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Estimating Current and Future Groundwater Resources of the Maldives

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ABSTRACT

The water resources of the atolls of the Republic of Maldives are under continual threat from climatic and anthropogenic stresses, including land surface pollution, increasing population, drought, and sea-level rise. These threats are particularly acute for groundwater resources due to the small land surface area and low elevation of each island. In this study the groundwater resources, in terms of freshwater lens thickness, total volume of fresh groundwater, and safe yield are estimated for the 52 most populous islands of the Maldives for current conditions and for the year 2030, with the latter accounting for projected sea-level rise and associated shoreline recession. An algebraic model, designed in previous studies to estimate the lens thickness of atoll islands, is expanded in this study to also estimate volume of groundwater. Results indicate that average current lens thickness, groundwater volume, and per capita safe yield is approximately 4.6 m, 1300 ML (million liters), and 300 L/day, and that these values will decrease by approximately 10%, 11%, and 34%, respectively, by the year 2030. Based on results, it is demonstrated that groundwater, in terms of quantity, is a viable source of water for the islands of the Maldives both now and in coming decades, particularly for islands with large surface area and low population. Study results can provide water resource managers and government officials with valuable data for consideration in water security measures.

Key Terms

Groundwater hydrology, Water supply, Climate variability/change , Drinking water

INTRODUCTION

The Republic of Maldives, comprised of about 200 inhabited small coral atoll islands in the Indian Ocean and with a total population of 320,000, faces serious immediate and future water security issues that threaten the sustainability of island resources. Specific security issues regarding water quantity and water quality include salinization of groundwater due to sudden climatic events, such as the 2004 tsunami (Woodroffe, 2008; Barthiban et al., 2012); current and impending climatic events, such as sea-level rise (SLR) and associated shoreline recession and coastal degradation (Pernetta, 1992; Khan et al., 2002; Lal et al., 2002; Mörner et al., 2004; Woodworth, 2005; Woodroffe, 2008); an increasing urban population resulting in contamination of aquifers by human and animal waste; and limited rainwater harvesting capacity. Furthermore, high costs and financial constraints prohibit wide-spread use of technological solutions such as desalinization (Sovacool, 2012).

Of principal concern is the threat to the groundwater supply, a historically important source of potable water for the population of the Maldives. Due to small land surface areas and the existence of a dual aquifer system that limits the thickness of the freshwater lens, groundwater is naturally a fragile resource for atoll island communities in terms of water quantity (White et al., 2007; White & Falkland, 2010). Furthermore, extremely low ground surface elevations (< 2-3 m on average) and the resulting thin layer of soil between the ground surface and the water table permits rapid advection of land surface derived pollution to the freshwater lens (Dillon, 1999). With a projected 60% increase in the number of households by 2033, groundwater pollution is and will continue to be a critical issue. SLR also is a particularly acute problem for groundwater quality, as an increasing sea level decreases the land surface of the island, thereby decreasing the spatial extent and thickness of the freshwater lens.

Despite these concerns, and although several islands have experienced groundwater pollution and depletion due to over-population and a general lack of water system infrastructure (Ibrahim et al., 2002), there are numerous islands, inhabited and otherwise, that likely have vast reserves of uncontaminated fresh groundwater due to adequate land surface area and relatively small populations. However, there exists a general lack of knowledge concerning quality and safety of island groundwater sources. Indeed, a number of islands rely on annual deliveries of desalinated of water from the capital city of Male' to meet water demand during the dry season. Hence, a general effort to accurately estimate the available groundwater resources of the islands is desired. Although several recent efforts have quantified groundwater quantity for a select number of islands (Falkland, 2000; Falkland, 2001; GWP Consultants, 2005; Bangladesh Consultants 2010a,b,c,d), a general baseline assessment of groundwater resources throughout the Republic of Maldives is needed for planning and management purposes.

