SALT-WATER ENCROACHMENT

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SOURCE OF SALT-WATER CONTAMINATION

GENERAL STATEMENT

A critical study of all available information obtained prior to July 1939 and the analysis of all pertinent data collected during the present investigation show without doubt that sea water in the Atlantic Ocean and in Biscayne Bay is the source of salt-water contamination of ground and surface waters in the Miami area. Two other possible sources that were studied and rejected are: the highly mineralized artesian water in the Floridan aquifer, which lies about 600 to 1,000 ft below the surface, and the highly mineralized water found at shallow depths in some areas of the Everglades.

Without exception, the deep artesian wells drilled in the Miami area yield water that contains about 1,000 to 3,000 ppm chloride. This water is unfit for most uses; therefore, most artesian wells in and near Miami have been abandoned. The rocks of the Floridan aquiclude that overlie the Floridan aquifer and confine its water under pressure, are impermeable; the only way that the mineralized artesian water could contaminate the Biscayne aquifer is through leaky well casings. Some leakage is known to occur, but most of the areas affected are within 1 mile of the coast, where the ground water is already contaminated by sea water. Furthermore, the concentration of dissolved mineral matter in water-table wells close to Biscayne Bay is several times greater than the concentration in the artesian water.

The concentration of dissolved solids in shallow ground water in the Everglades is generally higher in the vicinity of Lake Okeechobee than farther south toward Miami. Except in the encroachment zone along the coast, the large body of shallow ground water in the Miami area is not contaminated. Former invasions of the sea left saline residues in the water-bearing formations underlying large areas in the Everglades. These residues have been only partly flushed out, whereas in and near Miami they have been completely flushed out (Parker, 1945b, p. 119–143). As shown in the section on Quantitative studies in the Miami area, the Biscayne aquifer is replenished almost entirely by local rainfall. It is obvious, therefore, that at present the only source of salt-water contamination in and near Miami is the sea water from the Atlantic Ocean and Biscayne Bay.

ATLANTIC OCEAN

CHEMICAL COMPOSITION OF SEA WATER NEAR MIAMI

The chemical composition of the ocean water has been determined by analyses of samples collected from many places over the world. The concentration of dissolved mineral matter has been found to vary considerably from place to place and from time to time at a given point. However, the ratios between the more abundant constituents are essentially constant (Sverdrup, Johnson, and Fleming, 1942, p. 165). This fact has an important bearing on the study of ground water contaminated with sea water, in which the chloride content of the samples is taken as an index of the amount of contamination.

The analyses commonly taken to represent the average composition of sea water are those made by Dittmar on 77 samples collected from many parts of the world by the Challenger Expedition in 1884. The average of these analyses is given in table 65, together with an analysis of water collected on May 23, 1941, from the Atlantic Ocean about 50 ft offshore at 41st Street, Miami Beach. The concentrations of the different constituents in the sample collected off Miami Beach in 1941 are slightly greater than those reported by Dittmar. However, the percentage of chloride in the two samples is essentially the same.

Table 65.—*Analyses of sea water*

	Average of 77 sample[1]		Miami Beach sample[2]	
	Parts per million	Ratio to Cl (percent)[3]	Parts per million	Ratio to Cl (percent)[3]
Calcium (Ca)	419	2.17	423	2.14
Magnesium (Mg)	1,304	6.73	1,324	6.70
Sodium (Na)	10,710	55.35	10,970	55.49
Potassium (K)	390	2.02	429	2.17
Bicarbonate (HCO_3)	146	.75	147	.74
Sulfate (SO_4)	2,690	13.90	2,750	13.91
Chloride (Cl)	19,350		19,770	
Bromide (Br)	70	.36	49	.21
Total dissolved solids	35,000		35,800	

[1] Analyses by Dittmar from samples collected by Challenger Expedition, 1884.

[2] Atlantic Ocean at Miami Beach, May 23, 1941.

[3] Content of indicated ion divided by chloride content and multiplied by 100.

In the Miami Beach sample the computed chloride concentration was 19,800 ppm, which is the value used in this report as an index of the degree of contamination of ground water with sea water. The chloride equivalent to the bromide in that sample was subtracted from the weight of silver halides before computing the chloride concentration. In routine chloride determinations, however, total halides were titrated with silver nitrate solution and reported as chloride.

Variations in the chloride concentration of sea water in the vicinity of Miami were studied by Dole and Chambers (1918, p. 299–315) in 1914–15. Daily samples of sea water were collected at Fowey Rocks Light, 6½ miles off Cape Florida and about 15 miles southeast of Miami, within 1 or 2 miles of the western edge of the Gulf Stream. It was observed that periods of heavy rainfall were frequently followed by decreases in chloride concentration. Chloride concentrations ranged from about 19,300 to 20,200 ppm and averaged 19,930 ppm during the period of record.

The average chloride content of sea water in the Gulf of Mexico, as determined by Dole (1914, p. 69–78) on 54 samples collected twice daily between May 20 and June 16, 1913, from Southwest Channel in the Tortugas, was 19,934 ppm. Dole and Chambers concluded, therefore, that the normal chloride concentration of the Gulf Stream off Fowey Rocks is about the same as that of the Gulf of Mexico but that it decreases at times as a result of heavy rainfall and subsequent discharge of surface streams in the Miami area and of ground-water reservoirs along the coast.

Determinations made on several samples collected from the Atlantic Ocean during the present investigation show a range in chloride concentration from 19,180 to 20,420 ppm. It appears that the chloride concentration of 19,800 ppm in the sample collected off Miami Beach on May 23, 1941, represents approximately the average chloride concentration in sea water in the vicinity of Miami.

SPECIFIC GRAVITY OF SEA WATER

In order that the relationship between milligrams per liter and parts per million may be determined for water samples contaminated with different amounts of sea water, and also in order that corrections may be applied to water-level measurements in wells contaminated with sea water, it is necessary to know the specific gravity of sea water and that of sea water diluted with different amounts of fresh ground water. A full discussion of the determination of these specific gravities is given on pages 598-600. It was found that the average specific gravity of sea water in the Miami area, referred to distilled water at 25°/25° C., is 1.02680.

The effect of specific gravity on the factors relating milligrams per liter and parts per million was determined in the following way. Values of chloride were determined gravimetrically on several artificial dilutions of sea water with fresh ground water, and these were plotted with milligrams per liter as one coordinate and parts per million as the other. It was found that for dilutions in which the chloride concentration was below 5,000 milligrams per liter, adjustments to the above factors were small enough to be neglected. Above 5,000 milligrams per liter the adjustment increased with increasing concentration. Tables were prepared from which adjusted factors could at once be applied to chloride concentrations in milligrams per liter to obtain concentrations in parts per million. Unless otherwise specified, all concentrations given in this report are expressed in parts per million.

BISCAYNE BAY

CHLORIDE CONCENTRATIONS

Chloride concentrations at different places in Biscayne Bay often differ considerably from those in the ocean nearby and also differ from time to time at a given place. Differences in concentration were observed by Dole and Chambers (1918, p. 313, 315). They state that these differences probably were due to the diluting effect of fresh water from the Miami River and other smaller streams, and to the concentrating effect of evaporation in the shallow expanses of the Bay where circulation is sluggish. The present investigation confirms these conclusions.

During the present investigation, surface and bottom samples were collected in May 1940 from 22 stations in Biscayne Bay (the locations are shown in fig. 163). At some stations, samples were collected at middepth. Chloride concentrations determined on these samples are given in table 66.

The data in the table show that the chloride concentration in most of the samples was greater than that normally found in sea water. The higher values are the result of concentration of the water in Biscayne Bay by evaporation. Samples from Station 5 contained considerably less chloride than ocean water because of the diluting effect of fresh water discharged from the Miami River. Dilution was also observed in samples from Stations 12 and 13, near the outlet of the Coral Gables Canal, and from Station 15, near the outlet of Snapper Creek Canal.

Excluding the samples collected from Stations 5, 12, 13, and 15, the chloride concentrations in surface and bottom samples ranged from 19,080 to 21,170 ppm, and they averaged 20,270 ppm. Thus, the average chloride concentration in Biscayne Bay was 340 ppm greater than the average concentration of the Atlantic

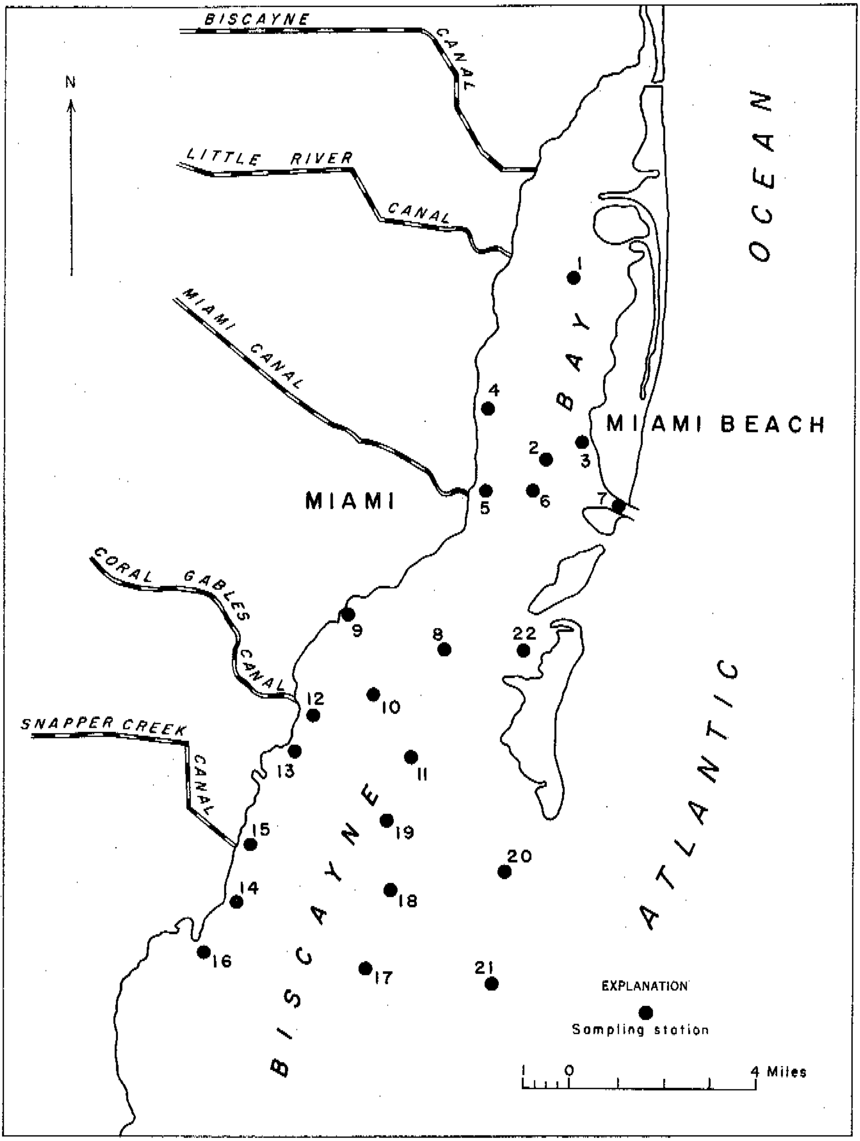

Figure 163. —Location of sampling stations in Biscayne Bay.

Ocean at Fowey Rocks in 1914–15 (Dole and Chambers, 1918, p. 299–315), and 500 ppm greater than the concentration determined in the sample collected from the ocean at 41st Street in Miami Beach in 1941.

Table 66.—*Chloride concentrations at sampling stations in Biscayne Bay, May 1940*

Station No. (see fig. 163)	Date	Time	Sampling point	Depth (feet)	Chloride (ppm)
1	May 7	11:07 a. m.	Surface	1	19,230
			Bottom	4	19,080
2	do	10:13 a. m.	Surface	1	19,890
			Middle	4.5	19,850
			Bottom	9	19,890
3	do	9:50 a. m.	Surface	1	20,040
			Middle	5	20,180
			Bottom	10	20,180
4	do	10:25 a. m.	Surface	1	19,560
			Middle	7.5	19,280
			Bottom	15	19,560
5	do	11:28 a. m.	Surface	1	11,930
			Bottom	5	15,920
6	May 17	8:55 a. m.	Surface	1	19,750
			Middle	4	20,800
			Bottom	8	20,320
7	May 7	10:25 a. m.	Surface	1	20,230
			Middle	15	20,040
			Bottom	30	20,080
8	May 17	9:30 a. m.	Surface	1	20,460
			Middle	5.5	20,700
			Bottom	11	20,610
9	May 7	12:21 p. m.	Surface	1	19,130
			Bottom	3	19,180
10	do	12:34 p. m.	Surface	1	19,320
			Bottom	4.5	19,280
11	May 17	10:48 a. m.	Surface	1	20,510
			Middle	5	20,420
			Bottom	10	20,700
12	May 7	1:00 p. m.	Surface	1	17,360
			Bottom	5	17,270
13	do	2:43 p. m.	Surface	1	18,700
			Bottom	3	18,610
14	May 17	11:50 a. m.	Surface	1	20,420
			Bottom	2.5	20,460
15	do	12:40 p. m.	Surface	1	15,630
			Bottom	2.5	19,700
16	do	12:10 p. m.	Surface	1	20,980
			Bottom	4	20,980
17	do	1:35 p. m.	Surface	1	20,890
			Middle	5.5	20,840
			Bottom	11	20,940
18	do	1:15 p. m.	Surface	1	21,080
			Middle	5.5	21,030
			Bottom	11	21,170
19	do	11:10 a. m.	Surface	1	20,980
			Middle	5	20,980
			Bottom	10	20,890
20	do	2:20 p. m.	Surface	1	20,700
			Middle	7.5	20,420
			Bottom	15	20,610

Table 66.—*Chloride concentrations at sampling stations in Biscayne Bay, May 1940*—Con.

Station No. (see fig. 163)	Date	Time	Sampling point	Depth (feet)	Chloride (ppm)
21	do	2:12 p. m.	Surface	1	20,800
			Middle	4	20,750
			Bottom	8	20,650
22	do	10:20 a. m.	Surface	1	20,610
			Middle	6	20,510
			Bottom	12	20,610

CHEMICAL COMPOSITION OF SALT-CONTAMINATED WATERS

SURFACE WATERS

Several samples of salt-contaminated water were collected from the Miami Canal. Analysis of the water showed that its composition was essentially the same as an artificial mixture of uncontaminated canal water and sea water.

GROUND WATERS

Analyses of samples of ground water collected from wells in and near Miami show that ground water that has been contaminated with sea water differs somewhat in composition from an artificial mixture of the two.

Samples of uncontaminated ground water from the Miami area were found to be relatively uniform in composition. (See the section on Quality of ground and surface waters, p. 727.) An average of 24 analyses of samples from typical wells is assumed to represent the average composition of uncontaminated ground water in the area. Using the chloride concentration as an index of the degree of contamination in other samples containing more than the average amount of chloride, the theoretical concentrations of the other constituents were computed. Typical analyses of uncontaminated and contaminated ground water are shown in figure 164.

The actual amount of calcium in each sample was more than the computed amount. In order to study the differences between actual and computed concentrations, all data for the chemical constituents in parts per million were converted to equivalents per million. (An equivalent per million means one unit chemical equivalent weight of a chemical constituent per million unit weights of solution. Concentration in equivalents per million is calculated by dividing concentration in parts per million by the chemical combining weight of the chemical constituent.)

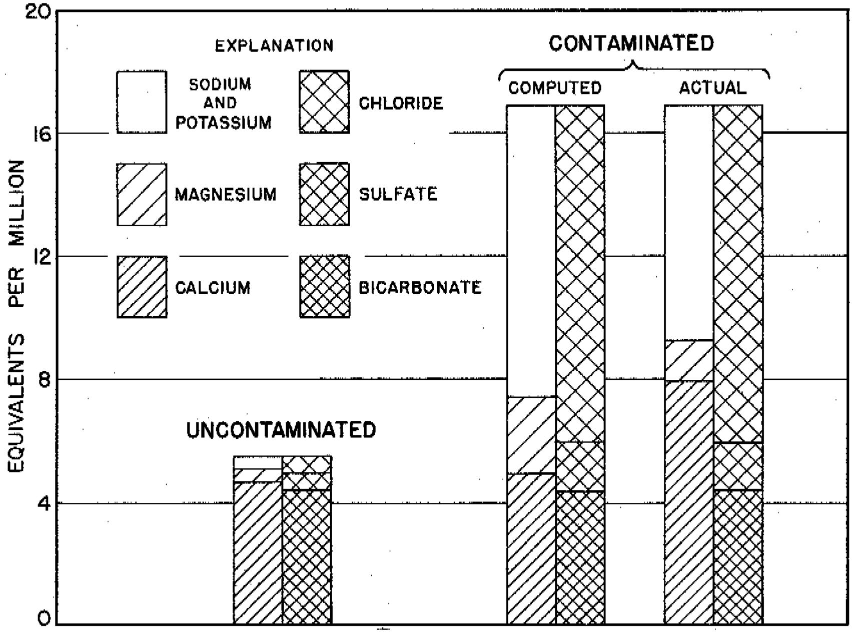

Figure 164. —Analyses of uncontaminated and contaminated ground water.

Differences in equivalents between actual and computed concentrations of bicarbonate were usually small and showed no tendency to be consistently positive or negative. Differences between actual and computed concentrations of sulfate were usually small, but somewhat larger than differences in bicarbonate. About half of the sulfate differences were positive and about half were negative.

The more prominent differences in concentrations occurred among the cations (calcium, magnesium, and sodium). Deviation of actual concentrations from computed concentrations of calcium were plotted against the algebraic sum of deviation of magnesium and sodium as shown in figure 165. In general, increases in calcium concentrations were compensated by losses in magnesium and sodium concentrations. This would suggest that for each equivalent per million of calcium gained, one equivalent of magnesium or sodium, or a mixture of the two, was lost.

A suggested explanation for the differences between actual and computed concentrations of cations in contaminated waters in the Miami area is based on the phenomenon of cation exchange (commonly referred to as base exchange). Many investigations of cation exchange have been made, primarily in the field of soil chemistry (Kelley and Brown, 1924; Chapman and Kelley, 1930, p. 391–406). Workers in soil chemistry have long known that soil colloids, usually the aluminum silicate clay components, possess the property of adsorbing one or more cations from water solutions and of releasing them again in exchange for other cations under suitable conditions. The conditions which determine the order and

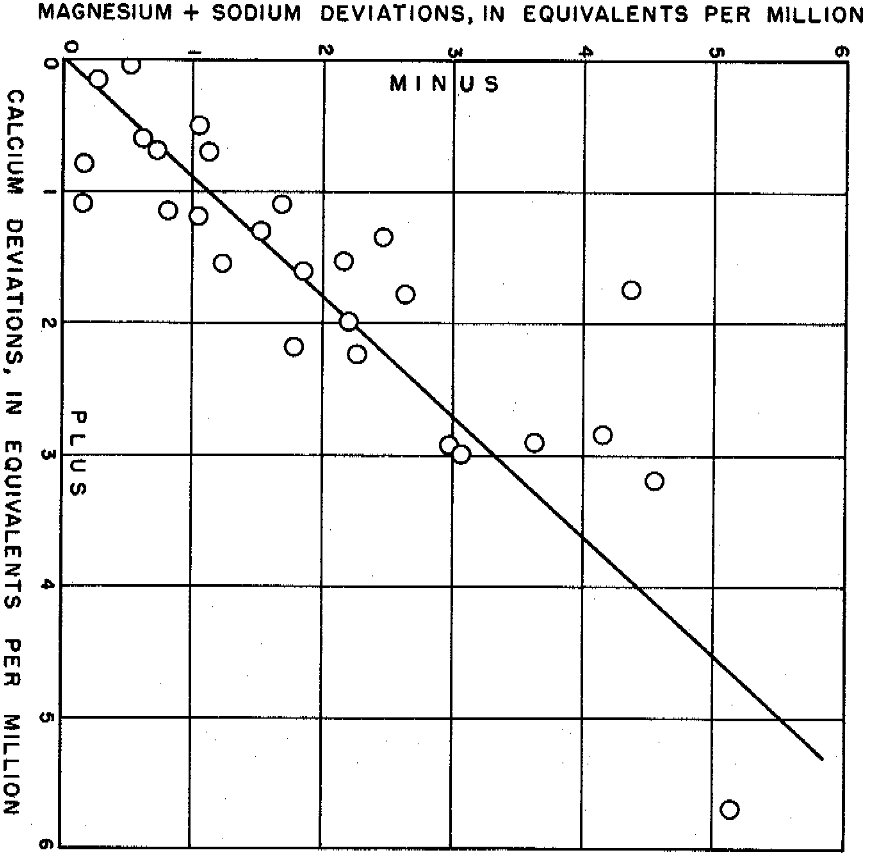

Figure 165. —Deviation of cation concentrations in contaminated ground water from computed cation concentrations.

mechanism of cation exchange have also been investigated (Jenny, 1932, p. 2217–2258; Walton, 1942, p. 306–337; Bray, 1942, p. 954–963).

It has been found that the cation-exchange capacity of many soils is also associated with the content of organic matter. McGeorge (1930, p. 181–312) concluded that the base-exchange capacity of highly organic soils is approximately a linear function of the percentage of carbon in the soil and that the exchange takes place in chemically equivalent proportions. Examination of well cuttings obtained during the drilling of test wells shows no evidence of aluminum silicate clays in the highly permeable Biscayne aquifer in the Miami area. It would appear, therefore, that cation exchange takes place largely through the medium of organic matter, which colors practically all the ground water in the area.

For additional discussion of cation exchange refer to the section on Quality of ground and surface waters, pages 821—822.

HISTORICAL REVIEW OF ENCROACHMENT IN THE MIAMI AREA

In the section on Ground water (Occurrence) there is a discussion of the development of water supplies, from the first supply taken directly from a large spring beside the Miami River near NW. 27th Avenue and 20th Street to the present (1946) well field in Hialeah and Miami Springs. These discussions indicate the principal conditions for the successive abandonment of supplies for larger ones more remote from salt-water encroachment. In the following discussion these conditions are reviewed, with particular attention given to the manner in which they developed.

EARLY CONDITIONS

During the latter part of the 19th century and the early part of the 20th century, geologists and naturalists began scientific explorations of the Florida peninsula. Prominent among them were Alexander Agassiz, Leon S. Griswold, George C. Matson, and Samuel Sanford, all of whom visited Miami and recorded their observations. Notes on early conditions also have been written by others, including Daniel G. Brinton, A. W. Dimock, Hugh L. Willoughby, and Fred C. Elliott. A thorough review and careful interpretation of some of their notes have yielded valuable information on the relation between fresh water and salt water prior to the construction of drainage canals in the area.

Shaler (1890, p. 144) made extensive geologic investigations along the southeastern coast of Florida in 1887 or 1888. In describing conditions in the Coconut Grove area, he observes "* * * the waters of the Everglades at a distance of only 3 miles from the shore in their time of lowest level lie 16 feet high above high tide. [Shaler does not indicate the source of his altitude figure. Ecologic, geologic, and topographic studies made during the course of this investigation indicate that Shaler's "16 feet above high tide" is about equivalent to 10 feet above mean sea level. Thus, an error of several feet in altitude is involved in Shaler's figure, which was probably based on an estimate.] In the rainy season they often rise to such an altitude that they pour over the reef wherever it is less than 20 feet in altitude. [The term "reef" as used here refers to the Atlantic Coastal Ridge.] A sufficiently wide canal, having a depth of 20 feet and a length of not over 4 miles, would drain the waters of the Everglades into Biscayne Bay. The rivers which flow over this part of the reef come down to the sea level over a series of rapids formed upon the harder layers of the reef, and thus the full escape of the Everglade waters is prevented. In the region more to the north, the entanglement of the vegetation about the headwaters of the streams, even where they have no rapids in their beds, likewise hinders the escape of the marsh waters."

