SALT WATER INTRUSION INTO GROUNDWATER; AN ASSESSMENT OF EFFECTS ON SMALL ISLAND STATES

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Salt water intrusion into groundwater; an assessment of effects on small island states due to rising sea level

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There are a number of different island types within the tropical oceans. The threat of sea-level rise, and impacts on groundwater resources, will be felt most on the low-lying reef-top islands and the reef islands of coral atolls. The freshwater lens on small islands is generally estimated using the Ghyben-Herzberg principle. This is a useful first order approximation but it has been shown to require refinement. Permeability and porosity of reefal sediments vary considerably, and the hydrogeology of individual islands is a function of reef structure and the pattern of the late Quaternary development of reefs and islands. Predicting change associated with sea-level rise is difficult because of uncertainty about individual island history, and as to how the processes of reef island formation will adjust to the various anticipated rates of sea-level rise that are predicted. If sea-level rise results in extensive erosion and retreat of the shoreline, a substantial reduction in the freshwater lens is likely as island size decreases. On the other hand, the continued production and transport of biogenic carbonate sediment, may, at least in the early stages of a slow rise in sea level, result in continued island accumulation. If sea level rises the water table will rise, and the central depression which is frequently a feature of both reef-top islands and atoll reef islands will be more prone to flooding, and will also become an area from which freshwater is lost more rapidly by evaporation and evapotranspiration. This higher water table, in some cases with increased salinity resulting from overwash, may require land use changes. Changes in the rainfall received or in the storminess of tropical seas, both of which have been predicted in some greenhouse scenarios, will also affect the groundwater resources of islands. However, despite uncertainties about the pattern of global change in our climate and hydrogeological characteristics of islands, the greatest threat to the freshwater lens, both now and over the next two or three decades, comes from anthropogenic factors such as over-abstraction and pollution.

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Introduction

The low-lying nations of the world are those that are most threatened by anticipated sea-level rise as a result of the greenhouse effect. Several entire nations consist solely of low-lying islands (Maldives, Tokelau, Tuvalu, Kiribati, Marshall Islands), and these are particularly vulnerable (Pernetta, 1988; Roy and Connell, 1989). In their case there is no higher land to which to retreat if the sea does rise.

The structure of oceanic islands varies considerably. Within the tropics reef-building corals play a major role in controlling or modifying island morphology. While the higher islands of the oceans are generally composed of volcanic rocks, many of the lower-lying are formed of reefal limestone and unconsolidated carbonate sediments. Darwin proposed a theory to explain the morphology of the major reef types, fringing reefs, barrier reefs and coral atolls, in terms of gradual subsidence of a volcanic basement (Darwin, 1842). His map of reef types emphasised that atolls are found in the centre of oceans (particularly the Pacific and Indian Oceans), whereas fringing and barrier reefs are more common around the margin. This distribution can now be understood in relation to plate tectonics. At plate margins tectonic movement of islands has uplifted reefs, and suites of emergent reef terraces are not uncommon. In mid-plate on the other hand, cooling and contraction of the ocean floor results in a deepening of the sea away from the mid-ocean spreading centre. Basaltic volcanic islands, formed over hot spots beneath the oceanic plate, are gradually moved tangentially into deeper water by plate motion. This together with isostatic compensation of the ocean lithosphere beneath islands explains why islands subside and how volcanic islands with fringing reefs may develop into coral atolls as hypothesised by Darwin (Scott and Retondo, 1983).

Island types

Figure 1 (modified from Scott and Retondo, 1983) illustrates some of the main types of islands. The simplest island is a volcanic island (i.e. Hawai’i); in mid-plate these are generally basaltic, whereas at plate margins, specifically on frontal arcs, volcanism is more usually andesitic. Gradual subsidence of a mid-plate volcanic island can mean that the fringing reef develops into a barrier reef with a lagoon separating the reef from land (i.e. Tahiti). An almost atoll, where only a small remnant of the volcanic mass remains above sea level and the reef is dominated by low, carbonate reef islands like those found on an atoll, represents a further stage in the evolutionary sequence (i.e. Aitutaki, Cook Islands). Still further subsidence results in the total disappearance of all of the volcanic mass beneath the sea, but the continued upward growth of the surrounding reef. Islands of carbonate sands and rubble form on the surrounding reef and the island is known as an atoll (i.e. Bikini, Marshall Islands; North Malé atoll, Maldives). Within groups of atolls there are sometimes smaller reef platforms which do not contain an interior lagoon, but which have an island over most of the area of the reef platform; these are termed reef-top islands in this account (i.e., Niutao, Tuvalu; Foammulah, Maldives). The sequence of islands, young volcanic island, island with fringing reef, island with barrier reef, almost atoll, atoll, is found in several linear island chains that occur in the Pacific Ocean, and along which potassium-argon dating of basalts has shown an increasing age towards the northwest. These chains are a spatial analogue of the temporal stages which any one island may go through. Beyond the northwestern-most island in the chain there are often submerged seamounts and guyots that represent further stages in the subsidence sequence.

While this pattern of gradual subsidence of islands applies through much of the Pacific plate, it is not the dominant trend at plate margins, nor is it the only possible scenario within mid-plate situations. At plate margins there is abundant evidence of islands that have been uplifted (Woodroffe, 1988a). On these there are characteristically flights of emergent reef terraces, such as those that have been used to calibrate late Quaternary sea-level fluctuations in Barbados, New Guinea and elsewhere (Broecker et al., 1968; Chappell, 1974; Bloom et al., 1974). While volcanic islands with emergent and fringing reefs and emergent limestone islands
are characteristic of plate margins (i.e. 'Eua and Tongatapu, Tonga), emergent islands can also be found in some locations in mid-plate settings. Some emergence of late Pleistocene reeval...  

![Image of diagram showing different types of mid-oceanic islands.](image)

**Figure 1:** Main types of mid-oceanic islands (modified from Scott and Rotondo, 1983).

limestones (specifically last interglacial limestones dated to around 120,000 years B.P.; oxygen isotope stage 5e) can be expected on islands that have undergone no vertical movement. This is because the consensus is that sea level stood slightly above present during the peak of the last interglacial, around 120,000 years ago. Such reefs are found up to 6-7m above present sea level on Oahu, in the Hawaiian chain (Ku et al., 1974).

Three other types of emergent island can be identified. An emergent atoll is an island that maintains an atoll form but upon which there are Pleistocene limestones above present sea level (i.e. Aldabra, western Indian Ocean). An emergent limestone island is an island which has lost any atoll form that it may have had (i.e. Nuie). A makatea island is one on which there is a highly eroded and degraded volcanic interior, surrounded by emergent limestones. The limestones ranging from Tertiary to last interglacial in age, have a highly irregular karstified 'makatea' surface, and are separated from the volcanic interior by a limestone cliff and low-lying swampy area. Several islands, including Makatea in French Polynesia, fall into this category, and although the present form suggests an uplifted barrier reef, it has been shown that the inner cliff to the limestone is a solutional feature and that the morphology results from solution of the inner part of the makatea limestone (Stoddart et al., 1985). Makatea islands are found exclusively in mid-plate settings, and their uplift appears to be related to flexure of the lithosphere in response to loading of the ocean floor by young volcanic islands (McNutt and Menard, 1978). Emergent limestone islands, while common at plate margins, can also be found on oceanic plates situated up-plate of a subduction zone; it appears that the islands may be located on a flexed bulge of the plate prior to subduction (i.e. Nuie; Christmas Island, Indian Ocean).

Of the island types depicted in Figure 1, the majority have land that reaches tens of metres above sea level (a,b,c,d,g,h,and i). Emergent atolls and emergent limestone islands may be
low-lying, and some do not rise above 6 m above present sea level, the level that is often quoted for the stand of sea during the last interglacial. However, these islands are composed of consolidated limestones and they are not nearly as threatened by erosion as islands of unconsolidated sediments. Those that are the most prone to inundation and erosion are the lowest-lying, namely atolls and reef-top islands.

Long-term geological evolution of coral atolls

Mid-oceanic coral atolls appear fragile, being composed of skeletal sands derived from corals, algae, molluscs and other organisms, and isolated in the middle of vast oceans subject to occasional extremely rough seas. Darwin's theory of the origin of atolls through the gradual long-term subsidence of a volcanic basement, has been generally proven as a result of deep drilling on several atolls in the Pacific (Stoddart, 1973; Braithwaite, 1982). Superimposed on the gradual (Darwinian) subsidence have been fluctuations in sea level. The most significant and most recent of these have occurred during the Quaternary over a vertical range of 100 m or more in response to the expansion and contraction of the polar ice sheets. When the ice sheets expand during glacials the volume of water in the ocean is reduced, and as the ice sheets melt the sea level rises. These sea-level fluctuations have occurred more rapidly than the rate of subsidence, and consequently played a more important role in determining atoll form.