In this study, a recently developed algebraic model created for atoll island groundwater systems (Bailey et al., 2010) is applied to the Maldives to estimate current (2012) and future (2030) available groundwater resources. The model accounts for the principal features of atoll island hydrogeology, including hydraulic conductivity and the depth to the solution unconformity between the upper and lower aquifers, and has been applied successfully to atoll islands in the Federated States of Micronesia (Bailey et al., 2013) to estimate freshwater lens thickness, with model results compared against observed lens thickness values for corroboration. This study applies the model to the 52 most populous islands of the Maldives to estimate freshwater lens thickness, volume of available fresh groundwater, and safe yield. Estimates are provided for current conditions (year 2012) and, using a range of predicted rates of SLR and associated shore-line recession, for the year 2030. Whereas previous use of the model is restricted to estimating lens thickness, this study presents a new method that uses the algebraic model to estimate the volume of available groundwater. Model results are tested against observed lens thickness and lens volume data provided from recent groundwater investigations (Falkland, 2000; Falkland, 2001; GWP Consultants, 2005; Bangladesh Consultants 2010a,b,c,d). Results provide water resource managers and policy makers within the Republic of Maldives with reliable general groundwater evaluations that can be taken into account for current and future water resource planning and management.

CLIMATE AND WATER RESOURCES OF THE REPUBLIC OF MALDIVES

Geography, Land, and Climate of the Maldives

The Republic of Maldives comprises a group of approximately 2000 coral islands, many of which are grouped into 20 administrative atolls in a north-south geographic area of approximately 90,000 km^2 in the Indian Ocean to the southwest of India (Figure 1). The geographic location of the Maldives is shown in Figure 1A, with a detailed map shown for Addu Atoll in Figure 1B to show the general nature of atolls, with a group of small coral islands surrounding an interior, shallow lagoon. It is estimated that the total actual land area of the Maldives is only about 300 km^2 (MEE, 2011), with 10% occupied by agricultural cultivated land, 3% by forested land, 3% by pastures, and 84% by miscellaneous infrastructure and native vegetation. The islands have extremely low elevations and small land surface areas. Average and maximum ground surface elevation are 1.5 m and 2.4 m, respectively, and thirty-three of the inhabited islands have a land surface area of less than 1 km^2. More than 80% of the country’s land has an elevation of less than 1 m above mean sea level (MSL). Approximately 200 islands are inhabited, with about 30% of the approximately 320,000 persons (The World Bank, 2011) living on Male’, the capital island. Based on national census data, the historical growth rate is 1.76 %/yr, with an annual urbanization rate of 4.2%, producing high-density communities with enhanced problems in water supply and potential freshwater pollution.

The Maldives experiences a warm, tropical climate year round with mean annual temperature and average relative humidity of 28.0 ^{o}C and 80%, respectively. Depth of annual rainfall increases from north to south, with the northern atolls receiving on average approximately 1700 mm/yr and the southern atolls receiving on average approximately 2350 mm/yr. The dry season occurs during the months of January to April, with the annual rainfall depth distributed evenly throughout the remainder of the year.

Atoll Island Hydrogeology

Atolls are generally composed of a circular chain of reefs and small coral island enclosing or nearly enclosing a shallow lagoon (Figure 1B). Smaller islands typically form on the windward portion of the atoll, whereas larger islands form on the leeward portion of the atoll. Groundwater for oceanic islands resides in a body of freshwater termed the “freshwater lens”, residing in the permeable sediments of the island subsurface and floating atop the underlying, denser seawater. Rainwater that is not intercepted by vegetation, evaporated, transpired by plants, or captured by rooftop catchment systems, percolates through the soil profile and recharges the lens at the water table. It is estimated that approximately 30-50% of rainfall on atoll islands is recharged to the freshwater lens (Hamlin and Anthony, 1987; Griggs and Peterson, 1993; Bailey et al., 2009).

