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Wave overwash impact on small islands: Generalised observations of freshwater lens response and recovery for multiple hydrogeological settings

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SUMMARY

Wave overwash events have the potential to result in severe consequences to the freshwater resources of small islands as a result of salt contamination of the aquifer. Due to the significant impact of overwash, it is important to characterise the susceptibility of small islands to these events. This study uses numerical modelling to evaluate the freshwater lens response and recovery to overwash events for various island hydrogeological settings (island types) observed worldwide. Models were developed for an example of each island type using a fully coupled surface–subsurface, density-dependent flow and solute transport modelling code. A theoretical overwash event was simulated, and the response and recovery of the freshwater lens were observed for 20 years. The freshwater lens response (degree of aquifer contamination) was largely determined by the vadose zone thickness. Lens recovery ranged from 1 to 19 years for the different island types, and was strongly affected by recharge rate. However, the recovery of potable water in the lens (and restoration of a water supply) was dominantly influenced by geological heterogeneities. The model results demonstrate the cumulative impact of the different factors affecting the freshwater lens response and recovery to the overwash event for each island type, and provide a generalised assessment of island susceptibility to overwash on a global scale, despite limited data availability for many small islands.

1. Introduction

Wave overwash events have significant impact on small island nations due to infrastructure damage and the economic costs of rehabilitation (Walsh et al., 2012). Overwash may also result in severe consequences to the freshwater resources of small islands as a result of salt contamination of the aquifer (Anderson, 2002). Wave overwash commonly occurs as a result of a storm surge during a hurricane, tropical cyclone or other high-intensity storm, whereby large waves break above normal high tide levels (Irish et al., 2008; National Oceanic and Atmospheric Agency (NOAA), 2014). Overwash may also result from oceanic tsunamis (Illangasekare et al., 2006). The projected changes in cyclone and hurricane behaviour under future climate change are uncertain (Knutson et al., 2010); however, due to the potentially large impact of overwash, it has been recommended that research be carried out to characterise the susceptibility of small islands to these events (Walsh et al., 2012).

On islands, fresh water resides in a freshwater lens (FWL) that floats on top of the surrounding salt water within the aquifer (Falkland, 1991). Groundwater moves from areas of high to low hydraulic head within the FWL and discharges along the coastlines (Falkland, 1991). The main impact of overwash on an island FWL is that it causes temporary surface inundation of seawater resulting in saltwater contamination of the FWL (Anderson, 2002). There are three principal mechanisms of saltwater contamination: (1) infiltration of salt water through the vadose zone during inundation; (2) ongoing infiltration of salt water from depressions that store ponded seawater; and (3) transport of salt water through open boreholes and/or trenches which provide direct access to the aquifer (Illangasekare et al., 2006; Terry and Falkland, 2010; Bailey and Jenson, 2014; Holding and Allen, 2015). The most rapid impact is through boreholes/trenches; however, the largest spatial impact is from infiltration through the vadose zone as contamination is able to occur over a wide spatial extent (Illangasekare et al., 2006).

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During and following overwash inundation, a saltwater plume develops within the FWL, which moves downward through the lens due to two gradients: a density gradient between the fresh water in the lens and the infiltrating seawater; and the hydraulic gradient that drives groundwater flow within the FWL (Terry and Falkland, 2010). Although the upper part of the lens becomes contaminated with salt, a pocket of fresh water trapped beneath the saltwater plume is often observed in field studies and modelling simulations (Terry and Falkland, 2010; Chui and Terry, 2012; Bailey and Jenson, 2014). However, effectively accessing this freshwater pocket for water supply poses an engineering challenge because drilling into the pocket is likely to lead to its contamination by the surrounding salt water. The water quality in the lens recovers over time as the saltwater plume discharges out of the lens (along the coast) and/or is diluted due to mixing with infiltrating fresh water from precipitation. Full recovery of the FWL is not always achieved as the occurrence of overwash may result in long-term changes to the FWL morphology (e.g. increased mixing zone thickness), especially when multiple overwash events impact the same aquifer in close succession (Anderson and Lauer, 2008).

Previous studies have identified several factors that influence the FWL response (i.e. degree of contamination) and recovery from overwash events. These factors include the recharge rate, the vadose zone thickness, the hydraulic properties, and geologic heterogeneities.

Recharge is the main driver of FWL recovery following overwash as it delivers fresh water to the system that flushes out the salt water (Illangasekare et al., 2006; Sivakumar and Elango, 2010). Areas of low recharge experience less flushing, and therefore the FWL recovers more slowly. In addition, low recharge rates typically lead to smaller FWLs, so that overwash may impact a larger proportion of the lens, thus having a greater overall impact on the island's freshwater supply (Bailey, 2015; Holding and Allen, 2015).

