Chapter 12
Atoll Groundwater Resources at Risk: Combining Field Observations and Model Simulations of Saline Intrusion Following Storm-Generated Sea Flooding

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Abstract The restricted nature of naturally-occurring freshwater resources on atolls is one of the greatest impediments to human settlement on these small, dispersed and remote islands. Any anthropogenic or environmental pressures that deleteriously affect the quantity or quality of atoll water resources are therefore a matter of concern. This chapter focuses on such issues. It first presents an overview of the principal characteristics of atoll fresh groundwater aquifers, which exist in the form of thin lenses within the Holocene sands and gravels that comprise the sedimentary substrate of low-lying atoll islets. Factors that influence the vulnerability of these freshwater lenses are then considered. The chapter continues by summarising the findings of recent studies that investigated the effects of storm-wave washover across atoll islets on freshwater lens profiles, and the subsequent patterns of recovery over time. Both field and modelling approaches are used. Combined results suggest that following groundwater salinisation by seawater intrusion, at least a year is required for full aquifer recovery. Of particular interest, it is found that in spite of a strong saline plume forming at relatively shallow depths, a thin horizon of freshwater sometimes remains preserved deeper within the aquifer profile for several months after the initial disturbance. In the Pacific basin, shifting geographical patterns in severe tropical storm events related to climatic variability and change are a threat to the continuing viability of atoll fresh groundwater resources and the human populations dependent upon them.

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12.1 Introduction

The atoll islets of the Pacific Ocean are some of the most difficult environments for permanent settlement on Earth. The limited land areas of atoll islets and their low elevation above sea level, their infertile and porous soils, natural rainfall variability, small groundwater resources, and periodic cyclones and drought, all pose significant impediments. This paper focuses on arguably the most severe environmental constraint of all for human habitation – the lack of freshwater. Its aims are threefold. The first aim is to offer an introductory overview of the nature and characteristics of the only significant freshwater resources on atolls: shallow groundwater aquifers that exist in the form of thin freshwater lenses. The second aim is to highlight the influences on vulnerability and principal threats to atoll groundwater resources, which involve a range of both natural and anthropogenic pressures. The third and final aim is to provide a synopsis of recent atoll groundwater investigations by the authors. These encompass both field observations on Pukapuka Atoll in the Northern Cook Islands and mathematical modelling studies. The work examines in particular saline intrusion caused to atoll freshwater lenses by wave-washover events driven by tropical cyclones. Effects on groundwater salinity profiles are illustrated, followed by an account of subsequent recovery over time, where this occurs. The results of these separate studies have recently been reported elsewhere (Terry and Falkland 2010; Chui and Terry 2012), but the key findings are drawn together here in order that a coherent picture can emerge regarding the continuing long-term viability of atoll groundwater resources. The outlook is discussed in the face of possibly changing geographical patterns in severe tropical storm events related to current climate variability and longer term climate change.

12.1.1 Harsh Environments, Hardy People

The remote atoll islets that are dispersed widely throughout the warm waters of Pacific tropical belt can be appreciated as amongst the world's most impressive landforms (Nunn 2010). These living rings of coral reef are entirely zoogeomorphic constructions, sometimes stretching for hundreds of kilometres in length to encircle shallow central lagoons. Their existence is owed to successive generations of hermatypic coral colonies, continually growing upward to keep pace with sea level over many millennia while the extinct volcanoes on which they are anchored slowly subside and become deeply submerged beneath the ocean surface (Darwin 1842). Most of the world's atoll islets are found in a broad sweep between the tropical latitudes of the Pacific Ocean, across the territories of Micronesia and Polynesia (mainly Federated States of Micronesia, The Marshall Islands, Kiribati, Tuvalu, Tokelau, Cook Islands and French Polynesia).

Commonly seen dotting the surface of these Pleistocene-age carbonate platforms are low-lying islets[1] that are known as *motu* by the indigenous Polynesian peoples of the Pacific. These islets probably began forming in the late-Holocene period, when global eustatic sea levels dropped to their present levels from slightly higher levels about 3,000 years ago. Islets are therefore formed of Holocene and recent deposits of calcareous sands and gravels that are produced by wave action on the atoll reefs and wash up to accumulate above the reach of high tide. Individual islets that are separated by surge channels may occasionally be small and elliptical in shape, but often they are narrow and elongate features that follow along the top of the reef for hundreds of meters to many kilometres (Fig. 12.1). The surge channels allow the free circulation of ocean water with the enclosed marine lagoon.

The natural environment of atoll islets is deceptively attractive. To the outsider, at first glance atolls appear exotic and tranquil, enjoying benevolent climates and bestowed with idyllic settings of white sandy shores that are fringed by coconut palms and washed by clear tropical seas teeming with marine life. Yet, in spite of the undeniable physical beauty of atolls, life on these remote islets is precarious and unforgiving (Terry and Thaman 2008). There is little land available for cultivation, and soils formed on the coralline sands are impoverished in nutrients. Only a limited terrestrial biodiversity can therefore be supported (Thaman 2008). Excessive porosity also means that the infertile soils are not able to retain sufficient moisture for many crops. Agricultural productivity is seriously constrained to the extent that eking out a sustainable living is extremely difficult. Nevertheless, it is true to say that Pacific Islanders inhabiting atoll islets are hardy and resourceful people. It is certainly astonishing to consider that they have endured for thousands of years on their isolated and harsh island homes in the face of these major environmental challenges.

12.1.2 The Nature of Atoll Groundwater Resources

A fundamental requirement for any human settlement on Pacific Islands is a supply of freshwater (Depledge and Terry, in press). In consequence, it is the restricted nature of freshwater resources on Pacific atoll islets that is arguably the greatest hindrance for permanent human habitation upon them. Since the permeable coral sands and gravels that form the substrate of the islets are readily infiltrated, rainfall and throughfall under vegetation canopies quickly disappears underground. Surface

[1] Some ambiguity arises with regard to the term 'island' in the context of atolls. To avoid confusion, here 'atoll' is reserved for the entire atoll configuration (i.e. coral reefs dotted with low sandy islands and encircling a central lagoon), whereas 'islet' is used to describe only the low-lying land above sea level. Islets may occur as either a few or more numerous individual small islands on top of the reef and may lie tens of kilometres apart on opposite sides of the lagoon. In some cases, the islets may be nearly continuous around the lagoon's perimeter, while in others they may only occur on parts of the perimeter.

Fig. 12.1 *Upper*: Aerial view of part of Majuro Atoll showing the oceanside reef, the inhabited area, and lagoon (Photo courtesy of R. Thaman). *Lower*: Hand-dug well, Pukapuka Atoll

freshwater bodies such as ponds, streams and lakes that are found on larger volcanic islands in the Pacific are therefore almost entirely absent on atolls. Additionally, the high permeability and small surface areas of islets mean that runoff collection is limited to rainwater harvesting from artificial catchments and constructed surface storages such as rainwater tanks which have relatively small capacities (Falkland 2002).

