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THE FRESHWATER "CENTRAL LENS" OF BERMUDA

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ABSTRACT

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The geology of Bermuda can be described as a sequence of Pleistocene, aeolian limestones displaying a full range of diagenetic grades. In the study area, containing the Central Lens, the two major rock bodies are of the Belmont and Paget Groups. They form adjacent parallel aquifers of greatly contrasting permeability. The older Belmont Limestone having undergone greater solutional alteration is the more permeable.

The long-term averages of eight years of data indicate that under steady-state conditions the Central Lens configuration supports the Ghyben—Herzberg theory. On a yearly average basis, however, the degree of disequilibrium is substantial. The water table is shown to be far more responsive to variations in recharge than is the interface and possible causes for this are discussed. On less than a yearly average basis the water-table levels are dominated by the influence of sea level, which cannot be readily removed, and, therefore, presents a major obstacle to short-term studies.

Demonstration of a relatively stable lens thickness, below sea level, allows a less cautious approach to management of pumping rates than previously taken. A maximum permissible thinning of the lens is considered as 45% in fresh areas and 60% in brackish areas. Under these conditions it is calculated from Henry's equation that ~75% of recharge could be abstracted.

CLIMATE

The climate of Bermuda is subtropical and frost free. The coldest and hottest months are February and August with average termperatures, respectively, of 16.7° and 26.7°C. The average annual precipitation is 1468 mm and is evenly distributed throughout the year, with a range of monthly averages of 60 mm. Potential evaporation has been calculated by a standard Penman technique, by Rowe (1981), using long-term monthly averages of climatalogical data. It ranges from 75 mm in January to 172 mm in July.

GEOLOGY

The Bermuda Islands (Fig. 1) comprise Pleistocene bioclastic calcarenites deposited in a tectonically stable environment. These limestones are

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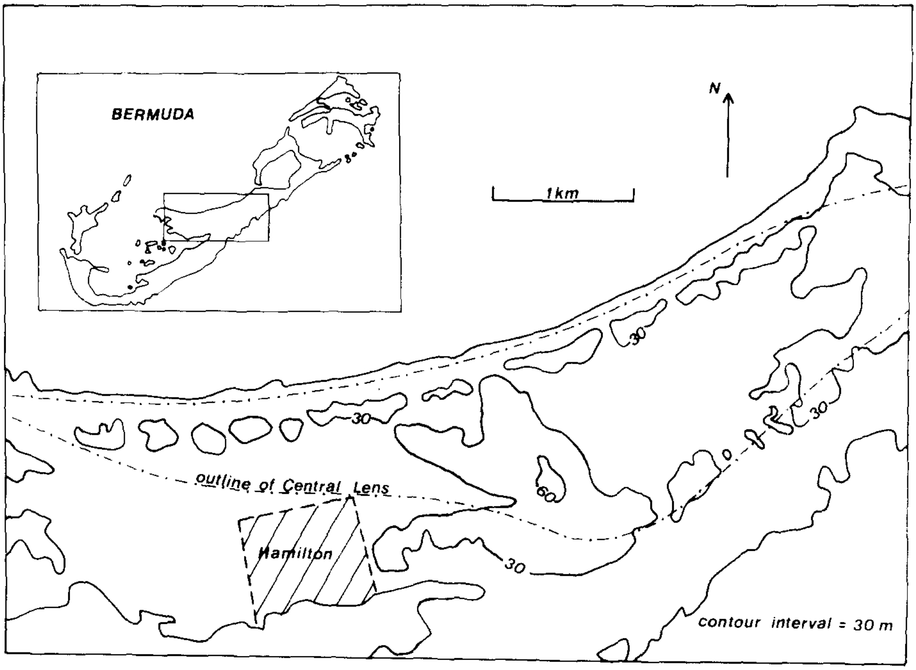

Fig. 1. Map of the study area.

predominantly aeolian, although they interfinger with interglacial beach deposits along limited coastal sections. At depths exceeding 35 m below sea level are basaltic lavas of a truncated volcanic seamount.

