GEOLOGY AND GROUND-WATER RESOURCES IN THE VICINITY OF THE AIR FORCE BASE IN ELEUTHERA

INTRODUCTION

Geography

Eleuthera, one of the main islands of the Bahama group, is about 70 miles east of Nassau, New Providence, and about 250 miles east of Miami, Florida. (See fig. 1, Part I.) It forms part of the eastern fringe of the Great Bahama Bank. The island is long, narrow, and elongate from northwest to southeast. The north half of Eleuthera is extremely narrow--exceeding 1 mile in width in only a few places and diminishing to less than one-half mile in some places. The island expands to a width of about 10 miles near the extreme southern tip. The Air Force Base is on the northeast coast of Eleuthera, approximately midway between Governors Harbour to the southeast and James Cistern to the northwest. (See fig. 1.)

Climate

Eleuthera has a subtropical climate; sharp changes in temperature are rare. The average range in temperature during summer months is between 79° F. and 83° F., and the average range during winter months is from 69° F. to 74° F. Humidity is usually high.

Large variations in rainfall are noted from month to month and from year to year. In general, however, the heaviest rainfall occurs from June through October. Rainfall during these months is extremely spotty, occurring usually in short, localized showers. During winter months cold fronts moving from the northwest are tempered after crossing the open ocean but occasionally produce general rainfall in Eleuthera and the northern Bahamas. The distribution of rainfall at the auxiliary airbase weather station on Eleuthera is shown in table 1. Also included are figures for average monthly rainfall at Dunmoretown, in Harbour Island (northern Eleuthera), and Nassau.

The prevailing winds are from the east and southeast. Winds are strongest and steadiest during winter and spring and decrease in force during late summer and early fall. Eleuthera lies in the path of frequent hurricanes which move northwestward or northward during summer and early fall.

Topography and Drainage

The outstanding topographic feature in Eleuthera is the high limestone ridge that runs lengthwise along the center of the island.

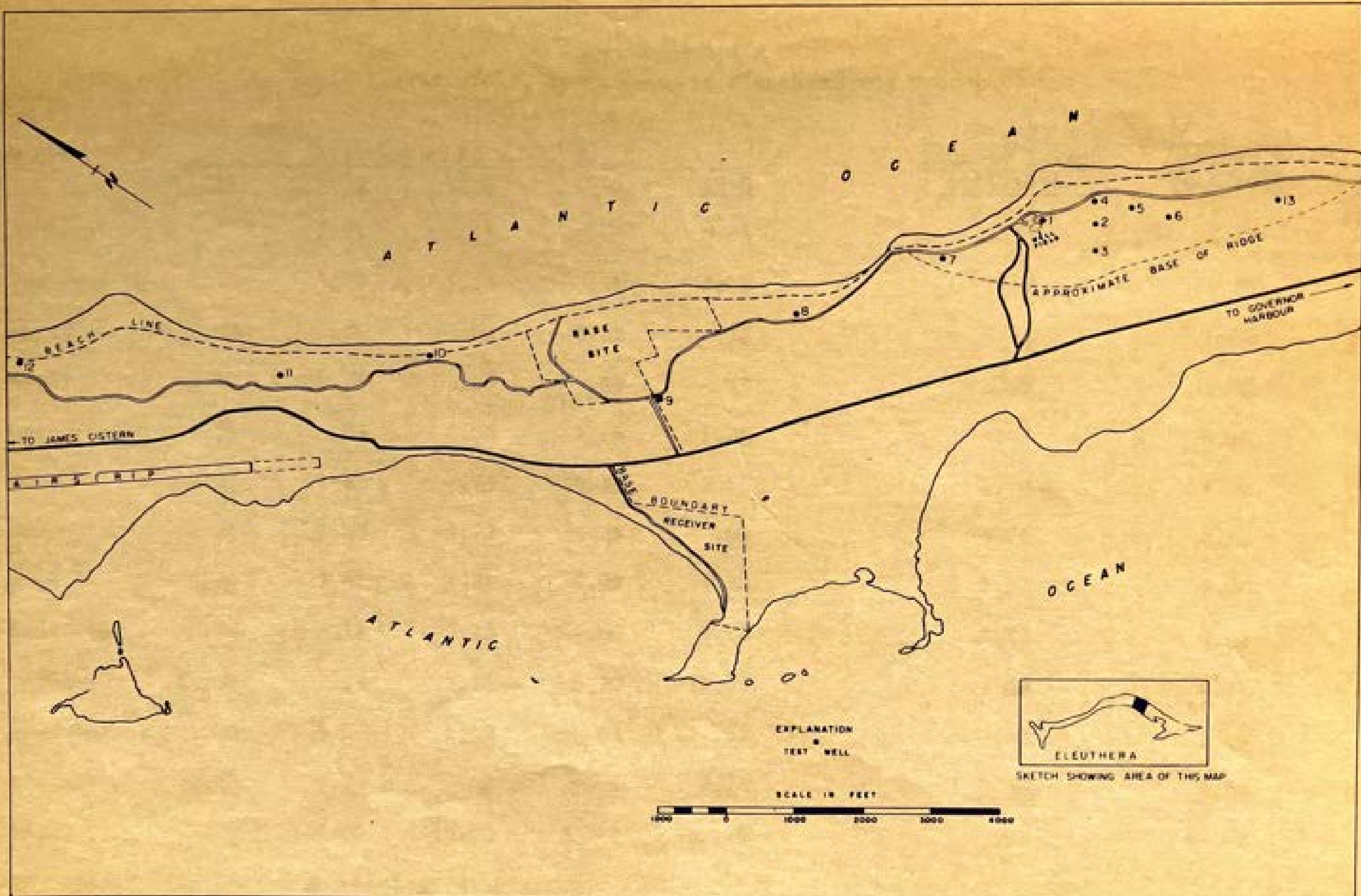

Figure 1. Map of part of central Eleuthera, B. W. I., showing the location of the Air Force Base and the test wells.

Table 1.--Rainfall, in inches, at Eleuthera and Nassau

Month	Eleuthera, A. A. F. B.					Average rainfall[1/]	
	1952	1953	1954	1955	1956	Harbour Island 1946-1954	Nassau 1945-1954
January	-	5.72	4.61	0.40	0.04	1.14	1.13
February	1.45	.49	5.55	.71	2.03	1.65	1.78
March	.00	.30	3.02	1.32	.26	1.71	1.31
April	1.40	1.75	3.29	.60	.85	1.90	3.04
May	8.36	.64	4.94	4.14	1.76	4.04	3.52
June	2.27	11.69	7.73	4.53	2.41	4.70	7.48
July	2.24	1.23	5.72	4.99	.60	4.76	6.19
August	6.24	7.47	1.31	8.00	4.98	5.57	7.06
September	5.26	3.18	3.15	4.60	9.12	6.19	6.95
October	12.37	7.24	5.14	5.70	12.05	7.48	8.81
November	1.00	6.05	1.49	.03	.86	3.62	3.08
December	2.69	.24	.08	.95	2.24	2.30	1.66
Total		46.00	46.03	35.97	37.20	45.06	52.01

1/ Record from Nassau Meteorological Station.

The limestone ridge is the oldest ridge on the island and was probably formed, during a period of emergence in Pleistocene time, by cementation of each sand previously deposited at a time when sea level was somewhat higher than at present.

The ridge attains altitudes of more than 100 feet above sea level in some places. As a result of solution and mechanical erosion the ridge is irregular in profile and outline, being marked by numerous depressions formed by the collapse of the surface because of underground solution by ground water. The ridge slopes off rapidly on the leeward or southwest side and terminates in low cliffs at the shallow ocean edge. Large beaches are formed only in protected embayments or reentrants.

On the windward or northeast side of Eleuthera a series of ranges of sand dunes occupy the area between the high limestone ridge and the beach. The dunes range in height from 10 to more than 60 feet above ocean level. They are elongate parallel to the shore and are composed of loose or partially cemented sand. These dune ridges are younger than the high limestone ridge in the center of the island. Their formation resulted from a repetition of the processes involved in the deposition of the higher ridge, but their composition indicates that they were formed of materials obtained from beaches along the eastern shore.

The valleys between the young sand dunes and between the dunes and the prominent ridge are generally low, having altitudes ranging from about sea level to more than 20 feet above sea level. The lower valleys are usually occupied by salt-water lakes or sloughs in which the water levels fluctuate in response to ocean tides.

Beaches are narrow but nearly continuous along the windward side of Eleuthera. They end abruptly at a wave-cut bench which in most places is at the base of a sandy beach ridge. In a few small areas on the windward side, just north of James Cistern, the high limestone ridge extends to the ocean and forms cliffs 60 to 70 feet high. These cliffs are composed of hard oolitic limestone and are resistant to erosion. Wave-cut notches in these cliffs are about 7 or 8 feet above ocean level. They are apparently at the same altitude as the limestone surfaces that form the low cliffs on the leeward side of the island and may be equivalent in age to the Silver Bluff shoreline in coastal Miami. An outstanding feature noted in these high bluffs is the occurrence, at various altitudes, of thin zones of red, iron-stained materials. These zones are composed of residual deposits concentrated by the solution and removal of calcium carbonate by percolating ground water.

