GEORGIA

STATE DIVISION OF CONSERVATION

DEPARTMENT OF MINES, MINING AND GEOLOGY
GARLAND PEYTON, Director

THE GEOLOGICAL SURVEY
Information Circular 20

RELATION OF SALTY GROUND WATER TO FRESH ARTESIAN WATER IN THE BRUNSWICK AREA, GLYNN COUNTY, GEORGIA

by
J. W. Stewart

ATLANTA
1960

GEORGIA

STATE DIVISION OF CONSERVATION

DEPARTMENT OF MINES, MINING AND GEOLOGY
GARLAND PEYTON, Director

THE GEOLOGICAL SURVEY
Information Circular 20

RELATION OF SALTY GROUND WATER TO FRESH ARTESIAN WATER IN THE BRUNSWICK AREA, GLYNN COUNTY, GEORGIA

by
J. W. Stewart

ATLANTA
1960

Prepared in cooperation with the United States
Department of the Interior, Geological
Survey, Water Resources Division
Ground Water Branch

CONTENTS

ILLUSTRATIONS

TABLES

Relation of Salty Ground Water to Fresh Artesian Water in the Brunswick Area, Glynn County, Georgia

By

J. W. Stewart

Introduction

Purpose of the report

The purpose of this report is to present the available information regarding the occurrence of salt water in the principal artesian aquifer in the Brunswick area. The investigation on which the report is based is part of the continuing program of collection and interpretation of basic data concerning the ground-water resources of the State.

The investigation of ground-water resources in Georgia is a cooperative project of the U.S. Geological Survey and the Georgia Department of Mines, Mining and Geology. The current study was made under the direction of P. E. LaMoreaux, Chief, Ground Water Branch, U.S. Geological Survey, and Garland Peyton, Director, Georgia Department of Mines, Mining and Geology, and under the immediate supervision of J. T. Callahan, District Geologist.

Location of the area

Glynn County is in the Atlantic Coastal Plain in southeastern Georgia (fig. 1). It is bounded on the north by McIntosh County, on the west by Wayne and Brantley Counties, on the south by Camden County, and on the east by the Atlantic Ocean. The county also encompasses Jekyll Island, St. Simons Island, Little St. Simons Island, and Sea Island. Brunswick, the county seat and largest city, is in the southeastern part of the county.

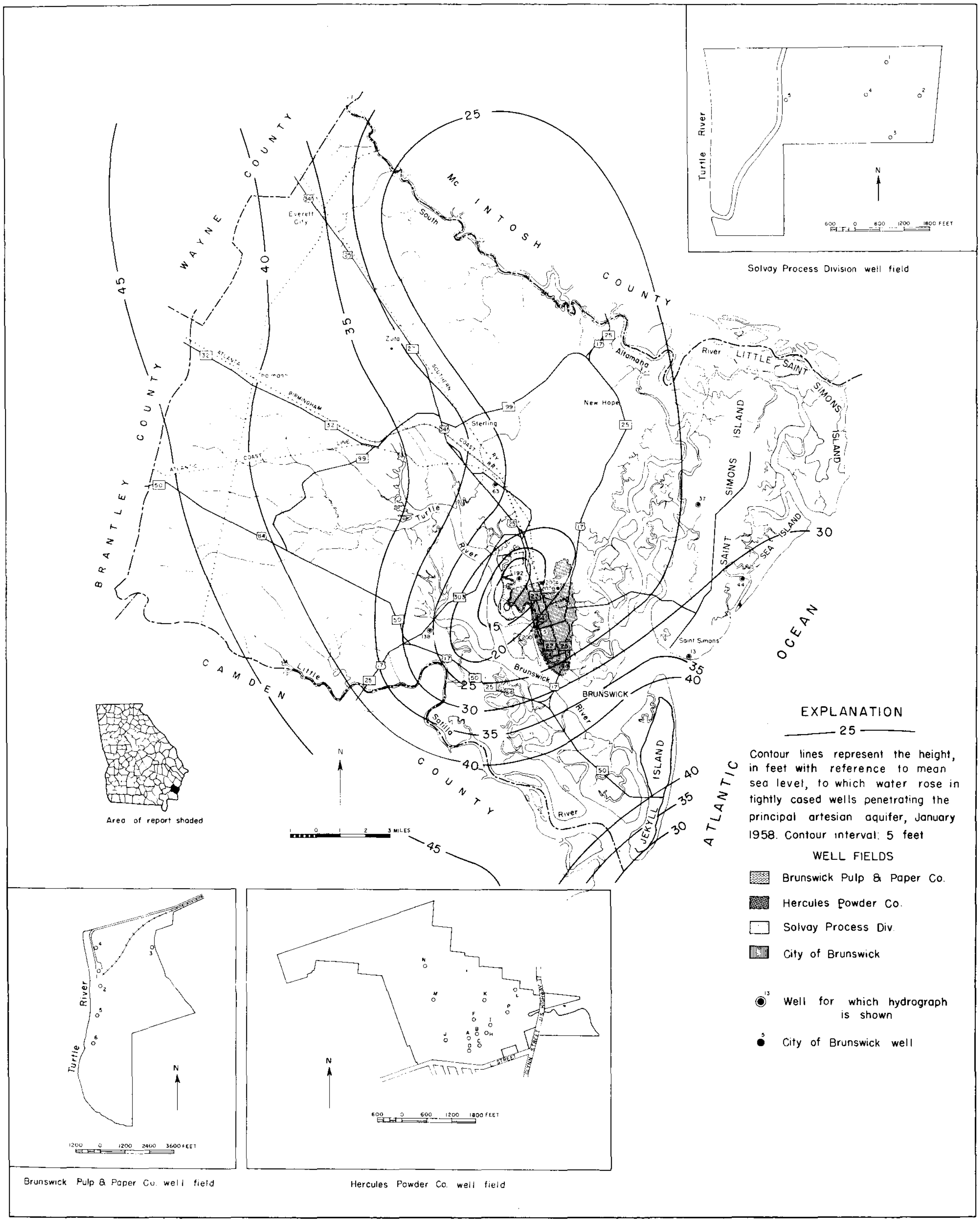


Figure 1 - Piezometric surface of principal artesian aquifer, Glynn County, Georgia.

Previous investigations

A report by Stringfield and others (1941) included information on the area of artesian flow in the coastal counties, a map of the piezometric surface of the artesian water in 1940, estimates of the withdrawal of ground water, and a discussion of salt-water encroachment. A comprehensive report on the hydrology of the principal artesian aquifer in the coastal area of Georgia was written by Warren (1944). Cooper and Warren (1945) included information of ground-water withdrawals, a map of the piezometric surface of the artesian water in 1943, and a discussion of salt-water encroachment in the Savannah area. The most recent reports containing information about the Brunswick area include those of Thomson and others (1946) and Stewart and Counts (1958).

Acknowledgments

The writer is indebted to many persons who contributed information used in this report. Special thanks are due officials in charge of municipal and industrial plants who were most helpful in supplying information on the chemical analyses of water, withdrawals of ground-water, and records of wells.

Contamination of Fresh-Water Aquifers

A problem of great concern in areas of heavy ground-water withdrawals near the seacoast is the possibility of contamination of fresh-water aquifers by the inflow of salt water under the reduced head caused by pumping. The contamination of fresh-water supplies by salt water is not a new problem, because reports of such conditions in parts of the coastal area of Europe date back as far as 1850. Salt-water encroachment has been noted in many areas of this country during the past 25 years, including Miami, Fla., Long Island, N.Y., Long Beach, Calif., Atlantic City, N.J., and Savannah, Ga., among the best known.

In most areas where salt-water encroachment has been noted, it has been accelerated by large ground-water withdrawals along the coast where pumping is heavily concentrated in small areas. A ground-water investigation by the U.S. Geological Survey is in progress in the Savannah area to determine the extent of salt-water encroachment in the principal artesian aquifer there, and a comprehensive report of the findings is to be published.

Ocean water ordinarily contains between 19,000 and 20,000 ppm (parts per million) of chloride. A chloride content not to exceed 250 ppm is recommended by the U.S. Public Health Service (1946) in potable water used on interstate carriers, and dissolved solids should not exceed 500 ppm, although, if water of such quality is not available, a dissolved solids content of 1,000 ppm may be permitted. A small amount of salt water may render ground water unfit for many uses and undesirable for domestic and public use. Water for industrial purposes also must meet certain chemical limitations, according to plant operations. Small changes in the quality of the water may affect processes greatly, and thereby make the water unfit for many purposes. Table 1 lists the suggested water-quality tolerances for several types of industrial processes.

Geology

The chief aquifer in the Brunswick area is a permeable limestone unit which ranges in age from early Miocene at the top to middle Eocene at the bottom (Herrick, S. M., 1959, oral communication). The principal source of artesian water is the Ocala limestone, of late Eocene age. The total thickness of the permeable limestone in the Brunswick area is not known, but a well drilled to a depth of 1,060 feet ended in dolomitic limestone. In an oil-test hole drilled 5 miles southwest of Brunswick, the limestone section extended from 560 feet to an approximate depth of 3,200 feet. It is probable, therefore, that the total thickness of limestone at Brunswick is as much as that penetrated by the oil-test well.

