indicate an even more rapid rise: 24 cm per century (Barnett, 1984) and 28 cm per century (Pirazzoli, 1987). These rates are of the same magnitude as the Holocene rise before 4000 y B.P.

HYDROGEOLOGY

Distribution of fresh groundwater and hydrostratigraphy

The hydrogeology of Bermuda's groundwater lenses is known from an extensive and on-going program carried out by the Department of Works and Engineering of the Bermuda Government. As the first step of that program (Vacher, 1974), the distribution of fresh and brackish groundwater was mapped (Fig. 2-14) by Vacher and Rowe from the conductivity of household wells and discussions with local well drillers. Now, after the drilling of hundreds of wells and monitoring boreholes by the Government, the occurrence and behavior of the freshwater lenses (Fig. 2-15) is known in detail. As shown in Figures 2-14 and 2-15, there is one main lens (the Central Lens; Rowe, 1984) in the heart of the Main Island and three minor lenses at the western and eastern extremities of Bermuda. There is also a constellation of small, thin discontinuous lenses near the south shore beaches of Warwick and Southampton Parishes (Rowe, 1991).

The key fact of the hydrogeology is that the location of the lenses is controlled by the distribution of hydraulic conductivity in the uppermost part of the saturated zone (Vacher, 1974, 1978b; Rowe, 1984). Because of the lateral accretion in the

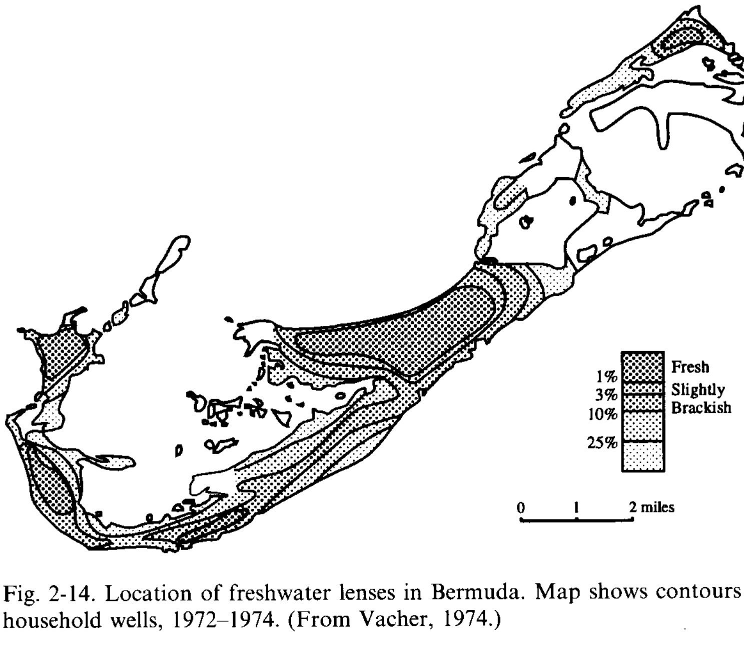


Fig. 2-14. Location of freshwater lenses in Bermuda. Map shows contours of percent seawater in household wells, 1972–1974. (From Vacher, 1974.)

