Management of Fresh Water Lenses on Small Pacific Islands

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Abstract The nature of shallow aquifers and the impacts of seawater intrusion in small islands within the Pacific Ocean are reviewed. Many Pacific islands rely on shallow fresh groundwater lenses in highly permeable aquifers, underlain and surrounded by seawater, as their principal freshwater source. It is argued here that, in small islands, the nature of fresh groundwater lenses and their host aquifers coupled with frequent natural and ever-present anthropogenic threats make them some of the most vulnerable aquifer systems in the world. A simple steady-state approximation is used to provide insight into the key climatic, hydrogeological, physiographic, and management factors that influence the quantity of, and saline intrusion into freshwater lenses. Examples of the dynamic nature of freshwater lenses as they respond to these drivers are given. Natural and human-related threats to freshwater lenses are discussed. Long dry periods strongly coupled to sea surface temperatures impact on the quantity and salinity of fresh groundwater. The vulnerability of small island freshwater lenses dictates careful assessment, vigilant monitoring, appropriate development, and astute management. Strategies to aid future groundwater sustainability in small islands are presented and suggested improvements to donor and aid programs in water are also advanced.

Keywords Freshwater lens · Salinization · Island hydrogeology · Climatic variability · Groundwater management

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Introduction

There are about 1,000 populated small islands in the Pacific Ocean, most of which are located in the tropical and sub-tropical zones of the central and southern Pacific (see Fig. 1). In many of these islands, groundwater is the main source of freshwater whose availability is often limited and whose quality is frequently compromised. Both the quantity and quality of island groundwater depend on the mixing and intrusion of seawater into the fresh groundwater and also on human activities. The amount of fresh groundwater available to island communities depends on a delicate balance between consumptive use and climatic, hydrogeological, and physiographic factors, particularly restricted island areas. The land area of many small islands is often less than 10 km^2 while in most atoll islands, areas are frequently less than 1 km^2 and their characteristic widths are often less than 1 km (Dijon 1983). Because of the high soil and regolith permeability of many small coral and sand islands, surface water is scarce or non-existent. Groundwater in small islands occurs as "fresh groundwater lenses", relatively thin veneers of fresh groundwater overlying seawater in highly permeable, phreatic aquifers. These lenses, which are vital to small island communities, are extremely vulnerable to both natural variations and changes and human-caused perturbations and, because of this, require careful assessment, vigilant monitoring, and astute management (White et al. 1999b; van der Velde et al. 2007).

This paper outlines the nature of freshwater lenses on islands in the Pacific Ocean, summarizes natural and anthropogenic threats to their groundwater resources, and describes management strategies to sustain these resources.

Some of the physical characteristics of selected Pacific Island Countries (PICs) are listed in Table 1. Most PICs in Table 1 have some very small islands and all use groundwater to some extent. There are many other small islands within larger countries near the Pacific Rim that have a similar range of geological types to those in Table 1. In some of these small islands, population densities can be as high as 12,000 people/km^2 posing major resource management problems, particularly for shallow fresh groundwater lenses (see Fig. 2).

This paper firstly discusses the nature and characteristics of freshwater lenses in small islands and uses a simple, steady-state analysis to demonstrate the key factors that determine the quantity of fresh groundwater and its salinity. Then examples are given of how both natural and anthro-

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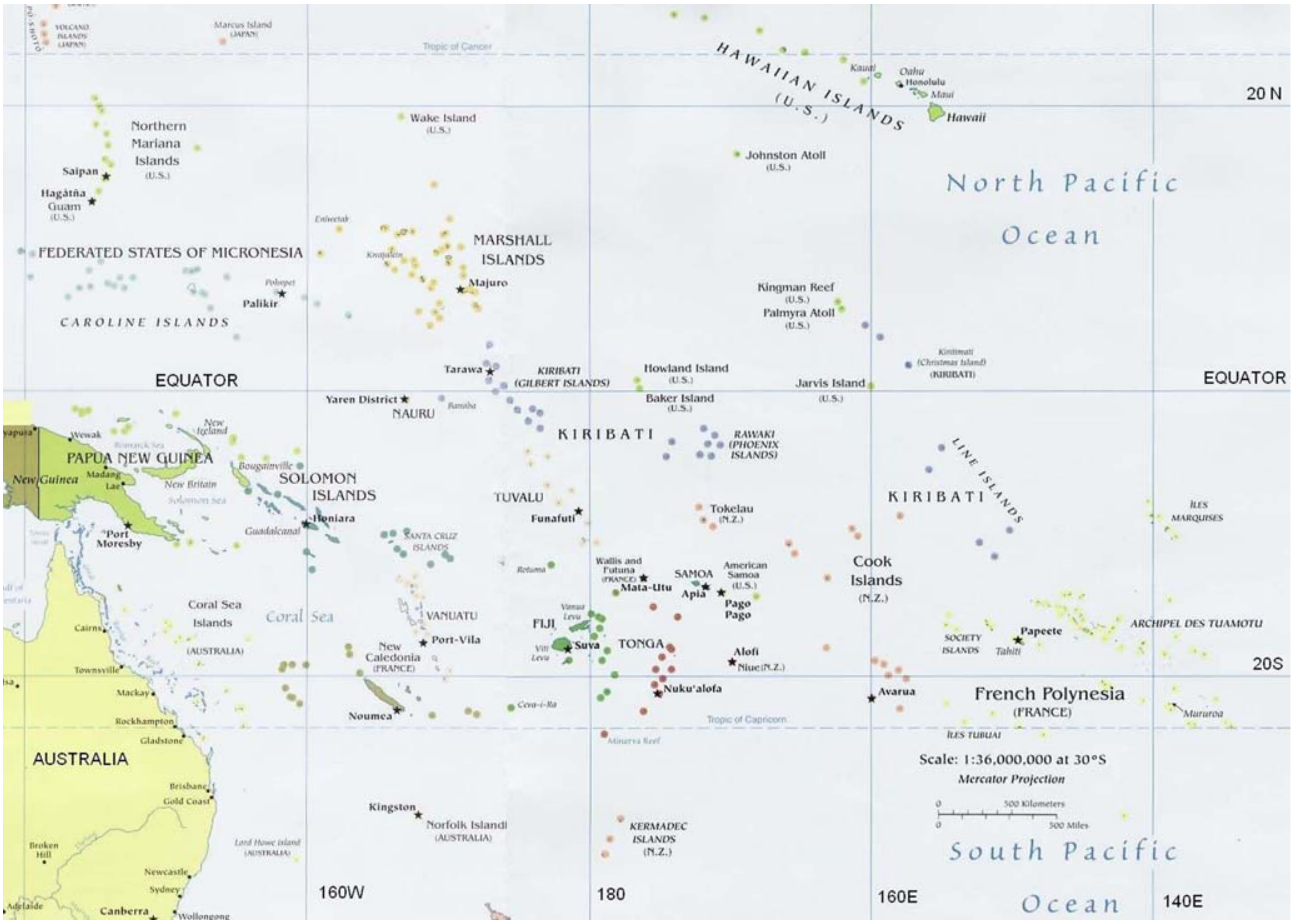

Fig. 1 Small island countries in the central and southern Pacific Ocean [with permission from Pacific Islands Applied Geoscience Commission (SOPAC)]

pogenic factors impact island groundwater and of the main threats to small island groundwater systems. Finally, strategies to conserve and manage fragile small island groundwater systems to ensure their sustainability are discussed.

Nature and characteristics of freshwater lenses

Freshwater lenses occur principally on low-lying carbonate islands where unconsolidated sands and gravels have been deposited unconformably on ancient karst limestone reefs as, for example, in Kiribati, Marshall Islands, Tuvalu, Tokelau, and parts of the Cook Islands, French Polynesia, Hawaiian Islands, Papua New Guinea, and Tonga (see Fig. 1). Others are on limestone islands of uplifted reef deposits as in the island states of Nauru and Niue and a number of islands in Tonga. An excellent overview of the geology and hydrogeology of carbonate islands is provided by Vacher and Quinn (1997). Less common are freshwater lenses on volcanic islands where variations in permeability of the regolith enable coastal aquifers to occur in some parts of the island but not in others. In Table 1, islands where freshwater lenses are known to occur are shown in *italics* in the right-hand column. Detailed field assessments and studies of the nature and dynamics of many freshwater lenses have been published, especially during the past 30 years, as cited in Vacher and Quinn (1997), UNESCO (1991) and other papers referenced here. Many other studies are described in unpublished reports.

The lower boundary between freshwater and underlying seawater in the thin lenticular groundwater body is not sharp as envisaged by the classical 'Ghyben-Herzberg' model (Badon Ghijben 1889; and Herzberg 1901). Rather, the lower boundary occurs as a wide transition or mixing zone where groundwater salinity increases with depth from freshwater to seawater (see Fig. 3) due to mechanical mixing and dispersion. The practical limit of the base of the freshwater zone of the lens is defined by some measure of groundwater salinity acceptable for human use such as the World Health Organization's drinking-water guidelines for chloride ion concentration of 250 mg/l (WHO 2004) or an equivalent electrical conductivity, EC (often reported in µS/cm) used routinely to measure groundwater salinity in the field.

Climatic, hydrogeological, and physiographic factors affecting freshwater lenses

A simple, steady-state analysis provides insight into the factors that influence the quantity and salinity of fresh-

Table 1 Summary of island data for selected Pacific Island Countries (see Fig. 1). Islands where freshwater lenses are known to occur are shown in *italics*

Country	Sub-region	Approximate population (2006–2007)	Total land area (km^2)	Number of islands or atolls	Island type according to geology
Cook Islands	Polynesia	22,000	240	15	Volcanic, volcanic and limestone, *atoll*
Federated States of Micronesia	Micronesia	108,000	702	607	Volcanic, *atoll*, mixed
Fiji	Melanesia	919,000	18,300	300 (approx.)	Volcanic, limestone, *atoll*, mixed
Kiribati	Micronesia	108,000	810	33	*32 atolls or coral islands, 1 limestone island*
Nauru	Micronesia	11,500	21	1	*Limestone*
Niue	Polynesia	1,600	260	1	*Limestone*
Palau	Micronesia	21,000	458	200 (approx.)	Volcanic, some with limestone
Papua New Guinea	Melanesia	5,800,000	453,000	?	Volcanic,*limestone, coral islands and atolls*
Republic of Marshall Islands	Micronesia	62,000	181	29	*Atolls and coral islands*
Samoa	Polynesia	214,000	2,930	9	Volcanic
Solomon Islands	Melanesia	567,000	28,000	347	Volcanic,*limestone, atolls*
Tonga	Polynesia	117,000	748	171	Volcanic,*limestone, limestone and sand*, mixed
Tuvalu	Polynesia	12,000	26	9	*Atolls*
Vanuatu	Melanesia	212,000	12,200	80	Predominantly volcanic with coastal sands and limestone

Populations (shown to nearest 1,000 where greater than 20,000 and the nearest 100 for less than 20,000) are from data and estimates for 2006 or 2007 (SOPAC 2009). Land areas are from SOPAC website. The number of islands is from various sources including National Environment Management Strategies (NEMS) for PICs. Some numerical differences were noted between different data sources

water lenses on small islands. The expression for the maximum thickness of a freshwater lens to an assumed sharp interface between fresh and saltwater, H_u (m) in the centre of a circular uniform island is approximated by (Volker et al. 1985):

$$H_u = \frac{W}{2}\left[(1+\alpha)\frac{R}{2K_0}\right]^{1/2} \qquad (1)$$

where W (m) is the width of the island, $\alpha = (\rho_s - \rho_0)/\rho_0$ with ρ_S, ρ_0 the densities (tonne/m^3) of sea and freshwater, respectively, R (m/y) the mean annual groundwater recharge rate and K_0 (m/y) the assumed uniform, horizontal saturated hydraulic conductivity of the phreatic aquifer.