Shaler (1890, p. 146) further describes the "reef" as so thickly covered with sinkholes "that nearly all the rainwater appears to find its way by underground channels to the sea, where we can note its emergence in great springs." In describing the western side of the "reef," Shaler states, "All portions * * * which were so situated as to be exposed to the waves of the lake, which in the rainy season covers this district, were very deeply corroded. * * * In the rainy season these waters rise to the height of from 5 to 8 feet above their level during the dry season, when I observed the district * * *. After the rainy season passes, the water is drained away by the numerous exits to the sea."

In a note appended to Shaler's paper (1890, p. 158), Alexander Agassiz makes the following comment: "To the damming up of the waters in the Everglades, and to the sudden outbursts of gigantic masses of water charged with organic matter and lime, we may trace the immense destruction of fishes which so frequently occurs on the shores of the Florida keys and the waters surrounding them." Griswold (1896, p. 53) mentions "great springs of constant flow" emerging "in large numbers along the shore." Fuller (1904, p. 266) in 1903 observed one of these springs in Coconut Grove flowing at the rate of 100 gpm from the base of a limestone bluff. He indicates that the water was used for drinking and was reported to have supplied the American fleet off Havana in 1898. The water was described as being clear and hard, and as containing sulfur.

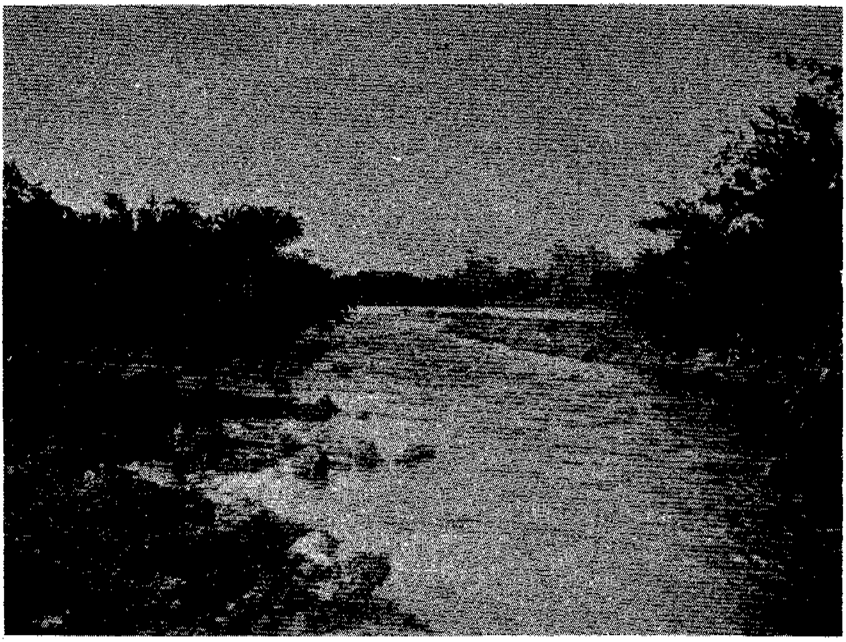

Figure 166. --Rapids of the Miami River before dredging of Miami Canal.

Likewise, (Matson and Sanford, 1913, p. 179, 256, 289) mentions the existence in 1908 of "springs of some size * * * flowing from the low ridges of Miami oolite near Biscayne Bay." Apparently, a few of the springs were used for domestic supplies and by fishermen.

Griswold (1896, p. 53) mentions the presence of a distinct "fall line" in the Miami River just west of the pineland. It has also been reported by Lilburn R. Railey, John W. Watson, and E. J. Sewell (personal communications) as having been near, and slightly west of, the present NW. 27th Avenue Bridge. A rather vivid description of the rapids and flow of the river at this "fall line" (fig. 166) is given by Willoughby (1898, p. 39). The discharge of this large volume of fresh water into the Miami River below the falls indicates that comparatively fresh water occurred in the channel within 2 or 3 miles of the salt water of Biscayne Bay.

Willoughby (1898, p. 65) says: "All along this shore [Coconut Grove] there are [Dec. 1896] places where the fresh water comes up through the rocks under the salt water with quite a head. It no doubt comes from the Everglades by subterranean passages."

John Sewell (1933) describes ground-water conditions in early Miami [see the section on Ground water (Occurrence)] and notes that hard limestone water was then obtainable in wells 50 to 60 feet deep at the mouth of the Miami River (fig. 167) and at the old Miami Hotel (now South Miami Avenue between SW. 1st and SW. 2nd Streets). He also describes the flowing fresh-water wells that were drilled 50 to 60 feet deep on the site of the present Miami Country Club (near NW. 11th Street and 10th Avenue). At first, these wells produced hard fresh limestone water without pumping, but gradually they ceased flowing and had to be pumped. Eventually they became salty and were abandoned.

Munroe (1930, p. 118, 218) says of early ground-water conditions, "The abundant spring water off the shore, while organically pure, and beautifully clear and tasteless, was somewhat hard * * *". He photographed boatmen obtaining fresh water from beneath salt water in Biscayne Bay.

The foregoing quotations, illustrations, and references give valuable background material in regard to early ground-water conditions in the Miami area. Shaler's observations are of particular interest because they indicate that a tremendous amount of water was formerly stored in the Everglades to within nearly 3 miles of Biscayne Bay. It is not difficult, therefore, to account for the presence of large fresh-water springs discharging into Biscayne Bay, along the base of the oolite ridge and through the floor of the bay itself. With such relatively high heads of fresh water continuously available in, and west of, the oolite ridge, it is highly improbable that the contact of salt water and fresh water

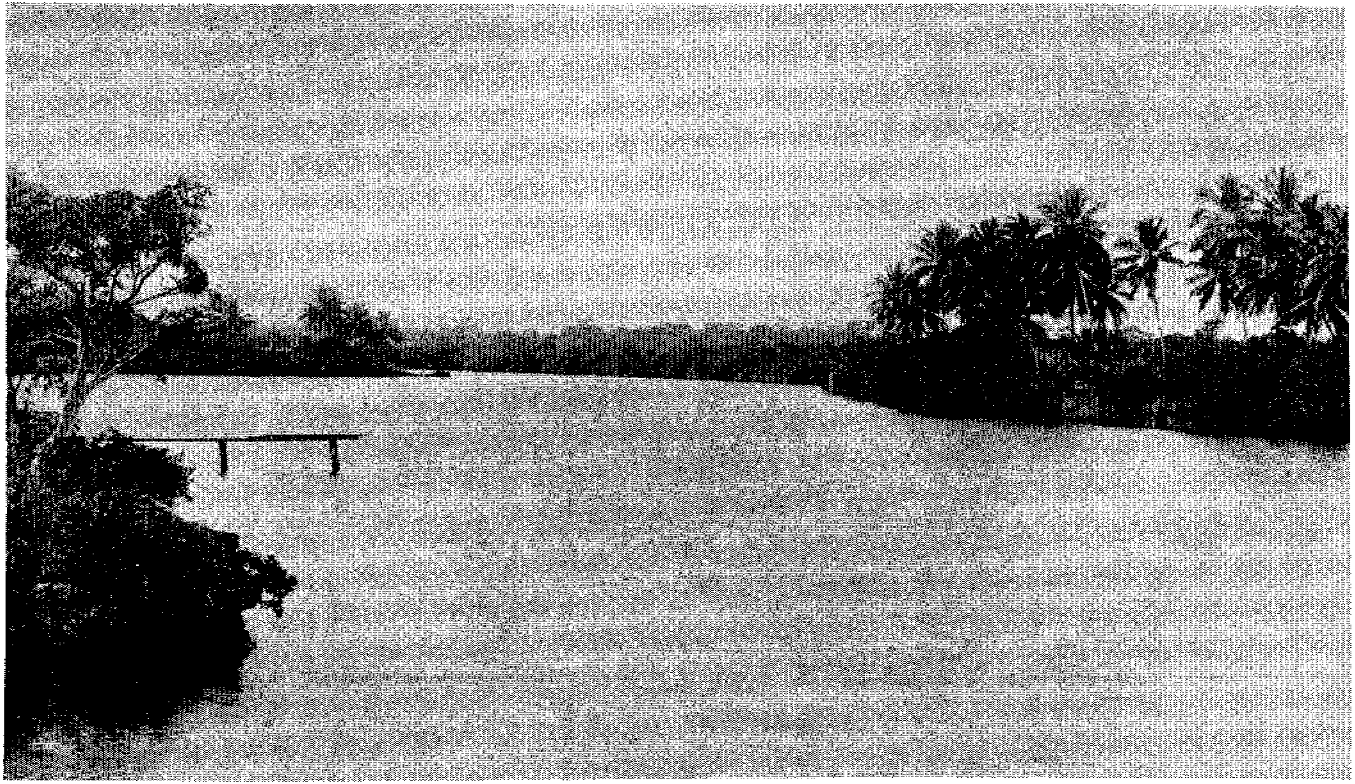

Figure 167. —Looking upstream from the mouth of the Miami River before dredging of Miami Canal.

was very far inland. Possibly at depths of 200 feet or more below mean sea level the contact might have been farther inland. At shallower depths, however, it appears that no encroachment could possibly have taken place because of the overwhelming weight and flow of fresh water from the land.

CHANGES BETWEEN 1907 AND 1939

In 1907 the first serious modifications of the natural equilibrium between fresh water and salt water in southern Florida were undertaken by man. Dredging operations, a part of a State-wide drainage program, were started at that time in the New River basin at Fort Lauderdale. However, not until 1909 was dredging begun in the Miami River. By 1910 a channel 10 feet deep had been opened through the "fall line," or rapids, at the head of the Miami River, and was extended about 4¼ miles into the Everglades. Water that was formerly ponded in the Everglades behind the coastal ridge and stored within the rocks of the coastal ridge itself was now free to waste through the canals into the ocean; and water at sea level, fluctuating with the tides, extended inland as far as the head of the cuts, or to the base of the temporary earth dams placed to form pools deep enough for the dredges to operate.

W. S. Jennings (1909, p. 122), in a letter to the trustees of the Internal Improvement Fund of the State of Florida, dated November 19, 1907, tells of his observations during a visit that he and Governor N. B. Broward made to the site of the dredging operations: "The canals reduce the water level from the surface to approximately 6 feet below the surface of the ground as shown by the water in the canal, and the land for a mile on either side of the canal is entirely reclaimed, and is practically ready for preparation for cultivation, and the general influence of the drainage reaches to a much greater distance than one mile. * * * Generally speaking, the work is a great success * * *. The influence on the river has never been and is not perceptible. The reduction of the water level to 6 feet below the surface of the ground is all and more than could have reasonably been expected * * * the superintendent finds it necessary to keep a sufficient quantity of water in the canal to float the dredge, while in front of the dredge is the water pouring over the front of the canal and falling 6 feet over a perpendicular dam to the water level of the canal and thus going on to the ocean.

"The result is that the reclamation of the land is fully demonstrated. We walked for a distance of ½ mile or more along an Indian trail or canoe route through the saw-grass, where 20 days ago the Indians traveled with their boats and canoes, the water having all been drawn off from this territory by the cutting of the canal, thus lowering the water level."

Nature's original equilibrium between fresh water and salt water, which was based on a high water table, was thus destroyed. As progress was made toward reestablishment of an equilibrium based on a lower water table, the springs along the shores of Biscayne Bay diminished in flow, then disappeared, and swampy areas upstream along the Miami and New Rivers began to dry out.

Clyde P. Ross (1919), of the U. S. Geological Survey, observed that originally the area covered by the Miami well field (the southeast portion of the old Royal Palm Golf Grounds—now the Miami Country Club—near NW. 11th St. and 10th Ave.) was swampy, but that it had drained and dried. Sanford (Matson and Sanford, 1913, p. 291) reported that in 1908 the Miami supply was derived from four flowing wells that ranged in depth from 73 to 95 ft. These wells were located in a swale underlain by a thick layer of relatively impermeable marl. The swale was partly surrounded by higher land, behind which the waters of the Everglades were impounded. These conditions were ideal for the development of local artesian wells, and therefore flowing wells existed in the Spring Gardens (Penniman Springs) area in those early days.

Twelve years after Sanford's investigation, C. P. Ross reported that the original wells had ceased flowing, that pumps had been installed, and that the wells had been plugged at a depth of 40 to 45 ft to avoid taking water from the deeper parts of the aquifer, which had become contaminated by salt water. This salt-water movement was further facilitated by drainage operations that began in August 1917 and continued until June 1923. During that period, the Miami Canal was dredged to an average depth of 12 ft from its junction with the Miami River northwestward to a point a quarter of a mile above (northwest of) its junction with the present South New River Canal (about 32 miles from Biscayne Bay).

In 1928 and 1929, chloride determinations were made on ground water samples collected from a number of drainage wells in the Miami area. The samples were collected at the time of drilling and should, therefore, represent true ground-water conditions. From these data an isochlor map, figure 168, was prepared. (An isochlor is defined as a line on a map connecting points of equal chloride concentration.) Although the data do not give complete areal coverage, they indicate reasons for water from the original Miami Water Company field at Spring Gardens becoming too salty for use. The isochlor representing a concentration of 10,000 ppm, based on samples from wells 70 to 100 ft deep, lies northwest of the well field. Thus the field occupied an area of even higher chloride concentration. Inasmuch as the field originally (1907) delivered fresh water, it is obvious that the boundary between fresh and salt water migrated inland largely as a result of dredging operations in the Miami River and construction of the Miami Canal.

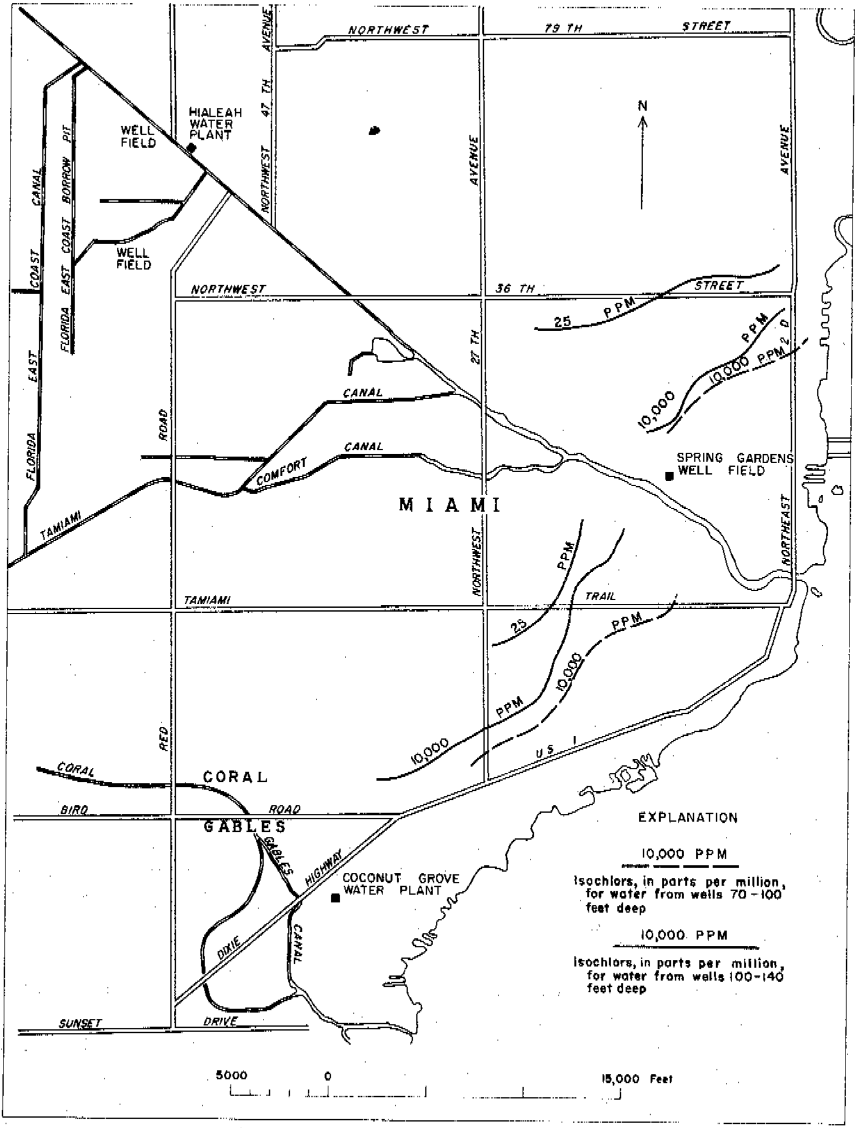

Figure 168. —Map of metropolitan Miami area showing isochlors for 1928-29, based on samples of ground water from drainage wells.

As mentioned previously, earth dams were built in each of the newly dredged canals to give the dredges sufficient water in which to operate. Although they were breached on a few occasions to allow barges and excavating equipment to pass, they were restored each time and remained in place until concrete locks and dams were built in 1912–13. If all these structures had been kept in good condition, they might have prevented many of the damaging results of the breaching of the natural barrier. Operation of the dams and locks has been irregular. Those on the South New River and North New River Canals were most effective and are still in use. The

Miami Canal lock and dam apparently was not effectively used and was finally removed when the Miami River was dredged to a depth of 15 ft in 1931–32. The deepening of the channel almost to the NW. 36th Street bridge did not greatly affect ground-water levels; however, it did expose new areas to salt-water contamination. Likewise, the dredging of several supplementary canals, largely during the period 1926–42, further dissected the Miami area and accelerated the drainage of ground water stored during the rainy periods. Table 67 gives the approximate construction periods for each of 10 canals in the Miami area. (See also fig. 184.)

Table 67.—*Canals in the Miami area and periods of their construction*

Name of canal	Period of construction[1]	Name of canal	Period of construction[1]
Biscayne	1925-26	Miami	1909-32
Comfort	1925-34	Opa Locka	1925-26
Coral Gables	1925-42	Snake Creek	1912-13
F. E. C.	No record	Snapper Creek	1912-13
Little River	1925-27	Tamiami[2]	1919-28

[1] Construction as originally planned. Most canals have been considerably modified during later years.

[2] Five and a half miles completed to 1926; remainder excavated as a borrow ditch for the State Road Department for building of the Tamiami Trail (U. S. Highway 94).

During periods of low water these canals provided 10 avenues along which salt water could move, and from which it could contaminate water-bearing formations.

CONDITIONS SINCE 1939

In 1933, Charles Morgan, who was then Miami City Chemist, called the attention of V. T. Stringfield, of the U. S. Geological Survey, to the increased salt-water encroachment in the Miami Canal and the salting of wells along that canal. However, it was not until the latter part of 1938 and the early part of 1939 that a severe drought in southeastern Florida forcibly demonstrated how seriously the original equilibrium between salt water and fresh water had been modified. At that time, the ocean level during high tide was above the fresh-water stage in the canals. This was caused by a combination of factors, including overdrainage of the coastal ridge, drainage of the Everglades, and rainfall deficiencies.

As the 1938–39 drought progressed, water that had formerly been stored behind the rock barrier of the coastal ridge wasted into the ocean. Flow reversals in the tidal canals occurred for periods of 2 to 5 hours during each tidal cycle, and salt water migrated farther and farther inland. As the length of the reversal periods increased, the salt water migrated more rapidly, until eventually it reached more than 10 miles inland in some canals.

The damaging effects of this inland salt-water movement in the drainage canals were noted when salty water appeared in certain wells in the Miami well field, which is near the Miami Canal, 7.5 miles inland from Biscayne Bay. Although public concern centered principally around contamination in this field, numerous private supply wells located near the salt water in the tidal canals of Dade and Broward Counties also became contaminated. The damage was widespread and costly, and even in temporarily salted areas it persisted long after seasonal rains reestablished fresh-water stages in excess of the maximum salt-water stages.

Figure 186 shows seasonal variations in the extent of salt-water contamination in the Miami Canal for the period January 1940 through December 1946. On the average, salt water extended up the Miami Canal approximately 4 miles. This is about 2 miles farther than in 1909, before drainage work began.

The general extent of salt-water contamination of the aquifer is shown in figure 169. The map for 1904 indicates the estimated and reported conditions in the area prior to any drainage work. Salty water probably extended only about 1½ or 2 miles up the Miami River, and fresh-water springs flowed at elevations of as much as 5 ft above mean sea level on the seaward side of the oolite ridge along the west shore of Biscayne Bay. Ground-water levels were high in the Everglades; probably, at times, they were even higher along the coastal ridge, inasmuch as springs were also reported on the western side of the ridge (Matson and Sanford, 1913, p. 289). The stippled areas in the figure represent the estimated zone in which wells about 80 ft deep would tap ground water having chloride concentrations of approximately 1,000 ppm or more.

The map for 1918 (fig. 169) indicates estimated, reported, and known conditions in the area about 5 years after completion of preliminary dredging of the Miami Canal. On the average, salty water probably extended inland about 3 or 3½ miles up the Miami River. Most of the perennial springs no longer existed on the east side of the coastal ridge, and certain swampy areas east of the ridge had been drained. Ground-water levels of the Everglades and the coastal ridge were lower, and an increase in chloride concentration had occurred in the areas (stippled) exposed, and already subjected, to salt-water contamination.

The map for 1943 (fig. 169) indicates observed average conditions in the Miami area after the canals had been dredged. Note the greatly increased width of the contaminated zone and its long extensions inland along the drainage canals. Note also that these inland extensions follow up every tidal canal. This map plainly shows why the Coconut Grove field, which lies entirely within the stippled area, had to be abandoned.

