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From days to decades: numerical modeling of freshwater lens response to climate change stressors on small islands

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Abstract

Freshwater lenses on small islands are vulnerable to many climate change related stressors, which can act over relatively long time periods, on the order of decades (e.g. sea level rise, changes in recharge), or short time periods, such as days (storm surge overwash). This study evaluates response of the freshwater lens on a small low-lying island to various stressors. To account for the varying temporal and spatial scales of the stressors, two different density-dependent flow and solute transport codes are used: SEAWAT and HydroGeoSphere. The study site is Andros Island in the Bahamas, which is characteristic of other low-lying carbonate islands in the Caribbean and South Pacific regions. In addition to projected sea level rise and reduced recharge under future climate change, Andros Island experienced a storm surge overwash event during Hurricane Francis in 2004, which contaminated the main wellfield. Simulations of reduced recharge result in up to 19% loss of freshwater lens volume, while sea level rise contributes up to 5% volume loss. The lens responds relatively quickly to these stressors, within 0.5 to 3 years. Simulations of the storm surge overwash indicate that the freshwater lens recovers over time; however, prompt remedial action can restore the lens to potable concentrations up to one month sooner.

1 Introduction

Small islands are particularly vulnerable to stressors associated with climate change. The freshwater lens is generally sensitive to hydrological disturbances, as a consequence of the low hydraulic gradient and limited thickness of the lens (Vacher, 1988; Falkland, 1991; Robins and Lawrence, 2000; White and Falkland, 2010). As groundwater recharge is the primary source of fresh water to the freshwater lens, an adequate amount of recharge is critical for maintaining the lens morphology (Falkland, 1991). Changes in groundwater recharge due to climate change are likely to result from increases in temperature and changes in the spatial distribution, frequency and

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magnitude of precipitation (Green et al., 2011). Conditions of reduced recharge disturb the balance of freshwater outflow necessary to maintain the extent of the freshwater lens, and may lead to loss of freshwater volume due to saltwater intrusion (Oude Essink, 2001; Ranjan et al., 2009).

5 Sea level rise may result in inundation and a landward shift of the saltwater interface, particularly on low-lying islands (Bear et al., 1999). This would result in a loss of freshwater lens volume, either by a reduction in areal extent and/or a thinning of the lens (Oude Essink, 2001). Projected changes in the frequency of hurricanes and tropical storms are uncertain (Intergovernmental Panel on Climate Change (IPCC),
10 2014); however, there is evidence to suggest that storms may become more intense, increasing the likelihood of storm surge occurrence (Biasutti et al., 2012). Storm surge overwash can lead to salt contamination of the freshwater lens and a temporary loss of fresh water (Anderson, 2002; Illangasekare et al., 2006; Terry and Falkland, 2010). Due to topography, low-lying islands are more susceptible to saltwater inundation from
15 sea level rise and storm surge overwash.

Previous modeling studies have investigated aspects of climate change impacts on the freshwater lenses of islands or coastal aquifers. Simulations of decreased recharge resulted in more saltwater intrusion and impact to water supply infrastructure than simulations of sea level rise alone (Rasmussen et al., 2013). However, for regions with
20 future projected increases in recharge, the impact of sea level rise and other stresses (i.e. increases in pumping) may be counteracted by increased recharge (Sulzbacher et al., 2012). Analytical and numerical models of sea level rise indicate that the degree of saltwater intrusion (or loss of freshwater lens volume) resulting from sea level rise depends on many factors. Whether the hydrogeological system is recharge-limited or
25 topography-limited (Michael et al., 2013) influences whether or not the water table rise that accompanies sea level rise can be accommodated by the system. Werner and Simmons (2009) showed that less saltwater intrusion is expected when the system is recharge-limited (flux-controlled). Unsurprisingly, the degree of land surface inundation was found to control the amount of saltwater intrusion (Behzad et al., 2013), and the

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impact of sea level rise on saltwater intrusion is enhanced by groundwater extraction from coastal wellfields (Bobba, 2002; Langevin and Zygnerski, 2013).

Models of storm surge overwash events have been developed to evaluate their impact on the freshwater lens. Most of these models used codes that neglect the surface domain. However, Yang et al. (2013) used a fully-coupled subsurface and surface approach that simulated tidal activity, coastal flow dynamics, and a hypothetical storm surge on a coastal aquifer. All models indicate initial salt contamination of the freshwater lens, which recovers to fresh concentrations over time due to fresh water recharging at surface and density-driven downward migration of salt water (Terry and Falkland, 2010). The occurrence of multiple storm surges (Anderson, 2002) and accumulations of salt water at the surface in low depressions (Chui and Terry, 2012) may increase the time for recovery of the lens. Where the vadose zone becomes thinner under conditions of sea level rise (because the freshwater lens has risen in the subsurface), the impact of storm surge alongside sea level rise may result in less salt contamination of the freshwater lens (Chui and Terry, 2013). However, the salt contamination that does occur under sea level rise conditions remains close to the surface of the lens (Terry and Chui, 2012). Wider islands generally result in less freshwater lens contamination than narrow islands, as a result of their thicker lens morphology (Chui and Terry, 2013).

Although many aspects of climate change impacts on freshwater lenses have been modeled previously, few studies have investigated both the spatial and temporal response of the freshwater lens to the stressors. Climate change related stressors operate at various spatial and temporal scales: island-wide impacts due to sea level rise and changes in recharge occur over long time periods, on the order of decades, whereas local-scale impacts due to storm surge overwash occur over short time periods, on the order of days. This study evaluates the spatial and temporal response of an island freshwater lens to various climate change stressors using a numerical modeling approach. To account for the varying temporal and spatial scales of the stressors, two different density-dependent flow and transport modeling codes are used. SEA-WAT (Langevin et al., 2007) models were developed at an island scale to simulate

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long-acting stressors, including sea level rise and change in recharge. HydroGeo-Sphere (Therrien et al., 2010) models were developed at a local scale to simulate storm surge which is a short-acting stressor. The study aims to identify critical factors and stressors that may affect freshwater resources of small, low-lying islands using Andros Island in the Bahamas as a representative island. The results of the study are intended to be applicable to other islands with similar hydrogeological settings.

2 Site description

The study site is Andros Island in the Bahamas. Andros Island has undergone limited development and groundwater exploitation; therefore, the hydrogeological data collected in the 1970s (Little et al., 1973) are considered generally representative of current conditions and can be used for baseline model calibration. Andros Island is representative of other low-lying carbonate islands with thin freshwater lenses commonly found throughout the Caribbean and South Pacific regions (Falkland, 1991; Vacher and Quinn, 1997).

Andros Island is the largest island in the Bahamas, and is located approximately 200 km southeast of Florida (Fig. 1). It is approximately 14 000 km² in area and is comprised of several smaller islands and cays. The highest elevation on the island is 20 m a.s.l. along a ridge that parallels the east coast, whereas lower elevations (< 1 m a.s.l.) are common towards the west. The western coastline is largely composed of wetlands and saltwater marshes, and therefore, the majority of settlements are situated along the east coast of the island (Fig. 1). The remainder of the island is largely covered in pine forest. There are no permanent surface water bodies on the island.