Equation (1) predicts that wider islands should generally have thicker freshwater lenses than narrower islands and islands with higher groundwater recharge rates should also have thicker lenses than those with lower recharge. Equation (1) also shows that islands whose phreatic aquifers have high saturated hydraulic conductivities should have thinner freshwater lenses than those with lower K_0. For a typical island 1 km wide with a recharge rate of 1 m/year and a K_0 of 1,300 m/year (~4×10^{-5} m/s), Eq. (1) predicts the average thickness of

Fig. 2 Betio Island, Tarawa Atoll, Kiribati has a population density of about 12,000 people/km^2. Pollution of the fresh groundwater lens by human settlement here has made it unfit for consumption

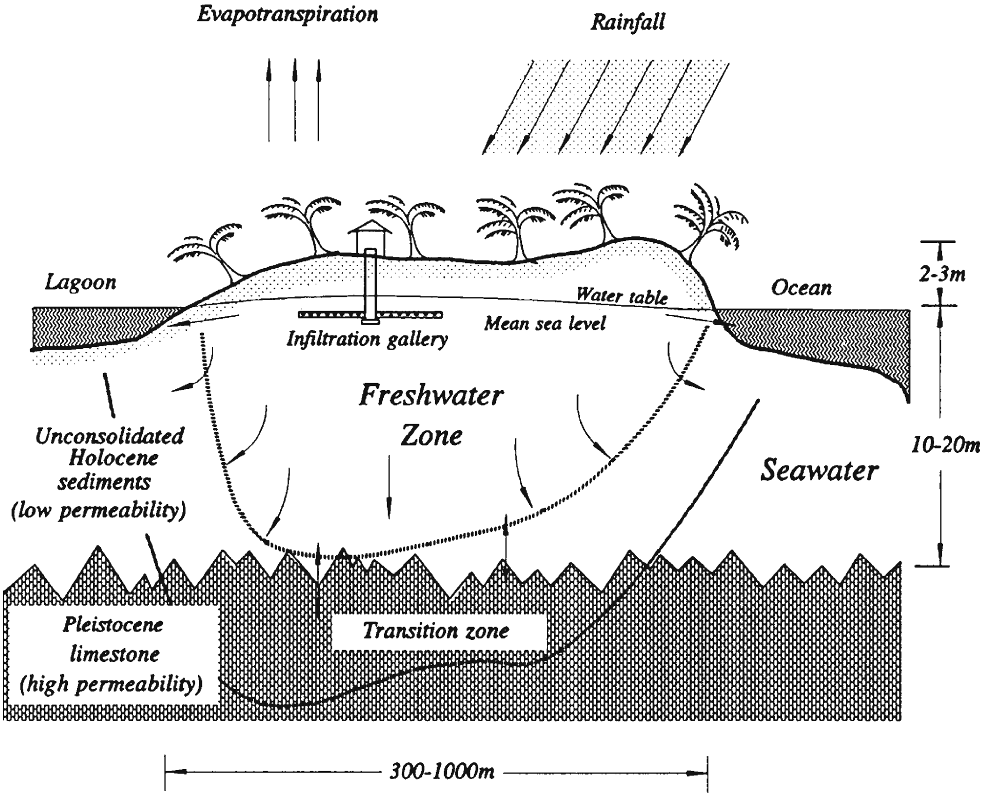

Fig. 3 Exaggerated vertical scale cross section through a small coral island showing the main features of a freshwater lens including the transition zone and the location of an infiltration gallery used for groundwater abstraction

the freshwater lens to the sharp interface should be about 10 m.

In the sharp interface model, the elevation of the water table above mean sea level (m.s.l.), h_0 (m) is governed by the density difference between fresh and seawater:

$$h_0 = \frac{\alpha}{\alpha + 1}.H_u \tag{2}$$

Water-table elevations are typically of order 0.2–0.5 m above m.s.l. and vary with changes in recharge.

In practice, islands are neither circular nor uniform. Islands lying within the cyclone belt generally have very coarse unconsolidated sediments and large hydraulic conductivities such as those in Tuvalu (Fig.1). These islands often have very limited or no viable freshwater lenses, consistent with Eq. (1). Freshwater lenses on atoll islands are often asymmetric with the deepest portion often displaced towards the lagoon side of the island (Figs. 3 and 4), due to cross-island differences in permeability. Figure 4 shows an example of an asymmetric freshwater lens on the island of Bonriki on Tarawa Atoll, Kiribati.

Islands in the Pacific are often subject to prolonged El Niño Southern Oscillation (ENSO) and related droughts of up to 44 months duration. To a first approximation, Eq. (1) can be used to estimate the impact of long droughts on the thickness of freshwater lenses. If H_d (m) is the thickness under a prolonged period of drought with recharge R_d (m/y), then: $H_d/H_u = (R_d/R)^{1/2}$. In a prolonged drought, if recharge is decreased to 25% of the mean recharge, the thickness of the freshwater lens should be reduced by about 50%.

Volker et al. (1985) provide an approximate, steady-state approach to predicting the width of the salinity transition zone under a freshwater lens based on the work of Wooding (1963, 1964) who examined two-dimensional flow in freshwater overlying saltwater. The ratio of the mean width, δ_u (m), of the transition zone to the mean maximum freshwater lens thickness at the center of a lens in a low coral island in the absence of pumping can be written as:

$$\frac{\delta_u}{H_u} = \frac{K_0}{R}\left(\frac{D}{\alpha\, WK_0}\right)^{1/2} \tag{3}$$

Here D (m^2/y), is the dispersion coefficient. Equation (3) predicts that the relative thickness of the transition zone will increase as K_0 increases and decrease with increasing island width and increasing recharge rate. At low recharge rates, the width of the transition zone may equal the thickness of freshwater. This is important if the lens is used as a freshwater source since the practical thickness of usable freshwater, H_{wu} is approximately $H_{wu} = H_u - \delta_u/2$. Usable freshwater zones are typically, about 5–20 m thick, with transition zones of similar thickness. Where freshwater zones are less than about 5 m thick, transition zones are often thicker than the freshwater zone. Useable freshwater lenses exist when $\delta_u < 2H_u$ or $R/K_0 > (1/2)(D/[\alpha WK_0])^{1/2}$.

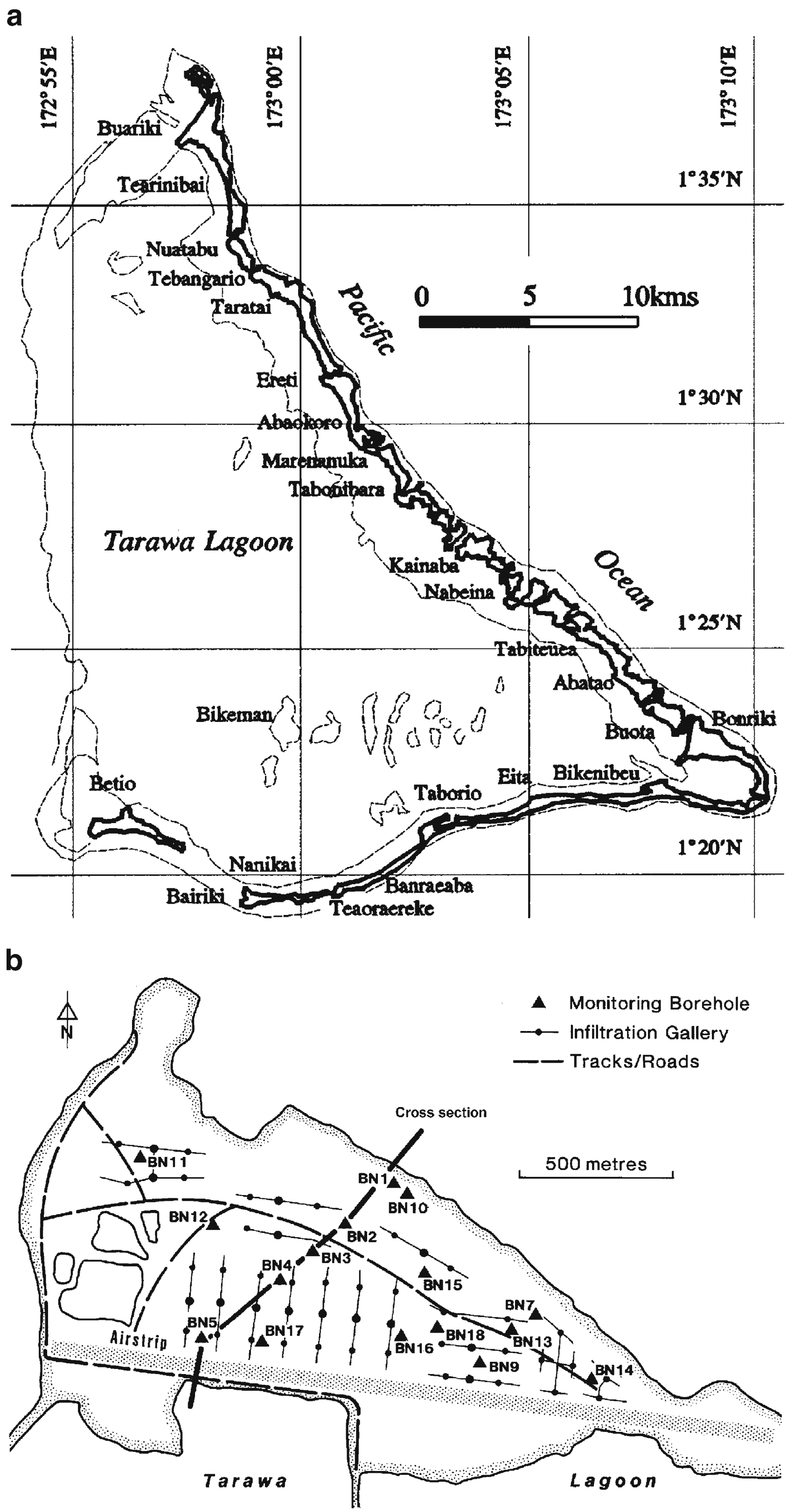

Fig. 4 Asymmetric freshwater lens on Bonriki Island, Tarawa Atoll, Republic of Kiribati. **a** Atoll map showing Bonriki in the southeast corner. **b** Plan of Bonriki showing several monitoring boreholes and infiltration galleries, and **c** cross section through boreholes BN1 to BN5, as shown in b, in the Bonriki freshwater lens showing depths to freshwater limit (EC taken as 2,500 μS/cm) and mid-point of transition zone (EC=25,000 μS/cm). Figure 4b and c are from Falkland and Woodroffe (1997) with permission from Elsevier

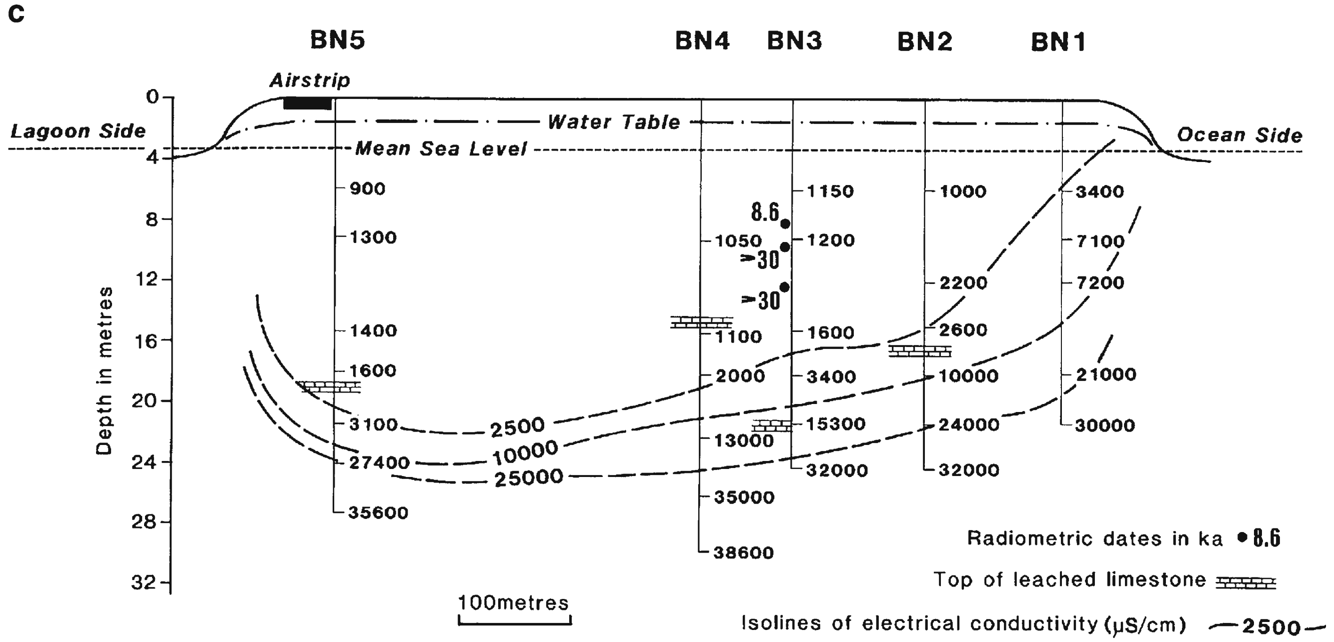

Fig. 4 (continued)

Equations (1) and (3) provide insight into the impact of long droughts on the width of the transition zone, δ_d(m). The ratio of the width in the drought to that under mean conditions is given by $\delta_d/\delta_u = (R/R_d)^{1/2}$. If recharge during a long drought is reduced to 25% of mean recharge then the width of the transition zone could be doubled. The practical thickness of useable freshwater during a drought, H_{wd} (m) is reduced by $H_{wd} = (R_d/R)^{1/2}\,(H_u - \delta_u[R/\{2R_d\}])$ and it is expected that the salinity of abstracted water should also increase during droughts. A useable freshwater lens will still exist provided $\delta_u < (2R_d/R)H_u$.

Equations (1) and (3) are steady-state approximations. Freshwater thickness and transition zone width, however, are dynamic, varying with fluctuations in rainfall recharge, land-use change and variations in groundwater abstraction.

Impact of pumping on freshwater lenses

When water is pumped at a constant rate, Q (m^3/s), from a freshwater lens of land area A (m^2), the steady-state analysis predicts that the maximum lens thickness to an assumed sharp interface between fresh and saltwater, H_p (m), at the center of an island is given by (Volker et al. (1985):

$$H_p = \frac{(1-q)^{1/2} W}{2}\left((1+\alpha)\frac{R}{2K_0}\right)^{1/2} = (1-q)^{1/2} H_u \qquad (4)$$

where q is the ratio of the specific pumping rate to recharge rate, $q = (Q/A)/R$. Equation (4) suggests that when the specific pumping rate is 50% of the mean recharge rate, the maximum thickness of the freshwater lens will be about 71% of the mean thickness of the unpumped lens.

