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Climatic and Human Influences on Groundwater in Low Atolls

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Population centers in low, small islands have water supply problems that are among the most critical in the world. Limited land areas and extremely large soil hydraulic conductivities severely reduce surface runoff and surface storage, so that thin lenses of fresh groundwater floating over seawater comprise the major source of fresh water for people in many atolls. Atoll groundwater is extremely vulnerable to frequent El Niño Southern Oscillation (ENSO)–related droughts, salinization due to storm surges and sea-level rise, and to human activities with vadose zone transit times from surface to shallow groundwater being less than 1 h. We examine the relationship between groundwater, rainfall, and ENSO events in a low atoll, Tarawa, in the central and western Pacific Republic of Kiribati. Droughts can last as long as 43 months and occur with a current frequency of 6 to 7 years. The impact of droughts on the quality and quantity of a fresh groundwater lens is explored. The local drawdown of the water table due to pumping from long horizontal infiltration galleries is found to be less than diurnal tidal variations. The saturated hydraulic conductivity, K_0, of the Holocene unconsolidated coral sands was estimated from infiltration gallery drawdown in two islands. The geometric mean K_0 was 14.6 m d^{-1} with a range from 0.9 to 111 m d^{-1}. These large K_0 values cause the rapid transmission of rainfall and surface pollutants through the unsaturated zone to groundwater. An example is given of *Escherichia coli* pollution due to traditional activities. Strategies for improving the adaptation of island communities and increasing resilience to climate change are discussed.

Abbreviations: EC, electrical conductivity; ENSO, El Niño Southern Oscillation; FDR, frequency domain reflectometry; PS, pumping station; SOI, Southern Oscillation Index.

The Barbados Conference on the Sustainable Development of Small Island States in 1994 focused world attention on the fragility and vulnerability of these small islands. This vulnerability is a product of their remoteness, small size, rapid population growth, restricted capacity and resources, and sensitivity to climate variability (Talu et al., 1979). Low gross domestic product, limited opportunities, and increasing urbanization are straining both traditional support mechanisms (Ward, 1999) and customary, traditional approaches to hazard reduction.

There are about 8000 inhabited small tropical islands in the Pacific, Indian, and Atlantic oceans. Many, formed as sand cays, coral atolls, or elevated limestone islands, are very small islands, with land areas less than 100 km^2 or with maximum widths less than 3 km. In these islands, surface water resources are usually nonexistent because of the large hydraulic conductivities of coral sands (of order 10–100 m d^{-1}). Fresh groundwater resources, which exist as thin freshwater lenses floating over seawater, can be very limited because of restricted land areas, high regolith permeabilities and tidal mixing and dispersion with the underlying seawater (Falkland, 1991; Underwood et al., 1992).

Small island countries face water problems that are among the most critical in the world (Carpenter et al., 2002). This is especially so in urban and peri-urban low coral atoll communities (Ward, 1999), on which we concentrate here. Storage of fresh water in atolls to reduce risks during dry periods is constrained by very small land areas, aquifer geology, pressures of human settlements and increasing demand, agricultural activities, and waste disposal. Frequent droughts, climate variability, and seawater inundation during storms, as well as conflicts between traditional resource rights and the demands of urbanized societies, add to the difficulties (Falkland, 2002; White et al., 1999a).

The atolls that are most vulnerable to climate variations and human impacts are densely populated low island atolls and cays that rely solely either on thin, fresh groundwater lenses for water supplies or those where rainwater is the only water source (Dawe, 2001). In both, limitations in water storage increase the risk of severe water shortages and disease outbreaks during dry times. In the past, normal climatic variability in some atoll nations has resulted in declarations of states of emergency and in the evacuation of entire island populations.

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In groundwater-dependent atolls traditional, subsistence crops, such as coconut (*Cocos nucifera*), swamp taro (*Cyrtosperma chamissonis*), breadfruit (*Artocarpus altilis*), and pandanus (*Pandanus* sp.), compete with humans for fresh water (White et al., 2002). Expanding urban atoll communities have the potential to rapidly pollute groundwaters with human and animal wastes so that water-borne diseases are often endemic. As a consequence, protection of human health is of paramount concern in small island water supply systems.

In this paper we examine the impact of ENSO-related droughts on freshwater availability and water quality in a densely populated central Pacific atoll, Tarawa, Republic of Kiribati. We also explore the impacts of human settlements on water supply and its quality. Finally, we look at strategies to protect water resources and reduce risks.

Study Location

This research was conducted on the Tarawa Atoll, in the central Pacific nation of the Republic of Kiribati. Table 1 lists some of the country's relevant attributes. Kiribati has three key features: very low-lying coral atolls predominate; its available freshwater supplies are unknown; and in its population centers, demand for water equals or exceeds supply. Tarawa Atoll (Fig. 1), the capital and population center of the Republic of Kiribati, had a population of more than 40,000 people in 2005, with population densities as high as 15,000 people km^{-2}. Most people live in South Tarawa between the islands of Betio and Buota (Fig. 1). North Tarawa is rural, with low population density. By 2010 the population of Tarawa is expected to exceed 50,000.

In South Tarawa, water supply for the reticulation system is extracted using horizontal infiltration galleries or skimming wells from freshwater lenses in groundwater reserves on Bonriki (Fig. 2) and Buota islands (Fig. 1) in the southeastern corner of the atoll. It is then reticulated along the populous South Tarawa as far as the port of Betio in the west. Infiltration galleries have been designed to have small water table drawdowns to minimize the risk of saline intrusion during pumping. Almost all households supplement that supply using dug domestic wells with water of variable quality in both salinity and in contaminants. Some also harvest rainwater to supplement supplies.

Although South Tarawa has an average annual rainfall of 2048 mm, it has a high coefficient of variability of 0.48 (Table 1) because of the influence of the migrating Pacific warm pool (Falkland and Woodroffe, 1997). It has experienced droughts as long as 43 mo. In response to the 1998–2001 drought, reverse osmosis desalination units were installed in South Tarawa. These have subsequently failed, and none are currently operating. Like many small island countries, Kiribati experiences difficulties in maintaining production from desalination plants due to intermittent power supplies, maintenance and operational costs, and lack of training. It has been estimated in Tarawa that the

TABLE 1. Summary of the key features of the Republic of Kiribati.

