Cyclic Flow of Salt Water in the Biscayne Aquifer of Southeastern Florida

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Abstract. Observations over a period of nearly 20 years confirm the fact that the salt-water front in the Biscayne aquifer along the coast of the Miami area, Florida, is dynamically stable at a position seaward of that computed according to the Ghyben-Herzberg principle. During periods of heavy recharge the fresh-water head is high enough to cause the fresh water, the salt water, and the zone of diffusion between them to move seaward. In addition to this bodily movement of the system, there is a seaward flow of diluted salt water in the zone of diffusion. When the fresh-water head is low, salt water in the lower part of the aquifer intrudes inland, but some of the diluted sea water in the zone of diffusion continues to flow seaward. Cross sections showing equipotential lines in terms of equivalent fresh-water head show that the sea water flows inland, becoming progressively diluted with fresh water, to a line along which there is no horizontal component of flow, after which it moves upward and returns to the sea. The cyclic flow acts as a deterrent to the encroachment of sea water because of return to the sea of a part of the inland flow.

Introduction. The basic premise of the Ghyben-Herzberg principle is that the position of the interface between fresh water and salt water in a coastal aquifer will be governed by a hydrostatic equilibrium between fresh water and the more dense sea water. *Hubbert* [1940, pp. 924–926] showed, however, that because fresh water was known to flow seaward, the position of the interface would be governed by a dynamic equilibrium between flowing fresh water and static salt water. This concept is shown in Figure 1 where the depth to a point on the interface (z) would be equal to the head of fresh water (h) with reference to sea level at the point on the interface multiplied by the ratio of the density of fresh water (ρ_f) to the difference between the densities of sea water (ρ_s) and fresh water. Observations over a period of nearly 20 years indicate that the salt front in the Biscayne aquifer of the Miami, Florida, area is dynamically stabilized seaward of the theoretical position given by either concept (Fig. 2). Recent studies indicate that the lack of agreement results from the fact that two assumptions inherent in the above developments are not fulfilled in the Biscayne aquifer. These assumptions are (1) that a sharp interface exists between fresh water and salt water in an aquifer and (2) that the salt water in the aquifer is static.

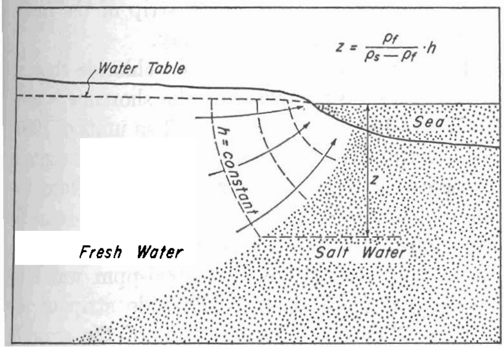

Fig. 1. Balance between fresh water and salt water in a coastal aquifer with the salt water static.

It is the intent of this paper to illustrate by field observations that the salt water is not static but flows in a cycle from the floor of the sea into the zone of diffusion and back to the sea and that the cycle acts to lessen the extent to which the salt water occupies the aquifer. The hypothesis of cyclic flow has been expressed by *Cooper* [1959].

Geologic and hydrologic characteristics. The Biscayne aquifer consists of solution-riddled limestone and calcareous sandstone. It is a water-table aquifer and extends from land surface to an average depth of 100 feet below msl (mean sea level). In general, coefficients of permeability are in the range 50,000 to 70,000 gpd/sq ft [*Parker*, 1951, p. 824].

The zone of diffusion. In the Biscayne aquifer the zone of diffusion is a zone of substantial