Table 1.--Suggested water-quality tolerances for paper and pulp products

Product	Hardness as $CaCO_3$ (ppm)	Total dissolved solids (ppm)
Paper and pulp:		
Groundwood	180	-
Kraft paper	100	300
Soda sulfite	100	200
High-grade light paper	50	200
Rayon (viscose):		
Pulp production	8	100

From Savannah the regional dip of the limestone is toward the southwest at an average of about 5 feet per mile. At Savannah the top of the limestone is about 200 feet below sea level and in the Brunswick area, about 65 miles southwest, it is about 550 feet below sea level, or about 560 feet below land surface.

A structural low extends across the southeastern part of McIntosh County and northwestern Glynn County; there the top of the limestone is at its greatest depth below sea level in the Coastal Plain of Georgia. It is not known what effect the structural low has had on the hydrology of the area, but possibly it has retarded the flushing action of fresh water, particularly at great depth. Thus, owing to incomplete flushing of the formation, salt water may remain in the lower part of the limestone.

The principal artesian aquifer is overlain by the relatively impermeable Hawthorn formation, which prevents or retards the upward movement of artesian water. The Hawthorn consists chiefly of marl, limestone, and clay, interbedded with sand, and ranges in thickness from less than 200 feet at Savannah to as much as 400 feet at Brunswick. It is overlain by younger formations consisting chiefly of sand and alluvium.

Ground-Water Utilization

The principal uses of ground water in the Brunswick area are industrial and municipal. In 1957 about 85 mgd (million gallons per day) was used by industrial plants and 3 to 4 mgd was used for municipal supplies. The well discharge of artesian water within a 3-mile radius of the Glynn County Courthouse was estimated to be about 90 mgd. Approximately 90 percent of this water was used by three industrial plants.

The largest single user of ground water in Glynn County and the largest in the Coastal Plain of Georgia is the Brunswick Pulp & Paper Co., about 2 1/2 miles northwest of Brunswick. In both 1956 and 1957 the pumpage at that plant averaged about 44.7 mgd.

The second largest user of ground water in Glynn County is the Hercules Powder Co. at its plant in Brunswick, which pumped about 25.4 mgd in 1957, an increase of about 1 mgd over the previous year. The plant of the Solvay Process Division of Allied Dye & Chemical Corp., about 3 miles northwest of Brunswick, pumped about 10.2 mgd in 1957, an increase of about 3 mgd as compared to 1956.

The use of ground water by other industrial plants is small in comparison to its use by the pulp and chemical plants. These small users include seafood packing plants, a textile-resin plant, a paint factory, and several small metal-products plants.

The city of Brunswick has the largest municipal supply in the county, which in 1957 pumped an estimated 3 to 4 mgd of water. The pumpage at St. Simons averaged about 480,000 gpd (gallons per day) and at Sea Island about 270,000 gpd.

Water Levels

According to Warren (1944, p. 134) the original static head in the Brunswick area was about 65 feet above mean sea level. In 1943 the water level was about 40 feet above mean sea level at a distance of about 1 1/2 miles from the area of heaviest pumping. Thus, the decline in water level there was about 25 feet at an estimated pumpage of 37 mgd, or about 0.7 foot per million gallons per day. In 1957 the pumpage in the Brunswick area was about 90 mgd, an increase of slightly more than 50 mgd since 1943. In January 1958 the water level was about 10 feet above mean sea level within half a mile of the area of heaviest pumping, about 2 to 2 1/2 miles northwest of Brunswick. Thus, the additional decline in water level in the area since 1943 was about 30 feet, or about 0.6 foot per additional million gallons per day.

The hydrographs in figure 2 show the changes in artesian head in six wells outside the area of heavy pumping in the county. Records are available for four wells commencing in 1940-42; measurements of two began in 1953.

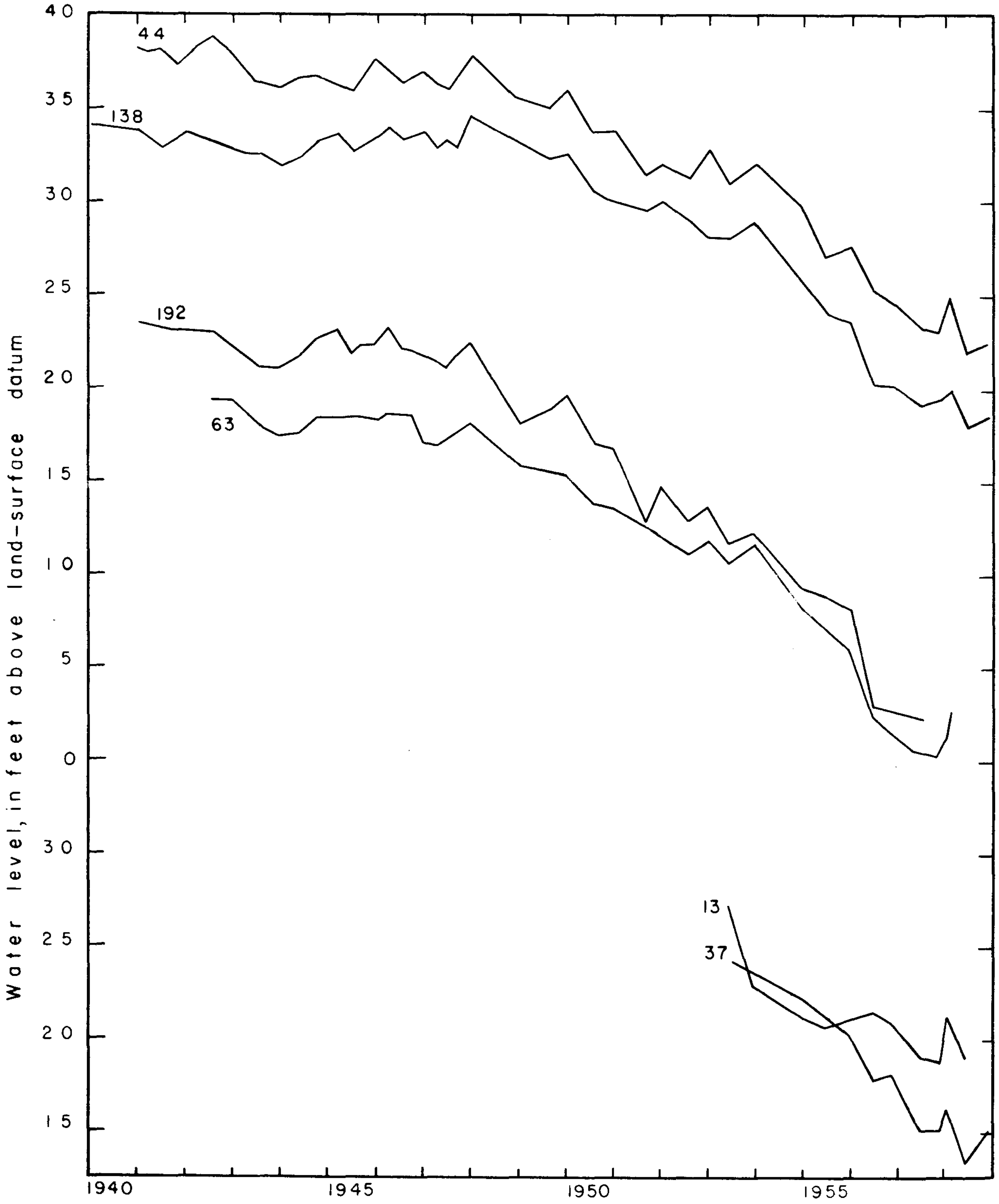


Figure 2.— Hydrographs showing changes of artesian head, Glynn County, Georgia.

The long-term records show the steady decline of water levels in the county over the period 1940 to October 1958. The small rise in early 1958 probably is seasonal, and is attributed to a slight decrease in pumping during the winter months. In general, water levels in wells northwest of Brunswick declined about 6 to 10 feet during the period 1948-53 and about 12 feet in 1954-57. In the area west of Brunswick, they declined about 5 and 9 feet respectively during the same periods, and in the area about 8 miles north of Brunswick they declined 5 and 7 feet. On St. Simons Island and Jekyll Island, water-level declines averaged about 5 and 8 feet respectively, for the same periods.

It was not possible to obtain water-level measurements in the center of the cones of depression at the different plants, but the present pumping levels appear to be well below mean sea level. It is probable also that the head in the Brunswick area is affected to some extent by the discharge of artesian water in other parts of Glynn and adjoining counties.

The nearest large-scale pumping is at St. Marys, Camden County, 30 miles south of Brunswick, where an estimated average of 26.5 mgd was pumped in 1957. The ground-water withdrawal at Fernandina, Fla., about 7 miles southeast of St. Marys, averaged about 52 mgd. In the Jesup area in Wayne County, about 40 miles northwest of Brunswick, ground-water withdrawals were about 42 to 45 mgd in the latter part of 1957. In the Savannah area, about 65 miles north of Brunswick, pumpage in 1957 averaged about 60 mgd.

Relation Between Fresh Water and Salt Water in Aquifers

The basic principle governing the relation between fresh and salt water in a water-bearing sand was first established by W. Badon Ghyben and Baurat Alexander Herzberg shortly before 1900. The results of this early work are commonly called the Ghyben-Herzberg theory. Brown (1925, p. 17) pointed out that "This theory appears to apply particularly to small islands and narrow land masses that are made up of freely pervious material, especially sand. It cannot be applied to large bodies or the continents, for it implies that sea water should be found in every locality where the water table is below sea level." More recent investigators have applied the theory to coastal-plain aquifers, with favorable results. For a more complete discussion of the application and limitations of the theory, the reader is referred to Muskat(1937), Hubbert(1940), and Wentworth(1942).