The limestone stratigraphy that has been established in recent island-wide mapping (Vacher et al., 1980), and in previous work by Vacher (1974), can be summarised as comprising three fundamental groupings. In order of decreasing age these are the Walsingham Formation, the Belmont Group and the Paget Group. They are distinguished in the field on the basis of diagenetic and topographic evidence. Important contacts are represented by red clay palaeosols.

Limestones in the vicinity of the Central Lens are more than 95% by volume of an aeolian facies. Only Belmont and Paget units are present. They form parallel topographic ridges that are separated by a linear depression of marshland (Figs. 2 and 3). The depression is continuous for 6 km except where it is bridged centrally, at Prospect, by a large tongue of Paget dunes.

THE AQUIFERS

The Belmont and Paget Limestones can be considered as separate aquifers because of the effects that different degrees of diagenesis have had on their pore-space characteristics. Older limestones, such as the Belmont, have undergone solutional alteration that has created substantial secondary porosity (Land et al., 1967). The youngest, Paget limestones, on the other hand,

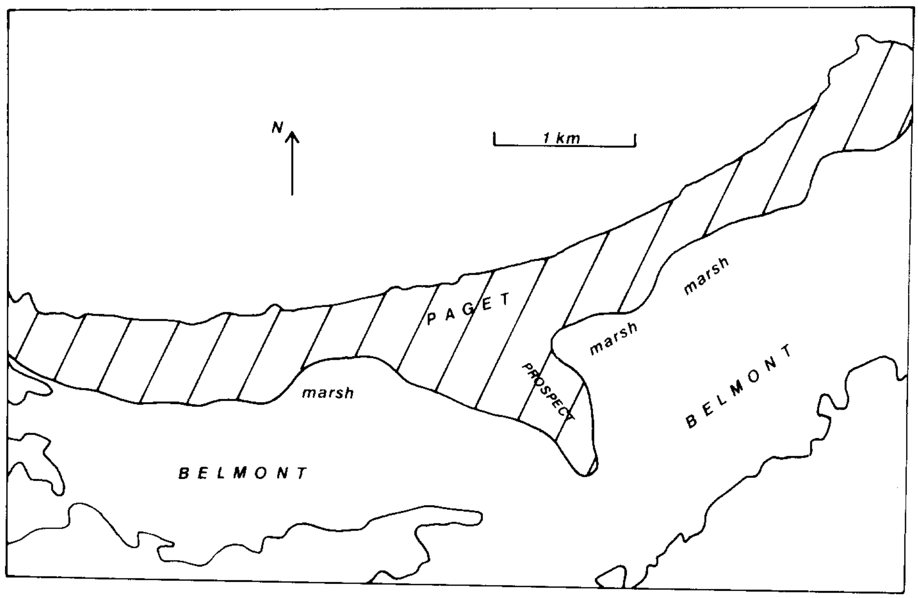

Fig. 2. Geology of the study area

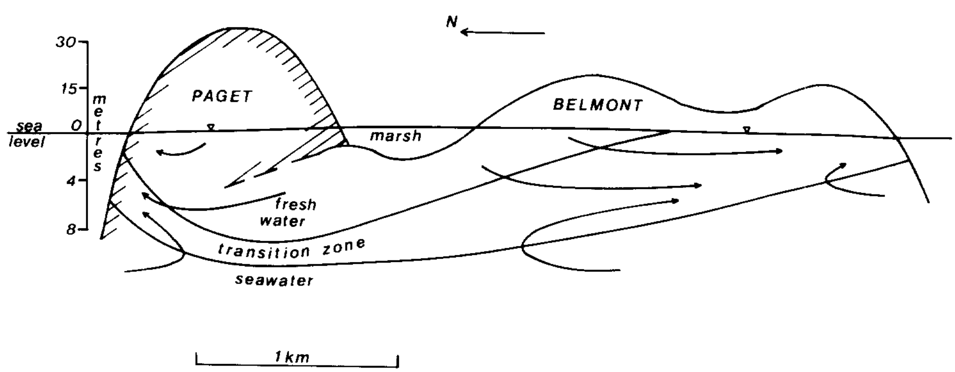

Fig. 3. Idealised cross-section of the study area, showing hypothetical flow lines for steady-state conditions.

retain much of their depositional texture with only limited development of secondary voids and of channels of preferential flow.