The general model of atoll island hydrogeology (Ayers and Vacher, 1986) is shown in Figure 2. A key, unique feature of an atoll island hdyrogeologic system is the dual aquifer system, in which a surficial particulate Holocene aquifer lies atop a high-permeable, limestone Pleistocene paleo-karst aquifer (Figure 2), with a solution discontinuity forming the contact between the two aquifer units. Typically, the contact is located at 15-25 m below sea level (Wheatcraft and Buddemeier, 1981), and the lower aquifer *K* is estimated to be one to two orders of magnitude higher than the upper aquifer *K* (Woodroffe and Falkland, 1997). For large atoll islands where recharge rates are high enough for the base of the freshwater lens to descend to the contact, freshwater below the Thurber Discontinuity is thoroughly mixed with the seawater due to the large contrast in *K* between the upper and lower aquifer units, thus truncating the freshwater lens along the contact and creating a flat lens base (Hamlin and Anthony 1987, Hunt 2007). The truncation of the lens on large atoll islands also suggests that the lens volume can be overestimated if the presence of the presence of the contact is not accounted for in analysis.

Hydrogeologic, Climatic, and Population Data for the Maldives

Hydrogeologic and climatic data was gathered to provide input data for the model and to provide observed data against which model results can be tested. Data was collected regarding observed groundwater conditions, the population of each inhabited island of the Maldives, historical daily rainfall data, rates of sea-level rise, and other data required for accurate groundwater analysis. Observed groundwater conditions for islands of the Maldives are obtained from the reports of Falkland (2000; 2001), GWP Consultants (2005), and Bangladesh Consultants (2010a; b; c; d), and provide data for both freshwater lens thicknesses and associated groundwater volumes. 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, and six islands with lens volume data. Observed lens volumes and data source are shown in Table 1. Observed lens thickness values are summarized in Tables S-1 and S-2 in Supporting Information. For most of the islands with data, only a few lens thickness values 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-3. In total, 173 observed lens thickness values were compiled for model corroboration for this study.

Methods used to quantify observed lens thickness and groundwater volume included geophysical surveys using the electromagnetic induction method, and groundwater level and salinity data logging at observation wells. Lens thicknesses ranged from 0 m to 23.5 m (for Gan Island, Western Addu atoll), and groundwater volumes ranged from 61 ML for Holhudhoo Island, Noonu Atoll to 14,200 ML for Gan Island, Laamu Atoll. Overall, much more data is available regarding lens thickness than for groundwater volume. Specific yield, the ratio of the volume of recoverable fresh groundwater to the volume of the bulk aquifer, is estimated to be 0.30 (Falkland, 2000; Falkland, 2001), and percentage of rainfall that recharge the freshwater lens is estimated to be approximately 40% to 45% (Bangladesh Consultants 2010a,b,c,d). Depth to the Holocene-Pleistocene contact is estimated from boreholes on the islands, with depths ranging from approximately 10 m to 20 m.

Daily rainfall data as tabulated by the TRMM (Tropical Rainfall Measuring Mission) was collected for three specific regions of the Maldives: 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 averages for the period of 1998-2011 for each of the three regions are shown in Figure 3. Overall, the average annual rainfall during the period 1998-2011 is 1.72 m for the 5N-10N region, 1.94 m for the 0-5N region, and 2.38 m for the 5S-0 region. Estimates of SLR rates for the geographic region of the Maldives are highly variable, with values ranging from 1.0 mm/yr (Church et al., 2006) to 6.5 mm/yr (Woodworth et al., 2002). Khan et al. (2002) reported a rate of 4 mm/yr for the islands of Male’ and Gan (Mimura et al. 2007). Population estimates for the year 2030 were obtained from the Republic of Maldives government, and indicate an increase in population of 40% between 2012 and 2030. Population data for the 52 islands assessed in this study are presented in Table S-4 in Supporting Information.

METHODOLOGY: ESTIMATING THE GROUNDWATER RESOURCES OF ATOLL ISLANDS IN THE MALDIVES

Methodology is presented for estimating lens thickness, lens volume, and safe yield for individual atoll islands of the Maldives subject to current climate conditions. The method for calculating these same system variables for the year 2030 also is presented. Estimates are performed for the 52 most populous islands, with populations ranging from 92,555 for Male' and 1,885 for Hanimaadhoo, according to the 2012 national census. Comparisons of observed vs. simulated values are presented for lens thickness and lens volume for model corroboration.