The drainage of the area is underground, through solution channels and permeable sands. No surface streams exist, and little or no surface runoff occurs. The rate of subsurface drainage differs according to the type of subsurface materials. The drainage is very rapid through the openings and sinkholes in the limestone, but it is relatively slow through the sand. After periods of heavy rainfall a few of the low sand-filled valleys become flooded and may remain swampy for 2 or 3 months.

GEOLOGY RELATED TO GROUND WATER

Surface materials on Eleuthera are chiefly oolitic limestone and calcareous, oolitic sand of Pleistocene and Recent age. The relatively hard oolitic limestone forming the high ridge is probably of Pleistocene age and, as previously stated, is the oldest exposed material on the island. The rounded dunes that form beach ridges flanking the ocean on the northeast shore are composed of windblown oolitic sand mixed with rounded shell fragments. These dunes are late Pleistocene or, in part, Recent in age. Test wells in the vicinity of the base were drilled in depressions, usually in sandy areas. The thickness of the sands penetrated by these wells ranged from 1 foot to more than 20 feet. The eolian sands are underlain by limestones that are probably of marine origin and Pleistocene to Recent age.

Limestone Areas

The high, conspicuous ridge in the center of the island and the cliffs ending abruptly on the leeward side of the island are composed of gray and tan oolitic limestone. The limestone is the predominant surface material in the vicinity of the base and in most of the area between the ridge and the southwest coast.

The thin outer shell of the exposed limestone is usually a layer of casehardened oolitic limestone formed by alternate wetting and drying of surface materials which causes the calcium carbonate to be dissolved and redeposited in the pore spaces in the limestone. The corrosive effect of the solution of limestone by rainfall and percolating ground water is evident at the surface as well as at depth in the limestone areas. The outer surface of the limestone is extremely jagged and is marked by numerous shallow, rounded-out weathering pits from which calcareous material has been dissolved. This effect is noted inland, at relatively high altitudes, as well as on the coast where the rock is subject to erosion by wave action.

Sinkholes and crevices ranging in size from small openings to holes 75 feet in diameter develop as a result of underground solution and the collapse of the overlying rock. Shallow sinks may be partially filled with sandy or marly organic soils which support vegetation. A series of intersecting sinkholes forms a wide depression that can catch and store rainfall, under certain conditions. The largest such sink in the area, James Cistern, is 75 feet in diameter and 85 feet deep and has subsurface connection with the ocean. This type of solution-riddled limestone furthers rapid infiltration of rainfall to the water table and speeds underground drainage.

As noted in fresh, unweathered road cuts, the limestone forming the ridge is relatively soft and friable below the casehardened surface and shows a type of crossbedding associated with dune deposits. It is composed almost entirely of partially cemented oolites, along with a minor amount of well-rounded shell fragments. The sorting is fair to good, and the grain sizes range from medium to coarse, medium size predominating. Test holes reveal that marine limestone, composed chiefly of coarse- and medium-textured, beach-worn shell fragments, underlies younger dune sands at about sea level or slightly below sea level. The permeability of the marine limestone ranges from moderate to high, depending upon the amount of calcium carbonate cement in the interstices. In general, however, the permeability increases with depth.

Sandy Beach Ridges

Unconsolidated calcareous sand in the form of elongated sand dunes covers most of the area along the northeast coast, between the beach and the high limestone ridge. (See fig. 1.) These sand dunes are younger than the indurated, higher limestone ridge. The sand is medium to coarse, well sorted, and composed of rounded shell fragments and oolites.

The thickness of the sand and the altitude of the base of the sand are controlled by the altitude of the old, eroded surface of the underlying limestone. In areas where the altitude of the base of the sand is 5 feet or more above mean low water (mlw), the sand appears to lie unconformably on the eolian limestone that forms the ridge. The contact is marked, in most places, by the presence of a hard layer of iron-stained, casehardened caprock. Well 3, near the base of the high ridge (fig. 1), penetrated 2 feet of brown sand overlying marine oolitic, rust-stained limestone. The top of the limestone is about 5 feet above mlw. This suggests that the high ridge sediments lie unconformably on older marine limestones.

About 3,000 feet to the southeast of well 3, in well 13, a similar thin layer of casehardened limestone was penetrated at an altitude of 4.5 feet above mlw. This layer is overlain by 10 feet of unconsolidated coarse to medium sand, similar to the dune sands, and is underlain by marine limestone to a depth of 6.5 feet below mlw. The marine limestone is crossbedded, oolitic, and highly coquinoid, indicating a beach or offshore-bar environment of deposition. Well 13 was completed with 10 feet of casing and 10.8 feet of open hole. No caving occurred below the casehardened layer during drilling. Other test wells in the valley, wells 1, 2, 4, 5, and 6 (fig. 1), penetrated soft, caving, poorly sorted oolitic sand and marl of low to moderate permeability. Screens are required to complete wells in this material. Figure 1 shows the locations of test wells in the sandy ridge areas.

GROUND WATER

Ground-water supplies in Eleuthera occur in two general types of nonartesian aquifers, as follows: (1) open-textured limestones of high permeability underlying the old dune ridge and (2) loose or partially cemented sand of low or moderate permeability underlying the beach ridges. The lithology of the aquifer and the conditions of occurrence of the ground water have important bearing on the quantity and quality of the water available at any given place.

Hydrologic Properties of the Limestone Aquifer

The open-textured limestones are the oldest exposed materials on Eleuthera. These limestones have been subjected to different periods of solution and erosion (by percolating ground water) that have produced an underground network of vertical and horizontal cavities ranging in size from minute openings to caverns or sinkholes 75 feet or more in diameter. Such an arrangement of interconnected openings in the limestone results in extremely high permeability; thus, ground water is free to move in all directions in the aquifer. Also, this type of solution in limestone causes a decrease in the amount of fresh water that the aquifer is able to retain in storage. Little or no fresh-water head is maintained in the aquifer throughout the year, and ocean water is free to move inland through the openings to contaminate most of the ground water in the highly permeable limestones in the vicinity of the base.

The concentration of chloride ranged from 1,200 ppm to more than 5,000 ppm in samples taken at the water table in test wells penetrating the limestone aquifer. These high chloride concentrations indicate that after rainfall infiltrates to the water table it moves rapidly toward the ocean, owing to the high permeability of the limestones, or is soon mixed with the underlying salty water.

Near James Cistern, 6 miles north of the base, moderate quantities of potable ground water are available in the highly permeable limestone aquifer. James Cistern is a natural sinkhole that was formed from underground solution by percolating ground water and the collapse of overlying rock. The cistern is 75 feet in diameter and has nearly vertical sides. The bottom of the hole is approximately 75 feet below sea level, indicating that the level of the ocean during Pleistocene time was much lower than it is now. Underground solution was active throughout a large area, as the sink is in the center of a large depression about three-quarters of a mile in diameter. The area is a natural basin which receives large quantities of recharge by rainfall. The fresh-water zone (which assumes the form of a lens resting on heavier salty water) is thickest in the sinkhole. The thickness of the lens varies throughout the year and from year to year--depending upon the amount of rainfall in the immediate area, the rate of evaporation of ground water, the natural losses by subsurface outflow, withdrawals by pumping, and losses resulting from the diffusion of fresh water into salt water. The lateral extent of the fresh-water zone is not definitely known, but it may be considerable.

No test wells were drilled near James Cistern. At the end of January 1954, water from native supply wells that were 2,000 feet from the cistern and about 200 feet from the ocean contained 600 ppm of chloride or more, indicating contamination from sea water. These were shallow dug wells that penetrated about 2 or 3 feet below the water table. The wells probably penetrated the extreme edge of the fresh-water lens. They were dug into limestones of low to moderate permeability that have the ability to hold considerable fresh water in storage. During January 1954, 4.61 inches of rain fell at the Air Base Weather Station and a nearly equal amount probably fell in the James Cistern area. This is above the normal rainfall for January and may be the reason for the moderate chloride content of the water in the shallow native wells near the ocean. Under normal rainfall conditions these ground-water supplies probably have a higher chloride content at this time of year, and one that would continue to increase until the major rains occurred in June through October.

Availability of Fresh Ground Water

In early August 1954 water samples were collected at various depths below the water surface in James Cistern, to determine the thickness of the fresh-water zone at its center. Similar samples were taken in mid-January 1955 and October 1955. A comparison of the chloride content of all samples is shown in table 2.