Estimates of hydrological parameters have been made from pumping tests (Vacher, 1974), solution of lens configuration equations (Vacher, 1974; Rowe 1981), computer modelling (Ayers, 1980), and solution of tidal dampening and lag-time equations (Vacher, 1974; Rowe, 1977). A consensus for the range of values of hydraulic conductivity within the Paget aquifer is 30—120 m day^{-1} and for within the Belmont aquifer is 750—1000 m day^{-1}. Storativity of the Paget is estimated at 0.1—0.2 and of the Belmont at 0.2—0.25.

RECHARGE

An attempt to calculate monthly recharge to the Central Lens has been made by Rowe (1981) using a Penman—Grindley technique (Penman, 1949; Grindley, 1967). It was adapted for the Central Lens as follows. Seven zones of recharge were defined from the percentage coverage by open land, housing, roads and marshland. The calculations took account of potential evaporation, actual evaporation, surplus soilwater, the contribution of road runoff and recharge through cesspits. An allowance was also made for some bypassing of the soil layer during heavy rainfalls regardless of the existence of any soil-moisture deficits (see Rushton and Ward, 1979).

The results provided a new insight into how recharge to the Central Lens varies in the short term. However, the value of 300 mm yr^{-1} calculated for the average annual recharge is not in agreement with other estimates. Vacher and Ayers (1980), by three independent techniques, came up with values that fall into the range of 330—450 mm yr^{-1}. A higher figure is also supported by Rowe (1981) and later in this paper.

Underestimation of recharge by the Penman—Grindley method for the Central Lens would support a finding of Rushton and Ward (1979). They claim that soil-moisture accounting done on a monthly basis [as carried out by Rowe (1981)], will generally lead to underestimation and that daily accounting must be used. Unfortunately, on this condition, correct application of the Penman—Grindley technique is restricted because, as in Bermuda, the required daily meteorological data are often lacking.

THEORY OF FRESHWATER LENSES

Under steady-state conditions the ratio of the head of fresh water above sea level, h, to the depth of fresh water below sea level, z, in a coastal aquifer will equal 1:40 according to the principle of Ghyben (1889) and Herzberg (1901). The principle assumes horizontal flow, or static conditions, and a sharp interface between fresh water and seawater, having densities, respectively, of 1.00 and 1.025 g cm^{-3}. These assumptions in reality are not strictly valid, and several exceptions to the principle have been demonstrated theoretically and in practice (Rowe, 1981). The exceptions can be summarised as resulting from the effects of inclined flow (see Visher and Mink, 1964) and as resulting from flow into a zone of dispersion below the lens (see Cooper, 1959; Kohout, 1960).

The size of a groundwater lens in a steady-state condition is dependent on the permeability, the dimensions of the island, the recharge and the ratio of the freshwater density to the seawater density. Numerous equations have been developed that relate these five factors. Some equations assume horizontal flow — the Dupuit assumption (e.g., Henry, 1964; Fetter, 1972) and others correct for inclined flow (e.g., Glover, 1959; Van der Veer, 1977). It is generally agreed, however, that "exact solutions" do not differ significantly from the approximate horizontal flow solutions, except near the coast where the latter underestimate lens thickness.

To illustrate the type of interrelationship of the five variables, that are common to all steady-state lens equations, it is sufficient for the purpose of this paper to quote Henry's expression for an infinite-strip island (see below).

$$y/l = [(V_0/K_1)\{(2x/l) - (x/l)^2\}]^{1/2}$$

where $K_1 = K(\rho_s - \rho_0)/\rho_0$; ρ_s = density of seawater ρ_0 = density of fresh water; K = hydraulic conductivity; V_0 = rate of uniform recharge per unit area; y = depth of interface below sea level; x = distance to shoreline; and l = half-width of island.

