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Key Points:

- Sea level rise elevates water tables above low points in surface topography to form lakes on ocean islands
- On islands in arid climates, lake evaporation can reduce fresh water lenses more than coastal inundation
- Loss of fresh water from lakes on arid islands increases most with lake width, then distance of lake from coast and evaporation rate

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Sea level rise and inundation of island interiors: Assessing impacts of lake formation and evaporation on water resources in arid climates

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Abstract Coasts of many low-lying islands will be inundated should sea level rise by 1 m by 2100 as projected, thereby decreasing water resources through aquifer salinization. A lesser known impact occurs if rising sea level elevates water tables above interior topographic lows to form lakes. Impacts of lake formation on water resources, however, remain unquantified. Here we use hydrological models, based on islands in the Bahamian archipelago, to demonstrate that on islands with negative water budgets, evaporation following lake inundation can cause more than twice the loss of fresh groundwater resources relative to an equivalent amount of coastal inundation. This result implies that in dry climates, low-lying islands with inland depressions could face substantially greater threats to their water resources from sea level rise than previously considered.

1. Introduction

Sea level rise poses poorly quantified risks to freshwater resources of nearly 50 million citizens of Small Island Developing States (SIDS) [*Nurse et al.*, 2014]. Many small islands have average elevations near sea level, particularly barrier islands [*Masterson et al.*, 2013] and islands composed of carbonate bedrock [*Vacher and Quinn*, 2004]. Sea level rise can shrink freshwater resources directly, through aquifer salinization and reduced groundwater catchment size following coastal inundation and, indirectly, through the dynamics of freshwater lenses [*Ketabchi et al.*, 2014]. These dynamics are governed by the Ghyben-Herzberg principle (Figure 1a), which states that, at equilibrium, the elevation of the water table above sea level (h) and the depth of the interface of fresh and saline groundwater (z) at the same location are related by

$$z = \alpha h, \tag{1}$$

where α is the density-difference ratio:

$$\alpha = \frac{\rho_f}{\rho_s - \rho_f} \tag{2}$$

and ρ_f and ρ_s are the densities of fresh and saline groundwater, respectively [*Vacher*, 1988]. With typical densities of fresh and marine salt water (ρ_f and $\rho_s = 1000$ and $1025\ \mathrm{kg/m^3}$, respectively), the thickness of the freshwater lens is approximately 40 times the elevation of the water table above sea level [*Vacher*, 1988]. The thickness of the freshwater lens is thus sensitive to changes in water table elevation (h) by a factor of 40 to 1. Modest reductions in water table elevation relative to sea level, such as those occurring from coastal inundation and reduced island area, can therefore result in substantial reduction in the volume of freshwater lenses [*Ketabchi et al.*, 2014] (Figure 1a).

Inundation by rising sea level has been widely considered to mostly threaten only low-lying coastal areas [*Dasgupta et al.*, 2009]; however, closed inland depressions with elevations below future sea levels, common to many barrier islands [*Masterson et al.*, 2013], atolls [*Ayers and Vacher*, 1986; *Woodroffe*, 2008], and other carbonate islands [*Martin and Gulley*, 2010], are also prone to inundation (Figure 1b). Such inundation would be similar to a switch from a recharge-limited to topography-limited coastal groundwater system [*Michael et al.*, 2013]. Some depressions experience transient flooding when water tables are elevated by heavy rainfall, astronomically controlled high tides [*Yamano et al.*, 2007; *Woodroffe*, 2008; *Masterson et al.*,