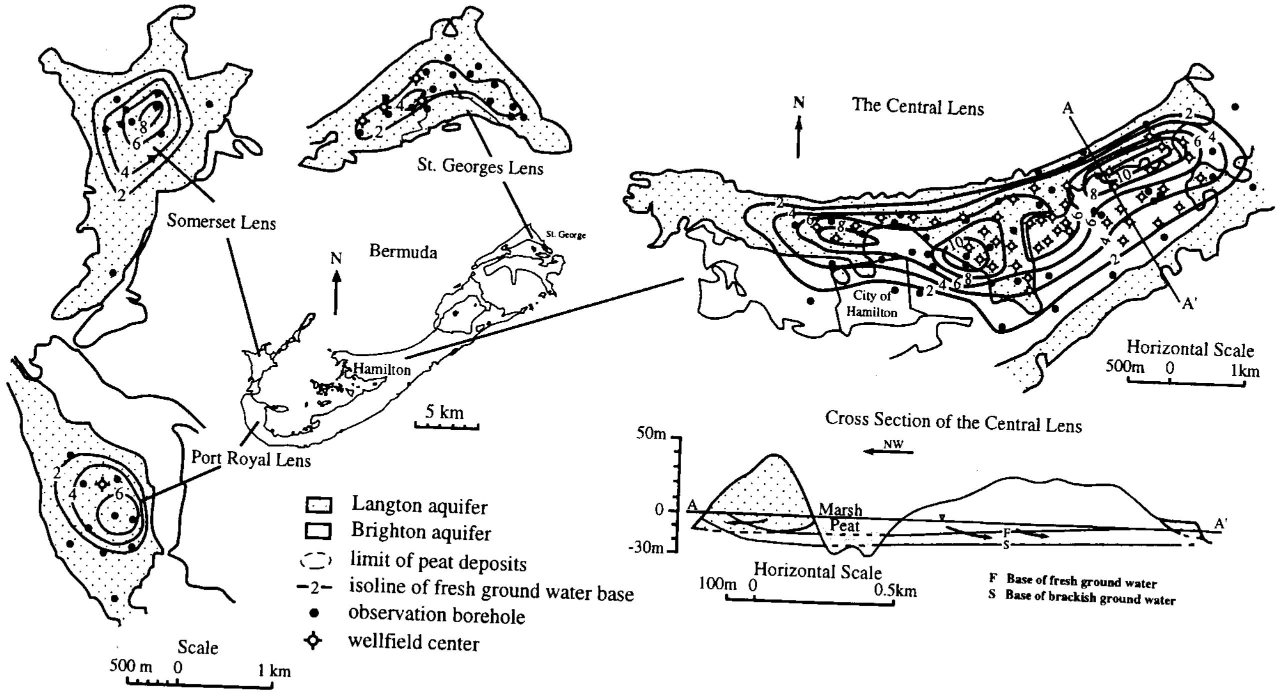


Fig. 2-15. Freshwater lenses of Bermuda. Map shows thickness of the freshwater lenses, distribution of Langton and Brighton Aquifers, and location of observation boreholes and extraction centres. (From Rowe, 1991)

buildup of Bermuda, there is a stratigraphic partitioning of the upper saturated zone. According to current nomenclature (Rowe, 1991; Vacher et al., 1995), the partitioning involves two hydrostratigraphic units (Fig. 2-15): the Langton Aquifer and the Brighton Aquifer. The Langton Aquifer consists of the Southampton, Rocky Bay and Belmont Formations of the lithostratigraphic classification and, therefore, is the younger body of rock. The Brighton Aquifer consists of the Town Hill Formation.

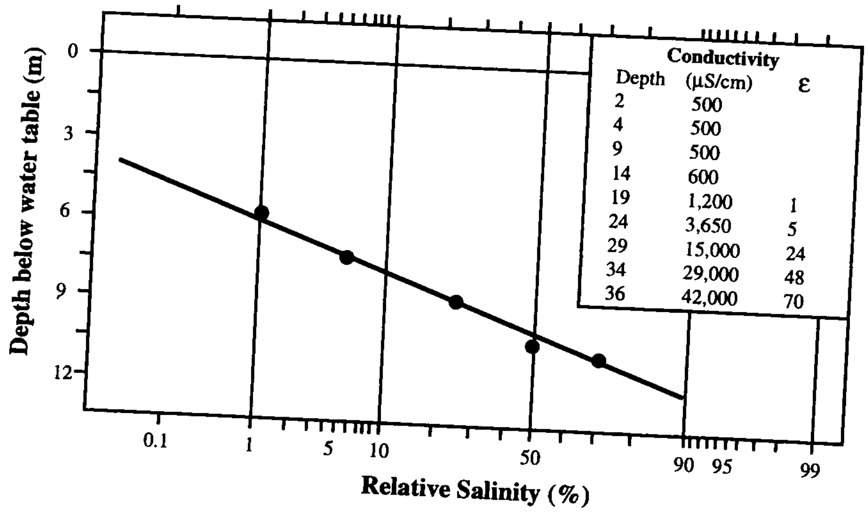
The hydraulic conductivity of the Langton Aquifer is some 30–120 m day^{-1}. The hydraulic conductivity of the Brighton Aquifer is on the order of 1,000 m day^{-1}, a number that clearly reflects increased secondary porosity. In addition to these two aquifers, there is a hydrostratigraphic unit corresponding to the Walsingham Formation. This unit does not usually figure in discussions of Bermuda hydrogeology because it is highly cavernous and, therefore, occupied by salty groundwater.

