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Estimating Transient Freshwater Lens Dynamics for Atoll Islands of the Maldives

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Abstract

The water resources of the atolls of the Republic of the Maldives are under continual threat from climatic and anthropogenic stresses, such as changing rainfall patterns, sea-level rise, and contamination from human activities and climatic events. Groundwater, a historically important resource of the island communities of the Maldives, is particularly affected due to the fragile nature of the freshwater lens on small atoll islands. In this study the dynamics of the freshwater lens are simulated during an extended (1998-2011) time period to determine the fluctuation of lens thickness of islands of the Maldives in response to annual and long-term changes in rainfall. Particularly, maximum and minimum lens thickness during the simulation period are assessed, as well as the occurrence of general trends, either decreasing or increasing, in lens thickness. Simulations are performed for a variety of island sizes, corresponding to the range of sizes of the islands of the Maldives, and for the various climatic regions of the Maldives. Results indicate that many of the atoll islands are expected to have a measurable freshwater lens during the majority of a long-term climatic period, although significant decreases in thickness can occur during the months of the dry season, with complete depletion occurring for small islands. Of particular note is the observation of a general decrease in lens thickness, approximately 2 to 4 cm/yr, over the 14-year period for the northern regions of the Maldives. If continued at current rates, these trends can have a significant impact on groundwater resources for the Maldives. Results imply that fresh groundwater, if properly protected from land surface-derived contamination and over-pumping and associated salinization, can be a valuable source of water for the Maldives, particularly for the larger islands. Overall, results provide water resource managers and government officials with valuable data for consideration in water security measures.

Keywords: Groundwater; Atoll island hydrology; Numerical modeling; Republic of the Maldives; Climate variability

1. Introduction

Water resources of the Republic of the Maldives are under serious immediate and future threat due to changing rainfall patterns, sea-level rise and associated coastal degradation (Pernetta, 1992; Lal et al., 2002; Mörner et al., 2004; Woodworth, 2005; Woodroffe, 2008), an increasing urban population for many of the islands, limited rainwater harvesting capacity, and contamination due to seawater intrusion, overwash events (Woodroffe, 2008; Barthiban et al., 2012), and land surface derived pollution. The nation, located in the Indian Ocean, comprises about 200 inhabited small coral atoll islands and has a total population of approximately 320,000. Communities on atoll islands are considered some of the most vulnerable worldwide in terms of freshwater scarcity and depletion of water resources due to small land surface, low elevations, geographic remoteness, and expected changes in climate (Nurse et al., 1998; IPCC, 2001; Carpenter, 2002; White et al., 2007; White and Falkland, 2010; Yamamoto and Estaban, 2013).

Of particular concern for the islands of the Maldives is the potential depletion of fresh groundwater, a historically important source of potable water for island communities of the Maldives. The body of fresh groundwater in the near-surface island sediments, termed the "freshwater lens" due to its volumetric shape, floats atop underlying seawater-saturated sediments and is naturally a fragile resource for atoll islands (White et al., 2007; White & Falkland, 2010) due to extremely small land surface area (< 1 km^2) and resulting thinness of the lens. As such, this resource is acutely affected by short-term and long-term changes in rainfall patterns, such as annual dry seasons and potential decrease in annual rainfall rates, respectively, as well as contamination from the land surface that is rapidly advected through the thin (< 2-3 m) unsaturated zone to the water table (Dillon, 1999).

Although several islands have lenses that are contaminated or depleted due to over-population and a general lack of water sanitation infrastructure (Ibrahim et al., 2002), likely there are numerous islands, inhabited and otherwise, that have groundwater of sufficient quantity and quality for sustained domestic use due to adequate land surface area and small populations. However, there exists a general lack of knowledge regarding quantity of groundwater of the Maldives during average annual climatic variation as well as during longer time periods. Although several recent efforts have measured lens thickness and estimated fresh groundwater volumes for selected islands (Falkland, 2000; Falkland, 2001; GWP Consultants, 2005; Bangladesh Consultants 2010a,b,c,d), a general baseline assessment of groundwater supply quantity as a result of temporally-varying rainfall patterns is needed for planning and management purposes throughout the Republic of the Maldives.