Estimating Freshwater Lens Thickness

Average lens thickness is estimated using an algebraic model developed for atoll islands (Bailey et al., 2010; Bailey et al., 2013), which calculates the lens thickness as a function of average annual recharge R (m/yr), Holocene aquifer K (m/day), island width (m), and the depth to the Holocene-Pleistocene contact, which acts as a limiting thickness of the freshwater lens. Derived from a comprehensive suite of numerical modeling simulations for atoll island hydrogeology (Bailey et al., 2009), the model captures the influence of these hydrologic and geologic parameters on lens thickness Z_{MAX} (m) under average climatic conditions by the following equation:

$$Z_{MAX} = Z_{Lim}\left(1-e^{-bR}\right)SC \qquad (1)$$

where b is a fitting parameter dependent on island width; and S and C are the conductivity and reef flat plate parameters [-], respectively, taking into account the influence of K and the reef flat plate (if present) on Z_{MAX}, and Z_{Lim} is the limiting magnitude of Z_{MAX} based on the width of the island and the depth to the Holocene-Pleistocene contact Z_{HP} (m), and is given by:

$$Z_{Lim} = y_0 + \left(Z_{HP} - y_0\right)\left(1 - e^{-dw}\right) \qquad (2)$$

where y_0 and d are constants (-16.07 and 0.0075, respectively) and w is the width of the island (m) at the location of lens thickness estimation. Charts for b, S, and C are provided by Bailey et al. (2010). In general, the expression $Z_{MAX} = Z_{Lim}(1-e^{-bR})$ describes the increase in Z_{MAX} as the recharge rate R is increased, but limited by w and Z_{HP} as contained in the expression for Z_{Lim} in Equation (2). In other words, the lens cannot become thicker than the value of Z_{Lim}, and this limit is dependent on both the width of the island and Z_{HP}. Including Z_{HP} in the algebraic model is essential for successful estimation of lens thickness for atoll islands, particularly for large islands that experience high rainfall volumes, and overcomes problems of over-estimation when other analytical models (Fetter, 1972; Chapman, 1985; Oberdorfer and Buddemeier, 1988) are applied to atoll islands.

Due to the inclusion of only one value for K, the model assumes a homogeneous, isotropic aquifer along the cross-section that is analyzed. Also, the freshwater lens defined by the lens thickness Z_{MAX} contains water with a salt concentration ≤ 0.00089 kg_{salt}/kg_{water} , as this value was used in the numerical modeling simulations to define fresh groundwater (Bailey et al., 2009). This value corresponds to a salt concentration of about 915 mg/L and a chloride concentration of about 550 mg/L, which are slightly lower than the World Health Organization (WHO, 1972) recommended benchmark of 600 mg/L.

The algebraic model was tested for the 22 islands with observed lens thickness values. For each island, the width of the island at the cross section where the lens thickness was measured was used, and the rate of recharge is set to be 40% of annual average rainfall, with annual rainfall depths varied according to the three geographic regions (1.72 m for the 5N-10N region, 1.94 m for the 0-5N region, and 2.38 m for the 5S-0 region). Z_{HP} is set to 15.0 m for each island, except for several islands of Addu Atoll which had values of 25.0 m based on borehole data, and Holocene K was treated as a calibration parameter, with a value of 200 m/day provided the best fit between the observed and simulated values. Holocene K for each island was assigned this value so as not to introduce bias into the analysis, as modifying K for each island could produce near-perfect matches. Comparison of observed and simulated values is shown in Figure 4A, 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. Using the same values Z_{HP} and Holocene K, and site-specific values of island width and R, the model was used to estimate the lens thickness for each of the 52 islands. Average island width for the 52 islands is approximately 450 m, with a maximum and minimum of 1400 m and 200 m, respectively.