During pumping, the increase in the width of the transition zone, δ_p (m), is given by:

$$\frac{\delta_p}{H_p} = \frac{1}{1-q}\left(\frac{K_0}{R}\right)\left(\frac{D}{\alpha\, W K_0}\right)^{1/2} = \frac{\delta_u}{(1-q)H_u} \qquad (5)$$

or $\delta_p = \delta_u/(1-q)^{1/2}$

So it can be seen that, as with drought, the width of the transition zone should increase, as should the salinity of the lens, as the pumping rate increases. The thickness of useable freshwater from a pumped lens, H_{wp} follows from Eqs. (4) and (5):

$$H_{wp} = H_p - \delta_p/2 = (1-q)^{1/2}(H_u - \delta_u/\{2[1-q]\}) \qquad (6)$$

Equation (5) indicates that when the specific pumping rate is 50% of the mean recharge rate, the transition zone will be 41% wider than that in an unpumped lens. So the effect of pumping is to decrease the lens thickness and to increase the width of the transition zone. This means that the practical depth of usable water under pumping is further reduced as in Eq. (6). A useable freshwater lens will continue to exist provided $\delta_u < 2(1-q)H_u$.

The approximate steady-state analysis above demonstrates how the freshwater lens thickness and the width of the transition zone at the base of the lens varies with: the effect of climate, through recharge, R; island physiography through the characteristic island width, W; aquifer hydrogeology through the saturated hydraulic conductivity, K_0; pumping through the non-dimensional specific pumping rate, q, seawater-freshwater interaction through the density ratio parameter α; and mixing through the dispersion

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coefficient *D*. Several important dimensionless groups besides α emerge including R/K_0, $q = (Q/A)/R$ and an atoll Peclet number, $\alpha W K_0/D$. These factors determine the rate of inputs of water to the freshwater lenses, the rates of pumping losses, and the rate of mixing with seawater. The balance between these factors determines the viability of a freshwater lens as a source of potable water and illustrates why in small island hydrology it is essential to accurately assess recharge rates, hydrologic conductivity, and pumping rates. While this analysis can provide insights into the impacts of changes on freshwater lenses, it cannot describe the detailed dynamics of freshwater lenses in heterogeneous small islands. For those situations, dynamic models involving numerical solutions are required (see e.g., Underwood et al. 1992).

Freshwater lenses in raised limestone islands

Freshwater lenses in raised limestone islands, unlike low islands, are predominantly contained in highly permeable karst Pleistocene limestone aquifers and vary from extensive and relatively thick on some islands, such as Niue and Tongatapu in Tonga, to very small or absent on others, such as Banaba in Kiribati and Nauru (see Fig. 1). Groundwater investigations on Niue (Jacobson and Hill 1980; Wheeler and Aharon 1997; GWP 2006) and Tongatapu in Tonga (Furness 1997; White et al. 2009) show significant fresh groundwater resources available for pumping for urban and village water supplies. In comparison, groundwater investigations in 1987 after a heavy rainfall period found Nauru had a small freshwater zone (Fig. 5) which was then simulated by numerical models (Jacobson et al. 1997). Investigations in 2008 during a drought, however, found no freshwater lens in the center of the island at all and only a few small pockets of fresh to brackish groundwater at one end of the island. This demonstrates the dynamic nature of freshwater lenses, their vulnerability to climate variability, the fundamental importance of long-term monitoring of small islands, and the sensitivity of groundwater models to input or calibration data.

The simple steady-state model above assumes that the aquifer is uniform and deep. In practice, in low coral atolls and islands in the Pacific, where Holocene sands and gravels are deposited unconformably over karst Pleistocene limestones, the depth of the unconformity frequently determines the freshwater lens thickness because of the extremely high permeability of the karst limestone as further discussed below.

Natural influences on freshwater lenses

As the steady-state approximation above illustrates, the main natural influences on the occurrence of viable freshwater lenses on small islands are rainfall recharge to the groundwater system and the losses from the aquifer, including evapotranspiration by phreatophytes, the storage capacity of the freshwater lens, the hydraulic losses at the edges of the island, and mixing with underlying seawater. These influences are discussed below.

Climate variability

Climate, particularly rainfall and evapotranspiration are key drivers of recharge. Average annual rainfall and rainfall variability varies considerably throughout the Pacific. On Kiritimati Atoll in the dry equatorial zone of eastern Kiribati (Fig. 1), the average annual rainfall is less than 1,000 mm and the coefficient of variation (Cv) is greater than 0.7. In the western Pacific, near Funafuti Atoll in Tuvalu (Fig. 1), the average annual rainfall is over 3,500 mm and the Cv is much lower, near 0.2. Variations in monthly and annual rainfalls in the Pacific are influenced strongly by inter-annual El Niño and La Niña cycles as the Pacific warm pool migrates from the eastern to western equatorial Pacific. On many Pacific islands, there is a strong correlation between sea surface temperatures (SST) or the Southern Oscillation Index (SOI, a differential air-pressure indicator of sea surface temperature differences) and rainfall patterns (e.g., White et al. 1999a). Figure 6 shows the strong correlation between

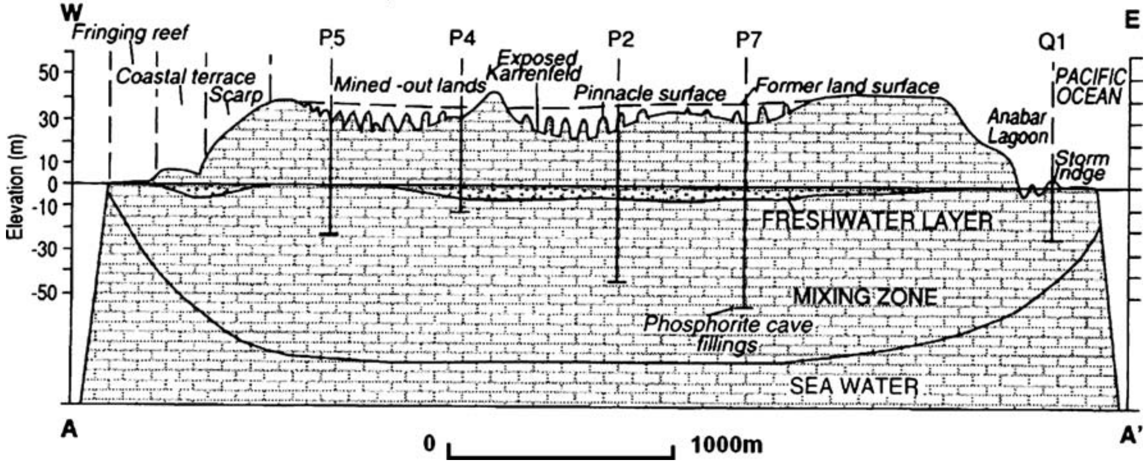

Fig. 5 Cross section through Nauru showing freshwater and mixing (transition) zones after heavy rainfalls in 1987 [from Jacobson et al. (1997) with permission from Elsevier]. Recent work in a dry period found no major viable freshwater lens

annual rainfall in Tarawa Atoll, Kiribati (Fig. 1) and the mean annual Niño Region 3.4 SST anomaly.

The frequency of low rainfalls in Tarawa and their strong correlation with negative SST anomalies are evident in Fig. 6. This correlation carries through to recharge. Groundwater salinity and the thickness of the freshwater lens are also correlated with SST or SOI (e.g., van der Velde et al. 2006; White et al. 2007a). Figure 7 shows the extent of sea water intrusion in a large atoll island lens that can occur during an ENSO-related, severe drought, raising groundwater salinity.

Evapotranspiration is a very important part of the hydrological cycle for small islands and can exceed more than half of the rainfall on an annual basis. It often exceeds rainfall for individual months or consecutive months during dry seasons or drought periods but the variability of evapotranspiration is much lower than that of rainfall. Typical annual potential evapotranspiration rates in the tropical areas of the Pacific are between 1,600 and 1,800 mm (Nullet 1987). Measurements of evapotranspiration on Bonriki Island, Tarawa Atoll suggested a lower annual rate closer to the equilibrium rate of about 1,420 mm due to the rapidly draining coral sands (White et al. 2002).

Island physiography

Island size, shape, and topography, particularly width and height of the island above mean sea level play a critical role in island water resources. Larger, higher, and wider islands are more likely to have either surface and groundwater resources or groundwater in greater quantities than smaller and narrower islands [Eqs. (1) and (3)].

Raised limestone islands are likely to have higher groundwater recharge for the same rainfall and vegetation conditions than low islands, as the roots of deep-rooted trees such as coconuts are unable to reach the water table and transpire water directly from the freshwater lens, as happens in low-lying atoll and reef islands. Where islands have narrow necks and peninsulas, the potential for seawater mixing and intrusion there is increased. Figure 8 shows a recent map of salinity distribution in Tongatapu, Kingdom of Tonga (Fig. 1) and shows areas where seawater intrusion increases groundwater salinity to the extent that the water is not fit for use.

Hydrogeological properties

As is demonstrated in the simple steady-state model, hydrogeological properties of the aquifer material have a direct bearing on the size, salinity, and sustainability of freshwater lenses on small islands. Small limestone islands are generally karst limestone, which has weathered from alternate periods of submergence and exposure due to fluctuating sea levels. Caves and solution cavities are often found along the shoreline and within the island. The hydraulic conductivity of the limestone is often greater than 1,000 m/day and, consequently, freshwater lenses are generally no more than about 10 m thick, even in wide islands such as Tongatapu (Fig. 8).

On atoll and reef islands, the aquifer material consists of two significant layers. The upper layer, consisting of recent Holocene sediments, mainly coral sands and fragments of coral, lies unconformably over an older Pleistocene karst limestone deposit (Woodroffe 2008). The unconformity, typically at depths of 10–15 m below mean sea level (Fig. 3), is one of the main controls to freshwater lens thickness (e.g., Hunt and Peterson 1980; Wheatcraft and Buddemeier 1981; Jacobson and Taylor 1981). Uranium-series dating of the older limestone in Tarawa Atoll indicates that it was formed 125,000 years ago (Jacobson and Taylor 1981). The upper unconsolidated sediments have been laid down over about the last 8,000 years with vertical accretion rates of order 5–8 mm/year. The freshwater zone is generally contained in the relatively low permeability coral sediments (with typical hydraulic conductivities of 5–20 m/day) as mixing of

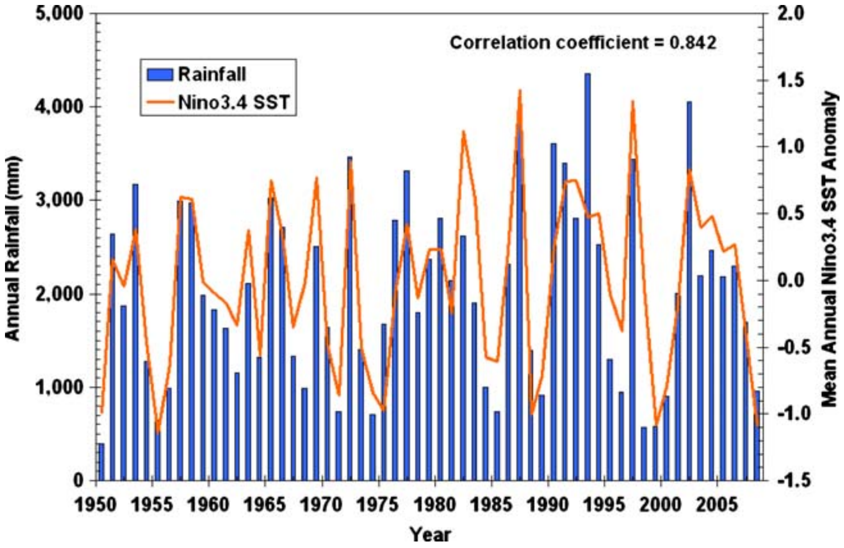

Fig. 6 The strong correlation between annual rainfall in Tarawa Atoll and the mean annual Niño Region 3.4 SST anomaly

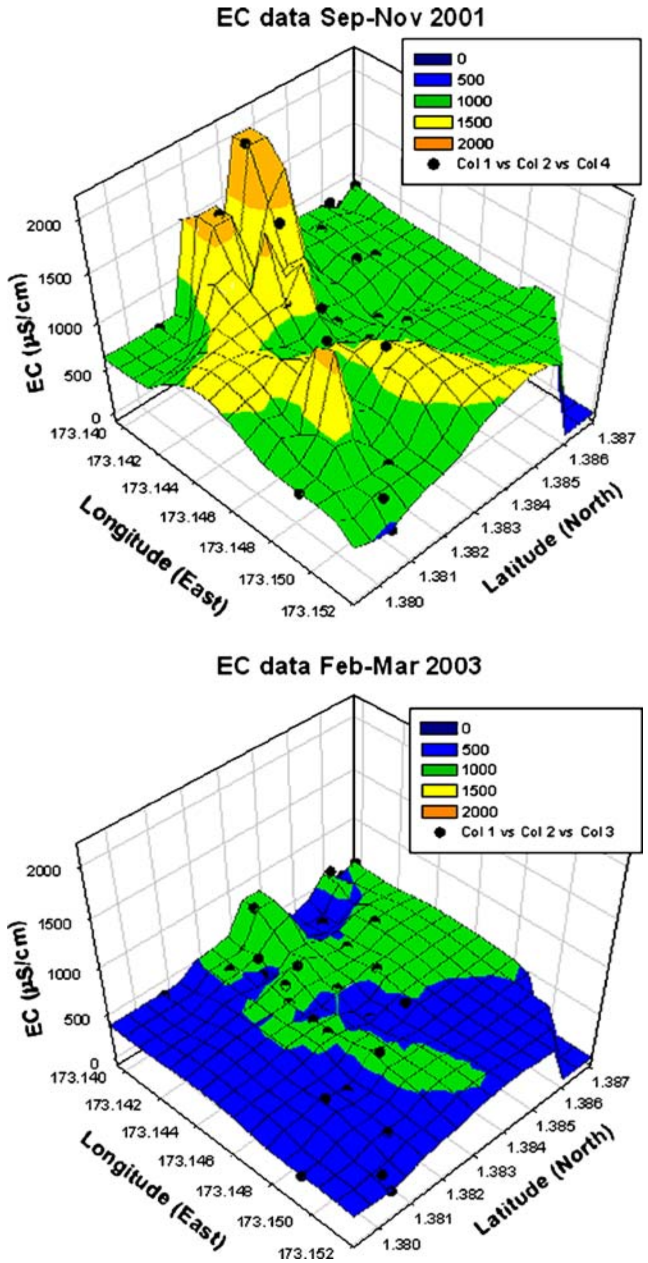

Fig. 7 Salinity (EC) distribution in Bonriki Island, Tarawa Atoll, Kiribati, showing seawater intrusion from the lagoon side at the end of the severe ENSO-related 1998–2001 La Niña drought compared with the distribution when the drought had broken (White et al. 2003). The Bonriki freshwater lens was being pumped at a rate of 1,300 m^3/day throughout this period

freshwater and seawater is rapid in the high-permeability karst limestone. Figure 9 shows the wide range of saturated hydraulic conductivities of the shallow, phreatic aquifers in the unconsolidated Holocene sediments on Bonriki and Buota Islands, Tarawa Atoll, Kiribati, estimated from pump drawdown tests in horizontal skimming wells or infiltration galleries (White et al. 2007b).