Property	Value
Geographic location†	1°25′ N, 173°00′ E (Tarawa)
Composition†	32 coral atolls, 1 raised coral island (Banaba)
Land area (km^2)†	811
Length of coast (km)†	1143
Length of coast/land area (km^{-1})†	1.41
Highest elevation (m above mean sea level)†	81 (Banaba)
Fraction of land elevation < 10 m above mean sea level (%)‡	99
Climate†	Tropical
Cyclones	No
Mean annual rainfall (P; mm)§	2048 (Tarawa)
Coefficient of variation of annual rainfall (%)¶	48 (Tarawa)
Annual potential evaporation (E; mm)¶	1795 (Tarawa)
Aridity ratio = E/P	0.88 (Tarawa)
Principal water sources§	Reticulated groundwater (South Tarawa) Private groundwater wells Public groundwater wells & galleries (outer islands) Private rainwater tanks Desalination# Seawater (washing, toilet flushing)
Estimated per capita demand freshwater (L capita^{-1} day^{-1})§	50 (Tarawa)
Estimated sustainable yield freshwater (L capita^{-1} day^{-1}††	50 (Tarawa reticulation system)‡‡
Agencies responsible for water supply	Public Utilities Board (South Tarawa) Ministry of Public Works and Utilities (outer islands) Households
Population†	103,092 (est. July 2005)
Population growth rate (%)†	2.25 (est. 2005)
Mean population density (cap km^{-2})	127
Environmental vulnerability index (EVI)‡	3.70
EVI ranking (out of 235 countries)§§	34/235

† CIA (2007).
‡ Pratt and Mitchell (2003).
§ Falkland (2005).
¶ Falkland and Woodroffe (1997).
# Desalination plants are currently inoperative.
†† Alam et al.(2002).
‡‡ Excludes use of private wells or rainwater tanks.
§§ Kaly et al. (2003).

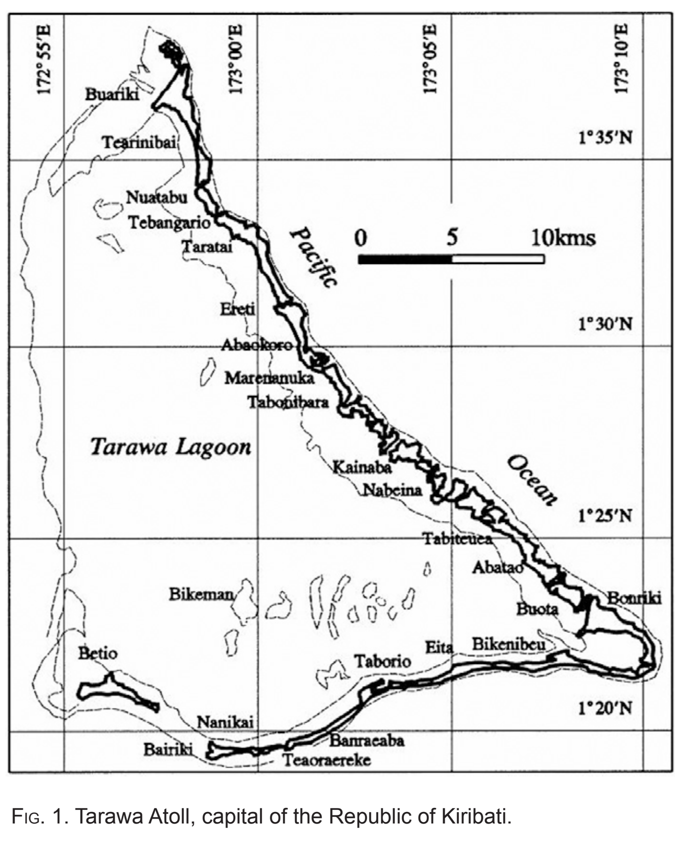

FIG. 1. Tarawa Atoll, capital of the Republic of Kiribati.

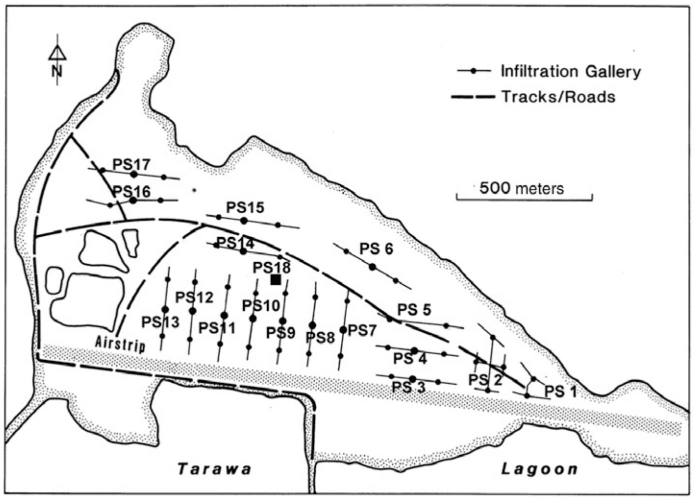

FIG. 2. Distribution of 18 horizontal infiltration gallery pumping stations (PS) in the water reserve on Bonriki Island located on the southwestern corner of Tarawa Atoll (Fig. 1).

cost of desalination is 16 times that of groundwater extraction (Metutera, 2002).

Materials and Methods

Climate Parameters

A weather station (Campbell Scientific, Logan, UT) was established in a cleared site in the middle of the Bonriki water reserve (near pumping station [PS] 18, shown in Fig. 2). The weather station measured solar radiation, wind speed, air temperature and relative humidity, and barometric pressure (Vaisala PTB 101B; Vaisala Oyi, Helsinki, Finland). Measurements were made at 1-min intervals and averaged over 15 min. The data were stored on a data logger (Campbell Scientific) and downloaded at approximately monthly intervals. Solar radiation, air temperature, wind speed, and vapor pressure deficit, calculated from the relative humidity, were used to calculate the potential evaporation.

Rainfall was measured using two 200-mm diameter tipping bucket rain gauge, and results were recorded on the data logger. Manual rain gauges, 100 mm in diameter and read daily, were positioned to estimate the contributions of coconut tree crown flow and crown interception to throughfall. Two 200-mm manual rain gauges, which were read daily, were placed alongside the tipping bucket rain gauges as backup. Calibration of the tipping bucket rain gauges against the manual gauges as well as the addition of known volumes of water, showed they recorded, on average, 94% of incident rain. Rainfall measurements at Bonriki were supplemented with the long-term rainfall record from the Betio Meteorological Office at the same elevation, but 35-km east of the Bonriki site.