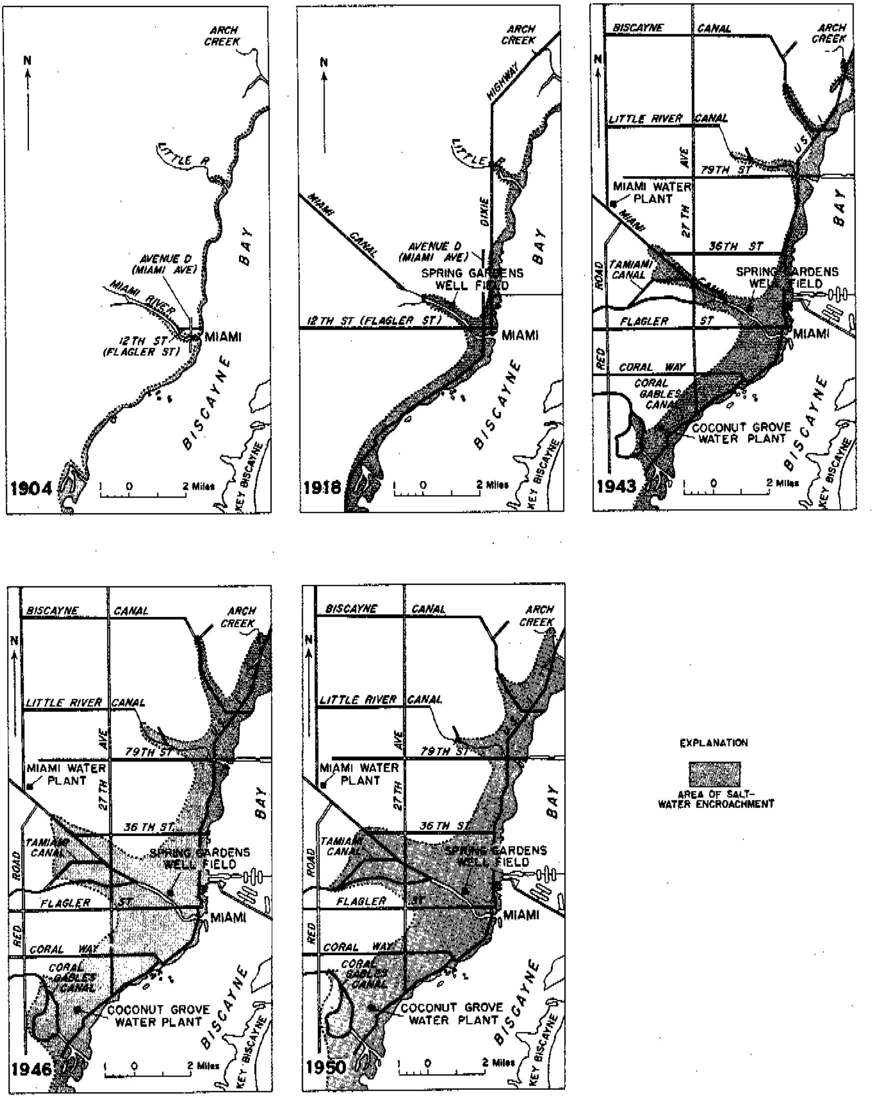

Figure 169.—Maps showing progressive salt-water encroachment in the Miami area, 1904–50.

The map for 1946 shows that the encroachment of sea water upon fresh water was continuing in most canals. (See the section on Encroachment in the tidal canals, p. 618 et seq.) Water levels were exceedingly low during this period, and effective control of them, by regulation of the canals, had not been established. However, a start was made by the Dade County Engineering Department in 1945 following a legislative act granting Dade County control over the water levels in canals and waterways within its boundaries.

The map for 1950 indicates the following developments: (1) increased rainfall and greater recharge to the aquifer as compared to the 1943–46 period; (2) effectiveness of temporary dams in the tidal canals in maintaining somewhat higher heads of fresh water in the canals and aquifer upstream from the dams, and in preventing salt-water movement in the canals for any significant distance above the dams.

The five maps in figure 169 show the general pattern of encroachment into the Biscayne aquifer of the Miami area over a period of 47 years. They show that the major spread of contamination probably occurred between 1943 and 1946. During that time a lengthy drought occurred, and in 1945 water levels fell to record all-time lows. Parker (1945a, p. 539) reckoned, on the basis of studies in the Silver Bluff area, that the rate of encroachment until 1943 had been approximately 235 ft per year. In a 27-month period that overlapped 1943—44, the front of the wedge of encroaching salt water advanced 2,000 ft, which is at the rate of 890 ft per year.

To arrest this threat to the water supply, Dade County and Miami cooperated in the building of temporary steel sheet-piling dams in tidal canals. Navigation and other interests prevented the building of dams in the Miami Canal east of the NW. 36th Street bridge site, and in the Coral Gables and Tamiami Canals east of Red Road. The encroachment pattern shown on the map for 1950, compared with that shown on the map for 1946, clearly describes the results. On the Biscayne, Little River, and Miami Canals actual seaward retreat of the inland ends of the tongues of encroaching salt water has occurred. In each of these areas the temporary dams, although makeshift and leaky, have prevented additional serious intrusion of sea water during the dry seasons and have conserved the fresh-water supply.

By contrast, contamination along the Tamiami and Coral Gables Canals is continuing. The former empties into the Miami Canal downstream from the 36th Street dam site; therefore, it is vulnerable to salt water movement up the unprotected channel. Both the Coral Gables and Tamiami Canals were dammed at Red Road, but low stage and low flow enabled sea water to penetrate as far as the dams. The continued spread of salt water in these two areas is directly attributable to the lack of downstream salt-water control dams.

In the intercanal areas parallel to the shoreline of Biscayne Bay, the salt water has generally maintained its 1946 position. This condition speaks well for the water-control program, which has not only excluded the sea water above the dams but has also resulted in somewhat higher water levels in the affected areas. This, together with the increased rainfall and recharge to the aquifer since 1947, has slowed the 890-feet-per-year encroachment rate to practically zero. Only in the area of Coral Gables Canal has the intercanal contamination zone migrated inland. This movement is probably caused by the increased opportunity for salt water to gain access from the bay through newly dredged canals in that area.

Water-table contour maps [see section on Ground water (Quantitative studies)] indicate that even though drainage has lowered water levels considerably, a low ground-water divide still exists in parts of the coastal ridge in the Greater Miami area. It is not a remnant of the original natural divide. In dry weather the present ground-water mounds owe their origin not to natural recharge, but to artificial recharge through irrigation (lawn-watering) systems and waste water from septic tanks, drainage wells, and similar media. In wet weather there is sufficient natural recharge to create a temporary divide. The artificial recharge is the result of water being taken from the aquifer in the Miami Springs-Hialeah area and delivered by the municipal water system to the downtown area and the coastal strip, where it is returned to the aquifer. Although springs no longer exist on either side of the ridge, it is evident from the water-table contours (flow is at right angles to contours) that for short distances, even during the lowest stages of water levels, ground-water flow occurs in some places from the ridge toward the Everglades.

Further details on the present extent of salt-water contamination in the Miami area are shown on the isochlor map, plate 17.

If similar maps could have been drawn for the period prior to drainage work, the isochlors would have been much nearer to Biscayne Bay than those shown in plate 17. They would have been parallel to the shore except where it bends inland at the Miami River and other tidal waterways emptying into the bay.

ENCROACHMENT IN THE AQUIFER DIRECTLY FROM THE OCEAN

HISTORICAL REVIEW OF LITERATURE ON COASTAL GROUND WATER

Significant studies of coastal ground water were made independently by Badon Ghyben and A. Herzberg shortly before 1900. The results of their investigations are reviewed by Brown (1925, p. 17-19), who points out that their work "* * * appears to apply particularly to small islands and narrow land masses that are made up of freely pervious material, especially sand. It can not be applied to large land bodies or to continents, for it implies that sea water should be found in every locality where the water table is below sea level. There are well-known interior land areas which lie many feet below sea level but in which the ground is entirely free from sea water. The application of the theory is also greatly modified by the kind of rocks and their structure. The importance of Herzberg's theory, however, is not to be ignored and has been most convincingly demonstrated by Pennink (Pennink, J. M. K., De 'prise d'eau' der Amsterdamsche duin waterleiding: K. Inst. Ing. Tijdschr., 1903–4, p. 183–238, The Hague, 1904) on the Coast of Holland."

Pennink's work clearly demonstrates that salt water underlies the land at a depth of 100 to 200 meters below sea level over a belt several miles wide that is adjacent to the Netherlands coast; that the depth to salt water is greatest where the water table is highest, and that the level of salt water rises under areas where the water table is low; that the zone of diffusion between fresh and salt water averages about 20 meters in thickness on the North Sea end of the contact; and that the general zone of contact between fresh and salt water is very regular and its center is occupied by the 1,000-milligram-per-liter isochlor (1,000 mg/l is approximately equivalent to 1,000 ppm). Irregularities in Pennink's isochlor pattern are readily explained by differences in lithologic character of the water-bearing beds.

Ghyben and Herzberg developed the principle that because salt water is denser and of greater specific gravity than fresh water, under conditions of static equilibrium it would take a column of fresh water 41 ft high to counterbalance a column of normal sea water 40 ft high. Stating it another way, a head of 1 ft of fresh water above mean sea level indicates a depth of 40 ft of fresh water below mean sea level, or a ratio between fresh-water head above sea level and depth to salt water below sea level of 1 to 40. This is the familiar ratio commonly used in predicting the depth at which salt water will be found in a given coastal area. Barksdale (Barksdale, Sundstrom, and Brunstein, 1936, p. 25) has aptly likened the manner in which fresh water (in a narrow coastal zone or island structure) "floats" on salt water, to the manner in which an ice mass floats on water, with most of its volume submerged.

Much of the significant early literature concerning coastal ground water has been ably reviewed in Brown's paper (1925). All these studies developed relationships and gave conclusions predicated on the assumption that static conditions were being considered. The Ghyben-Herzberg principle, however, requires the water table to be a convex surface intersecting the shoreline at mean sea level. The fact that the water table slopes toward the shoreline indicates flow—flow that is maintained by sufficient recharge to keep the water table above sea level.

Muskat's treatment (1937, p. 289) of gravity-flow systems offers an explanation of how that outflow takes place. Muskat shows that the water table does not intersect the ground surface at sea level, but that it does so at a higher elevation. The space between is a zone of seepage. Observations appear to confirm this theory in the Miami area, where the profiles made during the investigation indicate a water table sloping gently downward toward Biscayne Bay. Instead of intersecting the bay at mean sea level, however, the trend appears to be such that the intersection will occur above mean sea level and, in fact, even above the high-tide level. The profiles further suggest that the vertical height of the boundary or seepage surface is about 0.5 ft. This might suggest discharge by springs; however, no visible springs now exist along the shore, although in the early days, before drainage canals lowered the water table, many springs flowed near the base of the limestone cliff along Silver Bluff and elsewhere along the coast.

The wave-cut bench that forms the land surface between Biscayne Bay and the low sea cliff, Silver Bluff, slopes gently down from 5 ft above mean sea level to the water's edge. The water table is never very far below this surface, and the discharge of ground water here through evapotranspiration is much higher than that in adjacent areas inland from the cliff. The land surface of the wave-cut bench is always moist and near the shore is quite damp, indicating continuous ground-water discharge.

Wentworth (1942, p. 685) points out that ground water may be discharged in larger quantities by means other than seepage without substantially upsetting equilibrium conditions, if somewhat isolated leakage channels to the sea exist at depths where the hydrostatic pressure of the fresh water is greater than that of the salt water. This condition occurs in the Miami area, and the flow takes place both along a secondary system of vertical and horizontal solution channels in the limestone and through parts of the formation originally more permeable than others. The numerous large and small springs that formerly discharged along the shore and into the bottom of Biscayne Bay and connecting tidal canals gave vivid proof of the existence and operation of these shallow-depth channels of ground-water discharge. It is quite likely that considerable ground-water discharge still occurs in this manner, but owing to the small size of these submerged springs they are not readily noticed. Mention has already been made of the former perennial springs that now flow only during times of extreme high-water level.

These two avenues of discharge probably account for the principal discharge of fresh water moving seaward in this area.

STUDIES IN THE SILVER BLUFF AREA OF MIAMI

SELECTION OF THE SITE FOR STUDY

The Silver Bluff area was selected for intensive investigation largely because it appeared to be a representative area of the coastal ridge in Miami. There, the geologic section is quite similar to that of other areas along the coast of Dade County. Furthermore, this area offered the largest number of wells (points of access to the ground-water body) that could readily be used for observation; the depths of these wells ranged from about 45 to 125 ft. Thus, a fairly good observational net was already established. In addition, there were no tidal canals in the immediate neighborhood, although the general area (see fig. 200) is entirely surrounded by canals on the sides landward from Biscayne Bay. These canals are the Miami Canal on the northeast, the Tamiami and Comfort Canals on the north, and the Coral Gables Canal on the west and southwest. (See Brown and Parker, 1945.)

PRELIMINARY WORK

Considerable preliminary work was required before the first study could be attempted. This included a thorough inventory of all available wells to determine the areal and vertical distribution of points of access to the ground-water body.

For purposes of determining the altitude of the water table, 14 additional wells 2 in. in diameter were driven below the water table to insure that they would not go dry during drought periods. Wherever possible, the wells were installed adjacent to existing fire wells to permit a direct comparison between the true water table (as found in the shallow observation wells) and the water level in the deeper fire wells. Where both wells of any pair ended in ground water of normal chloride concentration (about 16 ppm) or, more properly, where the specific gravity of the ground water in each well was the same, it was expected that the water levels in the two wells would be nearly identical. However, where fire wells tapped ground water of high chloride concentration and where the specific gravity of the water within the well casings was therefore appreciably greater than that of water in the shallow observation wells, it was expected, and later confirmed by field measurements (p. 602—603), that the water level in the deeper wells would be appreciably lower than the true water table. Figure 170 shows the locations of most of the wells used in the Silver Bluff studies.

To obtain complete data on the tides and sea level in Biscayne Bay in order that their effect on the water table could be studied, a water-stage recorder was installed in the bay at the foot of Aviation Avenue. The record shows that the average sea level during the course of this investigation has been higher than the mean sea level established by the U. S. Coast and Geodetic Survey. Also, there has been a tendency for the mean tide stage to increase. See pages 441—443 for more detailed discussion of this matter.

Following is a summary of the record for the period preceding the studies reported herein:

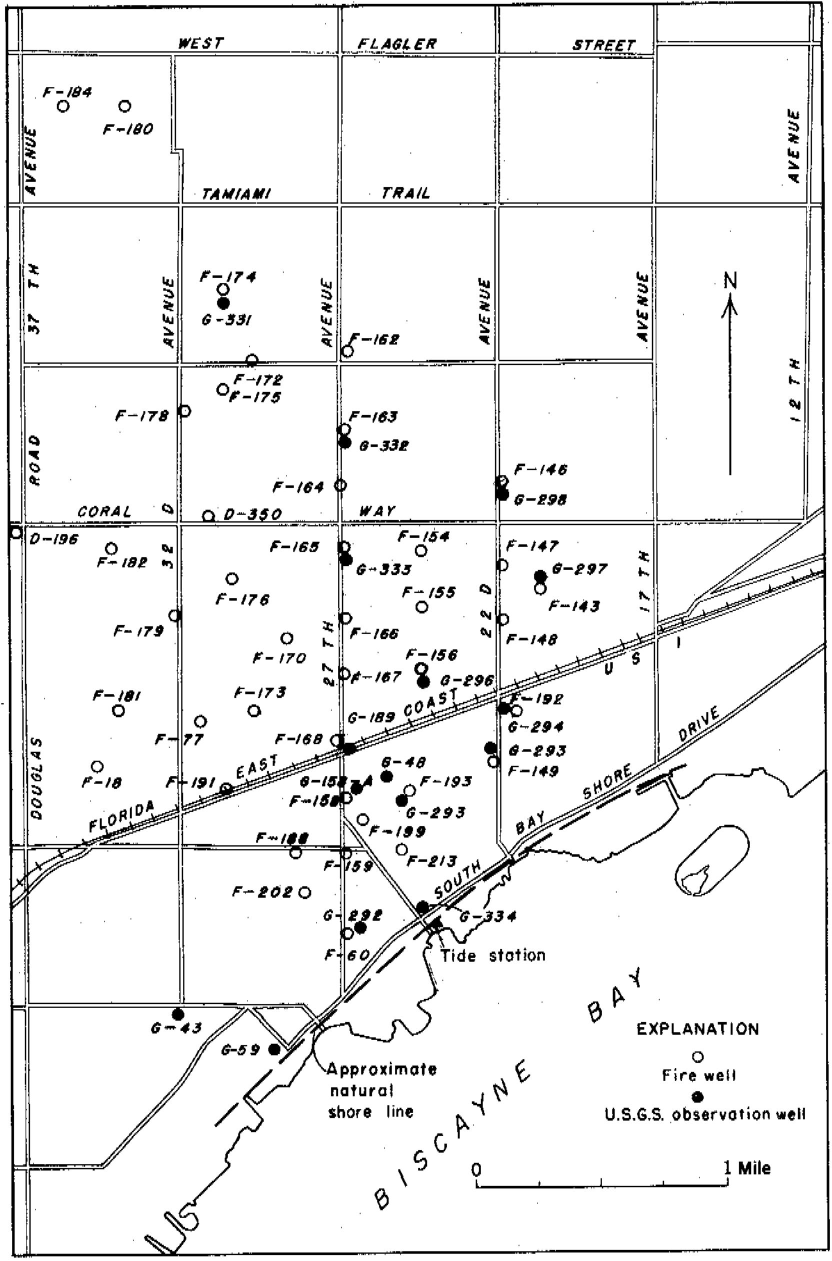

Figure 170. — Map of Silver Bluff area, Miami, showing the location of wells used in studies of salt-water encroachment.

Tidal elements and sea level

[In feet with reference to U. S. Coast and Geodetic Survey mean sea level datum of 1929]

Nov. 8, 1940, to July 26, 1941	
229 maximum stages, average	+1.44
229 minimum stages, average	-0.66
Average sea level	+0.39
Nov. 8, 1940, to Feb. 4, 1942	
436 maximum stages, average	+1.48
436 minimum stages, average	-0.59
Average sea level	+0.45

For the period 1941–1946, average water level in Biscayne Bay was found to be 0.61 ft above U. S. Coast and Geodetic Survey mean sea level. Detailed fluctuations in sea level are shown in figures 117–123.

OBJECTIVES

Investigations in the Silver Bluff area involved determination of: (1) The horizontal and vertical distribution of salty ground water; (2) the magnitude of cyclic seasonal shifts or changes in the position of the salt-water wedge; and (3) whether or not the salt-water wedge is gradually moving inland and contaminating parts of the aquifer formerly containing only fresh ground water. The first objective could have been reached through a single study; the second and third objectives, however, necessitated repeated studies to cover a variety of seasonal conditions and to be certain of long-term trends. In view of the fact that attempts are being made to control water levels and stop salt-water encroachment, the studies actually need to be continued over a much longer period of time.

PROCEDURES

The first intensive study in the Silver Bluff area was made on June 26, 1941. Results of this study were valuable primarily in devising efficient and thorough methods of conducting later studies. The following field procedures were adopted:

1. Selection of a date for conducting a study was based on rainfall records for the preceding several days. Because there are about 17 drainage wells scattered throughout the area (and numerous others in adjoining areas) that receive the discharge from storm sewers and catch basins, it appeared that the water table

and isochlor pattern near these wells would be distorted for several days following heavy rains. In effect, the drainage wells act as local recharge points for the ground-water body, and, where drainage wells end in salt water, fresh water is injected into the wedge of salty water. This not only dilutes the body of salt water locally but also creates localized mounds on the water table. Therefore, no study was attempted unless 3 or 4 days had elapsed since the last heavy rain.

2. All fire wells in the area selected for observation were pumped on the day preceding the date chosen for a particular study in order to remove the water standing in the casing and to draw in new water. In general, the fire wells were pumped in the approximate order of their estimated chloride concentrations—those in which the concentration was highest were pumped first. This made it certain that if all the fire wells could not be pumped on the day preceding the study, those remaining to be pumped on the day of the study would be low in chloride content. Thus, there would be no appreciable change, due to density differences induced by pumping, in the water level within these wells on the day of the study (see p. 613). Each well was pumped long enough to insure that the casing would be entirely emptied of water standing in the well and would be refilled with water drawn from the aquifer at the known depth of the well. A water sample was collected as soon as the pump had removed the standing water.

3. On the date selected for a study, the water levels in all fire wells and other observation wells were measured at hourly intervals over a 13-hour period to make certain that one complete tide cycle would be obtained for wells responsive to tidal variations. Drainage wells were not used, either for sampling or for observation purposes, because they contained considerable amounts of sludge and debris that affect both the quality of the water and the water level in the well.

The field work just outlined supplied data for the preparation of a composite cross section showing the profile of the water table and that of the isochlor pattern in a direction normal to the general trend of the natural shoreline. The profile of the water table was based on observations in the shallow wells and the isochlor pattern on chloride determinations of samples collected from the deep fire wells.

In compiling the results of the first study the shortest distance from each well to the shore was determined, making use of the many man-made irregularities in the shoreline. The composite water-table profile resulting from the use of these distances, however, appeared excessively uneven, so a smooth curve was drawn to represent what was judged to be the original or natural shoreline (fig. 170). The shortest distance from a well to this original shoreline then became the length of the normal, erected to this line, drawn to the well. Using these distances the water-table profile was readily plotted as a fairly smooth curve.

SPECIFIC GRAVITY OF SEA AND GROUND WATER

Before computations could be made to adjust water levels in wells containing different concentrations of salty water, it was necessary to determine the relation between chloride concentration and specific gravity of sea water, of ground water, and of mixtures of the two.

One of the most exhaustive studies of the relations among specific gravity, temperature, chloride concentration, and salinity of sea water was made under the direction of Knudsen (1901). Empirical equations, based on experimental data, were developed whereby the salinity and specific gravity of sea water can be calculated at any temperature between -2° C and 33° C if the chloride concentration in grams per kilogram is known. These equations were developed on the basis of atomic weights of the elements (as known in 1900). More recent investigation by Thompson and Wirth (1931, p. 232–240) indicates that Knudsen's tables are more accurate if the atomic weights of 1930 are substituted for those of 1900. There appears to be a marked relation between specific gravity and chlorinity in samples of sea water collected from many parts of the world. As defined by Thompson and Robinson (1932, p. 107), chlorinity is the number of grams of halides capable of precipitation by silver nitrate, calculated as chloride, contained in a kilogram of sea water. In this report the total halides reported as chloride are considered to be synonymous with chlorinity.

When sea water is diluted with runoff from land areas, the relation of specific gravity to chloride concentration, as well as to other constituents, may vary somewhat. Determinations were made, therefore, of the specific gravity of sea water and of several artificial dilutions of sea water with typical uncontaminated ground water of the Miami area. As the average temperature of ground water in this area is close to 25° C (77° F), the specific gravities were determined at 25° C. Computations are greatly simplified by assuming that such uncontaminated ground water has a specific gravity of 1.00000 at 25° C; the results are then expressed as specific gravity at 25°/25° C in accordance with the usual notation. Table 68 presents these determinations of specific gravity, arranged in order of increasing dilution from sea water to ground water.

A plot (fig. 171) of chloride concentration as abscissa and specific gravity as ordinate illustrates the results given in table 68.

Table 68.—*Specific gravity of sea water samples diluted with uncontaminated ground water*

Sample no.	Gravimetric chloride (ppm)	Specific gravity (at 25°/25°C)[a]	Computed specific gravity (at 25°/25°C)[b]
1[c]	19,740	1.02680	[d]1.02643
2	15,940	1.02161	1.02124
3	13,260	1.01803	1.01766
4	10,070	1.01374	1.01337
5	6,710	1.00922	1.00886
6	5,050	1.00700	1.00664
7	3,340	1.00472	1.00436
8	2,280	1.00333	1.00297
9	1,594	1.00239	1.00203
10	1,132	1.00179	1.00143
11	907	1.00148	1.00112
12	583	1.00107	1.00071
13	353	1.00078	1.00042
14	214	[e]1.00057	[e]1.00021
15	122	1.00050	1.00014
16[f]	....	1.00036	1.00000

[a] Determined in laboratory and referred to distilled water at 25°C. as unity.

[b] Referred to uncontaminated ground water as unity.

[c] Sea water.

[d] Computation for this value is as follows:

$$\text{Specific gravity} = \frac{1.02680}{1.00036} = 1.02643$$

[f] Ground water.