Analyses of the August samples show that the fresh-water lens was about 12 feet thick in James Cistern. The total rainfall recorded at the base from January through July 1954 was 34.91 inches. Analyses of the January samples indicate that the fresh-water lens had shrunk to less than 8 feet in thickness, owing to the fact that there was only 19.73 inches of rainfall from August 1954 to January 1955. The analyses of the October samples indicate a marked thickening of the fresh-water lens between January and October 1955. In table 2, the concentration of chloride in the October samples showed an increase from 245 to 520 ppm at a depth between 30 and 36 feet below the water surface. The large increase in thickness of the fresh-water zone is due to a series of heavy rains that occurred a few days before the samples were collected.

Table 2.--Comparison of analyses of chloride content of water from James Cistern

Depth of sample (feet below water surface)	Chloride 1/ (ppm)		
	August 1954	January 1955	October 1955
0	240	200	220
3.0	240	200	220
5.0	...	...	220
6.0	240	...	220
7.0	...	220	...
7.8	...	280	...
8.0	...	720	220
9.0	...	960	...
10.0	260	1,140	220
12.0	460	...	...
13.0	720	...	220
15.0	960	1,600	220
20.0	1,200	...	220
25.0	...	2,400	220
30.0	2,400	...	245
36.0	...	...	520
41.0	...	...	520
50.0	...	5,000	1,500/

1/ Field determination (approximate)

The fresh-water salt-water contact in James Cistern apparently responds rapidly to large increase of fresh-water storage in the aquifer. When large increases in recharge occur the contact is quickly depressed. The subsequent upward movement of the contact can occur no faster than the rate at which fresh water is discharged from the lens. Therefore, the period of time required for the contact to recover to its original position will be considerably greater than the time necessary to depress the contact.

James Cistern is the source of water supply for the Aviation Engineer Unit. Daily withdrawals of 15,000 to 20,000 gallons started in March 1954 and were continued throughout 1955. Water was pumped from the upper 2 feet of the fresh-water zone at a rate not exceeding 20 gpm. The relatively slow rate of pumping caused no measureable drawdown in the water table and, thus, minimized the danger of upward flow from the salty, deeper parts of the aquifer.

Figure 2 shows two curves which indicate the difference in the drawdown patterns of the water table when a well is pumped at high and low rates, under the assumed conditions of transmissibility and storage coefficient drawn. Under each condition, 12,000 gallons is pumped from storage. Curve A represents the drawdown at various distances (r, radius) from a well pumped for 600 minutes at the rate of 20 gpm. Curve B represents the drawdown after the well had been pumped for 60 minutes at a rate of 200 gpm. These curves are plotted by using an assumed coefficient of transmissibility of 100,000 gpd/ft and an assumed coefficient of storage of 0.2. No pumping tests were performed in this area, and it is emphasized that the coefficient of transmissibility of the aquifer in the James Cistern area may be (and probably is) much higher than 100,000 gpd/ft. The significance of figure 2, however, is that it emphasizes the difference in the drawdown patterns that result from low and high rates of pumping.

The sketches in figure 3 were drawn in conjunction with the drawdown curves and show the theoretical direction of ground-water flow under the pumping conditions illustrated in figure 2. The sketches are not drawn to scale. Under light pumping (fig. 3a), the water table is depressed a small amount but remains above sea level. The salt-water contact rises slightly in the area affected by pumping, but the ground-water flow toward the pumping area is all from the fresh-water zone. When pumping stops, the water table will rise to essentially the prepumping level, and the salt-water contact will be depressed to its original form. When the well is pumped at a high rate, however, the water in the vicinity of the well declines rapidly to a point below sea level, thus permitting the steep coning effect of the salt-water contact (fig. 3b). The ground-water flow pattern is upward from the salty zone as well as radial from the fresh-water zone. These sketches may be applied to the James Cistern area as well as to other fresh-water areas in Eleuthera.

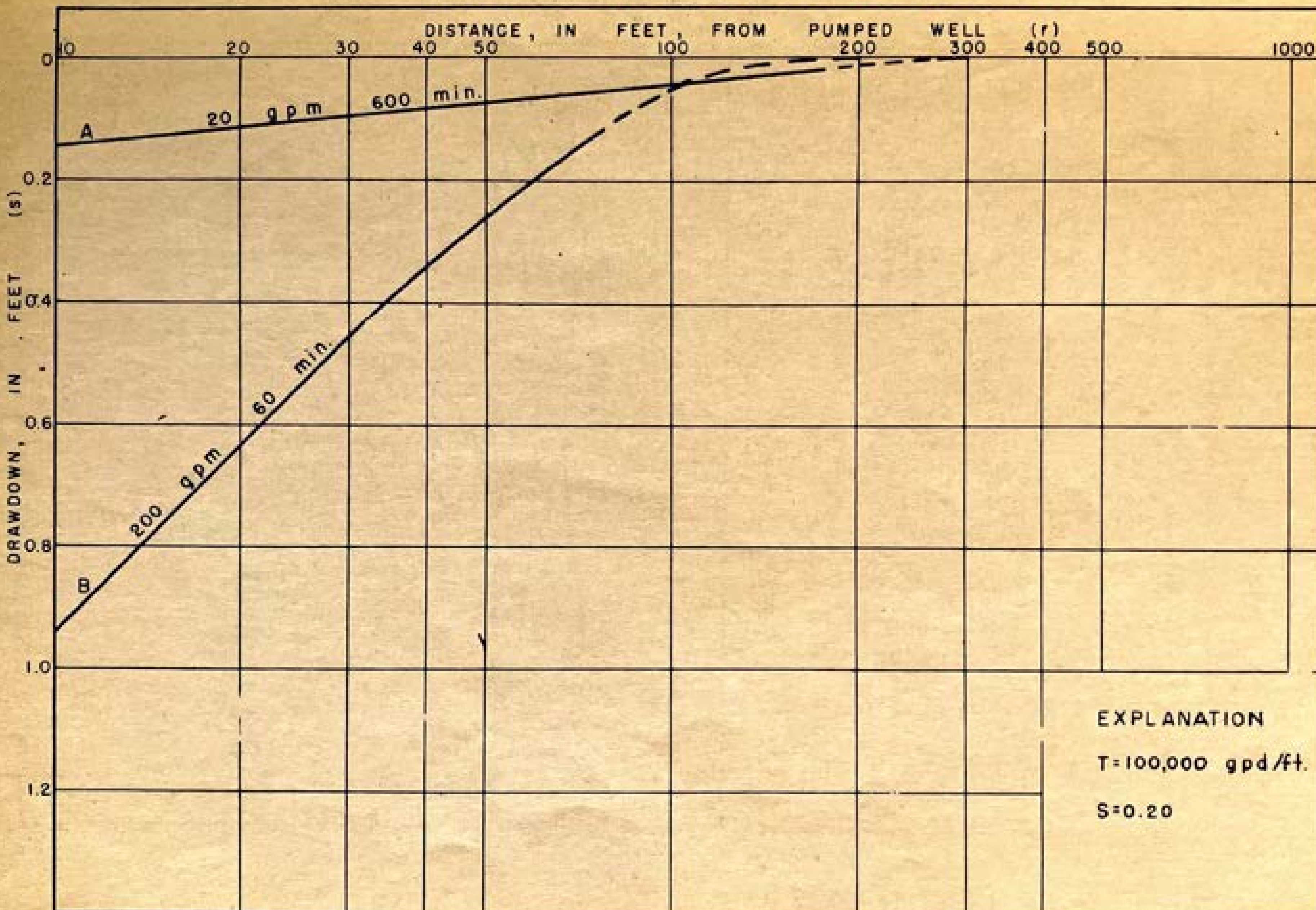

Figure 2. Graph showing differences in drawdowns resulting from low and high rates of pumping.