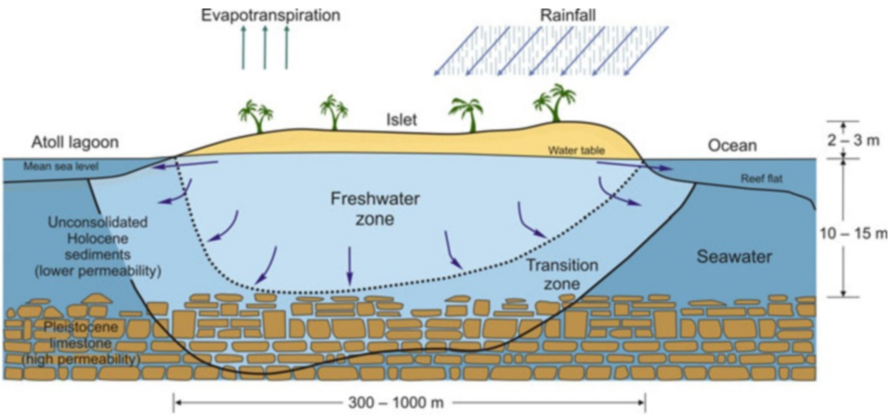

Fig. 12.2 Illustration of a freshwater lens within the substrate of an individual atoll islet (adapted from White and Falkland 2010). Cautionary note: the diagram is highly exaggerated in the *vertical* scale (relative to the *horizontal* scale). This gives an impression of a thick fresh groundwater profile, which is not common on coral islets

Consequently, the only natural potable freshwater resource on atoll islets occurs in the form of thin 'lenses' of fresh groundwater that occur beneath the surface of the larger islets (i.e. those wider than about 300–400 m). Many atoll dwellers are entirely dependent upon these freshwater lenses (FWLs) for drinking water and domestic uses and therefore strive to use available water as efficiently as possible (Nakada et al. 2012). Water is often drawn from simple hand-dug wells (Fig. 12.1) that reach the groundwater table at shallow depths. The close dependency of islanders on these meagre resources means that any short-term intrusion or gradual longer term deterioration in the quality of freshwater lenses can have serious consequences for the continuing viability of atoll settlement.

The stratigraphy of atoll islets is unique. Their fabric comprises unconsolidated coral sands normally approaching 10 to 15 m in thickness, overlying lithified and partly karstified reef limestone. Typical of atoll islets, the surface elevation of the loose sediments normally rise to just 2 to 3 m above mean sea level. Freshwater lenses are able to develop by rainwater infiltration into, and temporary retention within, the carbonate formation. Consequently, FWLs exist as unconfined aquifers that are contained mainly within the Holocene carbonate sands and gravels occasionally, in the case of thick freshwater lenses, within the Pleistocene reef limestone (Fig. 12.2). Owing to this configuration, atoll aquifers are described as 'dual aquifer' systems in hydrogeological terms (Ayers and Vacher 1986), in particular since the surficial sands are characterised by relatively lower permeability compared to the older reef limestone below.

Once the percolating rainwater recharges the aquifer, the groundwater moves gradually downwards and outwards through the permeable substrate. The groundwater mainly moves in a vertical direction and mixes with saline water at the base of the FWL. Near the coastal margin of the islet, some groundwater discharges to the sea. In the longer term, the total loss of groundwater through mixing and outflow at the margins is balanced with the recharge from rainfall on the islet (see below).

The average saturated hydraulic conductivity of the Holocene carbonate sands and gravels is estimated to be approximately 10 m/day according to observations on a number of atoll islets, for instance on Tarawa and Kiritimati atolls in Kiribati and South Keeling atoll in the Cocos (Keeling) Islands where conductivities have been measured using borehole falling head tests (Falkland 1994; Falkland and Woodroffe 1997; Woodroffe and Falkland 1997; White et al. 2007b). In contrast, the saturated hydraulic conductivity of Pleistocene limestone beneath is considerably greater, typically greater than 1,000 m/day (Oberdorfer et al. 1990) owing to karstification and diagenetic change during past episodes of emergence above sea level (Underwood et al. 1992).

The base of the FWL is not a sharp interface between freshwater and seawater, but rather a broad transitional zone of brackish water, where salinity gradually increases over several metres as the freshwater lens grades into seawater. On many small coral islets, the transition zone may actually be thicker than the freshwater zone above (Falkland 1994). Within the transition zone, both dispersion and outflow occurs mostly in a vertical rather than a horizontal direction (Underwood et al. 1992). Figure 12.2 illustrates a typical cross section through a small coral islet. One observation is the frequently asymmetrical feature of the FWL shape, with the thickest section often displaced towards the lagoon rather than the ocean side of the islet (Falkland 1994). In some cases, where the prevailing wind and wave direction is from the lagoon side, the FWL can be thicker on the ocean side of the islet.

Owing to density differences between freshwater and seawater, FWLs occur above denser seawater (Fig. 12.2). As such, the small average height of the groundwater table (upper surface of a FWL) above sea level varies between islets according to ground elevation, geology, nature of the sediments, and the shape and width of individual coral islets. Over a diurnal tidal cycle, the position of the water table moves up and down in response to the tidal signal but with a reduced amplitude and a lag typically varying between one and three hours. The efficiency of tidal propagation through the coral substrate varies between about 5 and 50 %, primarily depending on the grain–size of the sediments. Ponding of the groundwater at the surface can occur during excessively wet periods in areas where the FWL is close to the land surface, especially during high tides. Over the longer term and for average conditions, the classical Ghyben-Herzberg theory (Badon-Ghyben 1888; Herzberg 1901), which is based on a sharp interface between freshwater and seawater, states that the thickness of the FWL is directly related to the elevation of the water table above sea level; thus for every unit height of freshwater rising above mean sea level, there are approximately 40 equal units of freshwater below sea level. However, due to freshwater and seawater mixing at the base of the FWL causing a transition zone to form, the 1:40 ratio is not an appropriate method of determining the base of the FWL. The ratio may be used as a guide to estimate the mid-point of the transition zone (Falkland 1994). Accurate determination of the thickness and extent of a FWL is best provided through drilling and water sampling from