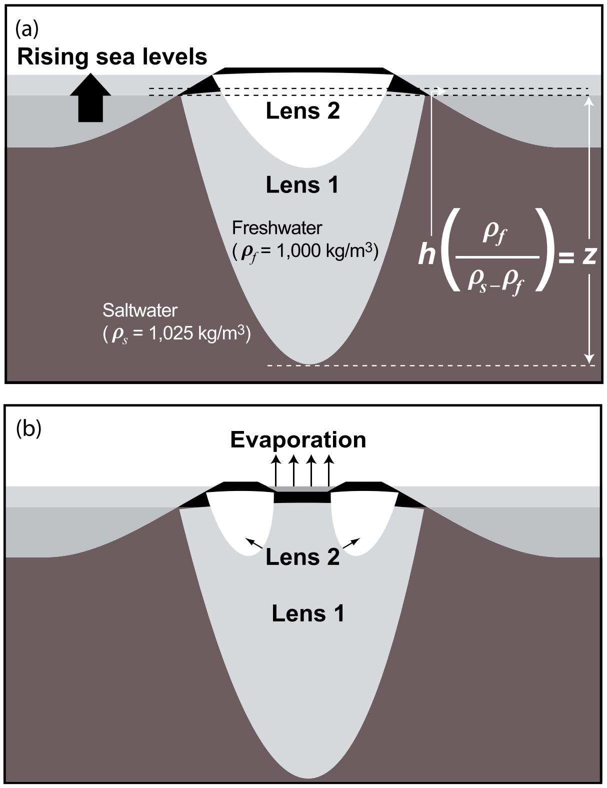

Figure 1. (a) Lens-shaped bodies of fresh water exist on ocean islands due to the difference in density between fresh and saline water (e.g., equations (1) and (2)). Sea level rise reduces island width and lowers water table elevation relative to sea level as the cumulative resistance to groundwater flow decreases. The freshwater lens thickness decreases by a factor of 40× that of the lowering of the water table. (b) Sea level rise elevates the water table relative to the island surface which can raise the water table and flood closed inland depressions to form lakes. These lakes evaporate fresh water from their surface, may allow upconing of salt water similar to withdrawal from wells, and can segment previously continuous freshwater lenses into separate lenses. These segmented lenses have groundwater flow paths that drain toward both the coast and the lake, further lowering water table elevations and enhancing the thinning of the lens (Figures 3a and 3c).

2013; *Rotzoll and Fletcher*, 2013] and regional increases in sea level associated with intradecadal climate oscillations and shifts in oceanic currents [*Sallenger et al.*, 2012].

Permanent flooding of depressions in response to future eustatic sea level rise has been overlooked in previous assessments of impacts to water resources [*Dasgupta et al.*, 2009; *Nurse et al.*, 2014]. The importance of this formation is clear from shallow lakes and other surface water features that formed on carbonate islands and platforms around the world when Holocene sea level rise elevated water tables into surface depressions [*Martin and Gulley*, 2010; *Gulley et al.*, 2014]. These lakes expose freshwater lenses to continuous evaporation with impacts that should depend on the balance of rainfall and evaporation [*Vacher and Wallis*, 1992]. In arid regions where evaporation can exceed annual rainfall, such as the southern Bahamian archipelago, evaporation from modern lakes has led to upconing of saline groundwater, lake, and aquifer salinization and even complete segmentation of freshwater lenses (e.g., Figure 1b) [*Vacher and Wallis*, 1992]. To date, however, no studies have evaluated how freshwater lenses will respond as rising sea levels and water tables form new lakes on islands in arid regions. Consequently, we use numerical simulations in this study to explore how various lake formation scenarios alter freshwater lens volumes on a generic strip island using aquifer and climate parameters from the Bahamian archipelago. These simulations improve understanding of how paleofreshwater lenses responded to lake formation during the Holocene and how projected sea level rise may impact modern low-lying island water resources.