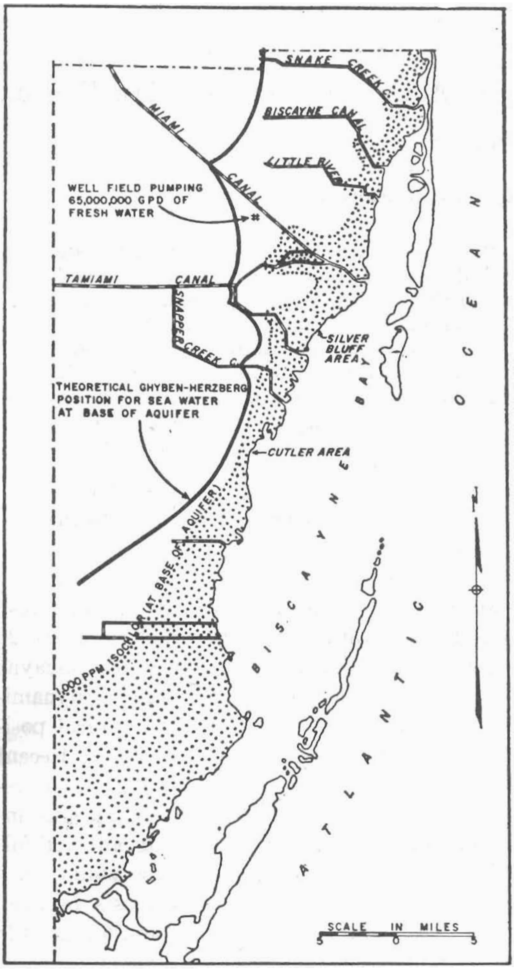

Fig. 2. Map of Dade County comparing the theoretical Ghyben-Herzberg position with the actual field position of salt water at the base of the Biscayne aquifer.

thickness in which there is a gradation of salt content from that of fresh water, 16 ppm (parts per million) chloride, to that of sea water, about 19,000 ppm chloride. Figures 3 and 4 are cross sections of the zone of diffusion in the Silver Bluff and Cutler areas; the locations of these areas are shown in Figure 2.

The distance from the bay to the inland toe of the wedge of salty water is more than 12,000 feet in the Silver Bluff area, but only about 1600 feet in the Cutler area. The toe of the wedge is blunt-nosed in each area. This convex-upward configuration of the salt front at the inland extremity is anomalous to the concave-upward parabola that would be present if assumptions of a sharp interface and static salt water were fulfilled in the field.

Seaward flow of salty water. The fluctuations of chloride content in well G 519A, which is 400 feet from Biscayne Bay in the Silver Bluff area, are shown in Figure 5 (also see Fig. 3 for position of the open-hole part of well G 519A in the zone of diffusion). The rapid decrease in chloride content at the three sampling depths during October 1953 resulted from a large increase in fresh-water head following heavy rainfall in early October. Salt water was rapidly expelled from the aquifer and the zone of steep concentration gradient (just below well G 519A in Fig. 3) was depressed downward and seaward.

A ground-water velocity test, with fluorescein dye used as a tracer, was performed at the site of well G 519A on January 4, 1954. The results of the test indicated that water containing 1500 to 2000 ppm of chloride (open-hole part of well G 519A, Fig. 3) was flowing seaward at a rate greater than 70 feet per day. This was considered quite significant because, obviously, a large quantity of salt water was flowing toward the ocean.

A rough calculation of the quantities of ground-water and salt outflow through a vertical section of the aquifer at the shoreline is pertinent. If the base of the seaward-flowing fresh-water section in the Silver Bluff area is assumed to be at the 5000 ppm isochlor (Fig. 3), the thickness of the flow section at well G 519A is about 35 feet. If the average velocity through this thickness is 70 feet per day and the effective porosity of the limestone is 0.2, the discharge of water through a 1-foot-wide strip of the fresh-water flow section is 490 ft^3/day.

From Figure 3, the average chloride content of the water discharging at the shoreline is estimated to be about 1900 ppm. Ten units of 1900-ppm water are closely equivalent in salt content to one unit of 19,000-ppm water; therefore, the equivalent of 49 ft^3/day of ocean water must b incorporated into the fresh-water flow section in order that 490 ft^3/day of 1900-ppm water b discharged from each 1-foot-wide strip of the aquifer. This rough calculation of the seaward movement of salt indicates that the ocean water being integrated into the fresh-water flow section