THE "STEADY-STATE" CENTRAL LENS

Fig. 4 shows the long-term (1975—1982) average position of the water table in the Central Lens as determined from weekly measurements in up to forty boreholes. Concentrated over-abstraction in the early years of development has caused the central depression, where, under pristine conditions, the high point in the water table is estimated to have stood at 0.35—0.40 m above sea level.

At present, conductivity profiling is carried out on a regular basis in ~ 25 boreholes in the Central Lens. Of these there are five boreholes that are not

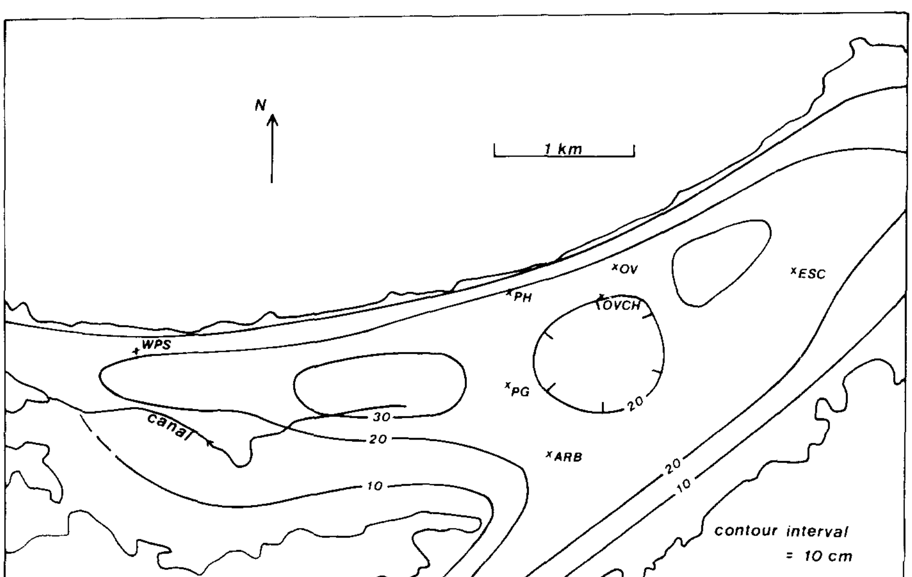

Fig. 4. Long-term average (1975—1982) water-table configuration and location of key observation boreholes.

TABLE I

Yearly average ratios (z/h) of head of water above sea level, h, to depth of the interface (50% seawater) below sea level, z

	Boreholes in Belmont		Boreholes in Paget			Boreholes in pumped areas	
	ARB	ESC	OV	PH	WPS	OVCH	PG
1975	36	40	55	—	52	61	52
1976	36	36	58	65	50	77	89
1977	32	33	30	36	33	35	38
1978	32	33	25	31	31	34	34
1979	41	34	42	53	45	61	74
1980	34	33	31	27	33	36	51
1981	33	32	—	36	36	32	41
1982	38	34	36	39	36	43	53
Average	35	34	40	41	40	47	54

Boreholes: ARB = Arboretum; ESC = Elliott School; OV = Ocean View; PH = Prospect Hospital; WPS = West Pembroke School; OVCH = Ocean View Club House; PG = Prospect Gym.

within pumping areas and have lengthy data records. These are Arboretum (ARB), Elliott School (ESC), West Pembroke School (WPS), Ocean View (OV) and Prospect Hospital (PH) (see Fig. 4). As shown in Table I, the first two in Belmont Limestone, have long-term average h/z ratios of 1:35 and 1:34, and the last three, in Paget Limestone, have ratios respectively of 1:40, 1:40 and 1:41.

The data are too limited for conclusive deductions, but it is apparent that the Ghyben—Herzberg principle, with Dupuit assumptions, is reasonably applicable to the Central Lens. It can be speculated that high recharge or large tidal mixing in the very permeable Belmont Limestone induces a substantial downward flow and reduces the h/z ratio. Conversely, the higher ratios — commonly greater than 1:50 (see Table I) — within pumped areas such as at Ocean View Club House (OVCH) and Prospect Gym (PG), can be interpreted as indicators of a component of upward flow.

