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Groundwater salinisation on atoll islands after storm-surge flooding: modelling the influence of central topographic depressions

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Abstract

Fresh groundwater lenses (FGLs) are of utmost importance for human survival on small and isolated atolls. This article examines saline damage to atoll FGLs from wave washover caused by storm surge and studies the particular influence of central topographic depressions (CTDs). We model storm surge over atoll islets of contrasting widths (400 and 800 m), both with and without CTDs of various sizes. Three key findings emerge. First, under equilibrium undisturbed conditions, the CTD slightly reduces the size of the FGL compared to atoll islets without this feature. Second, during marine flooding, prior saturated conditions at the base of a CTD impede seawater infiltration into the substrate, thereby limiting saline damage in that location. Third and most crucial, however, the amount of salt accumulated within the CTD is significant, ranging from 2 to 10 times higher than the net subsurface infiltration during the period of the storm inundation.

Introduction and aims

The widely dispersed coral atolls of the tropical Pacific Ocean are small, low-lying islands built of carbonate sands and gravels that have accumulated on atoll reef platforms (Nunn 2010), as illustrated in the top figure in Fig. 1. Land elevation is usually less than a few metres above sea level. For the human populations inhabiting these remote islands, one of the main environmental constraints is the limited availability of naturally occurring freshwater resources. Owing to the high porosity of the coral-derived carbonate sands that comprise the island sediments and the thin soils that develop upon them, any rainfall quickly permeates. Surface water storage (i.e. streams and lakes), therefore, does not exist. Many islanders must, therefore, use roof catchments to collect rainwater. Fresh groundwater resources are also very important and are normally exploited.

Fresh groundwater occurs as an unconfined aquifer within the substrate of an individual atoll islet, with the size of the fresh groundwater lens (FGL) dependent on factors such as the islet surface area and geology. The shallow FGL essentially floats hydrostatically on top of the seawater beneath, with a gradual transition zone of brackish water at the base of the lens where freshwater and seawater mixing occurs (Underwood *et al*. 1992). Percolating rainwater is the only mechanism that recharges the FGL (Falkland 1994) while freshwater discharges to the sea at the lens periphery and base (Oberdorfer *et al*. 1990) and to the lagoon enclosed by the atoll.

Given the importance of groundwater to the continuing survival of atoll island communities, it is crucial to understand possible threats to the long-term viability of FGLs. One reason is that with population growth and urbanisation on many atolls, groundwater resources are under increasing pressure (de Freitas *et al*. 2014). For example, 15 755 people live on Betio islet (1.7 km^2), which is the centre of commercial activity on South Tarawa atoll in the Republic of Kiribiti (Ministry of Finance, Kiribati 2012). Another reason is that FGLs are uniquely fragile, and therefore, at risk of damage by both anthropogenic activities (e.g. excessive pumping and contamination) and natural disturbance caused by periodic drought, coastal erosion or sea level rise (Dillon 1997; Singh & Gupta 1999; White *et al*. 2007a, b; White & Falkland 2010; Nakada *et al*. 2012; Ketabchi *et al*. 2014).

The focus of this article is a further type of natural threat to FGLs: storm-wave washover leading to groundwater salinisation. In general terms, intrusion of the saline washover