There are marked differences in hydrogeological properties of the upper sediments between atoll and reef islands located in areas that are prone to cyclonic activity and others in the central Pacific Ocean where cyclones do not occur. Islands within the cyclone belt such as Funafuti in Tuvalu and Pukapuka, Manihiki, Rakahanga and Penrhyn in the Northern Cook Islands (Fig. 1) are characterized, particularly on ocean sides, by high ramparts and coral rubble sediments with a significant proportion of boulders embedded in sands and gravels. Major changes occurred in Funafuti Atoll, including the deposition of a large amount of storm-driven boulders and reef blocks, as a result of Cyclone Bebe in 1972 (Woodroffe 2008). By comparison, islands in Kiribati and in the Maldives in the Indian Ocean, which are not within cyclone regions, have finer sediments with a much higher proportion of sand and gravel and very few boulder-sized particles. These finer sediments have lower hydraulic conductivities and, as predicted by Eq. (1), have thicker freshwater lenses for similar width islands. There are thicker freshwater lenses in the Gilbert chain of islands in the non-cyclonic region of western Kiribati (Fig. 1) than in the nearby cyclone-prone islands of Tuvalu, despite the higher and less variable annual rainfall in Tuvalu.

Tidal effects

On small islands, daily fluctuations in sea level, primarily due to tides, cause movement of the freshwater lens and promote mixing of fresh and seawater, increasing the transition zone thickness (Hunt and Peterson 1980; Wheatcraft and Buddemeier 1981). The classical theory of tidal signal propagation in continental coastal aquifers predicts that the ratio of the tidal amplitude in the groundwater to that in the sea, called the tidal efficiency, should decrease with distance from the coast. Correspondingly, the lag between the response of the groundwater to the tidal forcing should increase with distance from the coast. That is not the case in atoll islands where tidal lags and efficiencies in wells and boreholes in the unconsolidated sediments are independent of horizontal distance from the shore (e.g., Hunt and Peterson 1980; Wheatcraft and Buddemeier 1981; Ayers and Vacher 1986). Tidal lags and efficiencies on atolls are, however, greatly influenced by the depth of the boreholes. The reason for this apparent anomaly is the rapid transmission of the tidal pressure signal in the underlying high permeability karst Pleistocene limestone. Vertical propagation of tidal signals tends to be dominant in the middle of the island whereas both horizontal and vertical propagation are significant near the seawater margins. This aspect is important in developing conceptual models of groundwater flow in freshwater lenses and in their management, as described later. Figure 10 shows the response of water-table elevation to tidal forcing and to recharge on Bonriki Island.

The average tidal efficiency and lag on islands with finer-textured sediments are typically around 5% and 2.5 h, respectively (Peterson 1997; White et al. 2002) while those with coarser sediments can be approximately 45% and 2 h (Falkland 1999). In karst limestone islands, such as Nauru (Fig. 1), the tidal efficiency is generally higher, nearly 50% and the tidal lags shorter, around 1.5 h, than on atoll islands owing to the higher permeabilities.

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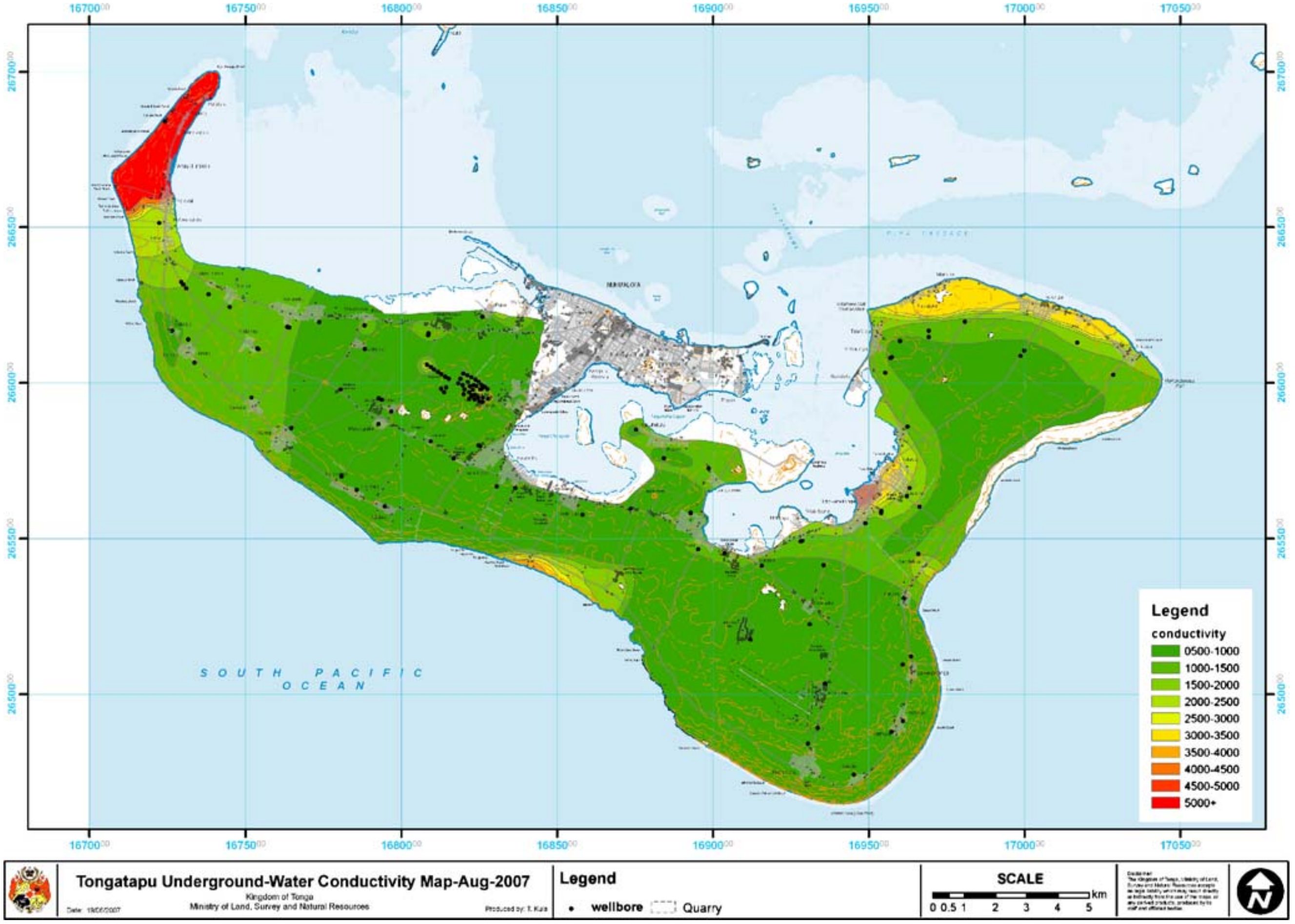

Fig. 8 Electrical conductivity (EC) distribution in the top 2 m of the groundwater sampled in vertical wells and bores (*black points*) in Tongatapu, Kingdom of Tonga, in August 2007 (White et al. 2009). *Grey areas* represent urban areas

Soils and vegetation

Soils and vegetation are important in groundwater recharge through their influence on evapotranspiration and infiltration. The high permeability soils of atoll, reef, and limestone islands promote rapid infiltration and lead to negligible surface runoff. Atoll and reef islands have only a thin surface soil covering above coral sands, which are generally deficient in organic matter and nutrients.

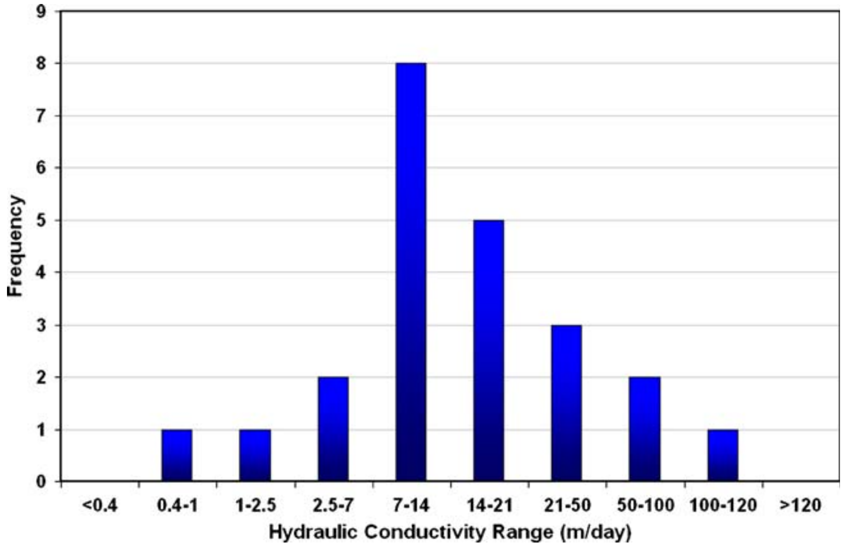

Fig. 9 Distribution of saturated hydraulic conductivity in the phreatic, unconsolidated Holocene aquifers, Bonriki and Buota Islands, Tarawa Atoll, Kiribati, measured by pump drawdown tests

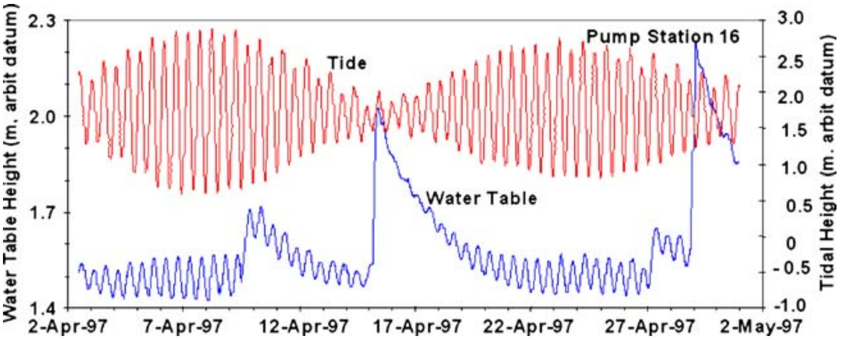

Fig. 10 Response of the water-table elevation in the pumping well of an infiltration gallery to tidal forcing and rainfall on 9, 15–16, and 29 April, Bonriki Island, Kiribati. This well is about 280 m from the ocean. Elevations are relative to arbitrary datums [from White et al. (2007b) with permission from Soil Science Society of America]

They have low water retention capacity and offer very little protection to underlying freshwater lenses from surface pollution sources. Soils on limestone islands are generally similar. Some have moderately thick to thick volcanic soils, such as the limestone islands of Tonga, due to past volcanic eruptions and these offer better protection from surface pollutants (van der Velde 2006).

The vegetation on small carbonate islands generally consists of a variety of trees, particularly coconut trees, and a limited range of bushes and grasses. The coconut tree is remarkably salt tolerant and can grow in water with relatively high salinity levels (Foale 2003). On a number of small islands, the native vegetation has been partially cleared and replaced with food crops. Vegetation both intercepts part of the rainfall and transpires water from the soil. Some deeper-rooted tree species such as coconuts can act as phreatophytes, transpiring directly from shallow groundwater. Both interception and transpiration decrease recharge and hence the amount of groundwater available for use. In dry periods, direct transpiration from groundwater significantly reduces the available groundwater. Measurements of individual coconut tree transpiration showed daily rates of 150 litres per tree and above on Tarawa Atoll (White et al. 2002). The high transpiration of coconut and other trees has management implications for freshwater-scarce areas where demand is high and groundwater abstraction needs to be maximized. Selective clearing can increase both recharge and the sustainable yield and decrease groundwater salinity.

