STATE OF FLORIDA
STATE BOARD OF CONSERVATION
DIVISION OF GEOLOGY

FLORIDA GEOLOGICAL SURVEY
Robert O. Vernon, *Director*

INFORMATION CIRCULAR NO. 29

GROUND-WATER RESOURCES OF NORTHWESTERN COLLIER COUNTY, FLORIDA

By
C. B. Sherwood and Howard Klein
U. S. Geological Survey

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
CITY OF NAPLES, COLLIER COUNTY
and the
FLORIDA GEOLOGICAL SURVEY

TALLAHASSEE
1961

Completed manuscript received
February 7, 1961
Printed by the Florida Geological Survey
Tallahassee

TABLE OF CONTENTS

ILLUSTRATIONS

GROUND-WATER RESOURCES
OF
NORTHWESTERN COLLIER COUNTY, FLORIDA

By
C. B. Sherwood and Howard Klein

ABSTRACT

This investigation was made to provide hydrologic information for use in the development of safe water supplies and water-control plans for northwestern Collier County. Previous development in this area has been limited to a narrow coastal ridge between the Big Cypress Swamp and the Gulf of Mexico; however, the agricultural development of large swampy inland areas is currently in progress.

The source of fresh ground water in northwestern Collier County is an extensive shallow aquifer, which extends from the land surface to a depth of about 130 feet. This aquifer is composed chiefly of permeable limestone and sand; however, its vertical permeability is restricted by thin beds and lenses of shelly, sandy marl in coastal areas and by a bed of very dense limestone which occurs near the surface in inland areas.

Recharge is by local rainfall and to some extent by surface water flowing seaward from the interior. Discharge of ground water is chiefly by underflow to the gulf or tidal streams, and by evapotranspiration. Water-level contour maps indicate a high ground-water mound beneath the center of the coastal ridge and perennially high water levels in the inland areas.

Chemical analyses show that ground water in the report area is relatively highly mineralized, except in areas on or immediately east of the coastal ridge. The mineralization along the coastal fringe areas results from recent salt-water encroachment, whereas that in inland areas apparently is due to residual salt water from former invasions of the sea.

Tests on the coastal ridge indicate that the aquifer will yield large quantities of water with moderate drawdown of water level; however, increased decline of water level caused by large additional ground-water withdrawals may cause further salt-water encroachment into the aquifer. In areas where surface water is available for recharge, drawdowns due to pumping may be greatly reduced by induced infiltration of water to the aquifer. The location of major well fields along the eastern edge of the coastal ridge is favored by higher transmissibility of the aquifer there and by the presence of a large source of surface water that can infiltrate into the aquifer.

INTRODUCTION

Purpose and Scope

During 1951-52 the U. S. Geological Survey investigated the ground-water resources of the Naples area in cooperation with the city of Naples. This investigation culminated in a report entitled, "Ground-water resources of the Naples area, Collier County, Florida," by Howard Klein, that was published in 1954 by the Florida Geological Survey as Report of Investigations No. 11. That study was requested by officials of the city of Naples who were concerned regarding the adequacy of the future water supply for the rapidly growing population. The investigation was designed to meet the immediate needs of the city as follows: (1) To determine feasible means to protect the city's existing water supply from contamination by sea water, (2) to locate additional supplies to meet new water requirements, and (3) to determine the available ground-water supply from aquifers that might be used in the future. The area covered by the early report was chiefly within the city boundaries.

Upon completion of Report of Investigations No. 11, a cooperative study was begun that was directed mainly at obtaining data to determine changes in the amount of ground water in storage and to monitor the movement of salt water in the area. Additional information was obtained on the physical character of the aquifer and the chemical quality of the water during construction of a new well field in the northeastern part of Naples. The construction of new highways into the Big Cypress Swamp in 1959, made exploratory work possible in the area east of Naples. This supplementary report was prepared chiefly from data obtained through the city's efforts to establish a permanent well field. The area investigated is shown in figure 1.

The investigation was made under the general supervision of P. E. LaMoreaux, chief, Ground Water Branch, U. S. Geological Survey, and Robert O. Vernon, director, Florida Geological Survey; and under the immediate supervision of M. I. Rorabaugh, district engineer, U. S. Geological Survey.

W. F. Lichtler, of the U. S. Geological Survey, conducted a 30-hour pumping test in the Naples well field and analyzed the test data. In 1959, as part of the field work for the investigation of the ground-water resources of Collier County, H. J. McCoy, of the U. S. Geological Survey, furnished data obtained from several test wells in the western part of the county.

Acknowledgments

The investigation was greatly aided by the cooperation and assistance of officials of the city of Naples and Collier County. The wholehearted cooperation of W. F. Savidge, superintendent, and other personnel of the Naples Water Department was especially helpful. W. H. Turner, county engineer, made possible the collection of geologic and water samples during the drilling of several privately owned wells.

Location of Area

The city of Naples is on the lower west coast of Florida (fig. 1). The area reported on extends from the mouth of the Gordon River northward to the Cocohatchee River and

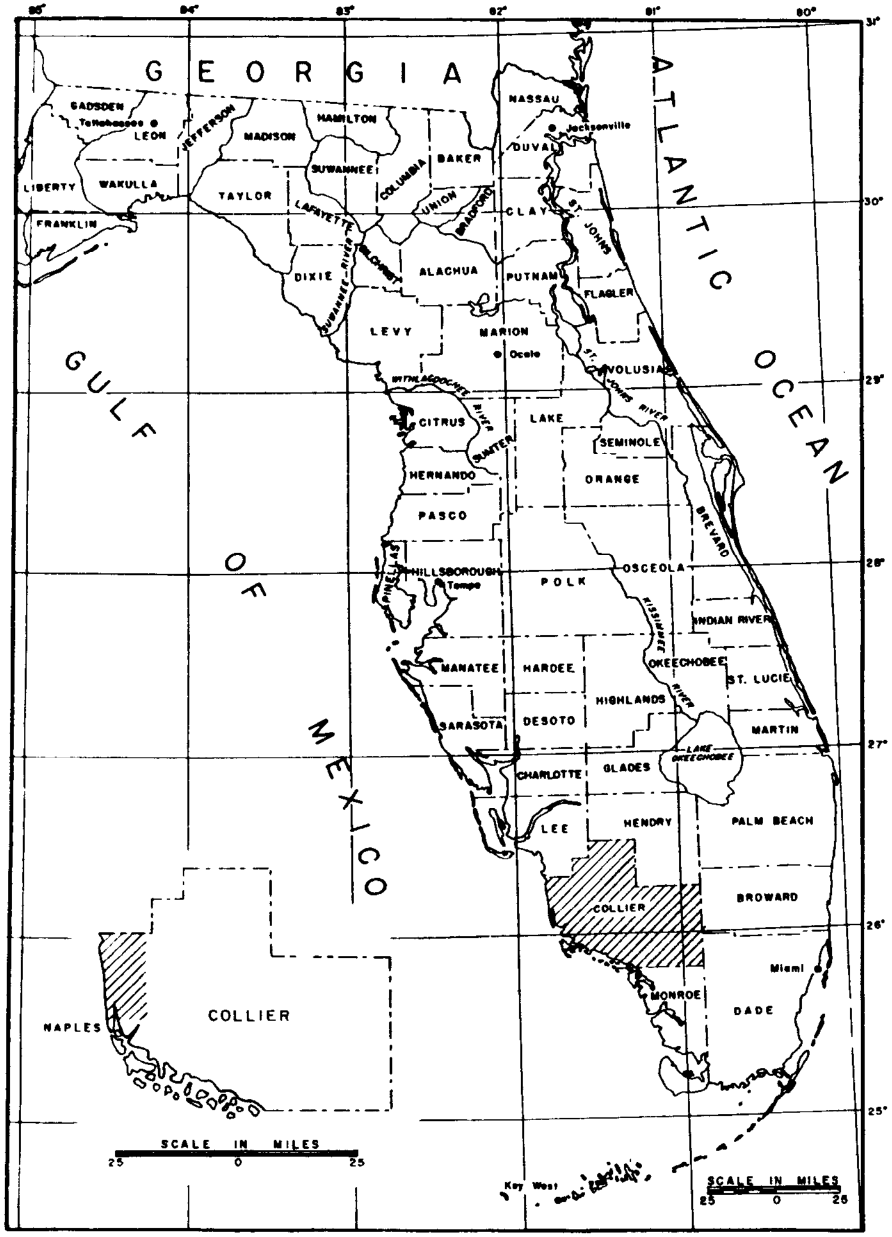


Figure 1. Maps showing the locations of Collier County and the area investigated.

from the gulf coast eastward for about 9 miles (fig. 2).

Climate

The climate of the Naples area is subtropical. Rainfall averages approximately 53 inches per year. Approximately 75 percent of the total falls during June through October which includes both the normal rainy season and the hurricane season. The average annual temperature is 76° F.

Topography and Drainage

The city of Naples is on a low coastal ridge about 2 miles wide, which rises from the marshes of the Ten Thousand Islands in southwestern Collier County and extends northward along the Gulf of Mexico. Figure 3, a compilation of U. S. Geological Survey topographic quadrangle maps, shows the topographic and drainage features of the area investigated. The coastal ridge is bordered on the east by Naples Bay and the Gordon River to a point near the northern city boundary, and north of there by a natural shallow depression that forms the upper reaches of the Gordon River drainageway. A poorly defined divide between the southward drainage to the Gordon River and the northward drainage to the Cocohatchee River is about 1 mile south of Vanderbilt Beach (fig. 3). The Gordon River drainageway is flooded or remains swampy during long periods of each year. The areas to the east of the river are occupied by cypress swamps, except for a small area east of Naples Bay that is well drained.

The land surface throughout most of the coastal ridge is 10 to 20 feet above msl (mean sea level) except in the southern part where the average altitude is about 5 feet. A large part of the coast is mangrove swamp less than 5 feet above msl. The Gordon River drainageway rises from near sea level at Naples Bay to about 10 feet above msl near the drainage divide. Farther eastward in the cypress swamps the land-surface altitude ranges from about 10 to 15 feet above msl.