The freshwater lenses are localized in the Langton Aquifer (Fig. 2-15). Groundwater in the Brighton Aquifer is generally brackish at the water table. Where fresh groundwater does occur in the Brighton Aquifer, it is usually an extension of a lens centered in the Langton Aquifer (Fig. 2-15).

There is an extensive literature on the hydrogeology of Bermuda (e.g., Vacher et al., 1974, 1978a,b; Plummer et al., 1976; Rowe, 1984; Thomson 1989; Morse and Mackenzie, 1990) that uses an earlier hydrostratigraphic nomenclature that may lead to confusion if used in conjunction with the more recent geologic map and lithostratigraphic column (Vacher et al., 1989, 1995). Earlier, the stratigraphic control was described in terms of two units: the Paget Formation and the Belmont Formation. The Paget Formation of those papers corresponds to the Langton Aquifer of the current nomenclature, and the Belmont Formation of those papers parallels the Brighton Aquifer now. Confusing the synonymy is the fact that "Belmont" during the early stages of the geologic mapping (1970s) was used for the vast body of rocks between the Walsingham Formation and what is now known as the Rocky Bay Formation. Now, the Belmont is restricted to the definition of Land et al. (1967), and nearly all of the volume of rock between Walsingham and Rocky Bay is identified as Town Hill Formation. It is this volume that, in the saturated zone, constitutes the Brighton Aquifer.

The freshwater lenses

The groundwater monitoring program carried out by the Hydrogeology Section of the Department of Works and Engineering now includes a network of more than a hundred drilled boreholes (Rowe, 1991). In most cases, the boreholes penetrate into the seawater beneath the freshwater lenses and underlying transition zone. Salinity profiles in all monitoring boreholes are measured quarterly with a conductivity probe. The thickness of the four main freshwater lenses (1993) is shown in Fig. 2-15. The Central Lens covers an area of approximately 7.2 km^2 and reaches maximum thicknesses exceeding 10 m. The Port Royal, Somerset, and St. Georges Lenses are all in the range of 0.5–0.7 km^2 in area. The thin lenses in Warwick and Southampton Parishes are not routinely monitored.



Depth	Conductivity (µS/cm)	ε
2	500	
4	500	
9	500	
14	600	
19	1,200	1
24	3,650	5
29	15,000	24
34	29,000	48
36	42,000	70

Fig. 2-16. Plot of percent seawater against depth in freshwater-saltwater transition zone. Relative salinity, which is plotted on probability scale, is calculated as the difference in salinity between the sample and unmixed fresh groundwater divided by the difference in salinity between the seawater endmember and the unmixed fresh groundwater. (From Vacher, 1974.)

The salinity profiles give information on the structure of the transition zone and the quantity of recharge-derived water in the lens. The salinity data generally produce straight lines when relative salinity is plotted on a probability scale vs. depth on an arithmetic scale (e.g., Fig. 2-16). These probability-paper plots indicate a simple error-function variation of relative salinity vs. depth, which is consistent with one-dimensional dispersion models. The error-function variation also means that the depth of particular percentiles of relative salinity can be read easily from the graphs. One of these, where the relative salinity is 50%, is taken as the position of the "interface", that is, where the base of the freshwater lens would be if there were no mixing. The thickness between the water table and this 50% datum provides a measure of the "meteoric water inventory" [see Chaps. 1, 22]; the (smaller) thickness of freshwater from a water-resources standpoint, of course, is given by the break in slope at the top of the transition zone.