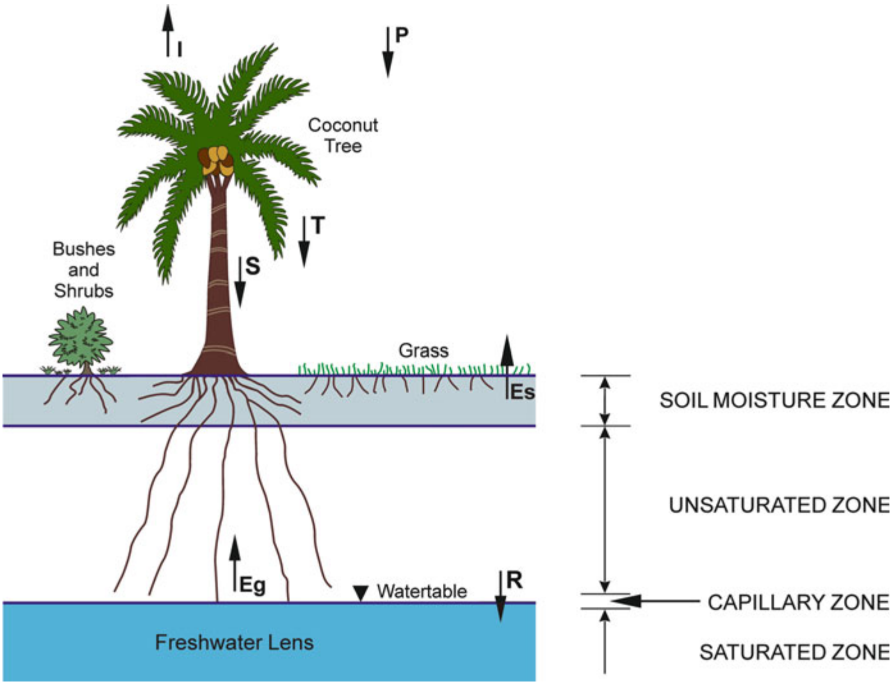

Fig. 12.3 Conceptual water balance model, under a vegetation canopy, illustrating the components that determine the amount of atoll freshwater lens recharge (Adapted from Falkland and Brunel (1993))

monitoring boreholes, although surface electrical resistivity and electromagnetic measurements techniques also provide reasonably good estimates (Anthony 1992).

Overall, the location, volume and quality of FWLs is determined by the size and shape of individual islets, the permeability and porosity characteristics of the soils and substrate, recharge through rainfall infiltration, the type and distribution of vegetation (Anthony 1992; Falkland 1994; White et al. 2002, 2007b; Bailey et al. 2009). For illustration, on Majuro Atoll in the Marshall Islands, the most extensive and best developed FWL has been measured in the west of the atoll at Laura where the area of the FWL approaches 0.9 km^2 (Hamlin and Anthony 1987).

The location, volume and quality of a FWL influences the type and distribution of atoll islet vegetation, as well as the location of village wells and taro pits used for cultivation. Some deep-rooted species among the native vegetation on atoll islets, particularly coconut trees, have evolved to use the shallow groundwater directly to supply most of their water demand (Falkland and Brunel 1993). These species are known as phreatophytes. Recharge to a FWL is equal to the precipitation, which occurs mainly as rainfall, minus evapotranspiration losses as shown in Fig. 12.3. The groundwater recharge model in Fig. 12.3 shows how the magnitude of recharge (R) in a given time period depends on the rainfall (P) and three evapotranspiration (ET) components (I, Es and Eg). The first ET component, I, is the rainfall that is intercepted by vegetation and which is subsequently evaporated. The remaining rainfall falling on trees becomes either throughfall (T) or stemflow (S). The second ET component (Es) is the evapotranspiration from the soil zone by shallow rooted grasses and plants and the shallow roots of trees. The third ET component (Eg) is the transpiration occurring directly from the FWL through the deep roots of coconut and other trees (phreatophytes). Coconut trees (*Cocos nucifera*) are known to transpire large quantities directly from the water table. Measurements by White et al. (2002) on mature coconut trees at Bonriki islet on Tarawa Atoll in Kiribati indicate that a single tree may transpire between 60 and 150 L of groundwater daily with a mean of about 120 L per day. The same study estimated that groundwater recharge (102 mm) was only 17 % of rainfall (603 mm) over a 6-month monitoring period when the rainfall was significantly below average. The average annual rainfall for Tarawa is approximately 2,000 mm and it has since been estimated that the long-term recharge for Bonriki islet is approximately 980 mm or nearly 50 % of rainfall (White et al. 2007b). On Majuro Atoll in the Marshall Islands, the annual evapotranspiration loss at Laura has been estimated by Hamlin and Anthony (1987) to be about 50 % of rainfall. Average annual rainfall is approximately 3,300 mm, so recharge of the freshwater lens at Laura can be estimated at roughly 1,650 mm per year. However, the exploitable groundwater resources (or sustainable groundwater yield) may be as low as 20 % of the mean annual recharge to the lenses (Anthony 1991).

A relatively common feature of atoll islet geomorphology that is important to mention is the low-lying depressions that often occur in the central area of larger islets (Rankey 2011). If the base of these interior topographic depressions reaches the water table, they become freshwater swamps that are effectively ‘windows’ onto the FWL. This makes them valuable sites for local people to cultivate staple food crops, especially the common taro (*Colocasia esculenta*), giant taro (*Alocasia macrorrhiza*) and giant swamp taro (*Cyrtosperma chamissonis*) (Thaman 2008; Fig. 12.4). Throughout the Pacific atolls, low-elevation depressions on islets containing freshwater swamps that are used for growing food are therefore known as ‘taro pits’ (Manner 2011).

12.1.3 Atoll Groundwater Vulnerability to Physical and Human Disturbance

Freshwater lenses on atoll islets are uniquely fragile types of aquifers, yet their existence is essential for maintaining the natural flora and fauna of atoll ecosystems and for sustaining human settlement. Unfortunately, the fragility of FWLs render them highly vulnerable to a range of human and natural disturbances (White et al. 2007a). Relatively large settlements on some atolls may cause water demand to exceed the local resources. On Tarawa Atoll in Kiribati, the small islet of Betio with an area of just 0.8 km^2 lies in the south west of the atoll. Inward migration from

Fig. 12.4 Cultivation of giant swamp taro (*Cyrtosperma chamissonis*) in a taro pit on Butaritari Atoll, Kiribati (Photo courtesy of R. Thaman)

outlying islands over recent decades and steady population growth means that Betio now has a population density in the region of 15,000 people per km^2. As a result, the local FWL lens is insufficient to meet demands (Depledge and Terry, in press), so water must be piped from larger aquifers on Bonriki and Buota, although these islets lie more than 30 km away in the south east of Tarawa (White et al. 2002). Similarly, tiny Ebeye islet (0.36 km^2) on Kwajalein Atoll in the Marshall Islands has a population density exceeding 40,000 people per km^2. Such horrendous overcrowding poses major challenges for public health, food security and water supply, which are under severe stress (Weir and Virani 2011).

Anthropogenic degradation of atoll FWLs can occur in a number of forms. At the base of a lens, saline intrusion may be caused by excessive groundwater pumping with inappropriate extraction methods (Diaz Arenas and Falkland 1991). Conventional groundwater extraction technology uses vertical bores or wells, but if these are over-pumped, upconing of seawater into the base of the lens can result. Nowadays, shallow horizontal infiltration galleries are recommended as a more appropriate extraction method, whereby freshwater can be ‘skimmed’ from the FWL surface, leading to greater yet sustainable yields compared to older vertical bore or well installations. Other types of FWL contamination can result from faecal contamination owing to a lack of adequate sanitation and effluent disposal, leading to levels of faecal coliform bacteria in groundwater (especially *Escherichia coli*) exceeding WHO guidelines for safe human consumption (Dillon 1997), while the use of crop pesticides and fertilizers must be carefully controlled to avoid groundwater contamination.