Andros Island is located on the Great Bahama carbonate bank (Fig. 1). The geology of the island is predominantly Pleistocene Lucayan Limestone Formation, which is approximately 40 m thick (Beach and Ginsburg, 1980). Discontinuity surfaces (unconformities) within the limestone are present as layers of paleosols recurring in the upper stratigraphy (Beach and Ginsburg, 1980). These layers represent episodes of

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sub-aerial exposure and are largely concentrated within the top 20 m (Beach and Ginsburg, 1980; Boardman and Carney, 1997). Underlying the Lucayan is a cavernous, highly karstic, and relatively more permeable unit termed the pre-Lucayan, which is present from approximately 43 m below ground surface (m b.g.s.) to at least 75 m b.g.s. (Boardman and Carney, 1997). The geology below this depth has not been observed as most studies focus on the shallow, freshwater-bearing units; however, deposits of carbonates on the Great Bahama bank are estimated to be up to 7 km thick (Cant and Weech, 1986).

Due to its large size, the freshwater lens on Andros Island represents the principal source of natural fresh water for the Bahamas. The majority of local residents rely on the municipal potable water supply system, which extracts groundwater from the lens via 11 wellfields distributed across the island (Fig. 1). The largest of these wellfields is the North Andros Wellfield. As is common with many freshwater lenses, there is potential for upconing of the underlying saltwater and degradation of the lens if wells are deep and the lens thin (Werner et al., 2009; White and Falkland, 2010). Therefore, the wellfields on Andros employ horizontal trench-based groundwater extraction or a series of interconnected shallow boreholes pumped at low rates. Typical depth of the wellfields is between 1 and 5 m b.g.s. Water flows within the trench-based wellfields under a very low gradient, towards a central low sump where water is pumped to storage reservoirs.

The hydrogeology of Andros Island is based on previous studies, most of which were conducted around the wellfields and other developed areas. The principal aquifer is the Lucayan Limestone as the older (deeper) geological units are too permeable and thus are not able to prevent fresh water from mixing with the surrounding saltwater (Cant and Weech, 1986; Schneider and Kruse, 2003). Soil zones are sparse, and minimal runoff occurs during precipitation events (Little et al., 1973; Tarbox, 1987). The freshwater lens is recharged solely through infiltrating precipitation, which generally occurs during the wet season from May to October (Bukowski et al., 1999). Average annual precipitation in the south is 39 % less than average annual precipitation in the north of Andros Island (Cant and Weech, 1986; Bahamas Department of Meteorology, Climate

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Averages 1979–2000). Based on resistivity surveys conducted in the north of the island, the thickness of the freshwater lens ranges from 3 to 20 m (Wolfe et al., 2001); however, previous studies cite the maximum thickness as 34 m (Cant and Weech, 1986) and borehole salinity profiles indicate the maximum thickness of the lens is up to 39 m (Little et al., 1973). The lens is generally shallower in the southern regions of Andros Island compared to the northern regions, with a measured thickness of at least 15 m b.g.s. (personal communication, 2013, municipal water supply managers, Bahamas Water and Sewerage Corporation). The elevation of the lens inland is approximately 2 m a.s.l. (Ritzi et al., 2001) with typical depth to water of approximately 1–2 m b.g.s., although it is deeper (up to 5 m b.g.s.) under the high topography ridge along the east coast (Little et al., 1973; Boardman and Carney, 1997). The hydraulic conductivity of the principal aquifer (Lucayan Limestone) is estimated to range from 86 to 8640 m day⁻¹ based on short duration, single-well specific capacity pumping tests conducted in the 1970s (Whitaker and Smart, 1997). The hydraulic gradient (ranging from 0.0005 to 0.001) was determined from historic field observations and estimates of the freshwater lens morphology (Little et al., 1973). Porosity ranges from 10–20 % (Bukowski et al., 1999). Sparse hydrogeological field data are available for the majority of the island; therefore, in the past, the morphology of the freshwater lens was largely inferred based on vegetation patterns, geological setting and anecdotal observations. Because Andros Island is composed of several small islands and cays, the freshwater lens is also composed of multiple lenses present on the different land masses. Lenses are anticipated to be present across most of the island, except in areas that are heavily intersected by saltwater marshes and wetlands.

In September 2004, Hurricane Frances caused a storm surge on the west coast of Andros Island, which resulted in extensive salinization of the North Andros Wellfield (Fig. 2). The hurricane ranged from a Category 4 to Category 2 on the Saffir Simpson Hurricane Scale while it travelled across the Bahamas from the southeast to north-west (Franklin et al., 2006). The surge occurred 3–4 September 2004, while Hurricane Frances passed near Andros Island. The exact time of occurrence of the storm surge

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and the actual extent of the overwash are unknown because the western coast of Andros Island is largely unpopulated. However, after the hurricane had passed, evidence of the overwash was observed, such as flooded ground and the presence of marine fish at inland locations (Bowleg and Allen, 2011). The likely extent of the overwash is thus based on observations of damage following the surge (e.g. water marks on trees, presence of seaweed and marine organisms, etc.) and is shown on Fig. 2.

Salinity concentration data from the southern wellfield (Fig. 2) were provided from the water managers for the dates: May 2004 (pre-storm), 7 September (immediately post-storm surge), 15 September (following remedial action) and July/August 2005 (approximately one year post-storm surge). These data are presented on Fig. 3, which illustrates the abrupt increase in salinity within the trenches following the storm surge and the eventual recovery to pre-storm concentrations. As a form of remedial action, the contaminated trenches were pumped to remove the ponded seawater beginning on 8 September (approximately 4 days following the storm surge). Salinity in the affected trenches improved, reducing by up to 88 % on 15 September, relative to the maximum recorded concentrations in each trench. However, remedial pumping of the trenches was not completed because fresh water was required to support post-hurricane relief efforts on other islands. Therefore, some of the contaminated trenches were closed off from the wellfield system to allow for extraction of fresh water from the unaffected parts of the freshwater lens and were not drained. Several of these contaminated trenches remained closed for two years due to poor water quality. Trenches that were drained are distinguished from those that were not in Fig. 3. The wellfield eventually recovered to normal salinity concentrations between one and two years post-storm, with all trenches recovered by 2009.

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hydraulic properties is supported by model calibration. Assigning a low conductivity to the paleosols resulted in the lens being perched, which is not observed in the field. Whereas, representing the paleosols as high conductivity layers within lower conductivity limestone resulted in thin lenses being developed, similar to field observations. This approach is consistent with other studies based in the Bahamas, which have suggested that layers of high hydraulic conductivity in the subsurface are responsible for thin freshwater lenses (Wallis et al., 1991). The optimal configuration of aquifer layers and hydraulic conductivities are provided in Table 1.