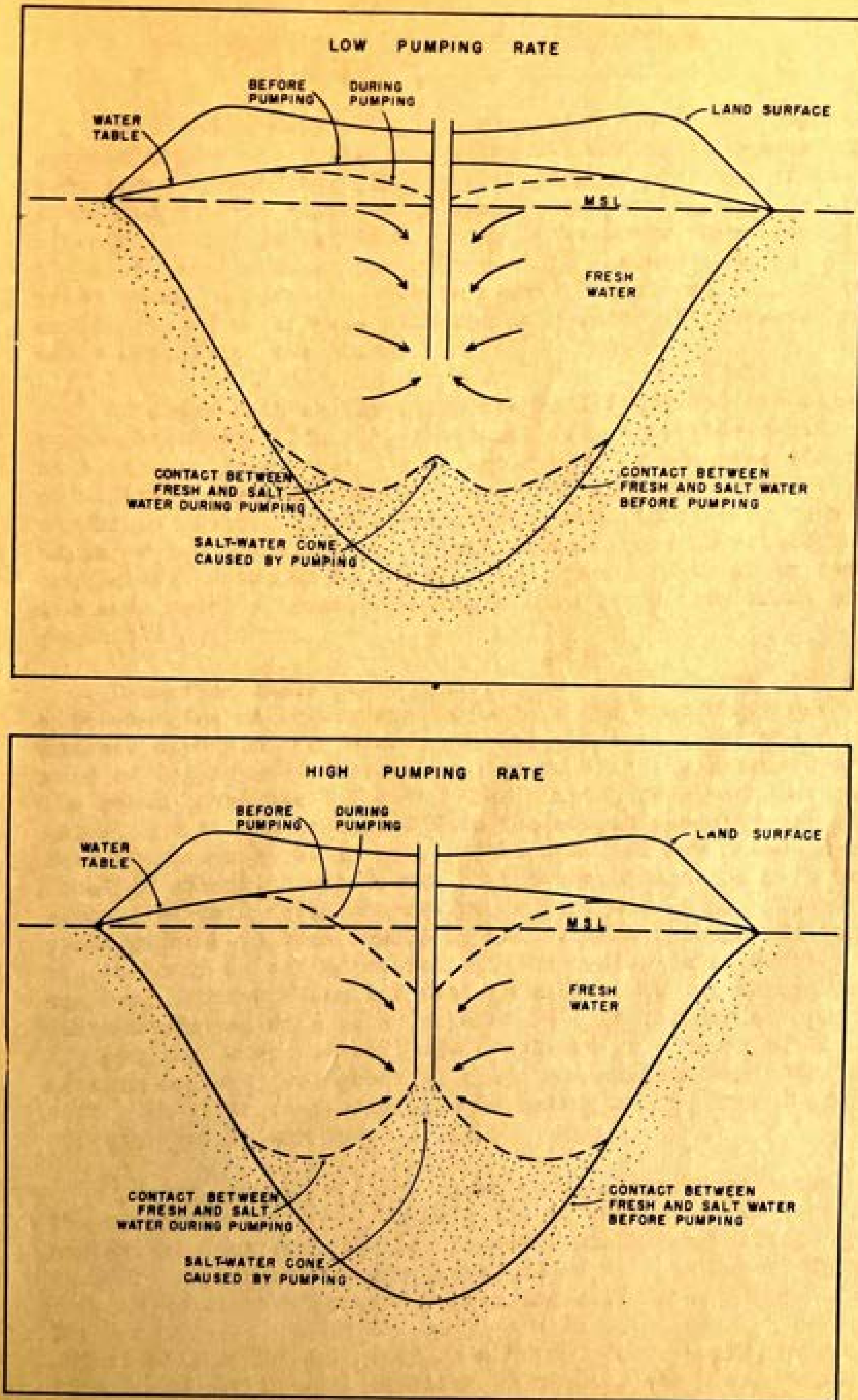

Figure 3. Schematic diagrams showing directions of ground-water flow during pumping of a well and the conditions under which a well will yield brackish water.

Hydrologic Properties of the Sandy Aquifer Under the Beach Ridges

The beach ridges along the northeast coast are composed of unconsolidated or slightly consolidated medium to coarse sand of moderate permeability. They overlie eroded surfaces of the old limestone ridge at an altitude of about 5 feet above mlw, or old marine limestones at lower altitudes. In areas where they overlie the highly permeable limestone of the ridge the sands do not yield much fresh water--apparently because rainfall that infiltrates to the underlying rock diffuses with the salt water at the water table or moves rapidly to the ocean.

In areas such as the Symonette well field and the adjacent valley to the southeast (fig. 1), the beach ridge overlies marine limestones at altitudes lower than 5 feet above mlw. The marine limestones are of moderate permeability, they are more heterogeneous than the younger, windblown material forming the ridge, and, in places, they grade into marls of low permeability. These factors tend to retard the vertical and lateral movement of ground water; thus, fresh water recharged in the area remains in storage longer than it does in areas having highly permeable aquifers.

Data from exploratory drilling and test pumping show that the water-bearing materials are nonuniform and that their permeability differs from place to place. Well 1, 11 feet deep, was pumped at a rate of 8 gpm, and after 10 minutes pumping the measured drawdown in the water level was 1.5 feet. The pumping rate was controlled by a valve, and it was estimated that the output capacity of the well at this depth was about 15 gpm. After the well was deepened to 13 feet a screened sandpoint was driven to the bottom and the well was pumped again. At this depth the maximum output was 2 gpm. This reduction in yield might have been caused by head losses through the sandpoint, but it could be an indication of poor hydraulic connection within the aquifer. During a similar test on well 13 it was determined that the maximum pumping rate at a depth of 16 feet (6 feet of open hole) was 2.5 gpm, but when the well was completed at a depth of 20.8 feet, the maximum capacity was about 15 gpm. Maximum pumping rates at various depths in other test wells in the valley ranged from 1 gpm to 10 gpm, but the average was about 3 gpm.

Pumping tests of short duration were run on selected wells in the Symonette field and on well 13, in an attempt to determine the approximate coefficients of transmissibility and storage for the aquifer. A recording gage installed on well 14 recorded the drawdown in water level caused by pumping well 21 at 5 gpm. (See fig. 4 for locations.) Wells 14 and 21 are 23 feet apart. The earliest effect of pumping was noted 15 minutes after pumping began, and the total drawdown in well 14 after 73 minutes was 0.015 foot.

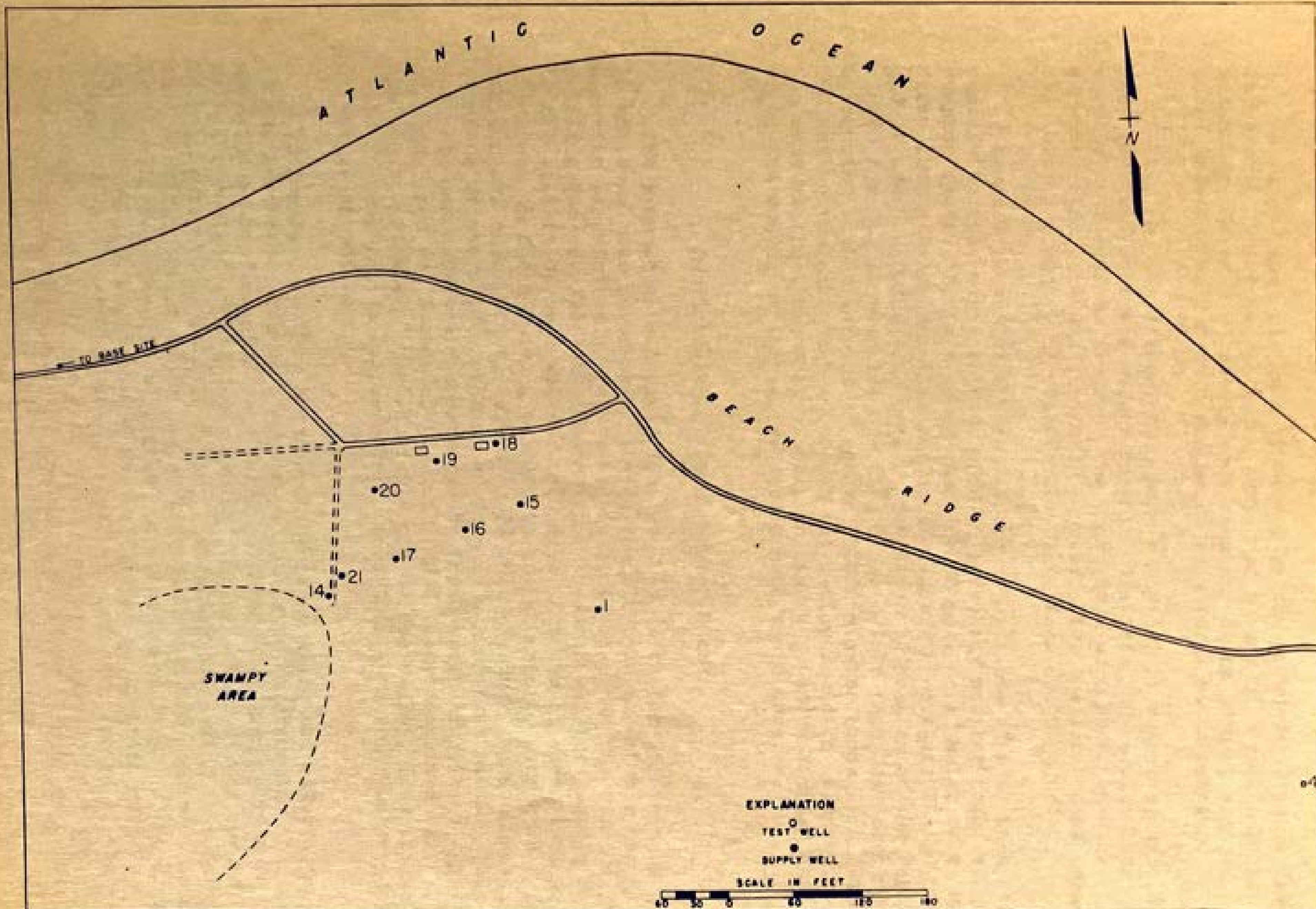

Figure 4. Map of the Symonette well-field area showing the locations of wells.