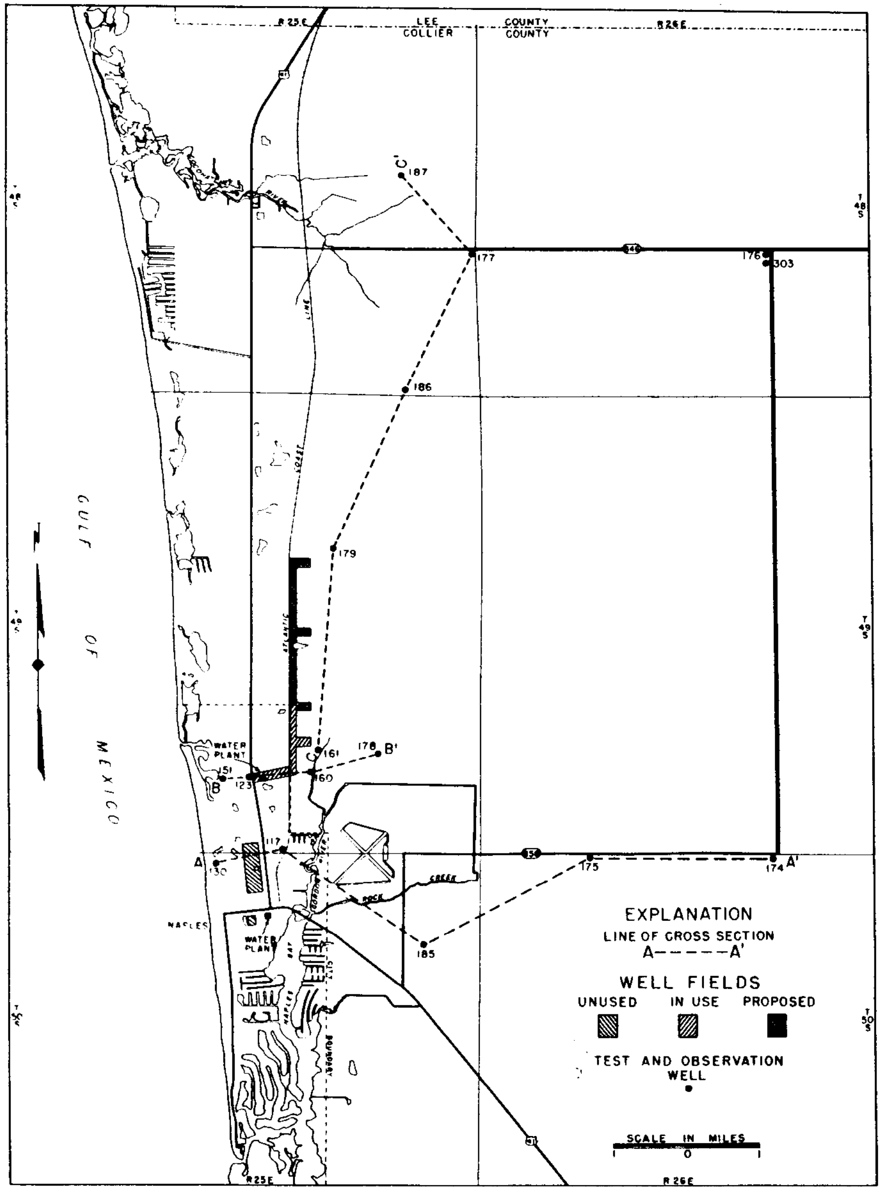
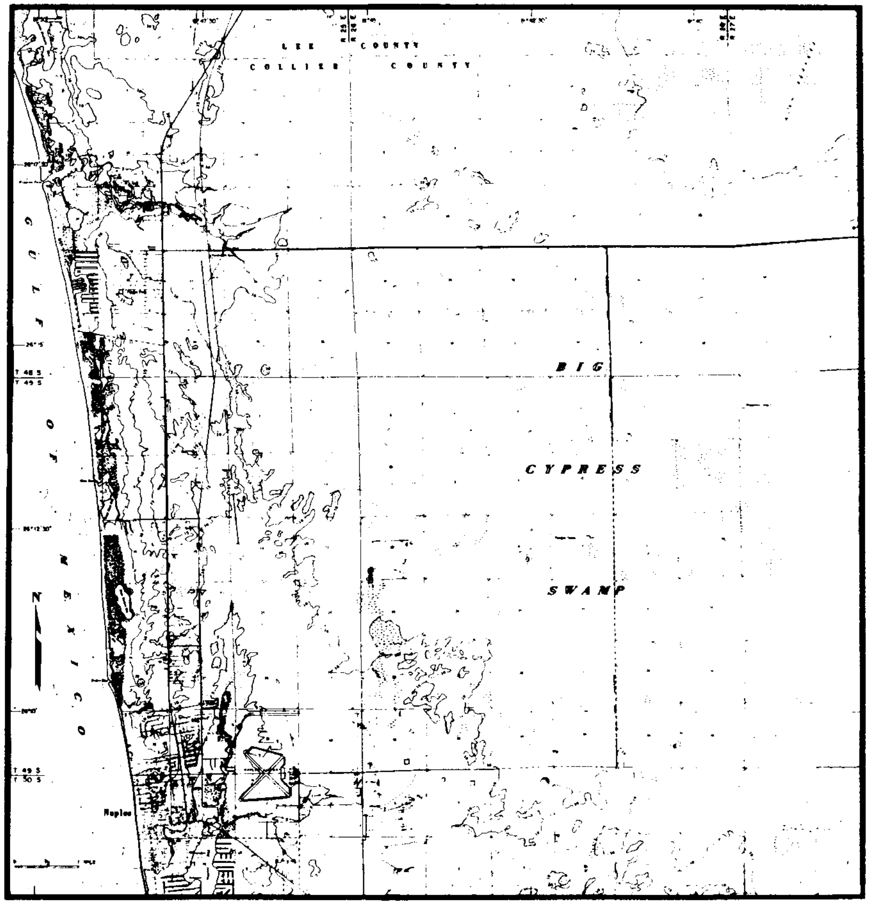


Figure 2. Map of northwestern Collier County showing the locations of the Naples municipal well fields and geologic cross sections.



Map compiled from USGS Topographic quadrangle maps
Belle Meade N.W., Bonita Springs, Corkscrew S.W., and Naples north

Figure 3. Map of northwestern Collier County showing topography and drainage.

Drainage of the coastal ridge is chiefly downward through the permeable sandy mantle. Ground water moves laterally to points of discharge in the gulf, Naples Bay, and the Gordon River. During the rainy season the depressions scattered along the ridge are filled with water and remain swampy for several months. Overland runoff appears to be restricted to the area east of the ridge where drainage is southward and southwestward as slow sheet flow. The extreme northern part of the area is drained by the Cocohatchee River. During each rainy season the eastern part of the area is inundated and remains swampy for long periods.

A recently constructed canal that extends several miles eastward from the Cocohatchee River has speeded the removal of flood water from adjacent lands. As a result of the improved drainage, new agricultural areas have been opened on both sides of this canal.

Summary of Well-Field History and Water Demand

Prior to 1945, the municipal supply for Naples was obtained from one 6-inch well and two 4-inch diameter wells located in the southern part of the city between Naples Bay and the Gulf of Mexico (fig. 2). These wells were closely spaced and were pumped heavily for short periods, which caused salt water to move inland and upward and, thus, to contaminate the aquifer.

During 1945-46, a new well field was established north of the original well field (fig. 2). This well field comprised 22 small-diameter wells (3-inch and 4-inch), spaced 400 feet apart. In order to diminish the effect of large local drawdowns of the water level each well was pumped at a rate not to exceed 30 gpm (gallons per minute). This method distributed the effect of pumping over a large area and reduced the hazard of salt-water encroachment. The annual pumpage from this well field increased from about 33 million gallons in 1947 to 122 million gallons in 1954.

The city officials proposed the establishment of a new permanent well field because of the constantly increasing demand for water (fig. 4), the high cost of pumping 22 wells, and the constant threat of salt-water encroachment from the Gulf of Mexico and the Gordon River to the old well field. Their ultimate objective was a well field in the cypress-swamp area, east and north of the city; but no data were available as to the continuity of the aquifer and the quality of the ground water in that area. The city officials believed that a productive field in this area could furnish sufficient water for all of the coastal ridge area of Collier County. With these goals in mind they established a well field at the present location (fig. 2) in the northeastern part of the city, assuming that further expansion of facilities would be inland. Total pumpage from this field in 1959 was 295 million gallons.

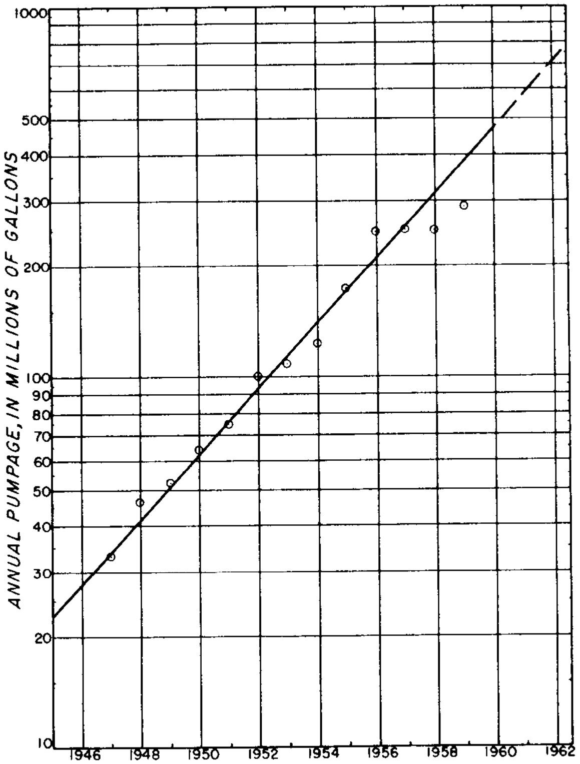


Figure 4. Graph showing pumpage in the Naples well fields.

In 1957 a system of coastal canals was constructed for a waterfront housing development directly west of the new well field. This canal network was a definite threat to the city water supply because it introduced a source of sea-water contamination about 2,000 feet closer to the well field. As a precautionary measure observation wells were drilled between the well field and the canal system in order to detect movement of the salt-water front in the aquifer by periodic water sampling. Similar wells were drilled east of the well field to monitor the extent of salt-water encroachment from tidal parts of the Gordon River.

Further geologic testing and exploratory work was begun as part of a plan to extend the well field northward along the western edge of the Gordon River drainageway. Also, an exploratory program was undertaken east of the Gordon River drainageway and northward toward the Cocohatchee River. These tests showed that, although the water-bearing materials were similar to those penetrated near the coast, the quality of the ground water was not as good as the existing supply. Additional exploration in 1959 and early 1960 indicated that most of the ground water in the large swampy area east of the ridge was not of acceptable quality for municipal use. The city still has the problem of obtaining water to satisfy increased demands from a small area close to the sea.

GEOLOGY AND TEST DRILLING

A shallow aquifer extending from land surface to a depth of about 130 feet is the only source of fresh ground water in northwestern Collier County. Limestones of the Floridan aquifer, at depths of 600 to 800 feet, yield large quantities of water under artesian pressure, but the water is highly mineralized and unsuitable for general use. The Floridan aquifer is not discussed in this report.

Information obtained from test wells and an inventory of existing wells indicates that the shallow aquifer ranges in thickness from about 110 to 130 feet and is underlain by relatively impermeable fine sand, silt, and marl. In general the aquifer is composed of permeable beds of soft shelly limestone, separated by thin layers or lenses of shelly marl of low permeability. The unconsolidated materials retard but do not prevent the vertical movement of ground water within the aquifer. The uppermost unit of the aquifer is well-sorted, medium-grained sand, about 20 feet thick. Infiltration in this material is rapid and surface runoff accordingly is negligible. The upper part of the aquifer is tapped by many small domestic or irrigation wells but most wells for large municipal or irrigation supplies are developed at depths ranging from 50 to 80 feet below land surface. Klein (1954, p. 8-22) described the geology of the southern part of the coastal strip and the water-bearing characteristics of the shallow sediments; therefore, no further discussion of these features is given in this report.

During 1957-59, approximately 15 test wells were drilled northeast and east of Naples in connection with the expansion of well-field facilities and the exploration of inland areas. The initial test wells were drilled in accessible areas to the east and northeast of the present well field, in the vicinity of the upper reaches of the Gordon River (wells 160, 161, 178, and 179, fig. 2). After the completion in 1959 of the highway system extending eastward from Rock Creek and the Cocohatchee River, the drilling program was extended to include these heretofore unexplored areas. The objectives of the test drilling were to furnish information relating to: (1) The extent of salt-water encroachment in the aquifer in the vicinity of the Gordon River, (2) the continuity, thickness, and general water-bearing characteristics of the shallow aquifer in the area east of the coastal ridge, and (3) the quality of the ground water in the area east of the coastal ridge.

Outpost-observation wells also were drilled west of the existing well field to detect salt-water movement from the Gulf of Mexico caused by large withdrawal of water at the well field and by the construction of the coastal canal system. The locations of test wells and the lines of geologic cross sections are shown in figure 2.

