainly near the water-table divides, at the coast, and along major discharge boundaries such as the Bass River in Yarmouth and Dennis.

The water table, which is the top of the saturated zone, is the upper boundary of the ground-water flow system (fig. 6). The lower boundary of the ground-water flow system is either bedrock, poorly permeable sediments such as silt and clay, or the transition zone between fresh and saline ground water. On the outer Cape, fresh ground water, referred to as the freshwater lens, is underlain everywhere by saline ground water. The freshwater lens in Truro is as much as 200 feet thick. In Eastham and Wellfleet, wells have not been drilled to the boundary between fresh and saline ground water at the center of the lenses, but computer-model analyses (Guswa and LeBlanc, 1985) predict that the lens is 275 feet thick in Eastham and 250 feet thick in Wellfleet. In some areas on the outer Cape, silt and clay interbedded with sand and gravel contain freshwater down to the transition zone, but the top of these poorly permeable sediments may be considered to be the lower boundary of significant freshwater flow.

On the inner and mid-Cape, the freshwater lenses are truncated by bedrock and by fine-grained sediments (fig. 6). Except near the coast, wells may be drilled to bedrock without penetrating saline ground water. Along Cape Cod Bay, silt and clay impede the discharge of fresh ground water to the ocean, and the boundary between fresh and saline ground water is displaced offshore.

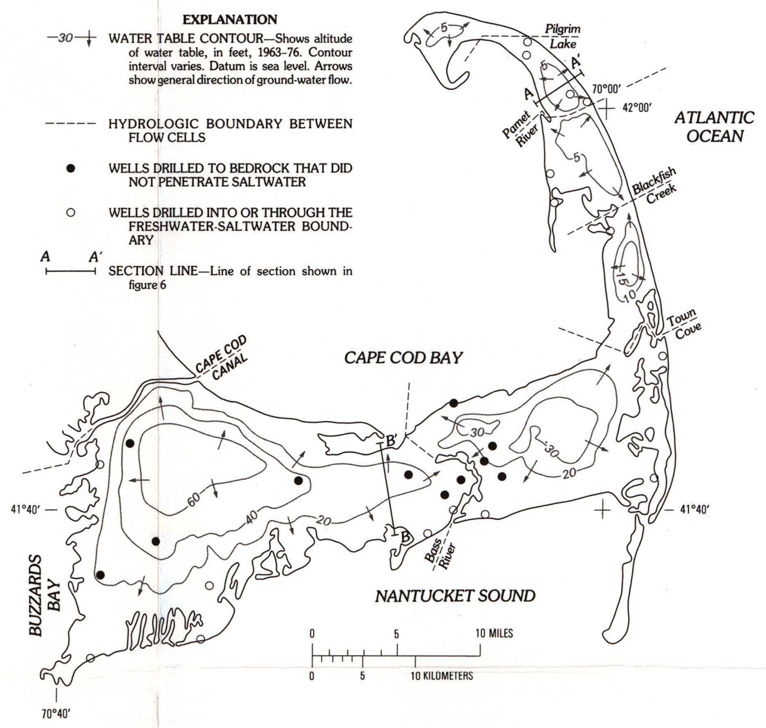
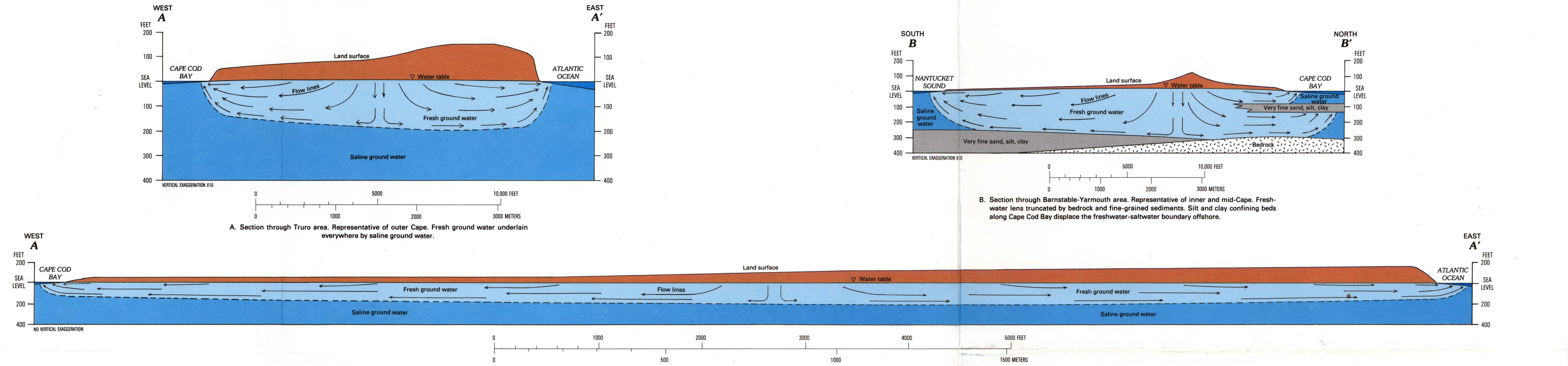