Threats to freshwater lenses

Freshwater lenses and coastal aquifers on small islands are vulnerable to threats from both natural events and human activities.

Natural threats

The main natural threat to freshwater lenses on small islands are extended droughts (Scott et al. 2003) and, for low-lying islands, partial or complete overwash from storm waves or storm surge particularly those associated with major tropical cyclones (Terry 2007; Spennemann 2006). Tropical cyclones are a major problem for many small island communities (Terry 2007). They often cause widespread damage and can generate storm surges with overwash of parts or all of some islands, resulting in seawater intrusion into freshwater lenses. Climate variability associated with inter-annual El Niño and La Niña cycles has significant impacts on groundwater availability in small Pacific islands. There are major concerns that climate change may increase the severity and frequency of these threats in small islands with increased frequency of drought, enhanced cyclone activity, rising mean sea levels and increased risk of island overtopping (Ali et al. 2001).

Droughts in the Pacific are closely associated with El Niño and La Niña episodes (White et al. 1999a; Scott et al. 2003). Islands in the southern and northern part of the Pacific are largely drought-affected during El Niño events such as Tonga (van der Velde et al. 2006) while those in the central Pacific, particularly Kiribati, are impacted by droughts during La Niña events (White et al. 2007b). As discussed above, during droughts, the fresh groundwater lens contracts. Figure 11 shows the relationship between the depth of the freshwater lens at the edge of a coral atoll island in the central western Pacific and La Niña and El Niño events identified by the SOI.

In small islands, where mean rainfall is relatively low and where annual rainfall has a high Cv, such as in Kiritimati Island, Kiribati (Fig. 1), only large freshwater lenses remain viable at the end of major droughts. Some severe droughts have forced the abandonment of several very small islands when fresh groundwater was exhausted.

Overtopping of low islands from storm waves or by seawater inundation due to storm surges, sometimes associated with high sea levels has salinized fresh groundwater on low-lying islands (Richards 1991; Oberdorfer and Buddemeier 1984). Six months after a storm surge which sent waves across part of Enewetak Island in Enewetak Atoll, Marshall Islands, the salinity of the groundwater dropped sharply to 15–25% of the immediate post-storm values during a period of negligible rainfall (Oberdorfer and Buddemeier 1984), indicating that recharge was not the factor that decreased salinity. More recently, saline intrusion into freshwater lenses as a result of cyclone-generated waves and storm surge on the three islands on Pukapuka Atoll, northern Cook Islands in 2005

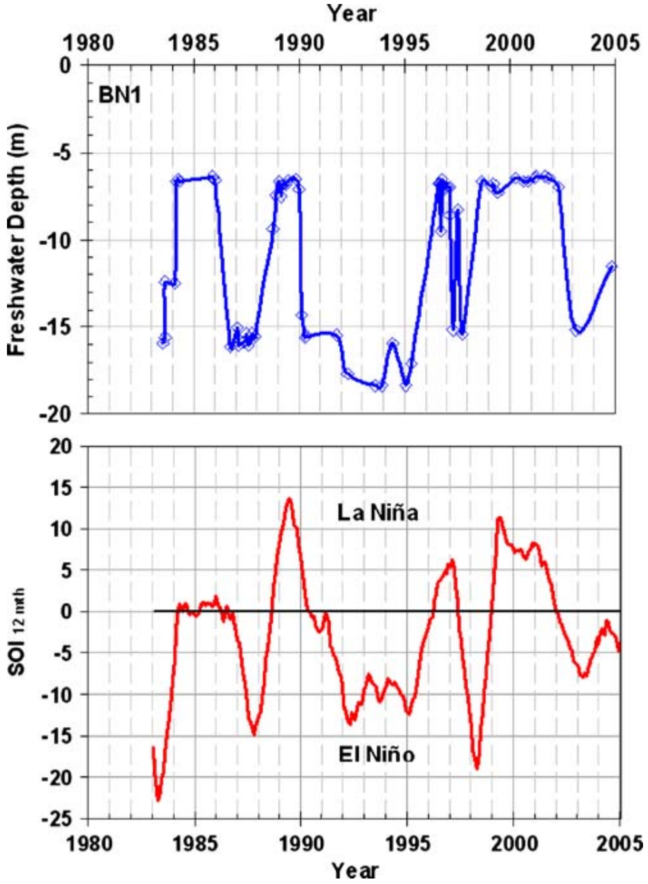

Fig. 11 Relationship between the depth of the freshwater lens below the land surface at the ocean edge of Bonriki Island, Kiribati, in the central western Pacific and La Niña and El Niño events identified by an average of the SOI over the previous 12 months

was found to have dissipated within 12 months due to density-driven downward migration of the seawater (Terry and Falkland, journal paper in preparation).

The impacts of droughts and overwash on freshwater lenses are temporary, as illustrated in Fig. 7. Freshwater lenses recover over periods of months or years after droughts or seawater inundation following recharge from significant rainfalls. More permanent changes occur with rising sea level and this is a major concern for the communities on low-lying islands of the Pacific (Ali et al. 2001; Burns 2002). The impacts on freshwater lenses from projected mean sea level rises and possible changes in recharge have been studied on several atoll islands using groundwater models. The two-dimensional model SUTRA (Voss 1984; Voss et al. 1997) has been used to analyze impacts for Enjebi Island, Enewetak Atoll (Oberdorfer and Buddemeier 1988) and Bonriki Island, Tarawa Atoll (Alam and Falkland 1997; World Bank 2000; Alam et al. 2002). It was found that sea level rises of up to 1 m would have little impact on freshwater lenses provided that land was not lost at the edges of the island. Indeed, the freshwater zone was predicted to slightly increase in thickness and volume as more of the freshwater lens will be within the upper, lower-permeability, Holocene sediments (Fig. 3). When, however, land is lost due to erosion at the edges of an island, then the island area is reduced, decreasing the volumes of freshwater lenses. Potential changes in recharge resulting from changes in rainfall were found to be more likely to have a larger impact on freshwater lenses. Further work is required to assess the relative vulnerability of different shorelines to sea level rise. Erosion is more likely to occur as the result of extreme events, such as storm waves, than gradual change in sea level (Woodroffe 2008).

In addition to the impacts of droughts, overwash and potential sea level rise, extreme events such as tsunamis and earthquakes can also impact small islands and cause disruption to groundwater resources. Groundwaters in many low-lying lands in the Indian Ocean were impacted following the Boxing Day tsunami (December 26, 2004). Tsunamis, which have devastated many islands and continents around the Pacific Rim, are not normally a major threat to mid-oceanic islands except where islands are close to tectonically active areas, such as Tonga, Samoa and Solomon Islands. Submarine landslides can also cause catastrophic changes to atolls with the loss of whole or parts of islands as have occurred, for example, on the atolls in the northern Cook Islands (Hein et al. 1997).

Threats from human activities

The main human threats to freshwater lenses are over-abstraction of groundwater and pollution from surface sources, particularly human, animal, and industrial wastes and spillages. Other threats include mining of sand and gravel for building materials from groundwater source areas and shoreline works which induce erosion. In PICs, rapidly expanding populations due to both natural growth and inward migration to urban centers are placing increasing demands on water supply systems which abstract groundwater from freshwater lenses. This is especially noticeable in population centers as, for example, on Tarawa and Kiritimati Atolls in Kiribati and, to a lesser extent, on Tongatapu in Tonga (van der Velde 2006). Significant water losses in piped distribution systems, sometimes up to 70%, place additional stress on the limited groundwater resources from the additional pumping required to cater for these losses.

Over-abstraction can be island-wide or localized. Localized over-abstraction is generally caused by inappropriate methods of pumping from vertical boreholes, which increases salinity through up-coning of the transition zone. Island-wide abstraction at greater than the sustainable yield of the island can be due to poor understanding, insufficient information or lack of regular monitoring, use of inappropriate pumping systems or demand pressures forcing management to pump at higher than sustainable rates. Figure 12 shows the change in pumping rate since 2003 compared to the estimated sustainable rate at Tarawa Atoll's groundwater sources when pumps at existing infiltration galleries were refurbished and additional pumps were installed at new infiltration galleries.

On Tarawa, population pressures and the limited land area for urban development place additional pressures on

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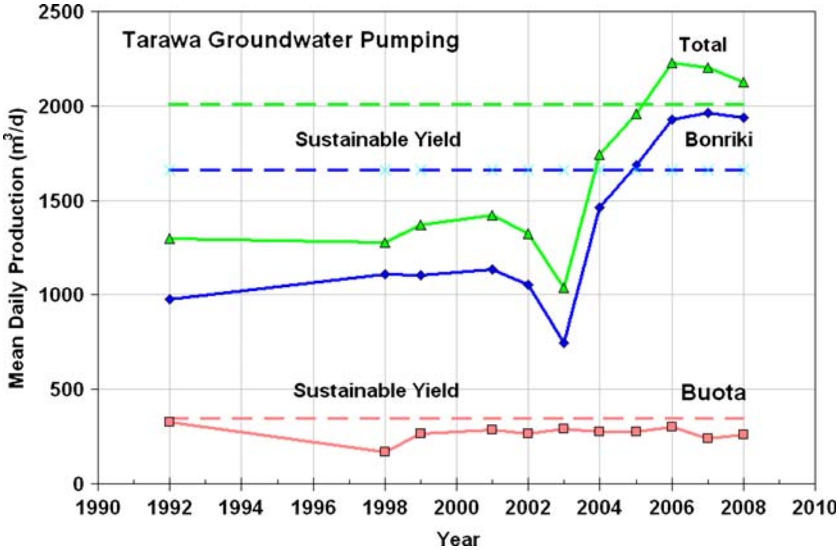

Fig. 12 Annually averaged mean daily groundwater abstraction rates using infiltration galleries from freshwater lenses in the islands of Bonriki and Buota, Tarawa Atoll, Kiribati (*solid lines and points*) compared with estimated sustainable yields (*dashed lines*). The rise in pumping rate was caused by the refurbishment of pumps and the installation of new infiltration galleries

the water reserve areas of Bonriki and Buota Islands used for groundwater abstraction. Illegal settlements and inappropriate land uses such as on the designated water reserves are major problems (White et al. 1999b, 2007a). Figure 13 shows the impact of encroachment on the quality of water produced from infiltration galleries in the Bonriki water reserve. This figure shows areas where comparative measurements between the ratio of dissolved organic carbon to total dissolved nitrogen in pumped water and the Redfield ratio for micro-organisms (C/N= 6.6 mole/mole) have been made.

Groundwater contamination on many small islands, caused by a variety of biological and chemical sources including sanitation systems, particularly pit toilets and septic tanks, animal wastes, rubbish disposal areas, cemeteries, fuel tanks, fertilizers, and agricultural chemicals (van der Velde et al. 2007), poses significant health risks. Detay et al. (1989) comprehensively reviewed pollution problems on small islands in the Federated States of Micronesia, the Marshall Islands, and Belau (Fig. 1), many of which are atoll islands. Human settlements over freshwater lenses are of major concern because of the potential for rapid pollution due to the shallow permeable soils and short travel times to the water table. This has caused the contamination of large areas of urban Tarawa so that groundwater is only fit for non-potable purposes (see Fig. 2). Specific pollution problems affecting the Bonriki and Buota freshwater lenses on Tarawa Atoll are outlined in White et al. (2005). Mining of sand and

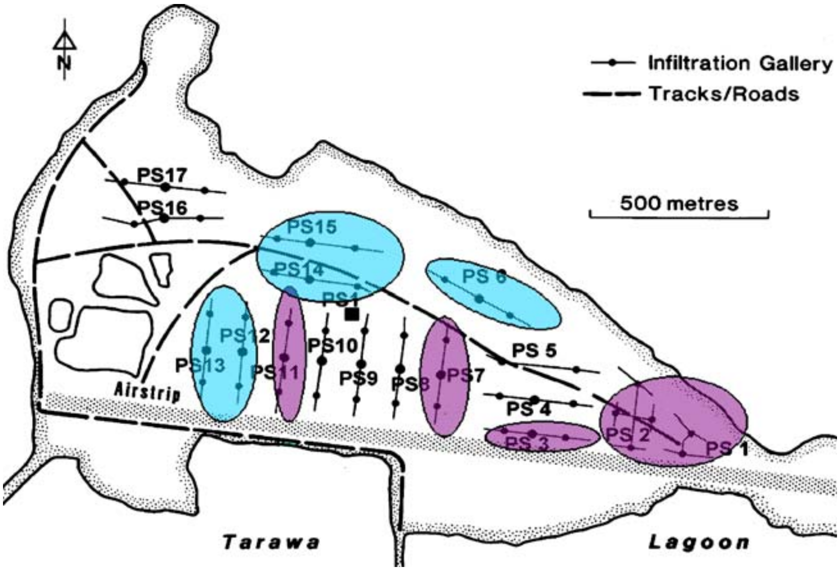

Fig. 13 Water from pumping galleries on Bonriki with dissolved organic carbon to total dissolved nitrogen ratios (i) close to the Redfield ratio for micro-organisms (*blue colored*) and (ii) significantly lower than (< 2.9) the Redfield ratio suggesting inorganic sources of total dissolved nitrogen (*purple colored*). Both colored areas correspond to land uses such as the raising of pigs, crop production, and cemeteries

gravel from freshwater lens areas creates additional risks by decreasing the soil depth over the water table and increasing vulnerability to pollution and, in some cases, increasing evaporation losses directly from exposed groundwater.