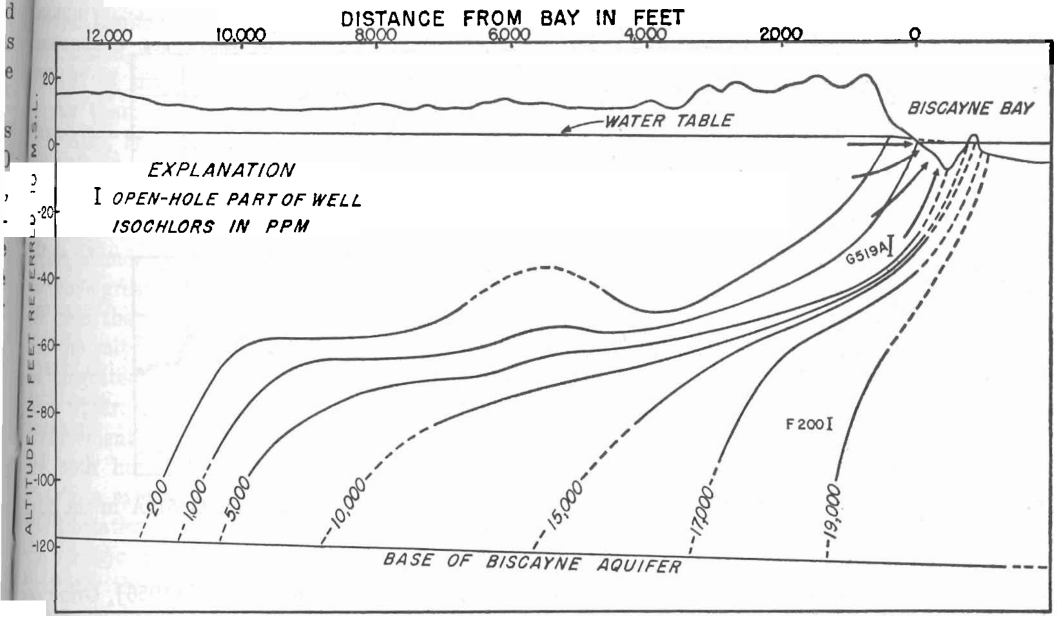

Fig. 3. Cross section through the Silver Bluff area showing the zone of diffusion, November 2, 1954.

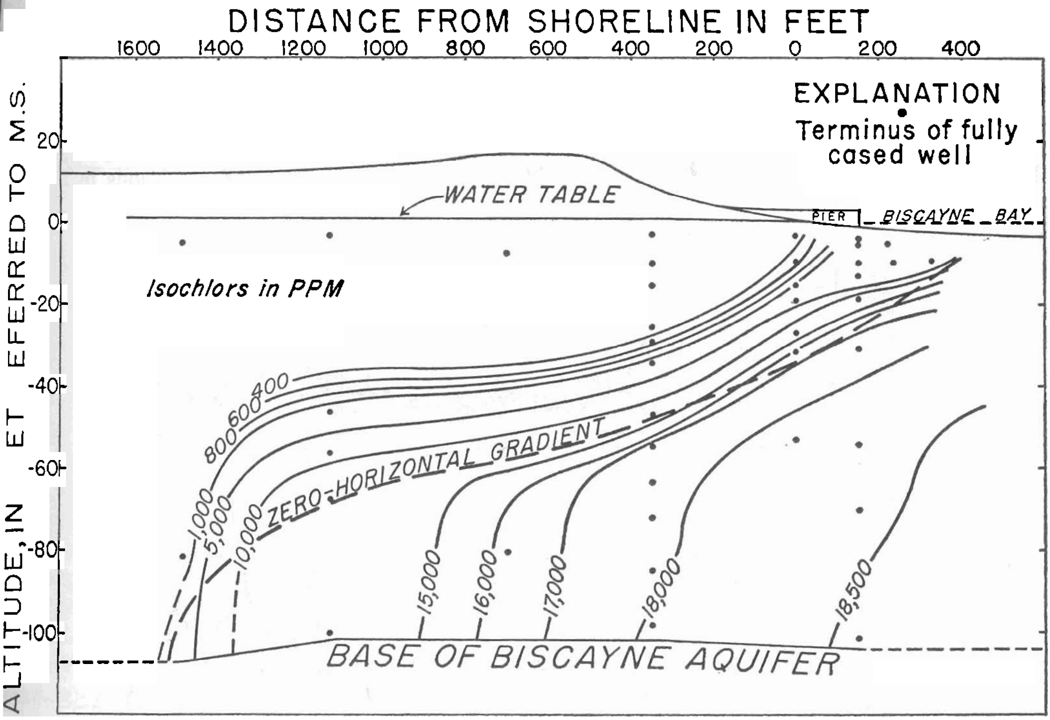

Fig. 4. Cross section through the Cutler area showing the position of the zero-horizontal gradient line within the zone of diffusion (traced from Fig. 10), September 18, 1958.