Figure 5.—Six ground-water flow cells and general directions of flow.



A. Section through Truro area. Representative of outer Cape. Fresh ground water underlain everywhere by saline ground water.

B. Section through Barnstable-Yarmouth area. Representative of inner and mid-Cape. Freshwater lens truncated by bedrock and fine-grained sediments. Silt and clay confining beds along Cape Cod Bay displace the freshwater-saltwater boundary offshore.

C. Section through Truro area undistorted by vertical exaggeration.

Figure 6.—Hydrologic sections through freshwater lens showing the vertical boundaries and directions of flow. Relationships from field data and digital-model simulations (Guswa and LeBlanc, 1985). Location of section lines shown in figure 5.

RECHARGE

The only source of freshwater to the Cape Cod aquifer is precipitation. Average annual precipitation ranges from 40 in/yr on the outer Cape to 47 in/yr on the inner Cape (fig. 7). Precipitation is slightly less during the summer than during the rest of the year (fig. 8A). During 1963-76, total annual precipitation (fig. 9F) ranged from 26.5 inches in 1965 to 66 inches in 1972.

Because the soils on Cape Cod are sandy and very permeable, precipitation quickly infiltrates the ground and only a small part flows overland to streams and ponds. The amount of runoff on Cape Cod is expected to be similar to runoff on Long Island, New York, a geohydrologic environment similar to Cape Cod, where direct runoff is less than 1 percent of the precipitation (Franke and McClymonds, 1972, p. F19). About 55 percent of the annual precipitation evaporates or is transpired by plants and returns directly to the atmosphere. The remaining 45 percent of the average annual precipitation becomes ground-water recharge (figs. 7 and 8B).

The rates of evapotranspiration and recharge were estimated by a water-balance method that relates evapotranspiration empirically to climatic factors such as day length, air temperature, and latitude (Thornthwaite and Mather, 1957). The recharge estimates are similar to estimates of recharge on Long Island, New York (Franke and McClymonds, 1972) and in Falmouth (Palmer, 1977) and were used in digital models of ground-water flow on Cape Cod (Guswa and LeBlanc, 1985).

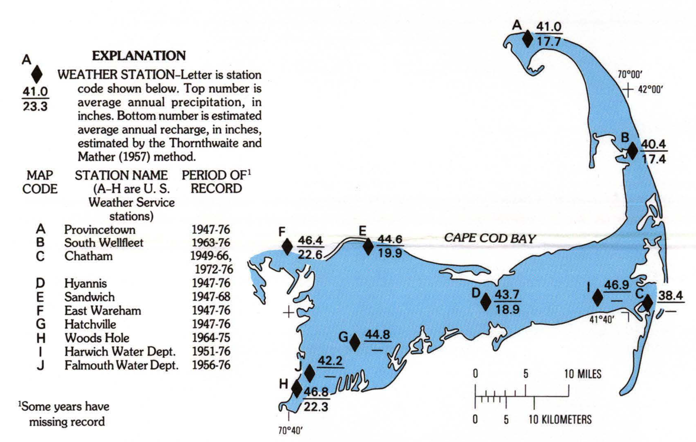


Figure 7.—Average annual precipitation and estimated annual recharge at 10 weather stations.