In this study, a general assessment of freshwater lens fluctuation over a decadal time period is performed for the most populous islands in the Republic of the Maldives to analyze the influence of annual and long-term rainfall patterns on groundwater resources. Specific objectives are first, to identify ranges and trends of lens thickness that result from decadal trends in rainfall patterns across the geographic region of the Maldives, with particular attention given to minimum lens thickness that occurs during periods of low rainfall rates; and second, to provide month-by-month estimates of freshwater lens thickness for the 201 most populous islands of the Maldives during the 14-year time period of 1998-2011. These objectives are accomplished in the two-step process of first, using a variable-density groundwater flow and salt transport numerical model to simulate time-dependent fluctuations of lens thickness for a variety of island widths during the years 1998-2011; and second, projecting these results to individual islands. All model simulations use daily-calculated recharge derived from daily rainfall data for the geographic regions encompassing the Maldives, and the range of island widths corresponds to those of the atoll islands of the Maldives. The models are corroborated using observed time-dependent lens thickness values from a number of islands of the Maldives. Results provide water resource managers and policy makers within the Republic of the Maldives with reliable lens fluctuation evaluations that can be taken into account for current and future water resource planning and management.

2. Climate, Geology, and Water Resources, of the Republic of the Maldives

2.1 Geography, Land, and Population

The Republic of the Maldives is located in the Indian Ocean to the southwest of India (Figure 1), and comprises approximately 2000 coral islands, many of which are administered as 20 atolls covering a geographic area of approximately 90,000 km^2. The coral islands have extreme low elevations and small land surface areas. Average and maximum ground surface elevation of 1.5 m and 2.4 m, respectively, and many of the inhabited islands have a land surface area of less than 1 km^2. More than 90% of the country’s land has an elevation of less than 1 m above mean sea level. Total actual land area of the Maldives is approximately 300 km^2 (MEE, 2011), with 84% occupied by miscellaneous infrastructure and native vegetation, 10% by cultivated land, 3% by forested land, and 3% by pastures. A detailed map of Laamu Atoll in the southern Maldives is presented in Figure 1, showing the typical land surface structure of atolls, with a circular or quasi-circular chain of small coral islands surrounding a shallow lagoon.

Approximately 200 islands are inhabited, with about 30% of the approximately 320,000 persons (The World Bank, 2011) living on Male', the capital islands. According to national census data, the historical growth rate is 1.76%/year. A high annual urbanization rate of 4.2% results in high-density communities on some islands, with resulting acute problems in freshwater pollution and water demand. Population data for the 201 islands assessed in this study are presented in Table S-1 in Supporting Information.

2.2 Climate and Water Resources

The climate experienced by the Maldives is warm and tropical year round, with mean annual temperature and average relative humidity of 28.0 ^{o}C and 80%, respectively. Annual rainfall is highest in the southern Maldives, with the southern atolls receiving approximately 2350 mm/yr on average, and lowest in the northern region, with the northern atolls receiving approximately 1700 mm/yr on average. Average intra-annual changes in rainfall rate occur according to a dry season-wet season pattern, with the dry season occurring from January to April and the remaining annual rainfall depth typically distributed evenly throughout the remaining months of the year.

The inhabitants of the Maldives rely on a combination of rain catchment water, desalinized seawater, and groundwater from the freshwater lens to meet freshwater demands for domestic and manufacturing needs. Due to the high permeability of land surface sediments the small land surface area, streams and lakes do not form on the islands, typical of atoll islands (Urish, 1951), and hence the freshwater lens is the only natural storage of freshwater. Desalinized seawater is typically used on high-urbanized islands such as Male', whereas the outer atoll islands use a combination of stored rainwater and groundwater. Rainwater, which is captured using individual household or communal roof catchment systems, typically is the primary source of drinking water, while groundwater is used for secondary purposes including bathing, washing, and toilet flushing. Similar patterns of water use are followed in other atoll island communities, such as within the Federated States of Micronesia (SOPAC 2007a), the Republic of Marshall Islands (SOPAC, 2007b), and the Republic of Kiribati (White et al., 1999).