The lithology and chloride content of the water at selected depths along the geologic sections are shown in figures 5-7. The test drilling indicated that the aquifer is continuous east of the ridge and north to the Cocohatchee River. A significant difference in the lithology is indicated by an increase in the proportion of limestone in the aquifer east of Naples and the thinning or disappearance of the uppermost sand component of the aquifer toward the eastern part of the area. Throughout much of the area east of the coastal ridge a layer of very hard, dense, tan to gray limestone occurs at or immediately below the land surface. Examination of this limestone, excavated during the construction of the canal east of the Cocohatchee River, indicated that its permeability is low. The low permeability of the rock retards downward infiltration of rainwater to the

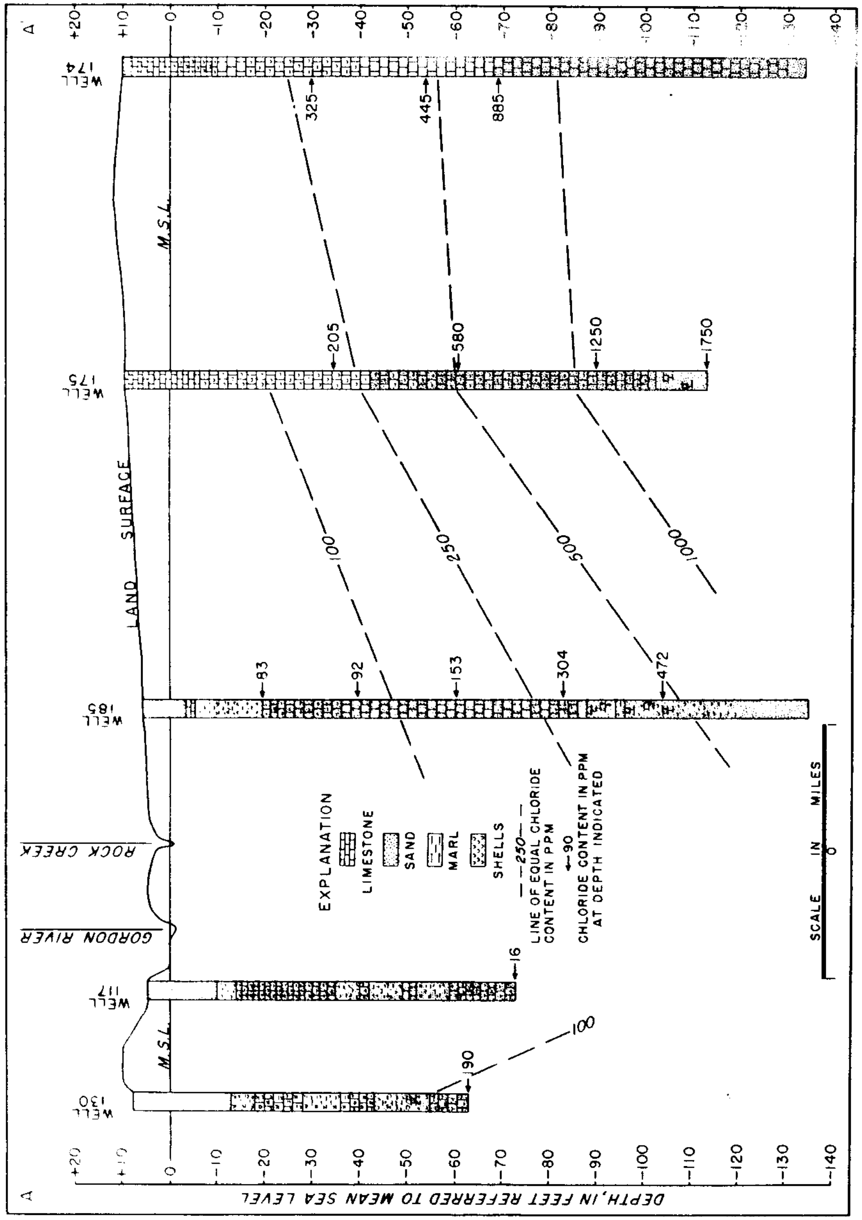


Figure 5. Geologic cross section and chloride content along line A-A'.

throughout the eastern area, and presumably they are, much of the potential recharge to the aquifer will be rejected and the overland runoff will be proportionally greater.

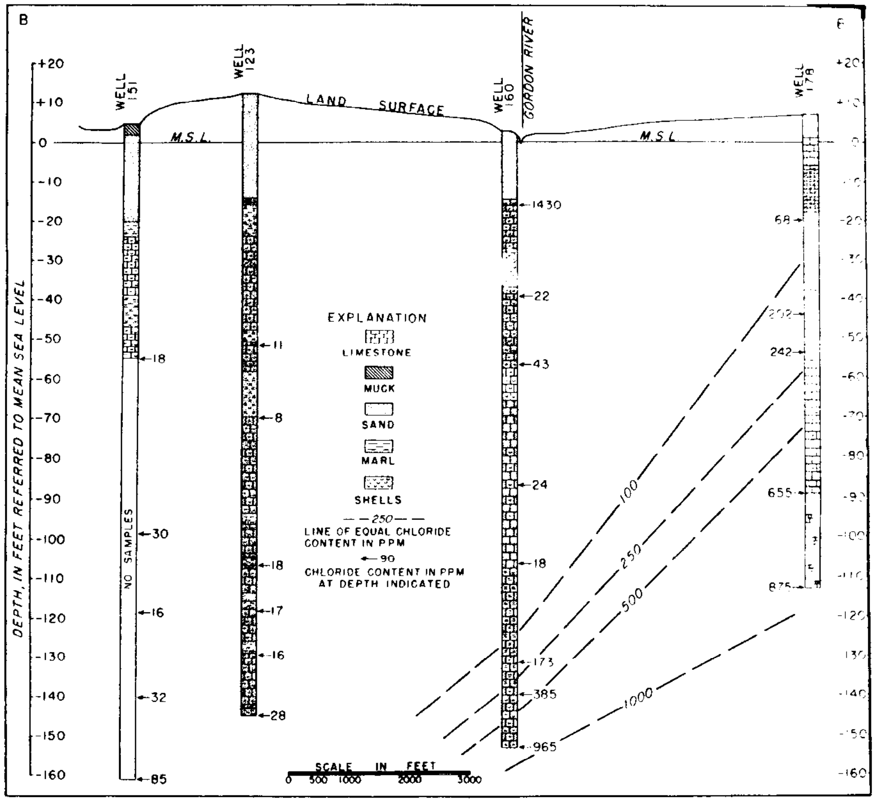


Figure 6. Geologic cross section and chloride content along line B-B'.

GROUND WATER

Local rainfall is the source of all the water that replenishes the shallow aquifer in the vicinity of Naples. Part of the rainfall is returned to the atmosphere by evapotranspiration, part infiltrates to the shallow aquifer, and the remainder runs off into streams and to the gulf. After reaching the saturated zone of the aquifer water flows under gravitational forces from points of recharge, where water levels are high, to points of discharge where water levels are low. In general, the limestone beds in the aquifer

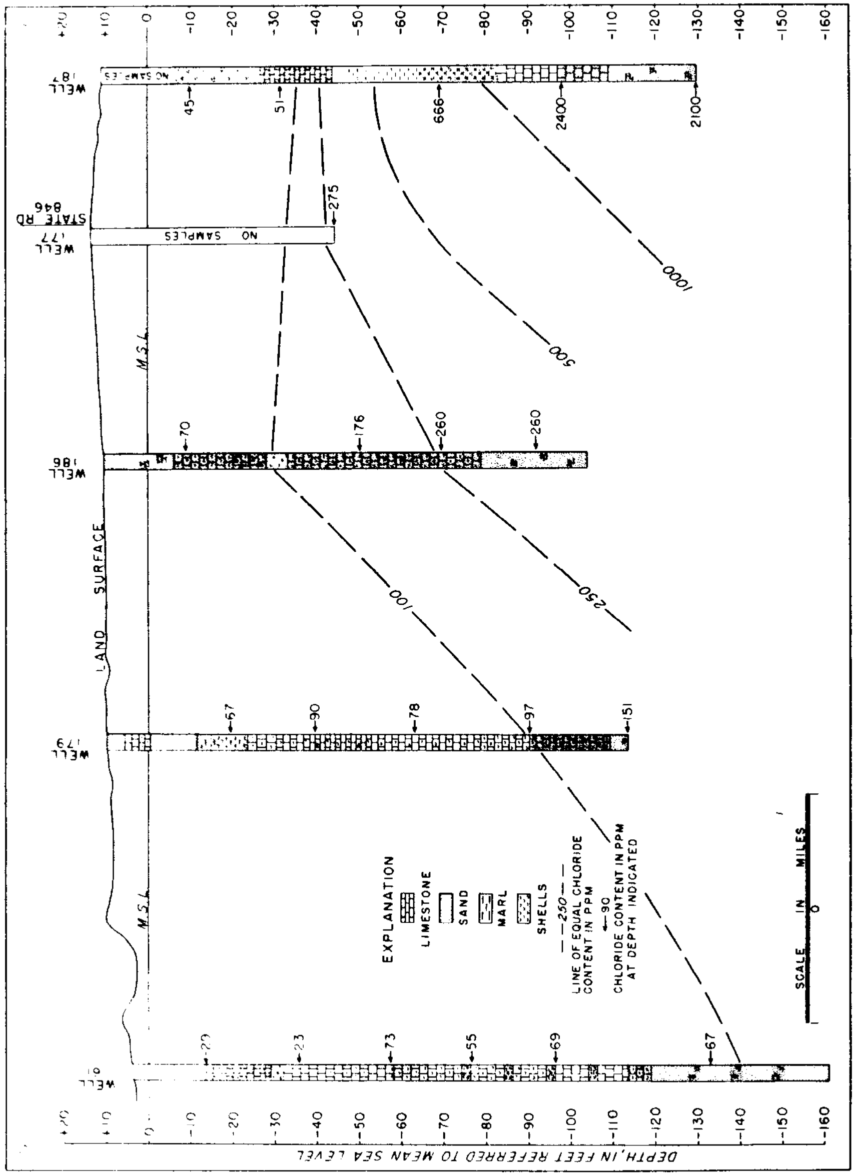


Figure 7. Geologic cross section and chloride content along line C-C'.

permeable and yield water freely to wells. Klein (1954, p. 15-22) described the hydrologic properties of the water-bearing materials and discussed the effects of recharge to and discharge from the aquifer in the Naples area; therefore they are not described in this report.

Water-Level Fluctuations

Fluctuations of the water table indicate changes in the amount of ground water stored in the shallow aquifer. Variations in ground-water storage are caused by recharge by rainfall, and by discharge to the gulf and to streams and canals, by pumping, and by evapotranspiration. The water table is highest during June-October, the wettest season, but is low during December-May, the drier season.

Figure 8 shows the approximate altitude and configuration of the water table in the Naples area on January 6, 1960. These contours are based on water-level measurements made in shallow wells that tap the uppermost section of the aquifer. A ground-water mound occurs about 2 miles north of the city boundary indicating that recharge occurs along the coastal ridge. A steep water-table gradient on the west side of the ridge suggests that the sandy surface material is only moderately permeable and can, therefore, retain large amounts of ground water in storage. In general, the water table conforms to the topography of the area; and the contours suggest that underflow is westward to the Gulf of Mexico and eastward to the Gordon River drainageway.

Figure 9 shows the configuration of the water table at the end of March 1960, after a period of deficient rainfall. The pattern of the contours is the same as that of January 6, 1960, but the altitude of the water surface is somewhat lower. The greatest decline occurred in the center of the ridge area and east of the ridge.

Figures 7 and 8 both show the effect of pumping in the municipal well field, which is indicated by a shallow water-table depression in the northeastern part of Naples.