The continuing viability of atoll FWLs also faces further perils from episodic natural climatic perturbations and (human-induced) threats associated with climatic and environmental change on longer timescales. Undeniably, any erosion of the physical substance of coral islets will also lead to a concomitant reduction in the size of the FWL contained within. For those atolls that lie in the tropical cyclone belts, such erosion may occur during the occasional passage of these intense weather systems, where considerable shoreline readjustment may be produced by powerful wave action. Regarding coral islet water balance, the dynamics of hydrological recharge means that FWLs are especially sensitive to disturbances in regular climatic patterns. For example, conditions of moisture deficit may occur during dry seasons that deliver less rainfall than normal. Accentuated dry spells may similarly result from shifts in the usual precipitation patterns across the Pacific, particularly driven by El Niño and La Niña events (White et al. 1999, 2007b; van der Velde et al. 2006). During extended droughts, 'negative' lens recharge occurs, reflecting that rainfall is insufficient to match evapotranspiration losses and hence acts to diminish the FWL volume (Falkland 2002) beyond that occurring due to mixing with underlying seawater and outflow from the lens perimeter (White et al. 1999). A depleted FWL may take over a year and a half to recover according to work by Bailey et al. (2009).

Wave overtopping of low coral islets by high waves and accompanying storm surge during cyclones is a further menace. During heavy storms, large waves coupled with strong winds may affect both the ocean and lagoon shores of atolls. The accompanying storm surge is the temporary sea-level rise experienced during cyclones, produced by the combination of low atmospheric pressure near a storm centre and forceful winds pushing seawater up against a shoreline (Terry 2007). The closer a cyclone track moves towards a coastline, the more probable it is for high waves to roll across the reef flat and inundate atoll islets. Even when the path of a cyclone does not directly traverse an atoll, if the timing of the closest proximity coincides with high tide and wind direction is onshore (Fig. 12.5), then seawater rushing up against a coastline allows wind-driven waves to partially or totally submerge the low-lying islets. Subsequent seawater infiltration into the ground causes salinisation of the aquifer.

12.2 Groundwater Observations in the Northern Cook Islands (A Case Study of Storm-Induced Salinisation and Recovery)

12.2.1 Introduction

In order to demonstrate the effects on atoll islet FWLs of sea flooding caused by storm waves and storm-surge washover, the goal of this section is to describe the impacts on the groundwater of Pukapuka Atoll in the Northern Cook Islands following Tropical Cyclone Percy in February–March 2005. Although the storm did not actually make landfall on the atoll, it passed close by and was the strongest

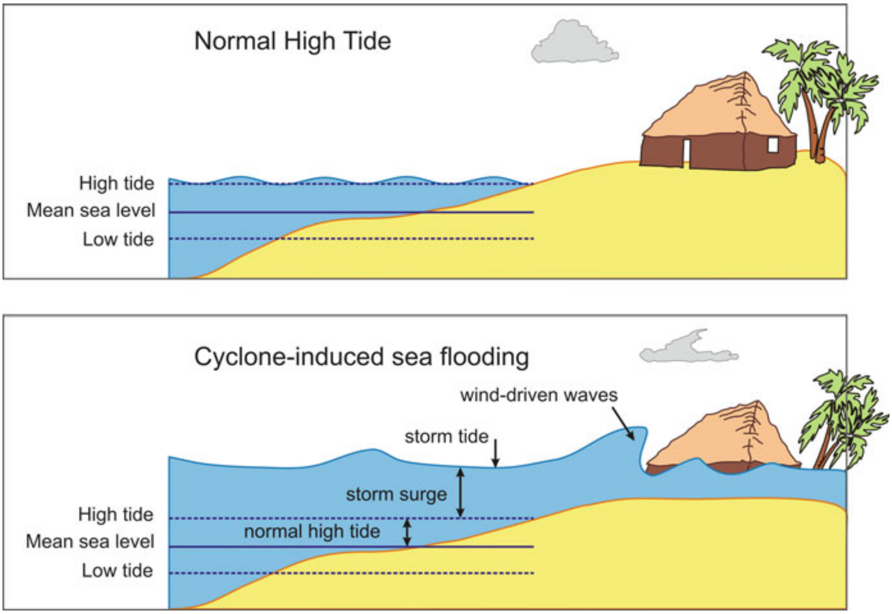

Fig. 12.5 Sea flooding of an atoll islet caused by the combination of wind-driven waves and storm surge at the time of high tide (Adapted from the Australian Bureau of Meteorology (BoM 2005))

storm to affect Pukapuka in recent decades. FWL salinity increases were measured shortly after the cyclone struck and the subsequent timescale of the lens recovery was monitored.

Pukapuka Atoll (10.85°S, 165.83°W) is a remote atoll in the Northern Cooks group (Fig. 12.6) lying more than 1,000 km northwest of Rarotonga, the capital of the Cook Islands. Pukapuka's reef platform is triangular in plan and upon it lie three small coral islets named Wale, Motu Ko and Motu Kotawa, with one islet at each apex of the triangular reef outline. The total land area of Pukapuka totals just 3.8 km^2, although the atoll supports a population of about 640 people, most of which lives in three villages on Wale. The islets comprise Holocene-age sands and gravels, the thickness of which ranges from 7 to 12 m, although the topography rises to only 2 m or so above sea level. The location experiences a diurnal microtidal environment, with mean and spring tidal ranges of only 0.31 and 0.37 m respectively (NOAA 2008). Freshwater for consumption is obtained from rainwater tanks and a limited number of shallow wells that access the water table, while giant swamp taro (*Cyrtosperma chamissonis*) is grown as the main subsistence starch crop in the freshwater swamps occupying the low-lying topographic depressions towards the centre of all three islets. A tropical marine climate prevails, with an annual rainfall averaging 2,845 mm, of which 63 % falls in the 6-month wetter season between October and March. In these same months, 9–10 tropical cyclones normally form over the warm waters of the west and central tropical South Pacific Ocean, but of these only 4–6 cyclones per decade enter Cook Islands waters.