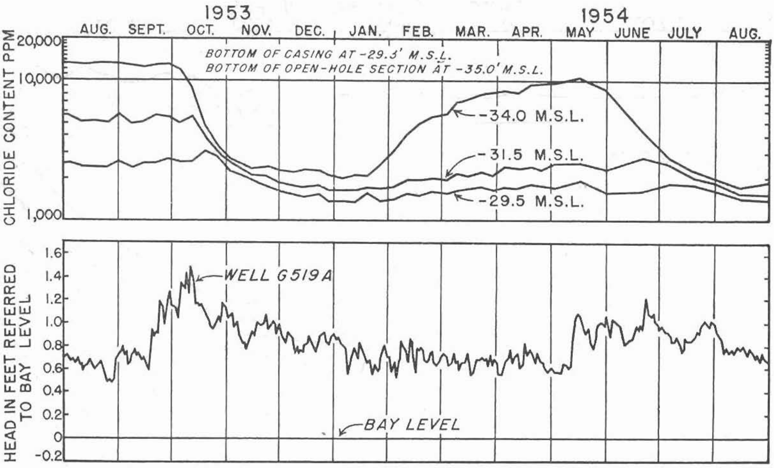

Fig. 5. Graph showing fluctuations of chloride content and water level in well G 519A in the Silve Bluff area.

may amount to 10 per cent (or more) of the total seaward flow of water.

Dispersion. As observations show that the diffused zone remains essentially unchanged although large quantities of salt are flushed back to the sea, it must be concluded that a mechanism much stronger than molecular diffusion is acting to recreate the zone of diffusion.

The growth of a zone of diffusion under a rinsing hypothesis has been described by *Wentworth* [1948, pp. 97–98]. More recent studies, by *Day* [1956], *Rifai, Kaufman, and Todd* [1956], *Kaufman and Orlob* [1956], *Orlob and Radhakrishna* [1958], and *Eriksson* [1958], have shown that variations of fluid velocity across the pores of a permeable medium will combine with molecular diffusion to cause a rapid intermingling of fluids of different concentration. This intermingling process is referred to as dispersion and consists of two separate mechanisms: convection, the mechanical transfer of one fluid into the region of another, and molecular diffusion [*Bosworth,* 1949, p. 465].

For an assumed set of conditions in a hypo-

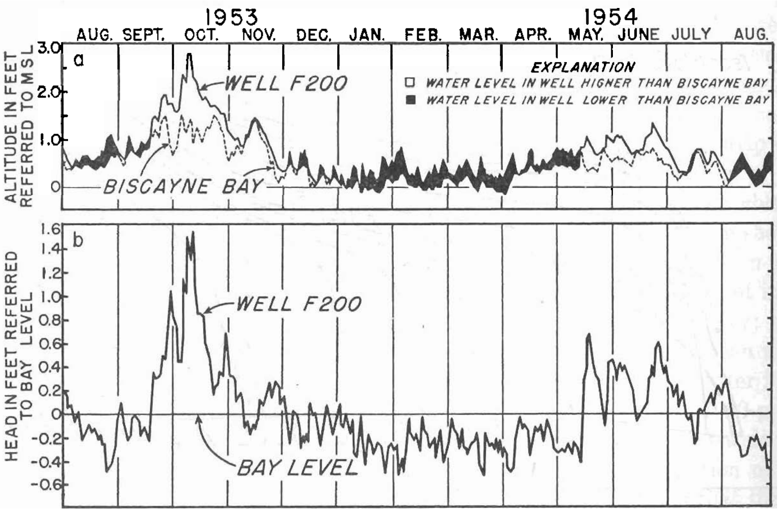

Fig. 6. Hydrographs of daily-average water level in well F 200 and Biscayne Bay.

thetical aquifer of sand under the influence of tidal action, *Cooper* [1959] calculated the coefficient of dispersion to be about 100 times greater than the coefficient of molecular diffusion. Also, he suggested that the coefficient of dispersion in an aquifer of nonuniform permeability may be considerably greater than that for a homogeneous aquifer. In the suggested mechanism, elements of salt water under tidal stimulus move greater horizontal distances in permeable beds than in adjacent less-permeable beds, and the salt-water projections thus formed will be integrated by the upward, cross-bed flow of fresh water.