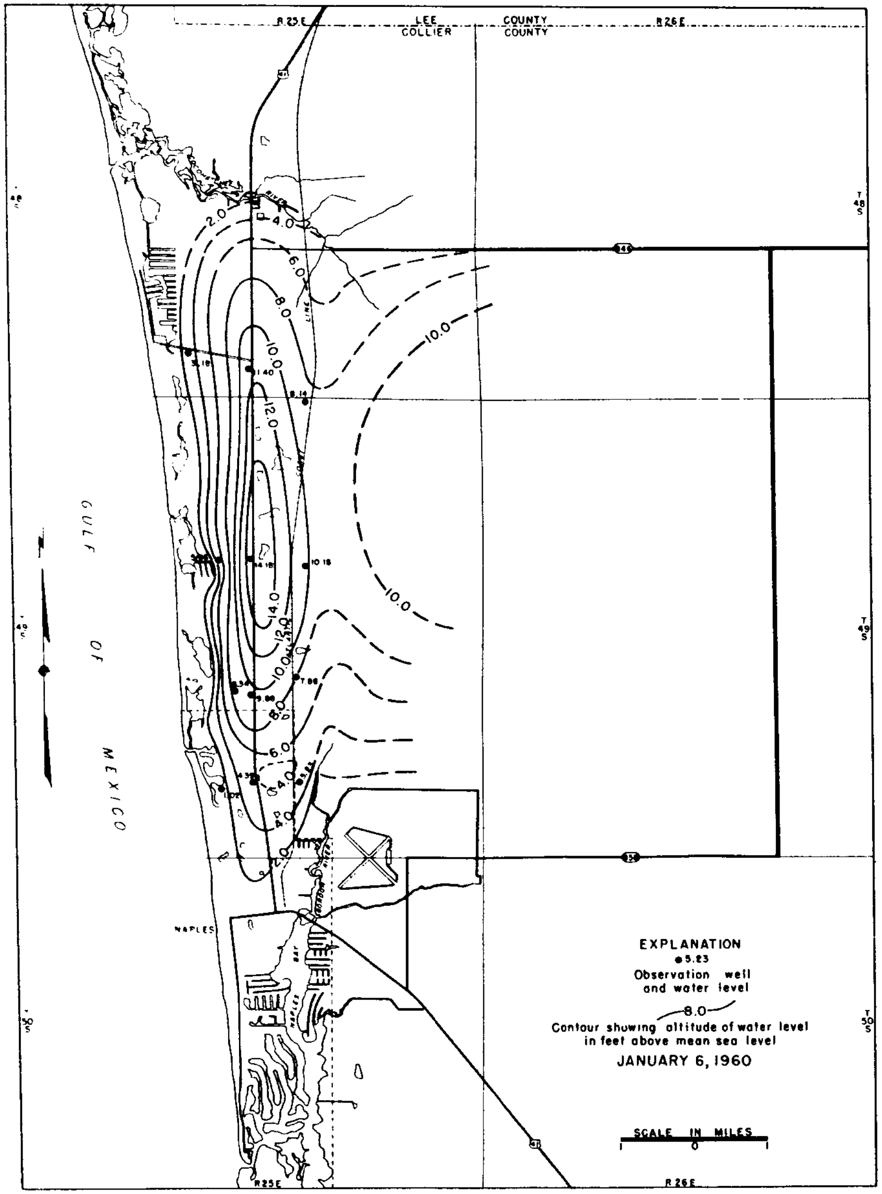


Figure 8. Water-level contour map of northwestern Collier County, January 6, 1960.

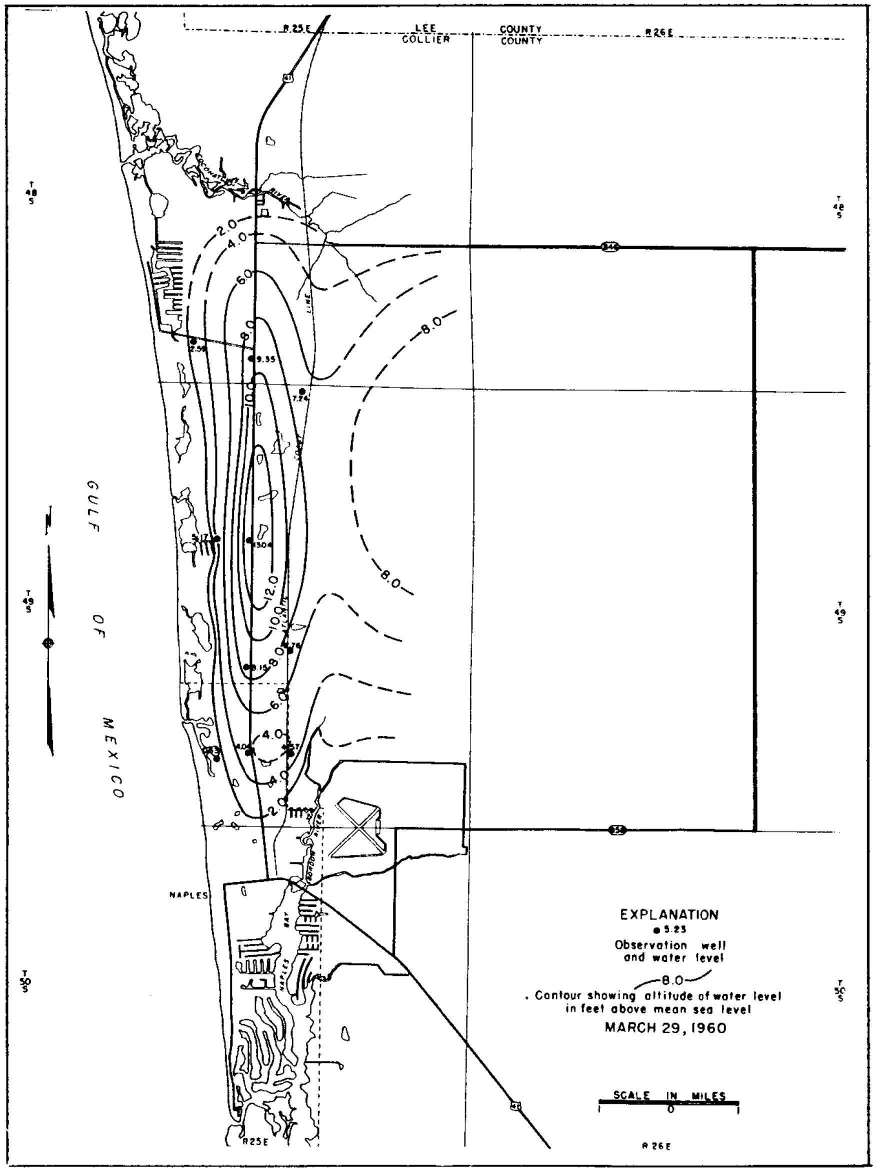


Figure 9. Water-level contour map of northwestern Collier County, March 29, 1960.

Water-level measurements made during the drilling of test wells and supply wells along the ridge area showed differences in head between the upper and lower parts of the aquifer. Along the central part of the ridge, the water levels in shallow wells (25-30 feet deep) ranged from 1 to 3 feet higher than the water levels in wells penetrating the deeper part of the aquifer (60 to 100 feet deep). This head differential would cause downward leakage of ground water. It is typical in the recharge areas and the magnitude of the differential is related to the degree of confinement. In the peripheral areas where ground-water discharge takes place, the head relationship is reversed. The water levels in deep wells range from 1 to 2 feet higher than those in shallow wells and upward leakage occurs. In the municipal well-field area, where wells 60 to 80 feet deep are pumped heavily, the head differential is substantial, and a large part of the water pumped is supplied by downward leakage in the area of the cone of depression.

The graphs in figure 10 show the relationship between pumpage, rainfall, and the water-level fluctuations at well 164, in the Naples well field, for the period June 1958—December 1959. Although well 164 taps the lower permeable zone of the aquifer, the response of the water level to rainfall in the well is rapid. Pumping is the chief factor that causes large declines in the vicinity of the well field; other fluctuations such as those caused by ocean tides and variations in barometric pressure are minor.

The effect of heavy municipal pumping is shown better in the hydrographs of figure 11 for the period September 6-20, 1958, when supply wells near the water plant were the only wells pumping in the area. Water levels in wells 151 and 164 are compared with pumping in the well field and rainfall. The locations of wells 151 and 164, with respect to the municipal wells near the plant, are shown in figure 12. Well 151 is about 2,500 feet west of the center of the well field and well 164 is about 4,000 feet northeast of the center of pumping. The drawdown due to pumping reaches well 151 considerably before it reaches well 164, and the fluctuation is greater in well 151 than in well 164. Also, the effect of starting and stopping pumps in the field is indicated by the

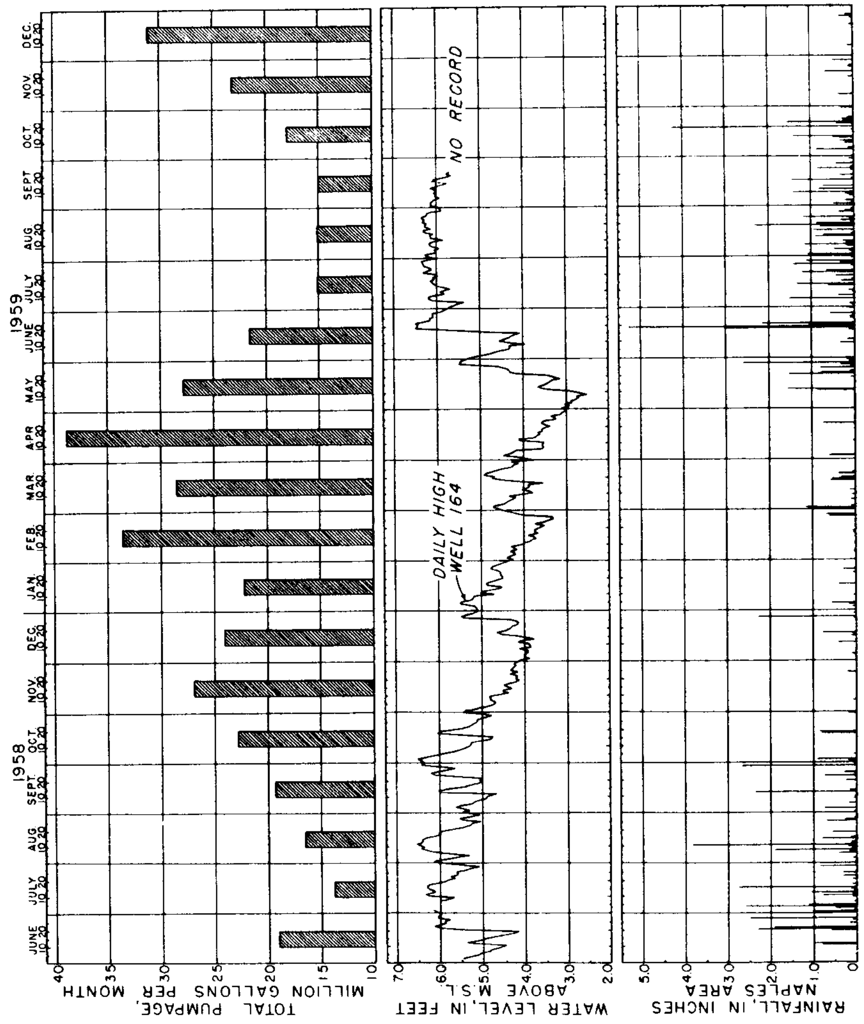


Figure 10. Hydrograph of well 164, monthly pumpage from the Naples well

irregularity of the water-level fluctuations in well 151, but this effect is less pronounced in the hydrograph of well 164 because of its greater distance from the well field. An interesting feature of the hydrograph is the rapid rise of the water levels caused by heavy rainfall on September 13. The hydrograph of well 164 shows a fairly rapid flattening of the drawdown curve caused by daily well-field pumping during September 17-19. The rate of flattening suggests that additional sources of replenishment are being intercepted and that the quantity of downward leakage to the lower permeable zone is approaching the quantity of water that is being withdrawn from the well field.