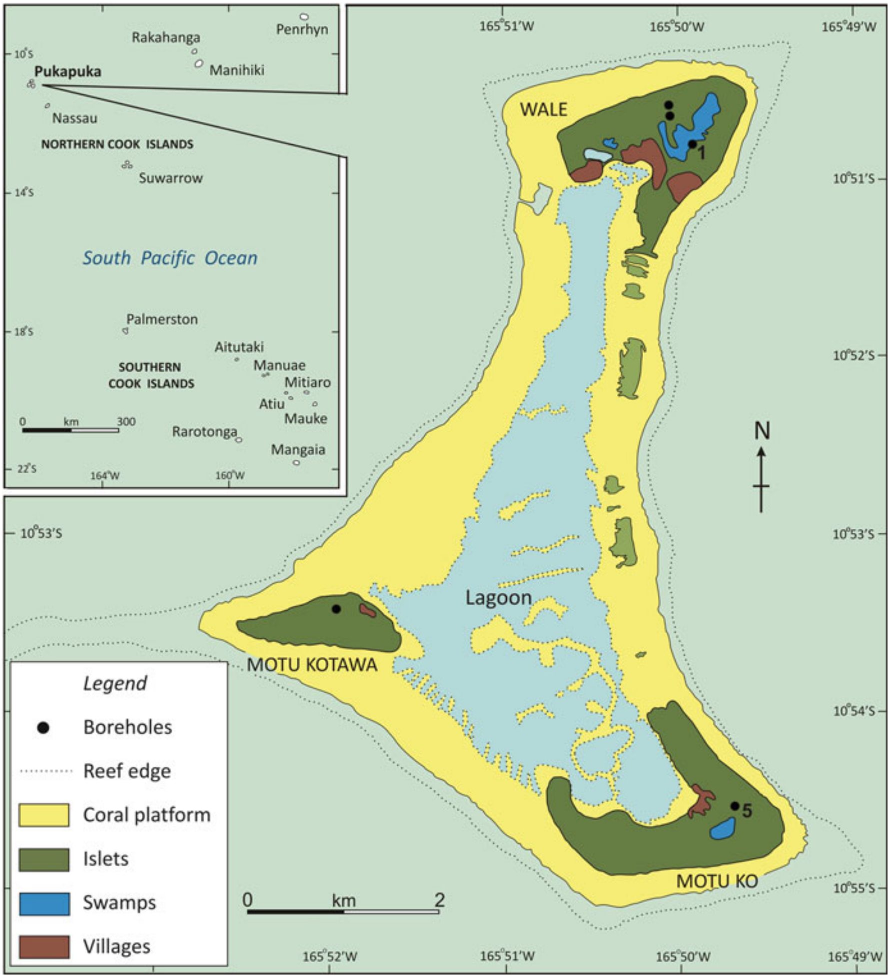

Fig. 12.6 Location and geography of Pukapuka Atoll, showing also sites of groundwater monitoring boreholes on the three islets

12.2.2 *Baseline Freshwater Lens Characteristics*

As part of groundwater resources assessments carried out on Pukapuka in February 2004, funded by the Cook Islands government, surveys of groundwater level and salinity in wells, ponds and swamps, and electromagnetic (EM) surveys were conducted. Full details are given in Falkland (2005). The maximum amplitude of the groundwater signal influenced by tides is approximately 0.09 m. The tidal efficiency TE (groundwater-to-sea-level amplitude ratio) is therefore approximately 0.30, which is a moderately high value indicating the relatively high permeability of the coral sediments. The assessment also included the installation

Table 12.1 Baseline FWL characteristics in two locations on Pukapuka Atoll prior to cyclone disturbance in January 2005

Borehole No.	Islet	Depth[a] to Pleistocene-Holocene unconformity (m)	Av. depth[a] to top of FWL (m)	Av. depth[a] to base of FWL (m)	Estimated FWL thickness (m)
Borehole 1	Wale	10.1	1.85	7.0	6.1
Borehole 5	Motu Ko	7.2	1.95	12.1	10.1

[a]Measured as the depth below ground level.

of five multi-level monitoring boreholes on the FWLs (Fig. 12.6). Boreholes were 89 mm in diameter, drilled to depths of 10–22 m, and installed with 8 mm nylon monitoring tubes to different depths. The base of each tube was fitted with a glass filter to prevent ingress of sand and the top of each tube was fitted with a snap coupling for attaching a portable electric pump to extract samples for salinity (electrical conductivity) measurements. Boreholes were backfilled with gravel and bentonite layers to form hydraulically-isolated zones around the end of each tube. No permanent casing was fitted inside the boreholes. Each borehole was fitted with a 50 mm PVC pipe to below the water table and protected with a cast-iron cover set flush with the ground surface.

A programme of groundwater salinity measurements then commenced, carried out by locally trained personnel initially at approximately monthly intervals to define the FWL salinity conditions and thickness. Measurements established the average depth to water table and base of the FWLs at each location, allowing estimation of FWL thickness on the three islets (Table 12.1). Electrical conductivity (EC) equal to 2,500 μS/cm was used to define the base of the FWLs. This EC value is chosen as the lower boundary of the FWL because on Pacific atolls such water is routinely used for non-potable domestic purposes, and 2,500 μS/cm is suggested as the upper limit for human use (equivalent to approximately 1,375 mg/L total soluble salts) (George et al. 1996). Thus, maximum FWL thickness was estimated to be 5.2 m, 2.6 m and 10.1 m thick on Wale, Motu Kotawa and Motu Ko islets, respectively, at the approximate centre of each lens.

12.2.3 Cyclone-Induced Impacts on Groundwater and Subsequent Recovery

For the Cook Islands, 2005 was an unprecedented year as 6 cyclones affected various parts of archipelago. Of these storms, TC Percy tracked nearest to Pukapuka (Fig. 12.7) resulting in sea flooding of the islets. The storm attained category-5 intensity (most severe category) on the standard Saffir-Simpson scale, with central pressure falling to 925 hPa around 06:00 on 27 February. At 21:00 the same day the

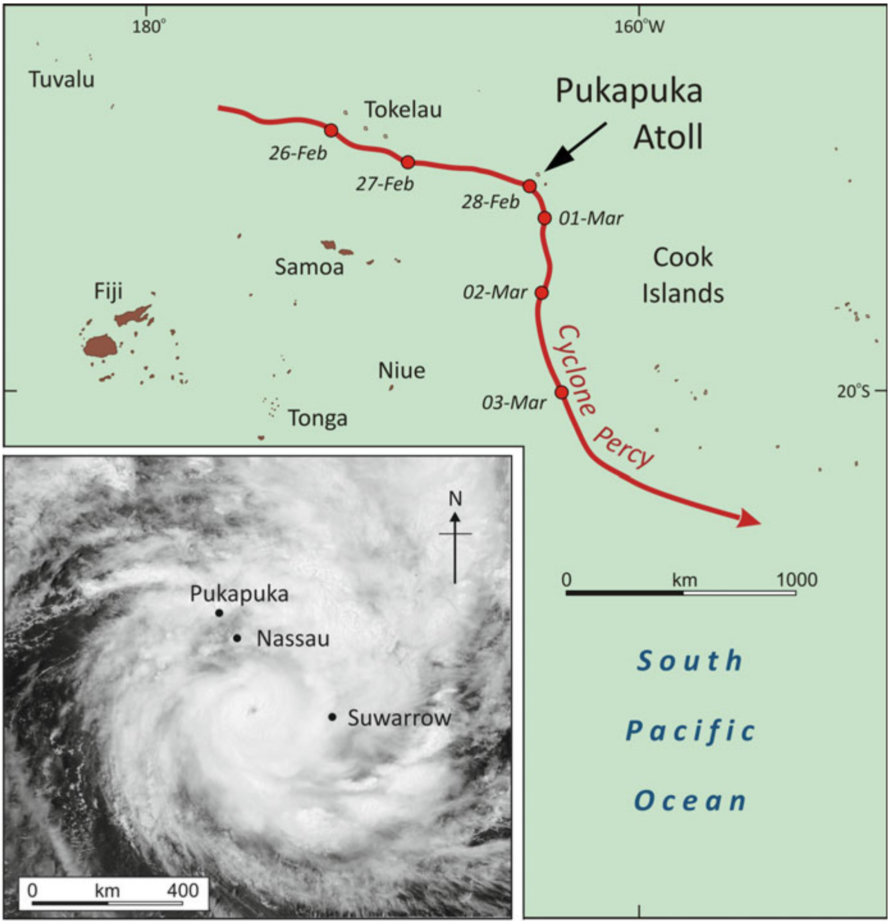

Fig. 12.7 Track of Tropical Cyclone Percy through Tokelau and the Cook Islands during February–March 2005; *red circles* show the position of the cyclone eye at midnight GMT. *Inset map* shows the visible satellite image at 00:40 on 1 March 2005 GMT, after Percy passed close to Pukapuka and Nassau a few hours earlier (Satellite base image courtesy of NASA)