A second test was made by measuring the drawdown in water level in well 13, while it was being pumped at a rate of 6 gpm, and then measuring the rate of water-level recovery after pumping stopped. A total drawdown of 2.2 feet was measured after 2 hours pumping.

After the water-level data were analyzed, it became evident that they were not accurate enough to permit satisfactory evaluations of the aquifer coefficients, because the tests were very short and the pumping rates were not constant. However, the coefficient of transmissibility probably is considerably less than 20,000 gpd/ft.

Figure 5 shows the theoretical configurations of the cones of depression that might be developed in the sandy aquifer under different pumping rates. It is assumed that 20,000 gallons of water is withdrawn from storage and that the aquifer coefficients are T = 20,000 gpd/ft and S = 0.20. The cone B, developed by pumping at the rate of 200 gpm for 100 minutes, is ~~five~~ ten times deeper than that developed by pumping at the rate of 20 gpm for 1,000 minutes (cone A). Lines indicating the direction of ground-water flow would be essentially the same as those shown previously in figure 3, and a similar type of upward coning of the salt-water contact would develop.

Availability of Fresh Ground Water

The Symonette well field (see fig. 4), with the adjoining valley, is the only area in the vicinity of the air base in which a significant quantity of relatively fresh water is available. At the time of test drilling (August 1954) the maximum thickness of the fresh-water zone in the well-field area was about 10 feet. It was of about the same thickness in the adjoining valley, to the southeast, except in a few small areas where it was thinner. In well 13, near the southeast terminus of the valley, the zone was more than 9 feet thick. This well did not completely penetrate the fresh-water lens, as a sample of water from the bottom of the well (20.8 feet) contained only 150 ppm of chloride. The entire length of the valley, from the well field to well 13, is believed to be underlain by a fresh-water zone of irregular thickness.

During January 1955 several of the test wells and existing wells in the Symonette area were pumped at low rates to determine the drawdowns, and water samples were taken to detect any changes in the chloride content of the water during pumping. Well 21 was pumped for 5½ hours at the rate of 7 gpm, and during the period of pumping the chloride content of the water increased from 140 ppm to 330 ppm. It is believed, therefore, that a pumping rate of 7 gpm is too high for this well. The bottom of the well is at an altitude of 3 feet below mlw, and the well field is near the northern fringe of the fresh-water lens. If the rate of pumping were lowered to 3 gpm, the increase in the chlorinity of the water would be slight, as indicated

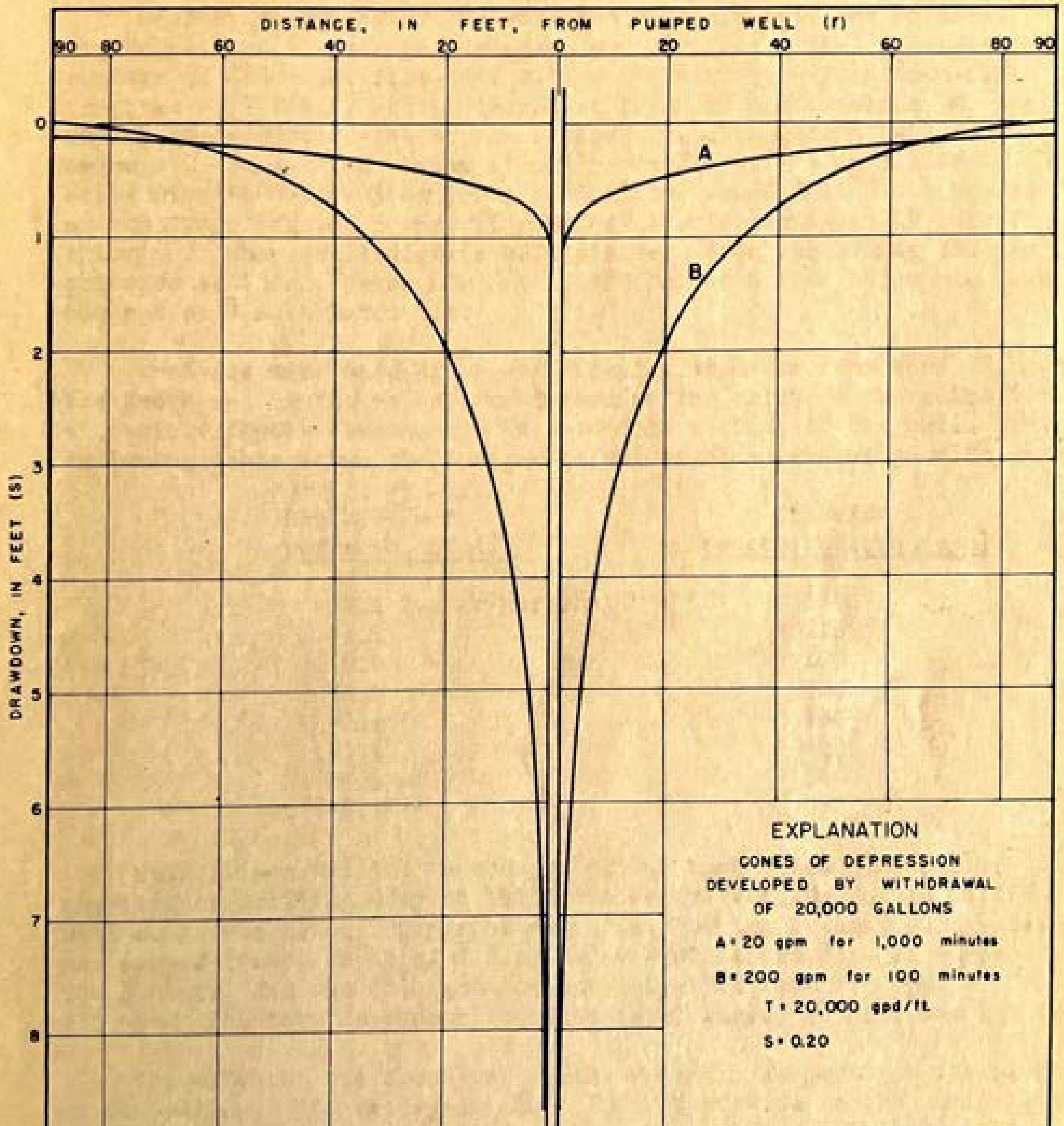

Figure 5. Theoretical drawdowns developed in sandy aquifer under different pumping rates.

by the chloride content of water pumped from well 20 (well 20 was pumped at 5 gpm for 3 hours, during which time the increase in chloride content was 50 ppm). Well 20 is 0.5 foot shallower (in reference to mlw datum) than well 21.

Well 4, southeast of the well field, was pumped for 6½ hours at the rate of 5 gpm. The drawdown was 1.7 feet. The chloride content of the water from this well was generally higher than that from the well field, and it increased from 320 ppm to about 380 ppm during the pumping. The bottom of the screen in well 4 is 3 feet below mlw datum. The bottom of the screen in well 5 is 3.5 feet below mlw, in material of low permeability. When well 5 was pumped at a maximum rate of 1 gpm, it yielded water containing 210 ppm of chloride. When drilled, this well yielded water containing 130 ppm chloride at 1 foot below mlw datum, 160 ppm at 3 feet below mlw, and 680 ppm at 7 feet below mlw.

Analyses were made of several samples of water from well 13, near the south end of the valley, to determine the chloride concentrations at various depths throughout the open-hole section of the well. The following table shows the changes in chloride concentration with depth.

Depth, (feet referred to mlw)	Chloride concentrations (ppm)
+2.1 (water surface)	170
+1.1	170
0.0	170
-1.1	220
-2.1	280
-3.1	420
-4.1	560
-5.1	560

Well 13 was drilled to a depth of 6.2 feet below mlw, and at the time of drilling (August 1954) the water from the bottom of the well contained about 150 ppm of chloride. During January 1955 water was pumped from a depth of 2 feet below mlw, at the rate of 6 gpm for 3 hours, and the chloride content increased from 170 ppm to 210 ppm. The total drawdown in water level during pumping was 2.2 feet.

The width of the fresh-water zone depends, in part, on the width of the valley. The valley is about 1,000 feet wide in the vicinity of the well field, but farther to the southeast, near well 13, the valley is less than 500 feet wide. The entire width of the valley, however, is not underlain by fresh water. Well 3, 400 feet from the base of the limestone ridge, penetrated water of high chloride content at the water table. It is assumed, therefore, that the entire length of the limestone ridge in this area is underlain by salty water, and the total area underlain by fresh water is considerably less than the total area of the valley. If the average coefficient of storage of the aquifer were 0.20 and the average thickness of the fresh-water zone were 6 feet in August 1954, the total volume of fresh water underlying the valley (4,000 feet by 300 feet) at the time of test drilling was about 10 million gallons. The average ground-water level in the area at that time was 3.0 feet above mlw, which was probably above the average for that time of year.

Only a part of the above-estimated volume of water was available for use. A large part was subject to loss by evaporation and transpiration, and another part to loss as a result of natural outflow from the aquifer to the ocean.