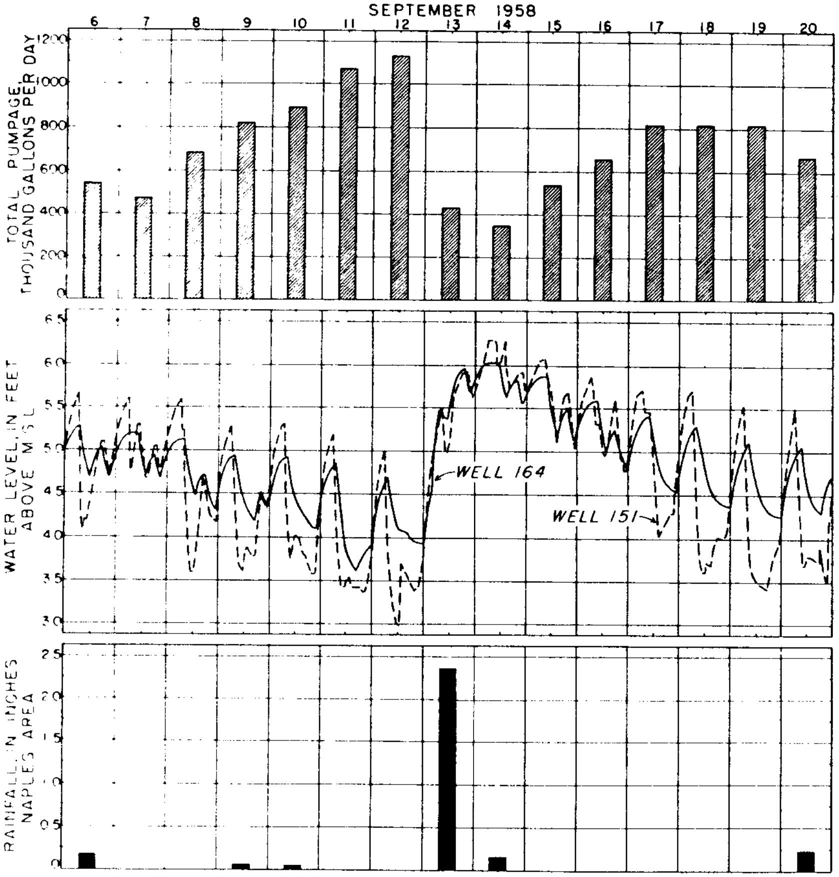


Figure 11. Hydrographs of wells 151 and 164, daily municipal pumpage, and daily rainfall at

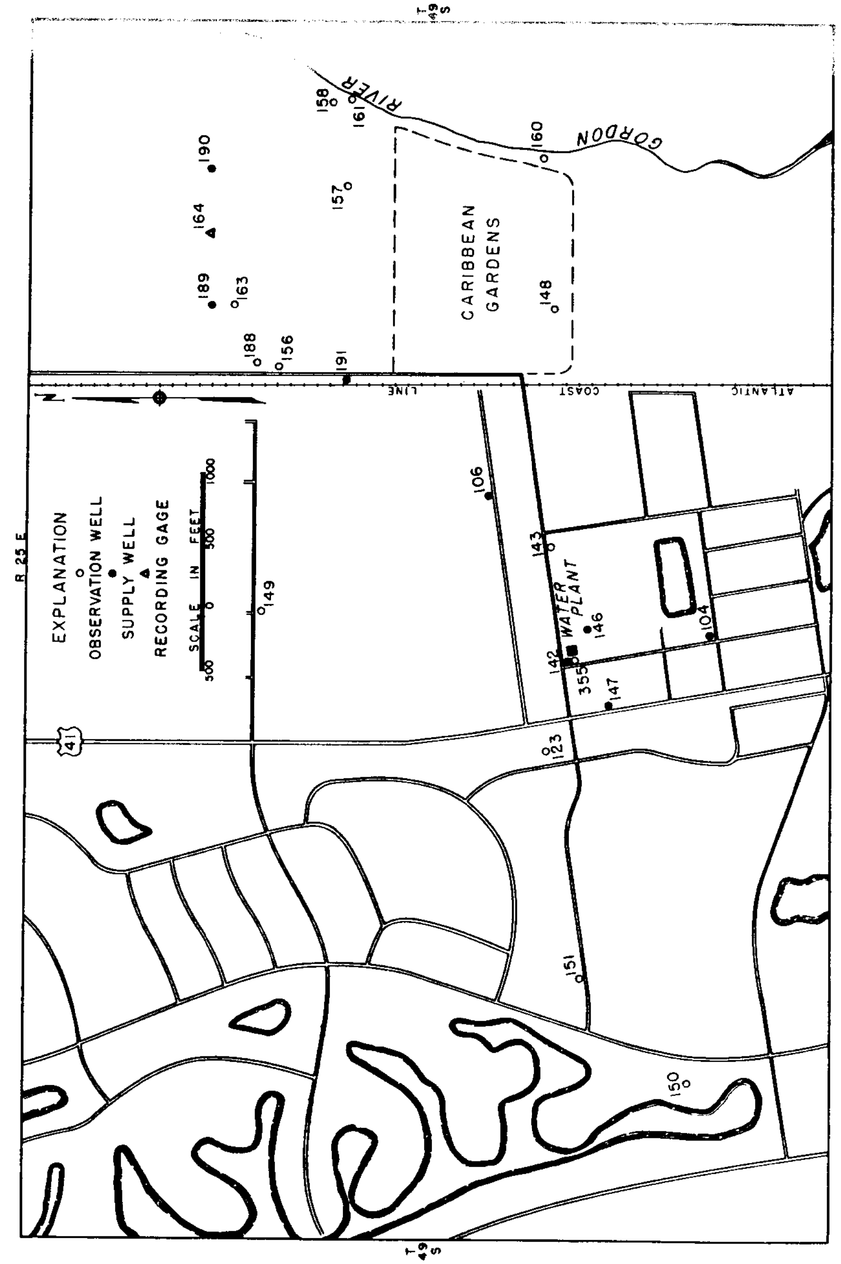


Figure 12. Map of the Naples well field area showing the location of municipal supply wells and observation wells.

Table 1. Analyses of Water from Selected Wells in Northwestern Collier County

(All results are in parts per million except those for color, pH and specific conductance)

	Date of collection	Depth of sample (feet below land surface)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Total hardness as $CaCO_3$	Color	pH	Specific conductance (micromhos at 25°C.)
1	8-22-57	135	---	---	---	---	---	---	---	---	---	---	---	---	304	204	---	---	493
3	3-19-58	24	11	0.04[1]	76	2.6	7.0	2.4	0	243	2.2	19	0.1	1.1	243	204	25	7.6	435
3	3-19-58	63	11	.27	72	.1	9.0	.9	0	220	1.0	18	.1	.7	225	180	28	7.6	394
4	7-16-58	41	17	.09	166	32	162	5.6	0	438	77	325	.2	1.5	1,000	731	20	7.3	1,720
5	7-17-58	44	12	.01[1]	166	15	97	2.6	0	464	7.5	205	.3	.9	735	572	23	7.3	1,270
7	7-20-58	58	24	1.0	134	29	162	7.2	0	418	122	275	.3	.1	960	565	17	7.3	1,640
8	7-28-58	28	---	---	119	6.6	35	.7	---	---	10	68	---	---	---	324	---	---	753
8	7-28-58	52	---	---	146	13	102	2.7	---	---	43	202	---	---	---	418	---	---	1,280
8	7-28-58	96	---	---	214	36	315	4.4	---	---	178	655	---	---	---	682	---	---	2,790
9	7-30-58	48	---	.06	105	6.3	41	2.0	---	---	12	90	---	---	---	288	---	---	742
9	7-30-58	85	---	.03	103	8.0	46	2.3	---	---	10	92	---	---	---	290	---	---	766
03	7-28-59	46	10	2.3	170	6.3	26	.2	0	520	4.4	46	.0	.3	599	474	68	7.1	911
03	8- 3-59	240	20	.76	196	89	631	21	0	236	440	1,150	.1	1.0	2,660	1,517	5	---	4,530

[1] Iron in solution at time of analysis

Table 2. Chloride Concentration in Water Samples from Selected Wells in Northwestern Collier County

Well No.	Depth of sample in feet, below land surface	Date	Chloride, in ppm
117	78	May 6, 1954	16
123	64	Mar. 7, 1952	11
	84	Mar. 7, 1952	8
	120	Mar. 14, 1956	18
	130	Mar. 14, 1956	17
	140	Mar. 14, 1956	16
	157	Mar. 14, 1956	28
		Mar. 20, 1958	25
		Feb. 13, 1959	21
		Mar. 4, 1959	17
		Dec. 3, 1959	21
		Mar. 29, 1960	14
130	72	Dec. 31, 1952	168
		May 15, 1953	181
		May 6, 1954	168
		Feb. 28, 1955	169
		Mar. 7, 1956	165
		Feb. 27, 1957	182
		Mar. 20, 1958	190
148	75	Feb. 28, 1955	20
		Mar. 7, 1956	15
		Aug. 5, 1958	17
		May 4, 1959	20
		June 8, 1959	26
		Dec. 3, 1959	16
		Jan. 6, 1960	15
		Mar. 29, 1960	24
149	32	Mar. 14, 1956	15
	74	Mar. 14, 1956	13

Table 2. (Continued)

Well No.	Depth of sample in feet, below land surface	Date	Chloride, in ppm
150	33	Aug. 16, 1956	22
	59	Aug. 16, 1956	25
151	60	Aug. 16, 1956	18
	123	Mar. 20, 1958	16
	145	Mar. 20, 1958	32
	166	Mar. 20, 1958	85
		May 4, 1959	79
		June 8, 1959	60
		Mar. 20, 1960	44
152	35	Aug. 17, 1956	14
	58	Aug. 17, 1956	13
156	50	July 29, 1956	18
158	51	Mar. 25, 1958	59
		Jan. 19, 1959	59
160	20	Aug. 20, 1957	1,430
	44	Aug. 20, 1957	22
	60	Aug. 20, 1957	43
	90	Aug. 20, 1957	24
	110	Aug. 20, 1957	18
	141	Aug. 20, 1957	385
	156	Aug. 21, 1957	965
		May 4, 1959	352
		June 8, 1959	340
		Dec. 3, 1959	615
		Jan. 6, 1960	470
		Mar. 29, 1960	1,020
161	17	Aug. 21, 1957	29
	40	Aug. 21, 1957	23
	61	Aug. 21, 1957	73
	80	Aug. 22, 1957	55

Table 2. (Continued)

Well No.	Depth of sample in feet, below land surface	Date	Chloride, in ppm
	100	Aug. 22, 1957	69
	135	Aug. 22, 1957	67
		Mar. 26, 1958	72
163	16	Mar. 19, 1958	18
	24	Mar. 19, 1958	19
	63	Mar. 19, 1958	18
174	41	July 14, 1958	325
	64	July 14, 1958	445
	144	July 16, 1958	885
175	44	July 17, 1958	205
	70	July 17, 1958	580
	123	July 17, 1958	1,750
		July 17, 1958	1,250
176	26	July 18, 1958	87
177	58	July 20, 1958	275
178	28	July 28, 1958	68
	52	July 28, 1958	202
	61	July 28, 1958	242
	96	July 28, 1958	655
	120	July 29, 1958	875
179	28	July 29, 1958	67
	48	July 29, 1958	90
	72	July 30, 1958	78
	100	July 30, 1958	97
	123	July 30, 1958	151
181	60	Nov. 13, 1958	38

Table 2. (Continued)