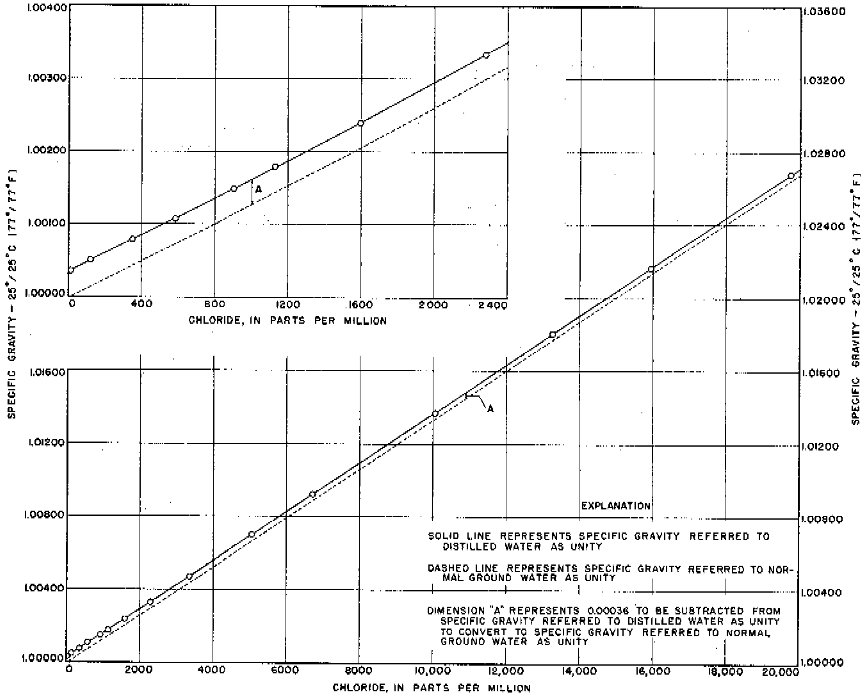

Figure 171.—Graph showing relation between specific gravity and chloride concentration in artificial mixtures of ground water and sea water.

The solid line resulted from direct plotting of the laboratory determinations of chloride and specific gravity values. As expected, it does not pass through the coordinate origin because, even with a chloride concentration of zero, other dissolved compounds are present and the specific gravity therefore remains greater than the value of the unit assigned to distilled water as a reference. The curve is essentially a straight line above a chloride concentration of about 3,500 ppm; below this point the curve is slightly concave upward.

The dashed curve shown in figure 171 was derived from the solid curve by plotting computed specific gravities, referred to normal ground water as unity, against chloride concentrations. It passes slightly to the right of the coordinate origin because a specific gravity of unity now represents normal ground water having a chloride concentration of 16 ppm. It is parallel to the solid curve and lies below it by an ordinate amount of 0.00036.

SILVER BLUFF STUDIES

Four complete sets of data concerning salt-water encroachment were collected in the Silver Bluff area following a study of the determinations of June 26, 1941. These data collections were made

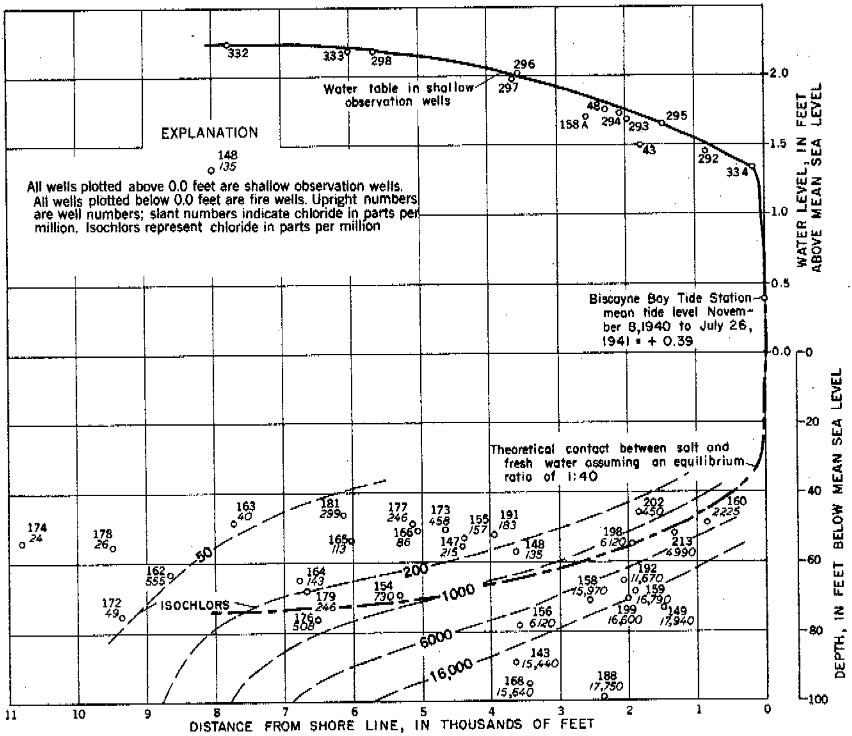

Figure 172.—Composite profile for salt-water encroachment study of July 26, 1941, Silver Bluff area, Miami.

on July 26, 1941, August 28, 1941, October 25, 1941, and February 4, 1942, and covered periods during which the water-table levels ranged from a stage slightly above average to one that was fairly low. Of the four collections, the one on July 26, included the highest water-table levels and the one on February 4 included the lowest. Data for these two collections are presented in this report so that the maximum observed seasonal changes in the salt-water encroachment pattern may be noted.

Table 69 gives the data collected at the time of the two water-table extremes, and figures 172 and 173 give the resulting composite profiles indicating isochlors and the water table. A line has been drawn on each of these profiles to represent the theoretical position of the boundary between fresh water and salt water, assuming perfect application of the Ghyben-Herzberg principle. The position of this line was determined by selecting a value of 1.025 as an average specific gravity for sea water (referred to normal ground water as unity), thereby developing a ratio of 1:40 for the relation between fresh-water head above mean sea level and depth to which fresh water extends below mean sea level. Using this ratio, computations were then made for enough selected points along the water-table curve to insure that the Ghyben-Herzberg equilibrium line would be well defined.

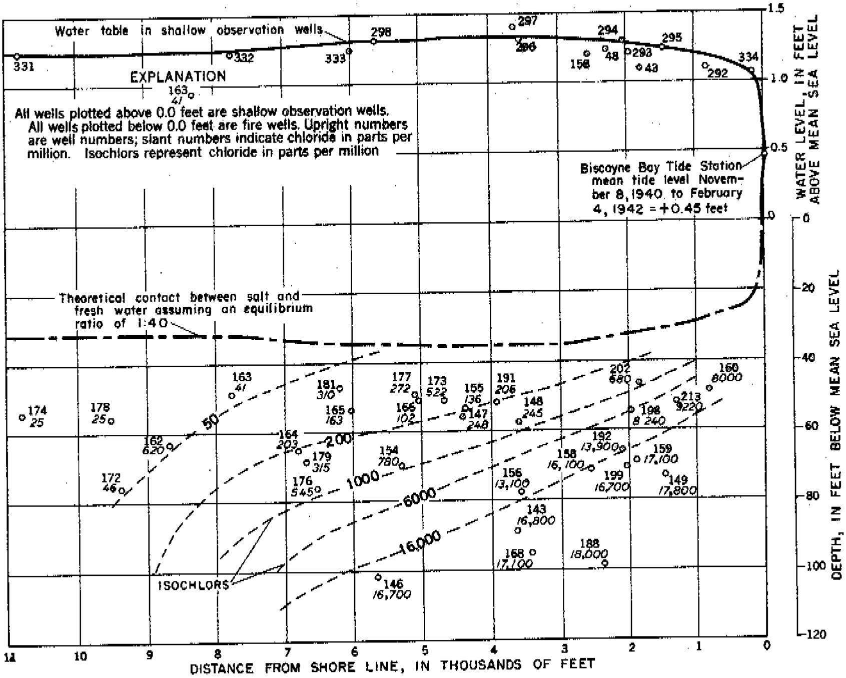

Figure 173. —Composite profile for salt-water encroachment study of February 4, 1942, Silver Bluff area, Miami.

Table 69.—*Salt-water encroachment data for Silver Bluff area, Miami; July 25, 26, 1941, and February 3, 4, 1942*

[Distance from shoreline measured normal to an arbitrary curve drawn to represent the approximate natural shoreline. Parentheses enclose the nos. of wells paired at the same location. Elevations are relative to U. S. Coast and Geodetic Survey mean sea level datum. Specific gravity referred to uncontaminated ground water as unity]

Well no.	Distance from shoreline (feet)	Land-surface elevation (feet)	Depth of well below datum (feet)	Mean water level elevation (feet)		Chloride (ppm)		Specific gravity	
				7-26-41	2-4-42	7-25-41	2-3-42	7-25-41	2-3-42
F184	14,840	14.7	71.9	0.99	0.40	[a]20	[b]20	1.0000	1.0000
F180	14,240	13.5	48.3	1.45	.83	[a]17	[b]16	1.0000	1.0000
(F174)	10,820	12.7	54.3	2.24	1.18	[a]24	[b]25	1.0000	1.0000
(G331)	10,820	...	1.1	...	1.22	...	...	...	...
F172	9,380	12.2	75.3	2.19	1.17	[a]49	[b]46	1.0000	1.0000
F178	9,500	10.7	55.6	2.22	1.20	[a]26	[b]25	1.0000	1.0000
F162	8,680	10.7	62.9	2.21	1.18	[a]555	[b]620	1.0007	1.0008
(F163)	7,760	13.1	48.6	2.23	1.23	[a]40	[b]41	1.0000	1.0000
(G332)	7,760	...	.7	2.24	1.21	...	...	...	...
(F146)	5,680	7.7	100.8	.29	-.58	[a]16,600	[b]16,700	1.0222	1.0223
(G298)	5,680	...	2.0	2.18	1.31	...	...	...	...
F164	6,800	12.9	65.4	2.16	1.21	[a]143	[b]203	1.0002	1.0002
(F165)	6,020	7.7	53.6	2.14	1.22	113	[b]163	1.0001	1.0002
(G333)	6,020	...	.9	2.19	1.23	...	...	...	...
F154	5,340	12.2	69.6	2.11	1.22	730	[b]780	1.0009	1.0010
F147	4,420	10.3	55.8	2.10	1.32	215	[b]248	1.0003	1.0003
(F143)	3,640	10.5	88.7	.51	-.14	15,440	[b]16,800	1.0206	1.0224
(G297)	3,640	...	.9	1.98	1.40	...	...	...	...
F166	5,060	9.9	50.9	2.10	1.24	86	102	1.0001	1.0001
F155	4,380	7.0	53.5	2.07	1.26	157	136	1.0002	1.0002
F148	3,620	11.1	57.4	2.03	1.34	135	245	1.0002	1.0003
(F156)	3,580	12.4	78.1	1.43	.22	6,120	13,100	1.0081	1.0175
(G296)	3,580	...	.8	2.03	1.30	...	...	...	...

(F192)	2,080	10.7	65.7	.98	.33	11,670	13,900	1.0155	1.0185
(G294)	2,080	...	1.0	1.73	1.28	...	...	...	...
(F149)	1,480	10.8	73.5	.30	-.04	17,940	17,800	1.0240	1.0238
(G295)	1,480	...	2.6	1.64	1.22	...	...	...	...
G48	2,300	10.0	2.7	1.75	1.23	...	...	...	...
(F158)	2,560	12.1	71.3	.53	.04	15,970	16,100	1.0213	1.0215
(G158A)	2,560	...	4.1	1.71	1.20	...	...	...	...
(F198)	1,960	11.8	55.4	1.48	.86	6,120	8,240	1.0080	1.0109
(G293)	1,960	10.4	2.6	1.68	1.20	...	...	...	...
F199	2,020	17.6	71.0	.45	.09	16,600	16,700	1.0222	1.0223
F213	1,320	16.4	52.7	1.30	.70	4,990	9,220	1.0065	1.0122
F176	6,540	10.0	76.1	2.04	1.26	508	545	1.0006	1.0007
F179	6,680	8.8	68.3	2.03	1.15	246	315	1.0003	1.0004
F181	6,180	5.5	46.9	1.93	1.21	299	310	1.0004	1.0004
F173	4,680	9.0	51.2	1.97	1.16	458	522	1.0006	1.0006
F177	5,120	5.8	49.7	1.87	1.15	246	272	1.0003	1.0003
F168	3,440	11.6	95.0	.45	-.25	15,640	17,100	1.0209	1.0229
F191	3,940	14.0	52.3	1.77	1.17	183	206	1.0002	1.0002
F188	2,400	17.1	98.2	.28	-.13	17,750	18,000	1.0237	1.0241
F202	1,860	15.5	46.5	1.53	1.12	450	680	1.0006	1.0008
G43	1,800	5.0	5.8	1.50	1.10	...	...	...	...
F159	1,900	16.1	69.4	.43	.03	16,790	17,100	1.0224	1.0229
(F160)	840	14.5	49.4	1.33	.72	2,220	8,000	1.0028	1.0106
(G292)	840	...	1.9	1.45	1.11	...	...	...	...
G334	180	4.3	2.1	1.34	1.06	...	...	...	...

[a] Sample collected July 26, 1941.
[b] Sample collected February 4, 1942.

In selecting the 1:40 ratio the ranges in specific gravity, as observed in the nearby ocean water, in the water of Biscayne Bay, and in the salty ground water of the Silver Bluff area, were taken into account. On the basis of the specific gravity of sea water the ratio would have been 1:37.8, but ratios ranging as high as 1:42 were noted for the bay and for the encroaching salt-water wedge in the Silver Bluff area. These facts, coupled with ease of computation, prompted use of an average ratio of 1:40.

The mean water level in Biscayne Bay for the periods of investigation in each case were above U. S. Coast and Geodetic Survey mean sea level datum. On July 26, 1941, the mean water level was 0.47 ft, and on February 4, 1942, it was 0.49 ft above mean sea level. However, the mean gage height for any given day is not satisfactory for use as a datum in correcting for salt water-fresh water balance as of that day; rather, the average sea level for a considerable time preceding the collection of data should be used. Thus, for the July 26 and February 4 data, average bay levels of +0.39 ft and +0.45 ft, respectively, were used.

Because the ratio of scales used in plotting the water table and the isochlors was 1:40, the Ghyben-Herzberg equilibrium curve is very nearly an exact inversion of the water-table curve. The inversion would plot exactly only if the actual observed mean tide level in Biscayne Bay agreed with the established mean sea level. It is significant to note that on the profile for July 26, the Ghyben-Herzberg equilibrium line parallels the entire isochlor pattern inland to about 2,500 ft and lies below the 1,000 ppm isochlor inland to about 4,800 ft; whereas on the profile for February 4, it lies above the entire plotted isochlor pattern. In spite of this great difference there is no proportionate shift in the isochlor pattern. This is a graphical illustration of the fact that a change in elevation of the water table does not immediately cause a change 40 times as great in the elevation of the isochlor pattern. Superimposing the two composite profiles (fig. 174) shows that the elevation of the water table on February 4 ranged from 0.3 to 1.0 ft lower than on July 26. The elevation of the isochlor pattern for February 4, however, averaged only about 4 ft higher than that on July 26. This had been anticipated, for Wentworth (1939) had previously shown that an adjustment of the equilibrium between salt and fresh water, in response to a change in water-table elevation, lags far behind the time of water-level change because it involves actual changes in "bottom storage", which take place slowly.

In figure 174, chloride data are given for three drainage wells drilled in the Silver Bluff area prior to July 26, 1941. Water samples were carefully collected as the wells were being drilled, but were not obtained as part of the July 26 and February 4 studies. The data for the two drainage wells, D 196 and D 350, indicate sharp downward trends of the isochlors about 8,000 ft from the shoreline. It is therefore evident that, in general, as of the date

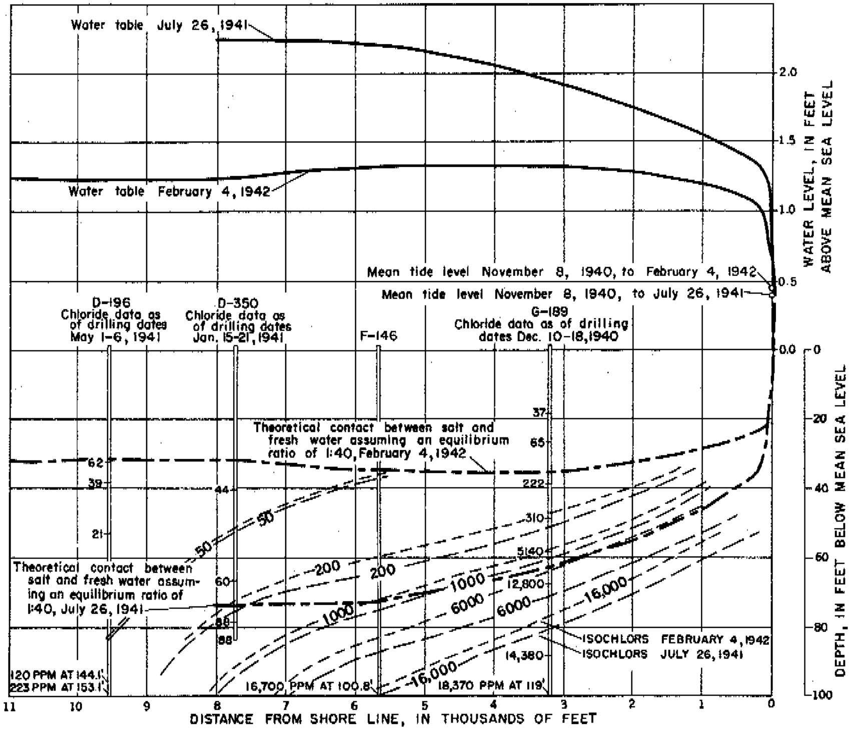

Figure 174.—Composite profiles for salt-water encroachment studies of July 26, 1941, and February 4, 1942, Silver Bluff area, Miami.

of these studies, the inland extent of salt-water encroachment in the Silver Bluff area at depths below 80 ft was about 8,000 ft. The maximum inland penetration of chloride in a concentration comparable to that of sea water is not known, but on the basis of the data obtained from the drilling of well D 196 it is evident that it is less than 9,600 ft, and samples pumped from well F 146 indicate that it is more than 5,600 ft. Somewhere between these boundaries, therefore, is the line of maximum inland penetration of high-chloride concentration within the Biscayne aquifer.

The chloride data for test well G 189 fit in satisfactorily with the isochlors as drawn for July 26. Although inspection of these data suggests that, except for the 16,000 ppm isochlor, the isochlors have been drawn at too low an elevation, it should be noted that the test well was drilled in December 1940, at a time when the water table was lower than on July 26, 1941. Thus the chloride pattern, as indicated by the well samples, would be expected to appear at an elevation slightly higher than shown by the isochlors.

The data collected for the studies of August 28 and October 25, 1941 (not presented in detail in this report), covered a shift in the isochlor pattern from low to high water-table conditions. On October 25 the water table averaged from 0.2 ft to 0.6 ft higher than on August 28, and the isochlor pattern on October 25 averaged about 2 ft lower than on August 28. Although this 2-ft shift is admittedly slight and could, to some degree, be accounted for by experimental error, it is believed to be significant.

Although only four comprehensive encroachment studies were undertaken in the Silver Bluff area, considerable supplemental data are available through periodic water-level observations and chloride analyses of well water. In figure 175, chloride results, plotted against time, are given for water samples collected from wells in the Silver Bluff area. Also shown on the graph, for comparison, is a hydrograph of F 179, a well on which a continuous water-stage recorder is maintained. F 179 is 6,680 ft inland from the bay. This is the greatest distance, in this area, at which a recognizable tidal effect has been noted in wells. The fluctuation of the water level in F 179 may be taken as representative of the other wells in this area.

The record of chloride changes in wells of high salinity (F 146, F 156, F 160, F 198, and F 192) during the period of 1940–46 is shown in figure 175. (Descriptive data for these wells, and all others referred to in this section, appear in table 69.) In general, the trend in chloride concentration in all wells was the same; they rose and fell in unison. Furthermore, these changes in chloride concentration seem to have occurred in response to changes in the water table—that is, when the water table was low, the chloride content tended to rise, and when the water table was high, the chloride content tended to fall. The net trend, however, was for an increase in chloride content.

Figure 175 also shows comparable data for wells of low salinity (F 147, F 162, F 163, F 164, F 165, F 174, and F 202). These wells are more distant from the bay or are shallower than those of the first group; therefore their chloride content was much less. The chloride in the water of these wells also responded to movements of the water table and, as in the wells of high salinity, also showed a net increase for the period of record.

The fact that the chloride content in the water of some wells changed more rapidly and to a greater extent than that in other wells is due to factors such as: (1) distance from the bay; (2) depth below mean sea level; (3) location with respect to nearby drainage wells that may introduce relatively large volumes of fresh water directly into the body of the salt-water wedge at depth, thus diluting the ground water locally and temporarily upsetting equilibrium; and (4) the presence of solution channels that may allow salt water easy access to the area or, conversely, may allow fresh water to discharge freely to the sea.

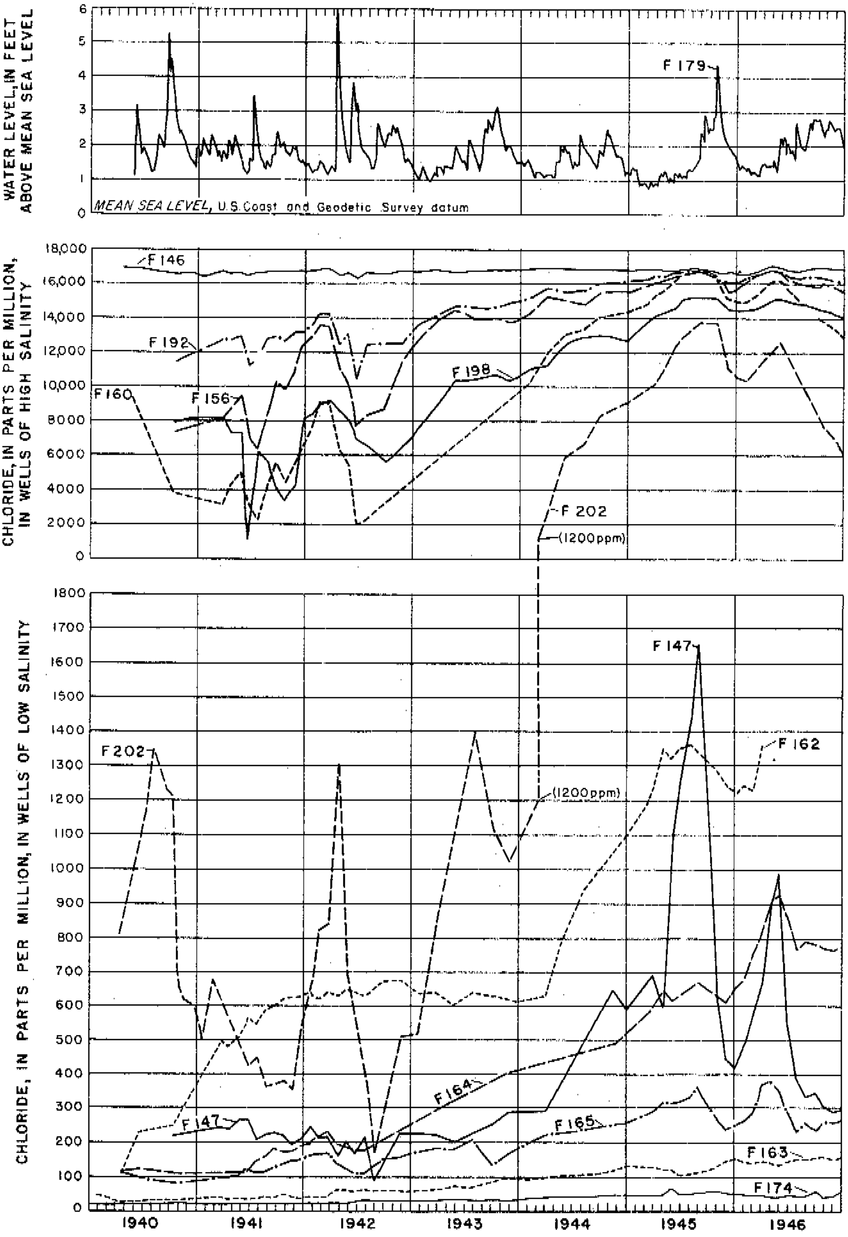

Figure 175.—Graph showing correlation between fluctuation of water level in well F 179 and chloride content in 12 wells of the Silver Bluff area, Miami, 1940-46.