The pattern of sea-level fluctuations during the late Quaternary has been reconstructed from the height and radiometric age of reef terraces on rapidly uplifting plate-margin coasts (e.g. Barbados, Broecker et al., 1968; New Guinea, Chappell, 1974, Bloom et al., 1974). The sea-level curve in Figure 2 is derived from a combination of reef terrace records from New Guinea and ice/ocean volumes determined from oxygen isotope analysis of deep sea cores (Chappell and Shackleton, 1986). The sea was close to its present level (arguably 6 m above

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**Figure 2**: Late Quaternary sea-level fluctuations and their effect on coral atolls. The lower diagram shows actual reconstruction of sea level and ocean volume variations for the last 140,000 years, based on raised coral reefs in New Guinea and oxygen isotope analysis of deep-sea cores (after Chappell and Shackleton, 1986). The atoll is gradually subsiding.
present level) during the last interglacial, 120,000 years ago. It underwent a series of progressively lower oscillations until reaching its lowest during the glaciation (80-150 m below present) 18,000 years ago. It has subsequently risen again to its present level as the ice sheets have melted, a period known as the post-glacial marine transgression.

When sea level was high an atoll perhaps somewhat similar to that presently found, would have existed where there are atolls today. When sea level was low, that atoll was exposed up to 100m above the sea as an emergent limestone island, and it underwent solution giving rise to a highly eroded karst surface (Figure 2). During the 100,000 years or so that it has taken for the sea to return to its present level, the atoll has gradually subsided so that the former (last interglacial) surface is about 10-20m below present sea level beneath the present atoll. This surface has been identified on a number of atolls (7-14m on Eniwetok, Szabo et al., 1985; 8-17m on Tarawa, Marshall and Jacobsen, 1985; 8-11m on the Cocos (Keeling) Islands, Woodroffe et al., in prep.), and as is demonstrated below plays an important role in controlling the form of the freshwater lens. The upper 10 or 20 m of reefal limestones and unconsolidated sediments built up in the Holocene (the last 10,000 years), with coral establishment over the karstic last interglacial limestones commencing about 8000 years ago (Marshall and Jacobsen, 1985).

It has become increasingly apparent in recent years that whereas the sea level record shown in Figure 2 is essentially a global phenomenon controlled by ocean volume, during the last few thousand years (Holocene) sea-level histories have not been the same for all coastlines of the world. The reason for this variability is that the earth has not remained undeformed by changes of loads upon it, but has undergone isostatic adjustments. It has adjusted both to ice loads (glacial isostasy), which accounts for rebound of those high latitude parts of the world loaded by ice during the glaciations, and it has adjusted to the load of water (hydro-isostasy), which accounts for subtle flexure of coastlines as adjacent shelves have been flooded by increasing water loads.

There is still some doubt over the exact timing of ice melt, particularly from Antarctica, but most post-glacial melting is thought to have finished by 6000 years ago (Nakada and Lambeck, 1988). Coastlines have however adjusted since that time, both to regional ice and water loads (as well as undergoing tectonic movements where tectonically active). Consequently the apparent sea-level history at any point depends upon those lithospheric adjustments as well as global (eustatic) sea-level history.

Geophysical models exist for a theoretical viscoelastic earth, and these permit modelling of global patterns of sea-level change (Clark et al., 1978; Nakada and Lambeck, 1988; Peltier, 1988). In terms of reefs and reef growth there are four broad sea-level provinces: West Indies, Central America, Australia, and the Pacific (Davies and Montaggioni, 1985). Sea-level pattern has differed for each region, and typical sea-level curves are shown in Figure 3. Each region is only a broad area within which rather similar patterns of sea-level change have been experienced, but there are within-region differences from place to place (i.e. Chappell et al., 1982).

For remote islands in the centres of the Indian and Pacific Oceans there is considerable evidence that the sea level was above present in the last few thousand years and that it has been falling relative to those islands. Cemented rubble deposits, called by various names, but classified under the general term conglomeratic platform below, have been radiometrically dated on many islands. Initially there was some reluctance to accept that these deposits did support a higher than present sea level (Shepard et al., 1967, Newell and Bloom, 1970). However more recent studies on islands in the Marshall Islands have interpreted elevated deposits on the windward reef flats as evidence of a higher sea level in mid to late Holocene (Tracey and Ladd, 1974; Buddemeier et al., 1975). Similar deposits support emergence throughout French Polynesia (Pirrazoli and Montaggioni, 1986, 1988), the Cook Islands (Woodroffe et al., in press a), Kiribati and Tuvalu (Schofield, 1977), and more recently also in the Indian Ocean, at the Cocos (Keeling) Islands (Woodroffe et al., in press b). There are analogous deposits
described from many other island groups, but not studied in detail (i.e. isolated outcrops in the Maldives, Gardiner, 1903).

Figure 3: Holocene sea-level changes for four reef provinces: a) West Indies, b) Central America, c) Australia and d) Pacific (after Woodroffe 1988b).

There is considerable evidence that the sea stood 1-2m above its present level with respect to many of the coral atolls (and presumably reef-top islands) of the Pacific and Indian Oceans about 4000-3000 years ago. In some cases sea level has fallen smoothly since that time to present (Chappell, 1982; Chappell et al., 1982); in other cases it remained high until around 1200 years ago (Pirazzoli and Montaggioni, 1986; see Polynesian sea-level curve in Figure 3); and in some cases complex oscillations of sea level are proposed (Yonekura et al., 1988).

The reef islands have developed since the formation of the conglomerate platform upon which they are perched. Many reef islands are only 2-3m above sea level; the highest point observed in the Maldives is 3.2m (Woodroffe, 1989), whereas in Cocos wind-built dunes rise to 9m above sea level. The majority of atoll reef islands cannot be older than 3000 years old (Pirazzoli and Montaggioni, 1986; Woodroffe et al., in press b). The pattern of sediment accumulation on reef islands is not well understood, and it is unclear whether islands have accreted gradually over that time, or have been built at a decelerating rate, or by episodic events. The issue is important in terms of gauging the response of islands to future sea-level rise, and is discussed in greater detail below.

The Freshwater Lens on reef islands

On small islands the freshwater lens is an important resource, both as a source of potable water and water for irrigation. Its quality can be impaired either by intrusion of salt water into the aquifer or by contamination of the lens from sewage, storm runoff, fertilisers, pesticides, industrial effluents and other contaminants.
Figure 4: Form of the Ghyben-Herzberg lens beneath reef islands showing flow of groundwater.

The freshwater lens is much more extensive on large islands than on small islands. The groundwater characteristics of emergent limestone islands are generally better known and understood (i.e. Bermuda, Vacher 1978a, Rowe, 1984; Grand Cayman, Bugg and Lloyd, 1976; Tongatapu, Hunt, 1979: northern Guam, Contractor, 1983) than are those of atolls and reef-top islands, but principles cannot always be scaled down to the lower islands.

Ghyben-Herzberg lens

Small islands composed of limestone or unconsolidated calcareous sediments represent a porous medium through which groundwater permeates. The first approximation of the freshwater lens of a small island is provided by the Ghyben-Herzberg principle. This relationship is based on density differences between rainwater and seawater; the lower density freshwater (specific gravity 1) floats on the underlying salt water (specific gravity 1.025). Within a homogeneous aquifer the form and position of the freshwater lens is related to mean sea level of the water in the surrounding ocean (Figure 4).

Within the island the upper surface of the unconfined freshwater lens, the water table also known as the piezometric or potentiometric surface, is domed, being higher in the centre of the island than at the margins. This gives the lens a head which is the reason why water flows horizontally from island interior to periphery. Flow is governed by Darcy's law:

\[ v = \frac{K}{n} \times \frac{dh}{dl} \]

where \( v \) is velocity of flow; \( K \) is hydraulic conductivity (or permeability); \( n \) is porosity; and \( dh/dl \) is the hydraulic head, that is the change of head with distance.
The elevation of the freshwater lens above mean sea level (hf in Figure 4), is a fortiieth of the depth of the lens beneath mean sea level (hs in Figure 4) according to the Ghyben-Herzberg principle, which assumes a homogeneous substrate, uniformly recharged, and without variations of the sea surface to mix waters. In modelling the Ghyben-Herzberg relationship the Dupuit approximation is used which assumes that equipotential lines are vertical (whereas in practice they are slightly off-vertical), and thus that flows are horizontal and at uniform velocities. Much of the modelling is further based on an aquifer which is underlain by an impermeable layer (Raudkivi and Callander 1976), though in practice this is rarely the case.