eye passed within 15–30 km to the south of Pukapuka, with maximum sustained 10-min winds of 90 knots (167 km/h) and gusts up to 120 knots (222 km/h) recorded on the atoll (NIWA 2005). Besides wind damage, high waves swept partially across all the low-lying islets causing seawater intrusion into the taro swamps and the few open wells. An urgent shipment of drinking water was organised by the Red Cross from American Samoa.

Subsequent to the sea flooding and wave washover of the islets caused by TC Percy in March 2005, groundwater salinity profiles were determined from borehole EC readings on eight occasions between May 2005 and May 2007. This dataset is unique as it is the only known atoll groundwater monitoring programme that provides post-disturbance assessment of saline intrusion and subsequent recovery. Figure 12.8 compares the baseline conditions of the FWLs (Jan-05 profiles, blue lines) the post-cyclone saline impacts (red lines, May-05) and subsequent slow groundwater recovery resulting from rainfall infiltration at the thickest part of the FWL on two of the islets: Wale and Motu Ko. The following patterns can be observed from the salinity (EC) profiles.

Baseline conditions prior to disturbance showed that Pukapuka Atoll had moderately thick fresh groundwater resources on each of its three islets. The thickest FWLs existed on Wale (5 m maximum) and Motu Ko (11 m maximum). Measurements at the water table (FWL surface) show groundwater was fresh (EC approximately 1,000 μS/cm). Two months after the cyclone in May 2005, water table salinity had notably increased, especially on Motu Ko (10,050 μS/cm). Over the following months, water table salinity partially recovered. By late January-March 2006, after 1 year of recovery, the water table had improved to pre-disturbance conditions, i.e. below 1,000 μS/cm.

Deeper within the profile of the thickest FWL on Motu Ko, an interesting recovery pattern was observed. The response to saline intrusion on this islet was stratification of the FWL, in particular the appearance of a salinity profile 'inversion' at depth. The inversion was the result of two identifiable features. First, the seawater intrusion produced a well-defined and persistent saline plume within the lens. The salinity profile for May 2005 shows this saline plume (15,450 μS/cm) at about 6 m below the surface. Second, deeper still at about 12 m, a thin horizon of freshwater (1,600 μS/cm) remained unaffected, lying sandwiched beneath the saline plume and the base of the lens. The substrate at this depth is limestone that is heavily fractured, so no geologic explanation can be proposed for the trapped freshwater layer. From the time of the initial sea flooding and for the next six months until September 2006, the saline plume remained in place and gradually decreased in salinity. Over the same period, the sandwiched freshwater horizon beneath the saline plume maintained salinity levels below 1,800 μS/cm (i.e. within usable limits), before gradually mixing and dispersing within the aquifer thereafter.

Overall, the FWL recovery time on Pukapuka was a function of both the sea flooding event and the amount of groundwater recharge over subsequent months. The storm occurred near the end of the cyclone season (March), immediately before the commencement of the dry season that lasts normally from April to September. It is likely that if the saline intrusion had occurred earlier in the wet season, the FWLs may have experienced faster recovery due to rainwater recharge in November and December 2004 (205 and 198 mm monthly rainfall, respectively) helping to flush away of some of the salt in the groundwater. Within the FWL on Motu Ko, the persistence of the trapped freshwater horizon was probably aided by Pukapuka's micro-tidal range of just 0.31 cm (NOAA 2008), because tidally-driven vertical mixing would have been a relatively inefficient mechanism for dispersal. Accessing this thin and fragile fresh horizon would be a difficult challenge, owing to the threat of seawater upconing into the base of the FWL.