Interception, Stemflow, and Tree Water Use

In addition to the paired 200-mm tipping bucket rain gauges and the 200-mm manual rain gauges in the open and under a coconut tree crown, 10 100-mm rain gauges were distributed in the open and underneath other coconut trees to assess interception losses by palm fronds. A stemflow gauge was attached to the only vertical coconut tree at the site to assess the flow of water down the stem of the tree. The stemflow gauge consisted of a U-shaped rubber channel that was wound two-and-a-half times around the tree and attached with staples and sealed with a silicone sealant. The rubber channel was led into a 25-mm diameter tube that delivered the stemflow to a sealed 20-L container. The volume of water in the rain gauges and the stemflow gauge was read daily.

Coconut tree water use was determined using two heat-pulse sap flow sensors inserted to a depth of 20 mm in the tree. The volume fraction of water in the tree trunk (0.72) was determined by sampling the tree and oven drying samples at 60°C for 2 d. Coconut trees are C_4 plants, and the entire cross-section of the trunk conducts water. The heat-pulse sensors were used to obtain the sap-flow velocity at 10-min intervals throughout the day. This data was stored in a data logger and downloaded at about monthly intervals. Sap-flow data was converted into transpiration rates using the cross-sectional area of the conductive tissue and the volume fraction water in that tissue. The coconut palm showed no wound response to the insertion of heat-pulse probes.

Soil Water Content

The soil water content was determined by gravimetric sampling to a depth of 0.55 m. In addition, a frequency domain variant of time domain reflectometry, FDR, (Topp et al. 1980; White and Zegelin, 1995) was used to monitor soil water content at 1 min intervals which were averaged over 15 min intervals. Data was stored in the weather station data logger. The FDR probes (Campbell Scientific) were 0.6-m long and were placed in two pits, one close to coconut trees, and the other in the open near the weather station. Probes were installed horizontally at soil depths of 0.15, 0.3, 0.5, and 0.7 m in the soil profile in the tree pit, while the two deeper probes were at depths of 0.45 and 0.6 m in the weather station pit.

Water Table Elevation

Water table elevations were measured using two temperature-compensated pressure transducers that were sensitive to changes in water level of 1 mm and were all measured manually, as well, to an accuracy of ± 1 mm. Pressure transducers were positioned at the bottom of the pumping well in all the infiltration galleries in Bonriki and Buota islands. An assessment of the local maximum drawdown of pumping was made by noting the change in groundwater level when the pump was switched off and then turned on again after groundwater levels had stabilized. Tests were also performed by using an additional variable-rate pump to increase pumping. The two transducers were moved to all the different pumping wells located in galleries across both islands' water reserves. The tidal record for Betio, South Tarawa, 30 km from the site, was also obtained from the National Tidal Facility (Australian Bureau of Meteorology). Tidally forced groundwater fluctuations were found in all wells, irrespective of distance from the ocean or lagoon.

Salinity Monitoring and Thickness of the Freshwater Lens

The thickness of the freshwater lens was measured using packed salinity monitoring boreholes (Falkland and Woodroffe, 1997) to determine the salinity profiles through the freshwater lens at two sites, one close to the center of the freshwater lens

(BN 16, 5 m to the east of PS7 in Fig. 2), the other close to the northern, oceanside edge of the freshwater lens (BN, 1340 m north northeast of PS18). These boreholes are specially designed to prevent the tidal mixing that occurs in open boreholes (see Fig. 3). There is no density-driven convection in these boreholes because in freshwater lenses, fresher water overlies seawater. Since the time between measurements is months and since the hydraulic conductivity of the surrounding unconsolidated coral sediments is so large (on the order of 10 m day^{-1}), the bentonite packers in the boreholes (Fig. 3) have negligible influence on measured salinity profiles. Salinity records for these sites have been available since the 1980s. The in situ electrical conductivity (EC) of water samples pumped from tubes installed at 3-m depth intervals from 6 m up to 30 m below the ground surface was measured using a field EC probe (TPS WP84; TPS, Springwood, QLD, Australia), which was calibrated with KCl solutions before measurements. The depth limit of the freshwater lens was taken as the depth at which the EC of the groundwater first exceeded 2500 μS cm^{-1}. This is generally the limit for acceptability of taste by the local communities. The EC of groundwater produced from the shallow infiltration galleries close to the water table was also monitored.

Chemistry of the Freshwater Lens and Detection of *E. Coli*

Water samples for chemical analysis were taken using clean 100-mL sample bottles from the same salinity monitoring boreholes and gallery pump stations. Samples were stored at 5°C and analyzed for Na, K, Mg, Ca, Sr, Cl, SO_4, NO_3 dissolved organic C, total dissolved N, and H_2S. Field tests for H_2S were performed using a Hach field test kit (Hach, Loveland, CO; www.hach.com). Samples for H_2S analysis were also taken by fixing samples with zinc acetate immediately at the time of collection and analyzing in the laboratory. Samples were also taken for ^{2}H and ^{18}O analyses. Saline samples were azeotropically distilled. The presence of *E. Coli* in water samples were detected using an IDEXX Colisure indicator kit (APHA and AWWA, 1998) using sterile sample bottles.

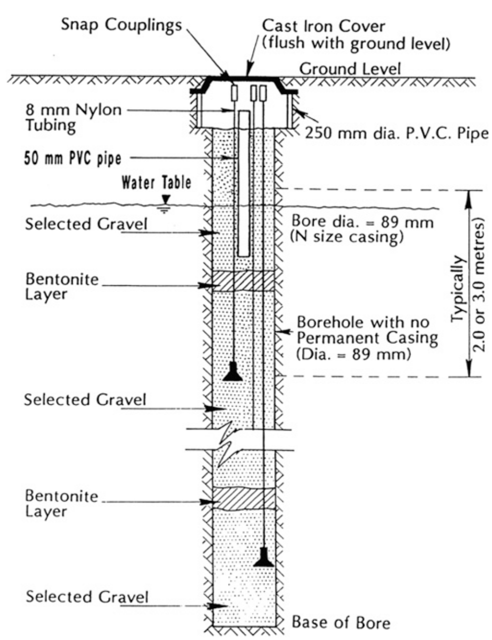

Fig. 3. Borehole for monitoring the salinity profile of the freshwater lens. Bentonite packing is used to prevent tidal mixing in the borehole.