By January 1955 the water table had declined to an average altitude of 2 feet above mlw, and by mid-March, after a period of drought, it had declined to an estimated average of 1 foot to 1.5 feet above mlw. Because of the low-water conditions, the greatest thickness of the fresh-water zone in March was estimated to be about 4 feet. The reduction of thickness at the center of the lens was accompanied by a large areal reduction in the size of the lens; thus, the total fresh ground water in storage in the area probably was reduced to considerably less than half the quantity that was in storage at the time of drilling.

The average yearly rainfall in Eleuthera is about 40 inches. The quantity of water that infiltrates to the water table depends, to a large extent, upon the intensity of rainfall in the area. Light rains of short duration--which are very common in Eleuthera--contribute little to ground-water storage because of losses by evaporation and transpiration. Moderate or heavy rainfall over a substantial period is necessary for appreciable additions to ground-water storage. Applying similar proportionate estimates as those used by Parker (1955, p. 231) for southeastern Florida, approximately 20 inches of rainfall (15 million gallons) may infiltrate to the water table yearly in the Symonette area. Because winds are persistently fresh throughout much of the year, because the water table beneath the valley is nearly everywhere within 10 feet of the land surface, and because the vegetation is dense, it is estimated that something like three-quarters of the recharge (11 million gallons) is lost by evapotranspiration. The remaining 5 inches of recharge (4 million gallons) is discharged by ground-water outflow. Thus the daily losses from the fresh-water zone of the aquifer would be about 30,000 gallons by evapotranspiration and about 10,000 gallons by outflow.

The amount of fresh water available from ground water in this valley is the amount of the natural discharge that can be salvaged. Obviously, appreciable quantities of fresh ground water can be recovered from the area if withdrawals are made immediately following heavy rainfall. Analyses of water samples from wells 4, 13, and 14, collected near the end of March 1957, showed chloride concentrations of 650 ppm, 505 ppm, and 485 ppm respectively. These analyses indicate that during relatively dry years little or no ground water of acceptable quality would be available.

Water-Level Fluctuations

In the Symonette well-field area and the adjoining valley, the water table fluctuates entirely within sand or partially cemented limestone of low or moderate permeability. These fluctuations are due chiefly to influence by ocean tides, to rainfall in the area, and to evaporation and transpiration. In most cases, however, the water-level changes due to evapotranspiration are masked by the influence of tides.

Figure 6 is a series of hydrographs showing the difference in the magnitude of water-table fluctuations in the highly permeable limestone aquifer (well 9), and the slightly to moderately permeable aquifer underlying the sandy beach ridges (wells 13 and 14). These fluctuations are compared with tidal fluctuations on the northeast coast. The magnitude of the fluctuations in well 9 is nearly equal to that of the tide; the fluctuations in well 14 are about one-fifth the magnitude of the tide; and those in well 13 are less than one-tenth those of the tide, indicating the progressively poorer connection between the ocean and each of the 3 wells. The hydrographs, in a general way, indicate the relative capacity of the aquifers to transmit water. Also, they suggest that where the magnitude of fluctuation is small the hydraulic connection with the ocean is poor. In areas where the hydraulic connection is poor, ground-water recharge is held in storage longer than it is where the connection is good.

Figure 6 shows also the considerable lag in time of peaks and troughs of the ground-water fluctuations as compared with the tidal highs and lows. Although wells 13 and 14 are close to the ocean, the ground-water highs and lows occur from 2 to 3 hours later than the tidal highs and lows.

The aquifer in the valley near the Symonette well field has a greater capacity to store recharge water than the highly permeable aquifer, retains a relatively high ground-water head throughout the year, and, thus, preserves some fresh water in the upper part of the saturated zone throughout the year. Throughout the period of record, as shown in figure 6, the mean tide level was about 1.4 feet above mlw datum and the average ground-water levels were 1.8 feet in well 9, 2.4 feet in well 14, and 2.3 feet in well 13. If equal quantities of recharge had been received in each of the areas, the resulting rise of the water table in well 9 would have been small as compared to the rise in well 13 or 14.

Figure 7 shows hydrographs which compare the magnitude of water-level fluctuations in wells 19 and 21 through a single tide cycle. Well 21 is a little farther from the ocean than well 19, and the fluctuations in well 21 are smaller than those in well 19. The magnitude of the ocean tide during this cycle was 0.9 foot. The hydrograph indicates an apparent reversal in water-table gradient between low tide and high tide. At 1:00 p.m. (low), the gradient between the 2 wells was 0.02 foot seaward and at 5:30 p.m. (high), the gradient was 0.04 foot inland.

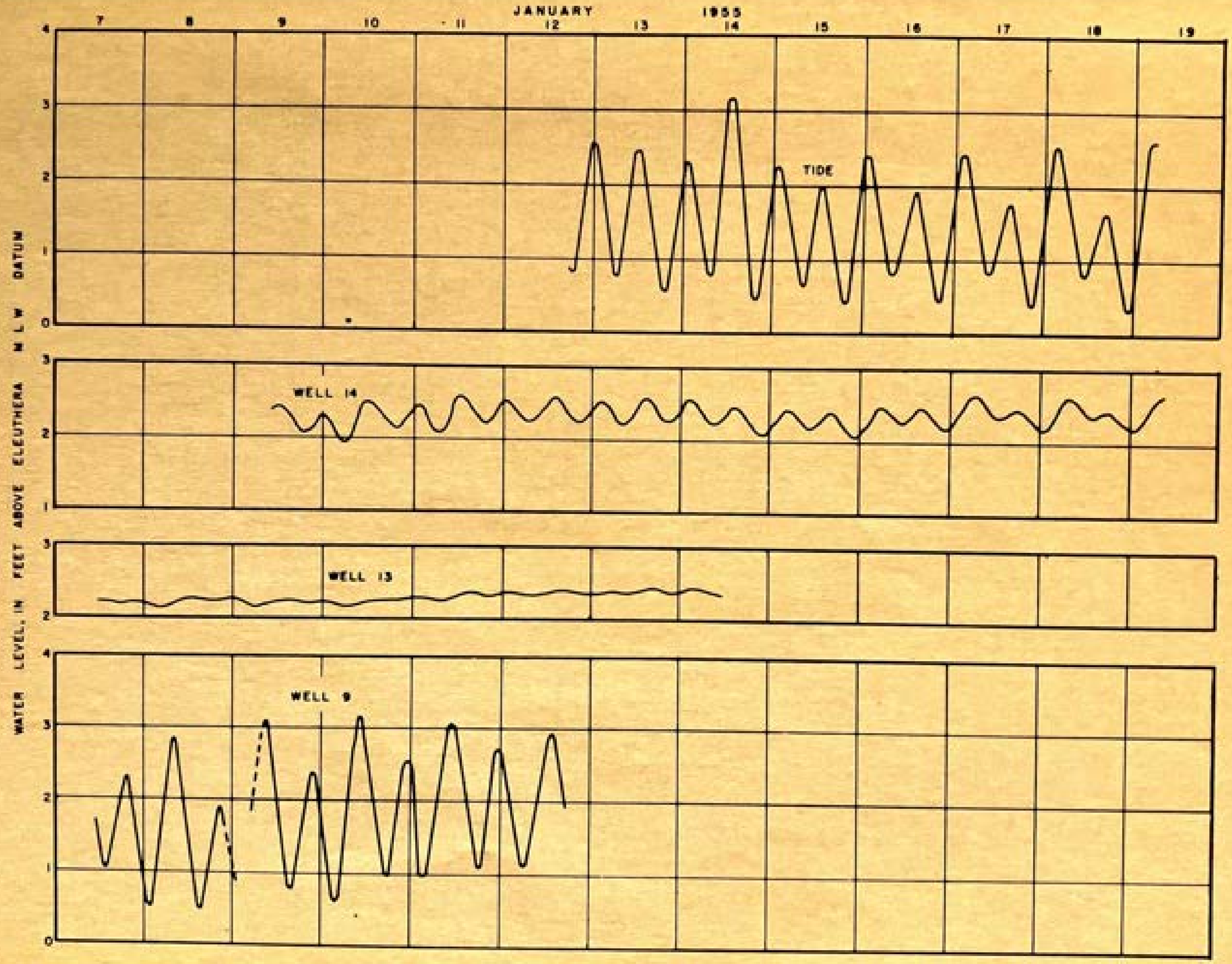

Figure 6. Hydrographs showing water-level fluctuations in various wells with respect to tidal fluctuations.