A general representation of the groundwater system for atoll islands (Ayers and Vacher, 1986) is shown in Figure 2A. Due to the differences in density between freshwater and seawater and resulting variable-density groundwater flow, the fresh groundwater floats atop the denser seawater within the island subsurface sediments. Rainwater that is not intercepted by vegetation, captured by rooftop catchment systems, evaporated, or transpired by plants, percolates through the thin soil profile and recharges the freshwater lens at the water table. The aquifer has two distinct units, the surficial particulate Holocene aquifer and the high-permeable, limestone Pleistocene paleo-karst, with a solution discontinuity forming the contact between the two units. The contact typically is located approximately 15-25 m below sea level (Wheatcraft and Buddemeier, 1981), and the hydraulic conductivity (K) of the Pleistocene aquifer is estimated to be one to two orders of magnitude higher than K of the Holocene aquifer (Woodroffe and Falkland, 1997).

The thickness of the freshwater lens, which controls the available volume of extractable fresh groundwater in the subsurface, is controlled by island width, the rate of precipitation and associated infiltration and recharge, K of the Holocene aquifer (Figure 2A), aquifer dispersivity, which controls the thickness of the mixing zone between the freshwater and seawater, and the Holocene-Pleistocene contact. Depending on these factors, lens thicknesses for islands in the Pacific and Indian Ocean basins range from less than a few meters to 25-30 m (Falkland, 1994; Anthony, 1997; Hunt, 1997; Falkland, 2000; Falkland 2001; Bailey et al., 2009), with drought conditions typically causing a complete depletion of fresh groundwater (Bailey et al., 2013). For islands in which rainfall rate is high enough and the island width is large enough for a thick (> 10 m) freshwater lens to develop and the base of the lens to reach the Holocene-Pleistocene contact, freshwater moving below the contact mixes with underlying seawater, thereby creating a sharp transition between freshwater and seawater and resulting truncation of the lens (Hunt, 1997; Woodroffe and Falkland, 1997).

3. Methodology

3.1 Quantifying Time-Dependent Lens Thickness

To estimate time-dependent lens thickness during the designated time period (1998-2011), the finite-element modeling code SUTRA (Saturated Unsaturated TRAnsport) (Voss and Provost, 2003) is employed, which simulates variable-density groundwater flow and salt transport in subsurface systems. SUTRA is selected due to its demonstrated utility and reliability in previous studies regarding coastal (Gingerich and Voss, 2005; Oki, 2005), small-island and, in particular, atoll island aquifers (e.g., Underwood et al., 1992; Griggs and Peterson, 1993; Peterson and Gingerich, 1995; Bailey et al., 2009), with recent studies assessing the effect of marine overwash events (Chui and Terry, 2012; Terry and Chui, 2012; Bailey and Jenson, 2013; Chui and Terry, 2013). Using a two-dimensional (2D) finite element mesh that represents the cross section of an atoll island from the lagoon to the ocean side (Figure 2B), the SUTRA code simulates groundwater flow and salt concentration within the island subsurface, from which the extent of the freshwater lens and its thickness can be determined. Using time-dependent values of recharge, the response of the lens to temporal changes in precipitation can be quantified.

Six different finite-element meshes are used to represent infinite-strip islands with widths of 200 m, 300 m, 400 m, 500 m, 600 m, and 1100 m, with the cross-section assumed to occupy the transect orthogonal to the island axis. These widths were chosen to span the range of island widths observed in the Maldives. Mesh discretization varies throughout the extent of the model domain, with finely-resolved discretization required within the vicinity of expected freshwater lens development to provide numerical stability during simulations. For the mesh representing the 400-m wide island, the mesh consists of 7,832 elements and 8,055 nodes.