The Bahamian archipelago consists of carbonate islands with similar aquifer compositions that extend 1000 km across a latitudinal water balance gradient, making it an ideal test case for understanding how lake formation may impact freshwater lenses (Figure 2). Rainfall and potential evaporation vary from an average of 1500 mm/yr and around 1350 mm/yr, respectively, in the north (e.g., Grand Bahamas Island) to $<$ 750 mm/yr and around 1550 mm/yr, respectively, in the south (e.g., Great Inagua; Figure 2) [*Whitaker and Smart*, 2004]. The switch from positive to negative water balance occurs around the latitude New Providence Island. With positive water balances, freshwater lenses are continuous and lakes contain freshwater [*Cant and Weech*, 1986]. Freshwater lenses also occur on islands with negative water balances, but lakes range from brackish to hypersaline, causing authigenic mineral precipitation (calcite and halite) [*Cant and Weech*, 1986]. These saline lakes tend to separate island freshwater lenses into separate, smaller lenses (Figure 1b) [*Cant and Weech*, 1986; *Vacher and Wallis*, 1992].

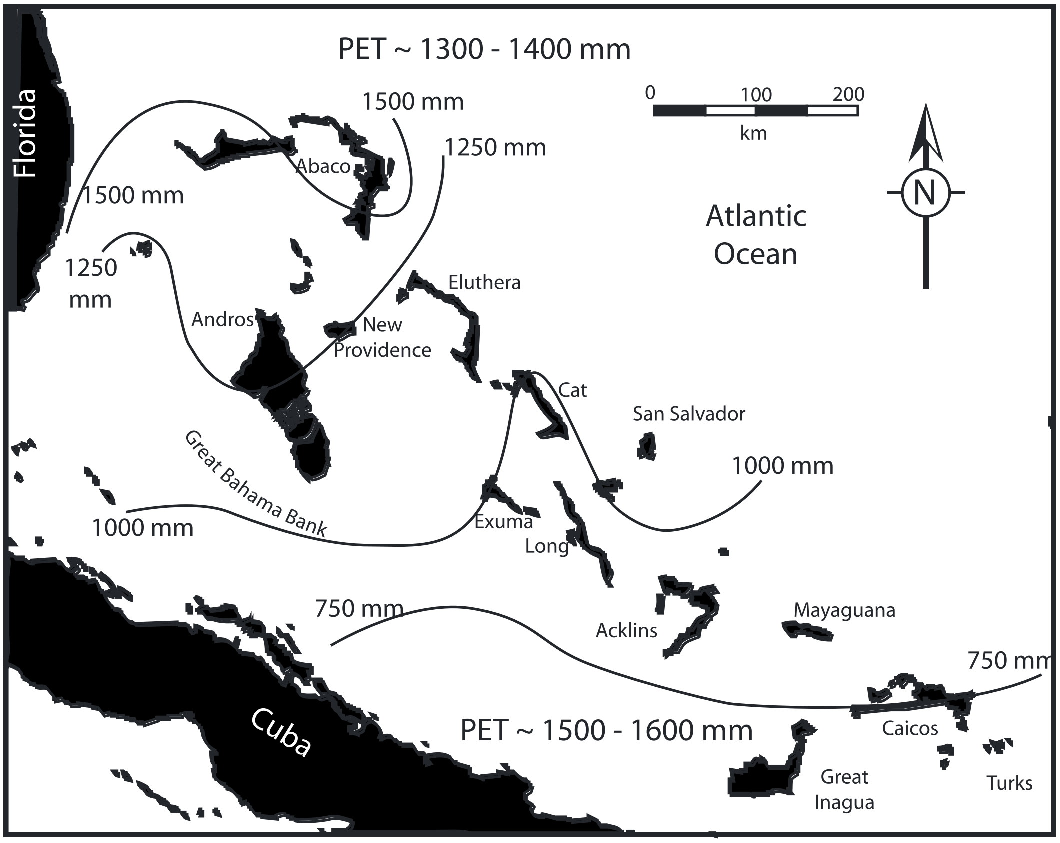

Figure 2. Average annual rainfall (solid lines) and potential evapotranspiration rates across the Bahamian Archipelago. Note that potential evapotranspiration exceeds rainfall south of Abaco. Based on data from *Whitaker and Smart* [2004].