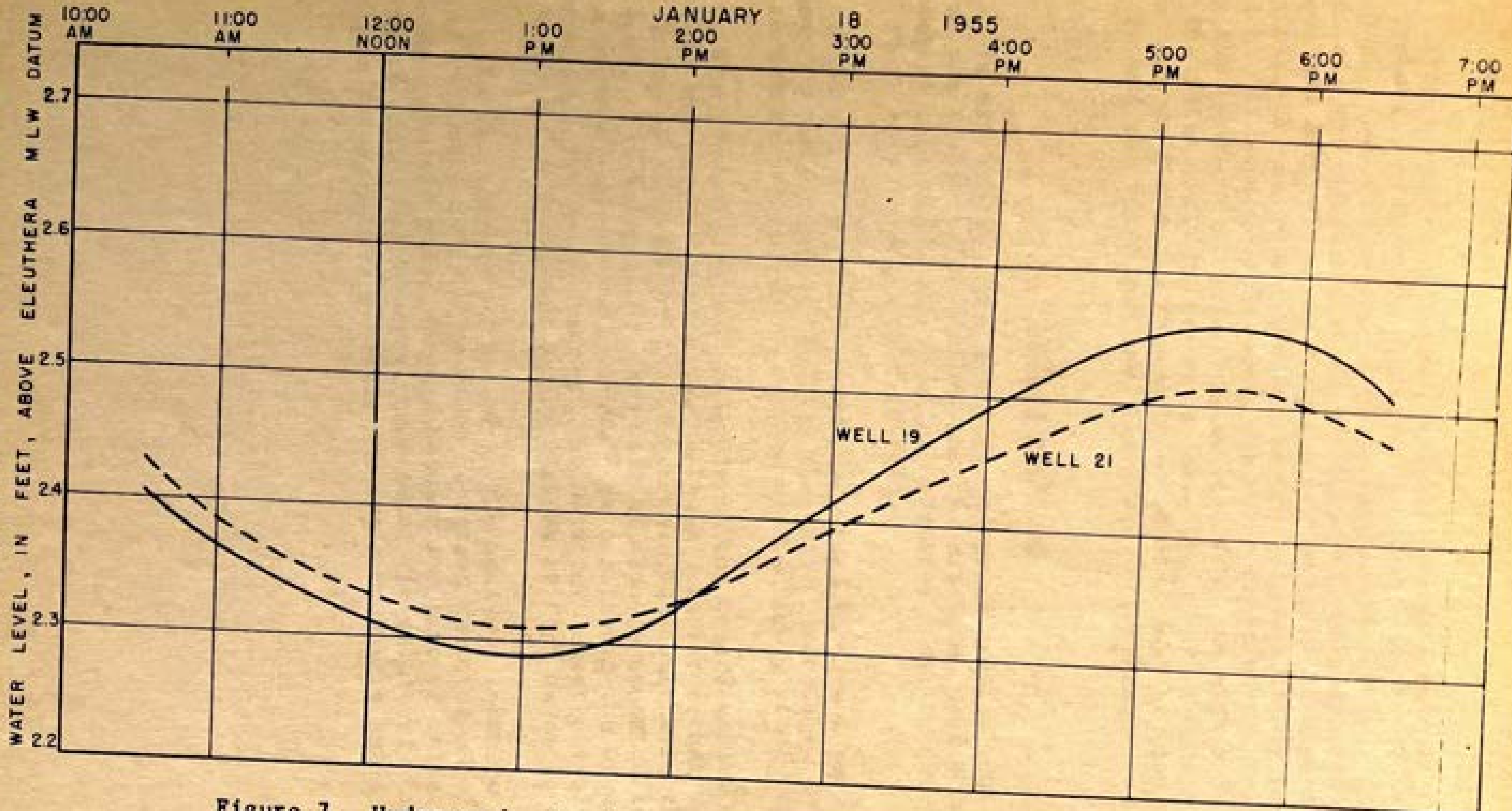

Figure 7. Hydrographs showing water-level fluctuations in wells 19 and 21 through a single tide cycle, January 18, 1955.

From a series of water-level measurements made in the well field on January 14-15, 1955, contour maps were drawn (figs. 8, 9, and 10), at high, low, and average tide levels, respectively. The contours indicate the shape and slope of the water table and its altitude above mlw datum. At low tide the ground water is highest in the vicinity of the well field and the water table slopes toward the beach. At average tide level the water table slopes toward the beach but the gradient is less than at low tide. At high tide the gradient of the water table is reversed, assuming a very slight inland gradient. The contour lines are interpolated for the area between the well field and the ocean and are, therefore, approximate.

Quality of Water

In mid-January 1955 three ground-water samples were collected from the Symonette well field and the adjoining valley for complete chemical analyses. The principal chemical constituents contained in these samples are listed in table 3.

The water is of the bicarbonate type and has a hardness of more than 300 ppm as $CaCO_3$. Much of the total hardness is due to calcium bicarbonate, which can be reduced by relatively simple treatment.

The concentration of chloride in the water samples ranged from 215 to 406 ppm. The analyses in table 3 indicate that water in the vicinity of well 13 had the lowest chloride content in the area. The overall quality of water from well 13 also is superior to that in the vicinity of the well field. The quality of the water changes throughout the year, however, the water of lowest dissolved-solids content being available during periods of high water levels.

The determinations for pH in the analyses indicate an alkaline type of water, but they may not represent the true pH of the water because several weeks elapsed between the time of collection and the time of analysis. However, because of the relatively high alkalinity of the samples, they probably underwent only very small changes in pH.

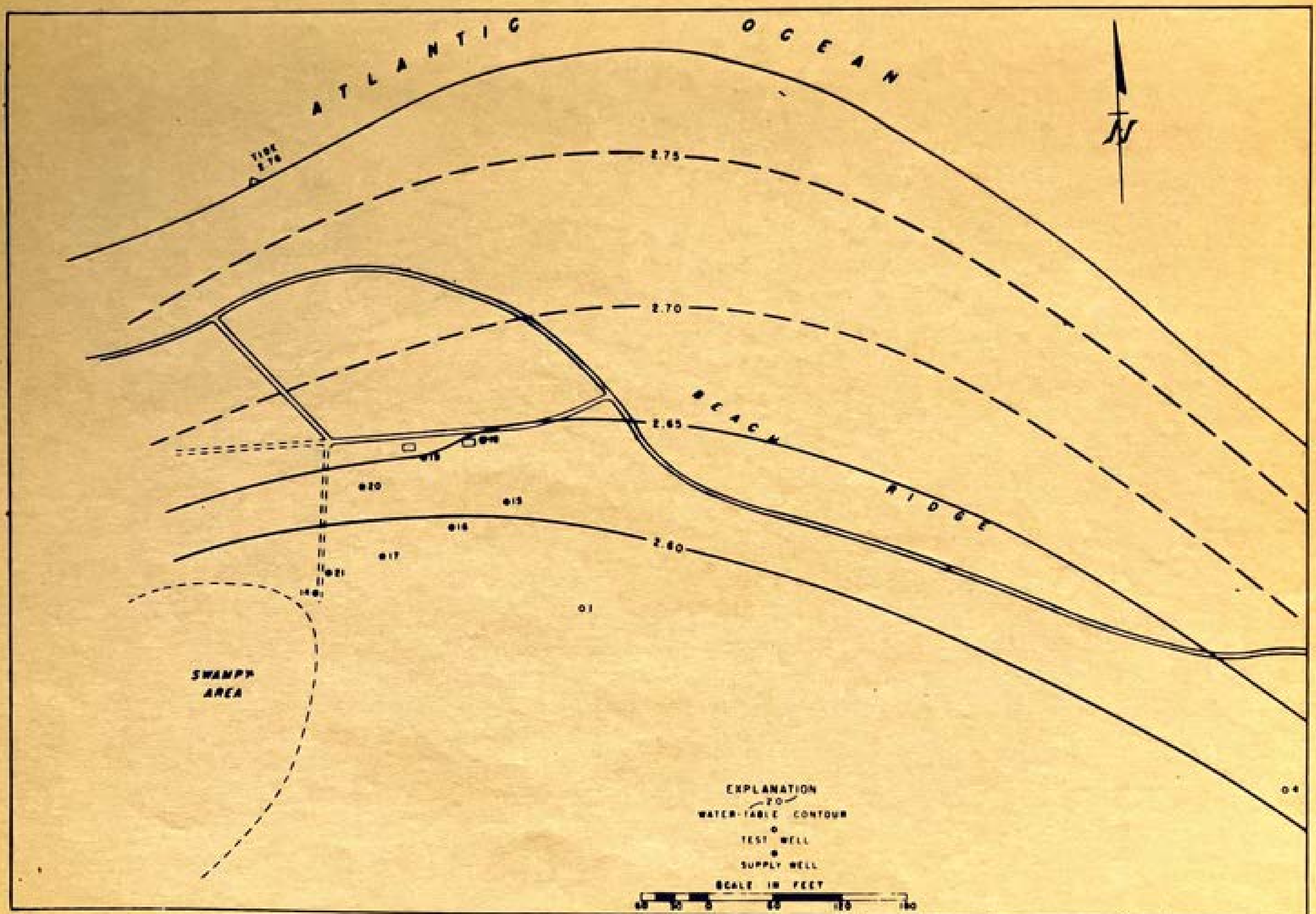

Figure 8. Map showing water-table contours in the Symonette well field and adjacent areas at average high tide, January 14-15, 1955.