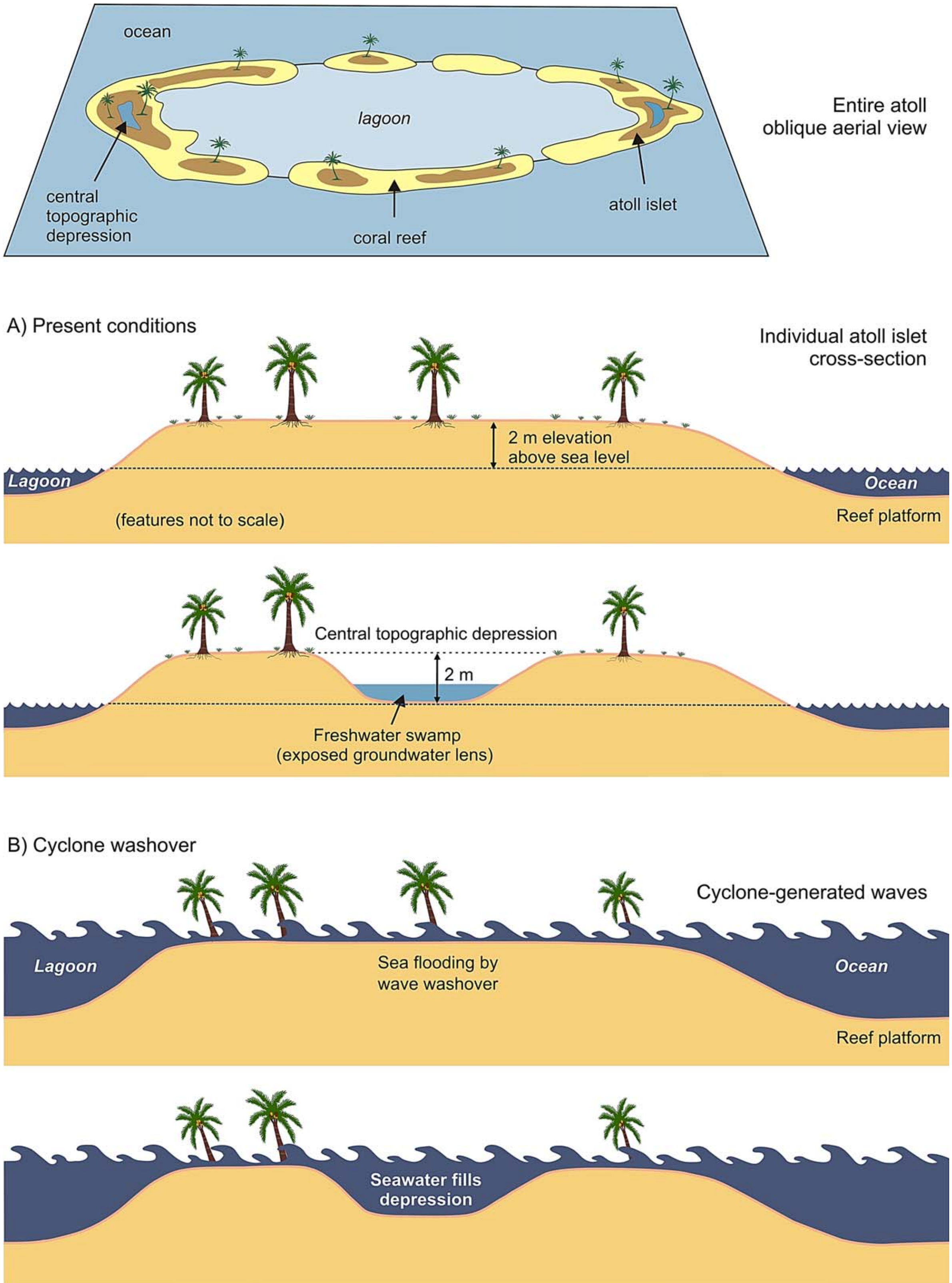

Fig. 1. Conceptual diagrams illustrating atoll configurations with and without a central topographic depression (CTD). (a) shows present undisturbed conditions and (b) a tropical cyclone event with storm-generated waves washing over an islet and filling the depression, where present, with seawater.

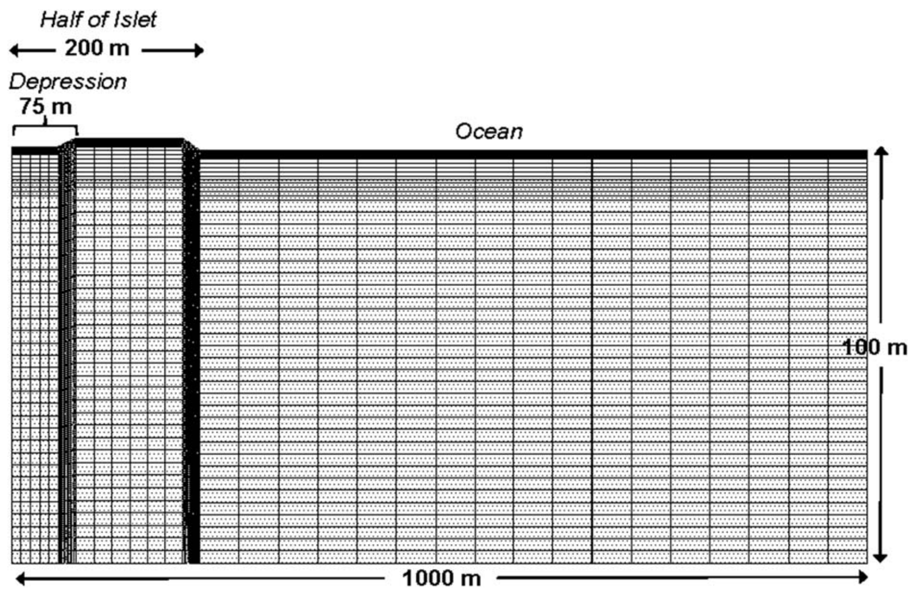

Fig. 2. Example solution domain and mesh for one of the modelling scenarios (i.e. scenario 2 in Table 1). The mesh elements along the top of the domain, along the bank of the depression and along the shoreline are so small that they appear as thick black stripes.

