Responses to Climate Change and Development Stressors on Small Oceanic Islands

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ABSTRACT

The freshwater lenses of small islands are vulnerable to stressors from climate change and development, in particular: sea level rise, storm surge inundation, changes to groundwater recharge, and increased pumping. This study evaluates the freshwater lens response to stressors on a low-lying limestone island as a case study representative of islands with similar hydrogeological setting. Recharge was modeled using the HELP hydrologic model, and then used as input to a density-dependent flow and solute transport model constructed using SEAWAT. The SEAWAT model was used to simulate altered recharge states, sea level rise and increased pumping. Ongoing work focuses on the lens response to storm surge. Stressors were modeled using scenarios of gradual and instantaneous change to determine the effect of the rate of change of the applied stressor on the magnitude and timing of the lens response. The modeling results were interpreted with geospatial analyses to quantify area and volume of the simulated lens, allowing quantitative comparison of lens morphology between different stressor scenarios. By the 2090s, sea level is expected to rise by 0.6 m and recharge is projected to decrease by up to 15% relative to baseline values. When applied instantaneously to the model, these stressors resulted in a reduction of the FWL volume by up to 42%. If stressors were applied gradually, the overall magnitude of impact to the FWL was reduced, suggesting that solver time stepping may be a factor. Upconing of the underlying saltwater was observed at all wellfield locations under increased pumping, but when climate change was included, the magnitude of upconing increased for all wells.

Keywords: Freshwater Lens, Small Islands, Numerical Modeling, Climate Change, Pumping

INTRODUCTION

The freshwater resources of small islands primarily comprise fresh water lenses (FWLs). The extent and morphology of the FWL is controlled by many factors, including the size, shape, topography, and geology of the island (Falkland 1991; Robins and Lawrence 2000). Groundwater recharge is the primary source of freshwater to the lens, and therefore, factors affecting the amount of recharge to the lens, such as precipitation and evapotranspiration, also have a significant impact on the FWL morphology (Ayers and Vacher 1986). The many factors controlling FWL morphology demonstrate that the freshwater resources of small islands rely on a delicately balanced hydrogeological system. Since the island hydrogeological system is self-contained and the FWLs are limited in size (due to the nature of small islands), there is a low capacity to buffer stresses when imbalances in the system occur. Therefore, the freshwater resources of small islands may be particularly vulnerable to degradation exacerbated by climate change and human activities.

This study evaluates the spatial and temporal response of an island FWL to major stressors including changes to recharge, sea level rise, and increased pumping. The research is based on Andros Island, The Bahamas, which represents a typical low-lying limestone island with a thin FWL, as is common throughout the Caribbean and South Pacific regions (Falkland 1991). Andros Island is comprised of several smaller islands and cays (Figure 1) and is relatively undeveloped, but has the largest FWL in The Bahamas. Groundwater is exploited via municipal wellfields located in 11 communities as well as a limited number of private wells. The southern regions of Andros Island receive approximately 39% less rainfall than the northern regions.

Figure 1. Andros Island with municipal wellfields indicated

METHODS

Recharge Modeling (HELP)

Recharge was modeled using the software HELP (Schroeder et al., 1994), which accounts for components of the water budget such as soil moisture storage, runoff, interception and evapotranspiration. A 100 year baseline climate data series, generated using a stochastic weather generator, was used as input to a vertical percolation column representative of the island. Recharge was then modeled for the 2090s using published climate change predictions for The Bahamas (McSweeney et al. 2010).

Numerical Modeling (SEAWAT)

A three-dimensional density-dependent numerical groundwater flow and solute transport model was developed using SEAWAT to simulate the FWL on Andros Island. The island was divided into a northern and southern model to allow for refined grid resolution and to optimize computational efficiency. The baseline model was calibrated to available field data.

Climate change scenarios were simulated by increasing sea level by 0.6 m and altering recharge to represent the projected climate state for the 2090s. Scenarios of increased pumping were simulated by raising the pumping rate of the wellfields incrementally by up to 10 times the current rate and observing recovery of the lens after pumping was stopped. These stressors were applied to the model both gradually and instantaneously to determine the effect of the rate of change of the applied stressor on the magnitude and timing of the lens response.