Well No.	Depth of sample, in feet, below land surface	Date	Chloride, in ppm
182	60	Nov. 13, 1958	34
183	55	Nov. 13, 1958	28
185	25	Nov. 17, 1958	83
	46	Nov. 17, 1958	92
	66	Nov. 17, 1958	153
	92	Nov. 17, 1958	304
	110	Nov. 18, 1958	472
186	20	Nov. 18, 1958	70
	61	Nov. 18, 1958	176
	82	Nov. 18, 1958	260
	103	Nov. 19, 1958	260
187	20	Nov. 21, 1958	45
	44	Nov. 24, 1958	51
	80	Dec. 21, 1958	644
	82	Dec. 21, 1958	666
	109	Dec. 21, 1958	2,400
	141	Dec. 21, 1958	2,100
206	32	Jan. 2, 1959	130
207	83	Jan. 2, 1959	172
208	32	Jan. 2, 1959	174
209	42	Jan. 2, 1959	134
220	120	Jan. 16, 1959	119
221	72	Jan. 16, 1959	127
303	25	July 29, 1959	28

Table 2. (Continued)

Well No.	Depth of sample, in feet, below land surface	Date	Chloride, in ppm
	99	July 29, 1959	72
	140	July 29, 1959	140
	240	Aug. 3, 1959	1,150
319	14	Nov. 11, 1959	51
320	14	Nov. 11, 1959	18
321	14	Nov. 11, 1959	19
322	14	Nov. 11, 1959	24
326	14	Nov. 12, 1959	30
327	14	Nov. 12, 1959	34
343	100	Mar. 28, 1960	314
344	61	Mar. 28, 1960	200
345	67	Mar. 28, 1960	530
346	72	Mar. 29, 1960	19
349	70	Mar. 29, 1960	190
353	50	Mar. 23, 1960	290
355	142	Mar. 29, 1960	20
356	45	Mar. 29, 1960	290

Quality of Water

Ground-water samples were collected at different depths during the drilling of the test wells and periodically from existing observation wells. The chemical character of the water in the aquifer was determined from 13 analyses of ground-water samples shown in table 1 and the chloride content of ground-water samples shown in table 2. The chloride content of water samples collected at different depths in the test wells are shown in figures 5, 6, and 7. Figure 13 shows the approximate chloride content of water samples from wells and surface water sampling points in the report area.

These data and the analyses reported by Klein (1954, p. 38-40) show that ground water in the area is relatively high in mineral content except along the coastal ridge. The chemical analyses of water samples from wells along the coastal ridge indicate a hard limestone water that is suitable for most uses. As ground water must seep through a considerable thickness of sand and rock to reach the producing zones in the aquifer, it is generally free of harmful bacteria and suspended material. However, it does exert a solvent action upon the rocks through which it moves. This action is aided by the presence of carbon dioxide absorbed by rainfall from the atmosphere and from organic material in the soil. Calcium and bicarbonate, from the solution of calcium carbonate in the limestone by water containing carbon dioxide, are the principal ions in solution in ground water in most of the coastal ridge area.

The high mineral content of the ground water in the area east of the coastal strip is due primarily to constituents derived from sea water, in addition to the calcium and bicarbonate derived from the limestone in the aquifer. The chloride content of the water ranged from less than 10 ppm (parts per million) to more than 2,000 ppm which may come from three possible sources: (1) Direct movement inland from the sea and along tidal reaches of streams; (2) residual sea water left in the sediments at the time of deposition or during former invasions of the sea; and (3) upward movement of salty water from deeper artesian aquifers.

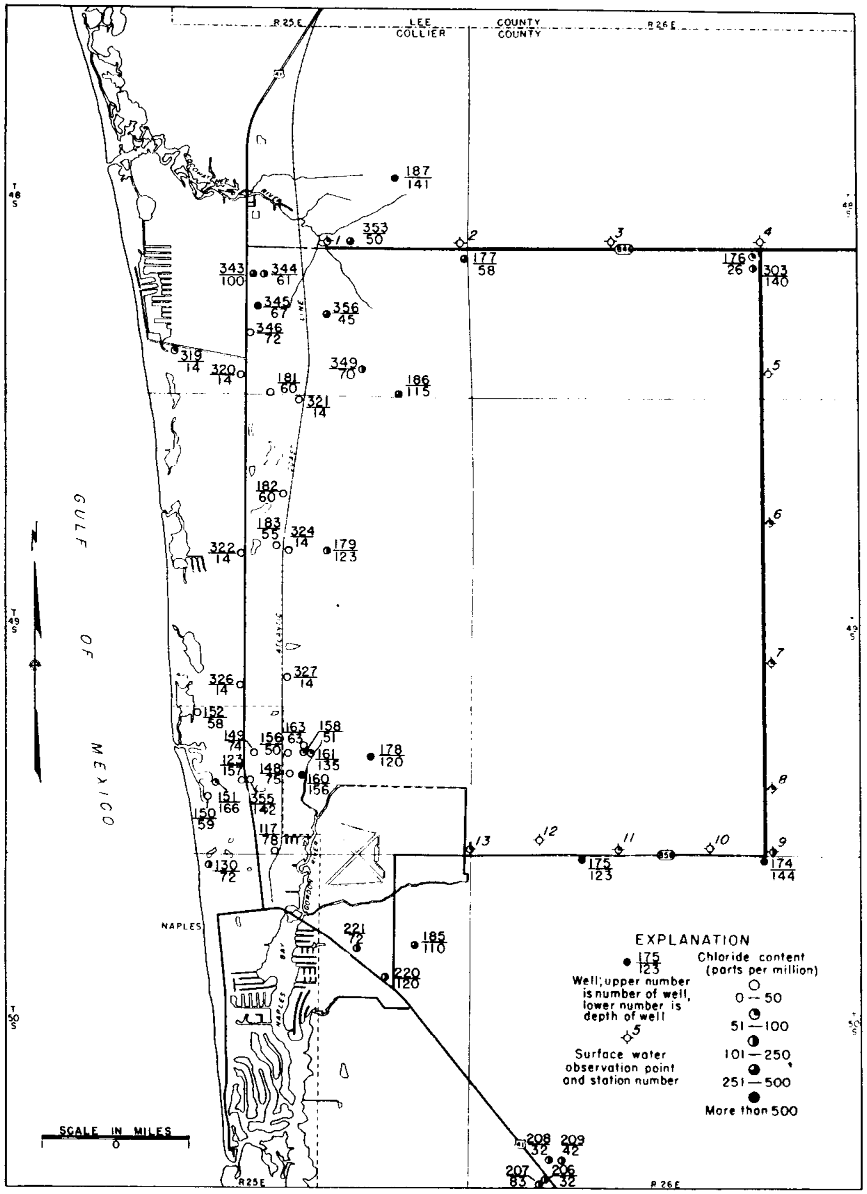


Figure 13. Map of northwestern Collier County showing the chloride content of water from selected wells and surface-water observation points.

Salt-Water Contamination

The encroachment of sea water into a coastal aquifer is governed by the relationship of ground-water levels to sea level. The lighter fresh water floats on top of the heavier salt water, and the depth to the salt water is related to the height of fresh water above sea level. If specific gravities of 1.0 and 1.025 are assumed for fresh water and sea water, respectively, then under static conditions, each foot of head of fresh water above sea level indicates 40 feet of fresh water below sea level. This relationship is modified by the mixing of fresh and salt water and the seaward flow of fresh water (Kohout, 1960), and by the presence of beds of low permeability in the aquifer, but it holds sufficiently well to be considered valid.

Contamination by the encroachment of sea water has occurred chiefly in areas adjacent to major streams and drainage canals that flow to the ocean. These waterways enhance the possibility of sea-water encroachment in two ways: (1) They lower ground-water levels, thereby reducing the fresh-water head opposing the inland movement of sea water; and (2) they provide access for sea water to move inland during dry periods.

Examples of both types of encroachment are shown by data collected during the drilling of well 160, located east of the well-field extension and near the upper tidal reach of the Gordon River (fig. 6, 7). Chloride analyses of water samples taken from test well 160, as shown in figure 6, indicate that salt water from the Gordon River had infiltrated downward to a depth of about 25 feet below msl in the uppermost limestone bed of the aquifer. The salt-water contamination from the river was reported to be the cause of the loss of several rows of litchi nut trees near the river in the Caribbean Botanical Gardens (fig. 12).

Lithologic (fig. 6, section B-B') and chloride data from well 160 show that the uppermost layer of limestone is underlain by 10 feet of marl which separates shallow water of high chloride content from deeper water of low chloride content. The difference in the quality of the water may be caused by either or a combination of the following factors: (1) The marl layer is sufficiently impermeable to form an effective seal between the upper and lower limestones; (2) well 160 is located near the Gordon River, a discharge area (see p. 15), and the pressure head in the lower part of the aquifer is greater than it is in the shallow part; therefore, the downward movement of salty water is prevented.

The high chloride content below 130 feet in well 160 indicates that salt water has moved inland beneath the Gordon River, presumably as a result of local lowering of the ground-water levels in the adjacent drainage area. The fluctuation of chloride content of water samples collected periodically from a depth of 156 feet below the land surface reflects the movement of the salt front deep in the aquifer in response to changes in ground-water levels (table 2). The low chloride content of the water at a depth of 135 feet in well 161 (table 2) indicates that in 1958 the deep salt wedge had not reached that well.

The extent of salt-water encroachment at depth in the Cocohatchee River basin has not been determined because of the lack of deep observation wells near the lower reaches of the river. However, the presence of water containing 664 ppm of chloride at a depth of 60 feet, and 2,400 ppm of chloride at a depth of 103 feet below land surface in well 187, suggests the possibility of recent encroachment beneath canals that extend inland from the river. A determination of the origin of this high chloride content water can be made by periodic sampling of the well and complete chemical analyses of the water.

Extensive encroachment from the sea has not occurred in the area west of the well field although water levels in the area are lowered by pumping in the well field and by the numerous canals extending inland from the gulf. However, inland movement of salt water is indicated by fluctuations of chloride content of periodic samples at a depth of 166 feet in well 151 which ranged between 44 and 85 ppm during the period March 1958 to March 1960.

Major encroachment probably is being retarded by high ground-water levels (fig. 8, 9, 11). There is close correlation between the hydrographs of wells 151 and 164 (fig. 11); accordingly, the long-term hydrograph of well 164 (fig. 10) suggests that the water levels in well 151 have probably averaged between 4 and 5 feet above sea level during the period 1958 through September 1959, a period of heavy rainfall and above normal ground-water levels. The head of fresh ground water above sea level would indicate that fresh water extends to the base of the aquifer at this point. Encroachment may be retarded also by the presence of beds of marl in the aquifer, which probably extend seaward under the gulf.

Although the encroachment of salt water toward the well field has been slight, the presence of the salt-water front near well 151 indicates that long-term lowering of ground-water levels caused by an extension of the canal system or increased pumping during an extended dry period could cause encroachment that would endanger the well field.

Since the chloride content of the water is an indicator of changes in mineral content, the data in figure 13 show that highly mineralized water occurs north of Naples near the Cocohatchee River and east of the coastal ridge as much as 10 miles inland from the coast. Comparison of the water-level contour maps of figures 8 and 9 and the topographic map of figure 3 indicates that ground-water levels in the area east of the ridge range from 5 to 15 feet above sea level. The lines of equal chloride content in figures 5, 6, and 7 show that the chloride content of the ground water increases gradually with depth in the eastern part of the area, but rises sharply in material of low permeability at depth in the aquifer. The high water levels and the inland location of the Big Cypress area indicate that the high mineral content of the ground water in that area is not caused by the recent encroachment of sea water. The high mineral content of ground water in materials of low permeability in the lower part of the aquifer suggests that the source of contamination is connate salt water or upward leakage from the deeper artesian aquifer.