Across the island (Fig. 2-17), the depth of the interface (50% relative salinity), the thickness of the transition zone (1% to 99%), and the thickness of the freshwater lens (depth to 1% relative salinity) all vary with the hydrostratigraphy and illustrate the geologic control on the distribution of fresh and brackish groundwater (Fig. 2-15). Clearly, compared to the Brighton Aquifer, the lower-permeability Langton Aquifer impedes the escape of recharge-derived fresh groundwater. Also, tides and other sea-level variations are less effective in mixing the freshwater and saltwater in the Langton Aquifer than in the Brighton Aquifer. The transition zone decreases in thickness inland in both units but more rapidly per unit distance in the Langton Aquifer than in the Brighton Aquifer.

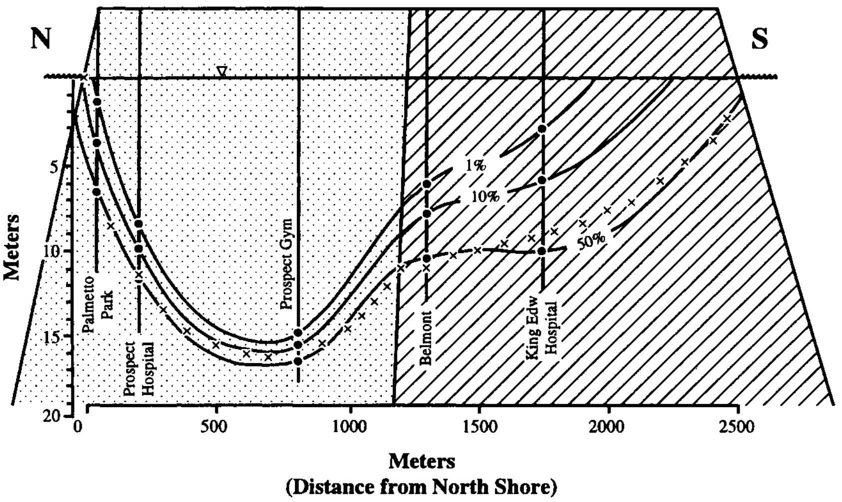


Fig. 2-17. Cross section of Central Lens according to Vacher (1974) showing across-island variation in thickness of fresh groundwater, thickness of transition zone, and depth to the "interface" (50% relative salinity). Evident correlation with the stratigraphy (Langton Aquifer on the left, Brighton Aquifer on the right). (From Vacher, 1974; also discussed in Plummer et al., 1976, and Vacher, 1978b.)

Vacher (1974, 1978b) has shown that simple analytical steady-state models can be used to explain the across-island variation in the depth of the "interface" (50% relative salinity). These models — Dupuit-Ghyben-Herzberg (DGH) models [see Chap. 1] — assume a sharp interface, a Ghyben-Herzberg relation between the elevation of the water table and the depth to the interface, the Dupuit assumptions of vertical equipotentials, and negligible outflow face (Vacher, 1988; Vacher et al., 1990). For example, the x's in Fig. 2-17 are for a DGH model assuming a strip island consisting of two sectors meeting at a vertical contact. In one sector (corresponding to the Langton Aquifer), the hydraulic conductivity is 80 m day^{-1}; in the other sector (Brighton Aquifer), the hydraulic conductivity is 1,000 m day^{-1}. In both, the assumed recharge is 0.35 m y^{-1}.

A long time series of water-table data is available at several monitoring boreholes in the Central Lens. To remove the effect of semidiurnal tides on a given measurement day, the water level is measured twice, six hours apart, and averaged. All monitoring boreholes in a particular lens are measured in one, or at most two, days. Over the years, with increasing sites in the monitoring network and changing priorities toward the direction of identifying long-term trends in lens thicknesses, the frequency of measurements has been reduced to once monthly. Levels are reduced to sea level as measured by the Hydrogeology Section at a tide recorder station on the north shore. The average height of the water table above sea level over an 8-year period (1975–1982) in the Central Lens (Rowe, 1984, Fig. 4) was about 1/40 the depth below sea level of the surface of 50% relative salinity for the same period

(Rowe, 1984). Thus, for long-term averages, the Central Lens can achieve Ghyben-Herzberg equilibrium (Rowe, 1984).