Results

Rainfall, Droughts, and ENSO Events

Annual rainfall in Tarawa (Betio) is strongly negatively correlated with the Southern Oscillation Index, SOI (correlation coefficient −0.78). High rainfalls occur during El Niño episodes, and low rainfalls occur during La Niña episodes. This strong correlation gives rise to frequent severe droughts (approximate frequency 6–7 yr) that have major impacts on the availability of fresh water in Tarawa (Falkland, 1992; White et al., 1999b). Figure 4 shows the strong negative relationship between 12-mo running totals of rainfall at Betio (Fig. 1) and the 12-mo running total SOI. The extreme variability of rainfall and the frequent drought periods are obvious. Table 2 lists the significant recorded hydrological droughts, taken here as rainfalls, for the particular totaling period selected, that are below the 10th percentile of all recorded rainfalls for the selected totaling period. Totaling periods of 12-mo and 30-mo rainfall totals have been selected as these rainfall periods eliminate any variations due to seasonality of rainfall. These rainfall periods are relevant to the response of groundwater systems. The duration of the drought is identified as the period from when the rainfall drops below the 40th percentile, down to below the 10th percentile, to when it returns to the 40th percentile rainfall (White et al., 1999b). This provides a repeatable measure of drought.

Droughts identified using 12-mo rainfall percentiles are relevant to domestic wells in islands with thinner freshwater

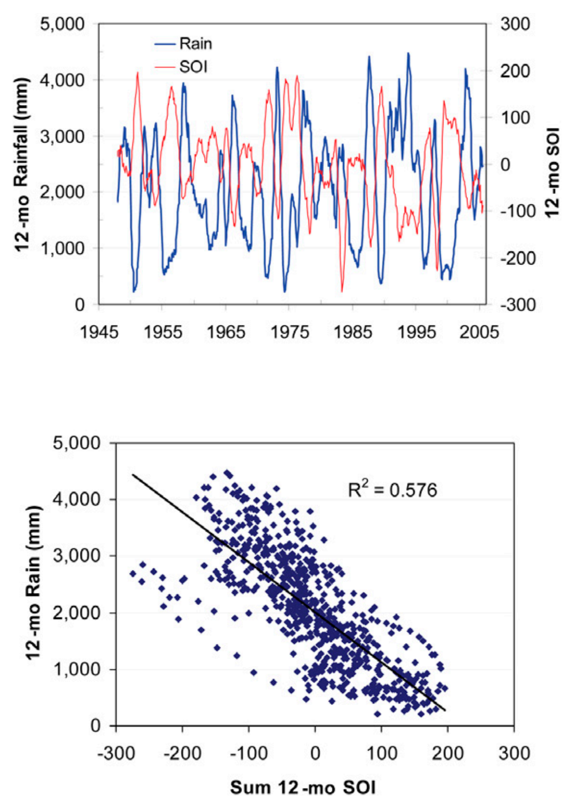

Fig. 4. Relationship between 12-mo running total rainfall and 12-mo running total Southern Oscillation Index (SOI) for Betio, Tarawa Atoll, Kiribati (Fig. 1).

TABLE 2. Significant droughts in Tarawa atoll for 12- and 30-mo rainfall totals.

12-mo rainfall				30-mo rainfall			
Start date (>40%)	End date (>40%)	Duration	Lowest percentile	Start date (>40%)	End date (>40%)	Duration	Lowest percentile
		mo				mo	
Jan. 1950	Aug. 1951	19	0.1	Aug. 1955	Feb. 1958	30	1.3
Oct. 1954	Aug. 1957	34	4.4	Mar. 1971	June 1973	27	9.5
Dec. 1970	June 1972	18	2.7	Nov. 1974	Nov. 1976	24	4.6
Dec. 1973	Apr. 1975	16	0.0	Jan. 1985	Apr. 1987	27	3.4
May 1984	Oct. 1986	29	9.1	Nov. 1998	June 2002	43	0.0
Oct. 1988	Mar. 1990	17	1.3				
Nov. 1995	Apr. 1997	17	7.6				
July 1998	Dec. 2001	41	2.0				
	Mean	24			Mean	30	

lenses, while 30-mo percentiles are more applicable to islands with thicker lenses, such as Bonriki (White et al., 1999b). While the drought from December 1973 to April 1975 registered the lowest 12-mo rainfall amounts on record, the more recent, November 1998 to June 2002, drought was the most severe for islands with larger freshwater lenses. With the definition of the start (rainfall < 40 percentile) and end of the drought (rainfall returns to > 40 percentile), the average duration of droughts (for rainfall < 10th percentile) for the 12-mo rainfall totals is 24 mo while that for 30-mo totals is 30 mo. Table 2 shows that that the 1998–2001 drought was the longest on record for both rainfall periods. During this drought, almost all rainwater tanks were exhausted, many domestic wells became saline, and saline groundwater caused the death or severe die-back of mature (40-yr-old) breadfruit trees.

Groundwater and Droughts

To a first approximation, the maximum thickness of a fresh groundwater lens, from which water is being pumped, to an assumed sharp interface between fresh and saltwater, H_p (m) is given by the steady-state expression (Volker et al., 1985)

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

where W is the width of the atoll, q the ratio of pumping rate to recharge rate, $q = (Q/A)/R$, Q/A (mm) is the annual pumping rate per unit area (A), R (mm y^{-1}) is the net annual groundwater recharge rate, $\alpha = (\rho_s - \rho_0)/\rho_0$, where ρ_s and ρ_0 are the densities (t m^{-3}) of sea and freshwater, respectively, K_0 is the hydraulic conductivity (m y^{-1}) of freshwater in the Holocene sediments in the horizontal direction, and H_u is the freshwater thickness of the unpumped groundwater lens. For Bonriki Island, the estimated mean fresh groundwater thickness in the absence of pumping is about 15 m.