EFFECT OF RAINFALL ON THE ISOCHLOR PATTERN

As indicated previously, it was difficult to select the optimum times to secure data for the salt water-fresh water studies in the Silver Bluff area. Heavy rains just before, or during, an investigation would cause local distortions in the water table and isochlor pattern sufficient to upset the most carefully collected data. Nevertheless, it was important to obtain information for conditions following heavy rains. Accordingly, the study of July 26, 1941, was conducted just after the rainy-season ground-water peaks that occurred about July 13. Figure 175 suggests that, even though a rainy-season peak had just passed, the time of the survey covered a period during which the water table had already declined to near-average level, or slightly below. Furthermore, examination of the chloride graphs for wells in this area shows that at the time of the study not all ground water was declining in chloride content, although in most parts of the aquifer this was true.

The composite profile in figure 172 indicates that at many points the isochlor pattern does not represent the chloride concentrations shown for the various wells. Apparently, therefore, even though the study was made several days following the last heavy showers, the large part of the year's total rain that had fallen during the preceding few weeks had a considerable and lasting disruptive effect on the regularity of the isochlor pattern. Especially tending to upset the regular plotting of the observed data was the direct discharge into the salt-water wedge of relatively large quantities of rain water from drainage wells. At the time of the study therefore, there was still a tendency towards a smoothing-out or stabilizing of conditions, but at the same time, water levels were declining. Postponing the study until the varying factors became stabilized, however, would have meant losing the opportunity for observing the nature of the factors bearing on salt-water encroachment during periods of high water-table conditions. In any study contemplated for a period of high water levels, therefore, unusual precautions should be taken to insure an ample collection of precise and complete data because of the difficulties that may later be experienced in attempting to fit the results together into one comprehensive picture.

In contrast to the study of July 26, 1941, conducted during a comparatively unstable high water-table period, the study of February 4, 1942 was made under conditions of a fairly low and gradually declining water table. The composite profile given in figure 173 reveals well-stablized conditions with good agreement between the chloride concentrations shown for the different wells and a smoothly-drawn isochlor pattern. Inspection of the chloride graphs in figure 175 shows that, without exception, chloride was increasing in all wells sampled at this time, and that the increases were apparently the direct result of the lowered water level.

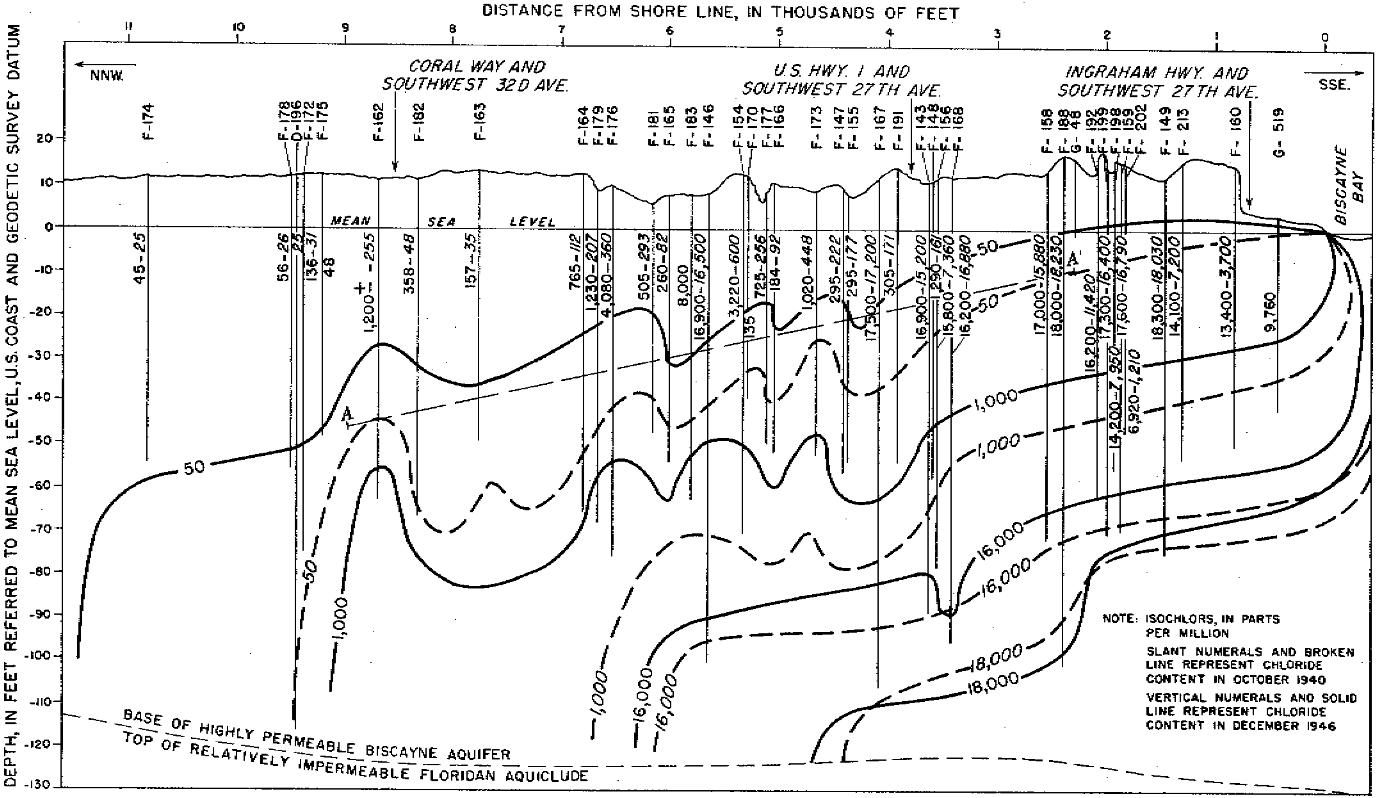

Figure 176. —Generalized cross section showing isochlor pattern in the Silver Bluff area, October 1940 and December 1946.

Figure 176 is a generalized composite cross section through the Silver Bluff area showing the change in isochlor patterns in the encroaching salt-water body as of the end of October 1940 and December 1946, the beginning and end of the month-end sampling program.

The cross section shown is more than 11,000 feet long in a general north-northwest direction, oriented normal to the bay shore, and all wells are shown as though they were situated along one line intersecting the bay. Actually, some are as much as several city blocks apart (in a general east-west direction) but they have been placed on the drawing at their correct normal distance from the bay. Locations of these wells are shown in figure 170. Most of the wells have been sampled monthly since 1940, and it was from these pumped samples that data for this plate and figure 175 were obtained.

One of the obvious characteristics of the isochlors drawn for October 1940 and December 1946 is their irregular or wavy shape. This is a characteristic frequently found, but it is especially pronounced following heavy rains in accordance with the information already offered. Some of the irregularity in the isochlor pattern is due to plotting the chloride data for each well at a point corresponding to the bottom of the well whereas actually, water is free to enter a well from any part of the open-hole section below the bottom of the casing.

The isochlors in the cross section actually may be shown less distorted than they would be if the conditions they represent in the aquifer were more precisely known. This is the result of incomplete sampling of the cross section. Enough points of access to the ground-water body are sampled so that a generalized cross section of the salt-water wedge can be drawn. The limitations of the data, however, must be realized.

CHARACTERISTICS AND CHANGES IN POSITION OF THE SALT-WATER WEDGE

It will be noted in figure 176 that the principal changes of the isochlor pattern between October 1940 and December 1946 took place at and near the inland margin of the salt-water wedge. There, the 1,000 ppm isochlor moved inland approximately 2,000 feet in the 1940–46 interval. There was also a considerable rise of the upper surface of the salt-water wedge, averaging perhaps 15 feet over the distance of more than 9,000 feet that the wedge extends inland from the bay.

The wedge is very blunt-nosed, as shown by the 1,000 ppm isochlor of 1946 and the 50-ppm isochlor of 1940. It will be noted that a knob-like shape in these two isochlors appears below well F 162. It is believed that this shape is due largely to differential dilution of the wedge seaward from F 162, and that a truer picture of the shape the wedge would assume if no such dilution effect occurred is shown by the light dashed-line *A–A'*. Similar straightening out probably could be done on each isochlor to gain an idea of how such an encroaching wedge would appear in a place not affected by fresh-water recharge directly into the salt-water body.

Comparatively small changes took place in the salt water of higher chloride concentration, the greatest changes taking place in the water containing less than 1,000 ppm chloride. For both 1940 and 1946, the 1,000-ppm isochlor lay near the center of the salt-water wedge, and the change from water of 50 ppm, or less, to water of 16,000 ppm, or more, took place within a thickness of 70 to 80 feet. These conditions are comparable to those found by Pennink (1904, p. 183–238) along the Netherlands coast where the diffusion zone averaged 20 meters (65.6 feet) in thickness.

The studies of salt-water encroachment made in the Silver Bluff area give evidence of the magnitude of seasonal and long-term changes in the elevation of the water table and in the shift of isochlor patterns. The fact that these patterns can show movement first in one direction and then in the other is of considerable significance. Equilibrium conditions (approximate) have not been reached over the whole area, and the isochlor pattern is probably destined to occupy, at some future date, a new position some distance inland from its present position. However, this movement, persistent as it may be, will be materially slowed down by the seasonal high-water periods of years of heavier-than-normal rainfall.

It has been pointed out that changes in the elevation of the water table do not immediately provoke changes 40 times as great in the position of the isochlor pattern. Indeed, there seems to be so much lag before adjustment can be made to one change in water-table elevation a new and possibly reverse change has occurred; therefore, a complete adjustment may not ever occur. Seasonal changes in the position of the isochlor pattern are therefore smaller than might be expected. The changes in salt-water contamination reflect long-term trends of the water table rather than overnight variations, and the observed relation between salt and fresh water in the Silver Bluff area is a reflection of conditions existing during preceding years.

Referring to the profile for the study of July 26, 1941 (fig. 172), representing near-average conditions, note that the line showing the theoretical contact between salt water and fresh water parallels the isochlor pattern and lies slightly above the 6,000-ppm isochlor at a point about 2,500 ft inland. This indicates that equilibrium, based on average yearly values, is probably established in accordance with the Ghyben-Herzberg principle over that distance. Beyond 2,500 ft, the theoretical line gradually flattens out, and at about 4,800 ft, it crosses the 1,000-ppm isochlor. Thus, equilibrium is almost reached at a point 4,800 ft inland. Inland beyond this point, however, the divergence between the theoretical line and the isochlors is great.

Figure 174 shows the relatively small amount of actual shift involved in the isochlor pattern between very low and near-average water-table stages and supports the conclusion that equilibrium, based on average yearly water-table elevations, has been reached at least 2,500 ft inland. However, the relation of low-water levels, such as those of February 4, 1942, to the position of the isochlor pattern is significant primarily to show existence of unbalanced conditions favorable for inducing inland movement of salt water. Certainly the isochlor pattern and the theoretical balance line as of February 4, 1942, show no direct correlation, whereas there is good correlation as of July 26, 1941.

The position of the salt-water wedge at any given time is a result of conditions prevailing over a relatively long period of time. The wedge may be moving very slowly inland, but it is constantly subject to advances and retreats. The leading edge probably can never advance inland beyond the average yearly position occupied by the particular water-table contour that is 2½ ft above true average sea level. This follows, inasmuch as a fresh-water head of 2½ ft above the true average level of salt water in the bay would depress the top of the encroaching wedge to the relatively impermeable sandy marls of the Floridan aquiclude that underlie the highly permeable Biscayne aquifer, and the salt-water advance would halt there.

It might be assumed that ground water flows approximately parallel to the dip of the highly permeable formations in the Silver Bluff area and that there would be a slight downward, as well as a horizontal, component of motion as the water approached the shore area. However, study of water-table maps for the entire area shows that this is not true, because the greatest flow is not down the dip—instead, it is toward the canals. A minor part of the total quantity of water moves seaward in the aquifer throughout the year and is effective in limiting the inland progression of the salt-water wedge—particularly at the leading, or inland, edge during the rainy season when the water table becomes fairly high and seaward ground-water movement is pronounced.

The seaward flow of fresh water over the wedge of salty water has a depressive effect on the shape of the wedge, and it probably accounts for most of the rapid vertical descent of the isochlors at a point more than 7,000 ft inland. The factors that are involved in this phenomenon are not known at present, but there is a possible association with the dissipation of the anterior part of the salt-water wedge through mixing with, and being swept away by, seaward-moving fresh water. The present shape of the inland front of the salt-water wedge at Silver Bluff may be compared with the steeply dipping isochlors of the inland front of the salt-water wedge in the Cutler area (see fig. 201). It is believed that in the Cutler area the present conditions are comparable to those in the Silver Bluff area before encroachment began, and that they show the normal salt water-fresh water relationship for this coastal zone (at localities where drainage and the consequent lowering of the fresh-water head do not distort conditions).

The pattern at Silver Bluff probably will retain its general shape; however, it is only the sweeping away of the inland front of the wedge that prevents advance farther inland, until, as previously noted, the encroachment would stop at the place where the average annual position of the water table is 2½ ft above true average sea level (about 3 ft above U. S. Coast and Geodetic Survey mean sea level).[1]

It has been pointed out (above) that the water level in a well tapping a section of the water-bearing strata containing high-chloride concentrations would be lower than the true water table, as indicated by the water level in an adjacent shallow observation well. By referring to table 69, a comparison of the water levels for paired wells can be made. Parentheses have been used to single out each combination of fire well and adjacent shallow test well. For any such pair of wells, in an area where only water of normal or near-normal chloride content is present, the water levels should be practically equal. Where the chloride concentration of the ground water tapped by the fire well is several hundred parts per million, or more, there will be an appreciable divergence between the water levels in the two wells. This divergence increases in proportion to the increase in chloride concentration. The maximum divergence on both July 26 and February 4 was for wells F 146 and G 298 and amounted to 1.89 ft. This divergance is associated with a chloride concentration of 16,600 to 16,700 ppm in well F 146.

To show how large a proportion of the divergence in levels can be accounted for through adjustments for density differences only, computations are presented for two selected distances from the shoreline utilizing data taken in part from the composite salt-water-encroachment profile (fig. 173) for February 4, 1942, and in part from two pairs of observation wells (F 158-G 158 A, and F 198-G 293). The maximum chloride concentrations determined in the two fire wells are about 16,000 ppm and 8,000 ppm, respectively.

In each of the two sets of sample computations the adjustment method, as devised, involved the necessity of converting to an

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[1] Since this report was written, several additional years of observation and collection of data have occurred. N. D. Hoy and Francis A. Kohout, geologists of the Miami office, have assembled data that indicate that the observed position of the salt-water wedge is in near-equilibrium with presently known hydrologic conditions.

equivalent water level for normal ground water the mean water level for the day of the study as observed in the fire well and the average corresponding level of the water table as taken from the composite profile (fig. 173). Thus, computations were made for each fire well to indicate the level at which the water would stand if the well casing contained water of normal chloride concentration instead of the salt-contaminated water. This involved the determination of the pressure on a unit area at the bottom of the well by means of the known specific gravity of the water in the well multiplied by the observed length of the water column. The length of the new column was computed by equating this pressure to that at the base of a column of normal ground water having a specific gravity of unity. Thus, for well F 158 the mean observed water level on February 4, 1942, was 0.04 ft above mean sea level. The bottom of the well was 71.3 ft below mean sea level (see table 69), and the length of the water column in the casing was 71.34 ft. The chloride concentration was 16,100 ppm, indicating (see fig. 171) a specific gravity of 1.0215. The figure 71.34 multiplied by the ratio of this specific gravity to that for normal ground water, $\frac{1.0215}{1.0000}$, gives 72.87 ft as the length of an equivalent column of normal ground water. The difference in lengths of the two columns, 1.53 ft, added to the mean observed water level, gives the level at which normal ground water would stand. Thus, 1.53 ft plus 0.04 ft equals 1.57 ft above mean sea level. On the composite profile shown in figure 173, however, the average water-table elevation for a site at this distance from the shoreline appears as 1.30 ft above mean sea level. To convert this to an equivalent elevation for normal ground water obviously requires the consideration of chloride concentrations ranging from 16 ppm at the water table (1.30 ft above mean sea level) to 16,100 ppm at a depth of 71.3 ft below mean sea level. In figure 177, two curves, obtained from the isochlor pattern drawn in figure 173, show the variations in chloride concentration with depth at the sites of the two fire wells used in these sample computations. The curves are terminated at the depths penetrated by the fire wells. Each curve applies only to one particular site, therefore its upper limit is determined by the average water-table elevation at that particular site as taken from the composite profile in figure 173. A normal chloride concentration of 16 ppm was arbitrarily assigned to the upper limit of each curve.

The computations for adjusting the average water-table elevation of 1.30 ft (at well F 158) to an elevation for an equivalent column of normal ground water are then resolved essentially into a determination of the area, shown in figure 177, bounded by the curve of chloride versus depth (the abscissas being drawn through the limiting chloride concentrations of 16 and 16,100 ppm) and the vertical coordinate axis. Therefore, to obtain the length of the equivalent column of normal ground water the curve was divided into short segments, an average chloride concentration was determined representative of each segment, and the specific gravity (fig. 171), indicated by each chloride concentration, was then multiplied by the height of vertical projection of the segment, and these products then were totaled. These computations are assembled in table 70 for each of the two selected sites.

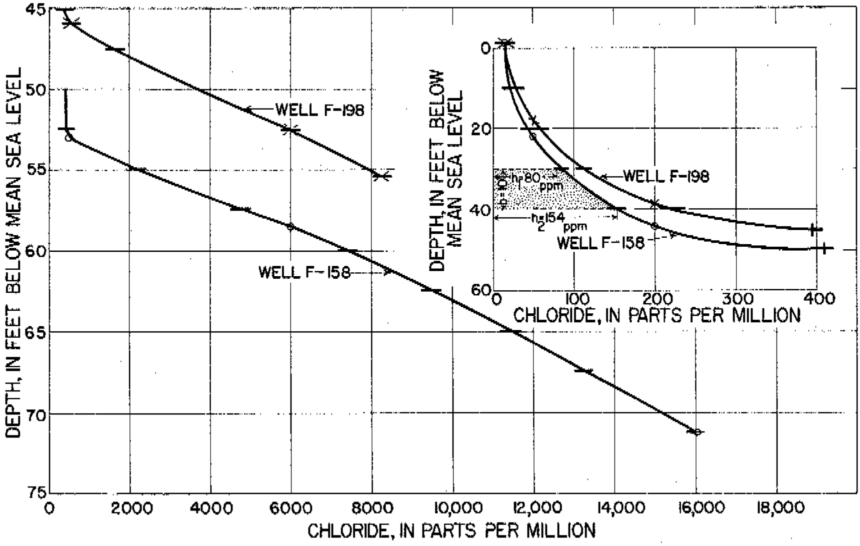

Figure 177.—Variation of chloride with depth in selected wells in Silver Bluff area, Miami, February 4, 1942.

In figure 177 the short, heavy bars cutting across the curves indicate the manner in which they were arbitrarily divided into segments. Also shown in this figure is a stippled zone representing the area between the vertical axis of the graph and a typical segment of the curve. The lettered dimensions for this area will explain the notation appearing in some of the column headings in table 70. In this table the total of column 1 (72.60 ft) is the length of the water column in the ground, and the total of column 6 (72.82 ft) is the length of an equivalent column of normal ground water that would have a weight about the same as that in column 1. An elevation of 1.52 ft is obtained by adding the difference in length of the two water columns, 0.22 ft, to the average water-table elevation of 1.30 ft, selected from figure 173. This compares very closely with the elevation of 1.57 ft previously obtained by adjusting the observed water level in fire well F 158. Before adjustments were applied, the water level in well F 158 differed from the average water-table elevations by 1.26 ft. After adjustment only for specific gravity, however, the difference has been reduced to 0.05 ft.

In similar fashion, computations were made (table 70) to adjust the water levels at the other selected site using data from well F 198. Before making the adjustment, the levels differed by

Table 70.—*Data and computations for adjusting water-table elevations at two selected sites in Silver Bluff area, February 4, 1942*

[See figure 177 for explanation of symbols]

Site 2,560 feet from shoreline (Well F 158)				Site 1,960 feet from shoreline (Well F 198)			
Depth interval (b)	Average—		Equivalent intervals of normal ground water [b (sp. gr.)]	Depth interval (b)	Average—		Equivalent intervals of normal ground water [b(sp. gr.)]
	Chloride concentration $\left(\frac{h_1 + h_2}{2}\right)$	Specific gravity $\left(\frac{h_1 + h_2}{2}\right)$			Chloride concentration $\left(\frac{h_1 + h_2}{2}\right)$	Specific gravity $\left(\frac{h_2 + h_2}{2}\right)$	
Feet	Ppm	(1)	Feet[2]	Feet	Ppm	(1)	Feet[2]
(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
[3]11.30	18	1.0000	11.300	[3]11.26	20	1.0000	11.260
10	32	1.0000	10.000	10	42	1.0000	10.000
10	62	1.0001	10.001	10	82	1.0001	10.001
10	117	1.0001	10.001	10	160.	1.0002	10.002
10	249	1.0003	10.003	5	289	1.0003	5.002
2.5	400	1.0005	2.501	2.5	835	1.0010	2.502
2.5	1,240	1.0016	2.504	2.5	2,595	1.0034	2.508
2.5	3,540	1.0046	2.512	2.5	4,810	1.0064	2.516
2.5	6,100	1.0080	2.520	2.9	7,120	1.0095	2.928
2.5	8,470	1.0112	2.528	56.66			56.719
2.5	10,520	1.0141	2.535				
2.5	12,415	1.0166	2.542				
2.5	14,260	1.0191	2.548				
1.3	15,645	1.0211	1.327				
72.60			72.822				

Adjustment of average water-table elevation of +1.30:
Length of water column in the ground = 72.60 feet, total of (1).
Length of an equivalent column of normal ground water = 72.82 feet, total of (4).
Adjusted water-table elevation is 1.30 + (72.82 - 72.60) = +1.52 feet.
Adjustment of observed fire well water-level elevation of +0.04:
Actual length of water column in well casing = 71.34 feet.
Length adjusted to an equivalent column of normal ground water, (71.34)(1.0215) = 72.87 feet.
Adjusted water-table elevation is 0.04 + (72.87 - 71.34) = 1.57 feet.