Fresh water tends to float on salt water because it is slightly lighter (its specific gravity is less) than salt water. The depth to which fresh water extends below sea level is determined by the difference between the heads and by the relative specific gravities of the two waters.

The position of the fresh- and salt-water interface is determined from the equation $h = \frac{t}{g-1}$, in which

h = depth to the interface, in feet below mean sea level.

t = head of the fresh-water body, in feet above mean sea level.

g = specific gravity of the salt water.

The value g-1 is the difference between the specific gravities of fresh water and salt water, because the specific gravity of fresh water is 1. The specific gravity of sea water of the Atlantic Ocean is about 1.025, which means that for every foot of head of fresh water above sea level the fresh water will extend 40 feet below sea level. It is apparent also that if the specific gravity of the sea water is less than 1.025, then the depth of the fresh water-salt water interface below sea level will be proportionately greater.

The Ghyben-Herzberg principle can be applied to aquifers which contain water under artesian pressure and which are hydraulically connected with the ocean. If the head of fresh water in the aquifer is great enough, fresh water will be discharged continuously into the ocean and will prevent inland migration of sea water. On the other hand, if the head of fresh water is lowered to such a point that fresh water is no longer discharged, then sea water will penetrate the aquifer to an altitude governed by the head of fresh water above sea level. If the aquifer is confined by impermeable beds, the most likely place for entrance of sea water into the aquifer will be at the submarine outcrop.

When an artesian well is pumped, a cone of depression (cone of pressure relief) is developed in the piezometric surface in the vicinity of the pumped well. There is no dewatering of the formation such as occurs in a water-table aquifer. The decrease in pressure is greatest at the pumped well, and less with distance from the pumped well. If ground-water withdrawals are large, the area of influence may extend many miles. If the cone of depression does not extend to the zone of diffusion, a ground-water divide will be established between the well and the ocean, and salt water will not move toward the well. However, if the artesian head is lowered to such a level that the cone of depression reaches the submarine outcrop, or reaches salt water which may have entered the aquifer through the outcrop, salt water will move into the aquifer along its base until a new position of equilibrium is reached. The rate of salt-water movement into the aquifer will depend upon the hydraulic gradient between the well and the ground-water divide and upon the transmissibility of the aquifer.

Salt-Water Contamination in the Brunswick Area

Prior to 1945, water from wells 600 to 1,027 feet deep in the Brunswick area had a chloride content of 15 to 25 ppm, a hardness as $CaCO_3$ of 175 to 225 ppm, and a dissolved-solids content of about 270 to 320 ppm. During the same period, however, two wells 1,057 and 1,063 feet deep yielded water that was considerably higher in these constituents. The first noticeable difference in the chloride content of the artesian water in the area was observed in a sample taken in October 1939 from Hercules Powder Co. well H. The sample was taken shortly after the well, which was cased to 560 feet, was completed at a depth of 1,063 feet. The chloride content of the water was 69 ppm, well above that noted in other wells in the area. The increased chloride content in water from well H probably was the first indication of salt-water contamination of the artesian water in the Brunswick area.

In June 1942 a water sample from the city well at the foot of F Street (well 200) also showed an unusually high content of chloride and dissolved solids, and considerable hardness. However, water from other wells of shallower depth in the area did not show any significant changes in chloride content and dissolved solids during that year.

The most recent, and by far the most marked, changes in the quality of the artesian water in the area occurred from about 1950 to 1958. Water from two shallow wells, 668 and 880 feet deep, at the Hercules plant had increases in chloride of as much as 92 to 214 ppm. Water from the deep wells at the plant also had large increases in chloride during this period, and in 1950 and 1958 the highest content of chloride was found in water of the two deepest wells at the plant. The increase in chloride in the water of the shallow wells probably has been accelerated by the increase in pumpage during the past 8 to 9 years.

During the period from September 1956 to January 1959, the artesian water in wells at the Solvay Process Division plant and at the Brunswick Pulp & Paper Co. plant, about 2 miles northwest of the Hercules Powder Co. plant, had a chloride content of only 17 to 29 ppm and dissolved solids of 182 to 318 ppm. The combined ground-water pumpage at the two plants averaged about 55 mgd in 1957, or slightly more than twice the amount pumped at the Hercules plant. The depths of the wells at the plants ranged from about 1,000 to 1,026 feet, slightly less than that of the deepest wells at the Hercules plant.

Table 2 lists analyses showing the hardness and the chloride and dissolved-solids content of the artesian water in Glynn County.

Table 2.--Partial listing of chemical analyses of ground water from wells in Glynn County, Georgia

Well No.	Location	Owner	Well construction: Diameter (inches)	Well construction: Depth (feet)	Well construction: Cased to (feet)	Date of collection	Chemical constituents (ppm): Chloride (Cl)	Chemical constituents (ppm): Hardness as $CaCO_3$	Chemical constituents (ppm): Dissolved solids	Source of data	Remarks
5	Brunswick	City of Brunswick[1]	12-10	1,003	440	12-18-12	17		304	Stephenson and Veatch, 1915, p. 267.	At 1525 Grant St.
	do.	do.[2]				2-13-31	16	210	312	Collins, Lamar and Lohr, 1934, p. 55.	Do.
	do.	do.				12- 4-51	32	242	-	U.S. Geol. Survey.	Do.
	do.	do.				12- 3-54	71	274	519	City of Brunswick	Do.
6	do.	do.[2]	8	600	-	1-23-41	18	212	321	Lamar, 1942, p. 38.	At Grant & F Streets.
5 & 6	do.	do.	10) 8)	1,003) 600)	440	12- 4-51	18	530	1,000	U.S. Geol. Survey	Composite sample from wells 5 & 6.
8	do.	do.[2]	8	750	375	2-13-31	16	175	270	Collins, Lamar, and Lohr, 1934, p. 55.	At Norwich & F Streets.
200	do.	do.	18-12	1,057	478	6-16-42	152	219	1,110	City of Brunswick.	At foot of F Street. Sample taken before bottom 57 feet of well was cemented.
	do.	do.				7- 9-42	146	-	-	Warren, 1944, p. 136.	
	do.	do.				9- 9-42	124	215	898	City of Brunswick.	
	do.	do.		1,000+		7-15-43	81	-	-	Georgia Geol. Survey	
	do.	do.				12- 3-54	231	546	1,170	City of Brunswick.	
	do.	do.				12- 4-51	202	578	-	U.S. Geol. Survey.	
	do.	do.		1,000+		2-10-58	103	880	2,250	City of Brunswick.	Sample from natural flow before bottom of hole was cemented.
	do.	do.				2-10-58	465	850	2,180	do.	Sample from natural flow through open pipe; bottom of pipe, 743 ft.
	do.	do.				2-10-58	475	870	2,080	do.	Sample from same source; bottom of pipe, 843 ft.
	do.	do.				2-10-58	545	920	2,360	do.	Sample from same source; bottom of pipe, 943 ft.
	do.	do.				2-10-58	505	920	2,230	do.	Sample from same source; bottom of pipe, 960 ft.
	do.	do.		957		2-26-58	112	340	840	do.	Sample from pump after bottom of hole was cemented at 957 ft. and mud cleaned out of well.
	do.	do.				3- 5-58	106	350	1,002	do.	Pumped sample.
200A	do.	do.	18-12	952	515	12- 4-51	18	196	283	do.	At Brunswick Villa.
	do.	do.				12- 3-54	18	186	295	do.	Do.
200B	do.	do.	12-10	750		12- 4-51	17	198	290	U.S. Geol. Survey.	At Goodyear Park.
173	do.	Hercules Powder Co.	16-14	696		1950	31	232	-	Hercules Powder Co.	Hercules well A.
	do.	do.				1958	44	278	-	do.	Do.
174	do.	do.	10	973	450	1950	32	218	-	do.	Hercules well B.
	do.	do.				1958	35	240	-	do.	Do.
175	do.	do.	10	668		1950	26	222	-	do.	Hercules well C.
	do.	do.				1958	118	355	-	do.	Do.
178	do.	do.	12	880	557	1950	29	220	-	do.	Hercules well F.
	do.	do.				1958	243	601	-	do.	Do.
179	do.	do.	18-12	1,063	560	10- ?-39	69	312	-	Georgia Geol. Survey.	Hercules well H.
	do.	do.				7-15-43	53	-	-	Warren, 1944, p. 137.	Do.
	do.	do.				1950	105	401	-	Hercules Powder Co.	Do.
	do.	do.				1958	264	587	-	do.	Do.
J-8	do.	do.	10	950	450	1950	22	210	-	do.	Hercules well I.
	do.	do.				3- 4-58	24	210	-	do.	Do.
	do.	do.				3-14-58	58	224	-	do.	Do.
	do.	do.				3-17-58	28	218	-	do.	Do.
	do.	do.				3-25-58	30	210	-	do.	Do.
	do.	do.				4- 7-58	27	214	-	do.	Do.
	do.	do.				5-12-58	29	240	-	do.	Do.
	do.	do.				6-29-58	28	246	-	do.	Do.
	do.	do.				8- 1-58	34	228	-	do.	Do.
	do.	do.				8-29-58	28	260	-	do.	Do.
	do.	do.				9-30-58	30	246	-	do.	Do.
	do.	do.				11-10-58	42	272	-	do.	Do.
	do.	do.				12- 4-58	27	237	-	do.	Do.
204	do.	do.	12	1,060	500	1950	109	469	-	do.	Hercules well J.
	do.	do.				1958	306	658	-	do.	Do.
	do.	do.				10-16-58	310	646	1,480	U.S. Geol. Survey.	Do.
J-10	do.	do.	12	1,050	550	1950	66	306	-	Hercules Powder Co.	Hercules well K.
	do.	do.				3-25-58	190	480	-	do.	Do.
	do.	do.				4- 7-58	199	488	-	do.	Do.
	do.	do.				5-12-58	198	500	-	do.	Do.
	do.	do.				6-29-58	204	530	-	do.	Do.
	do.	do.				8- 1-58	228	524	-	do.	Do.
	do.	do.				8-29-58	194	520	-	do.	Do.
	do.	do.				9-30-58	215	560	-	do.	Do.
	do.	do.				11-10-58	215	548	-	do.	Do.
	do.	do.				12- 4-58	216	552	-	do.	Do.
J-11	do.	do.	12	1,050	550	1950	47	214	-	do.	Hercules well L.
	do.	do.				3-25-58	42	240	-	do.	Do.
	do.	do.				4- 7-58	29	220	-	do.	Do.
	do.	do.				5-12-58	28	250	-	do.	Do.