Equation [1] can be used to estimate impacts of long-term drought on the thickness of the freshwater lens to an assumed sharp interface. The ratio of the freshwater lens thickness during prolonged drought, H_d, to the long-term mean freshwater thickness H_m, regardless of whether there is pumping, follows from Eq. [1]:

$$H_d = (R_d/R_m)^{1/2} H_m \quad [2]$$

where R_d and R_m are the long-term annual recharges under drought and mean conditions. If we assume that during long-term drought the long-term recharge falls from 980 (White et al., 2002) to about 200 mm year^{-1}, then Eq. [2] predicts that the thickness of the freshwater lens will be reduced to only about 50% of its long-term mean. This figure is consistent with measurements at Bonriki during the 1998–2001 drought. A 50% reduction in lens thickness suggests that the water table elevation could fall by about 400 mm from its long-term mean value during a prolonged drought. This estimate is more than predicted from the classical sharp-front Ghyben-Herzberg model because of the width of the diffuse transition zone.

A comparison of the measured water table elevation in boreholes across Bonriki at the end of the 1998–2001 drought with those in more recent, wetter times is given in Table 3. This shows that the mean water table elevation was at least 440 mm lower during the extended 1998–2001 drought than in wetter periods.

The thickness of the fresh groundwater lens also decreases during droughts. Figure 5 shows the change in depth below ground surface of the freshwater limit during wet and dry periods in the groundwater lens on Bonriki Island (Fig. 2), in a salinity borehole at the seaward edge of the island, to the 12-mo rainfall deciles. The edge of this thick freshwater lens responds

TABLE 3. Measured change in mean watertable elevation due to the 1998–2001 drought, Bonriki Island.

Measurement date	Mean water table elevation above arbitrary datum
	mm
3–4 Nov. 2001	190
27–28 Feb. 2003	630
Difference	440

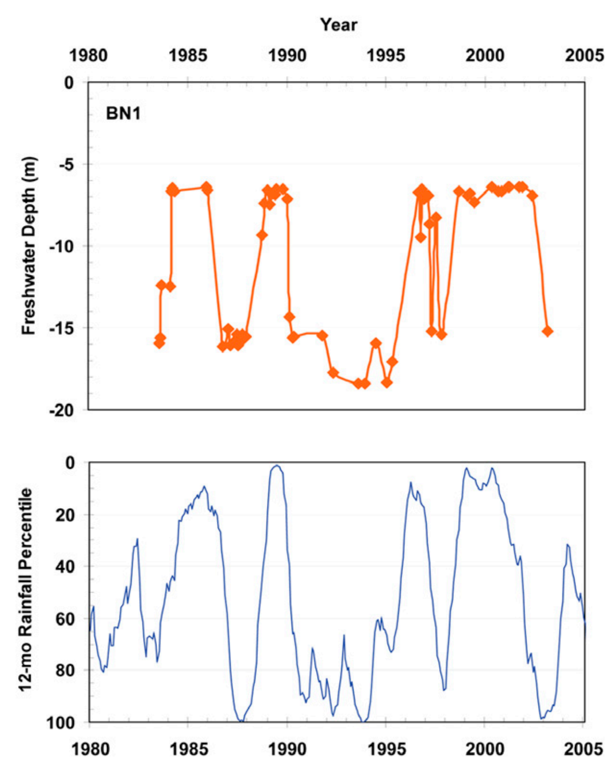

FIG. 5. Change in depth below ground surface of the freshwater–salinity transition zone for a salinity borehole (BN 1) at the northern ocean edge of Bonriki Island (Fig. 2), and its relation to 12-mo rainfall percentiles showing the effect of droughts on lens thickness.

dramatically to long dry periods. Boreholes toward the center of the island showed relatively smaller decreases in the thickness of the freshwater lens, which in the center is over 20-m thick.

As the lens thins during dry periods, the salinity of the fresh groundwater also increases. Figure 6 shows the increase in groundwater salinity (EC) of the combined groundwater pumped from both Buota and Bonriki groundwater reserves during the severe 1998–2001 drought. Even though the EC peaked at approximately 1000 μS/cm at the end of 2001, the water was still quite acceptable for domestic use. Since this was the worst drought on record for 30-mo rainfalls, this illustrates the robustness of large freshwater lenses in islands that are of widths approaching 1 km.

The impacts shown in Fig. 5 and 6 may not be from just climate alone, since groundwater is also extracted from these islands at combined rates now approaching 2100 m^3 day^{-1}, compared with the long-term sustainable rate of 1750 m^3 day^{-1}, estimated from the available climate data and both a water balance and using a three-dimensional ground water model (Alam et al., 2002). The impact of pumping on the freshwater lenses will now be considered.

Impact of Pumping on Groundwater Elevation and Thickness

Traditional landowners on islands used as groundwater sources for freshwater reticulation are concerned about the impacts of groundwater pumping on the health and productivity of traditional crops such as coconut trees and taro (White et al., 1999a). These concerns have centered on the effects of pumping on lowering unconfined water tables so that taro crops are unproductive or coconut yields are reduced. Pumping in existing fresh groundwater extraction reserves has also been blamed for the unhealthy appearance or death of coconut trees and increasingly brackish domestic wells, possibly through an increase in the salinity of the groundwater caused by pumping. Coconut trees have an unusually high requirement for chlorine (Foale, 2003) and can tolerate a moderate amount of salinity in groundwater provided the saline water table fluctuates with the tide or is sufficiently deep. While they can withstand brief exposures to seawater, however, permanent exposure to water with salinity of 2000 mg L^{-1} total dissolved solids or greater (EC above ∼3000 μS cm^{-1}) severely retards growth (Foale, 2003).