If the Ghyben—Herzberg principle is valid then Henry's steady-state equation should be applicable to cross-sections through the Central Lens. Two representative cross-sections for this purpose, are through the Paget Limestone at West Pembroke School — from the sea to the canal — and through the Belmont Limestone at Elliott School — from the north shore to the south shore. Applying Henry's equation, the inputs are for Paget and Belmont sections, respectively: hydraulic conductivity is 80 and 900 m day^{-1}; half-width of the island is 300 and 1020 m; distance from the sea is 270 and 970 m; and recharge is 0.34 m yr^{-1} (calculated by Penman—Grindley method: land-use type is the same for both sections; Rowe, 1981).

Solution of Henry's equation gives a theoretical depth to the interface at West Pembroke School of 6.4 m and at Elliott School of 6.6 m, compared to actual measured values of 8.3 and 9.2 m. These are significant errors that can only be corrected by an adjustment in value of the term V_0/K — recharge divided by hydraulic conductivity. In order to correctly reproduce the actual Paget and Belmont lens thicknesses at these locations the value of this term must be increased by more than 60% and 90%, respectively.

Since hydraulic conductivity has been measured by several methods over a wide area it is not likely that average values, given above, can be greatly in error. So, it remains that a higher recharge would be required if actual depths to the interface are to be reproduced by Henry's equation. The necessity for such a modification of inputs may in part be caused by an error in the rather simplistic treatment given by Henry's equation. It would, however, be consistent with a view that recharge has been underestimated by the Penman—Grindley method.

THE NON-STEADY-STATE CENTRAL LENS

Annual average water-table contour maps for the Central Lens reveal considerable variation in water levels from year to year. In relatively wet years the water-table height above sea level can be 50% above that of dry years. This demonstrates a good response to recharge. The levels are also meaningful in terms of illustrating the state of pumping areas by indicating the general extent and location of depressions. However, to draw any further information from water-table contour maps, on their own, is a mistake — a view supported by Visher and Mink (1964), who state that:

> "The height of the upper surface of a fresh water body relative to mean sea level has, in itself, little practical value in determining the magnitude of changes in the thickness of the fresh water body."

— and this is confirmed for Bermuda's Central Lens by relating water-table heights to interface depths. Even on a yearly average basis the water table and interface do not appear to equilibrate. The former is very sensitive to recharge, or lack of it, while the latter is relatively stable. In dry years z/h is high and in wet years it is low (at Ocean View the ratio has varied from 25 to 58), so that the Ghyben—Herzberg principle is seldom applicable to the dynamic lens.

Although disequilibrium is predicted by the theory of inclined flow, on which Visher and Mink based their statement, above, there may be a large contribution to the phenomenon by delay: such that, due to a vertical zonation of flow activity, the effect of an event at the water table only manifests itself at the interface after considerable dampening and lagging. A possible cause for this could be the development of a higher-permeability zone at the water table, but the presence or lack of such a feature, which has been observed in other environments, has yet to be proved in Bermuda.

SEA LEVEL AND THE WATER TABLE

The sea level at Bermuda oscillates in response to astronomical, isostatic and mass transfer effects (Pattullo, 1963). The important components of astronomical tides have semi-diurnal and diurnal periods and amplitudes of ~ 0.75 m. Isostatic effects can be divided into those resulting from changes in atmosphere pressure and those resulting from changes in density (or volume). The former cause sea-level fluctuations of widely ranging periods, with an average of ~ 6 days in Bermuda (Ayers, 1980), and an amplitude in daily levels of up to 0.2 m (Pattullo, 1963). Steric, or density effects, on the other hand, cause essentially an annual cycle of sea level, with an average amplitude also, of ~ 0.2 m. When raw sea-level variations are corrected for these known influences there remains a residual anomaly of ~ 60-mm range and an irregular period. This anomaly is thought to relate to mass transfer of ocean water. A summary is presented in Fig. 5 (from Shaw and Donn, 1964).