into the islet substrate causes salt contamination of the water table, which subsequently takes a significant period of time to recover to predisturbance freshness through natural rainwater percolation. One study on Pukapuka atoll in the Northern Cook Islands, possibly the only one of its kind based on observational data before and after a tropical cyclone, showed that in spite of saline damage to the FGL surface, a thin horizon of fresher water can remain preserved deeper within the lens profile following marine inundation (Terry & Falkland 2010). Additional work by these authors using modelling approaches has established that a lower water table position before a storm event, for example, observed during a dry period or caused by excessive groundwater pumping, rather than a longer duration of storm washover, results in more damage to the FGL, and that FGLs developed in smaller islets are generally less robust against external stressors than larger FGLs within bigger islets (Chui & Terry 2012, 2013). Recent simulations by Bailey & Jenson (2013) showed that on average 20 and 80% FGL recovery takes about 8 months and 20 months, respectively.

That being said, however, much remains to be learned concerning the role of various factors that affect the degree of FGL salinisation by storm-wave washover and the recovery mechanisms thereafter (Bailey & Jenson 2013). Consequently, the aim of this article is to investigate the role of atoll islet geomorphology, particularly the central topographic depression (CTD) and the extent to which it influences FGL damage caused by storm-wave washover. Although it is the case that most atoll islets exhibit subdued topography with little contrast in elevation across from the ocean to lagoon sides, relatively large or elongate islets that are referred to as type II, III and IV islets by Richmond (1992) are normally characterised by low-lying depressions towards their centre (Fig. 1). Spatial heterogeneity means that no precise data exists on the percentage of atoll islets exhibiting CTDs, but according to topographical cross sections shown in Woodroffe (2008), CTDs appear common in various atoll groups in the central Pacific and Indian Ocean, for example, the Kiribati – Tuvalu chain, the Cocos (Keeling) Islands and the Chagos Archipelago. For Pacific Islanders who live on atolls, CTDs are important because they often reach the water table and expose the surface of the FGL as a freshwater swamp. The swamps are where local people dig 'taro pits' within which are planted various types of swamp taro to provide the main staple food crop (Thaman 2008; Manner 2011).

There are several reasons why CTDs deserve special attention. First, although not all islets have obvious topographic depressions, where they do occur they are a dominant geomorphic feature. Second, in spite of their fairly common occurrence, CTDs are largely ignored in modelling studies of atoll hydrogeology, with the exception of recent

Table 1 Dimensions of atoll islets and central topographic depressions (CTDs)

Scenario	Atoll islet width (m)	Width of CTD (m)	Volume of CTD (m^3/m)[a]
1	400	0 (no depression)	0 (no depression)
2	400	150	260
3	400	300	560
4	800	0 (no depression)	0 (no depression)
5	800	300	560
6	800	600	1060

[a]The numerical models are 2-D, so volume is expressed per meter of distance into and out of the page, that is, m^3/m.

Table 2 Model parameters

Depth of boundary between sands and gravels, and reef limestone (m)	12
Intrinsic permeability of bedrock limestone – horizontal, vertical (m^2)	10^{-9}, 10^{-10}
Intrinsic permeability of unlithified sands and gravels – horizontal, vertical (m^2)	10^{-10}, 10^{-11}
Longitudinal dispersivity – horizontal, vertical (m)	10, 1
Transverse dispersivity (m)	0.1
Apparent molecular diffusivity of salt (m^2/s)	10^{-9}
Porosity	0.3
Residual moisture content	0.051
Van Genuchten parameters – α (m), n	0.134, 9.0
Specific pressure storativity (m.s^2/kg fluid)	9.0×10^{-9}
Fresh water concentration (kg salt/kg water)	0
Fresh water density (kg/m^3 water)	1000
Seawater concentration (kg salt/kg seawater)	0.0357
Seawater density (kg/m^3 seawater)	1025
Change in fluid density with change in salt concentration (i.e.$\partial\rho/\partial c$) (kg seawater/m^3·kg salt)	700
Fluid viscosity (kg/ms)	0.001
Gravitational acceleration (m/s^2)	9.81