The persistence of freshwater lenses on islands with negative water budgets [e.g., *Cant and Weech*, 1986] may seem counterintuitive. Lenses are able to form in spite of the negative annual water budget because rainfall exceeds potential evaporation some months of the year [*Vacher and Wallis*, 1992] and because some recharge occurs along vadose fast flow routes that are dissolved in the carbonate bedrock [*Jocson et al.*, 2002]. The persistence of freshwater lenses on modern islands with negative water budgets suggests that once recharge reaches the lens, carbonate bedrock protects it from intense evapotranspiration and the full, annual potential evapotranspiration rate is not realized. Where lakes expose water tables, however, there is no barrier to evaporative stresses and the full annual potential evaporation can be realized.

Our models presented here expand on classic studies of carbonate strip island hydrogeology [*Vacher*, 1988] and interactions of lakes with freshwater lenses [*Wallis et al.*, 1991; *Vacher and Wallis*, 1992] by considering how freshwater lenses change in response to lake formation expected from sea level rise.

2. Methods

All simulations assumed steady state conditions and were conducted with SEAWAT [*Guo and Langevin*, 2002] using hydrological properties and meteorological variables that have been employed in analytical models of Bahamian strip islands [*Vacher*, 1988; *Vacher and Bengtsson*, 1989; *Wallis et al.*, 1991; *Vacher and Wallis*, 1992]. The base model of a 1000 m wide strip island consists of 2 m wide and 1 m high cells with 500 and 200 cells in the lateral and vertical directions, respectively. Model parameters include aquifer hydraulic conductivity, porosity, and dispersivity of 50 m/day, 30%, and 1 m, respectively [*Vacher and Mylroie*, 2002; *Holding and Allen*, 2015]. Fluid properties include freshwater density, seawater density, and seawater salinity concentrations of 1000 kg/m^3, 1025 kg/m^3, and 35 kg/m^3, respectively. We use total dissolved solids (TDS) concentrations of ≤ 0.5 kg/m^3 to distinguish between potable freshwater from nonpotable seawater and to represent the boundary of the fresh water lens.

SEAWAT currently lacks the capability of directly simulating lakes. We thus simulate lakes as depressions by increasing the porosity to 100% and the hydraulic conductivity by a factor of 4 in a selected set of top cells of the model grid, so that the lake depths are 1 m, similar to Bahamian lakes [*Teeter*, 1995]. This modeling approach allows water and solutes to be transported by groundwater flow into cells representing lakes, allows for approximately completely mixed conditions in the lake cells, and allows water to be discharged from lakes by evaporation. However, these conditions do not allow salinities to exceed seawater concentrations through evaporation as observed in some Bahamian lakes. The impact of hypersaline lakes is the subject of future studies.

Scenario 1 serves as a reference for all subsequent models by establishing the thickness of a freshwater lens on a 1000 m wide lake-free island with an annual recharge of 20 cm/yr, although Precipitation minus Evapotranspiration (P-ET) is negative in the central Bahamian archipelago (Figure 2) recharge averages 20 cm/yr as determined using Cl concentrations in rainfall as a conservative tracer of ET [*Wallis et al.*, 1991]. To maximize intermodel comparability and because actual recharge rates are poorly constrained across the Bahamas [*Whitaker and Smart*, 2004], we keep land surface effective recharge the same in all models. For scenario 2, we simulate loss of potable water solely from coastal inundation by reducing the island width by 100 m without forming lakes (e.g., Figure 1a). While the model results are applicable to any relative rise in sea level that reduces island width by an equivalent amount, for our island topography, the relative rise in sea level was 0.4 m, a threshold that is predicted to be crossed this century [*DeConto and Pollard*, 2016].