Under these idealised conditions mixing of fresh and salt water would occur only by molecular diffusion and there would be a sharp interface, the salt water interface, at which pressure must be the same in the two liquids. The Ghyben-Herzberg model may apply in coastal aquifers where runoff from extensive hinterlands contributes to groundwater and ensures a large outflow at the shoreline. However, on small islands where outflow is not likely to be large, the ideal Ghyben-Herzberg lens is not found and there is a thick brackish transition zone (Falkland and Brunel, 1989). Several studies have suggested that the 1:40 ratio of fresh water above to that below mean sea level does not apply in practice, but that the ratio is nearer to 1:20 - 1:25 (Mather, 1975; Bugg and Lloyd, 1976; Lloyd et al., 1980).

There are a number of reasons why the ideal Ghyben-Herzberg relationship is not found. Firstly the surface of the ocean is not static. Semidiurnal tidal fluctuations have the effect of inducing mixing. The piezometric surface of the freshwater lens fluctuates up and down in sympathy with the tides. A consequence of this is that the interface is not a sharp discontinuity, but instead there is a brackish water transition zone. The width of the transition zone can be as thick, if not thicker, than the thickness of the freshwater above it. It is not potable, though it does contain rainwater derived from recharge which means that this is water effectively lost.
from the lens (Volker et al., 1985). The transition zone represents a zone of balance (Figure 5); the rate of salt water intrusion into the freshwater zone being balanced by the rate at which it is carried back to the sea by flow with the freshwater (Mather, 1975).

Figure 6: Pingelap atoll showing the reef island of Deke and a cross-section of the island. Island elevation, water level (in wells), tidal efficiency and tidal lag are shown (after Ayers and Vacher, 1986).
Figure 7: Dual aquifer model, showing the idea of vertical coupling of aquifers in Holocene and Pleistocene sediments.

Two-dimensional modelling of freshwater lenses makes the assumption, as required by the Dupuit approximation that water moves horizontally. It was generally assumed that the tidal signal also propagates horizontally through the porous medium. This propagation can be measured from tidal lags (the time delay between open water and island well registration of high and low tidal stages), and tidal efficiencies (the average ratio of well water level range to lagoon or open ocean water level range). These measurements give an indication of the relative ‘hydraulic connection’ that wells have with the sea. Small lags and high efficiencies (i.e. little attenuation of the range of open water level fluctuations) are indicative of high levels of hydraulic connection resulting in thinner freshwater lenses; long lags and small efficiencies indicate low levels of hydraulic connection resulting in thicker lenses. One would expect the centre of islands to have low levels of hydraulic connection compared with island periphery. Figure 6 reproduces data on island elevation, elevation of the water level (piezometric or potentiometric surface), tidal lag and tidal efficiencies for the island of Deke on Pingelap atoll, from Ayers and Vacher (1986). It shows a typical pattern of increasing water surface elevation and tidal lag and decreasing tidal efficiency towards the centre of the island, with the peak area displaced slightly lagoonward.

Dual aquifer lens

Recently the assumptions of horizontal flow, and horizontal tidal propagation have been questioned (Buddemeier and Holladay, 1977; Oberdorfer and Buddemeier, 1988). On Enjebi, Eniwekit Atoll, little relationship was found between water level fluctuations with the tide and distance from the edge of the island. However, tidal efficiency increased and lag decreased with depth in boreholes and pronounced variations were observed in salinity distribution in individual boreholes during tidal fluctuations, with isochlors (lines of equal salinity) moving vertically by as much as 3 m in some cases. These results have been interpreted to indicate that the freshwater lens is actually vertically coupled with a more permeable aquifer at depth rather than horizontally linked to open water (Figure 7). It should be emphasised that Figures 4, 5 and 7 are highly vertically exaggerated and that the lower more permeable aquifer is generally much closer to any well on the island than is the shoreline.

The dual aquifer concept relates to the hydrogeology of atolls. Deep-drilling on several atolls has confirmed the essential correctness of Darwin’s subsidence theory of coral atoll
development. Boreholes reveal superimposition of a series of shallow water reefal limestones deposited during phases when the sea level is high (interglacials) marked by solutional unconformities formed during periods of emergence when the sea level was low (glacials) (Schlanger, 1963). Modelling using the dual aquifer concept, and vertical coupling of aquifers has produced good correspondence with field data (Buddemeier and Holladay, 1977; Wheatcraft and Buddemeier, 1981; Herman and Wheatcraft, 1984; Herman et al., 1986; Oberdorfer and Buddemeier, 1986). A deep and variable transition zone of rather saline water is consistent with an incipient Ghyben-Herzberg lens truncated at shallow depth by a highly-permeable aquifer closely coupled to lagoon or ocean waters. The vertical coupling would suggest a low freshwater inventory, shorter residence times but also a greater resilience and ability to re-establish a lens than the traditional Ghyben-Herzberg interpretation.

**Hydrogeology and the form of the freshwater lens**

However, it is clear that even the dual aquifer model is not a perfect model of groundwater flow beneath reef islands. Not only do permeability and porosity vary between lithological units, they can show enormous spatial variation within any one unit. Holocene sediments vary substantially in their composition and also therefore in their permeability and porosity. Heavily cemented near-surface deposits are a feature of many atolls. These can comprise intertidal beach deposits, particularly beachrock, which tends to be extremely impermeable, and also a series of conglomerate deposits which form on atolls. Conglomerates composed of cemented coral boulders are a feature of many atolls. Their origin has been the subject of some controversy; in some cases they appear to have been deposited by a sea level above present, whereas in others they are considered to be formed from storm deposits, and are not considered to support a higher than present sea level (see above). The form and distribution of these conglomerate platforms varies from atoll to atoll (see discussion below). They tend to be most conspicuous and cemented into their hardest on the oceanward shore of Islands, and they underlie much of the seaward side of the Island (e.g. Home Island, Cocos (Keeling) Islands, Jacobsen, 1976), only in a few cases extending through to the lagoon shore. The oceanward part of the platform is often underlain by better lithified and deeper coral bearing limestone deposits, than the more lagoonward part of the platform (e.g. on Tarawa, Lloyd et al., 1980; on Home Island, Cocos, Woodroffe et al., in press b). The distribution of conglomerate platform, reaching 1-2m above sea level, on Deke, Pingelap atoll, is shown in Figure 6 (after Ayers and Vacher, 1986).
The conglomerate platform and the underlying limestones have several effects on the form of the freshwater lens (Figure 8). The platform itself is highly impermeable and acts as an aquitard, which confines the freshwater lens. A small perched freshwater reservoir can form above the platform within the island, but wells through the hard pan, reflect the true piezometric surface of the underlying lens (see Ayers and Vacher, 1976). A consequence of this aquitard is that this confined portion of the freshwater lenses may extend out beyond the island perimeter under the reef flat (Figure 8). Furthermore infiltration of sea water through the reef flat deposits, and also through the intertidal and supratidal parts of the platform after storms may be very limited. At the same time freshwater recharge is also likely to be negligible over this part of the island, as freshwater falling on a well-cemented conglomerate platform is more likely to runoff into the sea than to permeate through the platform surface (Ayers and Vacher, 1986).

The form of the lens reflects the permeability of the sediments through which groundwater permeates. The elevation of the upper surface of the lens (often difficult to measure in practice because of complicating tidal fluctuations), is an indication of lens thickness (following the Ghyben-Herzberg principle of a 1:40 relationship). In several studies the upper surface has been shown to reach its highest elevation not in the centre of the island, but offset towards the lagoon. This is shown for Deke, Pingelap (Figure 6). The lens is also therefore thicker towards the lagoon than it is towards the ocean shore, reflecting the fact that the unconsolidated sediments beneath the lagoonward portion of the island are less permeable than the relatively porous, partially-lithified coral-bearing sediment to oceanward. Asymmetry of the lens (Figure 8) has been demonstrated for several islands (i.e. Tarawa, Lloyd et al., 1980; Kwajalein, Hunt and Peterson, 1980; Laura, Majuro, Miller and Mackenzie, 1988).