RESULTS

The simulation of the FWL in the baseline model provides a snapshot of the average annual FWL morphology (Figure 2a). The northern region of Andros Island has a large FWL, whereas the southern region has several smaller lenses. By the 2090s, recharge will decrease by 11% in the north and decrease by 15% in the south relative to baseline values. SEAWAT simulations of future climate conditions (reduced recharge and sea level rise) result in reduction of FWL areal extent and volume (Figure 2b). Simulations of reduced recharge alone result in the majority of FWL reduction, with sea level rise contributing a smaller proportion of lens reduction. This is likely due to the hydrogeological system on Andros Island being recharge-limited and thus able to accommodate changes in water table elevation (Werner and Simmons 2009; Michael et al. 2013).

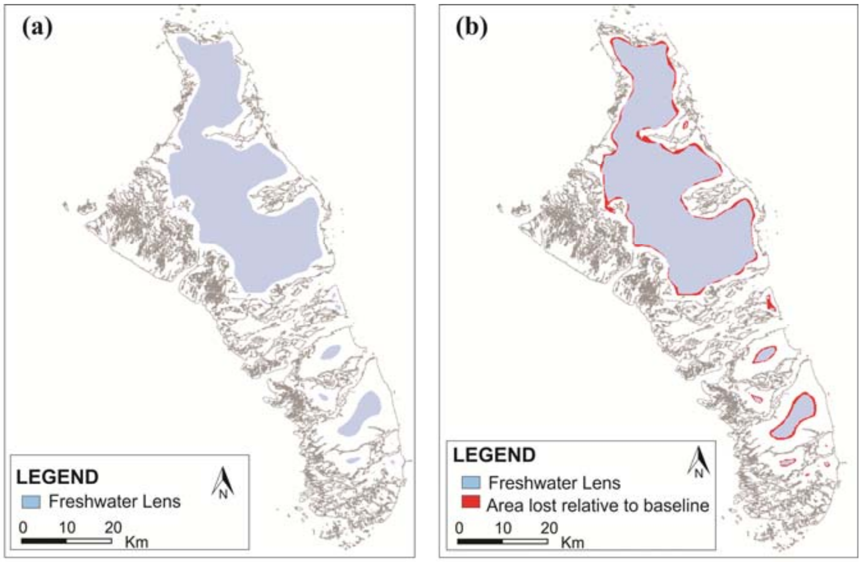

Figure 2. a) baseline FWL; b) climate change FWL (instantaneous shift model)

The gradual shift model had less FWL loss than the instantaneous shift model (Table 1), although the difference in area/volume change was significantly smaller in the northern model due to the larger lens size. In both the northern and southern models, the rate of change in concentration was higher near the periphery of the FWL than in the center of the lens as expected, because here the lens is thinner.

Upconing of the underlying saltwater was observed at all wellfield locations under increased pumping. However, when pumping was simulated under climate change conditions, the magnitude of upconing increased for all wells. In addition, the residual upconing after pumping stopped was larger under climate change conditions, and simulations of the southern model indicated that the FWL was highly degraded with saltwater.

Table 1. **Percent change in freshwater lens morphology relative to baseline model**

Modeled Region	Model Type	% Change Area	% Change Volume
Northern	Gradual	-4.1	-5.9
	Instantaneous	-4.5	-6.1
Southern	Gradual	-16.8	-24.2
	Instantaneous	-25.3	-42.1

CONCLUSIONS

Changes in the area and volume of the FWL were significant for the southern model, given that the baseline FWLs are small and thus more susceptible to change. The greatest impacts to lens morphology occurred along the periphery of the lens, where most settlements on Andros are located. Therefore, even small changes to the FWL can have significant implications for resource sustainability.

The response of the FWL was found to be sensitive to how the stressors were applied to the model. If applied gradually, the cumulative impact to the FWL was less than when the stressors were applied instantaneously. Model time stepping may be a determining factor. This result has important implications for how climate change stressors are applied to models because most modeling studies use instantaneously applied stressors.

The effect of multiple stressors, demonstrated in this study by simulating pumping and climate change together, also reduce the ability of the FWL to respond to and recover from stressors. Therefore, future studies should evaluate the cumulative impacts of stressors and interactions of various factors affecting the FWL. The approach used to characterize the FWL response on Andros Island is transferrable to other low-lying islands with similar hydrogeological setting.

Ongoing work evaluates the spatial and temporal response of the FWL to storm surge inundation and compares the results to the stressors evaluated in this study.

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