DISCHARGE

Ground water discharges to streams, wetlands, ponds, wells, and to the ocean. Discharge by evapotranspiration of ground water can occur where the water table is at or near land surface and plant roots reach the saturated zone. Evapotranspiration of ground water may be substantial in low-lying areas, especially along the southern coast of the inner and mid-Cape. Ground-water discharge to streams is particularly important on the inner Cape. The total measured flow of five streams in Falmouth and Mashpee (table 2) during a period of average flow was 35 Mgal/d, or about 20 percent of the estimated total discharge from the inner Cape flow system (Guswa and LeBlanc, 1985, p. 17). Because streamflow is mostly ground-water discharge, streamflows are directly related to ground-water levels (figs. 8D and 9E).

Table 2.—***Instantaneous discharge of streams at 11 sites measured during summer 1978 and fall 1979***

[To convert cubic feet per second to million gallons per day, multiply by 0.646]

Location: Figure	Location: Site number	Site description	Date	Instantaneous discharge, in cubic feet per second
14	A	Coonamessett River at Coonamessett Pond, Falmouth.	11- 7-79	1.06
14	B	Coonamessett River 500 feet south of Hatchville Road, Falmouth.	11- 8-79	.95
14	C	Coonamessett River 3,500 feet north of Sandwich Road, Falmouth.	11- 8-79	3.91
14	D	Coonamessett River at Sandwich Road, Falmouth.	11- 9-79	5.10
14	E	Coonamessett River 1,300 feet north of Route 28, Falmouth.	7-25-78 11- 9-79	13.27 9.01
14	F	Backus River at Route 28, Falmouth	11-20-79	1.02
14	G	Childs River 2,200 feet north of Route 28, Falmouth.	7-25-78	5.07
14	H	Quashnet River 600 feet north of Route 28, Falmouth.	8- 4-78	19.31
14	I	Mashpee River at Route 28, Mashpee	8- 4-78	15.49
18	J	Stony Brook at Setucket Road, Brewster	10-31-78	3.63
18	K	Herring River at Route 6, Harwich (U.S. Geological Survey gaging station 0108550).	8-23-78	14.52

WATER LEVELS AND THE WATER TABLE

WATER TABLE

Contour maps of the average altitude of the water table for the period 1963-76 are shown in figures 14 and 18. The average water levels during this period were estimated for 122 sites (figs. 14 and 18) by comparing water levels measured monthly for 14 years at 22 wells (Maevsky, 1976) to water levels measured monthly for 1½ years (1975-77) at 109 wells and ponds. The water table is less than 50 feet below land surface over most of Cape Cod, but is 230 feet below land surface in a well on Pine Hill in Bourne, the highest point on Cape Cod.

The altitude of the water table is controlled by factors that include the (1) location of discharge boundaries, (2) areal distribution of recharge, (3) artificial recharge, (4) pumping, and (5) hydraulic conductivity of the sediments. In general, the water table is highest at the greatest distance from the discharge boundaries. The water-table slope generally is steeper in the moraines than in the outwash because flow through the less permeable moraine requires a greater hydraulic gradient (head difference) than through the more permeable outwash. As a result of the difference in hydraulic conductivity between the moraines and outwash, the location of the highest water-table altitude on the inner Cape is displaced northwestward from the center of the land mass (figs. 5 and 14).

At any one location, water levels in wells open to the aquifer at different depths may be greater or less than the altitude of the water table. In recharge areas, near the centers of the water-table mounds, ground-water flow is predominantly downward. As a result, in recharge areas, water levels in wells screened deep in the aquifer are typically lower than in wells screened at shallower depths. Along discharge areas near the coast and near streams, water levels are higher in deep wells than in shallow wells because the direction of ground-water flow is predominantly upward. The difference between water levels in deep and shallow wells at any one location on Cape Cod generally ranges from 0.1 foot to more than 2 feet near water-table divides and discharge boundaries.

In areas where artesian conditions occur, vertical differences in hydraulic head of more than 5 feet have been measured across the confining beds. Along the northern coast of the inner and mid-Cape, the aquifer is commonly confined by lacustrine silt and clay (fig. 3). The lower permeability of these sediments impedes ground-water discharge from the underlying sand and gravel aquifer. Water levels in wells screened in the confined aquifer rise above the top of the aquifer and, in some locations, above the land surface. Flowing wells once supplied more than 1,000 gal/min to two fish hatcheries in Sandwich (Lloyd Raymond, Massachusetts Division of Fisheries and Wildlife, oral commun., 1982).