Recent modelling of freshwater lenses and their behaviour beneath small islands tends to have adopted either the dual aquifer model (Herman et al., 1986; Oberdorfer and Buddemeier, 1988), or the traditional Dupuit-Ghyben-Herzberg model (Ayers and Vacher, 1986). The models have important differences. The Dupuit-Ghyben-Herzberg model depends upon a long-term balance between recharge and outflow of fresh water from around the margin of the island. In the dual aquifer model the primary mechanism for loss of fresh water is degradation by downward mixing into the transition zone. Any particular reef island is likely to consist of a complex hydrogeology, and groundwater flow and recharge may adopt some subtle unique combination of horizontal and vertical movements.

Figure 9: Freshwater lenses beneath four reef islands: Bonriki, Tarawa (after Marshall and Jacobsen, 1985), Home Island, Cocos (Keeling) Islands (after Falkland, 1988), Kwajalein (after Hunt and Peterson, 1980), and Malé, Maldives (after Binnie and Partners, 1987). Note: potable water is taken as roughly fresher than 2600 μS/cm which is interpolated for Bonriki, Kwajalein and Malé.
Factors which influence the extent of the Freshwater lens

The principle factors which effect the size of the freshwater lens are island width, rate of freshwater recharge, and permeability of the aquifer (Mather, 1975). Tidal range can be important in that it influences the thickness of the transition zone. The amount and type of vegetation on the island, as well as man-made modifications to the surface of the island, influence the proportion of rainfall reaching the lens as recharge.

a) Size

Freshwater lenses only develop on islands that are large enough. Initial observations suggested that the threshold size was 1.4 ha, or a width of 200m (Wiens, 1962). However lenses are not found beneath all islands of that width and in some places 300-400m may be a more realistic minimum width for a lens to develop (i.e. in Kiribati, Cloud, 1952; Marshall and Jacobsen, 1985).

b) Rainfall

The rainfall an island receives is also important, Oberdorfer and Buddemeier (1988) have suggested a relationship where the depth of the lens, weighted for rainfall, can be related to island width:

\[
\text{Lens depth (m)/ Annual rainfall (m) = 6.94 X Log island width (m) - 14.38}
\]

This relationship based on nine islands is not particularly strong (r=0.72). Furthermore it includes the island of Tongatapu, which is not an atoll, but which unduly influences the line of best fit. Oberdorfer and Buddemeier (1988) suggest a minimum island width for freshwater lens formation of 120m; this value would be larger, and hence more in line with other observations if Tongatapu were excluded from the analysis.

Figure 9 shows the form of freshwater lenses beneath four reef islands. These islands all receive about 2000mm of rainfall annually. The lens can be a deep as 29m on Tarawa (Marshall and Jacobsen, 1985), but is much shallower on Malé in the Maldives, where water abstraction is leading to rapid contraction of the lens (Binnie and partners, 1987). Asymmetry is apparent in the lenses beneath Home Island, Cocos (Keeling) Islands (Falkland, 1988), and Kwajalein (Hunt and Peterson, 1980). Comparison is not made easy by differences of measurements in the different studies, and in a attempt to standardise potable water has been defined as water up to an electrical conductivity of 2600μS/cm, the Australian lim limit, which has been interpolated onto all lenses.

c) Hydrogeology

Hydrogeological characteristics of islands influence the rate of flow through island substrates and thus have an influence on shape and size of lens. The calcareous deposits which underlie small islands are porous and water flow is relatively rapid compared with most rock types. Flow rate, however, can vary considerably spatially, firstly because of different degrees of lithification and secondly because of different degrees of solution.

Islands are built on top of Holocene deposits which have either accreted as reef growth dominated by corals, or by sedimentation in a lagoon; often the islands straddle the interface between these environments (see Figure 8). Coral dominated deposits, often partially lithified by calcareous algae, contain sizeable voids which allow more rapid water movement through the lagoonal sands. Greater contrast in permeability is characteristic of the surface sediments, particularly the reef flat which is often sealed with an algal veneer, the conglomerate platform which is generally well-cemented and largely impermeable, and localised beachrock deposits formed in the intertidal zone.
These hydrogeological characteristics are not, however, entirely independent of water movement. The chemical composition of the water can be an important control on lithification in various environments. Particular cement types are associated with vadose (aerated) and phreatic (below water table) zones (Figure 10), and their mineralogy varies according to the salinity of water, low-Mg calcite being the dominant cement under freshwater conditions, and high-Mg calcite and aragonite being dominant under marine conditions. The formation of cemented intertidal deposits such as beachrock, which can form rapidly, are still the subject of debate. Initially it was interpreted as the result of mixing of fresh water and marine waters at the island margin where outflow of water from the lens would be expected (Russell, 1962). More recently this has been questioned because outflow does not appear necessary, and chemical changes within the water table, especially CO₂ degassing are believed to be involved (Hanor, 1978).

Studies of the mineralogy of cements and the characteristics of groundwater suggest that little lithification has taken place under present lens conditions (Marshall and Jacobsen, 1985). This should not be surprising given the recency of the formation of reef islands. The freshwater lens cannot be older than the islands, and these rarely if ever exceed 3000 years old. Furthermore the lens will have expanded as the reef island has accreted (discussed below). The calcareous sediments beneath islands must therefore have been infiltrated by sea water until that was displaced by freshwater after island formation.

Major lithological units have considerably different permeabilities, and older limestones are generally more permeable than younger ones. This is because extensive solution takes place at times of low sea level (see Figure 2), and large passages and conduits can be formed by solution. The differences in permeability can be most clearly seen on emergent limestone islands where two limestone units outcrop next to each other (i.e. on Grand Cayman the most extensive freshwater lenses are in the Tertiary Bluff limestones rather than the Pleistocene Ironshore limestones, Bugg and Lloyd, 1976; in Bermuda the older Belmont Formation limestones are more permeable than the younger Paget Formation limestones, and lenses are asymmetrical where the deposits are adjacent, Vacher, 1978a). In the context of coral atolls the last interglacial limestones form a more permeable aquifer than the overlying Holocene sediments.
Porosity, the ratio of voids to total volume of a sediment, varies in reefal settings. Effective porosity, that proportion of the voids through which flow actually occurs, is generally 10-30%, and is always less than total porosity which is characteristically 40-60%.

Permeability (K in the Darcy equation) is difficult to measure. It cannot effectively be scaled up to entire lithologies from observations from core samples, and really needs to be measured from test wells using pumping experiments. It is often based on hydrological inferences, and observations of tidal signal propagation (usually making assumptions of horizontal propagation according to the Dupuit-Ghyben-Herzberg principle).

Permeability tends to increase with depth. Unconsolidated Holocene sediments tend to show permeabilities of 1-10 m/day (Lloyd et al., 1980; Ayers and Vacher, 1986), whereas the permeability of the underlying Pleistocene limestones is likely to be around 1000 m/day (Hunt, 1979; Oberdorfer and Buddemeier, 1988). Coral-rich partially lithified Holocene sediments often have intermediate permeabilities (i.e. 200 m/day on Tarawa, Lloyd et al., 1980). However the conglomerate platform and reef flat permeability can be in the range 0.1-10 m/day (i.e. 5-22% porosity, <4 m/day permeability on Deke, Ayers and Vacher, 1986).

It is important to emphasise the variability, however. Microkarst, caves, deep sinkholes, solution-widened fissures all increase the speed with which water can move through the limestones, and give seawater access to interiors on islands. On Grand Cayman, excavations into the middle of the island have uncapped fissure through which seawater gushes with the incoming tide, and similarly fissures in Holocene reefal sediments have been observed allowing tidal incursion of seawater into the lagoon of Nui Atoll, Tuvalu (personal observations).

Water Balance

The size and shape of the freshwater lens is essentially a balance between what comes in and what is lost from a particular lens. In terms of working out such a balance it is useful to think of two systems, firstly a water balance for the island from which recharge can be calculated from rainfall, and secondly a balance for the lens (Falkland, 1989).

Recharge is generally less than 50% of rainfall (Buddenmeier and Holladay, 1977). On emergent limestone islands it is often 25-30% of rainfall (i.e. 30% on Tongatapu, Hunt, 1979; 25% in Bermuda: this was calculated both from water balance, and from the extent to which chloride was concentrated from its value in rainfall to that in the lens, Vacher and Ayers, 1980).