Recharge was applied to the top layer of the model with concentration of 0 g L^{-1} salt to simulate the average annual recharge to the aquifer. Recharge is the only input of fresh water to the hydrogeological system and, therefore, is the main mechanism by which the simulated freshwater lens develops in the model. The annual recharge amount for Andros Island was estimated using the United States Environmental Protection Agency's software HELP (Hydrologic Evaluation of Landfill Performance) (Schroeder et al., 1994). HELP utilizes a storage routing technique based on hydrological water balance principles. It accounts for soil moisture storage, runoff, interception, and evapotranspiration. HELP has been used to estimate recharge for a variety of climatic and physiographic settings (Scibek and Allen, 2006; Jyrkama and Sykes, 2007; Toews and Allen, 2009; Allen et al., 2010).

Within HELP, a representative vertical percolation profile was defined for the unsaturated zone. The depth of the profile was 2 m, based on a sensitivity analysis using the minimum and maximum observed depths to the water table on Andros Island. No soil zone was specified due to the generally thin/absent soils on Andros Island (Little et al., 1973). The lithology was homogeneous (representing limestone), with a saturated hydraulic conductivity (864 m day^{-1}) based on the mean value from field studies (Little et al., 1973) and the calibrated value from the baseline SEAWAT model. Vegetation cover was assigned to the highest class in the software (a leaf area index of 5) based on the large proportion of pine forests. The surface was assigned zero slope given that

seasons (between 2.8–3.2 °C). Changes to precipitation are projected to occur primarily during the summer (up to 42 % reduction relative to current conditions). Overall, the projected climate shifts represent conditions with less precipitation and higher temperatures – a drier and hotter climate state.

Changes to groundwater recharge were determined by re-modeling recharge in HELP using the projected 2090s climate. The seasonal climate shifts (applied evenly to each month according to season) were applied to the monthly normals for temperature and precipitation in the weather generator, and a new stochastic weather series was generated to represent the projected future climate. This approach is consistent with that used in other studies (e.g. Scibek and Allen, 2006). The adjusted climate data series was then used as input to the vertical percolation profile to determine the annual average groundwater recharge expected under projected climate change. As in the baseline recharge modeling, recharge estimates were produced for North and South Andros, and these values were applied to the SEAWAT models for each region, respectively.

Sea level rise was simulated by increasing the elevation of the specified head boundaries in the model domain. Loss of land surface due to inundation associated with sea level rise was not simulated, as the grid resolution of the model is larger than the inundation anticipated based on ground surface elevation. Therefore, the boundaries at the edge of the model domain are anticipated to remain at the same model grid cell, only representing a higher specified head value. Although sea level rise has been already observed over the last several decades (White et al., 2005), there is uncertainty as to the rate that it will occur in the future (Rahmstorf, 2007). Geographic variability in the rates of sea level rise is also expected (White et al., 2005). Therefore, a predicted mean sea level increase of 0.6 m by the 2090s (relative to 1980) was selected as an average estimate based on global and regional projections of sea level rise (IPCC, 2007; Rahmstorf, 2007; Obeysekera, 2013). The hydrogeological system of Andros Island is considered recharge-limited rather than topography-limited, because there is

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also falls within common definitions of fresh water containing less than 1.0 g L^{-1} of total dissolved solids (Freeze and Cherry, 1977; Barlow, 2003). The World Health Organisation (WHO) drinking-water guidelines do not stipulate a maximum threshold for salt in water, except as it relates to unacceptable taste. The WHO recognizes that water that tastes fresh often has a salt concentration of less than 0.25 g L^{-1} ; however, in regions where there is naturally more salt in the water there may be a higher taste threshold (WHO, 2011).

3.2 HydroGeoSphere model: short-acting stressor

Modeling the impact of storm surge overwash on a hydrogeological system involves simulating density-dependent flow and solute transport across the surface, the vadose zone and the saturated domain. HydroGeoSphere (HGS) was identified as the most suitable tool to simulate these coupled processes because it is a fully integrated surface and variably saturated subsurface model that is capable of simulating these processes across all domains. By solving the surface and subsurface flow equations simultaneously, HGS provides more realistic representations of the major processes than simpler or independently coupled models (Goderniaux et al., 2009).

One of the mechanisms of aquifer contamination following storm surge is from open wells or trenches that provide direct access to the water table and collect the salt water during inundation (Terry and Falkland, 2010). In addition, salt water trapped within a borehole, or other direct pathway into the aquifer, may lead to prolonged release of salt water into the surrounding aquifer over time (Illangasekare et al., 2006). These features may delay recovery of the aquifer and, therefore, are an important component to include in modeling studies of storm surge impacts (Chui and Terry, 2013). Major consequences to water supply are likely to result when storm surge waves strike trench-based wellfields or open boreholes, as occurred on Andros Island in 2004. Notwithstanding this risk, trench-based wellfields are commonly used on low-lying islands to limit upconing. The models developed for this study aim to characterise aquifer damage

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and recovery from a storm surge overwash, specifically in the context of a trench-based wellfield and the impact on water supply.

The model domain represents a highly discretized, two-dimensional cross-section of one of the trenches in the North Andros Wellfield (Fig. 4). The size of the model domain had to be made as small as possible for computational reasons. Therefore, several different model configurations were tested by varying the model domain width and the hydraulic conductivity distribution (limestone and paleosols) to identify the optimal combination of parameters that best approximates observed conditions. The physically-based seawater boundaries are important components in simulating flow within a freshwater lens. In reality, these boundaries are located along the coastline; however, the coastline is far from the North Andros Wellfield. Therefore, local-scale models were developed using boundary conditions assigned in such a way as to simulate a realistic flow field surrounding the trench. The local-scale models were calibrated based on critical factors that are expected to affect freshwater lens contamination and recovery. These critical factors include: recharge, thickness of the vadose zone, aquifer hydraulic conductivity, geological heterogeneity (e.g. paleosols), water table gradient, and thickness of the freshwater lens. Field data for each of these factors (as presented earlier) comprise the calibration criteria as summarised in Table 3.

With increasing model domain width, the elevation of the water table and gradient both increase, whereas the thickness of the lens decreases. The opposite response was observed when hydraulic conductivity was increased. The model setup that satisfied the calibration criteria with the smallest domain width was selected as the baseline model for this study (Fig. 4).

The model uses block elements that range from 0.35–1.0 m. Grid refinement was done in order to optimise simulation of flow and transport across the three hydrologic domains and to allow for the evaluation of small-scale changes in response to overwash. The model domain covers a horizontal extent of 2400 m and a vertical extent of 43.5 m, with sea level assumed to be 3.5 m b.g.s. The vertical extent of the domain was determined to represent the Lucayan Limestone. The model domain was 1 unit

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conditions are changed to reflect the different scenarios. The three phases are required to accommodate the different temporal scales (i.e. decades for lens development and minutes for storm surge occurrence) as well as to assign the time-varying boundary conditions. Most model simulations used the same initial steady state freshwater lens (Phase 1) and simulation of the storm surge overwash (Phase 2). Different scenarios of remedial action were simulated for Phase 3 and compared to the baseline recovery scenario.

3.2.1 Phase 1: freshwater lens development

Phase 1 is a model spin-up period during which the freshwater lens develops. The initial concentration in the baseline model domain was salty (35 g L^{-1}), with the only source of fresh water being recharge. The model was run for 50 years to reach steady state.