Recharge

Recharge has been evaluated in a variety of ways and, over the years, has been repeatedly revised upwards. In the early study, Vacher (1974; Plummer et al., 1976) used a water-budget accounting method to estimate recharge and actual evapotranspiration from monthly averages of rainfall and potential evapotranspiration and ignored the unnatural contributions; the result was about 18 cm y^{-1} (12% of the annual rainfall of 150-cm y^{-1}). Rowe (1981) applied a conceptually similar scheme but coupled it to a land zonation based on percentage coverage by housing, roads and marshlands; by including such processes as road runoff and recharge through cesspits, the recharge result increased to about 30 cm y^{-1}. Vacher and Ayers (1980) obtained values of 35–45 cm y^{-1} from three independent methods: evaluation of outflows and change in storage (hence inflows, by difference) in an area of diversion around a major development area; fitting of the lens geometry by DGH equations with independently inferred values of K; and the ratio of the Cl^- concentration in rainfall to that in the freshest part of the lenses. In his summary paper on the Central Lens, Rowe (1984) indicated that the earlier values from the water-budget accounting for natural surfaces were too low, because they were derived from monthly rather than daily values. Rowe (1984) suggested that the actual value for recharge, including the unnatural contributions, may range up to 55–65 cm y^{-1} in some places.

The most recent estimate of recharge is in connection with a steady-state model of the Central Lens (Thomson, 1989) developed as part of a U.N. study. In that model, the recharge is a distributed parameter which varies according to percentage of rooftop coverage. In Bermuda, most households capture water from their roofs and then dispose of it in soakaways. Thomson (1989) calculated cell-by-cell recharge as a weighted average of 90% of the rainfall that falls on impervious surfaces (roofs and roads) and the somewhat high figure of 25% of the annual rainfall that falls on natural surfaces. With these assumptions, combined with the percentage coverage by paved surfaces (5–40%), Thompson obtained recharge rates of 40–75 cm y^{-1} (Thomson, 1989). The same assumptions, of course, imply that in areas where the percentage coverage by pavement exceeds 22%, more than half of the recharge is obtained by recycling from these paved surfaces (with the total recharge being about 39% of the rainfall). This includes a significant fraction of the area of the Central Lens (Thomson, 1989).

Transient Behavior

Effects of sea level. With the exception of dug wells in some of the marshes, all the dug wells and boreholes in Bermuda are tidal, and most are strongly tidal. For a given distance inland of the shoreline, the tidal fluctuation is markedly larger in the Brighton Aquifer than in the Langton aquifer (Fig. 2-18), indicating greater dam-