Movement of ground water caused by the tide has both horizontal and vertical components. Clearly, a mechanism that permits a very rapid transportation and dispersion of salt is available.

Hydraulic gradient in the salt-water zone. Evidently the dispersion must occur at a rate large enough to maintain the zone of diffusion while a large quantity of salt water discharges seaward. To maintain this equilibrium, some means of transporting the salts from the floor of the sea through the aquifer and into the zone of diffusion must be available. However, in the regions below and seaward of the zone of diffusion (Figs. 3 and 4), the concentration gradient is too small for appreciable transportation of salt by dispersion. Therefore, the salts must be transported by hydraulic flow with an accompanying loss of head. In Figure 6, the daily-average water levels in well F 200 are compared with the daily-average water levels of Biscayne Bay. The chloride content ranged from 18,300 to 18,800 ppm during the period shown. The water level of the well, which closely represents the head of ocean water in the aquifer, is higher than the surface of the bay during heavy rainfall periods, as is shown in the unshaded intervals in Figure 6*a*, and lower than the bay during dry periods, as is shown in the shaded intervals. Clearly, the negative heads reflect the head losses of salt water as it flows landward through the aquifer. In Figure 6*b*, the daily-average head of the bay has been algebraically subtracted

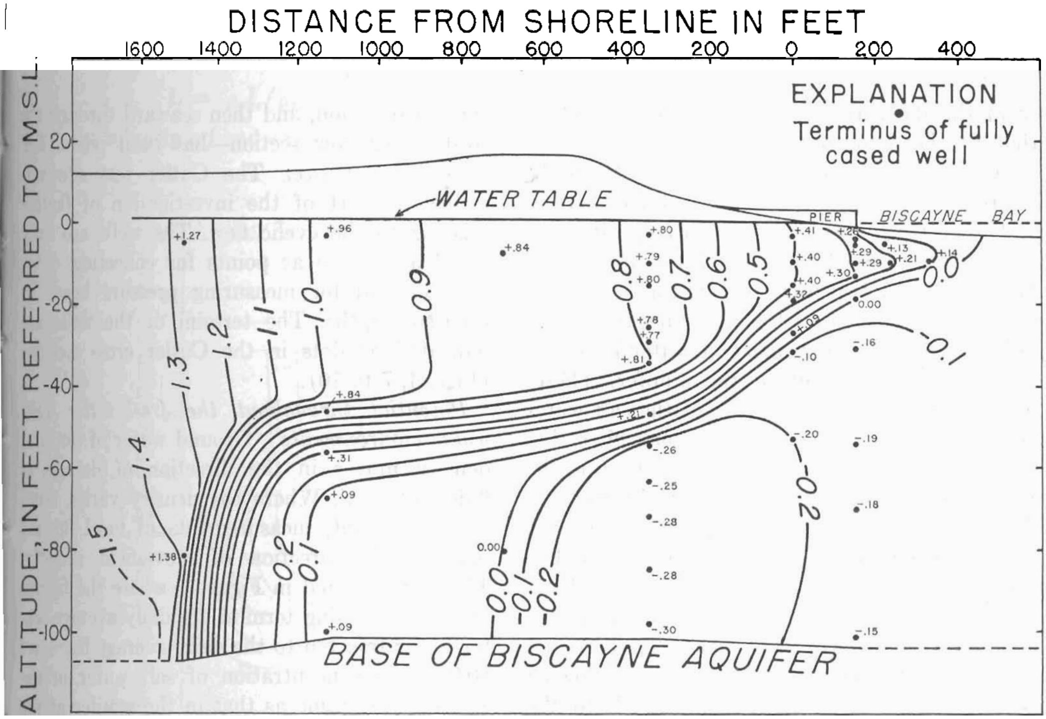

Fig. 7. Cross section through the Cutler area showing equipotential lines in terms of the environmental water, average head, September 18, 1958.