In addition to these direct threats, fresh groundwater can also be vulnerable because of inadequate legislation and regulations, inappropriate policies and limited financial and human resources to manage water source areas and water supply systems. The provision of appropriate training to water resource personnel is a critical need in small islands.

Conservation and management of freshwater lenses

Despite their vulnerability, many PICs do not know the full extent and quality of their water resources. In order to conserve and manage freshwater lenses sustainably and to protect the security of vulnerable groundwater supply systems, appropriate institutions, careful planning and strategic management are required. Focused and clear policies and achievable implementation plans, effective legislation and regulations, and well-trained personnel are key elements. The fragility of groundwater lenses and the increasing demands on them need thorough resource assessment, a commitment to ongoing monitoring and analysis, suitable groundwater development to minimize salinity, effective management of groundwater source areas, targeted demand management, public participation, training and mentoring of staff and attentive management of the water abstraction and supply systems. The limited resources in some PICs mean that these are major challenges (van der Velde et al. 2007).

Assessment of freshwater lenses

Many PICs have limited information on the amount and quality of their water resources. There are a number of techniques for assessing the location and thickness of freshwater lenses which range from preliminary "desk top" assessments through empirical techniques (e.g., Oberdorfer and Buddemeier 1988; Underwood et al. 1992; Peterson 1997) to more detailed geophysical and groundwater drilling programs. Empirical techniques in the absence of field data can be misleading, as freshwater lens shapes vary from island to island due to variations in physiography, climate and hydrogeological properties (see Fig. 4c).

Geophysical surveys using electrical resistivity (ER) and electromagnetic induction (EM) methods (Stewart 1988) provide reasonably accurate and relatively quick and cheap assessments of the locations and thicknesses of freshwater lens and have been successfully used on many atoll islands and some low-lying limestone islands in PICs, including Kiribati, Cook Islands, Federated States of Micronesia and Tonga (e.g., Anthony 1992; IETC 1998). They are much less effective in raised limestone islands due to the depth to groundwater. Both ER and EM surveys can be equivocal even on low islands and are better used to interpolate freshwater thickness between appropriately constructed boreholes in which vertical groundwater salinity profiles have been measured.

Groundwater monitoring boreholes between 15 and 30 m below ground surface have been driven into or drilled on a number of small atolls (e.g., Hunt and Peterson 1980; Hamlin and Anthony 1987; Falkland and Woodroffe 1997; GWP 2006). In order to monitor salinity profiles in groundwater lenses it is essential to avoid open boreholes or continuously perforated casings as these promote tidally induced mixing and give exaggerated saline transition zones (Buddemeier and Holladay 1977). Figure 14 shows a single borehole system with multiple tubes terminated at a number of pre-determined depths, between which bentonite sealing plugs and gravel backfill are placed to prevent the tidal-mixing that occurs in open boreholes.

A shallow piezometer tube within these boreholes permits water-level measurements and collection of samples from the groundwater surface. Measurements of water-table height above mean sea level are useful for examining the effects of pumping, climate variations and tides. More detailed groundwater assessment methods for small islands and examples are provided in Dale et al. (1986), UNESCO (1991), IETC (1998), SOPAC (2005) and SOPAC (2006).

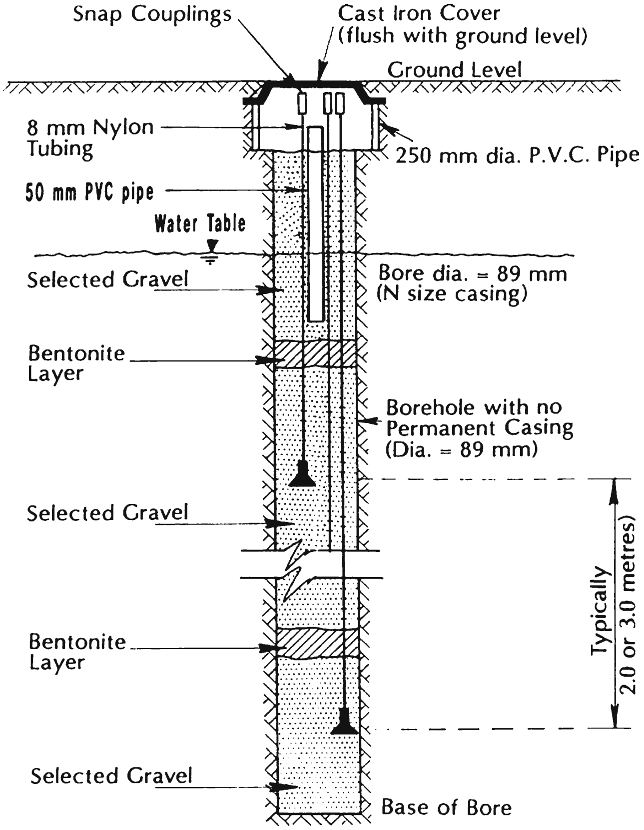

Fig. 14 Multi-level borehole monitoring system for measuring the water-table elevation and groundwater salinity at different depths in a freshwater lens. Bentonite layers prevent inappropriate tidal mixing

Groundwater recharge and sustainable yield estimation

The impacts of large natural variations in rainfall in PICs (Figs. 6 and 7) mean that determination of the sustainable groundwater yields requires careful estimation. Knowledge of groundwater recharge is fundamental to estimating sustainable yields from freshwater lenses. Preliminary assessment can be made using empirical curves relating annual recharge to annual rainfall (Falkland and Brunel 1993) and maps based on estimates from several islands (Nullet 1987). Preliminary estimates of recharge can also be made using a chloride ion balance approach (Ayers 1981). As Chapman (1985), however, has pointed out, dry salt deposition in small islands complicates this measurement making it better to measure salinity in the surface soil water (White et al. 2002).

Continuous water level records in conjunction with tidal and barometric records and rainfall have been used to estimate recharge (Furness and Gingerich 1993). Removing the effects of sea level and pressure changes from the water level hydrograph, allows recharge to be estimated from the residual trace and estimates of the aquifer specific yield.

Detailed studies of groundwater recharge on Tarawa Atoll, Kiribati (White et al. 2002) used rain gauges, a climate station, sap flow sensors, soil moisture probes, and groundwater level recorders to quantify the water balance above the freshwater lens and to assess recharge. This also enabled calibration of a water balance model for recharge estimation on atoll islands using daily or monthly rainfall data and either estimates of monthly potential evaporation or measured pan evaporation data. Measurements of the drainage fluxes beneath the root zone, such as on the raised limestone island of Tongatapu (van der Velde et al. 2005), may also be used to assess groundwater recharge.

Preliminary estimates of sustainable groundwater yield are normally taken to be a fraction of mean annual recharge. This recognizes that only a proportion of recharge (of order 25–50%) can be abstracted leaving a significant amount for maintaining the integrity of the lens. More detailed estimates of sustainable yields have used water balance approaches (Falkland 1993) and groundwater models, most commonly two-dimensional variable-density models such as the SUTRA model (Voss 1984; Voss et al. 1997). Case studies using the SUTRA model in atolls are in Oberdorfer and Buddemeier(1988), Oberdorfer et al. (1990), Griggs and Peterson (1993), Peterson (1997), Underwood et al. (1992), Alam et al (2002) and World Bank (2000). Other two-dimensional and three-dimensional models have also been used (Jacobson et al. 1997; Mink and Vacher 1997).

Groundwater modeling to estimate sustainable yield relies on the availability of good quality medium to long-term climatic and groundwater data. The use of models with limited data can lead to erroneous results (Fig. 5). Table 2 shows the progressive estimates of sustainable groundwater yields for the major water supply lenses in Tarawa Atoll over the past 40 years, which have used a variety of modeling and field investigation techniques. The current estimate is equivalent to just over 43 l/person/day of treated freshwater and demonstrates the importance of accurate estimation of sustainable yield.

Long-term monitoring

In the face of the extreme ENSO-related variability, climate change and increasing population growth and demand faced by many PICs, long-term climate and regular groundwater monitoring and analysis of the data are essential for understanding and managing these fragile groundwater systems. Monitoring is a major problem in many PICs because of the lack of trained personnel and shortages of equipment and resources, such as access to transport. A failure to appreciate the importance of adequate water resources monitoring pervades government agencies responsible for water supply and regulation. In some cases, lack of clear definition of roles between government agencies and competition for limited resources are further impediments.

Some of these problems are being addressed through projects such as the Pacific HYCOS project (Pacific HYCOS 2009). Ongoing capacity building and training and mentoring of staff in PICs is, however, required (van der Velde et al. 2007).

Minimizing salinity of pumped groundwater

The delicate hydrostatic balance between freshwater and the surrounding and underlying seawater in small islands is easily disturbed by inappropriate groundwater development. The most common method of obtaining groundwater on low-lying, coral islands is from hand-dug dug wells typically 2–3 m deep and approximately 1 m below the groundwater level. Groundwater is abstracted by buckets, hand pumps, or small electric pumps. Such systems work well at household levels, provided abstraction rates are low.

Table 2 Successive estimates of the daily sustainable groundwater yield from Bonriki and Buota water reserves, Tarawa Atoll, Kiribati

Year	Estimates of sustainable yield (m^3/day)			
	Bonriki	Buota	Combined	Reference
1973	110			Mather (1973)
1978	<85	<85	<170	Richards and Dumbleton (1978)
1982	750	250	1,000	DHC (1982)
1992	1,000	300	1,300	Falkland (1992)
2002	1,350	350	1,700	Alam et al. (2002)
2004	1,660	350	2,010	Falkland (2004)

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For public water supply pumping systems, single or multiple dug wells or drilled boreholes have been used on some coral islands. These vertical abstraction systems can cause upconing of the transition zone and increases in salinity of the abstracted water. In some cases, the groundwater can become too saline for potable use. Pumping from horizontal infiltration galleries or skimming wells has proved a far better abstraction method, particularly in islands with thin freshwater lenses. Infiltration galleries, consisting of up to 300-m-long horizontal slotted pipes buried below the water table (Figs. 3 and 15), skim the fresh groundwater from the surface of the lens, and thus distribute the pumping drawdown over a wide area. In so doing, they avoid excessive local drawdown and upconing of saline water that occurs in pumping from vertical boreholes.

Freshwater lenses contract during major droughts, so it is important that the local impacts on the freshwater lenses caused by pumping are minimized. By maintaining a small drawdown at each gallery pump well, the impact of pumping on the freshwater lens and on the salinity of abstracted water is minimized. Infiltration galleries are used in Tarawa and Kiritimati Atolls, Kiribati; Majuro and Kwajalein Atolls (Peterson 1997) in the Marshall Island; Aitutaki Island, Cook Islands; and Lifuka Island, Tonga (Fig. 1). On Lifuka, replacement of boreholes with infiltration galleries significantly lowered the salinity of the water supply (Falkland 2000b).

Measurements in 25 Bonriki and Buota gallery pump wells in Tarawa Atoll, Kiribati, have shown that the average groundwater drawdown of all galleries is 33 mm when pumped at mean rates of 88 m^3/day (White et al. 2007b). This drawdown is less than the magnitude of groundwater fluctuations due to tidal influence there of typically 70–80 mm (see Fig. 16). It is also much less than the longer-term groundwater level fluctuations of about 450 mm between very wet and very dry periods (Fig. 10).

For limestone islands, where depths to the water table are greater than 10 m and up to 50 m or more, abstraction using vertical drilled boreholes is currently the most practical method of developing freshwater lenses. Examples are found in Tonga (Furness 1997), Niue (GWP 2006) and northern Guam (Mink and Vacher 1997). In the future, directional drilling from the surface may be an option for installing horizontal infiltration galleries on these islands.

Management of freshwater lens areas

Effective land-use planning and management is essential for the protection of shallow groundwater resources from contamination on low-lying carbonate islands. "Groundwater protection zones" or "water reserves" coupled with regulation of landuses in these reserves has been tested in some PICs. Human settlements, agriculture involving raising of livestock, the use of chemicals and fertilizers and mining of sand and gravel all increase the risk of groundwater contamination. Such reserves, however, are often difficult to manage owing to pressures on limited land areas in small islands and the problem of ownership of water, which traditionally was owned by landowners.