For scenario 3, we simulate impacts of a 100 m wide lake forming in the center of the island (e.g., Figure 1b). Our specific model grid and island slope reflect a relative rise in sea level of 1 m, which is also a plausible rise in sea level by the end of the century [*DeConto and Pollard*, 2016]. Our models are, however, applicable to any sea level rise that results in flooding of inland depressions that are at lower elevations than future sea level. Land surface areas receive 20 cm/yr of effective recharge, but lake areas have an effective lake evaporation of 50 cm/yr. The effective land surface recharge and lake evaporation rates are thus similar to Long, Cat, Exuma, and San Salvador islands.

Because lake positions with respect to island coastlines and widths are variable across the Bahamian Archipelago, subsequent simulations examined impacts of lake widths, lake position relative to island centers, and lake evaporation rate. Effective lake evaporation was changed from 10 cm/yr (similar to southern Abaco) to 60 cm/yr (similar to Crooked Island and Long Island) as a proxy for climate. We simulated lake expansion with sea level rise in increments of 0.1 m; the initial lake had a 100 m base width, lake side slopes of 0.004 m/m, and evaporation of 50 cm/yr. To simulate impact of lake position on lens volumes, we migrated a 100 m wide lake from the island center to within 100 m of the coast and used a lake evaporation rate of 50 cm/yr. We normalize the changes in lens depth by dividing by the lens depth for an island with no lake and thus report the results as fraction changes in the lens depth.

3. Results and Discussion

In simulation 1, a 1000 m wide island with no lake has a maximum potable freshwater lens thickness of ~0.7, with a brackish zone extending down to approximately 1.0 dimensionless depth (Figure 3a). These dimensionless depths correspond to absolute depths of 8 to 11 m for a 1000 m wide island and are similar to Eleuthera, Exuma, and Long islands, which have similar widths and have average maximum lens thickness of 10.2 m, 11.8 m, and 6.2 m, respectively [*Cant and Weech*, 1986]. Coastal inundation that reduces the island width by 10% (scenario 2; Figure 1a) decreases the maximum dimensionless lens thickness by 21% (Figure 3b). In contrast, when 10% of the island is inundated by formation of a central lake (scenario 3; Figure 1b), the freshwater lens splits into two and reduces maximum lens thickness by 47% (Figure 3c). Despite equivalent amounts of inundation, reduction in lens thickness is greater when inundation occurs by elevation of water tables into a central depression than through direct coastal inundation by rising seas (Figure 3d).

Freshwater lens thicknesses depend on lake widths, locations of lakes relative to island centers, and evaporation rates. Expansion of a lake in the center of an island (Figure 4a) from 0.1 to 0.2 of the island width shrinks freshwater lenses from 53% to 12% relative to the lens volume on a lake-free island. Lake position reduces lens volume from 81% for lakes near an island's coast to 53% for lakes in the center of the island (Figure 4b). Increasing evaporation rates from 10 cm/yr to 60 cm/yr decreases freshwater lens volumes from 87% to 49% of the volume of a freshwater lens on a lake-free island (Figure 4c).