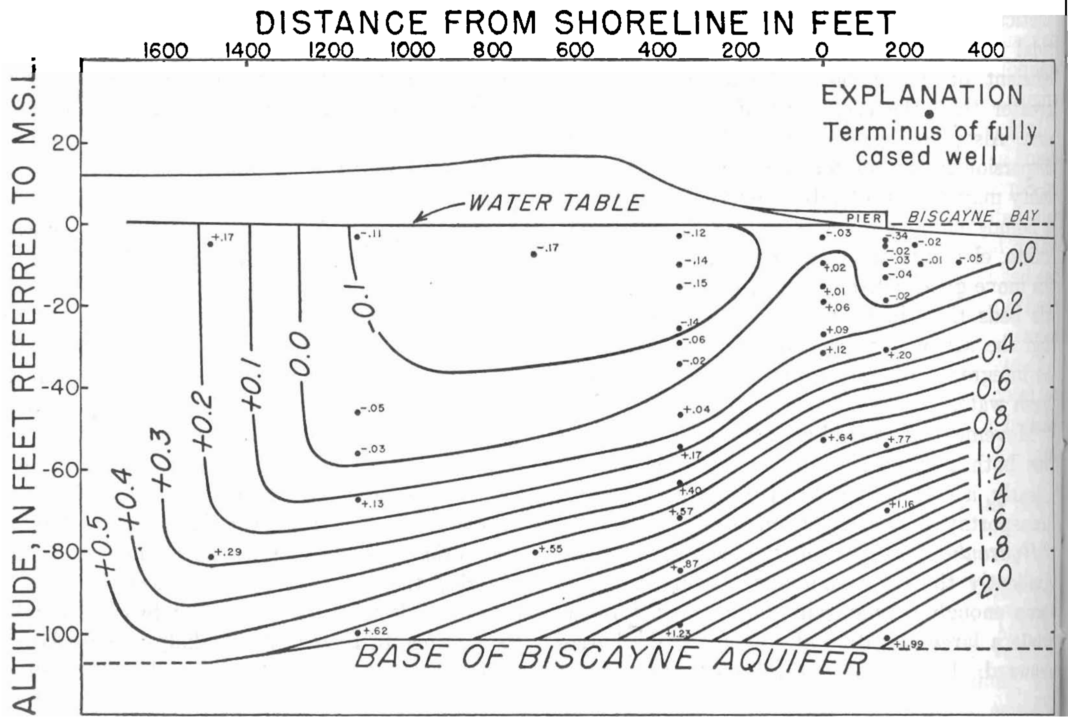

Fig. 8. Cross section through the Cutler area showing equipotential lines in terms of equivalent fresh-water head at 1335 EST (bay high tide), September 18, 1958.

from the daily-average head of well F 200, so that the head in the well each day is referred to a bay head of zero for that day. When the hydrograph is positive, salt water flows seaward, and when the hydrograph is negative, salt water flows inland. The hydrograph of well G 519A (Fig. 5), which is constructed in a manner similar to that of well F 200, is never negative. This indicates that the movement of water is always seaward at that point in the aquifer. Therefore, during the intrusion part of the salt-water flow cycle, there must be a line somewhere between the termini of these two wells (within the zone of diffusion, Fig. 3) where the water has the same head as the ocean and where the water is flowing neither inland nor seaward. The water along this line cannot be stagnant, however, because continuity requirements would then be violated. We may conclude, therefore, that salt water along this line must be flowing vertically upward along a return path to the ocean. Thus, a continuous cyclic flow of salt water—inland from the floor of the sea to the zone of diffusion, and then seaward through the fresh-water flow section—has been postulated.

Cutler test site. The Cutler test site was drilled as part of the investigation of factors relating to the cyclic flow. The wells are fully cased and serve as points for collecting water samples and for measuring pressure heads at isolated depths. The termini of the wells are indicated as dots in the Cutler cross sections (Figs. 4, 7 to 10).