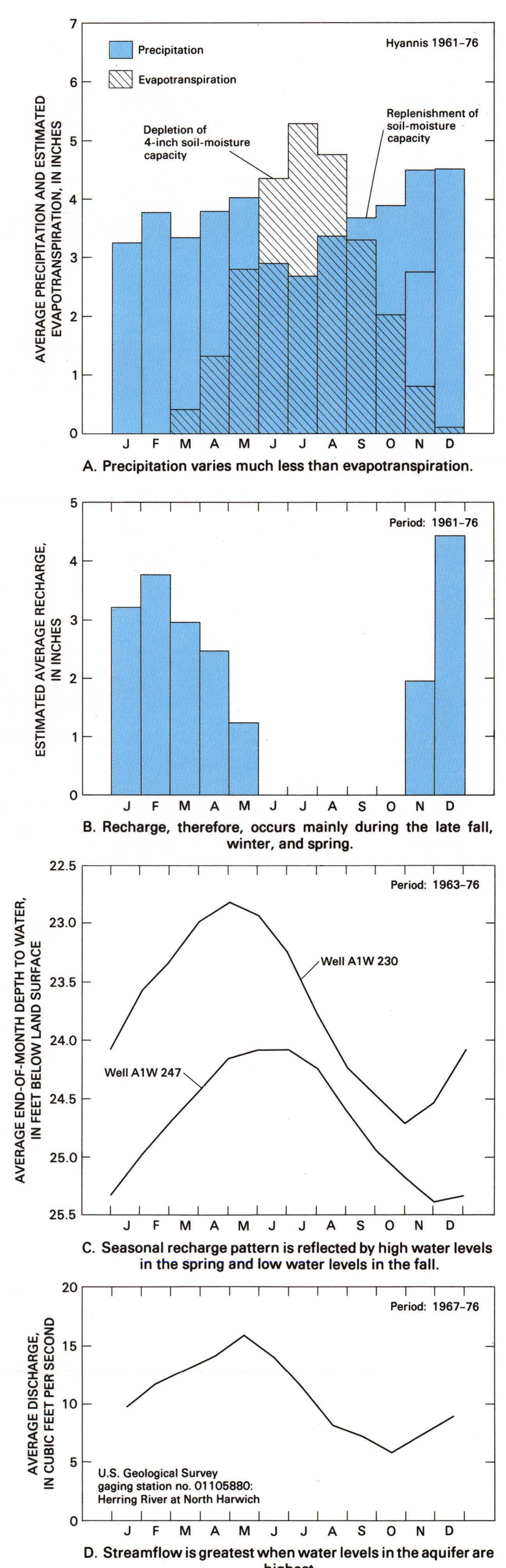
SEASONAL FLUCTUATIONS

Water levels fluctuate as a result of seasonal differences in the amount of recharge. Most recharge generally occurs during late fall, winter, and spring (fig. 8B) when plants are least active and evapotranspiration rates are low. During the summer, water demand of plants exceeds the replenishment of soil moisture by precipitation, and moisture in the soil zone also becomes depleted (fig. 8A). Soil moisture is replenished in the fall before recharge begins again. The seasonal variation of recharge causes water levels in the aquifer to range from high levels in early spring to low levels in the fall (fig. 8C).

LONG-TERM FLUCTUATIONS

Water levels also respond to changes in total annual recharge by declining during drought years and rising during wet years. On Cape Cod, ground-water levels (fig. 9) declined during the drought of 1964–66 but returned to near average levels after the wetter-than-average year of 1967. Above-average precipitation during 1972–73 caused record-high water levels. The effect of the wet and dry periods on water levels is greatest in interior areas and least near the coast (fig. 9). In coastal areas near discharge boundaries (wells SDW 252 and TSW 89), the difference between highest and lowest ground-water levels during 1963–76 (2.2 and 2.6 feet, respectively) is not much greater than the average seasonal fluctuation (1 to 2 feet). In inland areas near the water-table divide (well SDW 253), the long-term water-level fluctuation (9 feet) is much greater than the average seasonal fluctuation (2 to 3 feet). The greatest difference between highest and lowest water levels observed on Cape Cod during 1963–76 was 9.3 feet at U.S. Geological Survey well SDW 253 (fig. 9C).

No long-term trend of rising or declining average water levels is evident in water-level records collected during 1963–76 at 13 Survey observation wells. The steady average water levels reflect the balance between recharge and discharge in which ground-water discharge has adjusted naturally to equal average inflow from recharge.