The influence of sea-level movement on groundwater levels in the Central

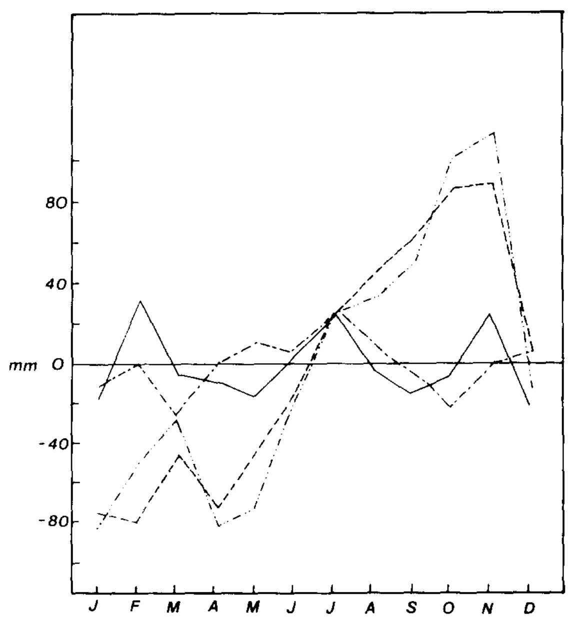

Fig. 5. Monthly averages of sea-level components (—··—··— = raw sea-level anomaly; —·—·—· = barometric correction; — — — — — = steric anomaly; ———— = residual sea-level anomaly). (From Shaw and Donn, 1964.)

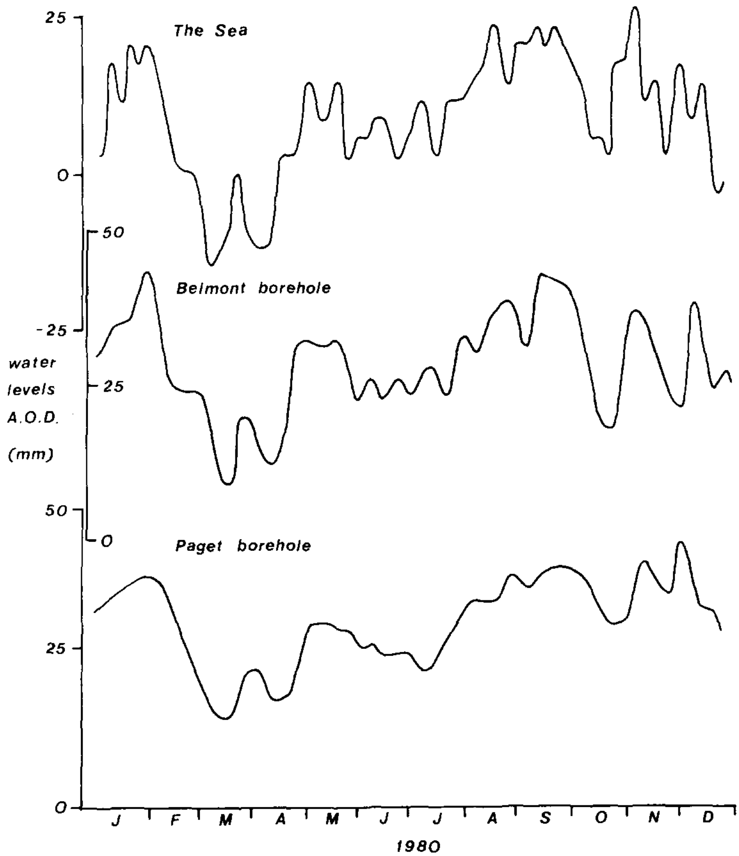

Fig. 6. A graph of sea level and graphs of water-table levels in two boreholes. One borehole is in the Belmont aquifer (at 750 m inland) and one in the Paget aquifer (at 270 m inland). Note preferential filtering of short-period waves.

Lens has been monitored with autographic level recorders. These have been placed at one time or another in over twenty boreholes. Semi-diurnal astronomical fluctuations are the most striking feature of recordings from the Belmont aquifer; whereas in the Paget aquifer these are greatly attenuated. Astronomical oscillations are superimposed on longer-period barometric oscillations, which in turn are superimposed on the annual steric fluctuation.