The relationship can be expressed as: \[ R = P - I - E - \partial S \] where \( R \) is recharge, \( P \) is precipitation, \( I \) is interception, \( E \) is evaporation and evapotranspiration, and \( \partial S \) is change in soil storage. A water balance can be calculated rather more easily for small islands such as atolls, than for high islands, because atolls do not usually have a recognised orographic effect (Nullet, 1987).

Interception, which includes all retention of water by vegetation before it gets to the ground, can be as much as 15% on islands, and is particularly high where there are coconuts. Evaporation and evapotranspiration also depend on vegetation. Coconuts transpire a lot of water, with estimates suggesting 70-130 litres per tree per day (human consumption of water varies from 20-350 litres per person per day on similar islands; and up to 1000 litres per person per day in some tourist resorts)(Falkland and Brunel, 1989). Coconut woodland therefore has a major effect on recharge; on Cocos (Keeling) Islands it has been calculated that recharge is 48% of rainfall where there are no coconuts and 25% where there is 100% cover of coconuts (Falkland, 1988, 1989). This implies that where there is dense coconut woodland recharge to the lens could be considerably increased by removing them in favour of less exacting vegetation. No account has been taken of anthropogenic factors which influence recharge; road construction and other urban development tend to severely diminish the volume of recharge.
Rainfall reaching the ground surface diffuses into the soil before replenishing the lens. Several zones occur above the water table (see Figure 10). The concentration of water in the soil water zone can vary from permanent wilting point to field capacity. When all soil particle surfaces are wet water can diffuse down the moisture gradient, through the aerated zone. Some water is held above the water table in the capillary zone, by capillary processes. The form of the lens can be modelled to some extent by one of the two models already described, the Dupuit-Ghyben-Herzberg model, or the dual aquifer model (generally modelled using a programme known as SUTRA based on mass conservation of water and salt).

A balance for the lens consists of: \( R = A + Q - \partial L \) where \( A \) is abstraction, \( Q \) is outflow at the island margins, and \( \partial L \) is a change in the volume of the lens which comprises both the freshwater lens itself and the transition zone (where freshwater is lost by mixing with salt water).

Sustainable yield (i.e. the volume of water which can be safely abstracted from the lens varies from island to island, but is probably 20-30% of recharge, approximately 6-12% of rainfall for coral atolls (Falkland, 1989).

Sea-level rise

There has been concern that the sea is rising and will rise at an accelerating rate. Monitoring tide gauges suggest current rates of sea-level rise in the order of 1.1.5 mm/yr (Gornitz et al., 1982), although records are spatially clumped and do not give reliable global coverage (Pirazzoli, 1986). On the other hand there have been a series of predictions which indicate that global warming (the greenhouse effect) will result in sea-level rise, and that this will accelerate with the accumulation of greenhouse gases in the atmosphere. The principle reasons for sea-level rise will be thermal expansion of the oceans, combined with melting of grounded ice, principally from glaciers. Ice-melt from the major Antarctic ice-cap is unlikely to occur until a considerable time has elapsed but could result in sea level many metres higher than present in some hundreds of years time.

A series of predictions by Hofman (Barth and Titus, 1984) are frequently quoted. These contain a number of different scenarios (conservative, mid-low, mid-high and high). They

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*Figure 11: Plan and cross-section of Foammulah, a reef-top island in the Maldives.*
suggest that the rate of sea-level rise will increase. They predict a rise of 4.8 cm (conservative) to 17.1 cm (high) by the year 2000; 23.8 cm (conservative) to 116.7 cm (high) by the year 2050; and 56.2 cm (conservative) to 345.0 cm (high) by the year 2100. Most generally acceptable scenarios suggested a rise in sea level of 20-140 cm by 2030 (Henderson-Sellers and Blong, 1989).

While these predictions purport to be global their verification from tide gauge data is not easy. Coastlines are not entirely stable, many are tectonically active and undergoing gradual movement, others may still be undergoing some isostatic adjustment. It is extremely difficult, given all the factors which account for the regular variability of tide records, to extract this longer-term trend from the data (Belperio, 1989; Bryant, 1988b). Even then measuring errors at tide stations need to be taken into account (Bird, 1988).

In a recent attempt to extract ongoing isostatic deformation from tidal records, Peltier and Tushingham (1989) suggest that there is a recognisable sea-level rise trend of $2.4 \pm 0.9$ mm/yr, this implies a sea 9-20 cm higher than present in 2050. A recent sea-level meeting in Australia also reduced the estimate for sea-level rise to $30 \pm 20$ cm above present by 2050 (Pittock, press release).

Given that Holocene sea-level changes appear to have shown different records from different places, and given the uncertainty of determining genuine sea-level trends from highly variable data where there are tide gauges, yet alone where there are none, we cannot be sure that the sea is presently rising relative to all atoll reef islands. These small islands are remote from good lengthy tidal records, and it is inappropriate to assume that because a rise in the level of the sea is observed in North America and in northwestern Europe, that there is a similar rise in sea level on all atolls.

There are several trends in the land-sea relationship that are relevant. Over the long-term islands may be undergoing subsidence. Rates of subsidence based on the depth of last interglacial reefal deposits (see above) are of the order 0.05-0.20 mm/yr, an order of magnitude less than geologically recent, and predicted, rates of sea-level rise. In the Pacific and

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**Figure 12:** Nui, Vaitupu and Nanumanga (the latter is a reef-top island), Tuvalu, showing various stages in the filling of the top of the reef platform and in the enclosing of the central lagoon (after Woodroffe 1988c).
eastern Indian Ocean there is widespread evidence that sea level was 0.5-1.5 m above present level 3000 years ago. This implies an average rate of fall (though it is unlikely to have been uniform) of 0.15-0.50 mm/yr. This trend may not have been universal, islands of different sizes will respond hydro-isostatically in a different way to post-glacial sea-level rise (Nakada, 1986).

Most reef islands have developed into the complexity of landforms now seen during a period of 3000 years or more of sea level close to its present level. The geomorphology of these islands indicates that the sea has not changed its relationship to the land by much in that time. A similar approach can be adopted to examine changes over the last few years using individual corals. Individual corals cannot grow above a level at which they are exposed too frequently somewhere between low neap and low spring tide level. Several intertidal massive corals (particularly of the genus Porites) adopt a flat-topped form, living only around the periphery, when they reached this level. These are termed microatolls; they commence growth as hemispherical corals but when they reach the limit to coral growth they die on their upper surface and continue to grow laterally. Their upper surface thus contains a record of past water level fluctuations. Analysis of the record from microatolls from several atolls in the Pacific and Indian Oceans indicates that those atolls have undergone negligible change in water level for the last 20-30 years, and that most have in fact seen a slight fall of sea level of several centimetres over the last decade (Woodroffe, 1989; McLean, 1989).

There seems to be some doubt that sea level is actually rising at this stage; and there is further doubt about the rate at which the sea will rise if and when it does.

The effects of rising sea level on atolls

If sea level rises then the effects most commonly predicted for atolls are shoreline erosion, flooding of low-lying areas, and saline intrusion into the freshwater lens. It is the third effect that we are particularly interested in in this report, but the former impacts need to be examined in order to assess their effect on the lens.

Comparison the Holocene transgression

The rates of sea-level rise predicted are similar to rates that were experienced during the post-glacial marine transgression (Holocene sea-level rise since the last ice age), 12-15 mm/yr. Reconstructing the changes that occurred during that recent period of sea-level rise provides a valuable insight into the kinds of changes that might be expected as a result of the greenhouse effect (Thom and Roy, 1988).

Three strategies of reef growth have been recognised in relation to sea-level rise: keep-up growth in which reefs closely track sea level; catch-up growth in which reefs, previously lagging behind sea-level rise (which has generally slowed or stabilised), are growing at rates which means that they are catching up and growing into increasingly shallower water; and give-up, where reef growth has been arrested, and present fore-reef buttresses are remnant reefal features veneered with only a thin live coral cover (Neumann and Macintyre, 1985).

Many reefs were growing as catch-up reefs during the early Holocene when sea level was rising at 10-12 mm/yr. Even if they grew as keep-up reefs there is no evidence that reef islands existed at this stage, and if they did they must have experienced frequent overwash (Pirazzoli and Montaggioni, 1986). Since sea level has stabilised in the Pacific and Indian Oceans (see sea-level curves in Figure 3), the majority of reefs have caught up and the surface morphological features of atolls, including reef islands, have formed.
Effects on reef islands

Reef islands can be divided into a number of types (Stoddart and Steers, 1977). On atolls there are often sand islands with shingle ridges on the more exposed rim; these are often known by the Polynesian term 'motu'. In more sheltered situations cays built entirely of sand are formed. The location of islands on atoll rims is usually a subtle but balanced outcome of patterns of wave and current activity. The cross-sectional form of reef flat depth and island topography often represents an 'equilibrium shoreface profile' and again is generally in balance with dominant processes (Thom and Roy, 1988).