Adjustment of average water-table elevation of +1.26:
Length of water column in the ground = 56.66 feet, total of (1).
Length of an equivalent column of normal ground water = 56.72 feet, total of (4).
Adjusted water-table elevation is 1.26 + (56.72 - 56.66) = 1.32 feet.
Adjustment of observed fire well water-level elevation of +0.86:
Actual length of water column in well casing = 56.26 feet.
Length adjusted to an equivalent column of normal ground water, (56.26)(1.0109) = 56.87 feet.
Adjusted water-table elevation is 0.86 + (56.87 - 56.26) = 1.47 feet.

---

[1] Computed from value in (2) and use of figure 171.

[2] Product of corresponding values in (1) and (3), divided by specific gravity of unity.

[3] Based on average water-table elevations for the two sites, +1.30 and +1.26 respectively, taken from figure 173.

0.40 ft; after adjustment, the difference was reduced to 0.15 ft. In view of the number of factors (already discussed) that tend to complicate work with data in the Silver Bluff area, the close agreement (within 0.05 ft) between the adjusted water levels in the first sample computation may be partly fortuitous. However, the adjustments effected in both sets of computations show the degree of importance that may be attached to the specific-gravity factor alone. Undoubtedly, other adjustments should be applied to accomplish complete reconciliation of the divergence in water levels indicated by the pairs of wells scattered throughout the Silver Bluff area. However, differences in specific gravity easily account for a major part of the divergence, and these are the only adjustments that have been considered in this report.

TIDAL-STORAGE CHANGES

Computations were made of the approximate order of magnitude of the maximum amount of salt-water movement inland that could occur during the short space of time elapsing between low tide and the following high tide. The accompanying sketch (fig. 178) represents a schematic profile in which the shaded area "A" indicates the wedge-shaped zone in which ground water is alternately stored and drained as a result of tidal fluctuations in Biscayne Bay. The length of this wedge was considered as 6,410 ft, the average distance from the shoreline to the three nearest wells in which tidal fluctuations became so small that they approached the limits of accuracy (nearest 0.01 ft) of the field water-level measurements, as determined during the study of June 26, 1941. The height of the wedge is 0.7 ft, which represents the amplitude

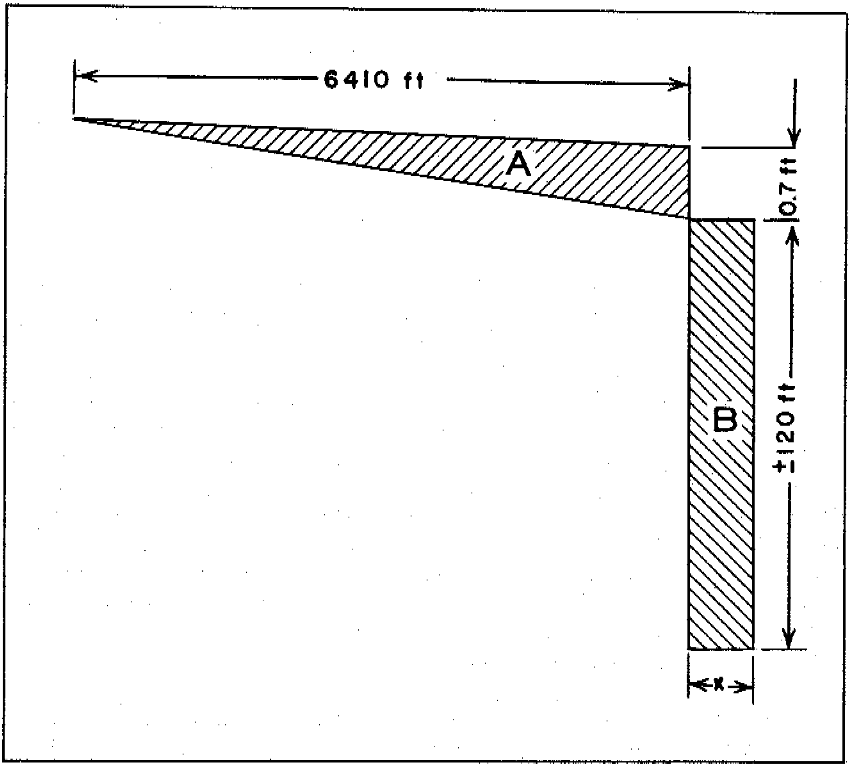

Figure 178.—Schematic profile to illustrate method of computing theoretical bulk change in ground-water storage due to tides.

of the tidal fluctuation in well G 334, located 180 ft from the shoreline. The shaded area "B" indicates a zone whose shape has been assumed for purposes of convenience in making the computation. Its height of about 120 ft is based on the known average thickness of the highly permeable Biscayne aquifer in this locality, and its width, "X" ft, equals the amount of inland movement of salt-water to be computed, assuming for convenience that the movement is entirely horizontal—as a solid wall of water. Therefore, for a unit length of shoreline, measured normal to the plane of the sketch, the volume of water stored in the wedge "A" may be equated to the volume of sea water moving in horizontally through the zone "B" Thus,

$$\tfrac{1}{2}(0.7)\,(6,410)\,(1) = 120X\,(1)$$
$$X = 18.7 \text{ ft}$$

This computation ignores the part of wedge "A" supplied by ground water flowing toward the sea. Therefore, the distance computed exceeds the actual average distance that salt water moves under the influence of tides. The same value, with opposite sign, would apply to the other half of the tide cycle so that the net movement of salt water for one complete cycle would be zero, provided that recharge to the ground-water body remained constant. If the recharge were decreasing, the zone "B" would not be pushed seaward as much as it moves inland each cycle, and there would be a steady advance inland of the salt water. Increasing ground-water recharge would have the opposite effect.

ENCROACHMENT IN THE TIDAL CANALS

By D. B. Bogart

The study of encroachment of salty water in the canals and canalized natural streams connected with tidal estuaries and bays has been an important phase of the investigations in southeastern Florida. In Broward and Dade Counties, most of the canals empty into the marine sloughs close to, and parallel with, the ocean beach, or into Biscayne Bay and its extensions to the southwest. The marine sloughs, prior to canalization for navigation, probably were brackish for most of the time, except near the ocean inlets or where they broadened into bays. Waterway developments, however, facilitated fresh-water runoff and inland movement of salty water, and the sloughs essentially became arms of the sea. The bottoms of the canals near the coast were excavated to below sea level, and salty water thus had access to them except where attempts were made to control flow.

Uncontrolled canals drain off water that would naturally oppose inland movement of salty water and also provide an easy path for salt-water encroachment because sea water is free to enter during the drier periods of the year. The canals thus perform an adverse dual function, but at the same time they are the key to the solution of the problem. It is only by controlling the canals that salt-water encroachment can be stopped in the canals and in the land.

As discussed previously, contamination of part of the municipal water supply of Miami focused attention on the problem of salt-water intrusion. That was sufficient reason for the investigation, but contamination of the canals and waterways is in itself undesirable for various reasons. Commercial vessels and yachts are moored in the fresh-water canals to discourage or destroy marine growths and organisms attached to their hulls. Water is pumped from the canals to the fields for farm and urban irrigation, and because many plants have a low salt tolerance, even mildly salty water usually cannot be used. Fresh water is preferred for cooling purposes in power stations and industrial establishments, and often the canals are used directly as sources of fresh water.

SALINITY INVESTIGATIONS

AREAS STUDIED

In view of the nature of the problem, the area of most intensive study was in the lower reaches of the Miami Canal. The secondary tidal canals of the Miami area, from Snake Creek Canal on the north to Snapper Creek Canal on the south, were also studied, starting in the spring of 1940. Data were collected to show the changing position of the salt front as affected by various water conditions.

Continuous drought conditions in 1943 and 1944 aroused interest in salt-water contamination in the Fort Lauderdale area. A reconnaissance sampling program was started in the tidal reaches of the lower New River basin in 1944 and was continued through 1946.

The destruction of crops by salty water in the marl flats east of Homestead activated interest in the contamination problem, and salinity investigations were started there in 1945. These studies also included the area to the south and southwest of Homestead. In addition, a number of special studies were made of smaller sections within the areas mentioned above.

SAMPLING PROCEDURE

Observation stations were established along the canals at fairly uniform intervals, particularly at bridges, to facilitate field work. Where bridges were not available, samples were taken from the canal banks. Locations other than the regular stations were used when additional detail was wanted. Observations were also made in lakes (usually in rock pits) connected with the canals and open to contamination.

Sampling procedure was simple. A sampling device holding a small corked bottle was lowered or thrown in the water. At the desired depth, the cork was withdrawn by jerking the line attached to the sampler, and the bottle was filled with water. Most of the samples were taken near the bottom of the canals, where salty water appears first and where the highest chloride concentrations occur. For special studies, samples were taken at other depths and at the surface. The samples ordinarily were collected at or near the time of high tide at the particular sampling station. The most difficult phase of the sampling procedure was the problem of coordinating the time of the collection with the time of high tide at numerous locations in a relatively large area.

DENSITY CURRENTS AND HYDRAULIC RELATIONSHIPS

Two or more miscible solutions of different specific gravities tend to remain unmixed when brought together under non-turbulent conditions, even when the difference in specific gravity is very small. The difference may be the result of suspended material (sediment) in one of otherwise similar solutions; it may be the result of temperature differences between identical solutions; or the solutions may be different in composition. When two such solutions are brought together, one will stay above or sink below the other, but motion will continue until hydrostatic balance has been established. When a liquid enters another liquid of slightly different density, the two liquids tend to maintain their separate entities, and the resulting relative motion of one of these liquids to the other is known as a density current. The phenomena of density currents have been described by a number of observers; one of the better general references is a paper by Bell (1942).

DIVIDED FLOW AND SHAPE OF DENSITY CURRENTS

The density currents discussed here are those occurring in natural waters, particularly where fresh and salt waters meet. The fresh water considered here is assumed to have a specific gravity of 1.000, and ordinarily this will be nearly correct. Normal sea water at Miami has a specific gravity of 1.027 (see p. 573), but it may be as high as 1.032 in shallow water where evaporation has increased the concentration; it will be lower where mixing with fresh water has occurred. Normal sea water in this area contains about 19,800 ppm of chloride. The surface waters of the Miami area range in chloride concentration from 15 ppm for fresh water in the Everglades to as high as 26,000 ppm where pools of highly contaminated water have partly evaporated.

Where a stream enters a body of salt water, the fresh-water discharge does not immediately mix with the salt water; instead, it may keep its identity as fresh water for a considerable distance.

The fresh water moves over the top of the larger body of water in a layer of decreasing thickness until it fans out and is dispersed by wind and wave action.

When fresh-water discharge in a tidal canal decreases below some critical quantity, salt water enters the mouth of the canal and moves upstream in a halting fashion underneath the outflowing fresh water. The salt water moves as a long tongue and is quite sharply separated from the fresh water, except for a narrow zone of intermixing. The tongue of salty water has a fairly steep front and the activity at the front is caused by friction and the impact with the fresh-water current. The interface between fresh and salt water extends toward the bay with an increasingly thick zone of mixed water. Depending upon the amount of fresh-water runoff, the interface disappears either at some point downstream or in the bay. Some mixing occurs as a result of wind and wave action, irregularities in the channel, and the effect of tributaries. Under the conditions just described the flow in the canal may be divided into two currents moving in opposite directions. Under other conditions, as discussed in the next section, both currents may be inland, or both toward the bay, but not necessarily with the same velocity.

A most interesting effect has been observed near Miami in Snapper Creek Canal, which is tidal in its lower reaches. This curious effect occurred when the canal was rising as a result of tidal rise in Biscayne Bay. A surface layer of fresh water about 0.8 ft deep was flowing downstream at a velocity of about 2 fps, and underneath this layer, 2 ft of strongly salty water was flowing upstream at 1.5 fps. The two currents seemed to be quite uniform, as indicated by small pieces of suspended material. In the surface between the two layers of water (the interface) were a number of small yellow elliptical leaves, roughly 9 in. apart horizontally. These leaves defined a plane and were motionless despite being only a fraction of an inch from waters moving swiftly in opposite directions.

THE MECHANICS OF SALT CONTAMINATION

The inland movement of salty water in tidal canals is based upon the relative densities of the waters, the quantity of fresh-water runoff, and tidal action. Salt water, as compared with fresh water, has a "density head" of 0.027 ft for each foot of depth; that is, it takes 1.027 ft of fresh water in a U-tube to balance 1.000 ft of sea water. This means that where a fresh-water stream 10 ft deep meets a bay, the fresh water must have a head of 10.27 - 10.00 = 0.27 ft if the salt water is to be kept out of the stream.

The flowing stream, in turn, has a head that is a function of the velocity; that is, the energy of the stream's motion is equivalent to a certain amount of static (or vertical) head. This is expressed in the relationship: velocity head, $h = \frac{v^2}{2g}$, in which v is the velocity and g is the acceleration due to gravity.

In the case cited above, the mean velocity of the stream would have to be 4.2 fps to keep the sea water out of the canal. If the velocity were less, the sea water would move upstream to where the velocity head plus the elevation head (the difference in elevation between the stream and bay at that point) equalled the density head of the bay. Thus, the salt water moves inland as fresh-water runoff decreases below the critical amount necessary to keep the stream fresh. Each location along the stream, in turn, has a critical rate of discharge which decreases inland.

The actual situation is not nearly so simple as this discussion implies because the stage of a tidal bay changes continually and movements of fresh and salt water are complicated by friction, obstructions, and tidal variations.

Tidal variations affect the stage and discharge of a tidal canal, and therefore the movement of the salt tongue also varies. Thus, with decreasing runoff, the tongue moves farther and farther inland with an intermittent motion. Upstream from the tongue, and over it, the fresh water alternately slows and accelerates toward the sea.

When the flow of fresh water decreases below another critical rate, reverse flow begins in the entire cross section near the mouth of the canal. The action of reverse flows and negative slopes is described in detail starting on page 444. When negative slopes occur in part of each tide cycle, the inland movement of the tongue is accelerated, but the mass of salty water does not move so fast as the reversal points, which travel as a function of storage rates. The same principles of velocity, elevation, and density head still hold as the salty water continues inland. The ultimate condition is reached when discharge from the upper reaches is less than the losses along the lower reaches, which result from evaporation and use. No fresh water reaches the sea; instead, the fresh water retreats and a net flow inland occurs. When this happens, a tidal canal will soon become contaminated throughout unless salinity controls are installed and operated.

When rains cause increased runoff after the end of a dry period, the salt tongue moves downstream in the same manner that it moved upstream and in response to the same natural laws. At a specific rate of increased discharge, reverse flows cease and all flow is positive. At a greater specific rate of discharge, the canal is cleared of all salty water.

Salt-water intrusion in tidal canals is retarded by constrictions, which increase the velocity of the fresh water and thus check the inland movement of salt water. Shoals affect flow the same way, but, in addition, they also act as submerged dams and delay the progress of the salt tongue along the bottom of the canal. If a shoal decreases the channel depth say, by about 25 percent, the salty water may be held back for a period of several weeks depending also upon other factors.

Aquatic vegetation retards the flow of both fresh and salty water and may be a beneficial factor in drought periods. The dense masses of bottom-rooted aquatic weeds that infest the canals of the Miami area act as dams, literally thousands of them, which individually are unimportant but which in the aggregate constitute an effective barrier. This damming effect reduces runoff and wastage of fresh water and blocks the inland movement of salty water. In the drought year of 1945 the aquatic weeds undoubtedly delayed the inland movement of salty water and shortened the period of high-chloride concentrations that existed at inland locations.

Dams in the Miami area can be used effectively to stop the intrusion of salty water. The problem is complicated, however, by the highly permeable nature of the rock formations through which the canals were mainly excavated. If a dam lacking a cut-off wall in the aquifer is closed so late in a drought period that negative heads develop at the dam during each tide cycle, salty water tends to seep through the porous rock beneath and around the ends of the dam and thus re-enter the canal above the dam. This may also occur if the drought is unduly prolonged, even though the dam may have been closed at a time when positive heads could be held.

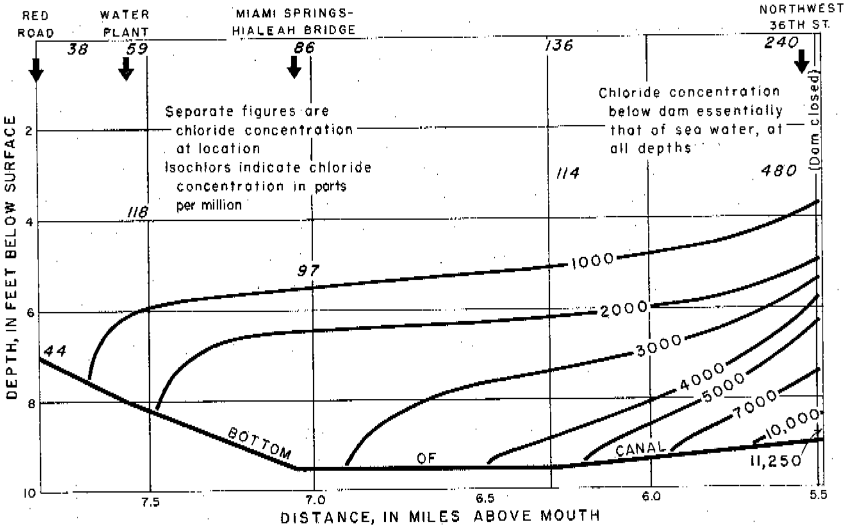

Figure 179. —Profile of Miami Canal above NW. 36th Street Dam showing chloride concentrations on May 15, 1945.

A condition that existed above the NW. 36th Street Dam in Miami Canal, on May 15, 1945, is shown in figure 179. At that time, the dam was temporary, consisting of interlocking steel piling. Negative heads occurred every high tide, and the water had almost the same concentration as sea water at the downstream face of the dam; therefore a sizable amount of leakage and seepage occurred that contaminated the canal for about 2 miles above the dam. It is fortunate that the rate of contamination was relatively slow because the situation with respect to the well fields was highly critical. Above the dam, the elevation of the water was 0. 55 ft, while the tidal stage below the dam averaged 0. 42 ft. The downstream stage at high tide on May 15 was 1. 62 ft, and a few days earlier it had reached a high of 1. 93 ft. The profile shows that salty water was still passing the dam, because the isochlors sloped inland. The typical rounded front also shows that a condition of hydrostatic balance had not been established. In this case, the trend of the intrusion was in one direction (inland), but the pattern observed resembles the patterns found where the salt front moves a considerable distance back and forth during each tide cycle. Note the more or less uniform gradation from relatively uncontaminated water to contaminated; this was also found along other profile planes parallel to the centerline of the canal.

Chloride concentrations in a canal are lowest at the surface and grade to the highest at the bottom. The gradation occurs whether the salty water in a canal is moving or still. Figure 180 illustrates the manner in which chloride concentrations vary from the bottom to the surface of a canal at a given location. The data for the sections were obtained at the same time as the data for figure 179.

The nearly horizontal layering of the salty water is evident. The variations in the figure from truly horizontal layering may have several explanations. The effect of wind on the relatively still pool that existed at the time may have caused enough turbulence to mix the water in some degree. This is supported by the fact that moderate chloride concentrations are found in the upper half of the canal prism, indicating that the fresh water from upstream, which was normally low in chloride, was mildly contaminated. Another possibility is that the cone of depression that extended from the center of the nearby well field to the canal bank at that time induced seepage from the canal toward the wells. This view is supported by the fact that the isochlors dip downward on the side toward the principal well field.

It should be remembered that any mixture of salt and fresh water is a true solution. Salt water will not "settle out" in a still pool of contaminated water, and whatever degree of mixing has occurred is irrevocable. This does not contradict the fact that a gradation of increasing chloride concentrations occurs with depth. The gradation results from the fact that waters of varying degrees

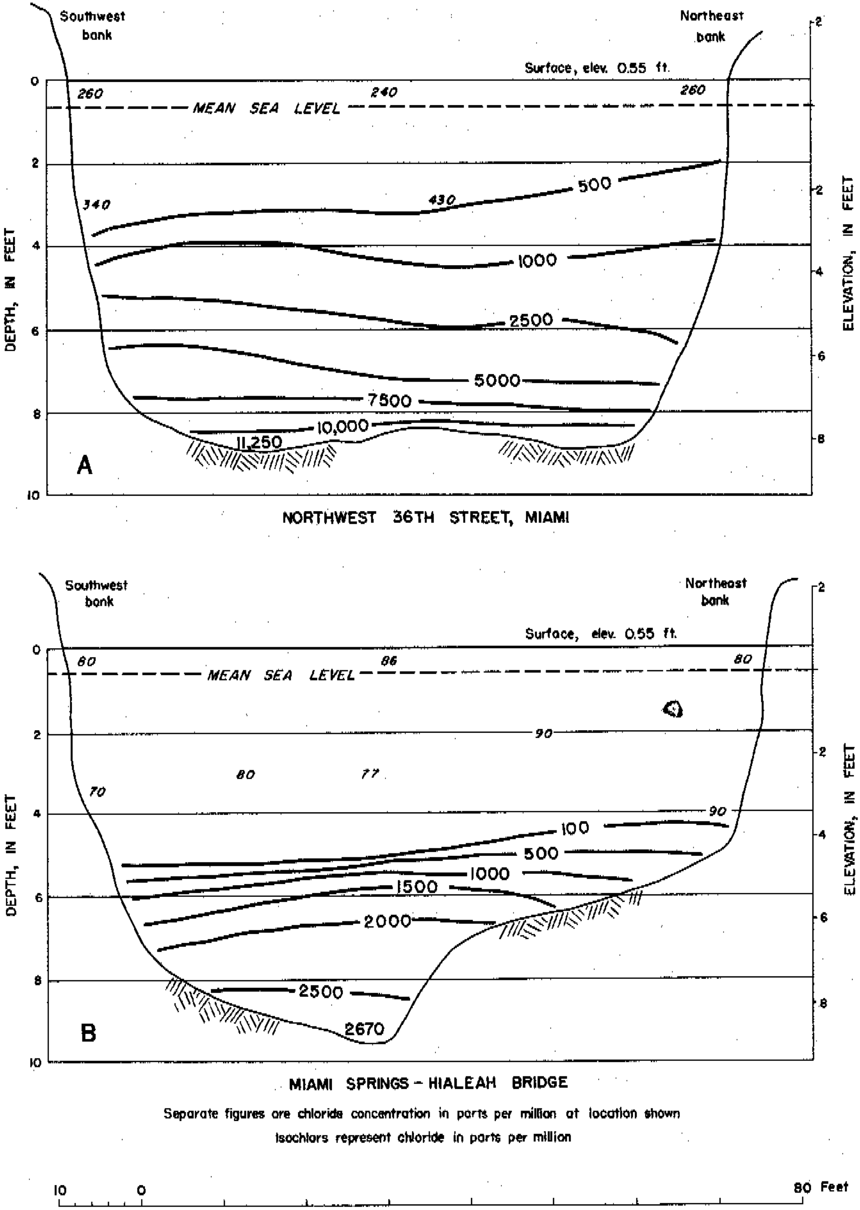

Figure 180. --Cross sections of Miami Canal, at NW. 36th Street and at the Miami Springs-Hialeah bridge showing approximate horizontal layering of salty water on May 15, 1945.

of contamination ordinarily do not have the opportunity to thoroughly intermix—turbulence is usually too small.