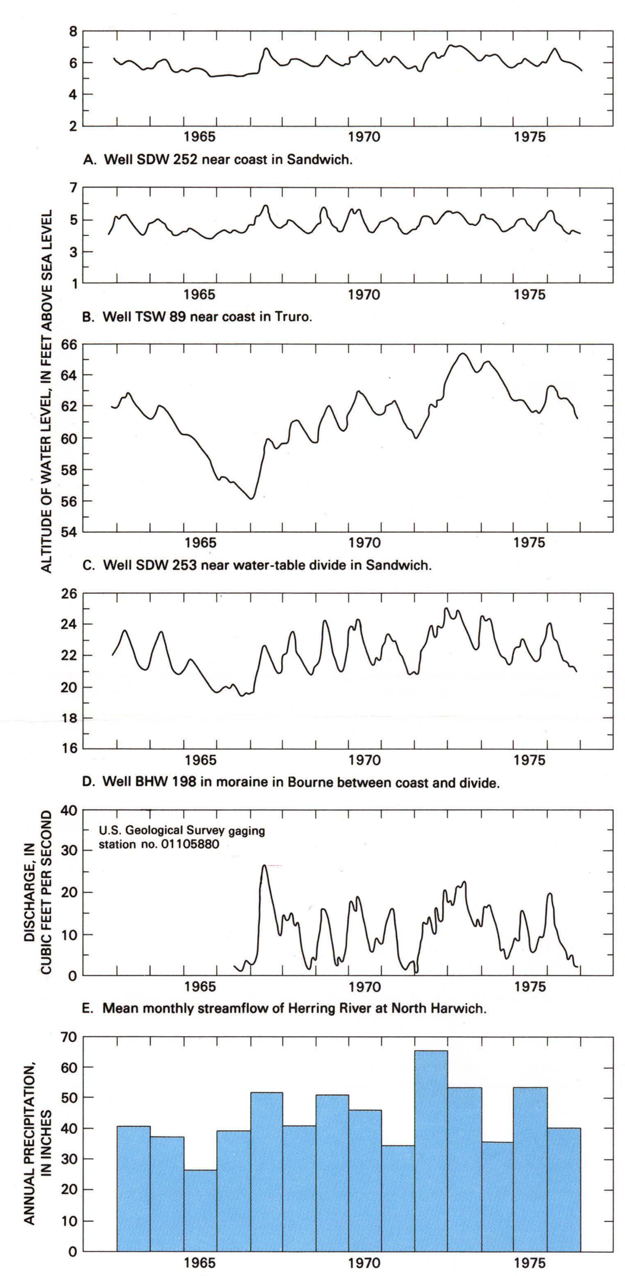
A. Precipitation varies much less than evapotranspiration.

B. Recharge, therefore, occurs mainly during the late fall, winter, and spring.

C. Seasonal recharge pattern is reflected by high water levels in the spring and low water levels in the fall.

D. Streamflow is greatest when water levels in the aquifer are highest.

Figure 8.—Seasonal variations in precipitation, evapotranspiration, recharge, ground-water levels, and streamflow.



A. Well SDW 252 near coast in Sandwich.

B. Well TSW 89 near coast in Truro.

C. Well SDW 253 near water-table divide in Sandwich.

D. Well BHW 198 in moraine in Bourne between coast and divide.

E. Mean monthly streamflow of Herring River at North Harwich.

F. Annual precipitation.

Figure 9.—Relationship of precipitation, ground-water levels, and streamflow for the period 1963-76. Precipitation data from the U.S. Weather Service stations at East Wareham, Woods Hole, Hyannis, Wellfleet, and Provincetown. Location of wells and gaging station shown in figures 14 and 18.

PONDS

There are more than 350 ponds on Cape Cod, 209 of which have an area of 10 acres or more. About 4 percent of the area of the Cape is covered by surface-water bodies (Brownlow, 1979, p. 14). Most ponds are present where land-surface depressions, such as kettle holes on the outwash plains, intersect the water table. The water-surface altitudes of the ponds correspond closely with the altitude of the water table around the ponds (fig. 10), and this relationship was used to help construct the water-table maps in this atlas. The levels of ponds that are not artificially controlled by dams or drains fluctuate in consonance with the seasonal and long-term water-table fluctuations.