Recharge from rainfall is assigned to nodes located at sea-level along the length of the island transect. Recharge for each day of the 1998-2011 time period is derived from daily rainfall values from the Tropical Rainfall Measuring Mission (TRMM). To account for the differences in rainfall rates across the geographic region encompassing the Maldives, daily rainfall was collected for three regions: the geographic region between the latitudes of 5N to 10N, the region between 0 and 5N, and the region between 5S and 0, with each region between the longitudes of 71E and 74E. Daily values for the period of 1998-2011 for each of the three regions are shown in Figure 3, with annual totals of rainfall for each region presented in Table 1.

Daily recharge values for each of the three geographic regions are calculated from daily rainfall depths using the soil water budget model of Falkland (1994), which account for interception storage by surface vegetation, evapotranspiration (ET), and soil water storage, with soil water exceeding field capacity assumed to recharge the water table. Interception storage, thickness of the soil zone, field capacity of the soil, and wilting point of the soil are assigned values of 1 mm/d, 500 mm, 75 mm, and 25 mm, respectively, and daily potential ET is calculated using the Thornwaite Method (Thornwaite, 1948). Water also can be removed from the lens via evaporation and transpiration, with the latter due to deep-reaching coconut roots

(Falkland, 1994). For days during which precipitation is less than daily ET, water is removed to represent evaporation, and coconut root transpiration from the freshwater lens is included by assuming the potential value of daily ET was extracted on days of no recharge. To simulate water table storage, specific storage values for nodes located at sea level (i.e., top layer of nodes in the mesh along the width of the island) are assigned values equal to the specific yield divided by half of the element vertical thickness (Griggs and Peterson, 1993). Estimated daily recharge depths are shown in Figure 3 for the three geographic regions, with annual depths of rainfall and recharge presented in Table 1. Overall, annual average of percent rainfall that recharges the freshwater lens is approximately 38%, 35%, and 39% for the three geographic regions, respectively. Notice that for the climate region of 5N-10N latitude, no recharge occurs during the dry season months of January through April. This occurs also for several years in the 0-5N latitude region, but does not occur for the wetter climate region of 5S-0 latitude.

Boundary fluid pressure is specified along the reef and the lagoon basement to simulate the presence of seawater (Figure 2B), with source water at the nodes along these boundaries assigned a salt concentration of 0.0357 kg_{salt}/kg_{water} (~36,600 mg/L) to represent seawater. The bottom of the mesh and the boundary representing the edge of the lagoon are designated as no-flow boundaries. Aquifer geology and hydraulic parameters (Table 2) are based generally on published literature for atoll islands (Hamlin and Anthony, 1987; Oberdorfer et al., 1990; Griggs and Peterson, 1993). Holocene aquifer K (Table 2) applied to each of the six island models was determined during initial model simulations as described subsequently in this section. For all simulations, the Holocene aquifer extends to depths of 13 to 18 m below sea level on the ocean and lagoon sides, respectively (Hamlin and Anthony, 1987).

The procedure for simulating freshwater lens dynamics during 1998-2011 was accomplished by first, running a model to steady-state conditions using a steady inflow rate of recharge water; second, using resulting steady-state conditions as initial conditions and running a four-year transient simulation using estimated daily recharge values, which establishes seasonal patterns for the given pattern of rainfall and recharge; and third, using the four-year transient simulation results as initial conditions and running the simulations for 1998-2011. For the second step, the four-year simulation required two runs to achieve steady seasonal patterns, with the second run using the final results of the first run as initial conditions. This process was performed for each island width model and for each of the three geographic regions, for a total of 18 model simulations. An iterative approach was taken between the first and second steps to determine aquifer parameters that allow steady fluctuations of the lens thickness for each model. Using this approach, horizontal and vertical Holocene aquifer K values of 75 m/day and 15 m/day, respectively, were selected and applied to each island width model.