Table 2.--Partial listing of chemical analyses of ground water from wells in Glynn County, Georgia - (continued)

Well No.	Location	Owner	Well construction: Diameter (inches)	Well construction: Depth (feet)	Well construction: Cased to (feet)	Date of collection	Chemical constituents (ppm): Chloride (Cl)	Chemical constituents (ppm): Hardness as $CaCO_3$	Chemical constituents (ppm): Dissolved solids	Source of data	Remarks
J-11	Brunswick	Hercules Powder Co.				6-29-58	27	244	-	Hercules Powder Co.	Hercules well L.
	do.	do.				8- 1-58	34	236	-	do.	Do.
	do.	do.				8-29-58	27	252	-	do.	Do.
	do.	do.				9-30-58	30	246	-	do.	Do.
	do.	do.				11-10-58	29	248	-	do.	Do.
	do.	do.				12- 4-58	33	254	-	do.	Do.
D-57	do.	do.	20-12	1,015	650	1950	38	243	-	do.	Hercules well M.
	do.	do.				1958	212	519	-	do.	Do.
D-58	do.	do.	20-12	1,015	691	1958	86	290	-	do.	Hercules well N.
J-12	do.	do.	20-12	1,014	671	1958	177	402	-	do.	Hercules well O.
J-13	do.	do.	26-12	1,050	549	1958	29	222	-	do.	Hercules well P.
	do.	do.				3- 4-58	24	204	-	do.	Do.
	do.	do.				3-14-58	44	222	-	do.	Do.
	do.	do.				3-17-58	26	220	-	do.	Do.
	do.	do.				3-25-58	30	236	-	do.	Do.
	do.	do.				4-7 -58	26	218	-	do.	Do.
	do.	do.				5-12-58	26	230	-	do.	Do.
	do.	do.				8- 1-58	26	234	-	do.	Do.
	do.	do.				8-29-58	26	252	-	do.	Do.
	do.	do.				9-30-58	26	240	-	do.	Do.
	do.	do.				11-10-58	25	250	-	do.	Do.
	do.	do.				12- 4-58	25	270	-	do.	Do.
E-49	Brunswick, about 2 mi. NW of	Solvay Process Div.	10	1,026	531	9-14-56	29	198	293	Solvay Process Div.	Solvay well 1.
	do.	do.				9-26-58	17	-	-	do.	Do.
E-50	do.	do.	12	1,021	448	9-14-56	29	211	309	do.	Solvay well 2.
	do.	do.				9-26-58	18	-	-	do.	Do.
	do.	do.				11-21-58	17	-	-	do.	Do.
	do.	do.				1-20-59	19	-	304	do.	Do.
E-51	do.	do.	12	983	501	9-14-56	26	204	316	do.	Solvay well 3.
	do.	do.				9-26-58	16	-	-	do.	Do.
	do.	do.				1-20-59	18	-	304	do.	Do.
E-52	do.	do.	12	1,000+	500+	9-14-56	26	205	330	do.	Solvay well 4.
	do.	do.				9-26-58	18	-	-	do.	Do.
	do.	do.				11-21-58	19	-	-	do.	Do.
	do.	do.				1-20-59	18	-	318	do.	Do.
E-53	do.	do.				9-14-56	32	205	293	do.	Solvay well 5.
	do.	do.				9-26-58	18	-	-	do.	Do.
	do.	do.				11-21-58	18	-	-	do.	Do.
	do.	do.				1-20-59	20	-	317	do.	Do.
E-54	Brunswick, about 2 mi. NW of	Brunswick Pulp & Paper Co.	16	1,000	490	1958	19	-	242	Brunswick Pulp & Paper Co.	Brunswick Pulp & Paper Co. well 1.
E-55	do.	do.	18	900	492	7-15-43	13	-	-	Warren, 1944, p. 137.	Do. well 2
	do.	do.	16	1,000	490	1958	21	-	275	Brunswick Pulp & Paper Co.	Do. well 2
E-56	do.	do.	16	1,000	490	1958	20	-	210	do.	Do. well 3
E-57	do.	do.	18	1,000	490	1958	18	-	182	do.	Do. well 4
E-58	do.	do.	20	1,000	490	1958	21	-	270	do.	Do. well 5
E-59	do.	do.	20	1,000	490	1958	25	-	260	do.	Do. well 6
-	St. Simons Island	Ocean View Hotel	-	500	-	6-10-11	18	-	202	Stephenson, and Veatch, 1915, p. 267.	Probably destroyed.
152	Sea Island	Sea Island Co.	8-6	812	540	1931	27	222	-	Sea Island Co.	Apartment well.
	do.	do.				1941	23	188	-	do.	Do.
	do.	do.				1-23-41	22	202	317	Warren, 1944, p. 139.	
	do.	do.				1-29-59	30	236	378	Sea Island Co.	Do.
148	do.	do.	6	619	180	1-29-59	30	246	378	Sea Island Co.	35th Street well.
	do.	do.	8	1,094	-	1-15-45	13	230	305	do.	Laundry well.
	do.	do.				1-29-59	27	244	378	do.	Do.
166	Jekyll Island	Jekyll Island Club	-	480	-	Prior to 1915	16	-	287	Stephenson and Veatch, 1915, p. 267.	Probably destroyed.
169b	do.	State of Georgia	8	706	-	6- 8-55	16	184	289	U.S. Geol. Survey	Jekyll 1a.
J-68	do.	do.	8	745	550	9-30-57	15	194	431	Georgia Geol. Survey	Jekyll 1.
J-67	do.	do.	8	755	529	9-30-57	16	191	431	do.	Do. 2.
J-64	do.	do.	8	711	500	10-16-58	16	190	456	do.	Do. 3.
J-59	do.	do.	8	764	523	10-16-58	16	208	454	do.	Do. 4.
J-63	do.	do.	8	767	540	10-16-58	16	208	454	do.	Do. 6.
J-53	do.	do.	8	739	494	10-16-58	16	206	313	U.S. Geol. Survey	Do. 8.
-	Brunswick	Mr. Schelander	-	750	-	12-10-56	24	-	506	Georgia Geol. Survey	
-	do.	W. W. Lloyd	-	485	-	Prior to 1915	27	-	308	Stephenson and Veatch, 1915, p. 267.	
-	do.	Unknown	-	-	-	11-18-11	19	-	289	Georgia Geol. Survey	Probably destroyed.
202	do.	Brunswick Marine	12-8	735	574	6-20-42	34	195	300	do.	Company well 2.
123	Everett City		-	480	-	6-2 -11	17	-	340	Stephenson and Veatch, 1915, p. 266.	Probably destroyed.
129a	Thalmann	Seaboard Air Line RR	-	400	-	12-? -09	28	-	291	do.	

[1]Formerly Mutual Light & Water Co.
[2]Formerly Peoples Water Service Co.

City of Brunswick wells.--The city of Brunswick has four supply wells ranging in depth from about 750 to 1,027 feet, and cased from 440 to 515 feet. Two wells are in the northern part of the city and two are in the western part near the water-supply plant at Grant and F Streets. (See fig. 1.)

The first indication of a high chloride content of water in a city well was noted June 16, 1942, when a water sample from well 200 had a chloride content of 152 ppm, a hardness of 219 ppm, and a dissolved-solids concentration of 1,110 ppm. (See fig. 3.) The well was completed June 1942 at a depth of 1,057 feet, and the sample described above probably was collected shortly thereafter. A sample of water from the well on July 9, 1942, had a chloride content of 146 ppm. On September 9, 1942, the chloride content of a sample was only 124 ppm but still was considerably higher than that from other wells in the area. The September sample was obtained shortly before the well was plugged at 1,000 feet. The well was cemented off at about this depth in September 1942, in an attempt to improve the quality by shutting out the salt water. Analyses are not available for the remainder of 1942, but a sample obtained July 15, 1943, had a chloride content of 81 ppm, indicating a decrease of 43 ppm after the bottom of the well was sealed off. Analyses are not available for the period 1944-50, but from December 1951 to December 1954 the chloride content of the water increased from 202 to 231 ppm and the hardness decreased from 578 to 546 ppm.