In most PICs, land over groundwater source areas is privately owned. Declaration of water reserves has generated major conflicts between government and private landowners. Their resolution requires appropriate administrative and financial provisions, the involvement of the local community in managing the reserve, or even the water supply system as in Tongatapu, and the provision of social services such as sports fields on the reserves (White et al. 1999a, 1999b). In islands where consumptive demand is approaching sustainable groundwater yield, the selective clearing vegetation, particularly coconut trees from the central parts of the islands, can decrease transpiration losses, enhance recharge, and increase the sustainable yield. This

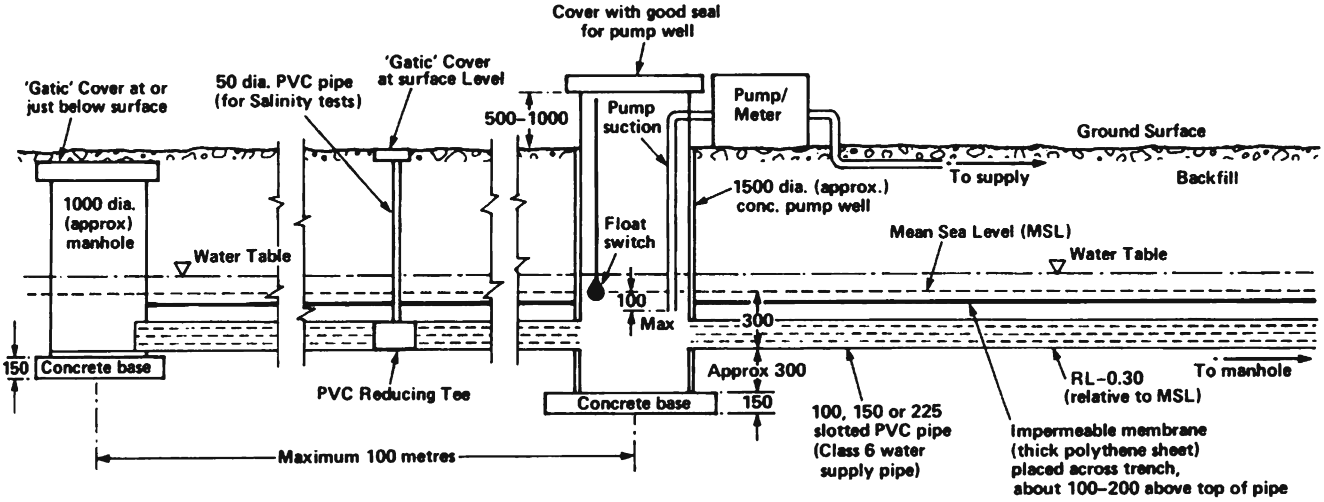

Fig. 15 Cross section through a typical infiltration gallery or skimming well [modified from Falkland and Brunel (1993) with permission from Cambridge University. Measurements are shown in millimeters

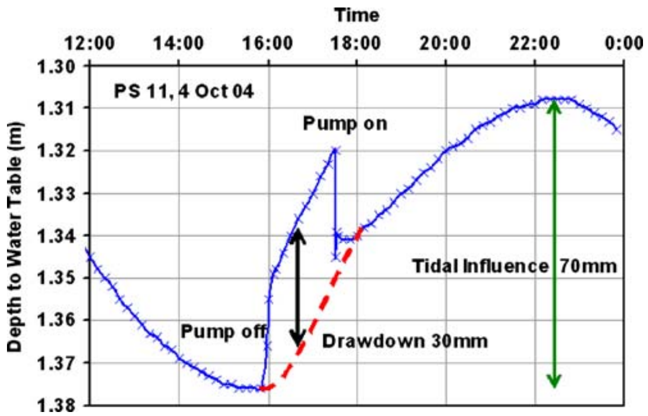

Fig. 16 Change in water-table elevation in an infiltration gallery pump well, Bonriki, Tarawa, due to the switching off and on of the pump. The pump drawdown is superimposed on the diurnal tidally induced fluctuation

leaves coastal margins in a natural state to ensure protection from erosion and to continue to provide a source of food, drink, and construction materials. In some islands, areas already cleared for airfields offer good opportunities for groundwater development.

Sanitation systems using septic tanks and pit toilets are a major source of biological contamination and health risks on many islands. In parts of some heavily populated atolls such as Majuro, Marshall Islands and Tarawa, Kiribati, piped sewerage systems using seawater for flushing, to conserve limited freshwater supplies, have been installed to overcome this problem. Compost toilets protect freshwater lenses as well as also conserving scarce water resources. These have been tested in a number of PICs including Kiribati, Tonga, and Tuvalu (Crennan and Berry 2002). While these toilets have many advantages and have been accepted in some communities, cultural attitudes have so far limited their widespread use in others. Other technical solutions are available including improved septic tanks and relatively simple effluent disposal and treatment systems. Further information is available, for instance, in Depledge (1997), UNEP (2002), Bower et al. (2005) and WHO (2008).

The most appropriate strategy is to ensure that human settlements including their sanitation systems are placed well away from freshwater lenses used for public water supply. A study using bromide tracer in Lifuka, Tonga, concluded there was no safe distance between pit latrines or septic tanks and water supply wells in an urban area because of the density of sanitation facilities (Crennan et al. 1998). Instead, it recommended that alternative strategies such as source control of pollutants as with composting toilets and water treatment are required.

Management of water supply systems

Water supply systems on islands that extensively use groundwater from freshwater lenses need careful management. Pumping rates should not exceed the sustainable yield, which requires metering and monitoring of pumps. Significant leakages, as high as 70% of extracted water from the reticulation system, are endemic in PICs. These leaks often occur in areas where the groundwater is saline or heavily polluted and are a waste of energy and water. Their minimization through regular detection and maintenance is a key step in increasing the availability of water. Demand management is a difficult issue in PICs as in many countries. There is both an aversion and an inability to pay for groundwater which traditionally was the property of landowners.

There is limited information on the proportion of rainwater used for domestic consumption in PICs. The conjunctive use of rainwater harvesting systems for potable purposes with groundwater reserved for non-potable uses offers an alternative and safer water supply than domestic shallow wells located beside pit toilets and pig pens. Domestic rainwater storages, however, are normally insufficient in long droughts but communal tanks, such as those in Tuvalu, are able to maintain modest supply. Incentives for increasing rainwater harvesting have proved valuable, although in some PICs there is a preference for groundwater.

The strong relationship between rainfall or groundwater salinity and climate indices such as Niño SST or the SOI in many PICs (Fig. 6) offers the potential to predict extremely wet and extremely dry periods. Use of simple rainfall deciles in Tarawa, Kiribati, enabled prediction of droughts up to 6 months before their maximum, with 50% accuracy (White et al. 1999a). Van der Velde et al. (2006) found that groundwater salinity in Tongatapu lagged 10 months behind the SOI. The Pacific Islands Climate Prediction Project (ABOM 2009) uses primarily SST measures of the ENSO cycle to generate probabilistic predictions or seasonal climate outlooks for rainfall, temperature or other climate related parameters in PICs.

Finally, attracting, training and retaining skilled staff in sufficient number in the water sector in PICs is difficult, as is assembling the necessary resources. Fortunately, there are regional organizations such as SOPAC that provide a resource and expertise base for PICs.

Future prospects

This paper has attempted to show that the climatic, hydrogeological, and physiographic factors compounded by human activities make fresh groundwater lenses used for water supply on small islands in the Pacific some of the most vulnerable groundwater systems in the world. Some small island population centers are already close to the limit of sustainable groundwater abstraction. Faced with climate change, rising sea levels, increasing frequency of extreme events, growing populations, restricted land areas, limited resources and capacity, their prospects appear bleak. Yet island populations have proved remarkably resilient in the past.

Desalination is seen by many as the solution to future water needs in small islands. Its success rate, however, in PICs to date has been poor. Desalination equipment is expensive to operate and maintain, often too complex for local technicians, and is energy intensive. Groundwater abstraction from lenses where the yield has been maximized by clearing deep-rooted vegetation, supplemented by domestic rainwater harvesting appears to be a more reliable and robust strategy. These enhanced-yield systems will require careful management and continued regular monitoring.

External donors and lenders have assisted and continue to assist PICs to develop and manage their groundwater resources. A number of aid and loan projects in the water sector, however, have had only limited success. Almost all projects have been relatively short-term and narrowly focused on infrastructure, and some have often been driven by the agendas of international agencies rather than the priorities of local populations. Many have also assumed that developed-world solutions, concepts, and "tool boxes" are universally transportable and applicable. Donor and aid programs that are sensitive to cultural nuances, recognize local priorities, value effective community participation, mentor staff in the water sector and appreciate the long time-scale for behavioral change are more likely to be successful (White et al. 2008).

Many of the pressing future problems can be addressed through six policy objectives:

- improve understanding and monitoring of water resources and their use;
- increase access to safe and reliable water supplies and appropriate sanitation;
- achieve financially, socially, and environmentally sustainable water resource management;
- increase community participation in water management and conservation;
- improve governance in the water and sanitation sector; and
- provide training opportunities for and mentoring of staff in the sector.

Village-level water committees have proven successful in rural areas in Tonga and Samoa and appear to offer a model for other PICs. They are appropriate for the cultural contexts in many PICs and would help return control of the protection and management of water resources to the local level in rural areas and outer islands. Such committees need, however, to be nurtured and resourced adequately.

The increasing complexity of water management as islands approach the limit of sustainable yield will pose difficulties for small islands, where sometimes only one or two people are responsible for water management. Regional organizations that pool expertise and local experience and provide training opportunities have and should continue to have a key role in supporting PICs in water management. It is important that these regional organizations are incorporated as partners into aid and donor programs in the water and sanitation sector in the Pacific.

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References

ABOM (2009) Australian Bureau of Meteorology Pacific Islands Climate Prediction Project (PI-CPP) http://www.bom.gov.au/climate/pi-cpp/. Cited 23 July 2009

Alam K, Falkland A (1997) Vulnerability to climate change of the Bonriki freshwater lens, Tarawa. Prepared for Ministry of Environment and Social Development, Tarawa, Republic of Kiribati, September 1997

Alam K, Falkland A, Mueller N (2002) Sustainable Yield of Bonriki and Buota Freshwater Lenses. SAPHE Project, Hydrogeology Component. Tarawa, Republic of Kiribati, February 2002

Ali M, Hay J, Maul G, Sem G (2001) Chapter 9: small island states. In Watson RT, Zinyowera MC, Moss RH, Dokken DJ (eds) IPCC Special Report on the Regional Impacts of Climate Change. An Assessment of Vulnerability. UNEP and WMO. www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/regional/index.htm. Cited 23 July 2009

Anthony SS (1992) Electromagnetic methods for mapping freshwater lenses on Micronesian atoll islands. J Hydrol 137:99–111

Ayers JF (1981) Estimate of recharge to the freshwater lens of northern Guam. Tech. Rpt. No. 21, Water Resources Research Center, University of Guam

Ayers JF, Vacher HL (1986) Hydrogeology of an atoll island, a conceptual model from a detailed study of a Micronesian example. Ground Water 24(2):185–198

Badon Ghijben W (1889) Nota in verband met de voorgenomen putboring nabij Amsterdam. (Notes on the probable results of the proposed well drilling near Amsterdam). Tijdschrift het Koninklijk Instituut voor Ingenieurs. The Hague, pp 8–22

Bower R, Crennan L, Navatoga A (2005) The sanitation park project. Fiji. SOPAC Technical Report No. 386, SOPAC, Suva, Fiji

Buddemeier RW, Holladay GL (1977) Atoll hydrology, island ground-water characteristics and their relationship to diagenesis. Proc. 3rd Internat. Coral Reef Symposium, Miami, 2:167–174

Burns WCG (2002) Pacific Island developing country water resources and climate change. In: Gleick PH, Burns WCG, Chalecki EL, Cohen M (eds) World's water 2002–2003: the biennial report on freshwater resources. Island Press, Washington, DC, pp 113–131

Chapman TG (1985) The use of water balances for water resource estimation with special reference to small islands. Bulletin No. 4. Pacific Regional Team. Australian Development Assistance Bureau, Canberra, Australia, pp 34

Crennan L, Berry G (2002) Review of community-based issues and activities in waste management, pollution prevention and improved sanitation in the Pacific Islands Region. IWP Technical Report 2002/03. In Wright A, Stacey N (eds) Issues for community based sustainable resource management and conservation: considerations for the Strategic Action Plan for the International Waters of the Pacific Small Island Developing States. The International Waters Programme, South Pacific Regional Environment Programme, Apia, Samoa

Crennan L, Fatai T, Fakatava T (1998) Groundwater Pollution Study, Completion of Phase Two, Lifuka, Kingdom of Tonga, report submitted to UNESCO Office of Pacific States, Apia, Samoa, December 1998

Dale WR, Waterhouse BC, Risk GF, Petty DR (1986) Coral island hydrology, a training guide for field practice. Commonwealth Science Council, Technical Publication Series, No. 214

Depledge D (1997) Sanitation for Small Islands: Guidelines for selection and development. SOPAC Miscellaneous Report 250. SOPAC, Fiji, September 1997

Detay M, Alessandrello E, Come P, Groom I (1989) Groundwater contamination and pollution in Micronesia. J Hydrol 112:149–170

DHC (1982) Kiribati – Tarawa water resources, Pre-design study. Prepared for the Australian Development Assistance Bureau by the Australian Government Department of Housing and Construction

Dijon R (1983) Some aspects of water resources planning and management in smaller islands. Natural Resources Forum, United Nations 7(2):137–144

Falkland A (1992) Review of Tarawa freshwater lenses, Republic of Kiribati. Report HWR92/681. Hydrology and Water Resources Branch, ACT Electricity and Water. Prepared for Australian International Development Assistance Bureau

Falkland A (1993) Hydrology and water management on small tropical islands. In Gladwell JS (ed) Proc. Symp. Hydrology of Warm Humid Regions. International Association of Hydrological Sciences Publ. No. 216:263–303

Falkland A (1999) Water management for Funafuti, Tuvalu. Prepared for the Australian Agency for International Development, Canberra, Australia, August 1999

Falkland A (2000a) Penrhyn, Cook Islands, Report on Water Investigations, June 2000. Prepared for Australian Agency for International Development, August 2000

Falkland A (2000b) An outline of recent water supply improvements for Pangai-Hihifo, Lifuka, Kingdom of Tonga. Prepared for Tonga Water Board, August 2000