studies by the authors (Terry & Chui 2012; Chui & Terry 2013). Third, in real examples of tropical storm events that have driven waves across atoll islets, it has been observed that seawater flows into and collects in the depressions. It might reasonably be anticipated that this seawater accumulation affects the behaviour of the FGL within the substrate in a different way than if the CTD were not present and may, therefore, be a critical factor influencing the amount of damage sustained by the FGL. As yet, however, the magnitude of this influence, if any, is unknown. All of these issues, therefore, raise the question of whether or not CTDs on atoll islets render their groundwater resources more vulnerable to the effects of marine inundation during storms. Following on from the above, this study, therefore, builds upon earlier work through the specific objective of comparing FGL responses to storm-driven washover events on atoll islets both with and without CTDs of various sizes.

Methods

Atoll islet configuration and numerical model

A representative atoll in the tropical Pacific Ocean is illustrated in Fig. 1. The diagram shows the typical features of islets that build up on the rim of such an atoll through the accumulation of coralline sediment above high-tide level. On the right and left sides of the configuration, respectively, lie the ocean and the enclosed lagoon, which are the only salinity sources under quiescent conditions. As seen, some islets have an obvious CTD while others do not. In the vertical dimension, two distinctive components of the islet geology are recognised: a firm limestone platform comprising old reef framework (Pleistocene age), on top of which are deposited unlithified coarse sediments of coral-derived carbonate sands and gravels (Holocene to recent age). The loose coralline sediments extend here to 12 m depth in their thickest vertical section while the islet land surface reaches a maximum elevation of 2 m above sea level. The bottom of the low-lying swamp that marks the lowest part of the CTD, where this is present, is at sea level. As might be anticipated, there is some natural variation between different atolls in the tropical Pacific Ocean, but these figures are nevertheless generally representative of many islets (Ghassemi *et al*. 2000).

Using this conceptual physical basis for atoll islet structure, model simulations of the FGL are performed using the two-dimensional (2-D) cross section domain with a mesh of 1950 discrete rectangular elements as depicted in Fig. 2. It is only necessary to include 'half' of the islet in the modelling domain because there is an assumed horizontal symmetry about the left boundary of the model from the middle of the CTD, with the islet extending to the atoll lagoon on the left side of the symmetry. This assumption of symmetry is reasonable where the lagoon responds to tidal phases in the same way as the open ocean, which is normally the case, except for less common examples where the atoll lagoon is almost entirely cut off from ocean circulation by a continuous enclosing island in a 'donut' shape around the atoll rim.

Two atoll islet widths, 400 and 800 m, were selected to represent the natural variation in islet sizes. Islets narrower than 400 m do exist on many atolls, but in such cases a viable FGL allowing permanent human settlement does not form. Likewise, some islets reach dimensions wider than 800 m, but these are not as common. For the two islet chosen sizes, different scenarios of topography are also modelled with various horizontal dimensions of the CTD as listed in Table 1.

Established modelling techniques are used to simulate the FGL within the islet substrate, as described in earlier investigations (Chui & Terry 2013). SUTRA is used which is a model for saturated–unsaturated variable-density groundwater flow with solute transport, developed by the US Geological Survey (Voss & Provost 2008). SutraGUI, the pre and postprocessor for SUTRA, is run using the Argus One program from Argus Interware, Inc. (Winston & Voss 2004). Note that 2-D groundwater modelling is preferred over 3-D methods used by some workers (e.g. Comte *et al*. 2014; Mahmoodzadeh *et al*. 2014). This decision stems from the tendency for many atoll islets to be elongate in nature, compared to other types of low-lying islets with elliptical shape, such as sand cays. Atoll islands often extend hundreds of metres or even kilometres in length along the top of suitable atoll reef surfaces, whereas their widths rarely exceed 1000 m. This means that no particular distance can realistically be chosen to represent atoll islet length, and inclusion of this dimension in modelling would not