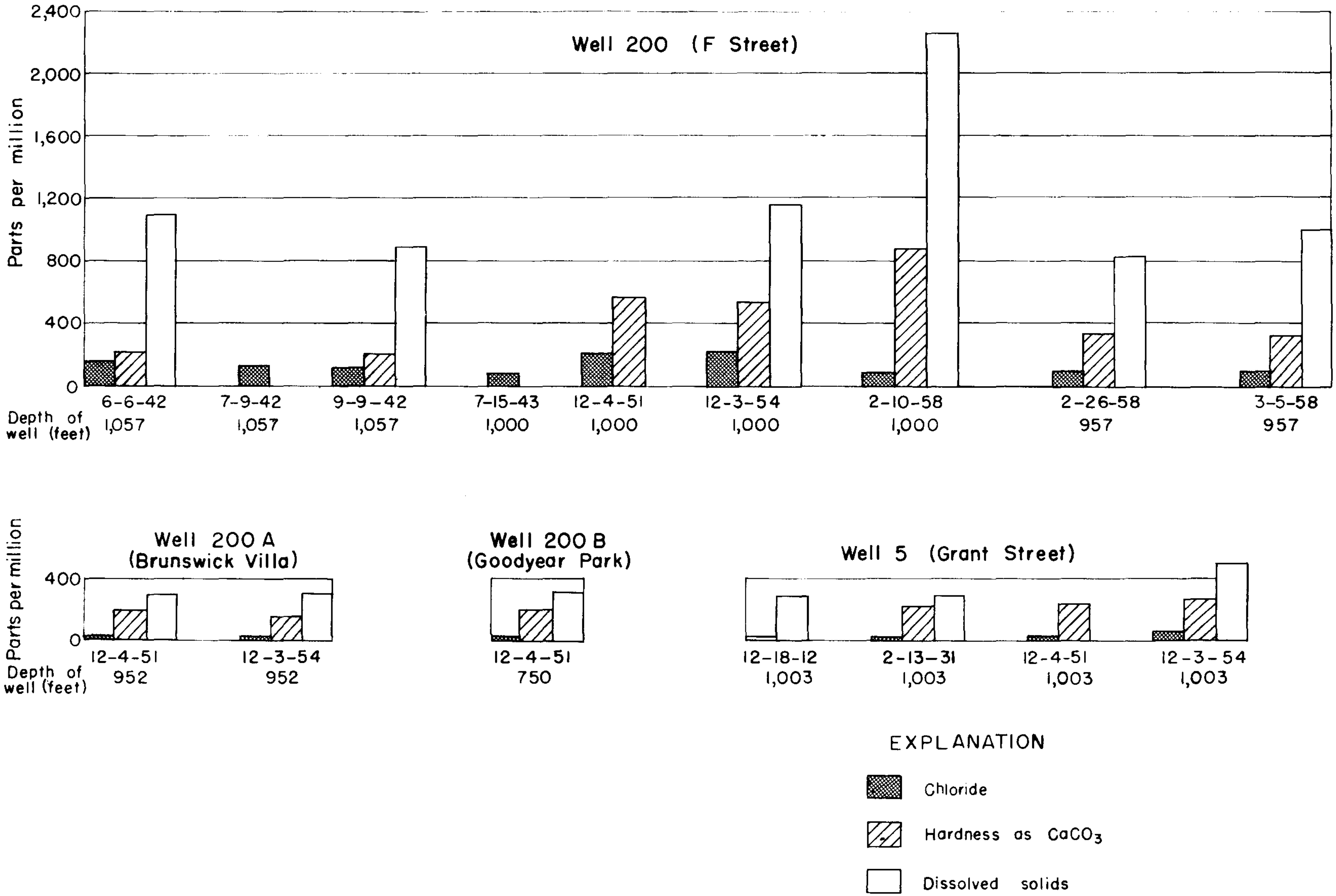


Figure 3.- Mineral content and hardness of water, city of Brunswick wells.

According to H. B. Lovvorn, City Manager of Brunswick (written communication, February 1959), citizen complaints about the taste and hardness of the water increased noticeably in 1957. In January 1958, the pump was removed in order to prepare for cementing the well. When the pump was removed, there was sufficient pressure for the water to rise several feet above land surface. A water sample taken from the natural flow of the well before cementing had a chloride content of 103 ppm, a hardness of 880 ppm, and a dissolved-solids content of 2,250 ppm (fig. 4). Additional water samples were collected at the overflow of a small-diameter pipe lowered to different depths in the well. At depths ranging from 743 to 943 feet the samples showed a progressive increase in chloride from 465 to 545 ppm; hardness increased from 850 to 920 ppm and dissolved solids increased from 2,180 to 2,360 ppm. The sample collected from a depth of 943 feet yielded water that was highest in these constituents. A sample collected at a depth of 960 feet had a chloride content of 505 ppm, a hardness of 920 ppm, and a dissolved-solids content of 2,230 ppm. The hole was then cemented at 957 feet. A pumped sample taken about a week after the hole was cemented had a chloride content of 112 ppm, a hardness of 340 ppm, and a dissolved-solids content of 840 ppm. It appears, therefore, that plugging the hole at 957 feet was effective in keeping out the high chloride water. Moreover, the hardness and dissolved solids were significantly decreased after the well was plugged. A sample taken in March 1958 did not show any changes in chloride content and hardness of the water in the well, but the dissolved-solids content had increased from 840 to 1,000 ppm.

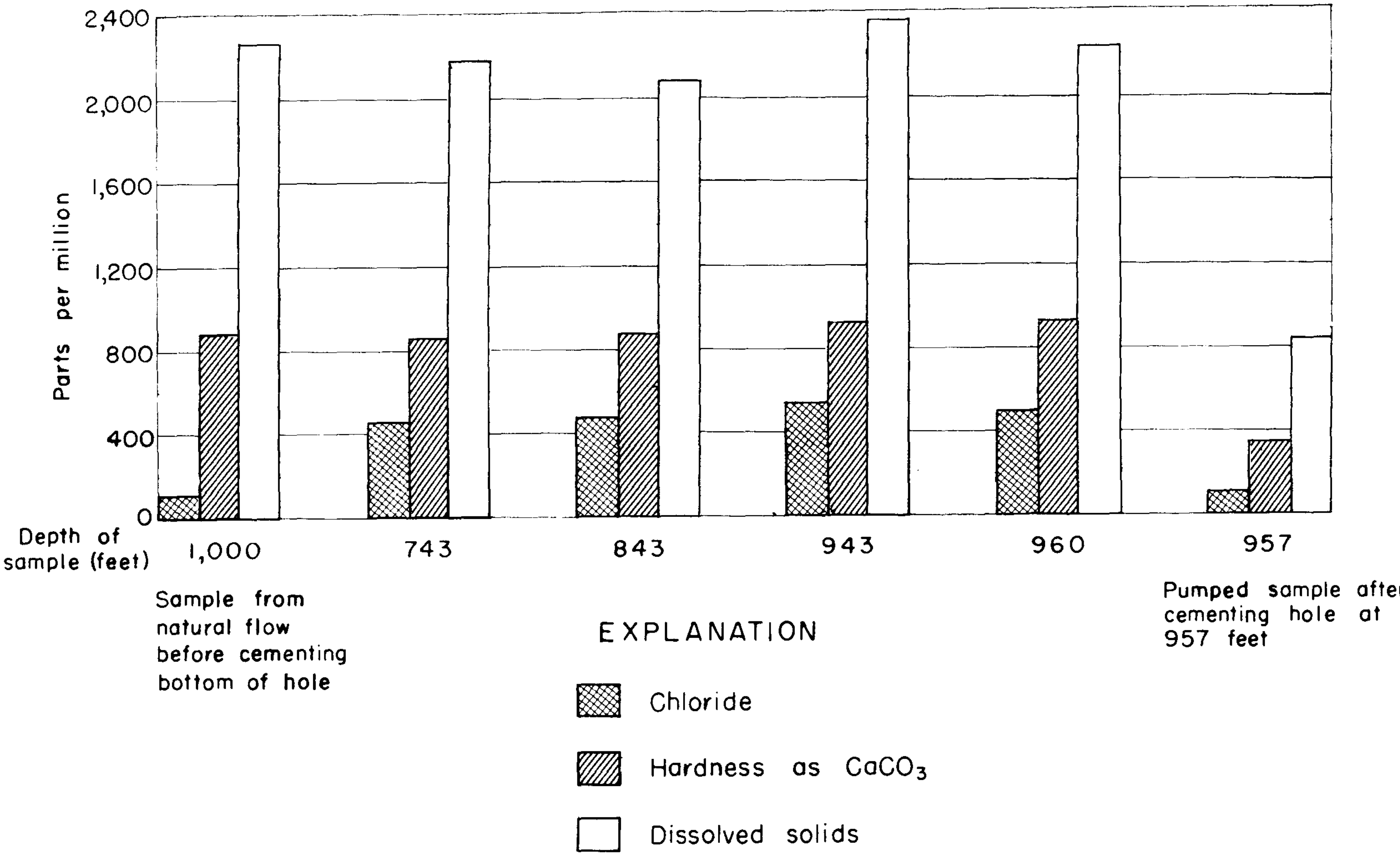


Figure 4.–Relation of depth of samples to hardness and mineral content of water, Brunswick city well at foot of F Street, 1958.