The annual water balance for a freshwater lens in a low coral atoll in which groundwater extraction by pumping is taking place is given by (Falkland, 1992):

$$R = GF + D + Q/A + \Delta S \quad [3]$$

where GF (mm) is the annual horizontal groundwater discharge to the sea and lagoon at the edge of the lens, D (mm) is the annual mixing or dispersion losses at the base of the lens, and ΔS (mm) is the annual change of freshwater volume per unit area stored in the lens (positive when recharge is greater than the losses, negative when recharge is less than the losses). The total from the lens is $GF + D$. In the long-term, ΔS is negligible and recharge equals losses:

$$R = GF + D + Q/A \quad [4]$$

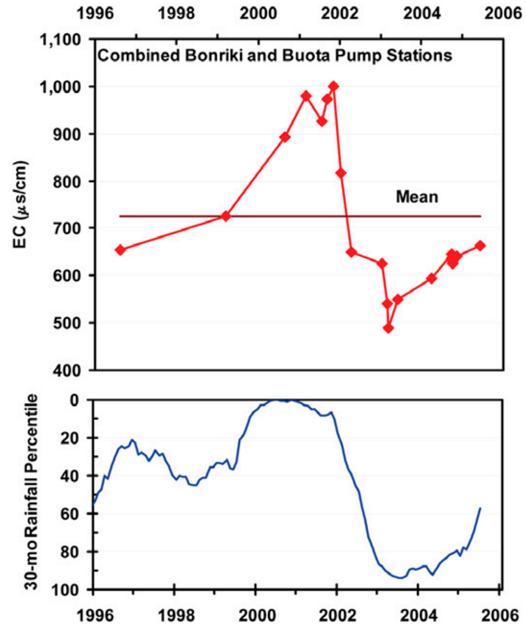

Fig. 6. Impact of the 1998–2001 drought on the groundwater salinity (electrical conductivity; EC) of combined waters pumped from the freshwater lenses in Buota and Bonriki islands (Fig. 1).

Estimated mean annual components of the water balance in Eq. [4] for Bonriki Island are given in Table 4. In Table 4, the evapotranspiration component is the water used by vegetation and lost from the soil. We have assumed here that this component is unchanged by pumping (White et al., 2002). Equation [1] suggests that the average mean groundwater thickness of the freshwater lens during pumping at the rate given in Table 4 should be about 10.9m. If h_0 is the height of the water table above mean sea level [$h_0 = H_u\alpha/(1 + \alpha)$], then during pumping, the average water table elevation should drop by about 140 mm (Table 4).

Figure 7 shows that the water table in Bonriki gallery pump stations fluctuates twice daily in concert with the tidal signal recorded at the Betio tide gauge recorder. This daily fluctuation is caused by the tidal pressure signal transmitted rapidly through the karstic Pleistocene limestone aquifer (with K_0 of order 1000–10,000 m

Table 4. Principal components of the annual water balance for Bonriki Island and the estimated impacts of groundwater pumping.

Component	Estimated depth	Estimated volume†
	mm	m^3
Mean rainfall, *P*	2,000	2.80×10^6
Mean actual evapotranspiration, ET	1,020	1.43×10^6
Mean net recharge, *R*	980	1.37×10^6
Before groundwater pumping		
Mean outflow + dispersion, *GF* + *D*	980	1.37×10^6
Mean fresh groundwater thickness	15,000	6.3×10^6‡
Mean water table height above mean sea level§	700	–
After groundwater pumping		
Sustainable pumping yield, *Q*	352	0.49×10^6¶
Mean outflow + dispersion, *GF* + *D*	628	0.88×10^6
Mean fresh groundwater thickness	12,000	5.04×10^6
Approx. mean water table height above mean sea level§	560	–
Approx. max. change in water table§	140	–

† Based on the estimated area of Bonriki island of 140 ha.
‡ Based on an estimated specific yield of 0.3.
§ At the center of the island.
¶ Based on the current estimated sustainable yield of 1350 m^3/day (Alam et al., 2002)

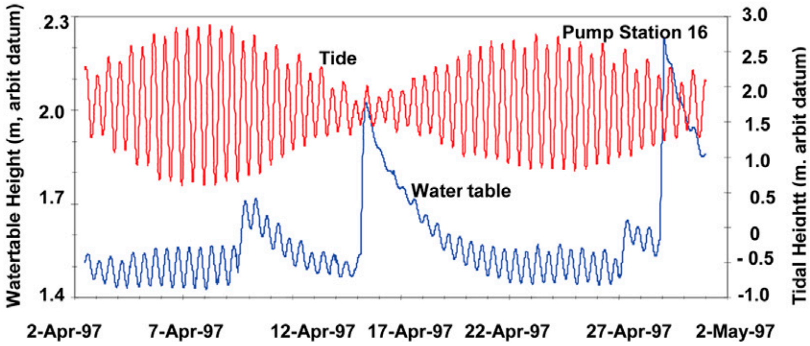

FIG. 7. Influence of the tidal cycle and rainfall on water table elevation in a Bonriki infiltration pump station (PS 16, Fig. 2).

day^{-1}) beneath the freshwater lens (Wheatcraft and Buddemeier, 1981; Oberdorfer et al., 1990) and then transmitted upward to the groundwater surface through the less-permeable Holocene coral sands. The results for the water table in the Bonriki gallery pump station PS 16 show a twice-daily change of up to 170 mm in water table elevation can be generated by the tidal cycle. In other galleries, tidal amplitudes of up to 300 mm have been measured in the water table elevation. The impacts of rainfall on water table elevation are also shown in Fig. 7 where it can be seen that rapid rises as high as 0.65 m can occur during rainfall.

Table 5 compares the magnitude of changes in the water table elevation in the Bonriki freshwater lens produced by natural processes, long-term drought, rainfall, and diurnal tidal fluctuations, with the change due to continued pumping. We conclude that the change due to pumping is smaller than changes due to natural processes and that pumping from horizontal infiltration galleries should have a negligible effect on traditional crops such as coconuts and swamp taro.

Water Table Drawdown Due to Infiltration Gallery Pumping Stations

To a first approximation, the maximum unconfined water table drawdown, δ (m), for an individual infiltration gallery pumping at a rate Q can be found by integrating Darcy's law:

$$\delta = W_G Q/(8K_0 H_{\underline{u}} L_G) \qquad [5]$$

where W_G (m) is the width of the gallery extraction zone and L_G is the length of the gallery. Typically, values for the pumping galleries in Bonriki (Fig. 2) are L_G = 300 m, W_G = 100 m, and H_u = 15 m. Hydraulic conductivities of the unconsolidated Holocene coral sediments vary between approximately 5 and 50 m day^{-1}, and individual pumping rates vary from approximately 40 to 140 m^3 day^{-1}. The estimated drawdown using these typical values in Eq. [5] is expected in the range of about 2 to 80 mm.

TABLE 5. Maximum observed changes in water table elevation at Bonriki due to natural processes compared to that estimated from pumping.