For model corroboration, results from the 1998-2011 simulations are compared against observed lens thickness data provided from recent groundwater investigations for the Maldives (Falkland, 2000; Falkland, 2001; Bangladesh Consultants 2010a,b,c,d). In total, there are 22 islands with lens thickness data, with the atolls on which these islands are located identified in Figure 1 with boxes. Observed lens thickness values are summarized in Tables S-1 and S-2 in Supporting Information. For most of the islands for which observations were made, only a few measurements of lens thickness were obtained (Table S-1). However, for four of the islands (Thinadhoo, Gaafu Dhaalu Atoll; Gan, Laamu Atoll; Holhudhoo, Noonu Atoll; and Velidhoo, Noonu Atoll), electromagnetic surveys provided > 25 values for each island, with the dataset for Thinadhoo shown in Table S-2. All observations were taken between November 2000 and May

2001. In total, 152 observed lens thickness values were compiled for model testing. Each observed value is compared to a corresponding simulated value from the applicable model, i.e., from the island width model that corresponds most closely with the width of the island from which the measurement was taken. Furthermore, observed values are compared to simulated values from the applicable time step, i.e., from the time step during the 1998-2011 simulation time period that corresponds to the date on which the measurement was taken. It should be noted that, in order to avoid bias, no attempt was made to calibrate parameters for specific islands, i.e. the same K values and depth to the Holocene-Pleistocene contact are used for each of the six island width models.

In analyzing simulation results, the upper limit of salt concentration for freshwater (i.e., water suitable for drinking) is defined as 0.00089 kg_{salt}/kg_{water}, which corresponds to a salt concentration of about 915 mg/L and a chloride concentration of about 550 mg/L. The chloride concentration is slightly lower than the World Health Organization (WHO, 1972) recommended benchmark of 600 mg/L. However, no health-based standard is proposed for chloride, although it is noted that concentrations above 250 mg/L may be detected by taste (WHO, 2011). Lens thickness (m) in results corresponds to the maximum lens thickness occurring across the width of the island, i.e., at or near the center of the island.

3.2 Lens Thickness Estimates for Inhabited Islands

Using the results from the numerical modeling simulations, monthly simulated lens thickness values during 1998-2011 are projected to the inhabited islands of the Maldives based on the average width of each island. For islands with widths in between the widths used for the numerical models (200 m, 300 m, 400 m, 500 m, 600 m, and 1100 m), linear interpolation was used to provide monthly estimates. This efficacy in using linear interpolation is possible due to the linear relationship between island width and lens thickness for each month of the 14-year simulation period, which will be discussed in Section 4. The islands included in this analysis, including population, the atoll on which the island is situated, and the average width (m), is presented in Table S-3 in Supporting Information.

4. Results and Discussion

4.1 Numerical Model Simulations

Results are shown as time series of maximum lens thickness (i.e., lens thickness at the center of the island), cross-section contour plots of salinity to display the delineation of the freshwater lens, and summary statistics for the 201 islands regarding maximum and minimum lens thickness during the 1998-2011 time period. The achieved steady seasonal pattern of lens thickness fluctuation for each of the island widths using the four-year transient spin-up simulations is shown in Figure 4 for each of the three geographic regions. The development of steady-state freshwater lens delineation during the initial steady recharge rate simulations is shown in Figure S1 in Supporting Information for each island width model. In Figure 4, notice that the lens thickness values for the 5S-0 latitude region are the highest among the three climate regions due to the higher magnitude of rainfall, with the average lens thickness for all island widths during the four-year period equal to 4.3 m, 3.9 m, and 3.5 m for the 5S-0, 0-5N, and 5N-10N regions, respectively. In general, the fluctuation of the lens between wet and dry season is most pronounced for the two northern regions.

The lens thickness fluctuation during 1998-2011 for each island width model for each of the three geographic regions is shown in Figure 5, and comparison of observed and simulated values of lens thickness shown in Figure 6, with a 1:1 line depicting a perfect match. The match between the observed and simulated values is reasonable ($R^2 = 0.625$), with large observed lens thicknesses generally matched by large simulated lens thicknesses, and small observed thicknesses matched by small simulated thicknesses. Similar to the steady seasonal fluctuation shown in Figure 4, the lens thickness values for the 5S-0 region are the highest among the three geographic regions, with average lens thickness for island widths equal to 4.4 m, 3.3 m, and 3.1 m for the 5S-0, 0-5N, and 5N-10N regions, respectively.