3.2.2 Phase 2: storm surge inundation

Phase 2 simulates the occurrence of a storm surge overwash event. The surface domain was inundated with up to 1 m of water, based on observations following the 2004 storm surge on Andros Island. Flooding was simulated at a gradual rate of 0.1 m per 10 min stress period to satisfy model convergence criteria. Once full inundation was reached (1.5 h after start of flooding), the maximum flood level was held constant for 2 h. The actual period of inundation is not known, so this period was estimated to allow for sufficient salt water to enter the system. The salt concentration of the flood water was assigned as 35 g L^{-1} to represent seawater.

3.2.3 Phase 3: recovery of the freshwater lens

Phase 3 involved simulating the recovery of the freshwater lens. Several different scenarios were tested to enable comparison of recovery times when different factors are varied. All scenarios are based on the output from Phase 2, with the head and

concentration boundaries of the surface domain unconstrained to allow release of the salty flood water. All other boundaries remained the same as the initial Phase 1 model.

A baseline recovery scenario was simulated for 10 years following the storm surge to allow the salt water to be flushed out of the system under the influence of recharge.

5 In the baseline recovery model, the freshwater lens returns naturally to its original morphology.

Several other scenarios were simulated to represent different remedial actions. Following a storm surge event when the trenches are filled with salt water, a common remedial action is to drain out the trenches to remove the captured salt water (Illangasekare et al., 2006; Terry and Falkand, 2010; Chui and Terry, 2012). Draining, or pumping out the trenches, is meant to improve the recovery time and assist with removal of the salt water from the system. However, draining may often be delayed due to access constraints or due to lack of coordination and emergency response following the storm surge. Therefore, models were developed where the trenches are drained at different times and for different durations to evaluate the impact of draining protocol on recovery times of the freshwater lens and impact to water supply. Scenarios were modeled whereby draining was delayed by one, two, three, or four days after the storm surge (to reflect a delay in action). Other scenarios modeled draining initiated one day after the storm surge, whereby the duration of draining was one, two, or three days (to investigate the effect of sustained periods of draining).

For all recovery simulations, observation points were assigned within and immediately below the trench to monitor salt concentrations during recovery. This allowed for the comparison of recovery times between different scenarios, specifically the number of days for potable water to return to the trench and aquifer.

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4 Results

4.1 Long-acting stressors

4.1.1 Baseline model

The simulated freshwater lens in the baseline model provides a snapshot of the average annual freshwater lens morphology. The model results indicate that a thin lens is present throughout most of the model domain (not shown); however, this study focuses on areas considered viable to provide a sustainable water supply, which are defined as having a lens thickness of greater than 2 m (Fig. 5). The shape of the lens is relatively symmetrical in cross-section with an average hydraulic head of 1.8 m a.s.l., which corresponds to typical elevations observed of 2 m a.s.l. The estimated total area of the viable freshwater lens on Andros Island is approximately 2000 km² with a volume of 3.93×10^{10} m³.

The baseline model was calibrated to observations, where available, although these were sparse and based on varying time periods (from the 1970s to early 2000s). The extent of the lens generally corresponds to observations of freshwater occurrence (i.e. the presence of wells and wellfields) and the results of previous studies (Little et al., 1973; Cant and Weech, 1986; Wolfe et al., 2001). The freshwater lens in the northern model is composed of a single lens that is much larger than the smaller, separate lenses in the southern model. Along the coastlines, particularly in the southern regions of the island, the simulated freshwater lens tends to be situated further inland than is observed; however, the depth of the simulated lens in the south is consistent with field observations. The depth of the simulated lens in the northern regions of Andros Island falls within the range of maximum observed lens depth (up to 39 m b.g.s.), although it is slightly deeper than typical observations of around 15 to 20 m b.g.s. Because most of the model parameters are based on field data and sensitivity analyses, the deeper simulated lens is likely the result of slight over-estimation of recharge in the HELP model. HELP applies daily precipitation to the lithology profile evenly over a 24 h period,

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when in reality, precipitation events occur within shorter time intervals (hourly) and leads to some pooled water on the ground surface. Given that the intensity of the precipitation events is not accounted for in HELP, the resulting recharge estimates may be slightly over-estimated. However, there is no clear basis upon which the recharge estimates can be adjusted to achieve better model calibration due to the lack of field data for actual evapotranspiration and recharge.

Some local-scale variations are neglected in the model due to the limitations of the large grid cell size required to cover the area of the island, which resulted in a low resolution of the ground surface elevation. In addition, the model was developed to represent the average annual freshwater lens morphology and, therefore, does not include seasonal variation. Although the worst case scenario (e.g. lowest recharge during the dry season) is not accounted for in this study, other studies have shown that there is little seasonal variation in groundwater levels for islands of similar hydrogeological setting (Momi et al., 2005). Overall, the simulated lens is within the range of observed depths, although it represents a slight over-estimation of the freshwater resources in the northern region of Andros Island. The model provides a generalized estimate of the freshwater lens morphology and serves as a reasonable baseline for investigating the impacts due to climate change stressors.

4.1.2 Climate change models

As noted above, the HELP model utilizes site-specific climate averages so that predictions can be made regarding the impact of future climate conditions on recharge. Recharge is projected to decrease by 11 % in the northern model and decrease by 15 % in the southern model by the 2090s relative to baseline (current) recharge. This is due largely to decreases in average annual precipitation, and slight increases in evapotranspiration rates. Minimal changes in soil storage were simulated in the HELP model.

The results of the climate change modeling, including a reduction in recharge and a rise in sea level, indicate that the freshwater lens will reduce in areal extent and

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volume under future climate change conditions. The percent change in freshwater lens area and volume relative to the baseline values are presented in Table 5. For both the northern and southern models, simulations of reduced recharge alone result in the majority of freshwater lens reduction, with sea level rise contributing a smaller proportion of lens reduction. In the southern model, the results indicate a 19% volume loss due to reduced recharge compared to 5% volume loss due to sea level rise relative to baseline morphology. Overall, the freshwater lens in the southern model is predicted to incur a greater percentage of loss of lens compared to the northern model under climate change conditions. The simulated lens at the end of the 100 year simulation is presented, illustrating areal loss of lens relative to the baseline model (Fig. 6).

The simulated time-varying dissolved salt concentrations in the observation wells are shown in Fig. 7. The simulated concentrations at most observation wells indicate that salinity in the lens progressively increases in response to the climate change shifts applied every 10 years starting at 50 years. Prior to 50 years, the model is spinning up from a fully salty state. Dissolved salt concentrations in all of the observation wells reach near steady state between stress periods (only very small changes continue to occur on the order of $10^{-10} \text{ g L}^{-1} \text{ day}^{-1}$). The time to reach steady concentrations is relatively similar in all wells, ranging from 0.5 to 3 years and increasing as the simulation progresses. This indicates that even though the climate change shifts in each stress period are the same magnitude, the freshwater lens takes longer to adjust to the shifts as the cumulative magnitude of climate change increases.