Data pertaining to the possibility of upward movement of salt water from deep water-bearing strata were collected during the drilling of well 303 in the northeastern part of the area. Well 303 was drilled to a depth of 300 feet in January 1959. The analyses of samples collected at 46 feet and 240 feet below land surface are given in table 1. Materials of very low permeability were penetrated between the base of the shallow aquifer (about 130 feet below land surface) and a permeable bed at 230 to 240 feet below land surface from which the lower sample was taken. Water levels measured as drilling progressed in the section of low permeability ranged from 5.4 to 14.8 feet below the land surface. Water levels in both the shallow aquifer and the lower permeable zone were less than 1 foot below the land surface. The extremely high mineral content of the lower sample from well 303 indicates the possibility of contamination from below the shallow aquifer, but the head differential between the two levels suggests that no upward flow was occurring.

The chloride content of a sample collected July 18, 1958, at 26 feet below land surface in well 176 was 87 ppm, and the chloride content of a sample collected July 29, 1959, from approximately the same depth in well 303 at the same location was 38 ppm. This decrease in chloride content of the water indicates flushing of ground water by continuous ground-water discharge into the adjacent drainage canal during the 1-year interval. Further evidence of flushing is shown by the analyses of samples collected from the bottom of canals (fig. 13) during June of 1960, when the canals were receiving ground water from the aquifer. The chloride content of the canal water samples that were collected along the eastern periphery of the area (fig. 13, stations 1-9) ranged from 35 to 239 ppm, whereas the chloride content of water from a shallow pond east of the Naples Airport (station 12) was 14 ppm.

The difference in the mineral content of the ground water underlying the coastal ridge and the inland areas probably is related to the amount of flushing that has occurred in each area. The permeable quartz sand and limestone that form the shallow subsurface materials on the coastal ridge allow rain to infiltrate rapidly into the aquifer. Also, the water-table contour maps in figures 8 and 9 show that the distances to points of ground-water outflow are short and the water-table gradients are fairly steep. In contrast, the presence of dense beds of relatively impermeable limestone at shallow depths in the inland areas probably greatly retards the infiltration of rainfall into the aquifer. This is suggested by the fact that the ground water at very shallow depths contains considerable chloride, whereas the surface water contains very little chloride. Moreover, the ground-water gradient toward points of outflow is flat, except in areas immediately adjacent to tidal streams or Naples Bay. Such evidence indicates that some improvement in the quality of ground water may occur with increased drainage in inland areas.

Quantitative Studies

Late in 1953 the city of Naples began preliminary work for a new well field and water plant in the northern part of the city (fig. 2). During the period 1953-59, four aquifer tests were made at wells in the vicinity of the water plant and in the area proposed for the well-field extension. These tests furnished information on the ability of the aquifer to store and to transmit water. Such data are useful in making predictions of drawdown due to pumping, and in determining the proper spacing of wells in a well field.

Aquifer Tests

The first aquifer test was made at the site of the water plant (fig. 12), in September 1953. Well 142, a 6-inch-diameter supply well, 96 feet deep, was pumped for 7 hours at the rate of 298 gpm (gallons per minute) and the water was discharged into a roadside ditch. Water-level measurements were made in well 123, 695 feet west of the pumping well, and well 143, 845 feet east of the pumping well. At the end of the 7-hour test the drawdown due to pumping well 142 was 1.68 feet in well 123 and 1.18 feet in well 143. In June 1955, a test was made on the same wells except that well 142 was pumped for 8 hours at the rate of 345 gpm and the water was discharged into the city's storage reservoir. Drawdowns measured in observation wells at the end of this test were 1.71 feet in well 123 and 1.18 feet in well 143.

In March 1958, the first aquifer test was made in the area of the well-field extension northeast of the water plant. Well 164 (fig. 12) was pumped at the rate of 360 gpm for $12\frac{1}{2}$ hours and the water was discharged into a shallow ditch which drained eastward toward the Gordon River. After the pump had been in operation for $4\frac{1}{2}$ hours a heavy rain started and continued for the duration of the test. A hydrograph of well 163, 545 feet east of the pumped well, for the period of the test, is shown in figure 14. The hydrograph shows the

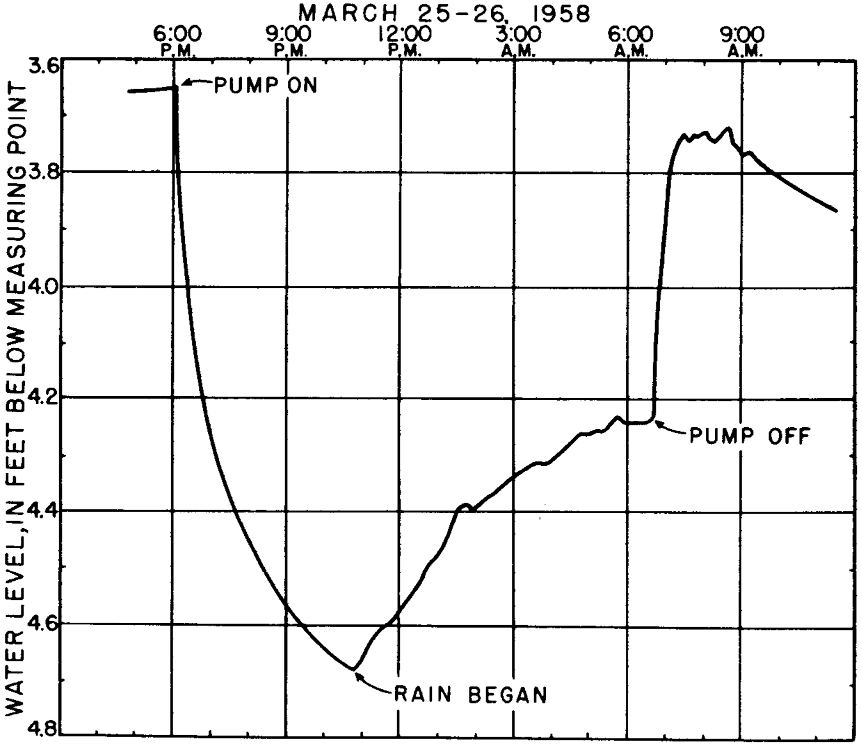


Figure 14. Hydrograph of well 163, in the Naples well field area, during

drawdown caused by pumping and the effect of recharge to the aquifer by the rain.

A final aquifer test of long duration was made in the area northeast of the water plant on January 9-10, 1959. Well 189 was pumped for 30 hours at the rate of 360 gpm and the water was discharged into the adjacent shallow drainage ditch. The ditch became clogged during the test causing flooding of a large part of the area between the pumping well and Gordon River. Figure 15 shows the drawdowns in different observation wells at the end of the 30-hour period of pumping, a sketch of the locations of observation wells, and an outline of the area which was flooded by discharge water. The drawdowns in the observation wells between the pumping well and the Gordon River were appreciably less than the drawdowns in wells west of the pumping well.

Analysis of Aquifer-Test Data

The drawdown data collected during the aquifer tests were adjusted to correct for fluctuations caused by factors other than pumping, such as variations in barometric pressure and evapotranspiration. The corrected drawdowns then were analyzed to determine the hydraulic properties of the aquifer. Because there was evidence of considerable downward leakage to the main producing limestone in the lower part of the aquifer, the test data were analyzed by use of a family of leaky-aquifer type curves developed by H. H. Cooper, Jr., U. S. Geological Survey, Tallahassee, Florida, from a method outlined by Hantush (1956). This method provides a means to compute the values of the coefficients of transmissibility and storage of the producing zone, and the coefficient of leakage of the semiconfining beds that overlie the producing zone. Figure 16 is an idealized sketch showing flow in a leaky aquifer (Jacob, 1946). Although the characteristics of the shallow aquifer in Naples do not match the theoretical conditions assumed in this method of analysis, the determined coefficients provide valuable indications of the capacities of the aquifer.

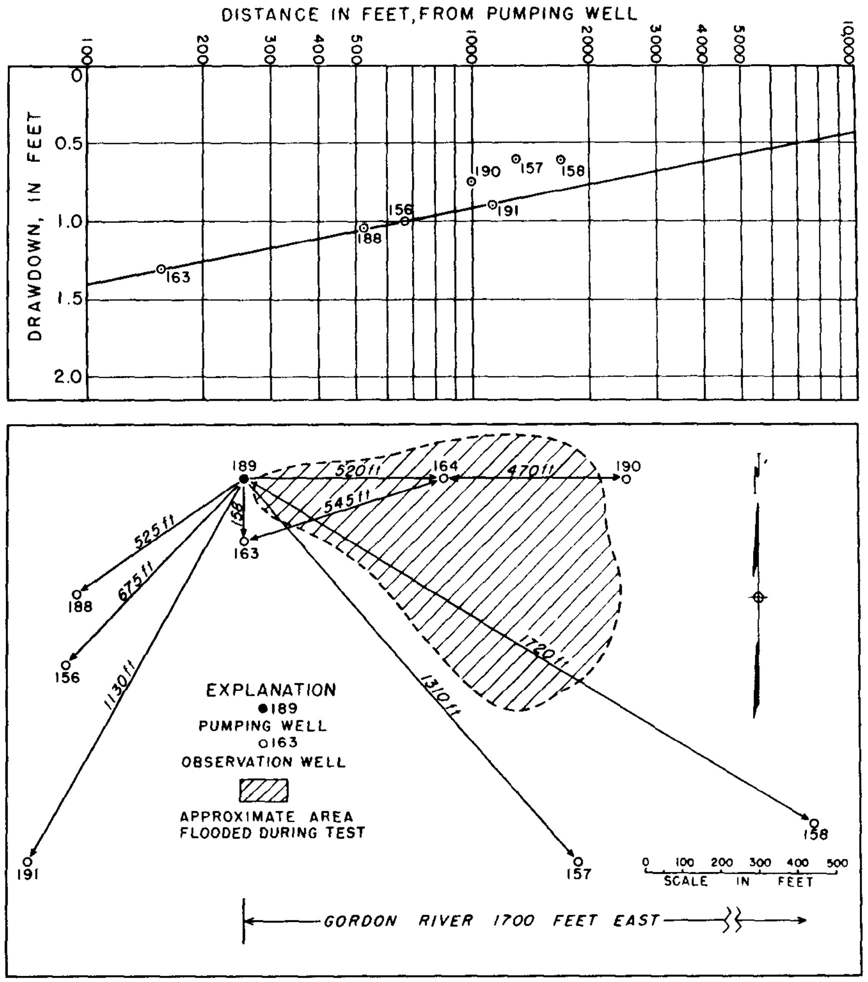


Figure 15. Graph showing drawdowns in observation wells at the end of the 30-hour aquifer test January 9-10, 1959, and a sketch showing locations of wells used in the test.

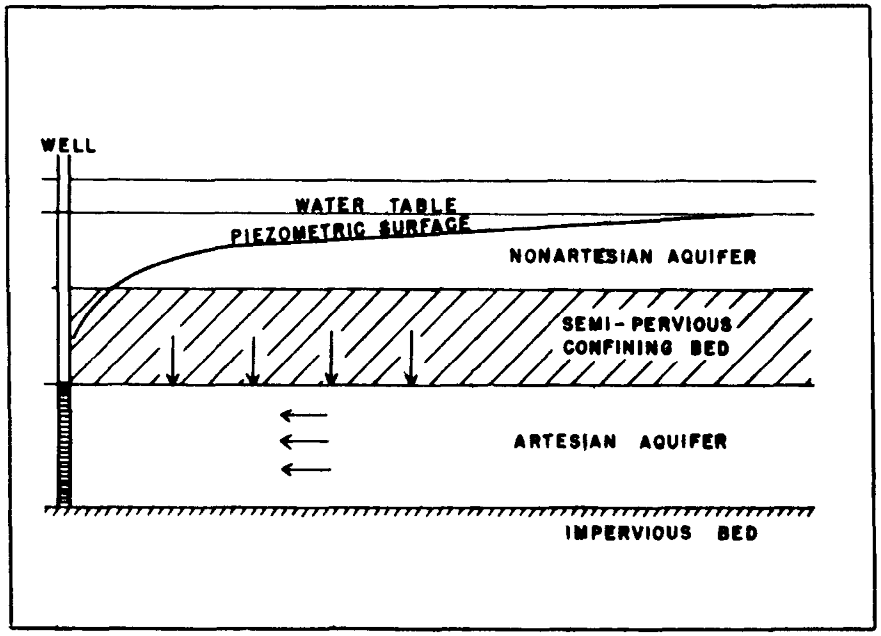


Figure 16. Idealized sketch showing flow in a leaky artesian aquifer system.