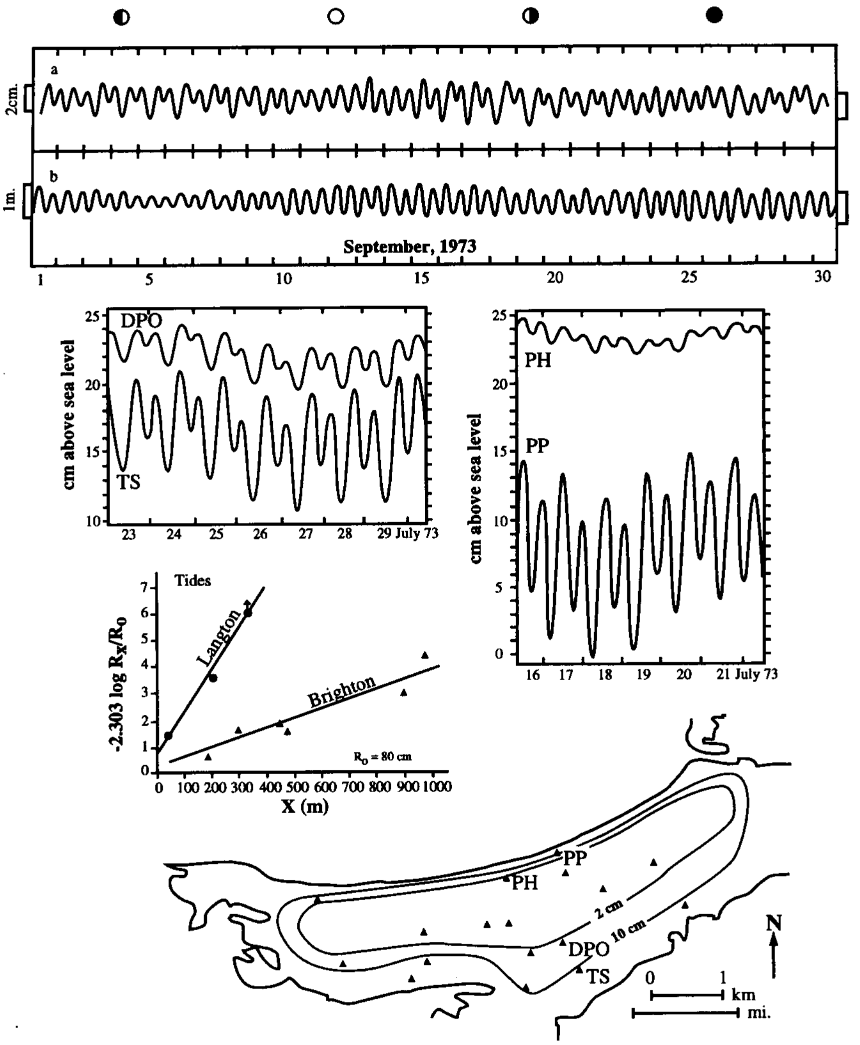


Fig. 2-18. Tidal fluctuations in the Central Lens. DPO and TS are observation boreholes in the Brighton Aquifer, and PH and PP are in the Langton Aquifer. The upper pair of curves compares the record at DPO to the tide gauge at BBSR. The various graphs show a greater dampening of the semidurnal component relative to the diurnal component, and a greater dampening in the Langton Aquifer than in the Brighton Aquifer. (From Vacher, 1974.)

pening in the latter unit. The water-table fluctuation is not a simple scaled-down version of ocean tide (Fig. 2-18): the semidiurnal inequality is significantly enhanced in the water-table fluctuation, indicating that the diurnal component passes through more easily than the semidiurnal component.

The simplest model treating the dampening of tides is that of Ferris (1951), which treats a single confined layer and a horizontally propagated signal. According to that model, the tidal amplitude decreases exponentially inland such that a semilog plot of tidal efficiency (well-to-ocean amplitude ratio) vs. distance would produce a straight line with slope proportional to the ratio of storativity to transmissivity and inversely proportional to the tidal period. Using such plots (Fig. 2-18), Vacher (1974, 1978b) found that the implied contrast in hydraulic conductivity between the Brighton and Langton sectors to be a factor of about 14. For comparison, the fit of the DGH lens of Fig. 2-17 assumes a Brighton-to-Langton hydraulic-conductivity ratio of 18. It should be noted that the straight-line plots of Fig. 2-18 do not go through the origin, and more data from more recent boreholes (Rowe unpub. data) suggest that the "lines" are curves that slightly decrease in slope inland.

If the diurnal component of the tide is dampened significantly less than the semidiurnal component, it should be no surprise that low-frequency behavior of sea level would have a large effect on the position of the water table in Bermuda. Thus, day-to-day variations in the water table reflect the barometric fluctuation of sea level (Vacher, 1978a; Rowe, 1984). As shown in Fig. 2-19, the day-to-day variations in the water table behave like tides in that they diminish inland exponentially, and at a greater rate in the Langton Aquifer than in the Brighton Aquifer. In addition, the year run of monthly or semimonthly averages tracks the seasonal, steric variation in sea level (Rowe, 1984).