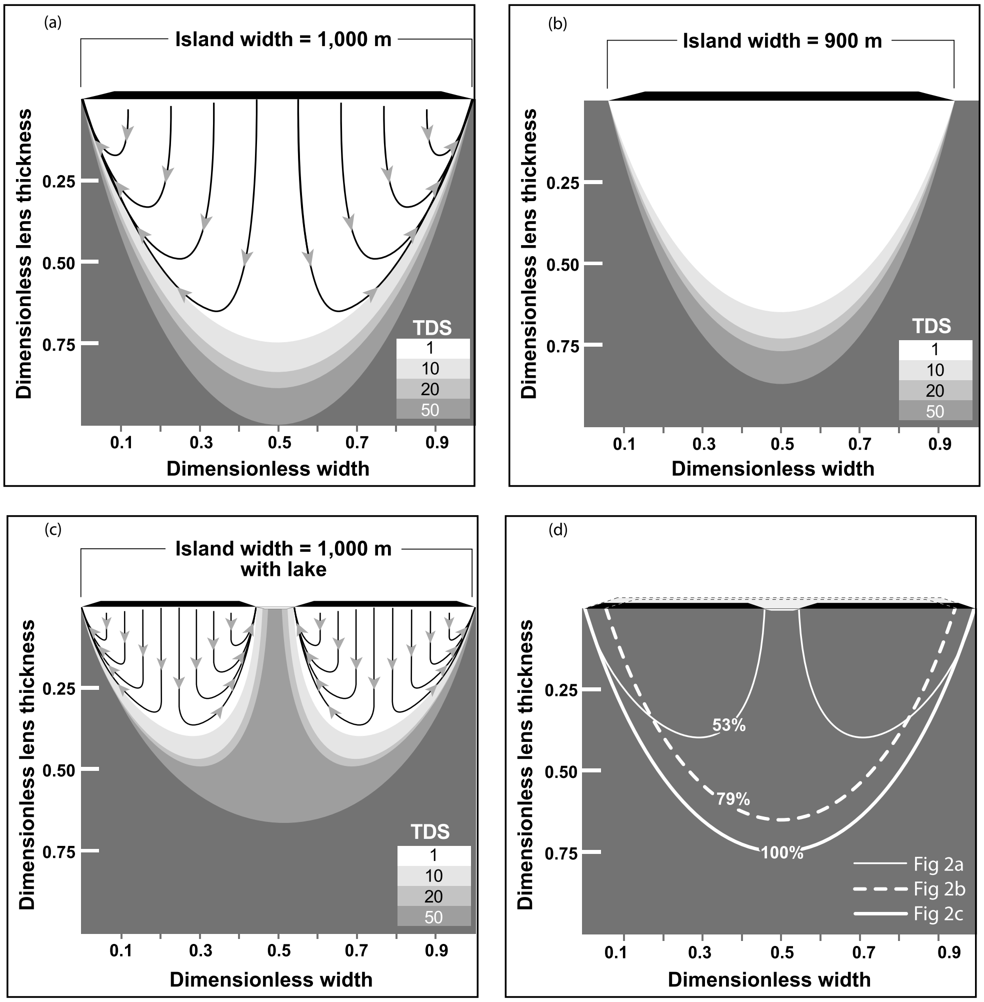

Figure 3. (a, b) Comparison of magnitudes of freshwater lens thinning due to a 100 m reduction in island width from sea level rise (scenario 1) relative to (c) formation of a 100 m wide lake (scenario 2). TDS concentrations are normalized to maximum potable water concentrations (0.5 kg/m^3). Lateral distance is normalized to island width distances (1000 m). Vertical distance is normalized to the maximum depth of the seawater (TDS = 35 kg/m^3 or dimensionless TDS = 50) contour for the nonlake case (11 m). Model parameters (recharge, hydraulic conductivity) are identical for each simulation and are described in Methods. Baseline scenario for all following estimates of lens volume that shows the thickness of and groundwater flow path directions in a lens formed in a 1000 m wide island without lakes (Figure 3a). Thickness of a lens in an island where sea level rise reduced island width to 900 m. Flow paths in this situation would mimic those in Figure 3a (Figure 3b). Groundwater flow paths and thicknesses of two freshwater lenses that remain after sea level rise elevated the water table into a depression to form a 100 m wide lake (Figure 3c). (d) Comparison of the portions of freshwater lenses that contain potable water (defined as less than or equal to 0.5 kg/m^3 total dissolved solids) in scenarios 1 and 2 and the percentage reduction relative to the base case shown in Figure 3a.

Figure 4d summarizes the changes in freshwater lens volume as a function of variations in lake properties and sea level rise. The reduction of freshwater lens volumes is approximately linear with evapotranspiration, lake width, and magnitude of coastal inundation but is curvilinear as lake positions approach the coast (Figure 4d). Increased lake widths decrease freshwater lens thicknesses by approximately 2.3 times that of coastal inundation for a given unit sea level rise. In contrast, increasing the magnitude of evaporation from a lake that is 0.1 times the island width results in about 16% more thinning than coastal inundation alone.