The thickness of the vadose zone, or depth to the top of the lens, also influences how the overwash impacts the FWL (Illangasekare et al., 2006). During inundation, the vadose zone fills with seawater, which does not drain away when the overwash subsides. Therefore, the greater the thickness of the vadose zone, the greater the pulse of salt water reaching the aquifer (Chui and Terry, 2012). The vadose zone thickness varies seasonally in response to recharge variations. Over the longer term, the thickness of the vadose zone may also change in response to sea level rise, which is projected under future climate conditions. Particularly, in recharge-limited systems, the FWL will rise in accordance with the rise in sea level, thereby reducing the thickness of the vadose zone (Werner and Simmons, 2009). With higher sea level, the FWL may become less contaminated during an overwash event because the vadose zone is thinner and the initial pulse of salt water that is captured in the vadose zone is reduced (Chui and Terry, 2012). However, a higher sea level may also lead to a lower hydraulic gradient within the lens such that flushing of the saltwater plume, and eventual recovery of the FWL, will take longer (Terry and Chui, 2012).

The hydraulic properties of the vadose zone and the saturated zone control the flow of water and the transport of salt within the lens. The hydraulic properties of the vadose zone determine the extent of saltwater contamination occurring during the initial inundation. If the vadose zone has relatively low hydraulic conductivity (K) (acting as a confining layer to the aquifer below), it may provide a protective layer above the aquifer and limit the amount of saltwater contamination reaching the lens. However, when the K of the vadose zone is high, it may lead to increased transport of salt water into the aquifer during inundation, resulting in a large saltwater plume. Aquifers with high hydraulic conductivity may have high groundwater velocities, which can help the FWL to recover quickly due to increased advective movement of the saltwater plume out of the aquifer. Within relatively low K aquifers, the presence of geological heterogeneities with high K may have a significant influence on the impact of overwash events. For the case of continuous high K layers, the saltwater plume will migrate downward through the lens, but flow will be diverted along the high K layer and discharge along the periphery of the lens (Chui and Terry, 2012). In contrast, low K layers may limit the depth of saltwater infiltration (Bailey and Jenson, 2014), but may also delay flushing of the saltwater plume.

The results of previous studies have identified factors that affect the impact of overwash events on an island FWL. However, these factors present themselves in varying configurations and combinations on any given island, depending on the island hydrogeological setting. The cumulative impact or relative importance of these factors is not well understood. The objective of this study is to characterise the FWL response and recovery to overwash events for small islands from a global perspective. Such an undertaking is challenging due to the large number of small islands and the lack of hydrogeological data available for many islands. As an alternative, this study employs an existing generic classification of small islands to characterise the FWL response and recovery to overwash for the different island types. The results provide generalised observations for any given island that is associated with one of the island type classifications. The small island classification system identifies six categories: Type I – Young Volcanic; Type II – Old Volcanic; Type III – Low Coralline Limestone; Type IV – Recent Sedimentary; Type V – Upland Limestone; and Type VI – Near Continental Bedrock (Robins and Lawrence, 2000). These island types are not only based on geology, but also climate, FWL morphology, and water balance for each island type; details of the classification are provided in previous studies (Falkland, 1991; Robins and Lawrence, 2000). The FWL response and recovery to overwash for each island type is characterised using a fully coupled surface–subsurface, density-dependent flow and solute transport modelling approach.

2. Methodology

Modelling the impact of overwash on a FWL involves simulating density-dependent flow and solute transport across the land surface, the vadose zone, and the saturated domain. Popular modelling codes used in other overwash studies include SUTRA (Voss and Provost, 2008), SEAWAT (Langevin et al., 2007) and FEFLOW (DHI-WASY GmbH, 2010); however, none of these codes have the capability to simulate the surface domain where salt water is introduced to the hydrologic system. HydroGeoSphere (HGS; Therrien et al., 2010) was identified as the most suitable code to simulate the coupled processes because it is a fully integrated surface and variably saturated subsurface model capable of simulating density-dependent flow and solute transport. The modelling presented in this study does not require dynamic simulation of the surface domain (as lateral surface flow is not simulated) and technically could also be simulated using boundary conditions applied to the top of the unsaturated zone. However, this approach would neglect draining of the accumulated salt in the surface domain when the boundaries are removed. Moreover, by developing the models in HGS with the surface domain included, it provides greater potential for future studies to integrate more complex surface dynamics.

In order to develop models for each island type, an example island (with available field data) was selected to represent the typical hydrogeological setting of the island type. Simplified cross-sections of the example islands are shown in Fig. 1. Data for the example islands were collected from a survey and literature review