City supply well 5 at Grant Street is about 800 feet east of well 200 at the foot of F Street. The well was drilled in 1912 to a depth of 1,003 feet and cased to 440 feet. A water sample collected in 1912 had a chloride content of 17 ppm and dissolved-solids content of 304 ppm. (See fig. 3.) Analyses of samples collected in 1931, 1951, and 1954 show a general increase in chloride, hardness, and dissolved solids. During the period 1931-51 the chloride content increased by 16 ppm and during 1951-54 an additional 39 ppm, more than double the increase during the previous 21-year period.

The sample collected in December 1954 had a chloride content of 71 ppm, a hardness of 274 ppm, and dissolved-solids content of 519 ppm. No recent samples have been collected from the well, but the constituents probably have increased since 1954. The continued decline in the artesian head in the area will increase the hazard of salt-water contamination of the fresh-water supply. It is expected, therefore, that in the near future the water in this well will have a chloride and hardness similar to that found in the F Street well before the lower part of the well was plugged.

Chemical analyses are available also of samples collected from well 200A (Brunswick Villa) in December 1951 and December 1954 and from well 200B (Goodyear Park) in December 1951. (See fig. 3.) These wells are about 2 miles north and northeast, respectively, of city well 200 at the foot of F Street. (See fig. 1.) The analyses indicate very little change in the quality of the water during the 3-year period. The water samples from the wells had a chloride content of 17 to 18 ppm, hardness of 186 to 198 ppm, and dissolved-solids content of 283 to 295 ppm.

Hercules Powder Co. wells.--The Hercules Powder Co. well field is about 1 1/2 miles northeast of the Brunswick city well at the foot of F Street, and about 3/4 mile south of city well 200B at Goodyear Park. (See fig. 1.) There are 13 supply wells at the plant, ranging in depth from 668 to 1,063 feet. The well casings are seated from about 450 to 691 feet below land surface.

Figure 5 shows the chloride content and hardness of the water from the supply wells in 1950 and 1958.

In 1950, 10 wells for which comparative analyses of water were available showed a general increase in chloride with increasing depth of the wells; however, the samples collected in 1958 do not indicate a consistent relationship (fig. 6A).

The hardness of the water increased 22 to 381 ppm from 1950 to 1958, and in 1958 its range was from 204 to 658 ppm. (See fig. 5.) Figure 6B shows the relation of the depths of the wells to the hardness of the water for 1950 and 1958. In general, the water of the highest hardness was found in the deepest wells, although the water from shallow well F had the second highest hardness found in the Hercules wells. Well F also had the greatest percentage increase in hardness from 1950 to 1958, an increase from 220 to 601 ppm.

During the period 1950-58, 6 of the 13 wells showed increases in chloride of 92 to 214 ppm, 3 wells showed increases of 3 to 13 ppm, and 1 well showed a decrease of 14 ppm. Records prior to 1958 are not available for three wells, and hence no comparison can be made of the changes in chloride content in these wells.

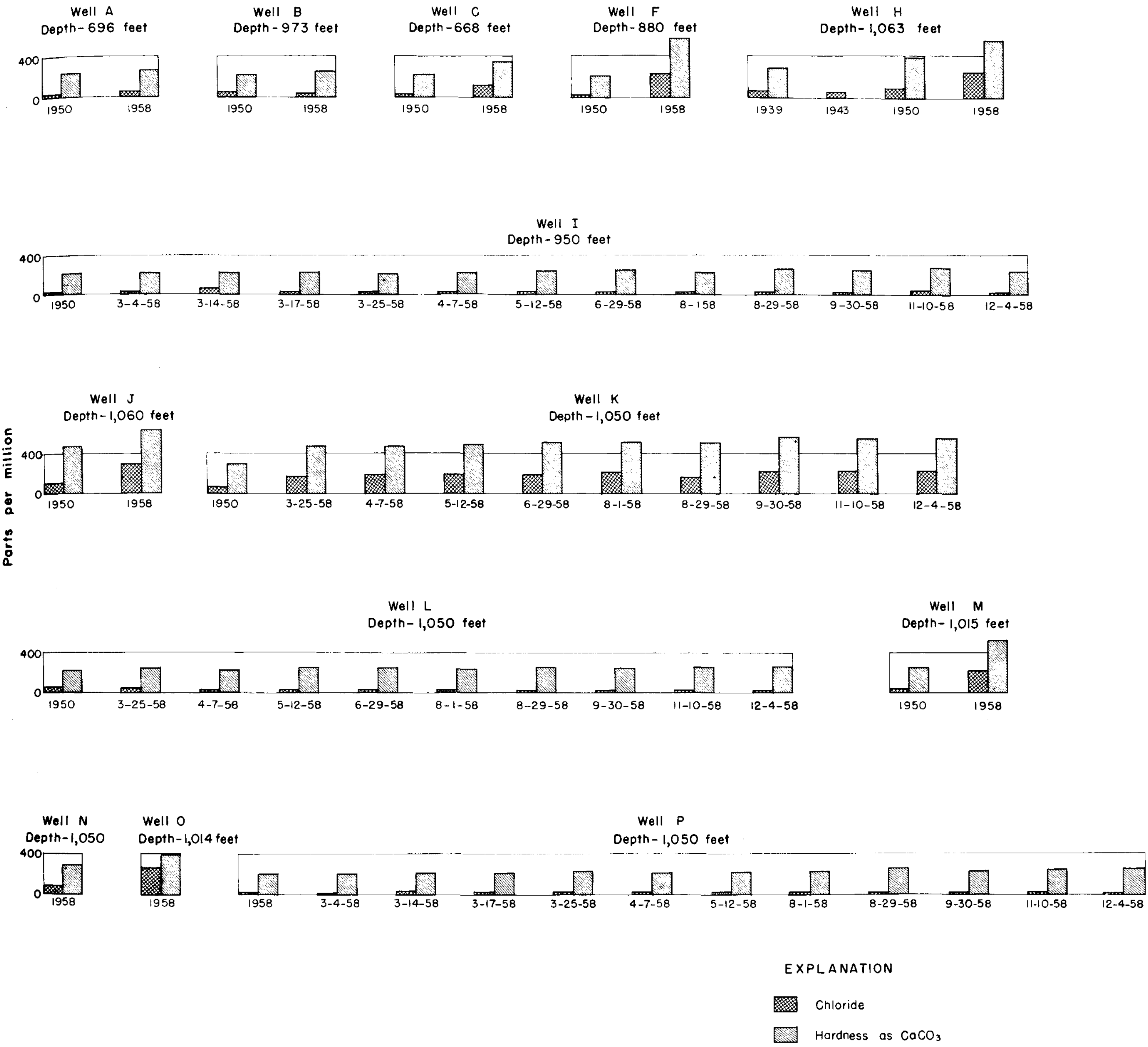
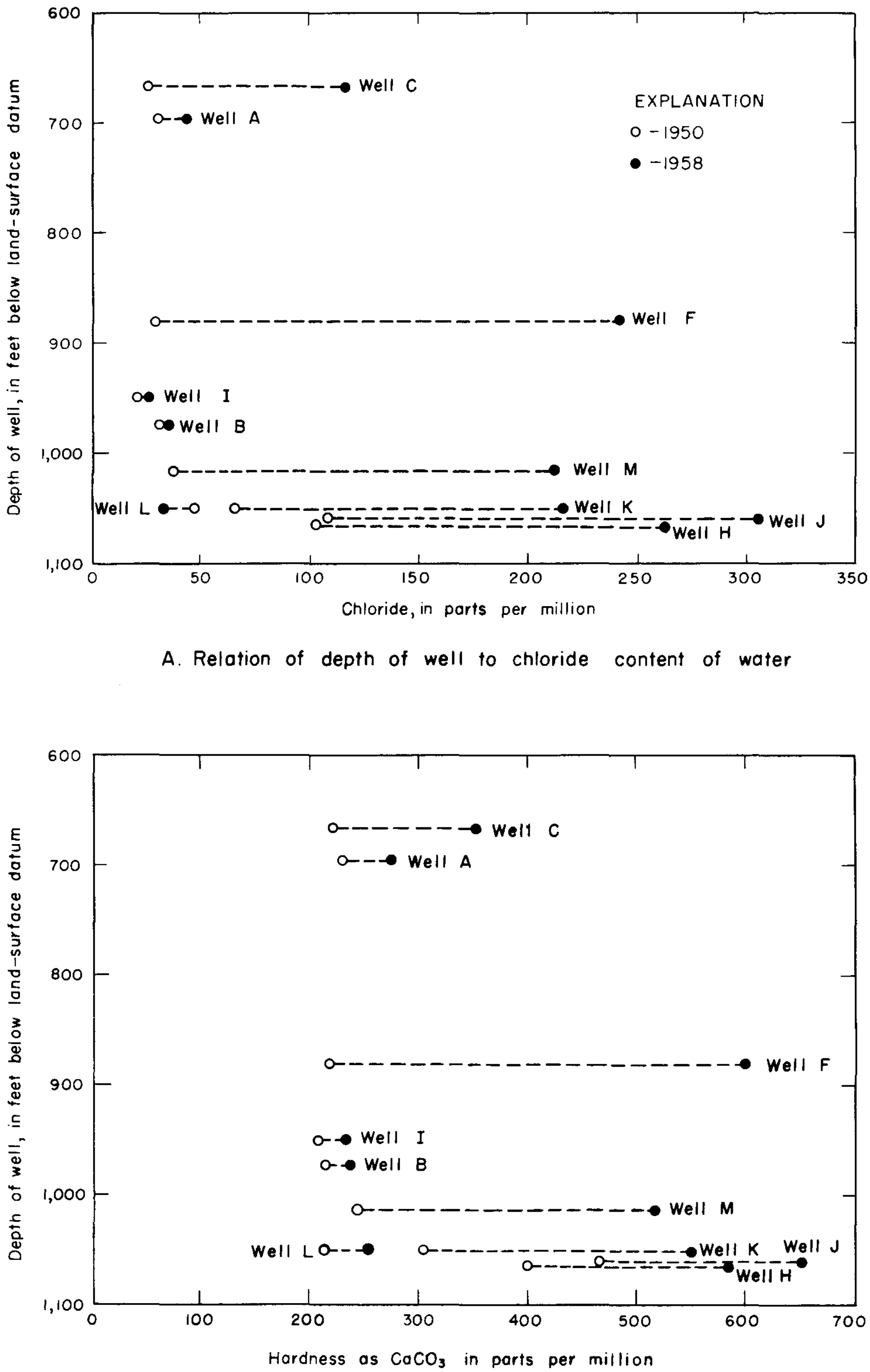


Figure 5.- Hardness and chloride content of water, Hercules Powder Co. wells.