Estimating Freshwater Lens Volume and Safe Yield

As the standard form of the algebraic model calculates only the maximum thickness of the freshwater lens for a given cross-section of the island, this study developed a procedure that expands the use of the algebraic model to estimate the volume of fresh groundwater under average climatic conditions. In general, the algebraic model is applied to successive cross-sections along the length of the island, with fresh groundwater volumes calculated between the cross sections. An adequate number of cross sections (typically 5 to 10) are used to capture the geometry of the island land surface, with the distances between the cross sections also measured. The two-dimensional (2D) area of the subsurface occupied by the freshwater lens is estimated based on typical freshwater lens geometry from numerical modeling results (Bailey et al., 2009), and the distance between the cross sections and the 2D cross section lens areas are used to calculate the volume of aquifer occupied by the freshwater lens between the cross sections, with these volumes summed and multiplied by the specific yield (0.30) to provide an estimate of the total volume of retrievable fresh groundwater for the island.

Comparison of estimated values with observed values for the six study islands with reported groundwater volume data is shown in Figure 4B, with values generally falling along the 1:1 line. Assuming that the observed lens volumes are without error, the error in the estimated values for Thinadhoo, Gan, Holhudhoo, Velidhoo, Kulhudhuffushi, and Dhidhdhoo is -15%, -28%, -16%, 15%, 22%, and -33%, with negative values indicating an under-estimation of the actual groundwater volumes. Overall, it is concluded that the method of calculating groundwater volumes is reasonably accurate, and the procedure is then applied to each of the 52 islands.

The daily volume of safe yield, as well as the per capita daily volume of safe yield, also is calculated for each of the 52 islands. The annual volume of safe yield is calculated using the method of Falkland (2000), which states that approximately 30% of the annual volume of recharge can be removed from the aquifer during the year without adversely affecting (i.e., depleting) the freshwater lens. The annual volume of recharge is calculated by multiplying the annual depth of recharge (40% of annual rainfall depth) by the lateral spatial extent of infiltrating rainfall (i.e., the island surface area), which is estimated using the cross sections widths and distances described in the algorithm for calculating fresh groundwater volume. The daily volume of safe yield is calculated by dividing the annual volume of safe yield by the number of days of the year, and the volume of per capita safe yield per day is calculated using the population of the island.

Estimating Groundwater Resources in Future Decades

Lens thickness, groundwater volumes, and safe yield are calculated for the year 2030 for the 52 islands using estimates of SLR and population increase. As sea level rises, the seawater encroaches on the beachfronts of the island, thereby producing shoreline recession and decreasing the island land surface area. As the thickness of the freshwater lens is dependent on island width and both lens volume and safe yield are dependent on island surface area, SLR can have a significant impact on groundwater resources, particularly for islands with gentle slopes.

The minimum reported rate (1.0 mm/yr) and the maximum reported rate (6.5 mm/yr) of SLR are used to provide a range of groundwater resources estimates for the year 2030. An average beach slope horizontal:vertical (H:V) value of 100:1 (i.e., a shoreline recession of 100 m for every 1 m rise in sea level), the average value for sandy beaches (Tysban et al., 1990) is used for most calculations, with H:V values of 50 (steep) and 200 (gentle) also used for lens thickness calculations to investigate the effect of beach slope. The rate of sea level rise and beach slope is used to calculate the decrease in island width and surface area by 2030 for each of the 52 islands. The percent decrease in island width and island surface area for each of the 52 islands is shown in Figures 5A and 5B, respectively, for both rates of SLR. Notice that the percent decrease is much lower for larger islands. Percent decrease in island width for the maximum SLR rate is less than 20% for all islands, with an average of 7%, and percent decrease for the minimum rate scenario is less than 4% for all islands, with an average of 1.1%. Percent decrease in island surface area is less than 13% and 3% for all islands in the maximum and minimum SLR rate scenarios, respectively, with average percent decrease of 6.1% and 0.9%.

It should be noted that neither changes in land cover type or projected temporal changes in rainfall, both of which can have an effect on the volume of rainwater that infiltrates and recharges the freshwater lens, have been taken into account in the analysis of groundwater resources in the year 2030. For the former, percent changes in land cover cannot be projected with confidence, and any modification of the average annual recharge in the algebraic model in regards to land cover change would be fraught with uncertainty. For the latter, estimated change in annual mean rainfall in the Indian Ocean during the next two decades is minimal (Lal et al., 2002), with a slight increase (1.9% +/- 0.6) expected, and hence this study provides a conservative estimate of groundwater resources in the year 2030.