Some ponds are perched above the water table because their bottoms are covered by sediments that have a very low hydraulic conductivity. These perched ponds are not in direct hydraulic contact with the main ground-water body. For example, Grassy Pond on Otis Air Force Base in Sandwich (fig. 14) is perched more than 100 feet above the regional water table.

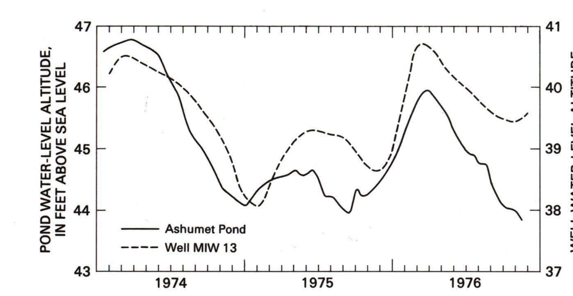


Figure 10.—Relationship between the water level of Ashumet Pond and the water table at well MIW 13 for the period 1974–76. Ashumet Pond is 11,000 feet west of well MIW 13. Locations are shown in figure 14.

EFFECTS OF TIDES

The loading and unloading effects of diurnal tidal fluctuations on ground water are transmitted hydraulically into the freshwater aquifer and cause similar fluctuations of smaller amplitude in the ground-water levels near the coast (fig. 11). The greatest change occurs at the shore, and the effect decreases sharply with increased distance inland from the shoreline. For instance, the water level in well WNW 82, which is located 500 feet from the shoreline in Wellfleet, has a tidally induced fluctuation that is one sixth of the fluctuation in Cape Cod Bay (fig. 11). The tidal range varies from about 2 to 10 feet at different points around the Cape (National Ocean Survey, 1974)—an important factor to be considered when estimating ground-water levels near the shore of a tidal water body.

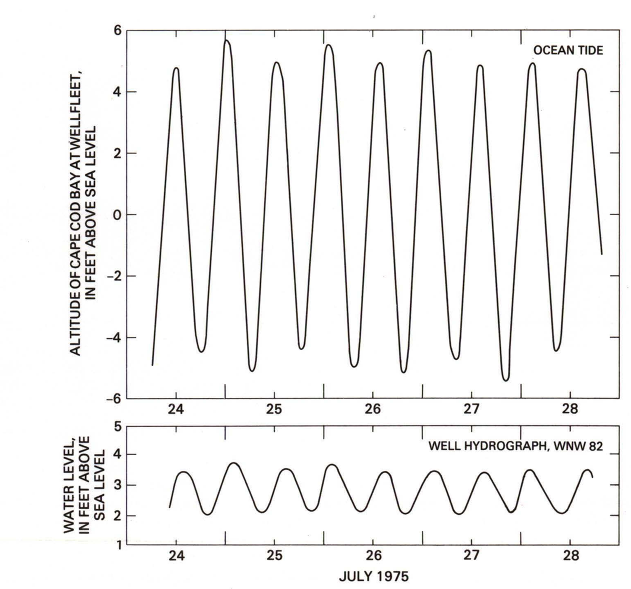


Figure 11.—Cyclic fluctuation of the water level in well WNW 82 in response to tidal fluctuations in Cape Cod Bay. The well is screened in freshwater between 37 and 40 feet below sea level. Ocean-tide data from the National Ocean Survey (1974). Location shown in figure 18.

EFFECTS OF WITHDRAWALS

Pumping from wells removes water from storage in the aquifer and results in a decline in water levels. Pumping from large-capacity wells such as Dennis Water District Well No. 12 (well D 87 in fig. 18), which yields 800 gal/min, can lower water levels in wells located several hundreds of feet away (fig. 12). Drawdown is greatest near the pumping well, and a cone of depression forms around the well. Because of the large scale of the water-table maps in this atlas, cones of depression around individual pumping wells are not shown. During a pumping cycle, drawdown and recovery will be superimposed on the seasonal and long-term trends of rising and falling water levels. For example, in figure 12, drawdown and recovery of water levels at well DGW 89 caused by pumping well D 87 are superimposed on the seasonal springtime trend of rising water levels.