Effects of recharge variations. Hydrographs in the marshes show a nontidal water-level variation related to changes in freshwater storage (Vacher, 1974). The marsh levels rise rapidly in response to rainfall, decay exponentially after the rainfall, and fluctuate with a diurnal periodicity in response to evapotranspiration-driven with-

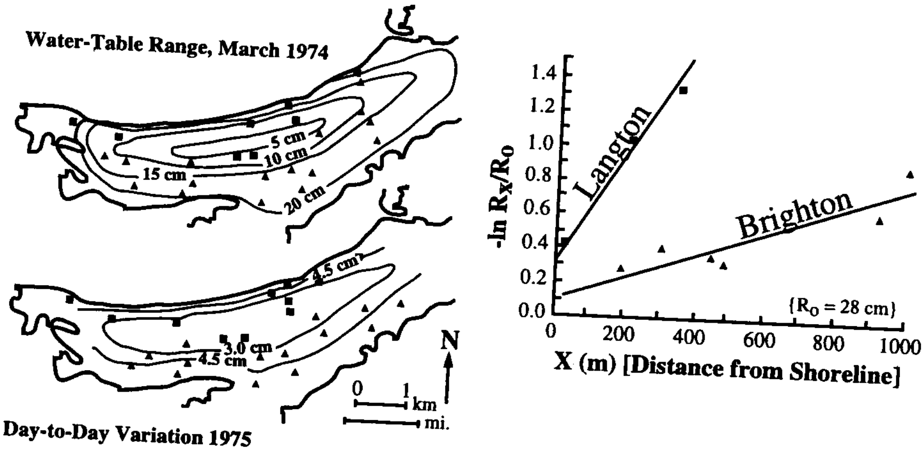


Fig. 2-19. Water-table fluctuations related to changes in atmospheric pressure, Central Lens. The water-table range for 1974 was from a single rise of the water table over a 10-day period when pressure dropped 28 cm. The "day-to-day variation for 1975" is the average of 12 monthly standard deviations of water-table elevation determined on 5–9 measurement days per month. The figures show that these statistics decrease inland from the shoreline in the same manner that the tidal amplitude does. (From Vacher, 1978a.)

drawals. In contrast, recharge events due to rainfall are not at all evident in hydrographs from boreholes in the limestone. As already noted, the dominant water-table fluctuations correlate with changes in sea level, not with volumetric changes in the lens. Attempts to subtract out the sea-level variation in order to look at volume-related residuals have been frustrated by the uniqueness of the sea-level influence at each borehole (Rowe, 1984).

Comparison of yearly averages do reveal variations due to recharge (Rowe, 1984). Maps of the annual average water table in the Central Lens are now available for some 20 years. During wet years, the reduced water levels can be 50% higher than those of dry years. The interface (50% relative salinity), however, is not in Ghyben-Herzberg equilibrium with this interannual variation. In a single borehole, the ratio of water-table elevation to depth of interface can vary from 1:25 in wet years to 1:58 in dry years. Thus the interface lags in its response to these water-table changes (Rowe, 1984). These results argue against the use of DGH models to simulate transient variation of the meteoric water inventory stored in the lens.

Groundwater chemistry

Plummer et al. (1967) examined the major-ion chemistry of the meteoric lenses and mapped the saturation state of aragonite and calcite in a study addressing rock-water interactions in phreatic diagenesis. Simmons et al. (1985) and Simmons and Lyons (1994) investigated the distribution of nitrogen and phosphorus in groundwaters of the Central Lens in a study addressing nutrient cycling. This cycling includes large inputs from the many cesspits and subsequent outflow to the nearshore marine waters. The outflow may sustain higher than normal algal growth in some areas, particularly the inshore water bodies (Morris et al., 1977; Lapointe and O'Connell, 1989; Simmons and Lyons, 1994).

WATER RESOURCES AND WATER SUPPLY

For the private household in Bermuda, the principal water supply is rainwater. Planning Department regulations require that each household have its own rainwater roof catchment (Fig. 2-3A) and subsurface tank. When the rainfall is average and is evenly distributed throughout the year, this supply is adequate.