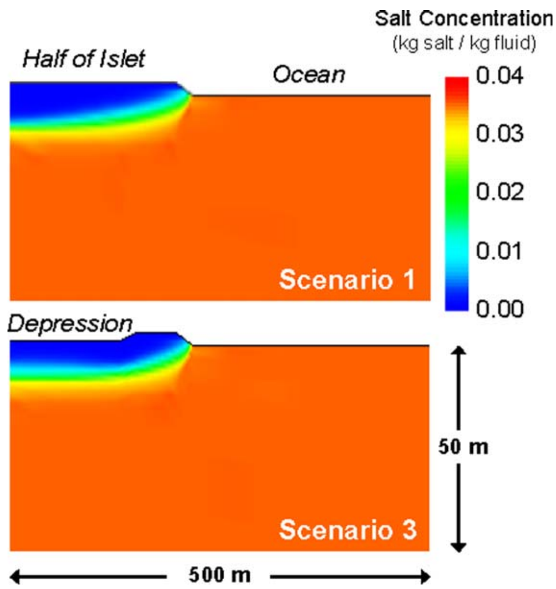

Fig. 3. Salinity distribution within an atoll islet during steady-state undisturbed conditions. The example shows scenarios 1 and 3 (see Table 1), representing an islet 400 m wide without a CTD and with a 150 m wide CTD, respectively. For convenience the figure shows only the relevant top left corner of the simulated solution, where the fresh groundwater lens (FGLs) and the CTD are situated.

yield meaningful information on longitudinal aquifer size or behaviour. More important here is the assessment of atoll island width and vertical thickness influences on FGL formation, for which task 2-D modelling is appropriate.

The work of Bailey *et al*. (2009) and Underwood *et al*. (1992) provides the value of parameters representative of uncemented carbonate sands and gravels on atoll islands. Similarly, substrate water retention and relative permeability functions are modelled according to published functions (van Genuchten 1980). Because the underlying limestone bedrock exhibits far greater permeability than the overlying coralline deposits, equivalent parameters are applied for simplicity with the exception that saturated permeability is set as an order of magnitude higher in the limestone. The values of all parameters adopted in this study are provided in Table 2.

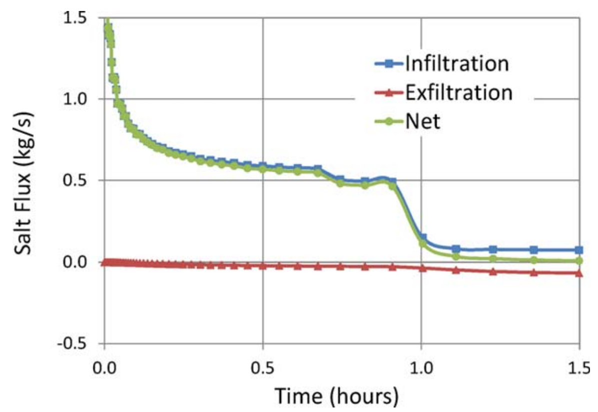

Fig. 4. Salt fluxes integrated along the entire top model boundary during storm washover of an example scenario (i.e. scenario 2, for an islet 400 m wide with a CTD 150 m wide). Only the first 1.5 h of the 10-h washover event are shown as the salt fluxes become stabilised afterwards and for the remaining duration of the event.

Initial steady-state solution

Steady-state simulations are used to produce the equilibrium situation for the FGLs forming in each atoll islet scenario (i.e. with and without CTDs, before disturbance). An inflow of rainfall infiltration at 3 mm/day is applied evenly over the land surface. This corresponds to an average annual rainfall of around 2000 mm with 50% evapotranspiration loss. This choice of annual rainfall is fairly typical for many Pacific atolls that experience a humid tropical climate, such as the atolls of the Marshall Islands (see Terry & Thaman 2008). In the modelling domain, no flow crosses the left boundary because of symmetry. The right boundary and the ocean floor are assumed to be at the hydraulic head of the sea level. The bottom boundary is also assumed to be no-flow. The boundary conditions for the salinity concentration are set at 0.0357 kg salt/kg seawater in the ocean and at 0 kg salt/kg water otherwise (i.e. for rainwater infiltration).

In the initial phase of the simulation, the level of the freshwater swamp in the CTD is not predetermined but instead responds to the other system inputs using the so-called 'groundwater window approach' as introduced in Chui &

Table 3 Surface water level of the freshwater swamp in the central topographic depression (CTD)

Scenario	Atoll islet width (m)	Width of CTD (m)	Swamp water level (m above sea level)
1	400	0 (no depression)	0.149–0.213[a]
2	400	150	0.211
3	400	300	0.202
4	800	0 (no depression)	0.258–0.343[a]
5	800	300	0.339
6	800	600	0.327

[a]The values for scenarios 1 and 4 (without depressions) are groundwater table elevations which vary across each islet. The highest values occur at the centre of the islets and the lowest values at distances 150 and 300 m away from the islet centres in scenarios 1 and 4, respectively.