For the 5N-10N region, minimum lens thicknesses occur in the years 2003-2005 due to below-average rainfall rates and associated recharge rates, with absolute minimums occurring during the dry seasons of these years. For the 0-5N region, minimum lens thicknesses occur in 2001 and 2006; and for the 5S-0 region, minimum lens thickness occurs during 2000-2002, followed by a steady increase in lens thickness during the latter months of 2002 and the first months of 2003. The minimum, maximum, and average lens thickness for each island width and for each geographic region is shown in Table 3. For each of the three geographic regions, the 200 m island experiences complete or nearly complete depletion of the lens for much of the 14-year time period; the 300 m island experiences depletion during the dry season of many of the years for the 0-5N and 5N-10N regions; and the 400 m island experiences near-depletion during the dry season for the 0-5N and 5N-10N regions. Cross-section contour plots of salinity, depicting the freshwater lens and the transition zone to seawater, are shown in Figure 7 for the models with island widths of 200 m, 400 m, 600 m, and 1100 m at the beginning of the 14-year period (January 1 1998) and at times of minimum and maximum lens thickness for the three geographic regions. For the plot showing the maximum lens thickness of the 1100 m island within the 5S-0 region, notice the truncation of the lens due to the base of the lens descending to the Holocene-Pleistocene contact.

Results of the 1998-2011 simulations shown in Figure 5 also provide information regarding general long-term trends in groundwater resources for atoll islands in the Maldives. The islands located in the 0-5N and 5N-10N regions experience an overall decrease in lens thickness during the 14-year period, whereas the islands in the 5S-0 region experience an overall increase, due to differences in rainfall patterns. Average rate of change in lens thickness for each island width model for each geographic region is presented in Table 4. The rates of increase in the 5S-0 region range from 0.39 cm/yr (200 m island) to 8.82 cm/yr (600 m island), with an average rate of increase of 4.0 cm/yr. The rates of decrease in the 0-5N region range from 0.24 cm/yr (200 m island) to 5.61 cm/yr (600 m island), and the rate of decrease in the 5N-10N region range from 0.23 cm/yr (200 m island) to 4.65 cm/yr (1100 m island). Overall, rates of decrease in lens thickness are most pronounced for the islands in the 0-5N region with an average of 3.75 cm/yr, compared to 1.87 cm/yr for the 5N-10N region. If continued at current rates, these trends can have a significant impact on lens thickness for the islands of the Maldives, particularly since the majority of islands are located in the two northern geographic regions.

4.2 Lens Thickness Estimates for Inhabited Islands

Using results from the 1998-2011 simulations, monthly lens thickness values for each of the 201 inhabited islands are estimated. The viability of these projections using linear interpolation is demonstrated in Figure S-2 in Supporting Information, which shows linear trends of lens thickness vs. island width for a number of time steps during the 1998-2011 simulation. R^2 values of the trends are all above 0.98, and typically above 0.99. Figure 8 shows an example of projection results for seven islands of the Maldives, selected to display the difference in lens thickness and fluctuation patterns according to island width and geographic region. Three islands are selected from the 5N-10N region (Kelaa, Haa Alifu Atoll, 1000 m; Vashafaru, Haa Dhaalu

Atoll, 225 m; Maakurathu, Raa Atoll, 725 m), two from the 0-5N region (Thoddoo, Alifu Alifu Atoll, 1100 m; Maavah, Laamu Atoll, 405 m), and two from the 5S-0 region (Maradhoo, Seenu Atoll, 405 m; Hulhudhoo, Seenu Atoll, 910 m).