Potential throughout the fresh-water salt-water environments. Ground water of uniform density moves in the direction of decreasing fluid potential. Where the density varies, from point to point, measurements of head do not indicate the direction of movement directly. This is illustrated in Figure 7 where the figures at the well-casing termini are daily-average water levels referred to the daily-average bay level (0.0). The concentration of salt water in the casing is the same as that in the aquifer at the casing terminus; the head values, as shown, are the original data.

Obviously, all flow cannot converge upon the sink surrounded by the −0.2-foot contour, and equipotential diagrams constructed from the original basic data are not usable.

In Figures 8 to 10 the equivalent fresh-water heads are shown for high, low, and average tide on September 18, 1958. For the wells that contain salty water, the equivalent head of fresh water has been computed, so that in all cases the heads are the same as if the casing had been filled with fresh water at the time of measurement.

Conversion of environmental salt-water head to fresh-water head in a given well is accomplished by application of the hydrostatic pressure equation:

$$p = \rho g l$$

where p is the pressure at casing terminus, ρ is the density of water in the casing, g is the acceleration due to gravity, l is the measured length of water column above the casing terminus. Equating the right term of the above equation for fresh-water and salt-water columns:

$$\rho_f g l_f = \rho_s g l_s$$

$$l_f = \rho_s l_s / \rho_f$$

where the subscripts f and s refer to fresh water and salt water, respectively. The density of fresh water is assumed to be 1.000.

The following table (using observed daily-average data for the deepest well, 350 feet inland from the shoreline, September 18, 1958, Fig. 10) gives a typical computation:

Salt-water head	+0.60 ft, msl
Depth of casing terminus	−97.9 ft, msl
Length (l_s) of salt-water column	98.50 ft
Density (ρ_s) of casing water (18,000 ppm chloride content)	1.0240
$l_f = \rho_s l_s / \rho_f$	100.86 ft
Fresh-water head (subtract 97.9 ft)	+2.96 ft, msl
Daily-average water level of Biscayne Bay	+0.90 ft, msl
Daily-average fresh-water head referred to Bay level	+2.06 ft

The equipotential lines pass vertically downward from their intersection with the water table and at depth deflect toward the horizontal. In the upper, fresh-water part of the aquifer, the lines indicate the potential of fresh water in a fresh-water environment, and hence indicate comparative potentials. As flow lines must be perpendicular to these equipotential lines, a seaward movement of fresh water is indicated.

In the lower and seaward part of the aquifer the equipotential lines indicate the potential of fresh water in a region occupied by salty water. *Hubbert* [1940, pp. 868–869] has shown that

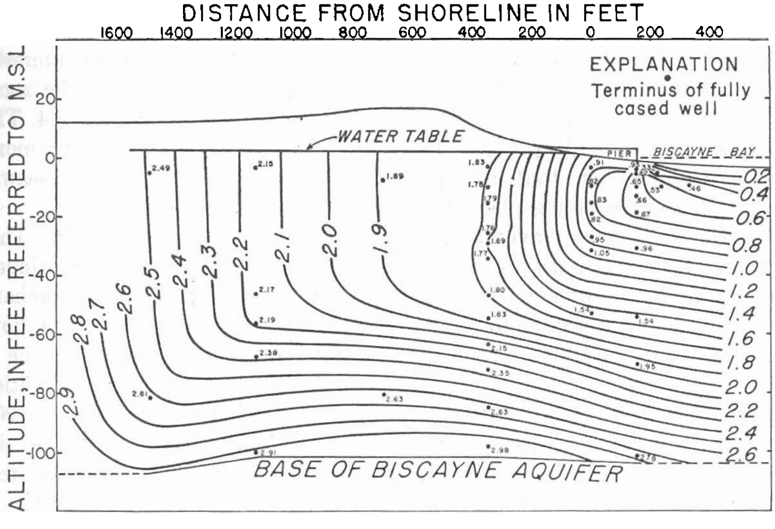

Fig. 9. Cross section through the Cutler area showing equipotential lines in terms of equivalent fresh-water head at 0750 EST (bay low tide), September 18, 1958.