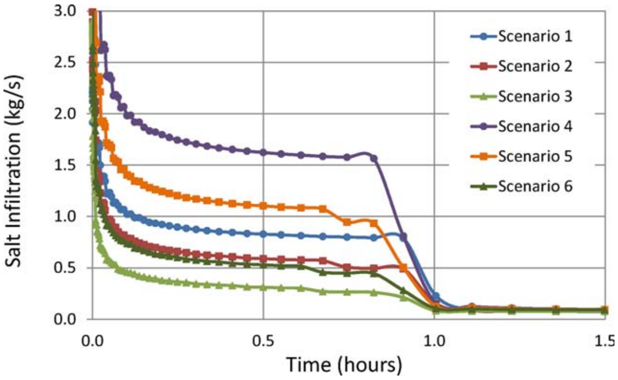

Fig. 5. Salt infiltration integrated along the entire top model boundary during a storm washover event for different islet sizes and topographic scenarios. Only the first 1.5 h of the 10-h washover event are shown since the fluxes become stabilized afterwards and for the remaining duration of the event.

Terry (2013) and outlined as follows. Groundwater hydrologists normally consider the freshwater swamps observed in atoll islet CTDs simply as surface expressions of the water table. Freshwater swamps are, therefore, 'windows' revealing the water table position, that is, the FGL surface. By accepting this approach, a steady-state solution can be first obtained for the atoll islets without a CTD, that is, where the centre of the islet has a hypothetically flat land surface at 2 m above present sea level. The resulting modelled position of the FGL surface within the substrate is then substituted to represent the level of the water table (swamp surface) for an equivalent sized islet where a CTD is actually present.

Simulation of storm-wave washover

To examine the potential FGL damages of the various atoll islet sizes, with and without CTDs, the equilibrium FGLs are then subjected to storm washover events. The steady-state solutions previously obtained are used as the initial conditions of 10-h wave washover simulations. The left, right and ocean floor boundary conditions remain the same as the steady-state simulations. The close passage of an intense tropical cyclone that can cause wave washover of an atoll islet typically lasts for between 1 and 3 h. Thereafter, as the storm moves away, seawater may continue to pond in low-lying hollows, especially in the central swamp and other topographic depressions. To represent the combined effect of wave overtopping and subsequent ponding, seawater is assumed to inundate the entire atoll for 10 h, divided into 2 h of storm-wave washover and 8 h of subsequent ponding time for seawater. To simulate these effects, a hydraulic head of 2.0 m is applied along the bottom of the CTD and also on the surrounding land surface of the islet to represent an inundation to the land surface and a CTD completely filled with seawater.

Results and discussion

Steady-state undisturbed conditions

During undisturbed equilibrium conditions, a FGL is formed which is typically thicker inland and thinner toward the ocean (Fig. 3) and the lagoon. There is also a transition zone at the base of the FGL where water increases in salinity from freshwater to seawater. As expected, the FGLs forming