A summary of the freshwater lens dynamics for all 201 islands is presented in Figure 9. Figures 9A and 9B show the maximum and minimum lens thickness for each island during 1998-2011, as a function of island width and as a histogram, and Figure 9C shows the percent decrease in lens thickness from the maximum to the minimum thickness values for each island. For the latter, values are displayed according to geographic region. From these results, as well as the complete lens fluctuation for selected islands as shown in Figure 8, it is evident that a significant change in lens thickness occurs during the period due to rainfall rate differences between the annual wet season and dry season, as well as during years of low rainfall and preceding or succeeding years of higher annual rainfall. As expected, lens thickness increases with island width, with scatter around this trend due to geographic region and associated rainfall rates for the individual islands. Lens thickness for large islands is limited by the depth to the Holocene-Pleistocene contact (~ 14-15 m). The majority of the islands have an island width of 500 m or less, and hence a relatively thin lens, with a complete depletion of fresh groundwater for at least one month during the 14-year period for islands with widths of less than 300 m.

The depletion of the lens for smaller islands also can be seen in Figure 9C as high percent decreases in lens thickness occur for small islands. From the values of percent decrease in lens thickness (Figure 9C), it can be seen that the lens can become completely depleted (100% decrease) for small islands (≤ 300 m in width) for one or more months during the 14-year period. For islands width widths smaller than 500 m, the percent decrease typically is more than 50%. Due to the shape of the freshwater lens, a 50% decrease in lens thickness equates to a much higher percent decrease in groundwater volume, and hence many of the islands can experience drastic changes in fresh groundwater reserves from the wet season to the dry season.

5. Summary and Concluding Remarks

This study presents an overall analysis of freshwater lens fluctuation for the atoll islands of the Maldives during a 14-year period (1998-2011) in an effort to further understand long-term (>10 years) behavior of groundwater resources for the nation. Numerical model simulations were performed using the variable-density groundwater flow and salt transport code SUTRA for a variety of island widths (200 m, 300 m, 400 m, 500 m, 600 m, 1100 m) and for three latitudinal belts (5N to 10N, 0 and 5N, and 5S and 0 between 71E and 74E) covering the Maldives atolls and the associated differences in annual rainfall patterns. The numerical models are constructed after the dual-aquifer atoll island model, with a surficial find-sediment Holocene aquifer underlain by a highly-permeable limestone Pleistocene aquifer. Daily recharge to the freshwater lens is derived from daily rainfall depths using a water balance model. Simulated lens thicknesses are compared against observed lens thickness values from 22 islands for model corroboration according to island width and date of measurement, and model results are projected to 201 inhabited islands of the Maldives based on average island width and latitudinal belt.

Model results indicate that many of the atoll islands are expected to have a measurable freshwater lens during the majority of a long-term climatic period, although significant decreases in thickness can occur during the months of the dry season. For the majority of the islands, the lens is very dynamic, with at least a 50% decrease from the maximum to the minimum lens thickness experienced during the 1998-2011 period. For small islands (≤ 300 m in width), complete depletion of the lens is expected to occur either due to typical dry season rainfall patterns or due to successive years of low annual rainfall rates. Due to higher rainfall totals, the islands in the 5S-0 region experience generally a thicker freshwater lens than the islands located in the 0-5N and 5N-10N regions. Of keen interest is the overall trend in lens thickness, with a general decrease in lens thickness over the 14-year period for islands subject to the rainfall patterns of the 0-5N and 5N-10N regions, and a general increase for the islands located in the 5S-0 belt. Averages rates of decrease of lens thickness are 3.75 cm/yr and 1.87 cm/yr for the 0-5N and 5N-10N regions, respectively, and the average rate of increase is 4.0 cm/yr for the 5S-0 region.

It should be noted that groundwater pumping, which occurs on many of the islands of the Maldives, was not taken account in the numerical modeling simulations and analysis. However, as model results generally correspond with observed results, this feature does not impact the general results of the study, particularly since lens thickness is depleted during the dry season for small islands due to rainfall patterns alone. Furthermore, by neglecting human effects, the 14-year trend in lens thickness due to changes in rainfall patterns is able to be elucidated. Also, it is noted that the simulations did not take into account the impacts of the December 26 2004 tsunami, which for several islands would result in salinization of the lens due to island overwash events, with about 1.5 years required to achieve pre-overwash lens thickness based on field observations and numerical modeling experiments (Terry and Falkland 2010; Bailey and Jenson, 2013). However, only several months of average rainfall would be required to provide potable groundwater at the depths accessed by hand-dug wells (Bailey and Jenson, 2013).