Process	Max. change in water table elevation
	mm
Natural	
Major rainfall events	650
Diurnal tidal forcing	300
Prolonged drought	440 (Table 3)
Pumping	
Est. max. decrease	140 (Table 4)

Local water table drawdown due to pumping was measured by switching pumps off and then on again, then following the change in water table elevation with a pressure transducer. Measurements were made in 17 infiltration gallery pumping stations on Bonriki (Fig. 2) and 5 on Buota (Fig. 1) A typical result of a drawdown test is shown in Fig. 8, which demonstrates that tidal fluctuations in the water table complicate the drawdown measurement. The mean pumping rate for the galleries was 88 ± 27 m^3 d^{-1}, and the mean measured drawdown was 33 ± 42 mm (median 20 mm), with a maximum measured drawdown of 200 mm and a minimum of 2 mm. This clearly indicates that groundwater pumping drawdown has an insignificant impact on traditional crops since the drawdown is less than amplitude of the diurnal tidally forced water table fluctuation.

Hydraulic Conductivity Estimation from Measured Water Table Drawdown

Equation [5] suggests that drawdown of the water table should be linearly related to pumping rate with slope $1/(8K_0H_uL_G)$. The pumping rate in several infiltration galleries on Buota and Bonriki was increased using an additional variable rate pump. Figure 9 shows that a linear relation between δ and Q for a gallery pump station on the island of Buota (Buota PS 2) explains 98.7% of the variance. Using the slope of this relation and the dimensions of the gallery gives K_0 = 8.4 m day^{-1}. Measurements of drawdown in 17 galleries on Bonriki and 5 on Buota gave a geometric mean K_0 = 14.6 m day^{-1} with minimum and maximum values of 0.9 and 111 m day^{-1}. Pump stations with lower hydraulic conductivity generally had higher salinity of pumped water.

Impacts of Land Use on Water Quality

In low coral atolls, the water table is close to the soil surface, and with the high hydraulic conductivities of the overlying coral sands as measured above, superficial contaminants are rapidly

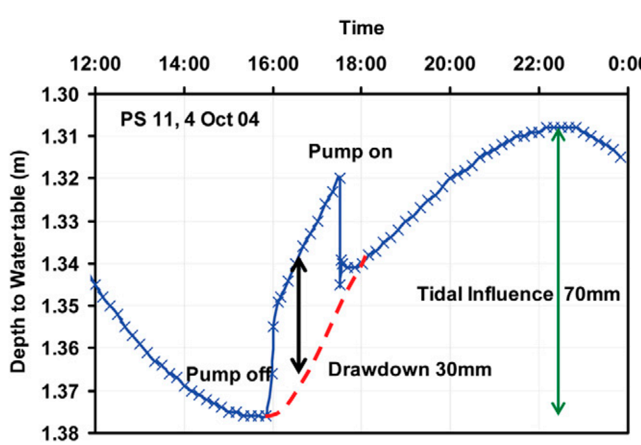

FIG. 8. Pressure transducer record of drawdown tests showing the impact of switching the pump on and off on the depth to the water table in an infiltration gallery pumping station on Bonriki Island.

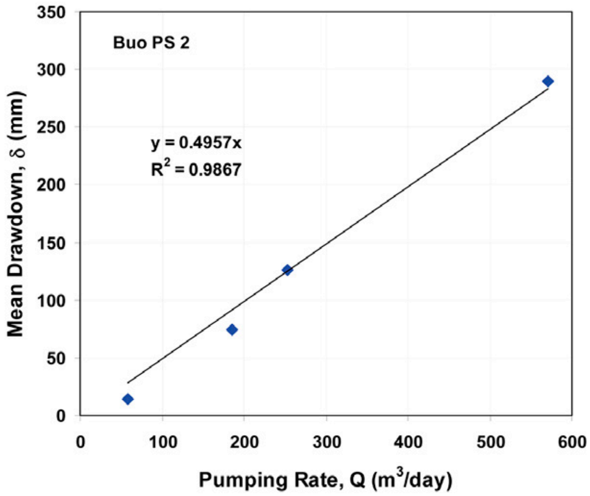

FIG. 9. Relationship between water table drawdown and pumping rate for an infiltration gallery pump station on the island of Buota (Buo PS 2).

translocated into the groundwater. Figure 10 shows the quick response of soil water at a depth of 0.7 m to heavy rainfall. Note that rainfalls up to about 25 mm are evapotranspired from the coral sands before they reach this depth.

Traditional practices in low-density populations have developed over millennia to minimize contamination risk. These include defecation on beaches downgradient from recharge areas, sweeping leaves and debris away from dwellings and domestic wells, and keeping pigs in pens on the lagoon or ocean side of islands, in groundwater discharge zones. Increasing populations are placing significant strains on natural resources and traditional practices. As a consequence, tensions have arisen between the traditional values and practices of subsistence communities and the demands of urbanized societies (White et al., 1999a; Perez et al., 2004). One important issue in urbanized atolls is the impact of animal wastes, particularly from pigs, on drinking water. In Kiribati there are an estimated 0.32 pigs per person (Saville and Manueli, 2002).

In some large coral islands that are used as groundwater sources for reticulation systems, one strategy used by governments to protect water quality has been to declare privately owned lands overlying groundwater source areas to be water reserves and to restrict land uses. Landownership and use, however, is central to existence in most island communities (Talu et al., 1979; Jones, 1997). Declaration of reserves is therefore problematic for the affected landowners, whose land uses and rights are restricted. In some cases, declarations have generated long-lasting disputes and have resulted in vandalism of water infrastructure (White et al., 1999a). A critical question raised in disputes between landowners and governments concerns the type of land uses that are acceptable in groundwater source areas. With land area severely limited, there are significant pressures to maximize land use, especially in agricultural production.

Squatters have encroached on Bonriki water reserve (Fig. 2) and have established market gardens and have pig pens on the water reserve. Water-quality testing for the presence of fecal contamination using *E. coli*, and for concentrations of dissolved organic carbon, total dissolved nitrogen, and nitrate and phosphate was performed on all infiltration gallery pump stations in Bonriki. The distribution of positive *E. coli* tests are mapped in Fig. 11. There are extensive, abandoned taro pits, squatter dwelling pig pens, a cemetery, and extensive market gardens in the vicinity of the positive galleries showing the presence of *E. coli*. Similar results were found for the other nutrients tested. Ratios of carbon to nitrogen in Bonriki groundwater indicated the presence of both microorganisms and added nitrogen.