The central wells were placed in areas that were anticipated to be more resilient to stressors, and the peripheral wells were located in areas that were anticipated to be more vulnerable to stressors (thereby showing a more immediate lens thinning). The simulation results are consistent with the anticipated behaviour. The peripheral observation wells have higher dissolved salt concentrations than the central wells because they are situated in the thinner part of the freshwater lens, and therefore, are more likely to intersect the base of the lens. The highest dissolved salt concentrations are in the peripheral well in the northern model, which is located closer to the coast than

the peripheral wells in the southern model. This is because the edge of the northern freshwater lens extends further coastward than the southern freshwater lens. Greater changes in dissolved salt concentration are also observed in the peripheral wells compared to the central wells, as might be expected.

4.2 Short-acting stressor

4.2.1 Freshwater lens development and storm surge inundation

The morphology of the freshwater lens reaches steady state within 25 years at a maximum depth of 23 m below sea level (m b.s.l.) (Phase 1; Fig. 8a). The model meets the calibration criteria outlined in Table 3. The maximum elevation of the freshwater lens is observed in the trench at 1.8 m a.s.l. The vadose zone surrounding the trench is approximately 1.7 m thick. The gradient across the model domain is 0.0015, with an average horizontal groundwater velocity of 0.87 m day^{-1} . The inflections on the sides of the lens at 9 and 14 m b.g.s. reflect the high hydraulic conductivity paleosol layers.

Simulation of storm surge inundation (Phase 2) resulted in high salt concentrations at the surface of the model up to 1 m above ground surface (Fig. 8b). The results of the inundation model are shown for a focus area within 25 m of the trench (focus area indicated on Fig. 8a). Within the 2 h inundation period, the salt water had already been transported into the vadose zone due to the hydraulic gradient associated with the surface flood, and had also filled the trench with salt water (Fig. 8b).

4.2.2 Aquifer recovery

The baseline recovery of the freshwater lens (natural recovery) is shown for six times post storm surge (Fig. 9): 12 h, 1 day, 2 days, 1 month, 2, and 10 years. The baseline recovery scenario indicates that the freshwater lens returns to its original morphology approximately 10 years post storm surge. The salt water is transported from the surface domain into the aquifer system, where it forms a salt plume within the subsurface.

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This plume is flushed out over time due to the infiltrating freshwater recharge. Salt concentration within the trench returns to levels below the potable water threshold within 149 days following the storm surge for the baseline recovery scenario.

The results of the different draining scenarios are shown in Fig. 10, alongside the baseline recovery scenario, as relative concentration data over time, where 1.0 represents salt water and 0.0 represents fresh water. The number of days to reach potable concentration in the trenches is indicated for each scenario. Observed concentration data for the North Andros Wellfield trenches are also presented in Fig. 10. Trenches that were drained following the storm surge, and those that were isolated from the system and not drained, are distinguished by different symbols.

There is little difference in observed concentrations between the trenches that were drained and those that were not. The observed concentrations are similar to the simulated concentrations immediately following the overwash event; however, at one year post-storm surge, the observed concentrations are slightly above the potable water threshold. By two years post-storm surge (not shown), the observed concentrations are similar to the simulated concentrations, and below the potable threshold.

Draining of the trenches generally results in a faster recovery. If draining occurs within one day of the storm surge, potable water returns to the trench by about 120 days (Fig. 10), approximately one month sooner compared to the baseline recovery simulation (149 days). With every day that draining is delayed, it takes longer for potable water to return to the trench (corresponding to the small vertical lines on Fig. 10 for each scenario). After a delay of three days, the recovery time for potable water to return is the same as the case when no remedial action is undertaken. Therefore, the improvements in recovery time are dependent on the timing of draining.

In contrast, the duration of draining (not shown) does not significantly improve recovery times. Draining that occurs for multiple days results in slightly longer times for potable water to return compared to short-duration draining (i.e. over a single day).

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Water and Sewerage Corporation, it is likely that the details of operations were inexact.

6. Lastly, other hurricanes passed near to Andros Island in the weeks and months following Hurricane Frances; however, it is unknown whether any of these caused an additional storm surge event (National Hurricane Center, National Oceanic and Atmospheric Administration (NOAA), 2014).

Although many factors contribute to the uncertainty in the calibration, the recovery models are likely reasonable representations that allow for comparison of the impact of remedial actions on recovery.

5 Discussion

5.1 Long-acting stressors

The loss of freshwater lens area and extent under climate change conditions is attributed more to the impact of changes to groundwater recharge than the impact of sea level rise. These results are supported by other studies, which show that conditions of reduced groundwater recharge (or prolonged drought, which results in reduced recharge) disturb the balance of freshwater outflow necessary to maintain the extent and thickness of the freshwater lens, thereby leading to loss of freshwater resources due to saltwater intrusion (Ranjan et al., 2009; White and Falkland, 2010; Mollema and Antonellini, 2013). In addition, the hydrogeological system on Andros Island is recharge-limited, meaning that the freshwater lens is able to rise in the subsurface in response to sea level rise. Therefore, it is less vulnerable to sea level rise because the freshwater lens is able to maintain a balance between the hydraulic gradient of the fresh and salt water (Michael et al., 2013). This assumption is only valid to a point; for higher magnitudes of sea level rise, the freshwater lens would likely become topographically-limited and, therefore, have a larger response (i.e. loss of lens) due to sea level rise.

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Although sea level rise appears not to be a significant factor for saltwater intrusion on Andros Island, it may increase the island's vulnerability to other events, such as extreme high tides and storm surge overwash. These events have the potential to result in significant impacts to the freshwater lens, as is discussed below.

The northern regions of Andros Island appear to be more resilient to climate change stressors than the southern regions. Several factors contribute to the difference in response between the northern and the southern regions: (1) the south is composed of smaller landmasses, resulting in smaller areas for the freshwater lenses to develop, (2) significantly less rainfall occurs in the south, meaning that there is less recharge to sustain the freshwater lenses, and (3) the topography of the south is generally lower than that in the north, resulting in a slightly lower hydraulic gradient of the freshwater lenses. The combined impact of these factors is that the southern region of Andros Island has smaller freshwater lenses that are more vulnerable to damage from stressors.

The simulated freshwater lens on Andros takes longer to respond to climate change stressors as the magnitude of the cumulative stress increases (i.e. lower recharge and higher sea level). The implication is that as climate change progresses over time, the ability of the freshwater lens to respond to these changes decreases. Because recharge is the main driver of lens formation and maintenance, when the rate of recharge is reduced, the response time of the hydrogeological system is also reduced. This has been observed in laboratory experiments (Stoeckl and Houben, 2012), whereby the lens takes longer to reach steady state when there is reduced input (i.e. specified flux or concentration boundaries) to the system. Therefore, areas where there is less recharge, such as the southern regions of Andros Island, are expected to take longer to react and adapt to stresses to the hydrogeological system.

5.2 Short-acting stressor

Trench-based wellfields result in large salt plumes that develop in the aquifer following a storm surge overwash. This is because the trench provides direct access for inundating salt water to travel into the aquifer. The salt plume remains larger surrounding the

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trench than in the rest of the aquifer throughout recovery, and takes 3 months longer to recover than the surrounding aquifer. This is supported by other studies where it was observed and modeled that areas where salt water pools or is collected during inundation (such as open boreholes or depressions) result in longer recovery times (Terry and Falkland, 2010; Chui and Terry, 2012).