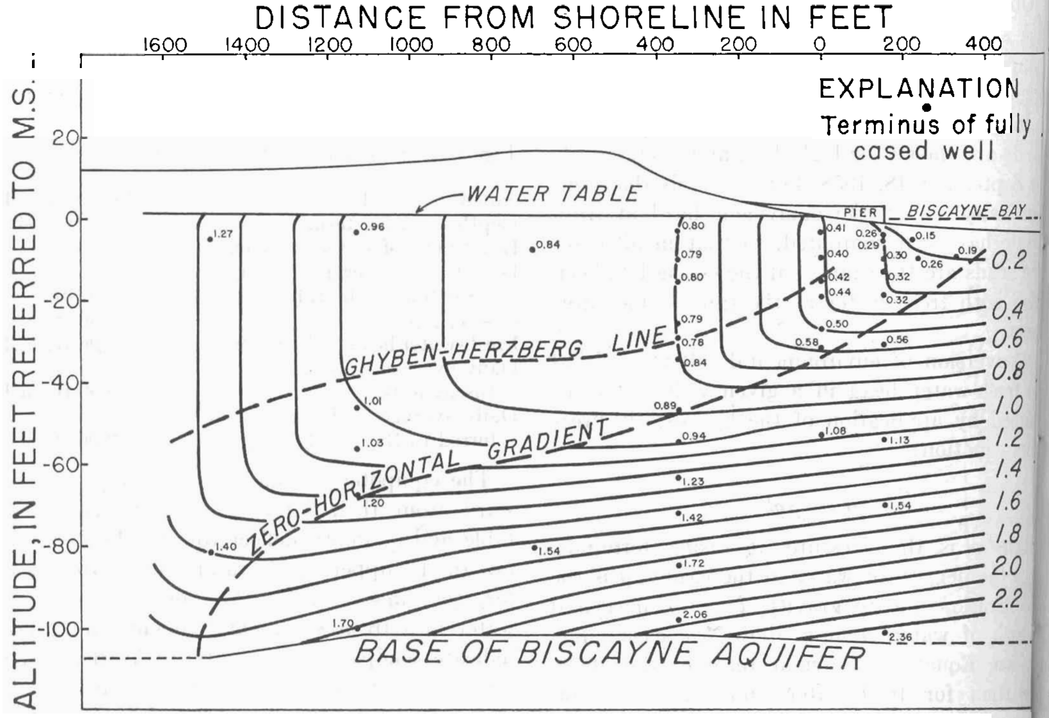

Fig. 10. Cross section through the Cutler area showing equipotential lines in terms of equivalent fresh water head, average for September 18, 1958.

fresh-water equipotential surfaces in a region occupied by salt water will be horizontal if the salt water is static. The equipotential lines in the salt-water regions of Figures 8 to 10 are not horizontal, but slope inland in Figure 8, seaward in Figure 9, and inland in Figure 10. From this it is concluded that the salt water is not static but must be in motion in the direction of the slope. The slope at high and low tidal stages is indicative of the flow that accommodates the changes of storage taking place in the aquifer at these times. The daily-average equipotential diagram (Fig. 10) indicates that the instantaneous movements occurring throughout the day average out in such a way as to produce a net inland movement of salt water on this date.

The pattern of fresh-water equipotential lines serves as a guide for separating the region of seaward-flowing water from that of the inland-flowing water (Fig. 10). Such a separation is formed by a line passed through the points of horizontality of the individual equipotential lines. Such a line is shown in Figure 10. At a points on this line the water must be flowin vertically upward.

The water above and below the line will hav seaward and landward horizontal components flow, respectively. It is of interest to see whe the line is located within the zone of diffusio Its trace is shown in Figure 4. The location i dicates that water containing more than 16,00 ppm of chloride may have a seaward horizont component of flow.

The salt-water flow cycle. The quantity inflowing sea water is not continuously balanc by an equivalent seaward discharge of dilut salt water through the upper flow region. F example, rough estimates of the movement salt under the intrusion conditions shown Figure 10 indicate that about 20 per cent the total salt that flows inland discharges s ward through the upper flow region; the maining 80 per cent stays in the aquifer to crease the volume of salt water in storage and replace discharged fresh water. Neverthele complete cyclic flow of part of the sea water occurs during the intrusion phase, and this cycle acts as a deterrent to the encroachment of sea water because of return to the sea of part of the inland flow.

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