Results imply that fresh groundwater, if properly protected from land surface-derived contamination and over-pumping and associated salinization, can be a valuable source of water for the islands of the Maldives, particularly for the larger islands. However, a significant decrease in fresh groundwater occurs between the wet and dry seasons, and hence supplemental sources of water such as rainwater captured and stored by rooftop catchment systems during the wet season should be used where available during the dry season. Furthermore, results indicate that long-term trends in fresh groundwater reserves are occurring due to changes in rainfall patterns, with detrimental trends (i.e., decrease in lens thickness) experienced by the northern (0-5N, 5N-10N) geographic regions. If continued at current rates, these trends can have a significant impact on groundwater resources for the Maldives. Finally, as this study only analyzes lens fluctuation for inhabited islands, likely there are numerous uninhabited islands that also have significant fresh groundwater reserves, which could figure into water resources planning and management. Overall, results provide water resource managers and government officials with valuable data for consideration in water security measures.

Supporting Information

Additional supporting information may be found in the online version of the article: Observed lens thickness values for islands of the Maldives (Table S-1), Observed lens thicknesses for the island of Thinadhoo, Gaafu Dhaalu Atoll (Table S-2), Population and average width for the 201 most populous islands of the Maldives (Table S-3), Results of steady recharge rate simulations for the six island width models (Figure S-1), and Lens Thickness as a function of island width for various time steps during the 1998-2011 simulation period (Figure S-2).

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Figure Captions

Figure 1. Map of the Republic of Maldives in the Indian Ocean, showing the north-south of chain of atolls. A close-up map of Addu Atoll also is presented to show the typical geologic setting of an atoll, with small coral islands surrounding a shallow lagoon. Data regarding groundwater resources is available for the islands identified by black boxes.

Figure 2. Cross section of a typical atoll island from the lagoon side to the ocean side, depicting the principal hydrogeologic features such as the contact between the Holocene (unlithified sediments) and Pleistocene aquifers, typically at a depth of 15-25 m below sea level.

Figure 3. Estimated daily average rainfall (mm) as tabulated by the Tropical Rainfall Measuring Mission and associated calculated daily recharge (mm) to the freshwater lens for the latitude regions of 5N-10N, 0-5N, and 5S-0 (longitudes of 71E and 74E) for the Maldives for the years 1998-2011.

Figure 4. Simulated freshwater lens thickness during the 4-year spin-up period for the 6 island width models (widths of 200 m, 300 m, 400 m, 500 m, 600 m, and 1100 m) for the three climate regions, demonstrating the achieved steady seasonal dynamics.

Figure 5. Simulated freshwater lens thickness for each month during the 1998-2011 time period for the 6 island width models (widths of 200 m, 300 m, 400 m, 500 m, 600 m, and 1100 m) for the three climate regions.

Figure 6. Comparison of observed and simulated freshwater lens thickness values for the islands of the Maldives, using the data reported by Falkland (2000), Falkland (2001), and Bangladesh Consultants (2010a, b, c, d) and the results of the 1998-2011 numerical modeling simulations. Comparisons are made based on island width and timing of the field measurement.

Figure 7. Spatial distribution of salinity concentration (as a percentage of seawater) for the island cross-section of the 200 m, 400 m, 600 m, and 1100 m models, at the beginning of the 1998-2011 simulation and at times of minimum and maximum lens thickness, for the three geographic regions.

Figure 8. Estimated lens fluctuation during the 1998-2011 time period for seven islands of the Maldives, based on results of the numerical modeling simulations.

Figure 9. Summary statistics for the lens thickness of the 201 islands of the Maldives during the 1998-2011 time period, showing the maximum and minimum simulated lens thickness for each island as (A) a function of island width and as (B) a frequency distribution; and (C) the percent decrease between the maximum and minimum lens thickness for each island.