The timing of remedial action (specifically draining of the trenches) is more critical than the duration of draining. It is critical to drain the trenches as soon as possible following a storm surge overwash in order to remove the initial salt load to the aquifer before it is transported deeper into the aquifer. After a certain period of delay, there is no improvement in recovery achieved by draining. This is illustrated in the simulation results as well as the observation data, where there is little improvement in recovery for trenches on Andros Island that were drained after a 4 day delay. The time of this delay threshold, where there is still benefit to be gained in draining the trenches, will depend on many factors, such as the hydraulic conductivity, the groundwater velocity, and recharge rates. For most typical low-lying islands, the delay threshold is likely quite soon after storm surge due to the high hydraulic conductivity of geological materials normally found on low-lying islands (Ayers and Vacher, 1986). Coarser aquifer material may allow for faster salt transport into the aquifer (Chui and Terry, 2012). Although this effect may also speed up recovery, it means that there is a limited time in which to perform remedial action to remove the salt water. On Andros Island, the delay threshold is 3 days. The duration of draining should also be short, because longer durations of draining may result in slower recovery times. This is likely due to the fact that draining of the trenches removes the recharging fresh water, along with the salt water.

6 Conclusions

Stressors act over varying spatial and temporal scales to impact the freshwater lenses of low-lying islands. Both short and long-acting stressors may result in significant loss of freshwater resources. The conclusions of this study are as follows:

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1. The impacts of stressors on the freshwater lens are predicted to occur primarily in areas where the freshwater lens is smaller or thinner, such as the periphery of the lens. Most settlements and related infrastructure are often located near to the coast on small islands, alongside a trend in coastal migration of settlements (Ranjan et al., 2009; Cashman et al., 2010), and therefore, even small-scale changes to the freshwater lens morphology in these areas may have significant implications for freshwater sustainability.
2. Groundwater recharge is identified as a key stressor, where greater impacts to the freshwater lens are observed in areas with lower recharge.
3. The response time of the freshwater lens (time to reach steady state) increases as the magnitude of the stressors increase. With increasing magnitude of change to the hydrogeological system, the freshwater lens takes longer to adjust to the new state.
4. The freshwater lens is generally able to recover from storm surge inundation over time as fresh recharge flushes the salt plume out of the aquifer. Eventually, the freshwater lens returns to the original morphology.
5. Trench-based wellfields increase the potential storm surge impacts on the freshwater lens; however, remedial action (such as draining the trenches) should be undertaken to improve recovery times. The sooner draining occurs, the more improvement in recovery, because, if draining is delayed by too long (in this case, 3 days or more), there is no improvement in recovery. The duration of draining has less effect on recovery and only needs to occur for a short period of time.

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Parameter	Value
Model Domain	200 m deep; lateral extent based on island area
Lucayan/Pre-Lucayan interface	40 m b.g.s.
Paleosol Depths	9–10 m b.g.s. and 14–15 m b.g.s.
Hydraulic Conductivity	Lucayan: 864 m day^{-1} – paleosols: 8640 m day^{-1} – Pre-Lucayan: 86400 m day^{-1}
Specific Storage	$1 \times 10^{-5} \text{ m}^{-1}$
Dispersivity	Longitudinal 1.0 m; Transverse (Vertical & Horizontal) 0.1 m
Specified Head Boundary	0 m a.s.l. along model domain periphery; specified density 1.025 kg L^{-1}
Concentration at Specified Head Boundary	35 g L^{-1} along model domain periphery
Initial Concentration	35 g L^{-1} throughout model domain
Recharge	877 mm year^{-1} (north) and 426 mm year^{-1} (south); concentration 0 g L^{-1}
Time Steps	Initial: 14 min; Maximum: 1 day;

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Table 2. Projected climate shifts for the 2090s, and the resulting projected values for monthly mean temperature and monthly mean precipitation for North and South Andros.

Parameter	D	J	F	M	A	M	J	J	A	S	O	N
Temperature Shift (°C)	+2.8			+3.0			+3.2			+3.2		
Projected Monthly Mean Temperature (°C) North/South	25.2	24.3	24.6	25.3	26.8	28.5	30.4	31.3	31.3	30.9	32.7	27.7
Precipitation Shift (mm)	−2			−18			−24			+12		
Projected Monthly Mean Precipitation (mm) North	45.3	48.3	49.6	47	66.3	90.1	188.7	137.5	210.1	189.5	175.6	97.7
Projected Monthly Mean Precipitation (mm) South	51.0	33.5	36.9	24.4	27.4	88.5	81.2	39.6	56.9	112.0	137.9	103.4

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Parameter	Value
Recharge	877 mm year ⁻¹
Vadose Zone Thickness	1.5–2 m
Water Table Elevation	2 m a.s.l.
Hydraulic Conductivity	86–8640 m day ⁻¹
Gradient	0.0005–0.001
Porosity	0.15
Average Velocity	0.3 m day ⁻¹
Thickness of Lens	15–20 m
Paleosols	9 and 14 m b.g.s.

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S. Holding and
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Parameter	Value
Model Domain	2400 m model domain width; 43.5 m domain depth (representing Lucayan Limestone)
Paleosol Depths	9–10 m b.g.s. and 14–15 m b.g.s.
Trench Dimensions	1 m wide, 2 m deep.
Hydraulic Conductivity	Lucayan limestone: 86.4 m day^{-1} ; paleosols: 864 m day^{-1}
Effective Porosity	0.15
Specific Storage	$1 \times 10^{-5} \text{ m}^{-1}$
Dispersivity	Longitudinal 1.0 m; Transverse Horizontal 0.1 m; Transverse Vertical 0.01 m
Specified Head Boundary	0 m a.s.l. along model domain periphery; specified density 1.025 kg L^{-1}
Concentration at Specified Head Boundary	35 g L^{-1} along model domain periphery
Initial Concentration	35 g L^{-1} throughout model domain
Recharge	877 mm year^{-1} ; concentration 0 g L^{-1}
Time Steps	Initial time step: 0.8 s Maximum time step: 1 day

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Table 5. Percent change in freshwater lens morphology relative to the baseline model for the combined effect of reduced recharge and sea level rise.