Conclusions

We have shown here that groundwater in small low atolls is vulnerable to both climate and human impacts. In the central Pacific, the strong correlation between rainfall and ENSO events results in frequent, severe droughts that can last as long as 43 mo. During these severe droughts, rainwater tanks are quickly exhausted, and many domestic wells tapping into thin fresh groundwater lenses in smaller islands become saline. We have shown here that the water table elevation of larger lenses in wider islands falls during droughts and that the thickness of the lenses decreases. Provided pumping rates are maintained at a sustainable rate, larger freshwater lenses can survive through extended droughts with only moderate increases in groundwater salinity.

Traditional owners of islands used as fresh groundwater sources for reticulation systems believe that groundwater pumping decreases the productivity of their subsistence crops such as

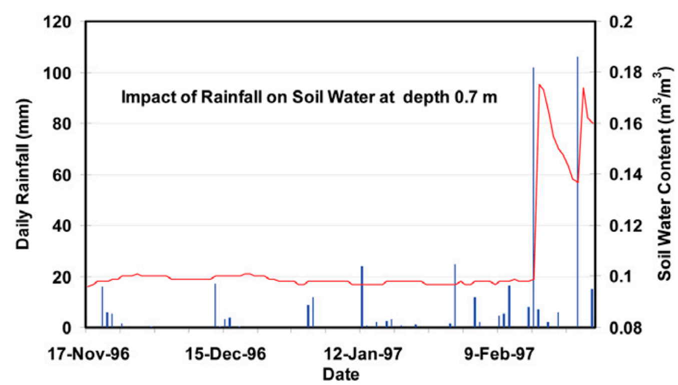

FIG. 10. Impact of rain on the mean daily soil water content at a depth of 0.7 m. Daily rainfalls of 25 mm or less have negligible influence on soil water content at this depth.

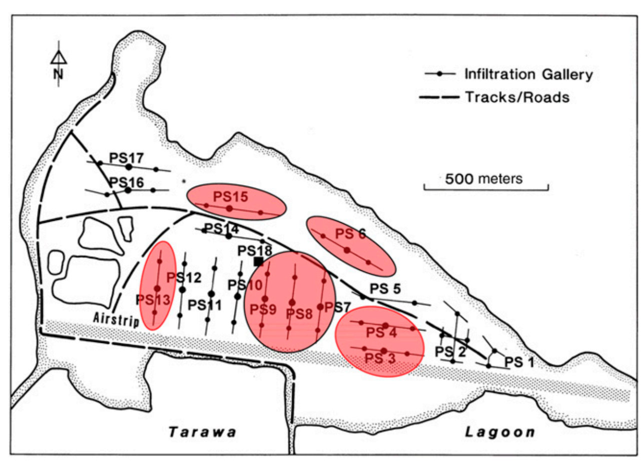

FIG. 11. Distribution of positive *E. coli* water samples from pumping galleries on Bonriki.

coconuts and taro by lowering the water table and increasing groundwater salinity. In some low-lying islands, infiltration galleries or skimming wells have been installed to minimize water table drawdown and upconing of underlying seawater. Here we used an approximate steady-state analysis and the groundwater balance to show that the drawdown due to pumping is less than the tidally induced diurnal fluctuations of the water table and less than the lowering of the water table during major droughts. We have also measured the local drawdown by galleries situated on two islands used to provide potable water for the densely populated southern part of Tarawa Atoll and found that the median drawdown of the generally 300-m-long galleries was 20 mm, which is much lower than the amplitude of the diurnal tidal fluctuation. We have also used these drawdowns to estimate the hydraulic conductivity of the Holocene coral sand aquifers of both islands and found a geometric mean value of 14.6 m day^{-1} with a range from 0.9 to 111 m day^{-1}. These values are consistent with other estimates for other atolls (Wheatcraft and Buddemeier, 1981; Oberdorfer et al., 1990; Underwood et al., 1992). Water pumped from galleries in regions with lower hydraulic conductivity tended to have higher salinities.

The large hydraulic conductivities of the coral sands mean that large rainfalls and any surface contaminants are rapidly transported through the soil to groundwater, as shown here. This means that many activities, particularly in densely populated islands, have the potential to pollute the groundwater. The keeping of pigs and market gardening pose particular problems in terms of fecal contamination of groundwater, and evidence has been presented here for that type of pollution, even in groundwater reserves. This make the identification of acceptable practices over groundwater sources a priority.

Adaptation Strategies to Decrease Risk and Increase Resilience

Locations, such as Tarawa Atoll studied here, where demand for safe water matches or exceeds available reticulated water supplies, are very vulnerable to climate variations and increasing population pressures. Available adaptation strategies for reducing risks and increasing resilience are limited, but a key factor is the provision of appropriate knowledge. On many small islands, meteorological services and water supply agencies are under-resourced, and their ability to predict water-related extreme events is limited. The actual amount of water that is available for use and its quality are largely unknown, particularly on outer islands. Monitoring and analysis are also at best sporadic. As well, there has been a general reluctance to announce national water policies, enact national water legislation, define rights and responsibilities, adopt whole-of-government approaches, and involve communities in planning and managing water and related land resources.

Proposed adaptation strategies for small islands can be grouped under three main themes: (i) capacity strengthening, (ii) demand management and refurbishment, and (iii) protection and supplementation of freshwater resources (Falkland, 2005). Within these themes, at least 10 strategies could help increase the resilience of small island communities to water–related climate and human changes (White, 2005):

- Establish a sound institutional basis for the management of water and sanitation (policy, regulations, incentives, plans, institutions and organizational reform and assignment of responsibilities).
- Improve community participation in water and related land management and planning and reduce conflicts.
- Increase capacity to manage water and sanitation at the household and community levels.
- Increase capacity to analyze and predict water-related extreme events.
- Improve knowledge of available water resources, their quality and demand for them.
- Improve water conservation and demand management strategies and reduce leakages.
- Increase household and communal rainwater harvesting and storage.
- Protect groundwater source areas from contamination.
- Improve sanitation systems to minimize water use and pollution.

Aid programs tend to focus on international priorities, and most are short-term. The sorts of programs needed in many small island states require regional solutions, local engagement, and long-term partnerships. Above all, the elucidation and sharing of appropriate knowledge is essential. In the sharing of knowledge, lengthy written reports are little used by island people whose traditional forms of knowledge transfer are oral.

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