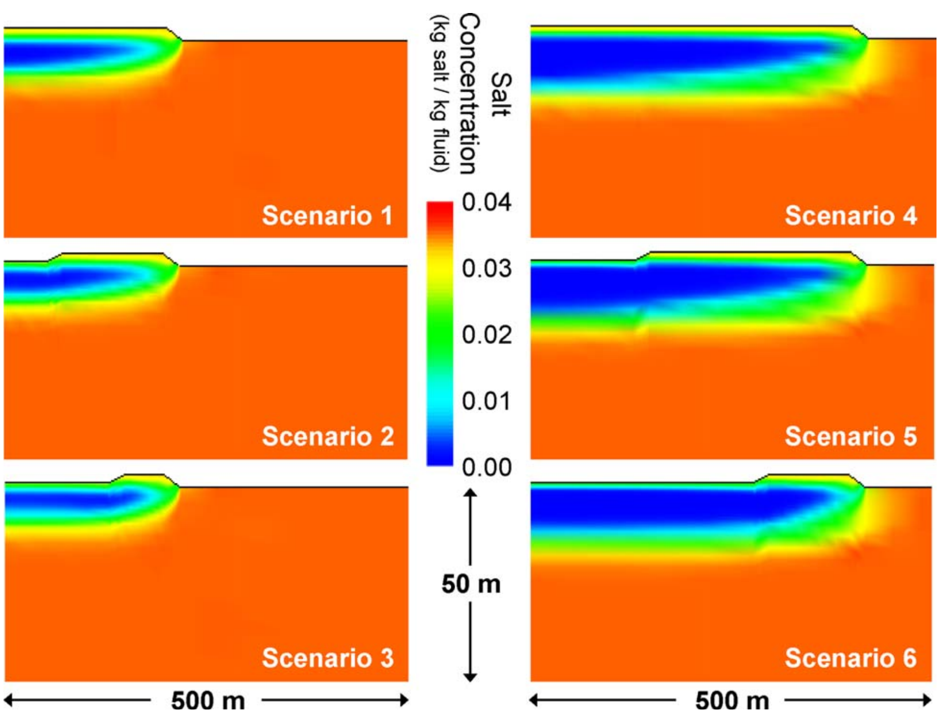

Fig. 6. Salinity distributions immediately after a storm washover event for two sizes of atoll islet (left: 400 m; right: 800 m) with different topographic configurations. For convenience, the figures show only the top left corners of the simulated solutions, where FGLs and CTDs are situated.

Table 4 Comparisons of salt budgets postwashover event on atoll islets with and without central topographic depression (CTDs)

Scenario	Atoll islet width (m)	Width of CTD (m)	[A] Net subsurface salt infiltration during inundation (kg/m)[a]	[B] Salt collected within CTD (kg/m)[a]	[A+B] Total potential salt damage to fresh groundwater lens (kg/m)[a]
1	400	0 (no depression)	6810	0	6810
2	400	150	4831	9514	14345
3	400	300	2572	20492	23064
4	800	0 (no depression)	12453	0	12453
5	800	300	8450	20492	28942
6	800	600	4290	42447	46737

[a]The numerical models are 2-D, so results are expressed per meter of distance into and out of the page, that is, kg/m.

within the narrower atoll islets (i.e. scenarios 1–3) are significantly smaller than those of the wider islets (i.e. scenarios 4–6). Overall, the shape and configuration of the FGLs generated by the model under steady-state conditions, therefore, conform to empirical observations of FGLs on various atoll islets (e.g. Hamlin & Anthony 1987; Anthony 1992; Falkland 1994). The water levels of the swamp surfaces as determined using the groundwater window approach vary by about 10 cm between narrow to wide islets, as indicated in Table 3. It is important to note that for islets of equivalent width, the presence of the CTD slightly reduces the size and changes the shape of the FGL. For example, the freshwater indicated by the blue region in Fig. 3 is slightly larger in scenario 1 without a CTD than scenario 3 with a CTD. Furthermore, the transition zone at the bottom in the middle of the lens, far left of Fig. 3, is more abrupt in scenario 1 but changes more gradually in scenario 3. However, the slight reduction in FGL size does not imply that the CTD reduces the overall freshwater availability because the swamp contained within the CTD also represents part of the entire freshwater body under undisturbed conditions.

Seawater infiltration and exfiltration during storm washover

During the 10-h storm event, seawater flooding over the islet surface and accumulating within the CTD infiltrates into the substrate. A small amount of seawater also exits the subsurface (i.e. exfiltration) along the shoreline. Figure 4 compares the infiltration and exfiltration of salt integrated along the entire top model boundary during the first 1.5 h of washover. Salt infiltration is very high during in the first 10 min of inundation (>1 kg/s) but then decreases rapidly to <0.15 kg/s after 1 h. This is because pore spaces in the islet substrate above the water table that were initially unsaturated before wave washover fill up rapidly and become completely filled with seawater, as explained in Chui & Terry (2012). Salt exfiltration, plotted as negative values in Fig. 4, is small when compared to infiltration at the beginning of the event. However, exfiltration increases in terms of relative importance over time as more seawater accumulates within the substrate. Results in Fig. 4 are extracted from scenario 2, but other scenarios produce similar patterns of salt infiltration and exfiltration during the storm washover event.

Figure 5 focuses next on comparing salt infiltration between the different islet configurations and reveals two important findings. First, for equivalent islet topography (i.e. equivalent relative size of topographic depression), the absolute amount of salt infiltration is less for the smaller islets, that is, infiltration in scenario 1 is less than scenario 4, scenario 2 is less than scenario 5, and scenario 3 is less than scenario 6. Second, the CTD in fact reduces the amount of infiltration that occurs during storm washover. Thus, for small islands (400 m wide), infiltration in scenario 3 (large CTD) is less than scenario 2 (medium CTD), which in turn is less than scenario 1 (no CTD). Similarly, for larger islands (800 m wide), infiltration in scenario 6 (large CTD) is less than scenario 5 (medium CTD), which in turn is less than scenario 4 (no CTD).