From Ferris' (1951) equations it can be shown that longer-period waves moving into a rock medium are dampened less but move more slowly than those of a shorter period. Therefore, the effects of a range of wave types moving from two sides of an inhomogeneous island should be substantially out of phase at different boreholes. As regards dampening, this theory is supported by Fig. 6. Long-period waves are shown to penetrate with little dampening through Paget and Belmont Limestones. Short-period waves, on the other hand, undergo a noticeable dampening that is greater within the Paget Limestone.

The dominant components of water-table fluctuation correlate with sea-level events rather than volumetric changes of the lens (see Fig. 6). Attempts to substract sea level from water levels have been frustrated by the uniqueness of the sea-level influence at each borehole. Even on a monthly average basis it has been shown that a single correction factor for all boreholes does not satisfactorily remove sea-level effects (Rowe, 1981).

The sure way to remove complex sea-level effects from groundwater levels is by the use of yearly average data: only on a yearly average basis can sea level be confidently accepted as approximating to a stable datum. In practice, however, quarterly, water-table contour maps of the Central Lens are produced. These represent the average, over a quarter, of weekly water-table measurements. They include some sea-level distortions, but give a good indication of seasonal states of the lens when interpreted in conjunction with conductivity profile data.

GROUNDWATER RESOURCES

Even though more wells are planned for the Central Lens, the existing 150 wells with their areas of influence account for a good coverage of the lens area (as defined by Fig. 1). With widely spread well-fields, abstraction can be likened to negative recharge to the whole lens, so that the effective recharge becomes the natural recharge less the total pumping rate. The lens adjusts to abstraction by equilibrating to the new "effective recharge". Storage is lost, as the lens thins, and coastal outflow diminishes. These effects are not contrary to the objectives of good resource management: reducing outflow increases available recharge, and exploitation of storage makes use of the aquifer as a reservoir instead of as simply a conduit.

Since drought years in Bermuda have only a subdued effect on the position of the interface, the need for a large buffer of groundwater storage is lessened and significant thinning of the lens should be acceptable. Thinning by half has once occurred in the middle of the Central Lens without serious consequences. Thinning by as much as one half has also been suggested by Mather (1975) as at least an initial basis for lens management in "small limestone islands".

The reduction in natural recharge that will produce a particular percentage decrease in lens thickness can be simply estimated from Henry's equation. For instance, if a 50% reduction of lens thickness is acceptable then $\sim 75\%$ of recharge can be negated by pumping. Development of the Central Lens along these lines has been implemented over the last two years. In the Paget and Belmont aquifers, respectively, 45% and 60% thinning are considered permissible. The less cautious figure for the Belmont aquifer is a result of the decision to desalinate the water here. In this area the shallow interface makes upconing into the more seaward wells inevitable.

Abstraction limits have been increased since the introduction of this new scheme. Spreading of the well-fields has allowed recovery of central areas, and at this stage — November 1983 — thinning of the lens nowhere exceeds 25% of the estimated original thickness. A conservative, phased approach to introduction of the scheme has made observation of changing conditions possible. Modifications to the original plans will be made on an empirical basis, but at the moment it appears that these will be minor.

The percentage thinning approach can be criticised as being only a "rule of thumb" technique for development of lenses. However, the only alternative technique, that can be considered as of greater sophistication, would be computer modelling. Hindrances to development of this tool, for the purpose of management of the Central Lens resource, are discussed in the following section.

NON-STEADY-STATE MODELLING

Volumetric changes of the lens are so heavily disguised by the sea-level influence in the short term that calibration of a non-steady-state model by conventional means is not possible. A successful calibration is ensured only through exact simulation of the sea-level influence. Failure to do this means that recharge cannot be verified.

Added to the complications of sea-level effects are those caused by disequilibrium between the water table and the interface. Together they have thwarted attempts, so far, to produce a non-steady-state model of sufficient reliability to have applications as a management tool.

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