![Diagram](image)

**Figure 13:** The possible responses of a reef island to sea-level rise: a) initial island morphology, b) the Bruun response, c) the equilibrium response, and d) continued growth. See text for details.

Reef-top islands are a special type of island found on the top of small reef platforms in atoll groups. Figure 11 shows a plan and cross-sectional profile of one such island in the Maldives, Foammulah. The interior of the island is low-lying, and it is surrounded by higher ridges. The island has a narrow reef flat around it. Several islands of this type occur in Kiribati and Tuvalu. Figure 12 shows three islands in Tuvalu (Nui, an atoll, and Vaitupu and Nanumanga which are reef-top islands) which show increasing levels on constriction of the lagoon. Nanumanga, a reef-top island, has an interior depression containing a pool of saline water (generally just below seawater salinity), and extensive mangrove forests, while Vaitupu still contains shallow lagoons with open connections to the sea. These islands presumably develop in a similar way to atolls, but as the reef platform is so small the interior lagoon becomes entirely lanukaowed, and as all sediment accumulates into one island they are often larger than the individual reef islands on large atolls. In some freshwater lenses are established (i.e. Foammulah) and they can be important agriculturally productive islands, whereas in others saline water persists in central depressions (i.e. Nanumanga). Little study has been made of the lenses on such islands, though Lam (1974) has examined the permeability of Swains Island, a similar enclosed atoll, in the southern Tokelau Islands.

Flooding of the lowest-lying parts of islands is likely to occur under higher sea level. The areas which are lowest lying at present are already subject to extensive inundation at exceptional high spring tides or by storms or surges. The areas are consequently dominated by salt-tolerant vegetation, often mangroves or scrubland of *Pemphix acidula*. These areas will be flooded more often when the sea is higher, and unless they are infilled by mud, the vegetation is
likely to die. Mangrove and *Pemphis* however will become established further landwards in areas that were previously beyond inundation but are now flooded. Many reef-top islands will flood from the interior; on Vaitupu and Nanumanga (Figure 12) the interior lagoon are likely to get larger. Other reef-top islands, now freshwater in the interior and agriculturally productive are likely to become more swampy as water table rises. These are considered below.

There are at least three responses of islands which can be envisaged as a result of sea-level rise. These are illustrated in Figure 13, and consist of i) the Bruun response, ii) the equilibrium response, and iii) continued growth.

a) **Bruun response**

The Bruun rule applied to the response of sandy beaches to sea-level rise indicates that the beach will erode and retreat (see Figure 13b), and that sediment will be deposited over the reef flat area in front of it (Bruun, 1988). It should be emphasised that rising sea level is not the only cause of beach erosion, nor indeed is it necessarily the most dominant, and beaches elsewhere show long-term trends of erosion and recovery significantly related to factors such as rainfall, storms and ENSO-related oscillations (Bryant, 1988a). Nor does the Bruun rule appear to hold over long-term sea-level rise, such as the Holocene marine transgression, where in some instances landward reworking of sand, presumably by overwash, has been demonstrated (Thom and Roy, 1988).
b) Equilibrium response

The equilibrium response is shown in Figure 13c. It differs only slightly from the Bruun response. The beach undergoes erosion, but some of the eroded sand is deposited on the ridge crest, building it up and maintaining a profile in balance with the processes dominating the shoreline. Surveys of reef islands have shown that many of them have a form similar to that in Figure 13a, with pronounced ridges (of sand, shingle, rubble, or a combination of each) on oceanward and a small ridge on lagoonward shores. These ridges prevent the majority of storms from overwashing into the island, and are presumably built up by frequent small storms. Reef island form therefore appears to be in equilibrium with processes operating on it (Stoddart et al., 1978; Bayliss-Smith, 1988; Woodroffe, 1989). If sea level rises at a rate that is not too fast, this equilibrium will be maintained at higher sea levels (Figure 13c). Erosion of material from the beachface will occur and some retreat of the shoreline is likely, although as the angle of the beachface is generally steep, this is unlikely to result in major retreat of the shoreline. Catastrophic retreat of shorelines is only going to occur where sea-level rise is so rapid that large storms which did not overtop the ridge under normal conditions frequently overtop it under the higher sea level. Overwash will be more frequent if storms do not permit the equilibrium to re-establish.

Equilibrium on such islands is an important but complex issue. While on some islands a morphology in balance with regular processes is established and does not change (i.e. a stable equilibrium), on others sediment is added and lost from islands over time, and there is a dynamic equilibrium between inputs and outputs. Catastrophic storms play an important role in both construction and destruction of many islands in seas which experience hurricanes (Stoddart, 1971). The effect of these episodic but high magnitude events is likely to be different on different types of island. Motus, which are sand and shingle islands typical of high-energy settings of atolls which experience storms, are built up in part by rubble-sized material which cannot be moved by regular processes; storms are obviously instrumental in moving this coarse material, and large reef blocks, onto the reef flat (i.e. Hurricane Bebe in Tuvalu, Maragos et al., 1973). It has been shown, however, that regular less severe storms breakdown and redistribute the storm rubble landwards (Baines et al., 1974; Baines and McLean, 1976; Bayliss-Smith, 1988). Rubble is usually an important constituent of a well-developed conglomerate platform beneath islands, a legacy of past storms. Sand on the other hand tends to be stripped off islands by storms, but to be moved back onto islands by the more regular processes.

Not all islands are affected equally by storms and the morphology of islands differs accordingly (McLean, 1980). Figure 14 illustrates the morphology of islands in different categories of storm occurrence. It is simplified, and represents a generalisation that is not universal; other processes associated with strong tradewinds outside hurricane belts can also serve to modify islands. Where storms are frequent, reef flats contain rubble ramparts or degraded rubble deposits on the motus of the high-energy reef flat; the algal ridge is well-developed, and conglomerate platforms are prominent and may extend across much of the reef flat, underlying entire islands (i.e. Tuvalu); sand cays are found in the less exposed areas. Where storms are not as frequent or as severe, there are less extensive rubble deposits; the algal ridge is less prominent and the conglomerate platform is not as extensive across the reef flat (i.e. Cocos (Keeling) Islands). In storm-free, low energy areas, rubble is not a major component in island construction; instead sand cays are found even on the outer atoll rim (i.e. Maldives).

Figure 14 also depicts a series of schematic responses of island form to processes (modified from Bayliss-Smith, 1988). Storms result in loss of sand from cays and motus, but an input of rubble in the form of ramparts to the motus. The motus which receive an input of rubble adjust with the medium-term breakdown and redistribution of that material as they return to equilibrium. Cays lose sand during storms, but are rebuilt to an equilibrium by beach recovery through normal processes. Relaxation time (time taken to readjust between high energy events) and recurrence interval (frequency of such events) are important in controlling reef island morphology. When storms are very frequent (or very severe) motus and cays may be
in disequilibrium for most of the time. When storms are occasional, complete recovery is possible between storms and islands may be in dynamic equilibrium. Where there are no storms cays should reach a stable equilibrium; a rare disturbing event such as a tsunami, or a rogue hurricane, can cause devastation on these islands, and such catastrophes will require a long time for recovery (Figure 14).

Hurricane frequency may have changed in the past, and is predicted to change in the future. Such changes may explain differences between island morphology and what might be expected from present storm regimes. Higher energy conditions may have been experienced on several shorelines in mid-Holocene before seaward reefs caught up with sea level, an effect known as the Holocene high energy window (Hopley, 1982; Bayliss-Smith, 1988); though detailed studies of storm frequency in the southern Great Barrier Reef have not identified any changes in storm frequency (Chivas et al., 1986). Increased hurricane frequency is predicted as a result of the greenhouse effect as more of the ocean's surface is warmer than the 27°C necessary for hurricane formation. The consequences of such a change could be devastating, particularly for atolls that do not experience such storms at present (i.e. Maldives), but are beyond the scope of this account.