Finally, Fig. 6 compares the subsurface salinity distributions of the different scenarios immediately after the end of the storm washover event. Not surprisingly, it is seen that the fraction of FGL damaged is higher in the smaller islets (scenarios 1–3) because the lenses are smaller and are, thus, more vulnerable than in the larger islets (scenarios 4–6). Of more significance concerning the role of islet topography, the major finding is that less seawater is infiltrated along the bottom of the CTD when compared with the equivalent area on an islet of the same size without a CTD (i.e. comparing between scenarios 1–3 and between scenarios 4–6). This confirms the earlier finding mentioned above.

The most likely explanation for these findings is as follows. Where a CTD exists, the substrate beneath the swamp bottom is fully saturated with water, therefore, the saturated swamp bottom impedes seawater infiltration (particularly scenarios 3 and 6). In contrast, the equivalent area of land in a flat islet without a CTD is in an unsaturated state before the storm washover occurs. During wave washover, these unsaturated surficial sediments with high porosity and permeability allow significant seawater infiltration above the FGL (scenarios 1 and 4).

Post-event influence of topographic depressions on fresh grounwater lens damage

Besides seawater infiltration occurring during the 10-h inundation period, it is important to consider that CTDs on atoll islets also accumulate seawater, which (1) replaces what was a freshwater swamp before disturbance and, therefore, equates to a loss of the exposed part of the FGL and (2) subsequently infiltrates and continues to damage FGLs after the storm has ended. The second last column in Table 4 reports the maximum amount of salt that can potentially be collected within the CTD. For simplicity, the amounts are approximated by multiplying the CTD volumes with seawater concentration. The reported values are double the simulated results as the solution domain is half of the actual system.

As observed, the amount of salt collected within the CTD can be significant, ranging from 2 to 10 times higher than the net subsurface infiltration during the inundation period for all islets with topographic depressions. To assess the total potential salt damage to a FGL of a storm washover event, the last column of Table 4 sums up the net subsurface infiltration for the duration of inundation together with the salt collected within the CTD that infiltrates postevent. Overall, it is clear that the presence of a CTD significantly increases the amount of salt that can potentially damage the FGL. Also, the larger the size of the CTD in proportion to the islet, the greater the damage potential. This finding suggests the severity of FGL damage may be minimised by pumping out the ponded seawater within the CTD as soon as possible after the storm event. This would significantly reduce the total salt budget for the FGL and by assumption aid longer term groundwater recovery from salinisation.

Several caveats to our findings need to be considered. First, in the days and weeks immediately following washover, some amount of rainfall will collect in the CTD and dilute the seawater inside. Although this particular influence of the CTD has not been analysed here, any post-disturbance rainfall accumulation in the CTD would be expected to expedite FGL recovery. Second, the role of vegetation through evapotranspiration has not been included, which has been shown to be important (Comte *et al*. 2014). As central swamps are used on many inhabited Pacific atoll islets for taro plantations, the death of these plants by wave washover may exert an additional influence. Finally, although this study makes a contribution to the conceptualisation of atoll island hydrology, we recognise that there is a limit to how much knowledge can be obtained from numerical modelling simulations, especially in the absence of empirical data against which model results can be compared. Thus, it is recommended that future studies should address continuing uncertainty through field measurement of FGL behaviour underlying CTDs and investigate how the salinity of seawater ponding in a CTD during a marine flooding event subsequently improves to fresh conditions over time.

Conclusions

(1) Numerical simulations were performed to examine the influence of a CTD on the saline damage to FGLs, as caused by a storm washover event on atoll islets of different sizes. (2) Under equilibrium undisturbed conditions, the presence of a CTD slightly reduces the size of the FGL, although this does not necessarily imply less freshwater availability because the swamp within the CTD itself forms a component of the overall resource. (3) During simulations of storm washover, the CTD actually reduces the rate of seawater infiltration compared to an equivalent flat islet because the sediment substrate at the swamp bottom is already fully saturated with fresh groundwater prior to disturbance. (4) Of far greater importance, however, is the accumulation of seawater within the CTD during the storm surge. This represents both a loss of the exposed part of FGL and a continuing source of seawater infiltration after wave washover ceases. The seawater collected within the CTD is significant, up to 2–10 times larger than the seawater which infiltrates throughout the duration of the inundation. (5) In conclusion, atoll topography is, therefore, recognised as an important factor influencing the potential severity of FGL damage by seawater infiltration in the aftermath of storm washover events, with larger surface depressions giving a corresponding increase in the potential for groundwater saline damage.

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