VARIATION OF CHLORIDE CONCENTRATION WITH TIDES

The variation of stage and discharge of tidal canals is discussed in detail in the section on Surface water, where it is shown that ordinarily the stage and discharge hydrographs are nearly opposed. At a location where the salt front is in a state of flux, chloride concentrations vary with tides in much the same manner as the stage hydrograph.

The vertical variations of chloride concentration in a tidal canal are shown in figure 181. Concentrations ranged between 2 and 70 percent of that of sea water, indicating the wide variation in contamination that can exist in a reach where the salt front is alternately advancing and retreating. At low tide, a small and nearly uniform degree of contamination was present. The curve for the high-tide condition shows that fresh-water discharge was completely stopped by the salty water; in fact, the flow was reversed. At the time of the observation, the net fresh-water runoff was quite small and the salt tongue was progressing inland.

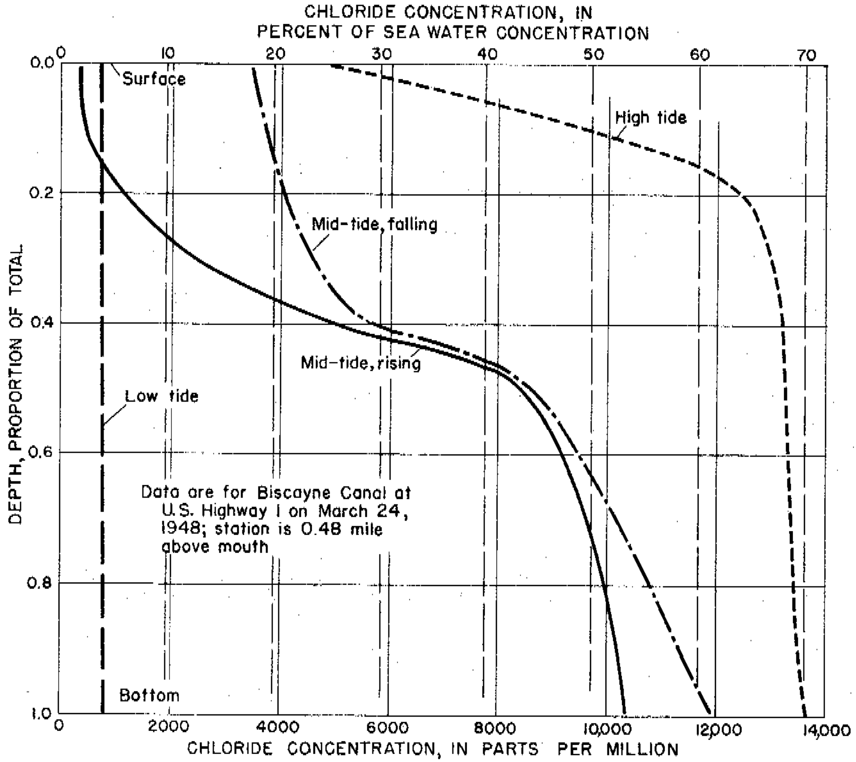

Figure 181. —Graph of vertical variations of chloride concentration in Biscayne Canal at four phases of a tide cycle.

The relationship among stage, velocity, and chloride concentration for Snapper Creek Canal at Coral Gables, Dec. 11, 1946, is illustrated in figure 182. As discharge is principally a function of velocity, the velocity curve can be considered essentially the same as discharge. The chloride and velocity observations were made at the bottom of the canal in the center of the breached salinity-control dam. The graph shows that the chloride varied in the same general form as the stage, but, more strikingly, the chloride varied inversely with the velocity, even to the minor variations.

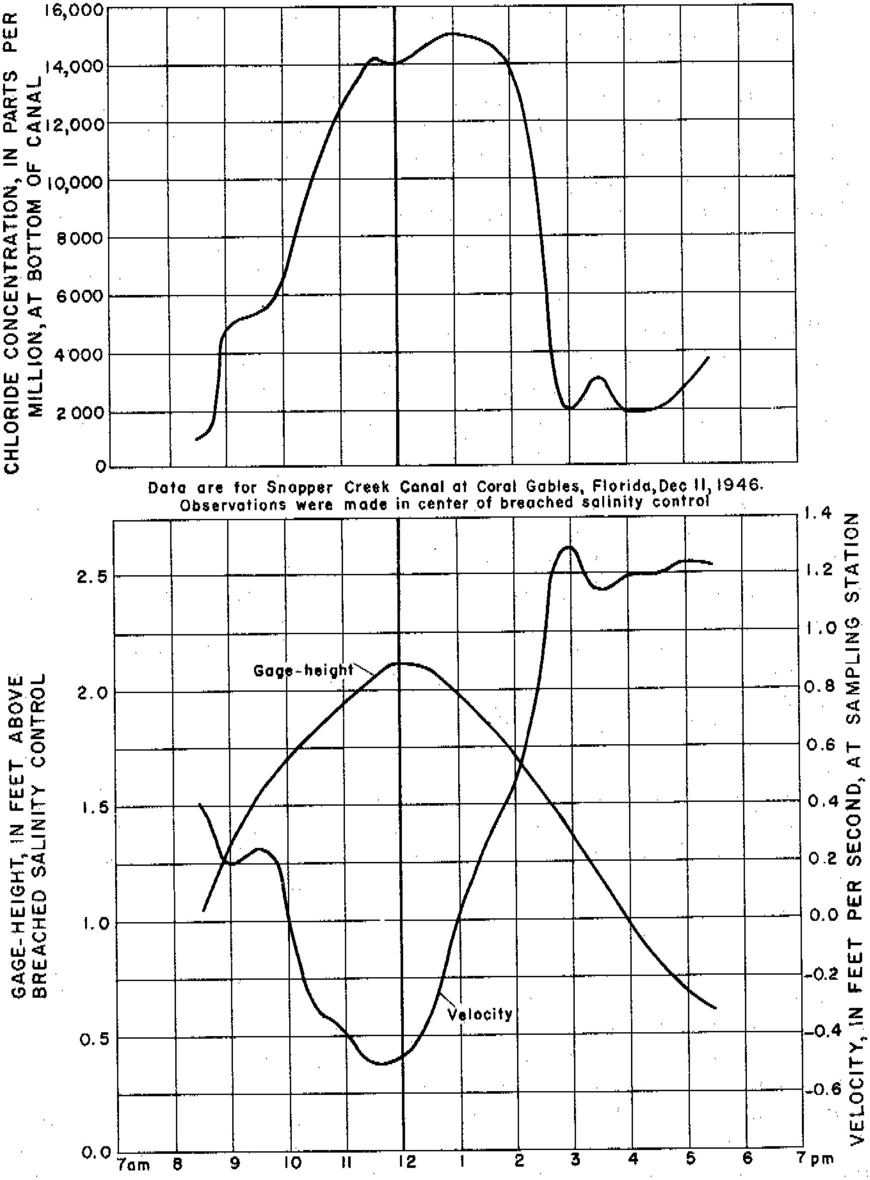

Figure 182. —Variations of stage, velocity, and chloride concentration in Snapper Creek Canal during one tidal cycle.

LOCATION OF SALT FRONT

The "salt front" of a tongue of salty water in a canal has been arbitrarily fixed as the location of the 1,000 ppm chloride concentration (about 5 percent of average sea water). Although lower concentrations often are significant, this degree of contamination is held to be critical. The salt tongue alternately advances and retreats as affected by tidal action and therefore the salt front likewise fluctuates. The 1,000 ppm concentration ordinarily is situated close to the inland end of the salt tongue, and thus it is an indicator of the extent of the contamination.

The salt front moves inland as discharge decreases, and it moves toward the sea as discharge increases. Just as tidal discharge may be expressed as a mean value for a day, the location of the salt front has a mean position that is related to mean discharge. For instance, it was found that a discharge of about 400 cfs in Miami Canal was required to hold the salt front below the site of the NW. 36th Street Dam (without the dam in place).

The change in the location of the salt front during a tide cycle may be considerable, as is demonstrated in figure 183. The distance travelled by the salt front was about 2 miles, and, at the lowest downstream location, the chloride concentration ranged between 600 and 14,000 ppm.

The high-tide profile shows an area of uneven chloride distribution at the surface near station 2. This may have resulted from turbulence connected with the point of reversal of flow, which was moving upstream at the time; or it may have been, in part, connected with the effect of wind. A strong area of contamination appears in the low-tide profile near station 5. This may have resulted from salty water being trapped upstream behind some high point or obstruction in the canal.

The movement of the salt front with tidal action illustrates the care needed to determine its position, especially the extreme inland position. Where canal water is used directly in an industrial process, the first salty water at the point of intake may disrupt the processing, even though the salty water may be present only a short time.

In the vicinity of well fields that are inducing infiltration from canals, contamination of the ground water may not be identified in the wells until an appreciable period has elapsed and a considerable volume of ground water has been affected. It is therefore especially important to know where the salt front is located and to take steps to stop its inland movement at a safe distance from the point of water use. In some cases, for example where pumpage from wells near the salt front is small, it may be satisfactory to permit salty water to penetrate to the vicinity of the well

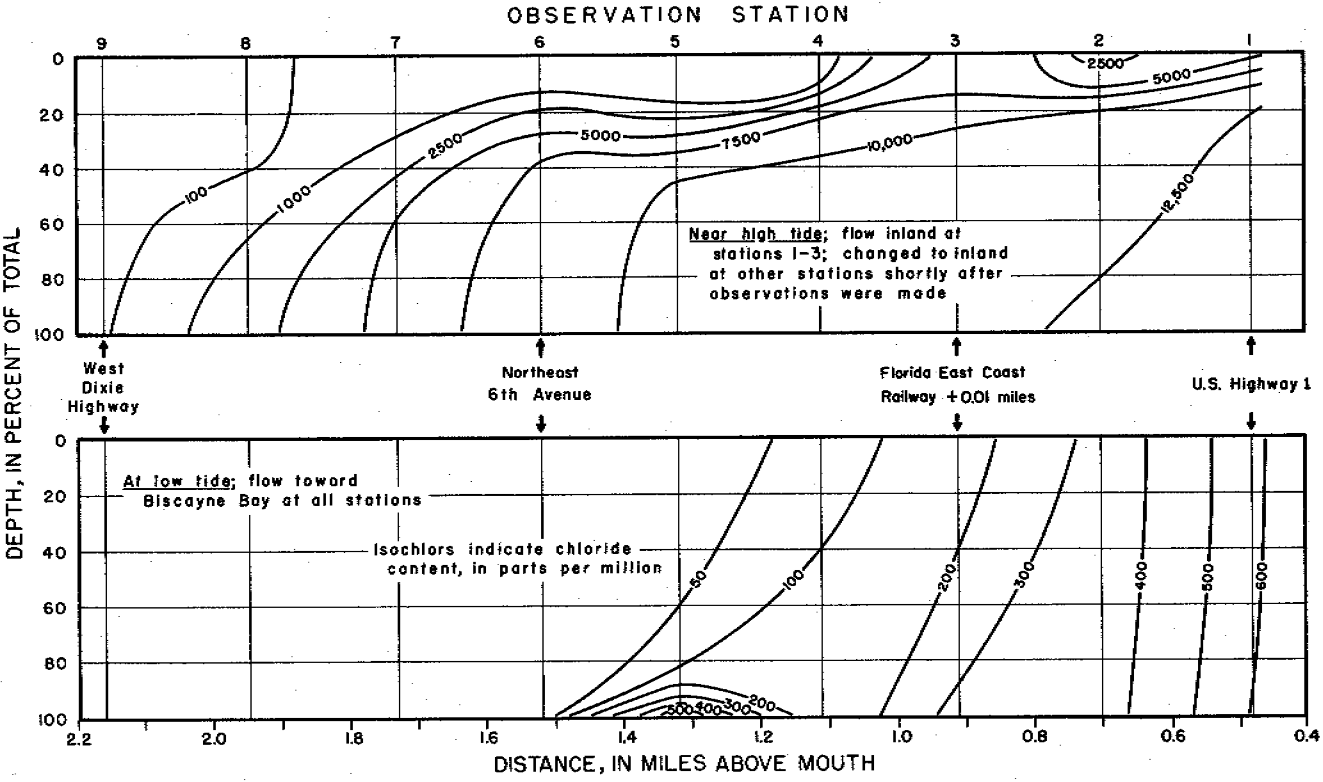

Figure 183.—Profile of Biscayne Canal showing isochlors at high and low tide on March 24, 1948.

field, as long as the average location of the front is safely downstream from the field. Where the cone of depression in the water table extends to the banks of the canal, the existence of salty water in the canal for any length of time will cause some degree of contamination, and the amount will increase with the length of time salty water is in the canal. This may occur even if salty water is present in the canal for only part of a tide cycle.

RESIDUAL CONTAMINATION

When drought conditions continue, runoff in uncontrolled tidal canals decreases to the point where salty water moves inland essentially unopposed, and net flow may be inland. This occurred in the Miami area in 1944 and 1945, when several of the shorter canals became contaminated throughout. Fresh-water runoff ceased, and seepage of salty water to the water table occurred along the canals. During the extreme condition in the spring of 1945, highly saline water was observed entering the ground with visible velocity at points where the bottoms of the canals were above the existing water table. That condition was not merely contamination of a small zone of ground water by contact, but was a direct pouring of salt water into the highly porous formation. It occurred continuously in the period when ground-water levels were below the bottom of the stub canals.

Drought conditions in southern Florida usually are relieved by the heavy rains of the summer and fall. Fresh-water runoff is resumed in considerable volume and salty water in the canals is usually flushed out. Sometimes, when water levels rise slowly, aquatic growth in the upper reaches of a canal may restrict runoff and cause salty water to remain in the upper channel for some time after the lower reaches have been cleared. This may continue until discharge is such that the weeds are beaten down and a flushing action occurs.

Either with or without the presence of weeds, salty ground water from the permeable formations along the upper reaches of a canal may contaminate the canal water. The ground-water levels rise in the formations that previously received salty water from the canals, and seepage toward the canals again occurs. Salty water then contaminates the fresh-water runoff in the canal and chloride concentrations may be found that are greater than those farther downstream. Not all of the salty ground water returns to the canal; some of it may gradually percolate through the formations to form a body of contaminated water beneath and adjacent to the canals. Such a contaminated body of water would be dissipated very slowly.

The extent to which salty water may remain in a canal channel, trapped either by weeds or a constriction, is shown by conditions that existed in 1945 in Opa Locka Canal, a tributary of Biscayne Canal:

Location	Chloride concentration (ppm)		
	June 29	*July 18*	*July 31*
Opa Locka Boulevard...	....	2,700	1,100
NW. 27th Avenue	21,900	19,700	10,000
Seaboard Air Line Railroad.................	42	1,800	73

The contaminated area in the vicinity of NW. 27th Avenue ultimately was flushed of highly saline water, but contamination existed there long after the salt front had been forced far downstream in all canals in the area; a sizable body of ground water probably remained in a contaminated state for a longer period.

MIAMI AREA

MIAMI CANAL

As all of the canals in the Miami area are connected with Biscayne Bay, salty water can move inland easily, the distance depending upon the amount of fresh-water runoff and the condition of the canals. During periods of moderate to heavy runoff the salty water usually is within 1 or 2 miles of the bay. During an extended dry period, however, salty water has moved inland more than 11 miles in Miami Canal, and two of the shorter canals have become contaminated throughout.

Miami Canal was uncontrolled between 1931 and 1943, and the secondary canals were not controlled until 1945–46. Samples from Miami Canal were collected periodically by the Miami Department of Water and Sewers during the period 1939 to 1946, the frequency of collections depending upon water conditions. In April 1940, the Geological Survey began a sampling program in which semimonthly series of samples were collected from Biscayne, Little River, Tamiami, and Coral Gables Canals. In April 1941, the work was extended to include Snake Creek and Snapper Creek Canals.

Surface and bottom samples were collected from about six regular sampling stations along each canal. Beginning in October 1942, only bottom samples were collected, because, with very few exceptions, bottom samples contained the maximum amount of chloride at each location. No effort was made to obtain complete records of concentrations at every station; instead, the series of samples were collected to locate the position of the salt front.

In the first several years, samples were collected from the six secondary canals without regard to tidal stages. The records, therefore, do not necessarily represent the maximum chloride concentrations. It is believed, however, that the data obtained define the trend of salt-water encroachment in the canals. Starting in 1944, the records were improved by collecting all samples from the tidal canals at times as close to that of high tide as was practicable.

The maximum chloride concentrations observed in the Miami area during the extreme drought of 1945 are shown in figure 184. The condition was serious and the only reason it was not worse in some of the canals is that their bottoms were exposed in places and salty water could not flow inland. Heavy weed growth also retarded movement of the salty water, and the dam in Miami Canal was partially effective.

The heavy contamination of Opa Locka Canal endangered the municipal wells at Opa Locka, and many smaller supplies throughout the Miami area were threatened or actually became salty for lengthy periods.

The most significant observation of the drought period in 1945 was at the western ends of Biscayne and Little River Canals. Water in Red Road Canal extended only about ¼ mile north and south of the ends of the two canals, and Red Road Canal was otherwise dry. Strongly salty water was observed running inland and sinking into the ground at the end of the wetted channel; thus, water with a chloride concentration three-quarters that of sea water poured directly into the aquifer. (Also see p. 630.)

The contamination of Miami Canal at Miami Springs was a real threat to the municipal well field. Fortunately, rainfall eventually forced the salty water in the canal downstream from the vicinity of the wells, but not before several of them were showing increased chloride content. The detection of the contamination of some of the wells in Miami Springs (ultimately, six of these 15 wells were significantly affected) naturally caused a large degree of concern, and arrangements were made to evaluate the problem and to explore for possible other sources of supply. The obvious source of salty water in the wells was Miami Canal, and a sampling program was established to observe the extent and degree of intrusion. Reconnaissances were made of all possible sources of water, reaching as far afield as Lake Okeechobee. In the meantime, the contaminated wells were pumped to waste, and a careful watch was kept on the chloride content of the other wells.

The first series of samples from Miami Canal, obtained April 25, 1939, showed a chloride concentration of 6,700 ppm at Water Plant, which is 7.7 miles upstream from Biscayne Bay, and decreasingly salty water was found as far as 2 miles farther inland.

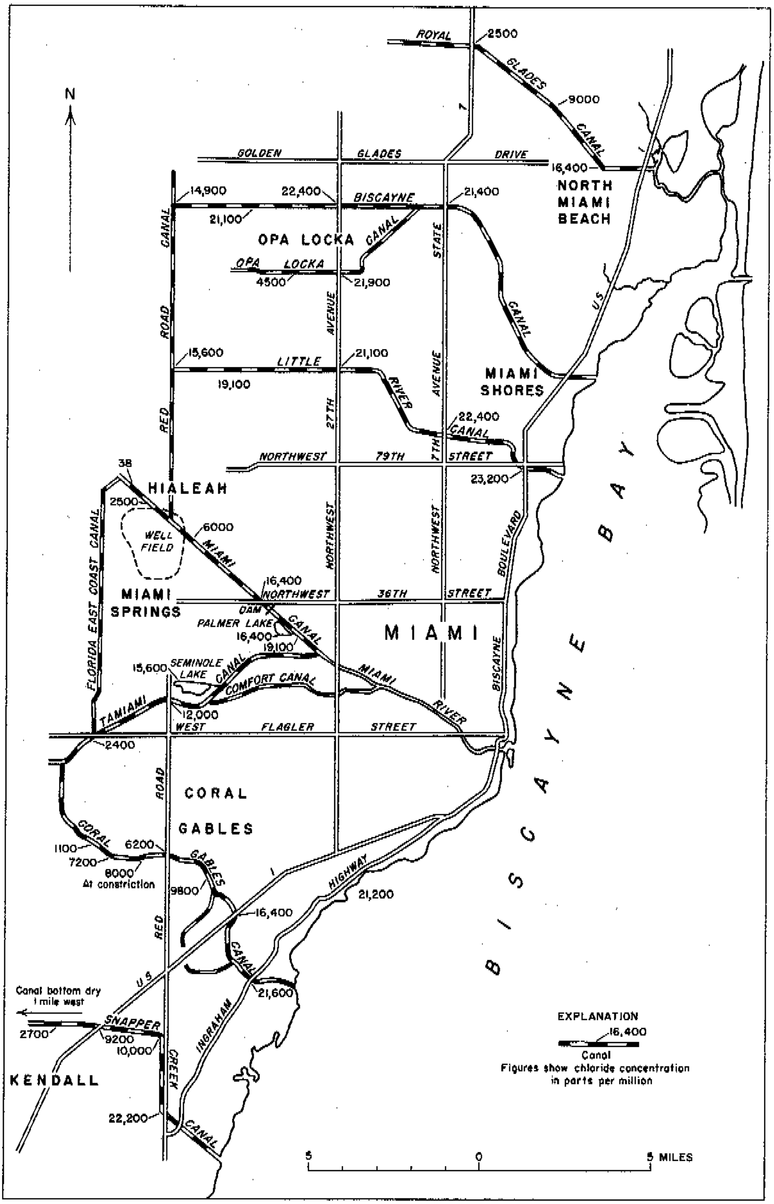

Figure 184.—Map of Miami area showing maximum observed chloride concentrations in the tidal canals, May-July 1945.

The advance of salty water in the canal continued until early in May when the chloride concentration in the canal at Water Plant reached 13,450 ppm and at NW. 36th Street reached 17,000 ppm. The farthest inland point at which salinity in excess of normal was found was about 4 miles upstream from Water Plant, or about 11.5 miles from Biscayne Bay.

The chloride concentrations determined from samples collected at three locations on Miami Canal in 1939 are listed in table 71. The variations in location of the salt front inland correspond to variations in the fresh-water runoff of the canal. Rains during May and June of 1939 caused increased runoff and forced the salt front downstream. Salty water moved inland again to a moderate degree during August but the usual heavy runoff in the fall forced the salt front downstream to a more satisfactory location with respect to the public water supply.

Table 71.—*Chloride in Miami Canal during spring and summer of 1939*

[Bottom samples. Analyses, in parts per million, made by Miles R. Mountien, city chemist, Miami]

Date of collection	NW. 36th Street (5.7 miles from Biscayne Bay)	Water Plant, Hialeah (7.7 miles from Biscayne Bay)	3 miles NW. of Water Plant, Hialeah (10.7 miles from Biscayne Bay)
Apr. 20	14,900	6,700	26
25	14,700	6,700	25
27	12,450	800	25
May 2	15,350	10,850	180
8	17,050	13,450	1,800
11	7,500	600	37
19	10,750	750	27
23	2,050	300	25
26	...	300	...
June 8	...	88	...
19	...	44	...
27	8,150	34	...
July 19	144	111	...
26	92	32	...
Aug. 1	340	34	...
7	60	43	...
14	1,900	33	...
21	1,100	34	...
28	35	27	...
Sept. 5	80	[1]335	...
12	111	77	...
Oct. 2	45	23	...
9	45	22	...
23	...	22	...
30	...	32	...

[1] Caused by salty water in city supply wells 13, 14, and 15 being pumped into canal.

Some of the data collected by the Miami Division of Water Supply are plotted in figure 185, which shows the most extreme condition of salt contamination in the Miami area that has been observed by the city or the U. S. Geological Survey. Irregularity of the curves may be due in part to the sampling procedure employed but may also be ascribed to variations in the cross section of the canal. The curve for May 11 shows that, although the main body of contaminated water had moved about 4 miles downstream (as compared with the condition of 3 days before), an appreciable degree of contamination remained in the canal above the main body of salty water.