Erosion and recovery of reef island beaches are processes which go on, and which need to be taken into account in gauging the response of islands to sea-level rise. It is clear that a major erosion event resulting from a storm might be misinterpreted as a consequence of sea-level rise, whereas such an event might have had the same effect at the existing sea level. What will be important however is whether the beach recovers as it would have under the previous sea-level conditions.

c) Continued growth

The third view of island response to sea-level rise is one of continued growth through sediment accretion (Figure 13 d). Reef island sediments differ in one important respect from sediment on mid and high latitude beaches, they are derived from organic remains and thus fresh sand is being generated continually from the death and breakdown of molluscs, algae, foraminifera, etc., and from the abrasion and bioerosion of live and dead coral.

The pattern of past reef island sediment accumulation, and of present reef island accretion is not well-understood. Islands may have accumulated entirely soon after their initiation 2000-3000 years ago, or they may have been built up by gradual, ongoing accumulation. The rate of sediment supply to reef island beaches presumably reflects water movements over the adjacent reef flat and lagoon. Sediment supply may be enhanced under a higher sea level. Hopley and Kinsey (1988) suggest that 'sand supply is not a limiting factor in cay accumulation. Greater inundation of the reef flat will allow for a extended period of sand movement under any prevailing set of weather conditions'. Greater efficiency of sediment movement may, in the short term, build up islands to match sea-level rise.

It has already been pointed out that many reef islands are perched on conglomerate platforms which are related (in a majority of cases) to higher sea level in mid-Holocene. We need to ask to whether reef island accumulation has taken place only because of this negative movement of sea level. It seems unlikely that it has; in the West Indies and Belize sea level appears to have been rising throughout the Holocene (see Figure 3), and yet sand cays have developed there.

If the sea rises at rates of only a few millimetres a year then reef islands are unlikely to be catastrophically affected; some shoreline erosion is likely, but the continued supply of sediment, both from that erosion, and as a result of enhanced sediment transport, is likely to build the shoreline up into a new equilibrium form. On several islands a rise of 50 cm would mean that the sea was no higher than it had been in mid-Holocene, and although there is no evidence of islands at that time, the cemented conglomerate platform provides some protection
for the present islands, and where such a platform exists would slow the rate of erosion of those islands. The islands which are most at risk by a rise of 50 cm are those in storm-free areas where coarse material is not abundant on the reef flat and where there is no conglomerate platform. Several islands in the Maldives are in this category, and a rise of 50 cm would mean that the sea was dangerously close to settlements on several of these islands.

A more rapid rise (for example more than 50 cm above present by the year 2050) would almost certainly exceed the potential for islands to keep up, and would result in very altered energy conditions at the shoreline. While much of many islands would still be above water, it is extremely doubtful whether sand cays with no consolidated sediments on them could remain, in the face of the higher energy wave conditions which would cross reef crests and reef flats under these circumstances. Most susceptible will be those islands which are not based on lithified deposits, and therefore have not firm base that acts as an anchor. Rates of sea level rise of this order were seen during the Holocene transgression, but reef islands almost certainly did not exist. The two situations are not entirely analogous because there are large sand deposits around at present sea level (as a result of 3000-6000 years of relative sea-level stability) which can be reworked by the rising sea level. Similar deposits presumably did not exist as the sea rose rapidly over last interglacial limestones approximately 8000 years ago.

Effects on reefs

Growth rates of up to about 5-25 mm/yr for massive corals and 100 mm/yr for branching corals have been recorded (see Brown, this meeting). Reefs, however, grow more slowly. When the sea rose at 10-12 mm/yr during the post-glacial marine transgression few if any reefs kept up. Growth rates of reefs have been determined from numerous cores on the Great Barrier Reef. Exceptionally the reef may accumulate at up to 16 mm/yr, where storm accumulation has occurred and branching corals comprise the matrix. However the most rapid reef growth rate consistently recorded, determined both from stratigraphy and chronology of reefs, and measurements of calcification rates from water chemistry, is 7-8 mm/yr, and this rate seems to have occurred in water depths of around 5m (Hopley and Kinsey, 1988). On atolls reef growth rates up to 3 mm/yr are characteristic (Hooley, 1982), with rates of up to 8 mm/yr rare (Marshall and Jacobsen, 1985).

Little change is envisaged to reef front or to reef crest in the initial stages of sea-level rise. Perhaps the most conspicuous response will be the recolonisation of extensive areas of presently bare reef flat by coral. Senile reef flats, often exposed at low tide on many atolls in the Pacific probably as a result of negative movement of the sea during the late Holocene, will revert to mature coral-covered reef flats in the first 50-150 years of sea-level rise; and in the longer term may become more similar to the less-frequently exposed, coral-dominated backreef areas characteristic of West Indian reefs where sea level has been rising for the last few thousand years (Hopley and Kinsey, 1988).

Effects on groundwater

If the sea rises the freshwater lens will be affected. It's sensitivity to changes in ocean water level is demonstrated by the oscillation of the water table in sympathy with the tides. Longer term changes in water table can also be related to ocean water level changes brought about by atmospheric pressure differences (Vacher, 1978b) and other atmospheric circulation patterns (Freshwater lens size varied on Christmas Island, Kiribati in relation to ENSO events in the 1980s, though this may be driven by the varying rainfall and consequently recharge rather than just ocean water level changes; Falkland and Brunel, 1989).

The overall importance of island width has already been emphasised as one of the key factors influencing the extent and form of the freshwater lens. If sea-level rise results in island erosion and a decrease in width, then the lens is likely to be smaller (see Figure 13). However, as already stressed it is not clear that islands will always suffer erosion, and erosion does not occur only as a result of sea-level rise. In some cases more sediment will be produced, and
sediment already there may become more mobile, so that islands might actually expand and the freshwater lens would become bigger (see Figure 13d).

![Diagram showing three ways in which salt water can intrude into a freshwater lens.]

**Figure 15:** Three ways in which salt water can intrude into a freshwater lens.

Salt water intrusion into a lens can occur in a number of ways. Firstly according to the Ghyben-Herzberg principle the position of the interface depends upon the flow of groundwater and the outflow of water from the edge of the island. Outflow over the long term will equal recharge. A change in recharge will lead to an adjustment of the lens and a new position for the interface. If water is abstracted then less water is lost as outflow and the lens will readjust. Over-abstraction, reducing outflow at the margins, can lead to the lens thinning to insignificance (Roy and Connell, 1989). It can take some time for the new equilibrium to be achieved, and this explains the not uncommon occurrence when a lens is over-pumped for a well to produce good water for several years and then suddenly to go saline. Fluctuations in the size of the lens occur quite naturally with saline intrusion at the lens margin when a lens contracts (Figure 15). At times of drought 'rainfall is insufficient to maintain a fresh-water head, permitting invasion of salt or brackish water through the pervious island sediments and rock foundation. The ground water in the narrower parts of the islands is soon contaminated, with the resultant death of breadfruit and eventual death even of coconut trees' (Cloud, 1952). The lens will expand again when more rainfall is received; the rapid extension of the lens on Christmas Island, Kiribati, after 2000 mm of rain was received between July 1982 and February 1983 (as a result of ENSO; the average annual rainfall is 840 mm) has been recorded (Falkland and Brunel, 1989).

More localised saline intrusion can occur as a result of local over-pumping. Again assuming the Ghyben-Herzberg relationship, the effect of over-pumping in a shallow well is to draw down the water table. If the water table is drawn down 0.03 m, this will result in upconing of the interface at the base of the lens by 1.2 m (i.e. 40 times the amount of drawdown). While this might not affect the shallow well from which over extraction has occurred, the interface can rise up into deeper wells causing salinisation (Figure 15).

The third way in which salt can intrude the aquifer is by overwash, also called freeboard washover (Roy and Connell, 1989). If storm waters overtop the seaward beach ridge then the seawater will flood the swale behind the ridge and percolate down to the water table, increasing the lens salinity (Figure 15). Frequent overwashing may result in increases of salinity which cause death of the vegetation, with at high concentration death even of coconuts. These would then be replaced by more salt-tolerant species.
Some chloride content is to be expected in the seaward part of the lens. Rainfall contains some chloride, and this will be accentuated by salt spray on the oceanward beach ridge of reef islands. Chloride will be concentrated through losses of water by evapotranspiration and abstraction and higher concentrations will be seen in the groundwater (Vacher and Ayers, 1960), though this mechanism is unlikely to render chloride concentrations high enough to make the water undrinkable.

One feature that is clear in each response in Figure 13 is that the rise in water table level is going to be most noticeable in the low-lying interior of the islands. In many cases the water table will rise above the ground surface and an open pool will result. On many reef islands the central depression is an important area for the intensive cultivation of taro (Colocasia and Cyrtosperma) in excavated pits. Taro are sensitive to salt, and will be killed by saltwater from excessive overwash.