Modeled region	% Change area	% Change volume
Northern	−4.1	−5.9
Southern	−16.8	−24.2

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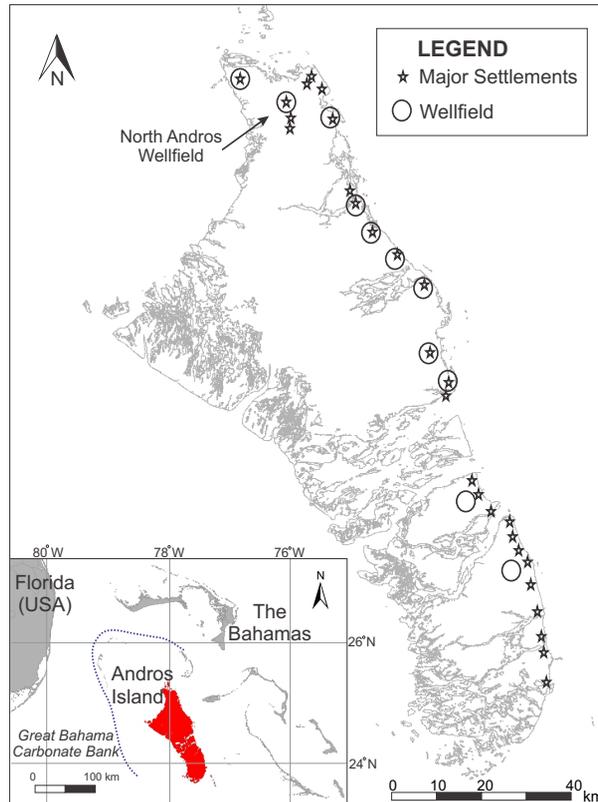
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Figure 1. Andros Island, indicating the location of settlements and wellfields.

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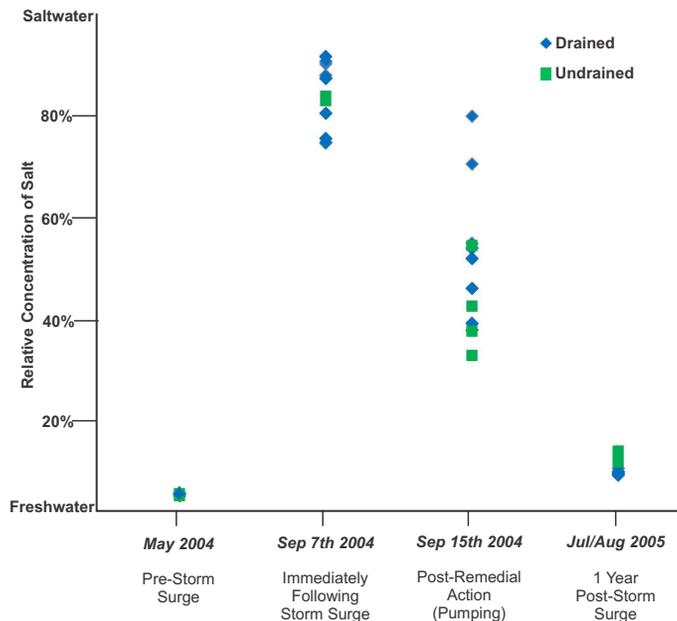


Figure 3. Salinity monitoring data before and after the 2004 Hurricane Frances storm surge. Data are shown for the southern trench segments of the North Andros Wellfield only. See Fig. 2 for the location of the trench segments.

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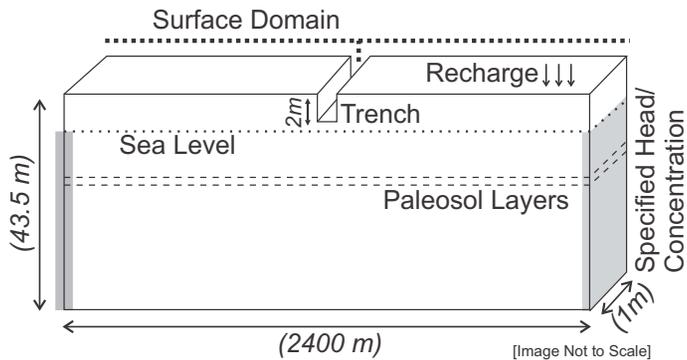


Figure 4. HydroGeoSphere model domain and boundary conditions.

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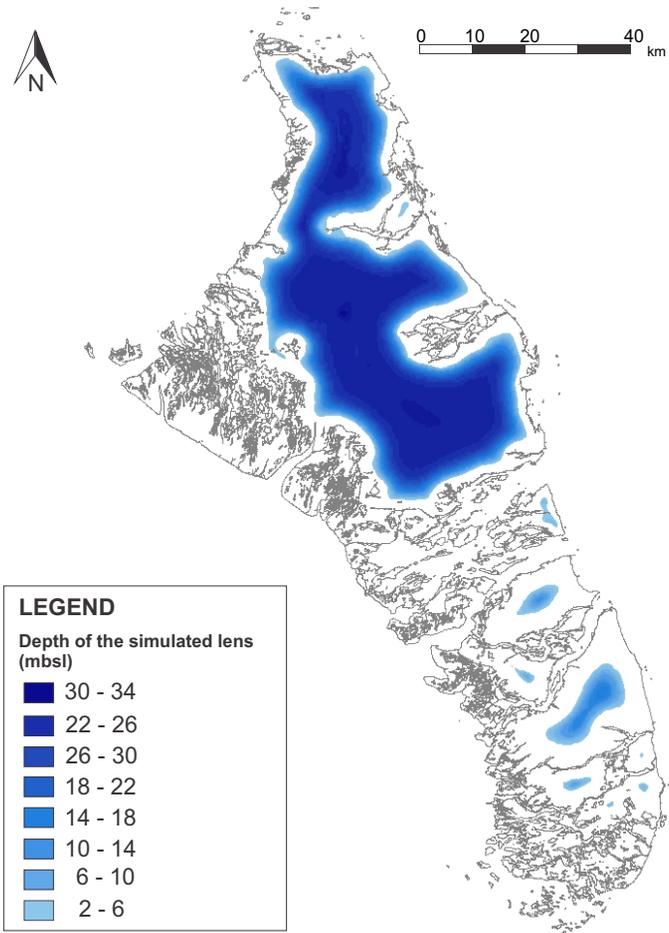


Figure 5. Baseline freshwater lens representing current conditions.

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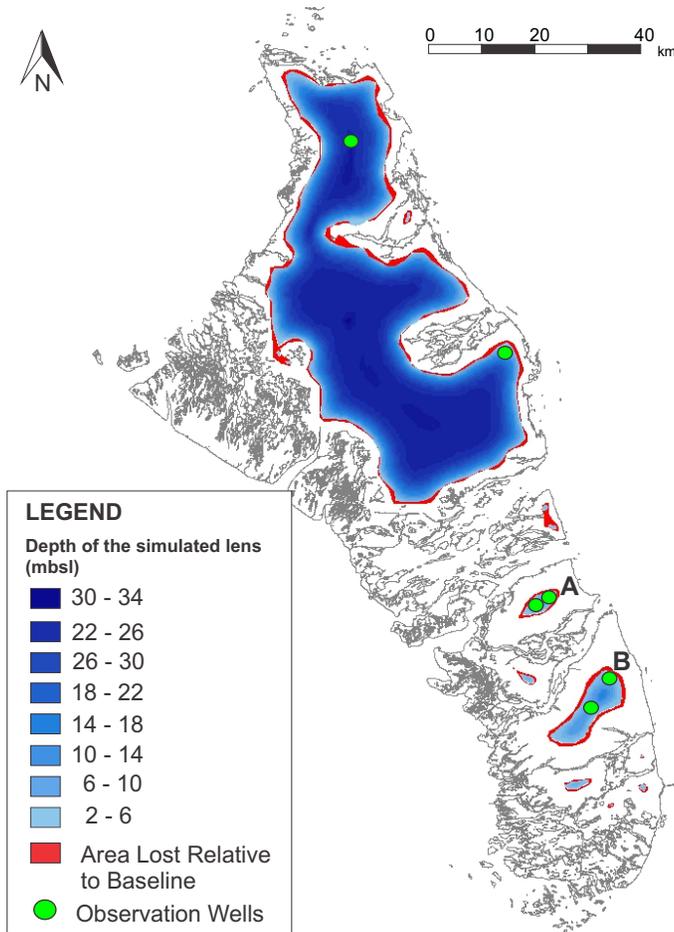


Figure 6. Model result for climate change simulations for the combined effect of reduced recharge and sea level rise, indicating area lost relative to baseline conditions.