These simulations show that in dry climates such as the Bahamian Archipelago, the presence of lakes, their position on the island, and most importantly lake width reduce groundwater resources more than coastal inundation (Figure 4). While coastal inundation reduces land area available to recharge and shortens groundwater flow paths, forming lakes reduces water resources by acting as large diameter wells that discharge

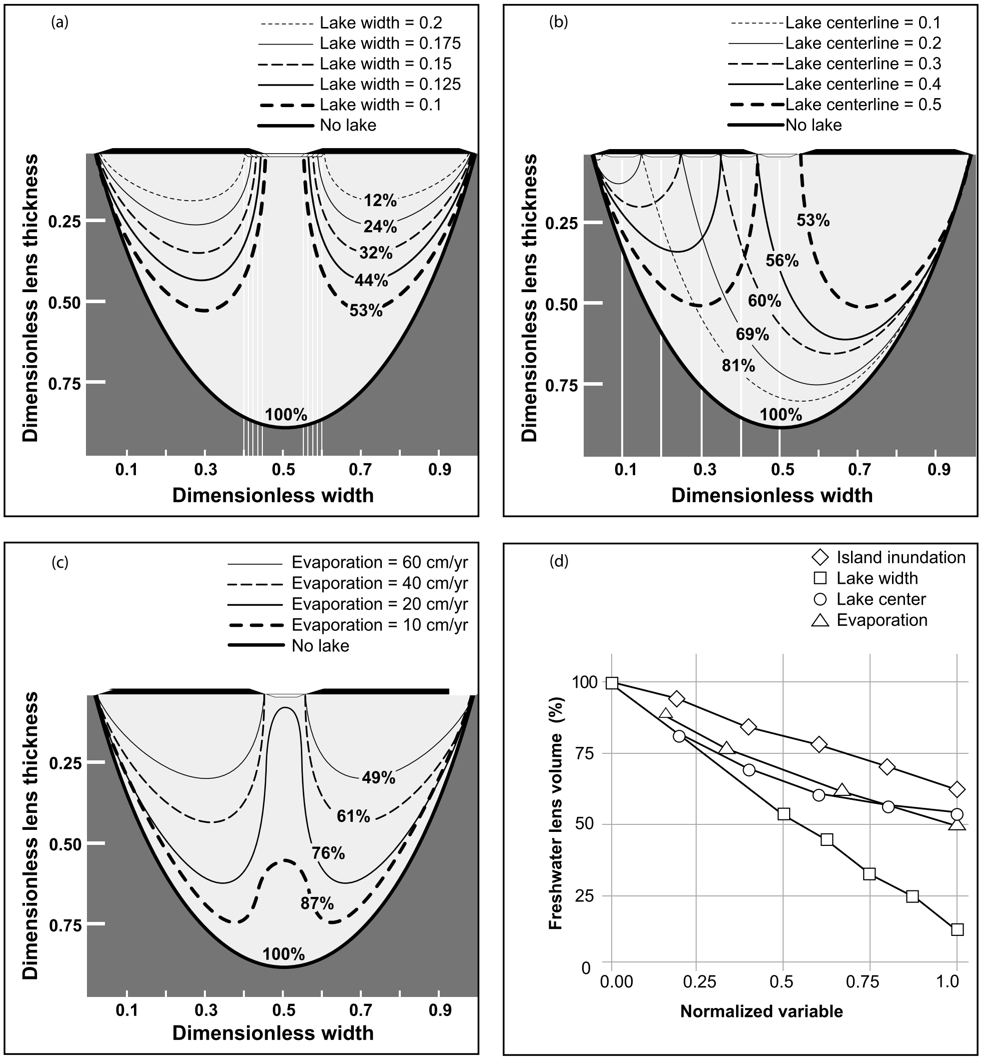

Figure 4. Comparison of different sea level rise and lake formation scenarios on lens thicknesses. Only portions of the lens that contain potable water are shown. Lateral distance is normalized to island width distances (1000 m). Vertical distance is normalized to the maximum depth of the seawater (TDS = 35 kg/m^3 or dimensionless TDS = 50) contour for the nonlake case (11 m). The percentage values show the change in volume of the new lens relative to a 1000 m wide island with no lake (i.e., Figure 3a). (a) Lake width expansion from 0.1 to 0.2 at 0.025 increments, normalized to island width (1000 m). (b) Position of a 100 m wide lake with respect to the island center. Lake positions are indicated for each case, normalized to island width (1000 m). (c) Increasing evaporation rates from 10 cm/yr to 60 cm/yr in a 100 m wide lake in the center of the island. (d) Comparison of the relative impacts of each sea level rise scenarios in Figures 4a–4c, as well as island inundation by coastal flooding (e.g., Figures 3a and 3c), on lens thickness. All changes to lens thickness are in reference to the base case scenario of a 1000 m wide island with no lake and are expressed as a percentage of lens thickness for that base case. Island inundation, lake width, lake center, and evaporation rate are normalized to maximum values (800 m, 200 m, 500 m, and 60 cm/yr, respectively).

groundwater to the atmosphere through evaporation. Lake evaporation locally lowers the water table relative to sea level, raises the base of the fresh water lens, and reorganizes groundwater flow paths (Figures 3a and 3c). Prior to lake formation (Figure 3a) groundwater flow paths radiate toward the coast from a central potentiometric high. Lowering of the lake elevations by evaporation reorients some groundwater flow paths toward the lake (Figure 3c). Lakes forming in the center of an island tend to have greater impacts on lens thinning than coastal inundation because the length of the flow path (and recharge) controls the maximum elevation of the water table above sea level, which controls lens thickness. In contrast, where lakes form close to the coast, one side of the island maintains a larger, continuous water table that has longer groundwater flow paths and higher water table elevations. Consequently, impacts to overall lens thickness decrease as the lake approaches the coast (Figure 4b).