The central depression already plays an important role in the water balance of the island (Ayers and Vacher, 1986). During wetter times of the year water tends to concentrate (by limited runoff) into the depression and recharge the lens, while in the dry season water is lost more rapidly from this area both by enhanced evapotranspiration because the water table is closer to the surface and more accessible to plant roots, or from direct evaporation for the water surface if there is an open pool in the depression.

When there is a higher water table loss of water from the lens will be enhanced. Evaporation from open pools will lead to greater water loss than occurs at present through transpiration alone, and is going to lead to an altered water balance. The raised water table is going to effect cultivation, swamping the roots of plants and making it impossible to grow some species.

On reef-top islands the raised water table will have the effect of expanding interior pools or lagoons. Where these are saline already (i.e. Nanumanga, Vaitupu), their salinity is likely to increase as a result of the larger surface area from which evaporation can take place. Where the centre of reef-top islands contain freshwater interior depressions will become more waterlogged. Already on some reef-top islands it is necessary to install gravity drainage systems to remove rainwater from productive taro pits (i.e. Foammulah). Such gravity systems will become harder to operate under a higher sea level (Titus et al., 1987), and it may be necessary to install pumps, flap-gates and to open controlling gates only for periods during low tide. These systems will be costly to install and will require careful management, at a time when demand for taro, in many countries where it is grown, is declining in the face of supply of imported foodstuffs.

If the sea continues to rise then the existence of either reef islands or freshwater lenses is in question. The exact response of the lens depends on assumptions made in the model adopted to predict lens behaviour. The traditional Ghyben-Herzberg model is particularly sensitive to alterations of island size, and there have been a number of predictions of considerable loss of island area and consequent diminution and eventual demise of the freshwater lens (Miller and Mackenzie, 1988; Roy and Connell, 1989). On the other hand modelling using the dual aquifer approach (and the SUTRA model), has suggested that if recharge and island width remain constant then freshwater lenses on reef islands may actually increase in size with a rise in sea level because of the larger volume of freshwater which can then be stored in the less permeable upper aquifer (Oberdorfer and Buddemeier, 1988).

Conclusions

It is impossible to predict the effect of sea-level rise on the groundwater resources of small islands because of uncertainty on three issues.
Firstly, it is unclear what rate of sea-level change is being experienced at present, if any, and what rates are to be expected in the future on these islands. While there is no doubt that sea-level rise is being observed in some parts of the world, the net trend over the last 3000 years on most Pacific and Indian Ocean atolls has been a slight fall of sea level. Furthermore, observations of microatolls on several atolls suggest that sea level is stable or still gradually falling over the last 50 years.

Secondly it is unclear what the response of reef islands will be to sea-level rise. The islands are formed from organic sediments which are still being produced. Sediment may continue to accrete on islands, indeed supply may even accelerate; on the other hand beach erosion is an important process in the adjustment and readjustment of islands, and it too may increase considerably under higher sea levels. I believe that in the short term (50 years) sea-level rise at a gradual rate, up to the order of magnitude experienced during the post-glacial transgression (approximately 10 mm/yr), should not lead to total devastation of islands. If, however, in the longer term (more than 100 years) the sea rises beyond a level at which the cemented reef flat and conglomerate platform can ameliorate waves or current action (1.2 m above present), then some reef islands may be totally eroded away, unless sediments are lithified (or artificially stabilised).

Thirdly, it is still unclear how freshwater lenses behave, especially in terms of patterns of flow and residence time. The two models which have been used, the Dupuit-Ghyben-Herzberg and Dual aquifer models, are based on radically different assumptions, and neither takes account of all the hydrogeological complexity of individual islands. Perhaps the extent to which there is a lack of consensus is illustrated by two papers on the effect of sea-level rise presented in sequence at the International Coral Reef Congress in Townsville in 1988. One study of a reef island on an atoll in the Marshall Islands, using the Ghyben-Herzberg approach, predicts that the island will become smaller and the lens will contract (Miller and Mackenzie, 1988). The following paper, also on a reef island on a Marshallese atoll, but using the SUTRA model of a dual aquifer predicts that if island size and recharge are held constant, the freshwater lens will actually increase because there will be a greater volume of fresh water within the upper, less permeable Holocene aquifer (Oberdorfer and Buddemeier, 1988).

While this paper has concentrated on the impact of sea-level rise, it should be emphasised that this is merely one consequence of climatic change that is predicted as a result of the greater accumulation of greenhouse gases in the atmosphere. Other effects are also predicted, such as increased rainfall, which would imply increased recharge on many islands, and increased hurricane range and frequency, which would increase the erosion or deposition of sediment by storms, and increase overwash of saline water onto islands. Climate models are as yet not accurate enough to predict these changes with credibility, and they are therefore not discussed. However, their impact may be at least as devastating or ameliorating as that of sea-level rise.

In view of such uncertainty, what should be done? It is clear that more fundamental research is needed to answer the questions of whether or not the sea is rising, what the pattern of reef island accumulation has been and what factors control it, and how the freshwater lens behaves and what factors control that behaviour. Perhaps still more urgently from the viewpoint of environmental management, it is essential to make good assessment of the resources that are available, and to monitor any change. Organised baseline studies of water levels, salinities in wells and shoreline position are the only yardsticks against which future change can be reliably assessed.

The groundwater resource on small islands is an important resource. It is often economically the easiest source of water, particularly for irrigation and agricultural uses. The impacts of sea-level rise on that groundwater resource are unlikely to be particularly significant over the next decade or so. By contrast anthropogenic impacts on lenses, which have not been examined in this paper, can be, and have been, enormous and devastating. There are already many lenses on heavily-populated islands that have been over-pumped and on which the lens has decreased in size. There are numerous cases where lenses are polluted. Construction and
urban drainage systems on the islands severely reduce (and often also pollute) the water that should be recharging the lens. These problems already exist, and the use and mis-use of groundwater resources is likely to increase rapidly on particular islands, especially regional centres such as capitals, through the patterns of population migration that are already occurring (Roy and Connell, 1989). The stresses that these demands will put on lenses are extreme, and the problems caused in the short term by any rise in the level of the sea will be minimal by comparison.

Alternative sources of water exist, and are already in use on the majority of islands (see Falkland and Brunel, 1989). The collection of rainwater, at a domestic level from roof catchments, and at a national level by collection from airport runways, and even synthetic surfaces provides potable water where lenses may already be considered undrinkable, and also cuts down on substantial losses that occur through evapotranspiration before rainfall is fed to a lens as recharge. Desalination of seawater is already providing water particularly to support tourist ventures on many islands. Water can be imported, usually at great expense, but may be economic if an island has a valuable export, and a fleet of ships that might otherwise return empty (i.e. Nauru). In some cases substitution of other liquids can suffice (i.e. coconuts for drinking).

Alternative strategies may be used to collect groundwater more efficiently. Shallow infiltration galleries are a particularly efficient way of tapping groundwater. Drinking water and non-drinking water supplies may be separated (see Falkland and Brunel, 1989, for a fuller discussion).

These and other issues are outside the scope of this paper. They indicate the dependence of island populations on water, and the role of groundwater among other sources in supplying those needs. Over-extraction and pollution of groundwater are already real and worsening problems on many small islands. The effect of sea-level rise on the freshwater lens is not clear at this stage; though neither islands nor lenses could survive the worst possible scenarios that have been proposed by some scientists. However, impacts are likely to be negligible over the coming decade.

Nevertheless groundwater has been poorly managed in the past. Greater public concern can be generated for pollution that is visible, whereas the fate of water that lies beneath the ground is rarely an issue until it is too late. Groundwater must be managed efficiently, and within that scheme of management there should be a programme of monitoring which will determine if groundwater resources are shrinking or becoming more saline. Only when a series of records from several years and from many places on an island has been collected will it be possible to determine whether that problem has come about as a result of sea-level rise, or some anthropogenic abuse of the resource.

Groundwater resources can be more effectively protected by protection of the natural environment. Preservation of natural vegetation on beach ridges, prevention of beach ridge degradation (mining for sand, construction, erosion, etc.) and maintenance of healthy reefs and reef flats which provide uninterrupted supplies of sediment, should help prevent overwash and hence salinisation of surface waters.

It will be important to reassess the situation periodically in an attempt to reduce the uncertainties which make prediction of the impact of sea-level rise on groundwater resources so difficult at present.
References


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