The range of water-level fluctuation from October 1975 to March 1977 is shown in figure 13. As described earlier, natural water-level fluctuations are greater in the center of the Cape than near the coast. Pumping causes exceptions to this general rule, as in Barnstable, Yarmouth, and Dennis, where the greatest water-level range is observed in the general vicinity of large-capacity wells that are heavily pumped for public supply during the summer. Because most water pumped from wells is returned to the aquifer as recharge from onsite or municipal wastewater disposal systems and irrigation, the net withdrawal from the aquifer by wells is much less than the total volume pumped.

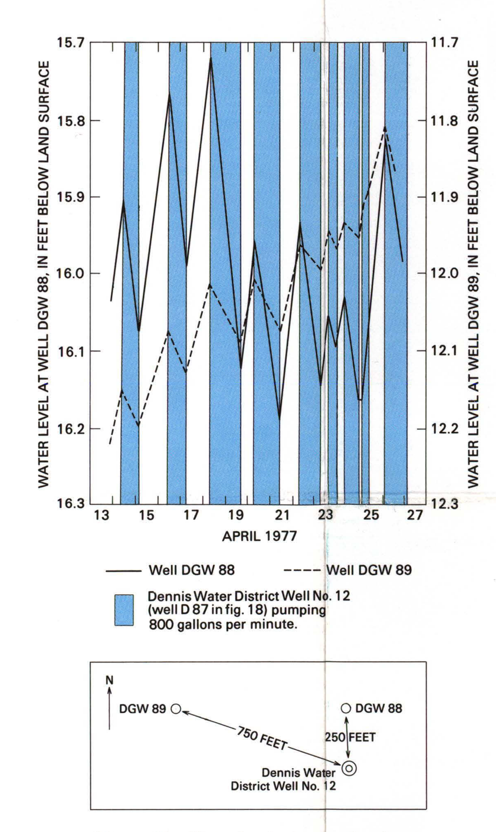


Figure 12.—Water-level changes in observation wells that are located 250 and 750 feet from a well that is pumped intermittently at 800 gallons per minute.

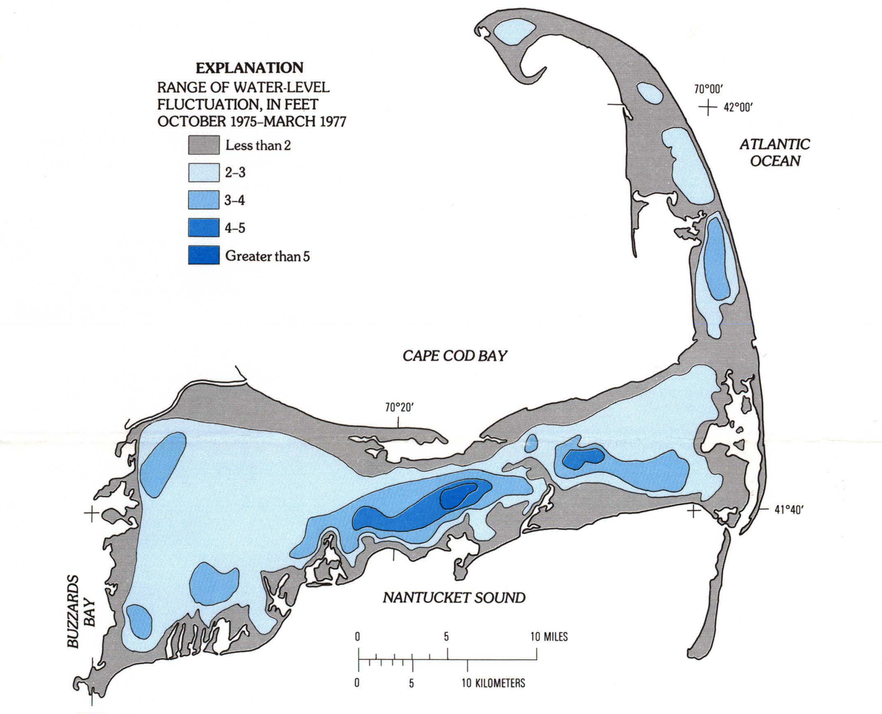


Figure 13.—Range of water-level fluctuation, October 1975 through March 1977. This period includes one annual cyclic fluctuation of water levels. Water levels were measured monthly in 126 observation wells.

GROUND-WATER RESOURCES OF CAPE COD, MASSACHUSETTS

By
Denis R. LeBlanc, John H. Guswa, Michael H. Frimpter, and Clark J. Londquist

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