Lakes also exacerbate groundwater resource loss resulting from locally changing climatic conditions that would result in higher effective lake evaporation rates. Models of increased lake evaporation from 0.5 to 3 times the aquifer recharge (10 to 60 cm/yr) reduced lens thicknesses from 87% to 49% of the lake-free island (Figure 3c). Carbonate islands in the Caribbean, most of which have lakes, are expected to have drying conditions in the coming century [*Taylor et al*., 2013], indicating impacts from lakes should be considered in future water resources assessments. In contrast, islands that have positive annual water budgets would have steady state freshwater lenses that look like our no lake scenarios (e.g., Figures 2a and 2b). Evaporation of such lakes during dry seasons or droughts, however, could result in seasonal depletion of water resources, but transient simulations, which require code development, are needed to address this issue.

Ultimately, predictions of how groundwater resources on individual islands will respond to sea level rise require high-resolution topographic and water table elevation data. These data would allow estimates of when and where lakes would form, and how large they would be given various sea level rise scenarios. Nonetheless, models presented here suggest that lake formation and growth should be included in assessments modification of groundwater resources with sea level rise and provide methodology for such assessments.

4. Conclusions

While direct inundation of island coastal areas is a well-recognized threat of sea level rise, lakes can form where sea level rise elevates water tables above low points in surface topography. Consequently, lake formation may increase areas of islands that can flood in response to sea level rise. On islands with negative water budgets, lake formation will reduce groundwater resource availability relative to islands that have topography that is not conducive to lake formation. In all of our simulations of lake impacts on island freshwater lenses, lake formation and evaporation reduced groundwater resources more than a comparable amount of coastal inundation. Further, groundwater resources decreased more as lakes formed in island centers and had higher evaporation rates. Our results suggest that the lifetimes of water resources for island nations in arid regions may be substantially shorter than previously predicted.

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