RESULTS AND DISCUSSION

Results for lens thickness, lens volume, and safe yield estimates for 2012 and 2030 for the 52 islands are summarized in Figures 6, 7, and 8, respectively. The estimated lens thickness for the islands for the year 2012 is shown in Figure 6A as a function of island width, with lens thickness values ranging between 0.92 m and 12.7 m. The average for the 52 islands is 4.6 m. Due to many islands having small widths, the majority of islands have a lens thickness of less than 4 m. Generally, lens thickness is positively correlated to island width, with the lens thickness on large islands limited by the presence of the Holocene-Pleistocene contact at a depth of 15 m.

The percent decrease in lens thickness for each island by the year 2030 is shown in Figures 6B and 6C as a function of island width, with estimates shown in Figure 6B for the minimum and maximum SLR rates, and estimates shown in Figure 6C for the three beach slope values, with the latter used in conjunction with the maximum SLR rate of 6.5 mm/yr. As can be seen in the figure, mid-size islands (300 to 800 m) are impacted the most. For small islands (< 300 m), lens thickness is governed principally by rate of recharge, and hence island width does not have a strong impact on the freshwater lens geometry. For large islands (> 800 m), the change in island width is small compared to the original island width (see Figure 5A for the percent decrease in island width), and hence the lens is not affected significantly. The large percent decrease in lens thickness occurs for islands with an island width of 500 m, and is approximately 10%, 1.5%, 18%, 10%, and 5% for the scenarios of 6.5 mm/yr SLR, 1.0 mm/yr SLR, H:V = 200, H:V = 100, and H:V = 50, respectively (Figures 6B and 6C). For the worst-case scenario (maximum SLR of 6.5 mm/yr, steepest beach slope of H:V = 200), the average estimated lens thickness in 2030 for the 52 islands is approximately 3.6 m and the average percent decrease is 12.3%.

The estimated lens volume for the islands for the year 2012 is shown in Figure 7A as a function of land surface area, with the fresh groundwater volumes on a 0-12,000 ML scale and the surface area on a 0-6 km^2 scale. Due to the large difference in lens volumes for the 52 islands, and since the majority of islands have small land surface area and hence comparatively low lens volumes, an inset chart is included for the smaller islands. As can be seen in Figure 7A, the vast majority of the islands have volumes of less than 2000 ML, with most having volumes of less than 500 ML. In general, smaller groundwater volumes are associated with islands that have smaller land surface areas, with scatter around this trend due to variation in rainfall between the three identified geographic regions. Calculated per capita safe yield (L/day) for 2012 for each island is shown in Figure 8A, with again an inset chart used to show detailed results for small islands. The majority of island have estimated per capita safe yields of less than 300 L/day, much higher than recommended value of 50 L/day by the World Health Organization (WHO, 2011) to ensure basic needs for drinking, cooking, and cleaning. However, these values do not include requirements for industry or distributed sanitation systems. Also, it should be stressed that these results do not take into account water quality. Many islands may have contaminated groundwater not conducive to human consumption, although many of the islands have vast vegetated areas, and hence locations wherein thick freshwater lenses develop and groundwater contamination likely has not occurred.

The percent decrease in lens volume for each of the 52 islands by the year 2030 is shown in Figure 7B as a function of land surface area, for both the minimum and maximum SLR rates. The percent decrease in lens volume is much lower for larger islands, due to the relatively small change in land surface area compared to the original surface area (see Figure 5B for large islands). For the SLR rate of 6.5 mm/yr, the average percent decrease in lens volume is 11.4%, with a maximum of 16.0% for an island with a surface area of 5.5 km^2 and a minimum of 2.7% for an island with a surface area of < 0.1 km^2. Again, scatter around the trend exists due to various island surface geometries and differences in annual rainfall depth according to geographic location.