A. Relation of depth of well to chloride content of water

B. Relation of depth of well to hardness of water

Figure 6.—Relation of depth of wells to chloride content and hardness of water, Hercules Powder Co., 1950 and 1958.

Wells L and P, the most easterly wells of the Hercules Powder Co. well field, are nearest the seacoast and about 800 feet northwest of a tidal marsh extending along the eastern boundary of the plant site. (See fig. 1.) The wells are 1,050 feet deep and are cased to about 550 feet. The chloride content of the water from well L decreased in 1958 and by December was 14 ppm less than in 1950. Well P was drilled in 1957. Water samples collected from the well monthly in 1958 show a gradual decrease in chloride during the latter part of the year. In 1957 this well was the largest producer at the site, averaging about 4,000 gpm.

Well I, about 500 feet southwest of well P, is the next most easterly well at the site and is 950 feet deep. Well K is about 580 feet northwest of well P and is 1,050 feet deep. During the period from 1950 to December 1958, the chloride content of the water in well I increased from 22 to 27 ppm, and that in well K increased from 66 to 216 ppm.

In 1950 and 1958 water of the highest chloride content came from wells J and H, the deepest wells at the Hercules plant, 1,060 feet and 1,063 feet deep, respectively. From 1950 to December 1958 the chloride content of the water in well J increased 159 ppm, and that in well H increased 201 ppm. During the same period, water from well A, 696 feet deep, and well B, 973 feet deep, located between the two deepest wells, showed increases in chloride of 13 ppm from well A and 3 ppm from well B.

Wells C and O are in the southern part of the well field, and are 668 and 1,014 feet deep, respectively. In well C the chloride increased from 26 to 118 ppm during the period 1950 to 1958. In well O the chloride content was 177 ppm in 1958; analyses are not available for 1950.

Wells M and N, 1,015 and 1,050 feet deep, respectively, are in the western part of the site. In well M the chloride increased from 38 to 212 ppm from 1950 to 1958. Analyses are not available for well N in 1950 but a sample obtained in 1958 had a chloride content of 86 ppm. The largest percentage increase in chloride content of water was in well F, an 880-foot well near the center of the well field, which increase was from 29 to 243 ppm.

A summary of the chloride content of water from the 13 wells at the Hercules plant in 1958 is as follows:

212 to 310 ppm in 5 wells
118 to 177 ppm in 2 wells
86 ppm in 1 well
25 to 44 ppm in 5 wells

An analysis of the data on chloride content available for the wells indicate several pertinent facts:

1. In 1950 and 1958, water of the highest chloride content was found in wells H and J, the deepest wells at the site.
2. During the period 1950-58 samples from two shallow wells (C and F) and four deep wells (H, J, K, and M) showed significant increases in chloride.
3. The greatest increase in chloride content of water was in well F, a shallow well near the center of the well field.
4. Water from well C, the shallowest well at the plant, had a much greater increase in chloride than that from several deeper wells.
5. The chloride content of water from two deep wells (L and P) nearest the bay decreased in 1958.
6. In 1958 samples from six of the eight wells deeper than 1,000 feet had a chloride content of 86 to 310 ppm, and two had a chloride content of 25 to 33 ppm.
7. The lowest concentration of chloride in water from wells deeper than 1,000 feet was found in the extreme northern and eastern parts of the area.

Brunswick Pulp & Paper Co. wells.--The Brunswick Pulp & Paper Co. well field is about 1/2 to 1 mile southwest of the Solvay plant, and about 2 miles west of the Hercules plant. (See fig. 1.) The plant is served by six supply wells ranging in depth from 900 to 1,000 feet, and all cased to about 490 feet. Five wells are within 500 feet of an estuary of the Brunswick River, and one well is about 3,200 feet east of the estuary.

In 1957 the pumpage at the plant averaged about 44.7 mgd, about four times as much as that at the nearby Solvay plant. The 10-foot water-level contour encloses the well fields at both plants. (See fig. 1.) The deepest part of the cone of depression probably is within the area of the Brunswick Pulp & Paper Co. well field, which is the most heavily pumped area in Glynn County. Water-level measurements in 1958 were not available for the supply wells but it is probable that the pumping level within the cone is as much as 20 to 40 feet below sea level.

The chloride content of the water at the Brunswick Pulp & Paper Co. plant has increased but slightly during the past decade, despite the large ground-water pumpage in the area. On July 15, 1943, a water sample from company well 2 had a chloride content of 13 ppm. Analyses made in 1958 of samples from six wells showed chloride concentrations of 8 to 25 ppm and dissolved solids of 182 to 275 ppm (table 2). It appears, therefore, that the artesian water in the Brunswick Pulp & Paper Co. well field has not been contaminated with salt water.

Solvay Process Division wells.--The Solvay Process Division plant is about 1/2 to 1 mile northeast of the Brunswick Pulp & Paper Co. plant. (See fig. 1.) It has five supply wells ranging in depth from about 983 to 1,026 feet, which are cased from about 448 to 531 feet. In 1957 ground-water withdrawals at the site averaged about 10.2 mgd. Analyses of samples from the wells during the period September 1956 to January 1959 show concentrations of chloride of 16 to 32 ppm and dissolved solids of 293 to 330 ppm (table 2). The samples from four of the wells showed a decrease in chloride content of 8 to 12 ppm between 1956 and 1959 and that from one well showed a decrease of 12 ppm between 1956 and 1958. Analyses were not available for the latter well in 1959. The chloride content of the artesian water was about the same as that at the Brunswick Pulp & Paper Co. plant, but the dissolved-solids content averaged slightly greater than that at the paper plant.

Offshore island wells.--Chemical analyses of samples from a number of wells on St. Simons Island, Sea Island, and Jekyll Island do not indicate any systematic changes in the quality of water for the periods of record available (table 2). A sample collected from an 812-foot well on Sea Island in 1931 had a chloride content of 27 ppm and a hardness of 222 ppm; in January 1959 the water from the same well had a chloride content of 30 ppm and a hardness of 236 ppm. Analyses of samples collected in 1955 and 1957-58 from wells on Jekyll Island indicate an average chloride content of 16 ppm and an average hardness of 200 ppm. The wells on Jekyll Island range in depth from 706 to 767 feet and are cased to depths of about 494 to 550 feet.

In 1957 an estimated 0.75 mgd of water was pumped for municipal use on St. Simons Island and Sea Island. Ground-water withdrawals on Jekyll Island are relatively small. The island is a recreational center and most of the water is used during the summer for drinking and picnic areas.

In 1958 the artesian pressure on the offshore islands was about 30 to 40 feet above mean sea level, considerably higher than that in the Brunswick area. The decline of water levels along the coastal islands has been less than that on the mainland, largely because of the small withdrawals of ground water in these areas.

Sources of Salt-Water Contamination

Of the several ways in which the limestone aquifer in the Brunswick area might become contaminated with salt water, the following are most likely: (1) lateral migration of sea water inland because of reduced head due to overpumping, (2) upward vertical movement of salt water through the limestone underlying the principal artesian aquifer, and (3) contamination through leaky casings.

Lateral migration.--Lateral migration of salt water through the formation because of the reduced head caused by pumping appears to be the least likely source of contamination. Ground-water withdrawal in the Brunswick area is much greater and is much more centralized than in any other area in the Coastal Plain of Georgia. However, water-level data collected in 1958 do not indicate that the piezometric surface of the artesian water has been lowered to such a point that the cone of pressure relief reaches the ocean outcrop, resulting in the establishment of a hydraulic gradient from the ocean to the Brunswick area wells. A piezometric map of Glynn County for January 1958 (fig. 1) indicates the area affected by large ground-water withdrawals in the Brunswick area. The 10-foot contour line encloses the well fields of the Brunswick Pulp & Paper Co. and Solvay Process Division plants, the most heavily pumped area in the county. The cone of depression produced by pumping in this area is enclosed by the 25-foot contour line, which delineates a kidney-shaped cone extending from Camden County into McIntosh County. A cone of depression also exists at the Hercules plant, but measurements were not available to define the cone exactly. Water-level measurements were not made in the production wells at the three industrial plants, but it is probable that the present pumping levels are as much as 20 to 40 feet below mean sea level.