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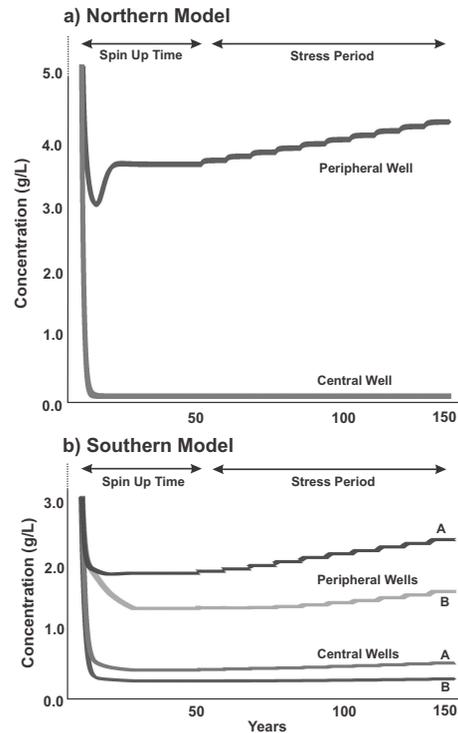


Figure 7. Simulated dissolved salt concentrations over time at the observation wells for climate change models. **(a)** Northern model **(b)** southern model with two observation wells for each landmass shown.

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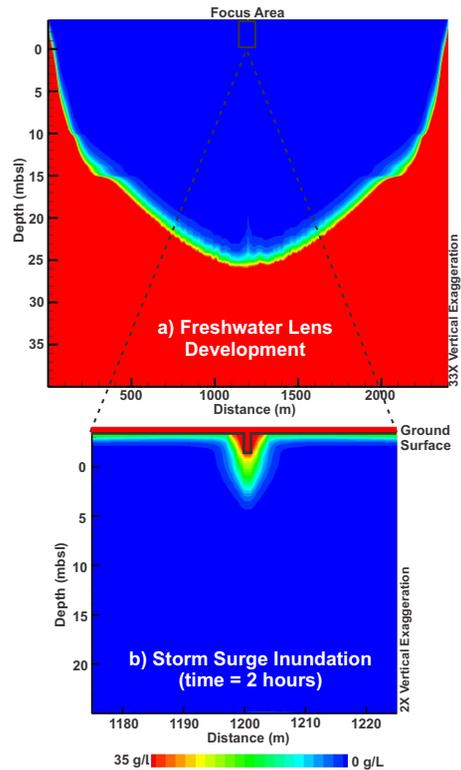
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Figure 8. (a) Freshwater lens development after 50 years (Phase 1), (b) storm surge inundation in the focus area at 2 h (Phase 2).

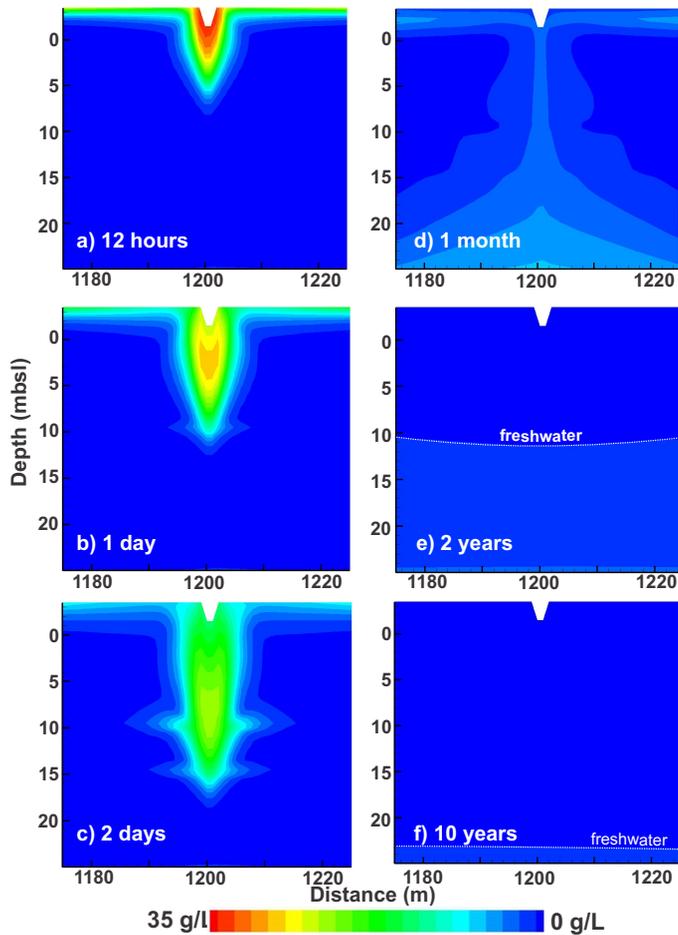


Figure 9. Baseline recovery of the freshwater lens post storm surge at **(a)** 12 h, **(b)** 1 day, **(c)** 2 days, **(d)** 1 month, **(e)** 2 years and, **(f)** 10 years.

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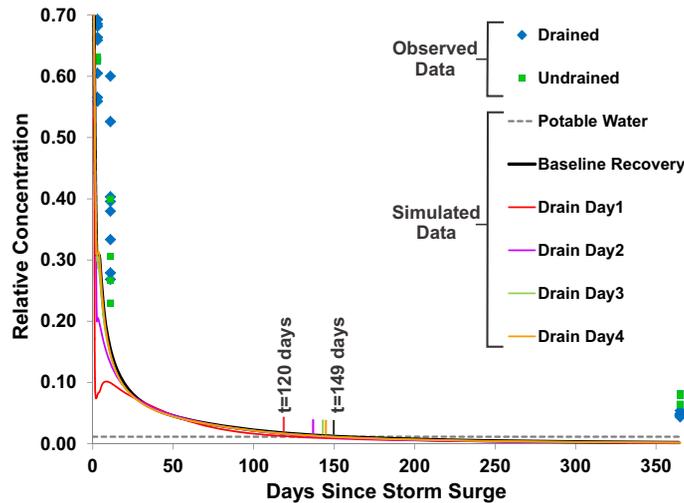


Figure 10. Observed and simulated concentrations within the trench. The times for concentrations to reach potable water threshold are indicated by the small vertical bars for the baseline recovery scenario (149 days) and the various scenarios of draining on different days following the surge (120 days for draining on day 1).

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