Several hundred feet below the dam site at NW. 36th Street, at the head of the channel improvement completed in 1932, the channel of the canal becomes wider and deeper. There is a 4-foot step at the bottom of the canal where the change in depth occurs, which has a considerable effect on the movement of salty water in the channel. Salty water, moving along the bottom of the canal, is held by the step until the quantity and velocity of the overlying fresh water decreases to the point where the depth of the salty water becomes great enough to pass the step. Once past a barrier of this type, the salty water will move inland relatively swiftly unless checked by increased runoff or some other barrier. The proportions of the cross-section of a submerged barrier have little bearing on its effectiveness because it is the height of the barrier that is the important factor.

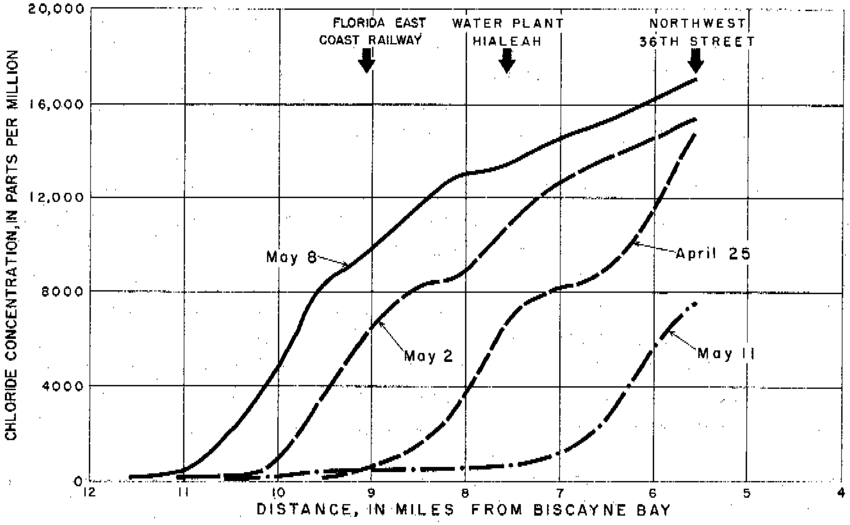

Figure 185. —Graph of chloride concentrations in lower Miami Canal during drought period of 1939.

LOCATION OF SALT FRONT

The relation of the position of the salt front in Miami Canal to the fresh-water runoff is shown in figure 186. The record to June 1943 includes the combined discharge of Miami Canal at Water Plant and Tamiami Canal at Red Road. Also included on the graph is a continuous log of the installation and operation of dams at NW. 36th Street. In regard to the periods in which the dam is indicated as being partly open, no attempt was made to record the amount of the opening, which varied from nearly closed to widely breached.

The principal characteristic of the salt-front discharge graph is the opposing effect of the two quantities—the salt-front curve drops when the discharge curve rises, and vice versa. This demonstrates the effect of increased discharge in forcing the salt front downstream, the effect of the dam operation at NW. 36th Street, and the steady inland advance of the salt front during drought periods. It will be noted that in the period of record the farthest downstream location of the front was just below NW. 12th Avenue.

From information obtained during the study it appears that when the combined discharge of Miami Canal at Water Plant and Tamiami Canal at Red Road is in excess of about 1,000 cfs, salty water is flushed out of the canal as far downstream as NW. 27th Avenue. When the sum of the discharges at the two gaging stations is 1,000 cfs, it is probable that the discharge at NW. 27th Avenue is greater than 1,000 cfs, owing to the intermediate ground-water inflow. Further study shows that a discharge of approximately 400 cfs is required to hold the salty water at NW. 36th Street. The differences in the quantities of flow at the two locations is a reflection of the relative areas of the channels.

In discussing figure 186, the yearly graphs are taken in chronological order. It should be remembered that the locations shown for the salt front represent the point of the salt tongue as it lay in the bottom of the canal but do not necessarily indicate that the entire cross section of the canal was contaminated. The discharge curves were plotted from daily mean discharges, which do not indicate the tidal variations of discharge but which give a truer picture of runoff conditions. The discharge curve for Miami Canal at Water Plant is the same as that appearing in figures 117–123.

1940.—With the usual dry winter conditions developing, the Miami Division of Water Supply started a sheet-steel piling dam at NW. 36th Street in mid-January. Construction of a boat lift to move small craft around the dam was carried on at the same time and the dam was not closed until April 26 according to A. B. DeWolf, of the Miami Board of Waters and Sewers. Early in May, the crest of the dam was lowered from 2.0 ft to 0.5 ft at the request of farmers adjacent to the canal upstream. Hinged wooden

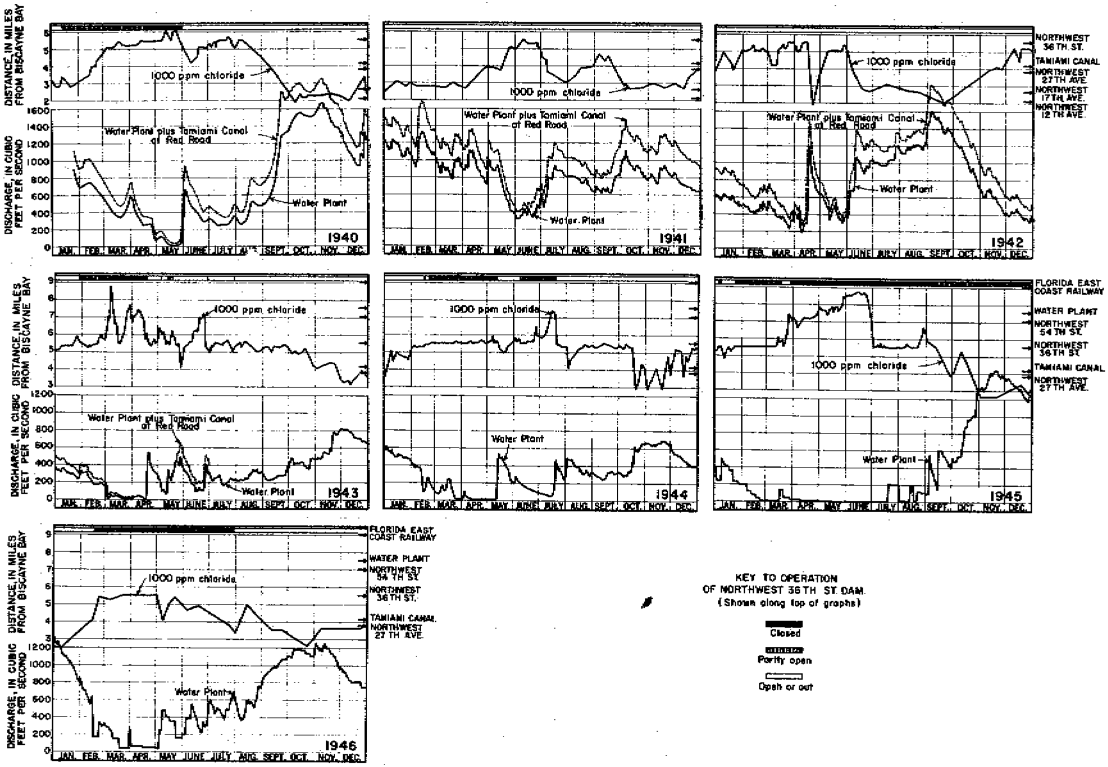

Figure 186. —Graph of location of 1,000-ppm chloride concentration and discharge of Miami Canal, 1940-46.

gates were installed on the dam to permit overflow toward the sea and to prevent reverse flow at high tide. The effect of this activity may be observed in the chloride graph. Some salty water passed the dam and reached the Miami Springs–Hialeah bridge, where a concentration of 800 ppm was observed, but no salty water reached Water Plant.

On May 24, County Line Dam, 16 miles upstream, was breached to release water from the reservoir area above the dam—the effect shows on the graph. Heavy rains at the end of May alleviated the situation and early in June the 36th Street dam was removed. Rainfall in the early part of the summer was very light and in July the salt front again reached the vicinity of NW. 36th Street. However, increasing amounts of rain, starting in August, forced the salt front downstream to the vicinity of NW. 12th Avenue, and no further threat occurred. The fall and early winter period was relatively wet and was noteworthy because the peak discharge of Miami Canal did not occur until early in November.

1941.—With sizable carryover of water in the hinterland from the preceding year and with rains in the normally dry winter period, the inland movement of salty water did not become significant until June. The salt front reached the vicinity of NW. 36th Street only briefly in June and was no problem during the remainder of the year. It will be noted on the discharge graph that runoff was consistently above the 400 cfs required to hold the salt front below NW. 36th Street.

1942.—Following a rather dry winter period, the salt front reached the vicinity of NW. 36th Street several times but was never a threat to the municipal well field. The great storm of mid-April, one center of which was in the Hialeah area, forced the salt front far downstream, but the lack of sustained runoff soon allowed the salty water to move far inland. The increasingly heavy rains in the summer produced large runoff which reached a maximum early in September. However, rainfall in the remainder of the year was very scanty, runoff decreased, and by December the salt front was far inland, although the situation was not critical. It is suggested that the great drought of 1943–45 actually started in the last quarter of 1942.

1943.—With the salt front relatively near the well fields for the early part of the year, and with no large rainfall anticipated for several months, the Miami Department of Water and Sewers late in January started the construction of a pneumatic dam for NW. 36th Street. A temporary emergency dam was constructed to provide protection while the new steel dam was being installed and a large gate was provided to permit boat passages. Because of boat traffic and a sizable amount of leakage around the dam, salty water moved inland to a point more than a mile upstream from Water Plant. Moderate rainfall, augmentation of the available water by release of supplies from the upstream reservoir, and the completion of the new dam improved the situation, but a critical condition existed until mid-April. The usual rains in the spring and summer gradually forced the salt front downstream from the critical zone, but at the end of the year it was still far inland. The maximum chloride concentration observed in samples collected from Miami Canal opposite Water Plant was 7,800 ppm on March 6.

1944.—The salt front progressed steadily inland early in the year and the pneumatic dam was operated starting in mid-February—the chloride graph shows the effectiveness of this operation. However, a certain amount of leakage occurred through and around the dam structure and probably a much smaller amount seeped through the rock and beneath and around the ends of the dam. This permitted quantities of salty water to move inland nearly to Water Plant. This action was caused by the occurrence of negative heads on the dam as great as 2 ft at low tide. The pneumatic dam was lowered to the bottom of the canal in July and was not operated thereafter. Rainfall and runoff were only moderate, however, and at the end of the year a near-critical condition existed.

1945.—With salty water in the vicinity of NW. 36th Street, the dam was operated in a partly opened position starting early in January. On March 17, the dam failed, and, until a temporary sheet piling dam was installed 10 days later, a condition of unobstructed flow occurred. In this critical period, salty water moved upstream to the vicinity of Water Plant and despite the emplacement of the temporary dam, remained there for a period of 3 months and even moved farther inland, nearly to the Florida East Coast Railway bridge. Rains at the end of June flushed the salty water downstream as far as NW. 36th Street, where it remained at the downstream face of the dam until the last part of August when a short incursion occurred. The second period of contamination above the dam was short, and soon afterwards the salty water started moving downstream. By the end of the year it was in a favorable location insofar as the protection of the public water supply was concerned.

1946.—A nearly water-tight temporary sheet-piling dam was in operation from mid-February to the end of July. Despite the fast decline in runoff early in the year, the salty water was held effectively at the downstream face of the NW. 36th Street dam for more than 2 months. Increasing runoff in the remainder of the year obviated any further need for the dam.

From the preceding discussion it is apparent that properly constructed barriers can effectively hold the inland movement of salty water. Despite the inevitable leakages that occur and the tendency of the salty water to by-pass the dams through the permeable formations, the dams were highly effective.

The chief problem in the operation of any dam at NW. 36th Street was that of protecting the municipal water supply and at the same time meeting the water-level demands of land owners adjacent to the canal above the dam. Because of the legal aspects of the problem, emplacement and operation of the dams was sometimes delayed longer than the technical aspects of the problem indicated, with the result that too much water was lost to the sea and not enough remained to hold the desired water levels above the dam. In 1945 the problem was resolved, in part, when Dade County was constituted by legislative action as a water control district and took over the operation of the 36th Street dam.

The dams at NW. 36th Street can be considered to be experimental to a large extent and to have shown that, despite the well-known permeable nature of the adjacent limestone formations, a useful and important degree of water control can be achieved; in fact, properly built and properly operated structures are the only way that satisfactory water control and reduction of contamination can be accomplished. The problem and its solution concerns not only the canals and waterways but also the contamination of underground water.

PALMER LAKE

Just east of the Seaboard Air Line Railroad and south of Miami Canal is Palmer Lake, a rock pit area of about 20 acres that is connected to Miami Canal (see fig. 184). As it is uncontrolled, the lake is subject to unimpeded tidal action. Palmer Lake has a maximum depth of about 30 ft, and much of it is more than 15 ft deep. Its connection with Miami Canal is about 9 ft deep. When salty water moves up Miami Canal to the Seaboard Air Line Railroad and NW. 36th Street some of it enters Palmer Lake. The lake is much deeper than the canal; therefore this salty water tends to remain there after the canal and upper part of the lake are free of contamination.

The chloride concentrations in the lake often show a gradation from lowest at the surface to highest at the bottom. However, in periods of extreme drought, as in June 1945, the entire body of water becomes uniformly contaminated and may have chloride concentrations as high as 80 percent of that of sea water. Palmer Lake is significant, therefore, not only in the problem of contamination of ground water in the immediate vicinity, but it is also associated with the problem of protecting the municipal well field. In dry periods, only a low ground-water divide exists between Palmer Lake and the cone of depression around the wells. If, under continued drought conditions, this low divide should be dissipated, the lake would be another potential source of contamination for the wells.

TWIN LAKES

Twin Lakes is a small abandoned rock pit, now used only as a scenic attraction, in the center of Miami Springs (see fig. 189). Although smaller than Palmer Lake, it is even more of a threat to the municipal water supply because it is very close to the well fields. Fortunately, its connection to Miami Canal lies above the NW. 36th Street Dam. In periods when contaminated water moved above the dam, some of it entered Twin Lakes and moved toward the well fields. The entrance to the lakes is shallow, however, and no serious situation has occurred there. For the most part, Twin Lakes, has remained fresh or only mildly contaminated.

SNAKE CREEK CANAL

Because of its weed-choked channel and numerous constrictions, Snake Creek Canal has never offered an easy route for salty water to move inland. Thus, the salt front fluctuated over a relatively short reach of canal during most of the 6 years of observation. The chloride concentrations observed are presented in table 72. The lower reaches of Snake Creek Canal, south and east of the center of North Miami Beach, are normally contaminated during much of the year. In the wet season, however, the salty water usually is flushed completely out of the canal as far as its mouth at Oleta River. The most notable event shown by the record occurred in 1945 when salty water was detected at State Highway 7, which is 4.4 miles by canal from Oleta River. This occurred despite the heavy weed growth that existed in much of the canal, and the salty water must be credited with killing much of the growth. The salt front was stopped in 1945 by construction of a temporary dam in Snake Creek Canal at U. S. Highway 1.

Table 72.—*Chloride concentrations in Snake Creek Canal, Miami*

[Parts per million. Before October 1, 1941, the values are the highest obtained from either surface or bottom samples (usually the latter); after October 1, 1941, the values are from bottom samples. Mileages in parentheses indicate distance from mouth of canal at Oleta River]

Date	U. S. Highway 1 (0.18 mile)			Dixie Highway (0.38 mile)	Flagler Boulevard (0.76 mile)	Miami Drive (1.02 miles)	Miami Gardens Drive (2.41 miles)	State Highway 7 (4.39 miles)
	Prior to control	Below control	Above control					
1941								
Mar. 1	11,370	......	......	......	......	45	36	16
Mar. 14	780	......	......	......	......	37	33	17
Apr. 3	10,350	......	......	......	......	37	37	18
Apr. 18	165	......	......	......	......	42	35	19
May 1	11,670	......	......	......	......	31	30	20
May 20	11,470	......	......	......	......	36	31	20
June 4	17,560	......	......	......	......	37	29	20
June 17	18,890	......	......	......	......	660	27	21
July 3	17,650	......	......	......	......	61	23	20
July 17	205	......	......	......	......	33	21	13
July 30	14,140	......	......	......	......	35	29	18
Aug. 18	13,320	......	......	......	......	34	29	17
Sept. 3	15,250	......	......	......	......	33	31	20
Oct. 1	11,100	......	......	......	......	31	27	17
Oct. 17	11,500	......	......	......	......	37	33	19
Oct. 31	14,900	......	......	......	......	34	32	17
Nov. 14	8,780	......	......	......	......	27	23	17
Nov. 28	11,800	......	......	......	......	33	34	17
Dec. 26	1,130	......	......	......	......	37	32	18
1942								
Jan. 3	15,300	......	......	......	......	34	35	18
Jan. 16	12,600	......	......	......	......	34	33	18
Feb. 4	13,700	......	......	......	......	35	38	20
Feb. 17	17,700	......	......	......	......	402	30	18
Mar. 4	14,100	......	......	......	......	32	32	19
Mar. 19	17,500	......	......	......	......	55	34	19
Apr. 2	17,000	......	......	......	......	385	31	19
Apr. 28	74	......	......	......	......	30	30	15
May 8	75	......	......	......	......	35	33	17
May 22	5,680	......	......	......	......	42	36	19
June 9	160	......	......	......	......	37	26	16
June 24	122	......	......	......	......	38	27	14
July 9	135	......	......	......	......	43	28	17
July 24	880	......	......	......	......	31	27	19
Aug. 6	12,000	......	......	......	......	31	29	19
Aug. 22	15,100	......	......	......	......	26	26	18
Sept. 4	12,100	......	......	......	......	23	22	14
Oct. 7	13,750	......	......	......	......	24	23	15
Nov. 9	16,000	......	......	......	......	35	23	17
Nov. 14	......	......	......	......	......	......	31	......
Nov. 24	12,600	......	......	......	......	35	......	20
Dec. 10	16,000	......	......	......	......	36	27	13
Dec. 23	9,200	......	......	......	......	32	27	16
1943								
Jan. 6	14,550	......	......	......	......	34	28	18
Jan. 24	15,350	......	......	......	......	36	......	18
Feb. 8	16,120	......	......	......	......	30	26	16
Feb. 26	......	......	......	......	......	30	28	17
Mar. 15	16,450	......	......	......	......	210	25	17
Apr. 2	11,900	......	......	......	......	12,200	3,380	24
Apr. 17	19,200	......	......	......	......	......	2,400	30
May 5	14,800	......	......	......	......	360	155	17
May 15	18,300	......	......	......	......	164	98	15
June 1	15,800	......	......	......	......	......	109	17

Table 72.—*Chloride concentrations in Snake Creek Canal, Miami*—Continued

Date	U. S. Highway 1 (0.18 mile)			Dixie Highway (0.38 mile)	Flagler Boulevard (0.76 mile)	Miami Drive (1.02 miles)	Miami Gardens Drive (2.41 miles)	State Highway 7 (4.39 miles)
	Prior to control	Below control	Above control					
1943—Con.								
June 19	19,200	....	....	....	....	8,680	102	20
July 4	14,200	....	....	....	....	165	149	17
1945								
June 29	....	....	....	....	....	16,400	8,000	2,500
July 20	....	....	....	12,200	....	....	9,000	1,500
July 31	12,800	....	....	....	....	940	900	230
Sept. 3	14,000	....	....	....	....	420	378	34
Sept. 24	12,400	....	....	358	....	232	199	19
Oct. 4	9,620	....	....	....	....	....	....	....
Oct. 10	11,100	....	....	....	....	440	130	17
Oct. 15	13,100	....	....	....	....	....	....	....
Oct. 23	12,000	....	....	....	....	....	....	....
Nov. 1	298	....	....	255	....	105	61	20
Nov. 6	272	....	....	....	....	....	....	....
Nov. 13	260	....	....	....	....	....	....	....
Nov. 20	10,100	....	....	225	....	117	69	19
Nov. 27	10,100	....	....	....	....	....	....	....
Dec. 4	12,700	....	....	....	....	....	....	....
Dec. 10	13,000	....	....	8,780	....	101	100	72
Dec. 19	....	16,600	16,200	....	....	....	....	....
Dec. 26	....	15,200	86	....	....	....	....	....
1946								
Jan. 2	....	13,800	40	78	....	35	34	19
Jan. 9	....	15,800	56	....	....	....	....	....
Jan. 16	....	17,300	45	....	....	....	....	....
Jan. 23	....	17,500	108	....	....	54	28	19
Jan. 30	....	16,600	129	....	....	....	....	....
Feb. 6	....	17,500	220	....	....	....	....	....
Feb. 13	....	18,000	235	....	....	40	32	24
Feb. 20	....	18,200	245	....	....	....	....	....
Feb. 27	....	18,700	275	....	....	....	....	....
Mar. 6	....	18,700	250	....	....	68	38	17
Mar. 13	....	18,000	250	....	....	....	....	....
Mar. 20	....	19,200	265	....	....	....	....	....
Mar. 26	....	19,700	8,000	....	....	328	54	20
Apr. 3	....	19,100	970	....	....	....	....	....
Apr. 12	....	19,800	860	....	....	....	....	....
Apr. 17	....	20,400	5,680	....	....	315	50	24
Apr. 24	....	20,200	4,920	....	....	....	....	....
May 1	....	20,800	9,670	....	....	380	75	32
May 8	....	19,800	1,550	....	....	....	....	....
May 15	....	19,300	260	....	....	....	....	....
May 22	....	18,300	250	....	....	65	63	23
May 29	....	19,000	255	....	....	....	....	....
June 5	....	15,200	255	....	....	....	....	....
June 12	....	13,800	55	....	....	38	52	30
June 19	....	15,400	81	....	....	....	....	....
June 26	....	17,200	140	....	....	....	....	....
July 3	....	13,500	92	....	....	86	46	....
July 10	....	15,900	96	....	....	....	....	....
July 17	....	16,400	82	....	....	....	....	....
July 24	....	18,000	110	....	....	....	....	....
July 31	....	1,400	40	....	....	40	40	30
Aug. 14	....	17,200	140	....	....	....	....	....
Aug. 28	....	16,500	20	....	....	30	30	20
Sept. 11	....	13,600	13,400	....	....	50	....	....
Sept. 25	....	....	13,700	....	....	61	52	22

Table 72.—*Chloride concentrations in Snake Creek Canal, Miami*—Continued

Date	U. S. Highway 1 (0.18 mile)			Dixie Highway (0.38 mile)	Flagler Boulevard (0.76 mile)	Miami Drive (1.02 miles)	Miami Gardens Drive (2.41 miles)	State Highway 7 (4.39 miles)
	Prior to control	Below control	Above control					
1946-Con								
Oct. 9	....	10,800	249	....	....	....	....	....
Oct. 23	....	14,500	14,500	....	50	40	60	50
Nov. 6	....	12,200	12,000	....	50	....	....	....
Nov. 13	....	13,000	14,500	....	50	....	....	....
Nov. 20	....	14,500	14,500	....	50	50	50	10
Nov. 27	....	14,000	14,000	....	50	50	....	....
Dec. 4	....	15,600	14,000	....	6,600	50	....	....
Dec. 11	....	16,300	15,900	....	5,780	57	34	17
Dec. 18	....	15,000	5,100	....	40	50	....	....
Dec. 24	....	14,500	14,000	....	50	40	....	....
Dec. 31	....	17,000	14,000	....	50	50	50	30