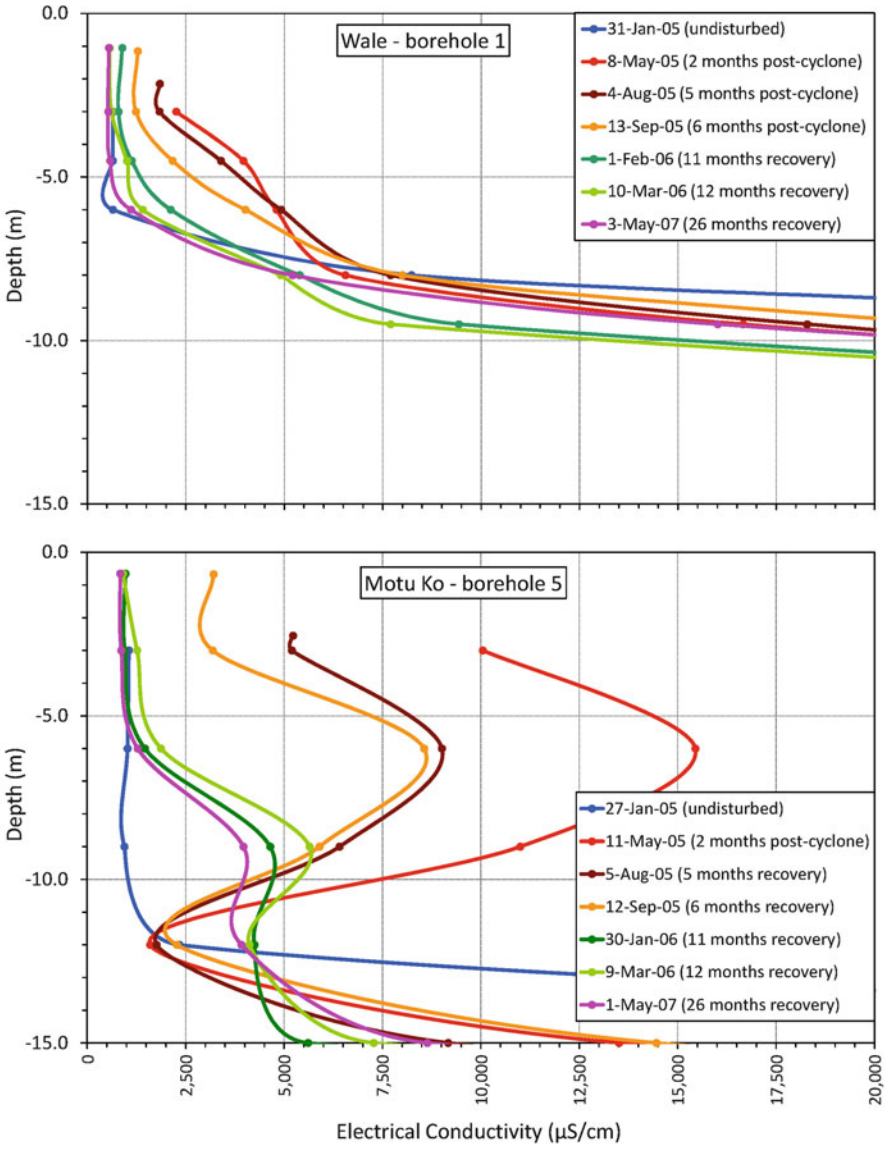

Fig. 12.8 Salinity profiles over time in FWLs, measured from two boreholes on Wale (*top*) and Motu Ko (*bottom*) islets. The Jan-05 profiles (*blue lines*) represent average baseline groundwater conditions prior to cyclone disturbance. The saline intrusion on top of the FWL during TC Percy is clear from the May-05 profiles (*red lines*). Subsequent salinity profiles show the slow recovery of the FWLs until the most recent data in May 2007. Notes: (1) For clarity, only the top part of the FWLs profiles are shown (to 15 m depth). (2) The upper limit of the x-axes (20,000 μS/cm) is approximately 40 % seawater salinity. (3) On the y-axes, 'depth' means 'depth below ground surface'

12.2.4 Modelling Approaches

As in other branches of hydrology, numerical modelling is a valuable technique that complements the findings of field investigations, or can be employed along with appropriate field data in order to facilitate better understanding of atoll groundwater resources. Modelling can assist with both appreciating different properties of atoll FWLs and quantifying the responses to real or anticipated changes in natural and human influences. A number of comprehensive studies have investigated many different scenarios and undoubtedly made important contributions about atoll groundwater sensitivity to different environmental parameters (see, for example, Oberdorfer and Buddemeier 1988; Oberdorfer et al. 1990; Underwood et al. 1992; Griggs and Peterson 1993; Peterson and Gingerich 1995; Singh and Gupta 1999; World Bank 2000; Bailey et al. 2009). This section starts with a brief overview of previous modelling studies on atoll groundwater resources. In line with the theme of this chapter, it then presents a summary of the key findings from a recent investigation (Chui and Terry 2012) that models the impacts of storm-driven wave washover on atoll FWLs.

12.2.5 Overview of Previous Modelling Studies on Atoll Groundwater Resources

The work of Oberdorfer and Buddemeier (1988) was one of the first attempts to use a numerical model to predict the effects of climate change on groundwater in a small atoll islet. They found that for Enjebi islet on Enewetak Atoll in the Marshall Islands, the total freshwater inventory is a monotonic but nonlinear function of recharge. Regarding sea-level rise (SLR), they postulated that it actually improves groundwater availability by increasing the ‘useful volume’, i.e. the amount of freshwater in the upper portion of the lens above the high-permeability zone. Later, a major economic assessment by the World Bank (2000) on managing and adapting to environmental change in Pacific Island economies dedicated a section to island water resources. Within this, a numerical model was used to examine the impacts of a range of climate change and SLR scenarios on the Bonriki islet FWL, which is the main groundwater supply source for Tarawa Atoll in Kiribati. Water balance modelling suggested that by the year 2050, a 10 % decline in rainfall would result in a 14 % reduction in groundwater recharge, whereas a 7 % rainfall increase would give a 5.5 % increase in recharge (Table 12.2). It was also noted that although evapotranspiration increases as climate warms, its effects on groundwater recharge are less significant than projected changes in annual rainfall. In terms of SLR, the World Bank report concluded that a 0.4 m rise would have little consequence on the Bonriki FWL and would even slightly raise its volume. This is due to the fact that the average level of the freshwater lens, which is influenced by mean

Table 12.2 Modelled responses of the Bonriki islet FWL on Tarawa Atoll in Kiribati, after various projected climate change and sea-level rise scenarios

Climate change scenario	Percentage change in groundwater thickness modelled
Current[a] sea level, 7 % increase in rainfall	+5.5
Current sea level, 10 % reduction in rainfall	−14.0
0.2 m SLR, current rainfall	−0.9
0.4 m SLR, current rainfall	+2.0
0.4 m SLR, 10 % reduction in rainfall	−12.0
0.4 m SLR, current rainfall, reduced island width	−29.0
0.4 m SLR, 7 % increase in rainfall, reduced island width	−19.0
0.4 m SLR, 10 % reduction in rainfall, reduced island width	−38.0

Data from World Bank (2000)
[a]2000 values

sea level, would rise slightly into less permeable Holocene sediments from the highly permeable underlying Pleistocene limestone. However, possible reduction in islet width associated with inundation is a further consideration, as this would diminish lens thickness even without precipitation decrease.

More recently, Bailey et al. (2009) evaluated the sensitivity of atoll FWLs to several climatic and geologic variables. Their work noted that lens thickness is most sensitive to the hydraulic conductivity of the uppermost Holocene aquifer and the depth of the Holocene–Pleistocene unconformity. The temporal variations of the lens thickness, on the other hand, are sensitive to fluctuations in the recharge rate.

Other modelling studies have focused attention on understanding the transition zone below FWLs and the propagation of tidal influences through them. In a simulation of the FWL within Enjebi islet on Enewetak Atoll, Oberdorfer et al. (1990) determined that tidally-induced flow predominates over density-driven flow and creates an extensive mixing zone of brackish water. Underwood et al. (1992) similarly established that mixing within a FWL is mostly due to the oscillating vertical flow caused by tidal fluctuations and depends to a lesser extent on transverse dispersion. The dispersive mixing is controlled by the combined effects of tidal range, vertical longitudinal dispersivity and vertical permeability.

Numerical modelling also has a crucial role in the development of groundwater management strategies. For example, Griggs and Peterson (1993) simulated groundwater flow in the Laura area of Majuro Atoll in the Marshall Islands and reached the conclusion that multiple pumping centres, instead of individual ones, are more efficient in extracting groundwater. Likewise, Singh and Gupta (1999) were able to arrive at a safe groundwater pumping scheme using a modelling approach for the Lakshadweep Islands in the Arabian Sea. They established that a pumping rate up to 13 m^3 per day was sustainable for wells more than 400 m apart and where the water table was at least 0.15 m above MSL.