The piezometric map of 1958 shows that the steepest hydraulic gradient is to the southwest toward Camden County and the gentlest gradient is north into McIntosh County. Seaward from Brunswick the piezometric surface of the artesian water rises, and at Jekyll Island and St. Simons Island it is as much as 35 to 40 feet above mean sea level. In the city of Brunswick the piezometric surface is 20 to 25 feet above sea level. In view of the relatively broad, shallow cone of depression and the high heads seaward from the coast line, it is unlikely that lateral migration of salt water is occurring in the Brunswick area.

It is significant that the piezometric surface has declined less at Brunswick than at Savannah or St. Marys, indicating that the aquifer is more productive at Brunswick than at these other two areas. This difference presumably is due partly to differences in the permeability and thickness of the aquifer (Stringfield, Warren, and Cooper, 1941; Warren, 1944).

If lateral encroachment of sea water were taking place, then wells of comparable depths and in the same immediate vicinity probably would show somewhat similar changes in the quality of the water.

Vertical movement.--The most likely means by which salt-water contamination of fresh-water supplies is taking place in the Brunswick area is by upward movement of connate salt water into the aquifer. Water rises through the limestone of and underlying the aquifer because of a reduction in head caused by pumping. Upward leakage of water may occur in poorly constructed wells that penetrate the upper part of the mineralized zone. Artesian water having a chloride content of 69 ppm and a hardness of 312 ppm was found as early as 1939 in a well drilled in that year to a depth of 1,063 feet at the Hercules Powder Co. plant. In 1942 a Brunswick city well (200) 1,057 feet deep had a chloride content of 152 ppm, hardness of 219 ppm, and a dissolved-solids content of 1,110 ppm, before the bottom 57 feet of the well was cemented. At the same time, analyses of samples from shallower wells in the area did not show the concentrations of these constituents to be nearly so high.

It appears, therefore, that water of a chloride content above the average for the area was present in the limestone at depths greater than 1,050 feet prior to 1939. In 1950 and 1958 water of the highest chloride content was found in the two deepest wells in the Brunswick area, indicating a more mineralized water at the greater depths.

It is believed, therefore, that mineralized connate water occurs at a depth of 1,050 feet and greater in the vicinity of city well 200 and the Hercules plant. On the other hand, the Brunswick Pulp & Paper Co. wells, which range in depth from 900 to 1,000 feet, and Solvay Process Division wells, which range in depth from 983 to 1,026 feet, have not shown any marked changes in chloride content of the water for the period of record (1943-58). The lack of contamination of the water at the Brunswick Co. well field where pumpage and reduction in head are greatest probably is due to the fact that salt water occurs at considerably greater depths in this area than at the Hercules plant. Thus, the occurrence of rather mineralized water at different depths throughout the area would account for the great differences in the quality of water obtained at the various plants.

In 1942 the Brunswick city well at the foot of F Street, originally drilled to a depth of 1,057 feet, was cemented off at 1,000 feet and the water contained significantly less chloride at the shallower depth. However, by 1954 the chloride content of the water had increased nearly 300 percent from a low of 81 ppm recorded in 1943. In 1958 water samples collected at different depths in the well showed a progressive increase in chloride with increasing depth. The well was cemented off again at 957 feet and subsequent analyses indicated a water of better quality at the shallower depth. The chloride content of the water decreased about 78 percent, the dissolved-solids content decreased about 62 percent, and the hardness decreased about 63 percent. (See figs. 3 and 4.)

Analyses of samples from the city well indicate that hard water having a high dissolved-solids content was entering the well at a depth below 957 feet. A lowering of the piezometric surface should cause a rise of salt water. As pumping continues to increase in the Brunswick area, the cone of depression will continue to expand and grow deeper, and the artesian head will decrease in all directions from the center of the cone. A reduction in the piezometric surface will disturb the balance between the fresh water and salt water and a new position of equilibrium will be established, thereby increasing the hazard of salt-water contamination.

In 1958 the piezometric surface was below sea level in the heavily pumped well fields, but because of the high fresh-water head between the areas of withdrawal and the coast, salt-water encroachment would not occur even though the water levels in the pumped areas were below sea level. It appears, therefore, that other factors influence the position of the salt water-fresh water contact in the principal artesian aquifer. In all probability, the high productivity of the limestone aquifer, its thickness, and the probable changes in permeability of its different zones all affect the rate of movement of salt water in the Brunswick area.

Contamination through leaky casings.--Salt-water encroachment may result from improperly cased holes or leaky well casings through which salt water under higher heads may leak into the fresh-water aquifer. However, it is believed that the contamination of the fresh-water aquifer through defective wells is a minor contributing factor in the Brunswick area.

The content of chloride in the artesian water in the Brunswick area is not dependent entirely on the depth of the wells, although the deepest wells have the highest chloride content. During the period 1950-58 the water from several shallow wells at the Hercules plant also showed significant increases in chloride. On the other hand, samples from several deep wells showed decreases in chloride content. The factors which will influence encroachment of salt water in the Brunswick area are (1) amount the artesian head is lowered by pumping, (2) position or depth of the fresh water-salt water interface, and (3) relative permeability of different zones in the limestone.

Summary and Conclusions

Salt-water contamination of fresh-water supplies in the Brunswick area is due to the upward movement of connate salt water from the deeper limestone as a result of the reduced head caused by pumping. A minor amount of contamination may result from upward movement of salt water through defective wells that penetrate the upper part of the mineralized zone. Present data indicate that salty water is present in the deeper limestone underlying the area; water from the deepest wells has the highest chloride content. Moreover, during the past few years water from several shallow wells had increased significantly in chloride content.

Since 1943 the artesian head has declined about 30 feet near the area of heavy pumping. In the center of the cone of depression water levels probably are as much as 20 to 40 feet below mean sea level. Since 1943 the average daily ground-water withdrawals in the area has increased from 37 to 90 mgd.

Salt-water contamination in the Brunswick area will depend in part upon the rate of ground-water withdrawals and the corresponding decline of artesian pressures throughout the area. A continued decline in the artesian head will disturb the balance between the salt water-fresh water interface and a new position of equilibrium will be reached. Any disturbance in the zone of contact between the two waters will increase the hazard of salt-water contamination of fresh-water supplies.

A practical approach to the problem of salt-water contamination should include the following:

1. Dispersal of wells so as to avoid concentrated areas of heavy ground-water withdrawals. This would minimize interference between wells and reduce excessive lowering of the water level in the center of the cone.

2. Reduction of the waste of water from uncapped flowing wells in the county. In 1957 the estimated 6 to 8 mgd of water discharged by these wells was wasted; in the adjacent counties of Camden and McIntosh an estimated 20 to 22 mgd of water was wasted by flowing wells.

An intensive ground-water investigation is now in progress to determine the extent of salt-water contamination of fresh-water supplies in the Brunswick area. Comparatively few hydrologic data are available for the area; moreover, much of the information obtained in earlier years should be brought up to date. A systematic ground-water program should include the drilling of several test holes at strategic locations to delineate more precisely the salt water-fresh water interface and to observe the rate of movement of salt water into the fresh-water aquifer by means of a systematic water-sampling program; the testing of drill cores to determine the range of permeability of the limestone aquifer at different depths; construction of peizometric maps to show the changes in artesian pressures throughout the area; and a complete inventory of ground-water withdrawals in the county.

References

Brown, J. S., 1925, A study of coastal ground water with special reference to Connecticut: U.S. Geol. Survey Water-Supply Paper 537, 101 p.

Collins, W. D., Lamar, W. L., and Lohr, E. W., 1934, The industrial utility of public water supplies in the United States, 1932: U.S. Geol. Survey Water-Supply Paper 658, 135 p.

Cooper, H. H., Jr., and Warren, M. A., 1945, The perennial yield of artesian water in the coastal area of Georgia and northeastern Florida: Econ. Geology, v. 40, no. 4, p. 263-282.

Hubbert, M. K., 1940, The theory of ground-water motion: Jour. Geology, v. 48, no. 8, pt. 1.

Lamar, W. L., 1942, Industrial quality of public water supplies in Georgia, 1940: U.S. Geol. Survey Water-Supply Paper 912, 83 p.

Moore, E. W., 1940, Progress report of the committee on quality of water tolerance of water for industrial use: New England Water Works Assoc. Jour., v. 54, p. 271.

Muskat, Morris, 1937, The flow of homogeneous fluid through porous media: New York, McGraw-Hill.

Stephenson, L. W., and Veatch, J. O., 1915, Underground waters of the Coastal Plain of Georgia: U.S. Geol. Survey Water-Supply Paper 341, 539 p.

Stewart, J. W., and Counts, H. B., 1958, Decline of artesian pressures in the Coastal Plain of Georgia, northeastern Florida, and southeastern South Carolina: Georgia Geol. Survey Mineral Newsletter, v. 11, no. 1, p. 25-31.

Stringfield, V. T., Warren, M. A., and Cooper, H. H., Jr., 1941, Artesian water in the coastal area of Georgia and northeastern Florida: Econ. Geology, v. 36, no. 7, p. 698-711.

Thomson, M. T., Herrick, S. M., and Brown, Eugene, 1956, The availability and use of water in Georgia: Georgia Geol. Survey Bull. 65, 329 p.

U.S. Public Health Service, 1946, Drinking water standards: v. 61, no. 11, p. 371-384.

Warren, M. A., 1944, Artesian water in southeastern Georgia with special reference to the coastal area: Georgia Geol. Survey Bull. 49, 140 p.

Wentworth, C. K., 1942, Storage consequences of the Ghyben-Herzberg theory: Am. Geophys. Union Trans., pt. 2, p. 683-693.