Falkland A (2002) Tropical island hydrology and water resources: current knowledge and future needs. In: Gladwell JS (ed) Proc. Second International Colloquium on Hydrology and Water Resources Management in the Humid Tropics, 22–25 March 1999, UNESCO-IHP, CATHALAC, Panama City, Panama

Falkland A (2004) Preliminary Design Report for Four Infiltration Galleries at Bonriki, Tarawa, Kiribati. SAPHE Project, Hydrogeology Component. Tarawa, Republic of Kiribati, August 2004

Falkland A, Brunel JP (1993) Review of hydrology and water resources of humid tropical islands. In: Bonell M, Hufschmidt MM, Gladwell JS (eds) Hydrology and water management in the humid tropics. Cambridge University Press, UNESCO, International Hydrology Series, pp 135–166

Falkland A, Woodroffe CD (1997) Geology and hydrogeology of Tarawa and Christmas Island, Kiribati. Chapter 19. In: Vacher HL, Quinn TM (eds) Geology and hydrogeology of carbonate islands. Developments in Sedimentology 54. Elsevier, Amsterdam, pp 577–610

Foale M (2003) The coconut odyssey: the bounteous possibilities of the tree of life. Australian Centre for International Agricultural Research, Canberra, p 132

Furness LJ (1997) Hydrogeology of carbonate islands of the Kingdom of Tonga. Chapter 18. In: Vacher HL, Quinn TM (eds) Geology and hydrogeology of carbonate islands. Developments in Sedimentology 54. Elsevier, Amsterdam, pp 565–576

Furness LJ, Gingerich S (1993) Estimation of recharge to the fresh water lens of Tongatapu, Kingdom of Tonga. In: Gladwell JS (ed) International Association of Hydrological Sciences Publ. No. 216:317–322

Griggs JE, Peterson FL (1993) Ground-water flow dynamics and development strategies at the atoll scale. Ground Water 31 (2):209–220

GWP (2006) Groundwater resources investigations on Niue Island for Government and South Pacific Applied Geoscience Commission (SOPAC), GWP Consultants, Charlbury, Oxford, United Kingdom, March 2006

Hamlin SN, Anthony SS (1987) Ground-water resources of the Laura area, Majuro Atoll, Marshall Islands, USGS Water Resources Investigation Report 87–4047, Hawaii, U.S.A.

Hein JR, Gray SC, Richmond BR (1997) Geology and hydrogeology of the Cook Islands. Chapter 16. In: Vacher HL, Quinn TM (eds) Geology and hydrogeology of carbonate islands. Developments in Sedimentology 54. Elsevier, Amsterdam, pp 503–535

Herzberg A (1901) Die Wasserversorgung einiger Nordseebäder (The water supply on parts of the North Sea coast). Jour für Gasbeleuchtung und Wasserversorgung, München 44:815–819 45:842–844

Hunt CD, Peterson FL (1980) Groundwater resources of Kwajalein island, Marshall Islands. Tech. Rpt. 126, Water Resources Research Centre, Univ. of Hawaii

IETC (1998) Source book of alternative technologies for freshwater augmentation in Small Island Developing States. International Environmental Technology Centre in collaboration with South Pacific Applied Geoscience Commission and the Water Branch of UNEP, Technical Publication Series No. 8

Jacobson G, Hill PJ (1980) Groundwater resources of Niue Island. Bureau of Mineral Resources Record No. 1980/14, Canberra, Australia

Jacobson G, Hill PJ (1988) Hydrogeology and groundwater resources of Nauru Island, Central Pacific Ocean. Bureau of Mineral Resources Record No. 1988/12 Canberra, Australia

Jacobson G, Taylor FJ (1981) Hydrogeology of Tarawa atoll, Kiribati. Bureau of Mineral Resources Record, No. 1981/31, Canberra, Australia

Jacobson G, Hill PJ, Ghassemi F (1997) Geology and hydrogeology of Nauru Island. Chapter 24. In: Vacher HL, Quinn TM (eds) Geology and hydrogeology of carbonate islands. Developments in Sedimentology 54. Elsevier, Amsterdam, pp 707–742

Mather JD (1973) The groundwater resources of southern Tarawa, Gilbert and Ellice Islands. Hydrogeological Department, Institute of Geological Sciences, UK, 54 pp

Mink JF, Vacher HL (1997) Hydrogeology of northern Guam. Chapter 25. In: Vacher HL, Quinn TM (eds) Geology and hydrogeology of carbonate islands. Developments in Sedimentology 54. Elsevier, Amsterdam, pp 743–759

Nullet D (1987) Water balance of Pacific atolls. Water Resour Bull 23(6):1125–1132

Oberdorfer JA, Buddemeier RW (1984) Atoll island groundwater contamination: rapid recovery from saltwater intrusion. Annual Meeting of the Association of Engineering Geologists. Boston, Mass. USA, 9–11 Oct. 1984

Oberdorfer JA, Buddemeier RW (1988) Climate change, effects on reef island resources. Sixth International Coral Reef Symposium, Townsville, Australia, 3:523–527

Oberdorfer JA, Hogan PJ, Buddemeier RW (1990) Atoll island hydrogeology, flow and fresh water occurrence in a tidally dominated system. J Hydrol 120:327–340

Pacific HYCOS (2009) Pacific hydrological cycle observing system. http://pacific-hycos.org/. Cited 23 July 2009

Peterson FL (1997) Hydrogeology of the Marshall Islands, Chap. 20. In: Vacher HL, Quinn TM (eds) Geology and hydrogeology of carbonate islands. Developments in Sedimentology 54. Elsevier, Amsterdam, pp 611–636

Richards R (1991) Atoll vulnerability: the storm waves on Tokelau on 28 February 1987. In: Hay J (ed) South Pacific environments: interactions with weather and climate. University of Auckland, Environmental Science, pp 155–156

Richardson and Dumbleton International (1978) Water resources, Tarawa, report on feasibility study. Prepared for the UK Ministry of Overseas Development on behalf of the Government of the Gilbert Islands

Scott D, Overmars M, Falkland A, Carpenter C (2003) Pacific dialogue on climate and water. synthesis report. SOPAC, February 2003, 36pp

SOPAC (2005) First Groundwater Training Course. Hydrological training on surface water and groundwater, SOPAC Secretariat, 4th – 22nd April 2005, sponsored by NZAid, NIWA, UNESCO and SOPAC

SOPAC (2006) Second Groundwater Training Course. Hydrological training on surface water and groundwater, SOPAC Secretariat, 12th – 30th June 2006, sponsored by NZAid, NIWA and SOPAC

SOPAC (2009) Pacific Islands Applied Geoscience Commission. Water, Sanitation and Hygiene website http://www.pacificwater.org/index.cfm. Cited 23 July 2009.

Spennemann DHR (2006) Freshwater lens, settlement patterns, resource use and connectivity in the Marshall Islands. Transforming Cultures eJournal 1(2):44–63

Stewart M (1988) Electromagnetic mapping of fresh-water lenses on small oceanic islands. Ground Water 26(2):187–191

Terry JP (2007) Tropical cyclones, climatology and impacts in the South Pacific. Springer, Berlin Heidelberg New York

Underwood MR, Peterson FL, Voss CI (1992) Groundwater lens dynamics of atoll islands. Water Resour Res 28(11):2889–2902

UNEP (2002) A directory of environmentally sound technologies for the integrated management of solid, liquid and hazardous waste for Small Island Developing States (SIDS) in the Pacific Region. Compiled by OPUS International in conjunction with South Pacific Regional Environment Programme (SPREP) and South Pacific Applied Geoscience Commission (SOPAC), July 2002

UNESCO (1991) Hydrology and water resources of small islands, a practical guide. Studies and reports on hydrology No 49. prepared by A Falkland (ed) and E Custodio with contributions from A Diaz Arenas and L Simler and case studies submitted by others. UNESCO, Paris, France

Vacher HL, Quinn TM (eds) (1997) Geology and hydrogeology of carbonate Islands. Developments in Sedimentology 54. Elsevier, Amsterdam

van der Velde M (2006) Agricultural and climatic impacts on the groundwater resources of a small island. Measuring and modeling water and solute transport in soil and groundwater on Tongatapu. PhD Thesis, Faculty of Biological, agricultural and Environmental Engineering, Catholic University of Louvain, 263 pp

van der Velde M, Green SR, Gee GW, Vanclooster M, Clothier BE (2005) Evaluation of drainage from passive suction and nonsuction flux meters in a volcanic clay soil under tropical conditions. Vadose Zone J 4:1201–1209

van der Velde M, Javaux M, Vanclooster M, Clothier BE (2006) El Niño-Southern Oscillation determines the salinity of the freshwater lens under a coral atoll in the Pacific Ocean. Geophys Res Lett 33:L21403. doi:10.1029/2006GL027748

van der Velde M, Green SR, Vanclooster M, Clothier BE (2007) Sustainable development in small island developing states: agricultural intensification, economic development, and freshwater resources management on the coral atoll of Tongatapu. Ecol Econ 61:456–468

Volker RE, Mariño MA, Rolston DE (1985) Transition zone width in ground water on ocean atolls. J Hydraul Eng 111(4):659–676

Voss CI (1984) SUTRA, A finite-element simulation model for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport. USGS Water Resources Investigation Report 84–4389, 409 pp

Voss CI, Boldt D, Sharpiro AM (1997) A graphical-user interface for the US Geological Survey's SUTRA code using Argus ONE (for Simulation of Variable–Density Saturated-Unsaturated Ground-Water Flow with Solute or Energy Transport), US Geological Survey, Open-File Report 97–421, Reston, Virginia

Wheatcraft SW, Buddemeier RW (1981) Atoll island hydrology. Ground Water 19(3):311–320

Wheeler C, Aharon P (1997) Geology and hydrogeology of Niue. Chap. 17. In: Vacher HL, Quinn TM (eds) Geology and hydrogeology of carbonate islands. Developments in Sedimentology 54. Elsevier, Amsterdam, pp 537–564

White I, Falkland A (2004) Effects of pumping from infiltration galleries on crop health and production in low coral islands: groundwater impacts. ACIAR Project LWR1/2001/050, Equitable Groundwater Management for the Development of Atolls and Small Islands, Australian Centre for International Agricultural Research, Canberra. November 2004

White I, Falkland A, Scott D (1999a) Droughts in small coral islands: Case study, South Tarawa, Kiribati. UNESCO IHP-V, Technical Documents in Hydrology, No. 26, UNESCO, Paris, 55 pp

White I, Falkland A, Crennan L, Jones P, Metutera T, Etuati B, Metai E (1999b) Groundwater recharge in low coral islands Bonriki, South Tarawa, Kiribati. Issues, traditions and conflicts in groundwater use and management. UNESCO IHP-V, Technical Documents in Hydrology, No. 25, UNESCO, Paris, France, 39 pp

White I, Falkland A, Etuati B, Metai E, Metutera T (2002) Recharge of fresh groundwater lenses: field study, Tarawa Atoll, Kiribati. Hydrology and Water Resources Management in the Humid Tropics, Proc. Second International Colloquium, 22–26 March 1999, Panama, Republic of Panama, IHP-V Technical Documents in Hydrology No 52, UNESCO, Paris, 2002, 299–332

White I, Falkland A, Perez P, Metutera T, Metai E (2003) Water resources of Tarawa Atoll, Republic of Kiribati. ACIAR Project LWR1/2001/050 Equitable Groundwater Management for the Development of Atolls and Small Islands, Australian Centre for International Agricultural Research, Canberra, May 2003

White I, Falkland A, Metutera T, Metai E (2005) Effects of landuse on groundwater quality in a low coral atoll: coliforms, nutrients and metals. ACIAR Project LWR1/2001/050, Equitable Groundwater Management for the Development of Atolls and Small Islands, Australian Centre for International Agricultural Research, Canberra, May 2005

White I, Falkland A, Perez P, Dray A, Metutera T, Metai E, Overmars M (2007a) Challenges in freshwater management in low coral atolls. J Clean Prod 15:1522–1528

White I, Falkland A, Metutera T, Metai E, Overmars M, Perez P, Dray A (2007b) Climatic and human influences on groundwater in low Atolls. Vadose Zone J 6:581–590

White I, Falkland A, Metutera T, Katatia M, Abete-Reema T, Overmars M, Perez P, Dray A (2008) Safe water for people in low, small island Pacific nations: the rural-urban dilemma. Development 51:282–287

White I, Falkland A, Fatai T (2009) Vulnerability of groundwater in Tongatapu, Kingdom of Tonga: groundwater evaluation and monitoring assessment. Report to Pacific Islands Applied Geoscience Commission, EU EDF8, February 2009, ANU, Canberra

WHO (2004) Guidelines for drinking-water quality. 3rd edn., including addenda in 2006 and 2008. World Health Organization, Geneva, Switzerland

WHO (2008) Sanitation, hygiene and drinking-water in the Pacific island countries. Converting commitment into action. World Health Organization and SOPAC, 2008

Wooding RA (1963) Convection in a saturated porous media at large Rayleigh number or Peclet number. J Fluid Mech 15:527–544

Wooding RA (1964) Mixing-layer flows in a saturated porous media. J Fluid Mech 19:103–112

Woodroffe CD (2008) Reef-island topography and the vulnerability of atolls to sea-level rise. Global Planet Change 62:7–96

World Bank (2000) Cities, seas and storms, managing change in Pacific island economies, Volume IV, Adapting to Climate Change, Papua New Guinea and Pacific Island Country Unit, World Bank, November 2000