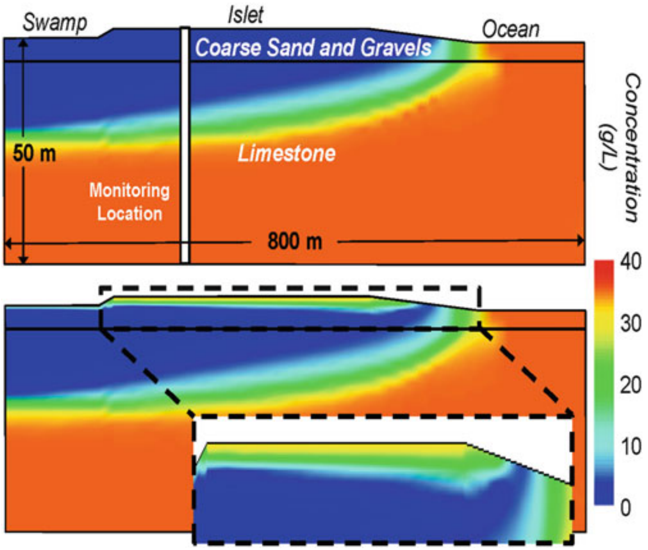

Fig. 12.9 Salinity distributions in the FWL for undisturbed conditions (*top*) and immediately after wave washover (*bottom*). Note: for clarity half of the atoll islet is shown, from the middle of the islet to the ocean side, with an assumed symmetry about the left side of the diagram towards the atoll lagoon

12.2.6 Effects of Storm-Wave Washover on Freshwater Lenses

In recent work, Chui and Terry (2012) examined the saline intrusion as well as the subsequent recovery of a FWL, following wave-washover of an atoll during an intense tropical storm. The initial part of the study involved modelling a coral islet in the tropical Pacific Ocean with specified size, substrate composition, rainfall and infiltration characteristics. Simulation of average long-term conditions thus obtained a FWL typically observed in atolls, as shown in the top image in Fig. 12.9. The study then subjected the FWL to saline intrusion caused by the storm-wave washover, and examined the immediate response, longer term behaviour and subsequent recovery of the aquifer. During the storm-generated washover, seawater quickly infiltrated into the unsaturated zone of the coarse sands and gravels, and caused a salinity increase in the top part of the FWL as seen in the bottom image in Fig. 12.9. After the washover event, the observed saline plume first migrated downwards through the overlying coral sand and gravel sediments, but then exited the FWL to the ocean laterally through the more permeable limestone at the base of and below the FWL. Figure 12.10 illustrates the evolution of the salinity profile at selected time intervals at the simulated ‘monitoring’ location marked in Fig. 12.9. Interestingly, the profile reveals the existence of a layer of relatively fresher water sandwiched between the saline plume above and seawater below, 2 months and 1 year into the recovery period.

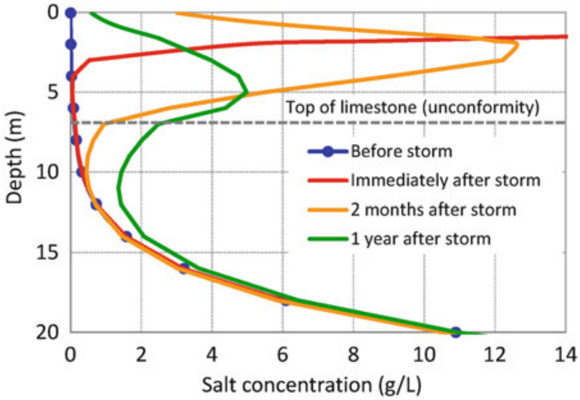

Fig. 12.10 Salinity profiles before and after the storm at the monitoring location marked in Fig. 12.9

This behaviour closely mirrors the field observations reported by Terry and Falkland (2010) on Pukapuka Atoll in the Northern Cook Islands after Cyclone Percy in 2005, as described in Sect. 12.2.3. Model sensitivity analyses also indicated, as expected, that a saline plume takes longer to disperse (i.e. extended recovery time for a salinised FWL) for an atoll with a drier climate.

A notable attribute of Chui & Terry's model is the incorporation of a central low-lying depression (i.e. a freshwater swamp under undisturbed conditions), which is a topographic feature typical of some larger atoll islets. Seawater accumulates in the swamp during marine inundation of the islet and remains there for a number of days after the event. Seawater also accumulates on the surface of the FWL surrounding the swamp, owing to the high infiltration rate through the coral sediments in the unsaturated zone. This affects the deeper part of the FWL and prolongs the later stage of freshwater lens recovery. One suggested mitigation measure in such circumstances is to pump out stagnating seawater from the swampy depression if possible. This would need to be done with caution and at low pump rate so as not to induce further seawater intrusion from below.

12.3 Conclusions and Outlook

A source of clean, potable freshwater is a prerequisite for human existence on small islands in the Pacific (Depledge and Terry, in press; White et al. 2008). From the synopsis presented in this chapter of published research over recent decades, it is clear that the limited fresh groundwater resources found on coral atolls are both uniquely fragile and at risk of disturbance from a range of natural and human-induced pressures. Amongst these threats are over-extraction and pollution associated with growing urban populations, drought and salinisation related to climatic variability and episodic extreme storm events. The last of these has been the subject of recent investigation by the authors. Post-cyclone field measurements on Pukapuka Atoll in the northern Cook Islands over the period 2005–2007 indicated that at least a year is necessary for a freshwater lens to recover completely from seawater intrusion due to storm-wave washover. Since it is believed that the Pukapuka study is the only documented account of cyclone-induced atoll groundwater salinisation and subsequent recovery, it is suggested that further work of a similar empirical nature should be a matter of priority on affected atolls, in order to improve our understanding of the processes involved. Analysis using a modelling approach has also proved valuable. Simulations show how seawater that accumulates in the low-lying topographic depressions in the interior of some atoll islets during wave washover may prolong the recovery time of a salinised freshwater lens.

In the scientific literature on climate change, discussion continues on the relationships between observed rising sea-surface temperatures and geographical patterns of tropical cyclogenesis and storm intensities, especially in the South Pacific context (Terry and Gienko 2010; Walsh 2004). Although much uncertainty remains, it is nonetheless the case that occasional anomalous episodes and El Niño events have been identified as responsible for generating more cyclones east of 180° longitude (Chu 2004; Terry and Etienne 2010). Additional supporting evidence is provided in the comprehensive review by de Scally (2008) of historical cyclones over the period 1820–2006 in the Cook Islands, where a clear signal of increased cyclonic activity is apparent during El Niño events (even weak ones), compared with La Niñas or neutral ENSO conditions. Such findings imply that possible future climatic swings towards a more sustained El Niño-like state in the South Pacific (Walsh et al. 2012) may portend a heightened level of storminess for the Polynesian atolls of Tuvalu, Tokelau, the Cook Islands and French Polynesia, i.e. atolls which lie in the vicinity and east of the 180° meridian.

Connected with this, there are fears that projected sea-level rise associated with carbon dioxide emissions and global warming might lead to irreversible physical erosion of atoll fabric. The startling scenario of many low-lying atoll islets possibly 'vanishing' later this century as a direct consequence of eustatic sea-level rise is an image that has already captured media attention in recent years and fuelled worldwide public concern about the plight of mounting numbers of Pacific Island 'environmental refugees'. Although many individual atoll islets in reality demonstrate geomorphic resilience to sea-level rise over decadal timescales (Webb and Kench 2010), anticipated higher sea levels will nevertheless enhance the potential for marine inundation of islets during tropical storms, especially if the strongest cyclones also become more intense in future (Elsner et al. 2008). If such scenarios are realised over the coming decades (whatever the timescales may be), then it is not unreasonable to postulate that the attendant risk of atoll groundwater salinisation resulting from storm-wave washover will similarly increase (Terry and Chui 2012). Sound management of atoll water resources is therefore an imperative that cannot be ignored, if continued and sustainable human habitation of atoll islets is to be ensured.

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