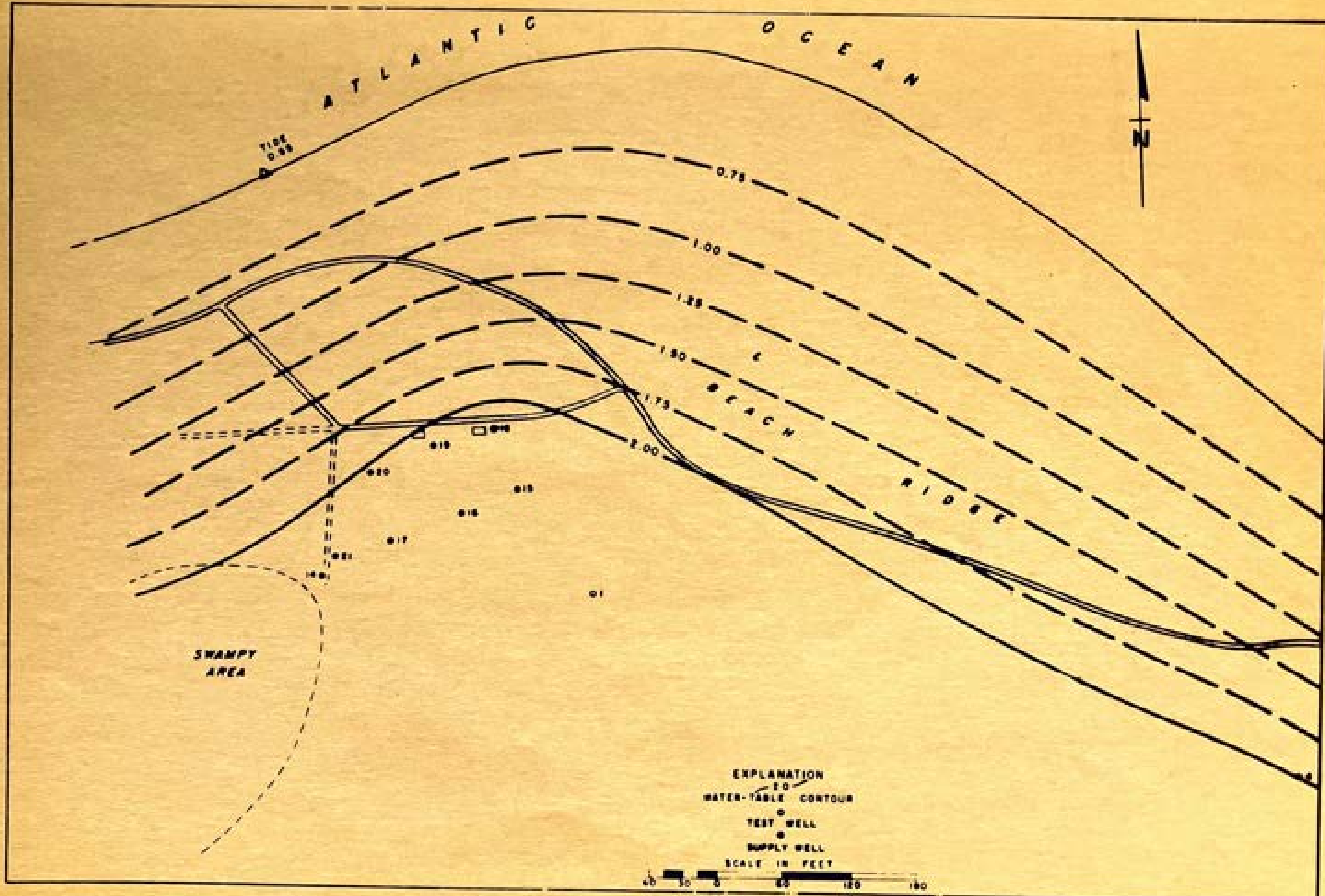

Figure 9. Map showing water-table contours in the Symonette well field and adjacent areas at average low tide, January 14-15, 1955.

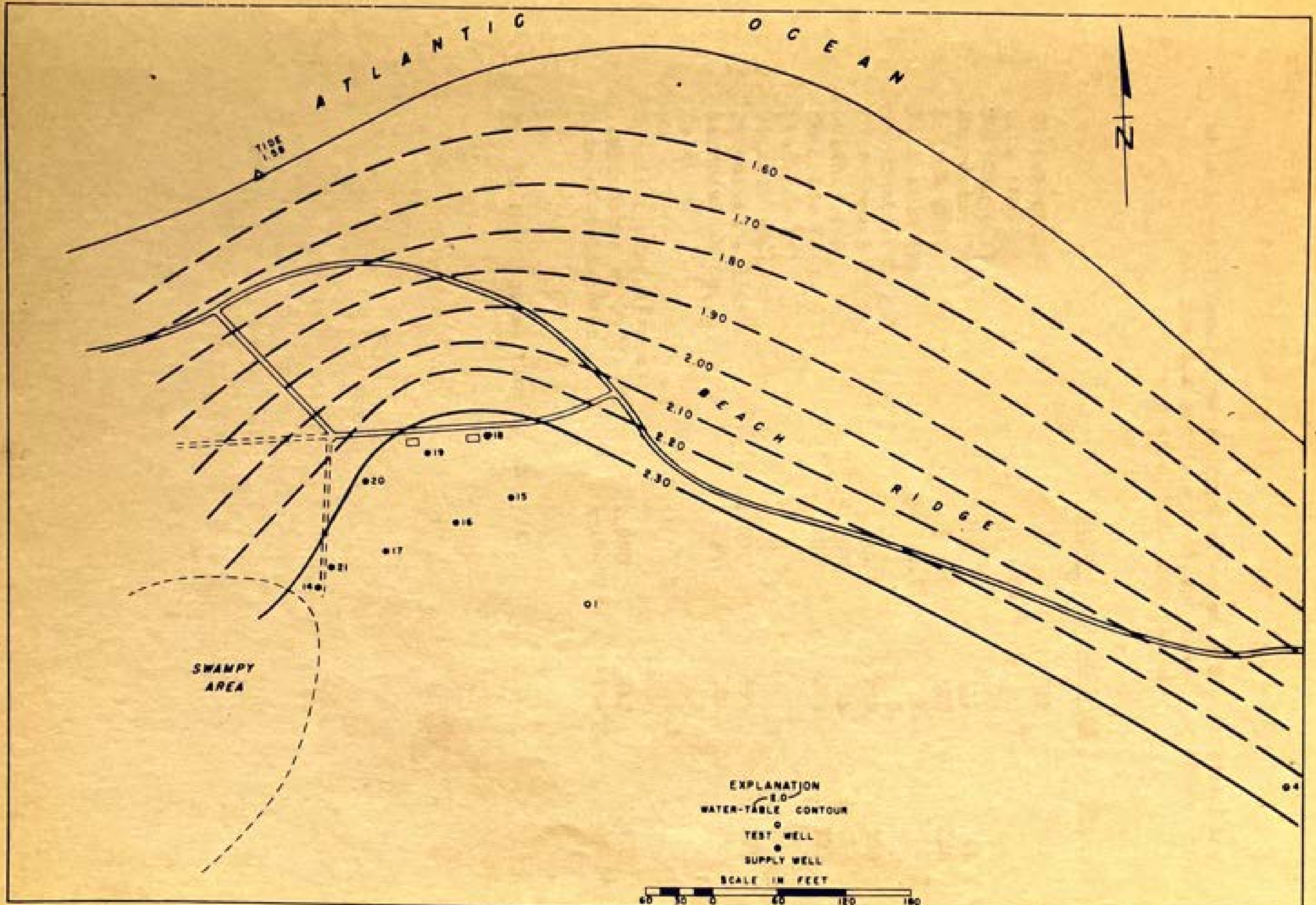

Figure 10. Map showing water-table contours in the Symonette well field and adjacent areas at average tide, January 14-15, 1955.

Table 3.--Analyses of water from selected wells in Eleuthera. (All results are in ppm except those for color, pH and specific conductance)

	Well 4	Well 13	Well 21
Silica (SiO_2)	7.4	17	19
Iron (Fe) 1/	.01	.01	.01
Calcium (Ca)	74	77	92
Magnesium (Mg)	46	27	41
Sodium (Na)	258	122	226
Potassium (K)	6.7	1.2	6.8
Carbonate (CO_3)	0	0	0
Bicarbonate (HCO_3)	308	307	398
Sulfate (SO_4)	107	35	47
Chloride (Cl)	406	215	382
Fluoride (F)	.8	.4	.2
Nitrate (NO_3)	.5	.7	.5
Dissolved solids	1,130	692	1,100
Hardness as $CaCO_3$	374	303	398
Color	4	3	6
pH	7.8	7.5	7.4
Specific conductance (micromhos at 25°C)	1,920	1,210	1,900
Date of collection	1-12-55	1-19-55	1-16-55

1/ In solution at time of analysis.

UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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