The coefficient of transmissibility is a measure of the ability of an aquifer to transmit water. It is defined as the quantity of water in gpd (gallons per day) that will flow through a vertical section 1 foot wide and extending the full saturated height of the aquifer, under a unit hydraulic gradient, at the prevailing temperature of the water (Theis, 1938, p. 892). The coefficient of storage is a measure of the capacity of an aquifer to store water and is defined as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The leakage coefficient (Hantush, 1956, p. 702) characterizes the ability of semiconfining beds above or below an aquifer to transmit water into the bed being tested. It may be defined as the quantity of water that crosses a unit area at the interface between the main aquifer and its confining bed if the difference between the head in the main aquifer and the beds supplying the leakage is unity.

Computed coefficients of transmissibility and storage for the water-plant area were approximately 80,000 gpd per foot and 0.0004, and for the area of the well-field extension 185,000 gpd per foot and 0.0004. Because of the short duration of the first three tests and major interference by other influences than the test pumping, the coefficient of leakage was computed only from the data obtained in the January 1959 test. Computations based on data from the latter part of that test indicated that the coefficient of leakage ranged from 0.001 to 0.008 gpd per square foot per foot of head differential. The largest coefficient was computed from the data from well 190 which is adjacent to the shallow ditch into which water was discharged. In general, the leakage coefficient increased eastward. This may be a reason for the variation in drawdowns shown in figure 15.

In an ideal leaky aquifer system (fig. 16) in which water levels in overlying beds are maintained constant by some source of recharge, pumping causes a cone of depression, which expands until downward leakage equals the amount of water taken from storage by pumping. However, in the ridge area of Naples the supply of water in the upper sand beds is limited; when the water table declines the amount of leakage through the confining bed declines and the cone of depression continues to expand.

Figure 17 shows the drawdown curves for wells 158 and 188 during the January 1959 test. The curves have been extended to show the water-level changes that might occur if pumping had been continued. The rapid rate of flattening of the water-level plots near the end of the test indicates that leakage through the confining material was supplying most of the water pumped. If water levels were maintained at a constant position in the beds supplying the leakage, the drawdown would have remained the same during continued pumping at the constant rate, and any increase in the rate of pumping would have caused a proportional increase in drawdown. If unwatering of the upper part of the aquifer had occurred the extended drawdown curve would have declined and the cone of depression in both parts of the aquifer would have expanded. After an extended period, if no recharge had occurred, the water level in the sand supplying the leakage would have approached the head in the permeable zone that was being pumped, and the entire aquifer would act as a unit under water-table conditions.

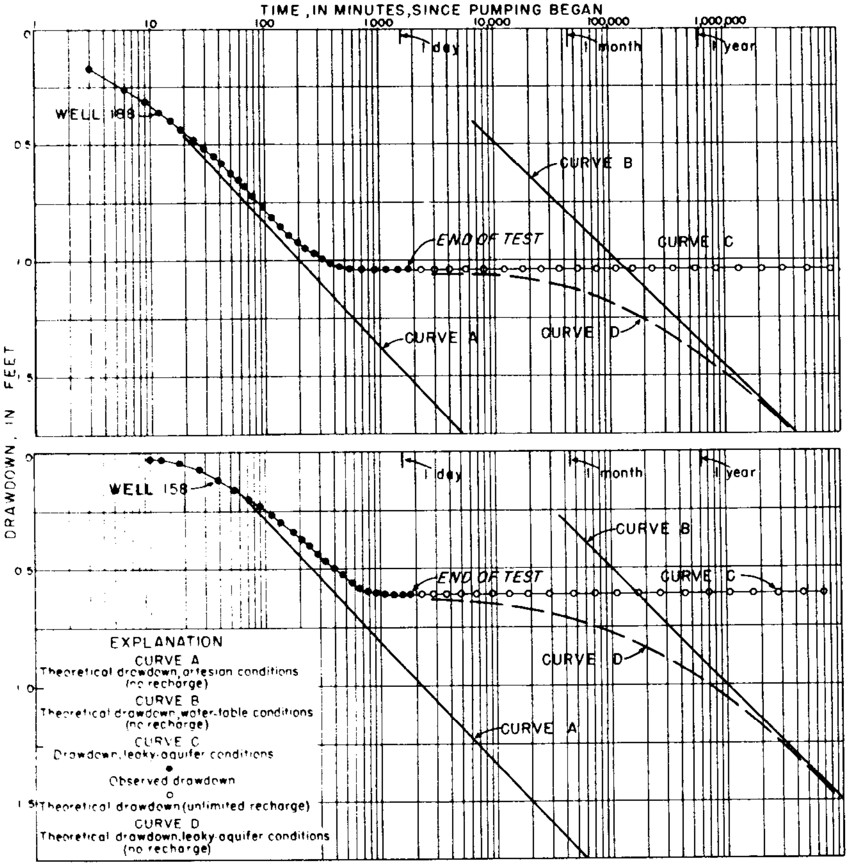


Figure 17. Graph showing drawdowns observed in wells 158 and 188 during aquifer test January 9-10, 1959, and theoretical drawdowns for artesian water-table, and leaky-aquifer conditions.

Curve A was constructed by using the coefficients of transmissibility and storage determined from the test and assuming that artesian conditions exist in the aquifer. Curve B was plotted by using a coefficient of storage of 0.15 (characteristic of water-table conditions) and a coefficient of transmissibility somewhat (10 percent) higher than that computed for the test (to take into account the transmissibility of the upper beds); it shows the theoretical drawdown under water-table conditions after extended time. Curve C extends the test data assuming an unlimited water supply on the surface. Curve D indicates the theoretical drawdown under conditions of no replenishment to the upper zone. The drawdown caused by long-term pumping from the deep zone is reflected at the water table, and it is controlled by the coefficients of storage and transmissibility of both the pumped zone and the overlying beds and by the availability of recharge from surface sources. The possibility of large drawdowns in the shallow beds in this area is decreased by the diversion of water from the Gordon River and its drainageway for recharge.

Cities in southeastern Florida have developed large supplies near the sea by locating well fields near canals which drain large areas of the Everglades. Water levels in the well fields near these canals are maintained by infiltration of water from the canals into the aquifer. Detailed studies of the development of water supplies by induced infiltration in these areas were presented by Parker (1955, p. 277-290, 482-484). The development of a theory on induced infiltration was described by Rorabaugh (1956). Supplies developed by this method would generally carry more mineral matter than the surface water but less than the ground water. Salt-water encroachment through surface channels in these areas has been effectively controlled by salinity-control dams located downstream from the well fields.

The topography and drainage pattern of northwestern Collier County and the hydraulic characteristics of the aquifer indicate that supplies equal to present water needs can be developed along the eastern edge of the coastal ridge and the adjacent drainageway. Additional supplies to meet very large future needs may be developed from the same area by the use of induced infiltration in conjunction with the drainage of inland areas. Present and future well fields may be safeguarded from salt-water encroachment from the sea by the construction of salinity-control dams near the gulf in major streams.

SUMMARY AND CONCLUSIONS

Fresh-water supplies in northwestern Collier County are obtained from an extensive shallow aquifer which extends from the land surface to a depth of about 130 feet below the land surface. It is composed chiefly of permeable sand and shelly limestone; however, its vertical permeability is restricted by thin beds and lenses of shelly, sandy marl in coastal areas, and by a bed of very dense limestone that occurs near land surface in areas east of the coastal ridge.

The aquifer is recharged by local rainfall and to some extent by surface water that flows overland from the interior toward the coast. Water-level contour maps show a ground-water mound underlying the coastal ridge and steep gradients westward toward the Gulf of Mexico and eastward toward the narrow Gordon River drainageway east of the ridge. The contour maps and topographic maps suggest that water levels in inland areas are perennially near or above land surface (10 to 15 feet above msl) and that discharge is westward into the Gordon River drainageway, southward into tidal streams, and northward into the Cocohatchee River and its tributary canals.

Chemical analyses of water from selected wells show that the chief factor limiting the use of ground water is mineralization due to contamination by sea water. Ground water in the area is relatively high in mineral content except in areas on or immediately east of the coastal ridge. The chief source of the mineralization in the fringe areas along the gulf, Naples Bay, and tidal streams is recent salt-water intrusion, whereas the source of mineralization in the inland areas is apparently residual sea water left in the sediments during former invasions of the sea. Because of the poor quality of ground water in the inland areas, local ground-water supplies for Naples and other coastal communities are available only in a relatively small area close to the sea.

The results of aquifer tests in the municipal well fields indicate that the aquifer will produce large quantities of water with moderate drawdowns in water level, especially in areas where surface water can recharge the aquifer readily. Data from test drilling and aquifer tests suggest that the permeability of the aquifer increases near the eastern edge of the coastal ridge where relatively large sources of surface water can be diverted into the aquifer.

The topography and drainage pattern of northwestern Collier County and the hydraulic characteristics of the aquifer indicate that supplies equal to present water needs can be developed along the eastern edge of the coastal ridge and the adjacent drainageway. Additional supplies to meet future needs may be developed from the same area by the use of induced infiltration in conjunction with the drainage of inland areas. Present and future well fields may be safeguarded from salt-water encroachment from the sea by the construction of salinity-control dams near the gulf in major streams.

A continuing appraisal of the quantity and quality of water in storage will be needed for the maximum development of the area. The immediate need is for water-level and streamflow data for use in the design of a comprehensive water-control system.

Studies of flood-control and drainage systems in southeastern Florida have shown that, with proper location and operation of salinity controls and carefully planned overall drainage systems, large inland areas can be developed for urban or agricultural use without depletion of essential ground-water resources.

REFERENCES

Hantush, M. C.
1956 Analysis of data from pumping tests in leaky aquifers: Am. Geophys. Union Trans., v. 37, no. 6, p. 702-714.

Jacob, C. E.
1946 Radial flow in a leaky artesian aquifer: Am. Geophys. Union Trans., v. 27, no. 2, p. 199.

Klein, Howard
1954 Ground-water resources of the Naples area, Collier County, Florida: Florida Geol. Survey Rept. Inv. 11, 64 p. 15 figs.

Kohout, F. A.
1960 Cyclic flow of salt water in the Biscayne aquifer of southeastern Florida: Geophys. Research Jour., v. 65, no. 7, p. 2133-2141.

Parker, G. G.
1955 (and others) Water resources of southeastern Florida, with special reference to the geology and ground water of the Miami area: U. S. Geol. Survey Water-Supply Paper 1255, p. 277-290, 482-484.

Rorabaugh, M. I.
1956 Ground water in northeastern Louisville, Kentucky, with reference to induced infiltration: U. S. Geol. Survey Water-Supply Paper 1360-B, 168 p., 17 pls., 25 figs.

Theis, C. V.
1938 The significance and nature of the cone of depression in ground-water bodies: Econ. Geology, v. 33, no. 8, p. 892.