The household rainwater catch is augmented by about 3,000 household wells. Drinking of water from these wells requires approval of the Health Department and is generally discouraged. The well water is used largely for flushing toilets.

According to Hayward et al. (1981), the usage of freshwater has increased from about 30 L day^{-1} person^{-1} since the mid-1940s to about 100 L day^{-1} person^{-1}, and typical figures for tourists can run up to 450 L day^{-1} person^{-1}.

The main groundwater extractors are the Government and a private water company which, together, operate a limited mains distribution network. The primary purpose of this distribution system is to deliver treated groundwater to offices and hotels. More recently, the Government has allowed the construction of cluster developments, which are properties with roof areas that are too small to catch sufficient rain to meet the demand of the residents; these cluster developments are supplied by the mains distribution system. Hotels that are outside the reach of the mains system or need supplemental supply use seawater desalination systems. Households that need to supplement their catch typically buy water from truckers, who, in turn, are supplied from licensed wells, typically Government's.

Total groundwater abstraction by major commercial and Government operations in Bermuda amounts to an average of 5,900 m^3 day^{-1}, some 90% of which is from the Central Lens. This development is managed by the Department of Works and Engineering and overseen by a statutory body of citizens, the Water Authority. The development plan makes use of a safe-yield concept (Rowe, 1984, 1991), where the lens is allowed to be thinned to about 1/2 of its pre-development thickness while maintaining certain standards with respect to salinity. These are that traditionally fresh areas of the Langton Aquifer must remain fresh (less than 700 mg L^{-1} TDS) and that parts of the Brighton Aquifer and coastal locations in the Langton Aquifer used as source water for RO and electrodialysis plants must remain only slightly brackish (less than 1,200 mg L^{-1} TDS). The provision that the lens can be thinned to half of its predevelopment thickness means that total extractions are 3/4 of the recharge (Rowe, 1984), because the development philosophy is to spread extractions and use a large number of small-yield wells; thus extractions are designed to resemble negative recharge. As yet, there has been no case where a groundwater resource in Bermuda has had to be abandoned because of saline intrusion or upconing. One or two areas that were overpumped did experience upconing prior to imposition of localized controls which, concurrently, protected groundwater quality and forced the spread of abstractions. Currently, the Central Lens is developed to about 80% of its estimated safe yield (Rowe, 1991).

CASE STUDY: HERMENEUTICS AND THE PLEISTOCENE SEA-LEVEL HISTORY OF BERMUDA

In a recent analysis of geologic reasoning, Frodeman (1995) introduced the term *hermeneutics* to the geologic community. He argued, "Geologic understanding is best understood as a hermeneutic process" (Frodeman, 1995, p. 963). He explained: "The term *hermeneutics* means theory of interpretation; hermeneutics is the art or science of interpreting texts.... Hermeneutics has claimed that the deciphering of meaning always involves the subtle interplay of what is 'objectively' there in the text with what the reader brings to the text in terms of presuppositions and expectations. In effect, hermeneutics rejects the claim that facts can ever be completely independent of theory" (Frodeman, 1995, p. 962).

It has been said that Bermuda offers a "tide gauge" for reading Pleistocene sea levels. The record of that tide gauge has been read and reread, and those readings have been drawn up in a number of sea-level curves. Reading a "Pleistocene tide gauge," however, is not like reading an oceanographic tide gauge. The Pleistocene curves depict subjective interpretations of rock exposures and necessarily reflect —

tidal efficiency (well-to-ocean amplitude ratio) vs. distance would produce a straight line with slope proportional to the ratio of storativity to transmissivity and inversely proportional to the tidal period. Using such plots (Fig. 2-18), Vacher (1974, 1978b) found that the implied contrast in hydraulic conductivity between the Brighton and Langton sectors to be a factor of about 14. For comparison, the fit of the DGH lens of Fig. 2-17 assumes a Brighton-to-Langton hydraulic-conductivity ratio of 18. It should be noted that the straight-line plots of Fig. 2-18 do not go through the origin, and more data from more recent boreholes (Rowe unpub. data) suggest that the "lines" are curves that slightly decrease in slope inland.

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