The estimated per capita safe yield from groundwater for each of the islands for the year 2030 using only the anticipated increase in population for each island is shown in Figure 8B, and the decrease from these baseline values due to SLR rates of 6.5 mm/yr and 1.0 mm/yr is shown in Figure 8C. Taking into account only population increase (Figure 8B), the decrease in lens volume by the year 2030 is approximately 30% for each island. The average percent decrease from these baseline values is 6.1% if the SLR rate is 6.5 mm/yr, and 0.9% if the SLR rate is 1.0 mm/yr, with a maximum percent decrease of approximately 12% for the smaller islands. Taking into account both population increase and SLR, the average decrease in per capita safe yield by the year 2030 is 34%. Overall, the decrease in safe yield is largely controlled by changes in population rather than a change in sea level and associated decrease in land surface area. Using the maximum SLR rate of 6.5 mm/yr, on average approximately 87% of the decrease in per capita safe yield due to population increase, and 13% is due to SLR and accompanying shoreline recession.

SUMMARY AND CONCLUDING REMARKS

This study presents an overall analysis of groundwater resources for the major population islands of the Republic of Maldives for current conditions and for the coming two decades. Groundwater analysis encompasses estimates of the thickness and usable volume of the subsurface freshwater lens, and per capita safe yield for the 52 most populous islands of the Maldives, with island populations ranging from 1,800 persons to over 90,000 persons. Thickness and volume of the lens are estimated using a steady-state algebraic model designed for groundwater analysis of atoll islands, with a methodology for groundwater volume calculation developed specifically for this study. The model takes into account the influences of the major geologic (island width, hydraulic conductivity of the Holocene aquifer, depth to the contact between the Holocene and Pleistocene aquifers) and climatic (annual depth of recharge) features of atoll islands. For groundwater resources in the coming two decades, with results reported for the year 2030, varying rates of projected sea level rise (SLR) (1.0 mm/yr and 6.5 mm/yr) are used in conjunction with varying levels of beach slope to determine decreases in island width and land surface area, which impact the areal extent, thickness, and volume of the freshwater lens.

For the 52 islands, with an average width of approximately 450 m, the average freshwater lens thickness is 4.6 m, and the average volume of groundwater and safe yield per person is approximately 1300 ML (million liters) and 300 L/day, with the latter well above the 50 L/day minimum value recommended by the World Health Organization. Using the maximum rate of sea level rise (6.5 mm/yr), it is estimated that by the year 2030 the average percent decrease in freshwater lens thickness, lens volume, and safe yield is approximately 10%, 11%, and 34%, respectively. For lens volume, the vast majority of islands have volumes of less than 2000 ML, with most having volumes of less than 500 ML. Future safe yield is controlled primarily by population increase, with 87% of safe yield change by 2030 due to population increase and only 13% due to a decrease in island surface area. Overall, it is predicted that mid-size islands (300 m to 800 m in width) will be most affected by groundwater resources depletion due to future SLR and associated shoreline recession.

It should be noted that reported values do not take into account water quality, which can be of critical importance since islands may have contaminated groundwater due to land surface-derived pollution. However, many islands assessed in this study have large portions of land surface covered by vegetated areas, and hence contain locations wherein thick freshwater lenses develop with little to no groundwater contamination. Also, it should be noted that estimates are based solely on available geologic and hydrologic data, with no attempt made to incorporate the effects of pumping on groundwater resources. However, since algebraic model results compare favorably with reported observed values (see Figure 4A), the effects of pumping likely are compensated by the calibrated value of Holocene aquifer *K* used in the algebraic model. Also, it should be noted that future changes in rainfall have not been taken into account in the analysis of future groundwater resources. These changes, and their impact on groundwater resources, will be explored further in future studies.

Despite the small surface areas and the threat of SLR and associated shoreline recession, results in general demonstrate that groundwater is a viable source of water for the islands of the Maldives both now and in the coming decades, particularly for islands with large surface area a low population. Such an assessment, particularly used in conjunction with studies on groundwater contamination and remediation strategies, is a key component in analyzing water security for the nation and to appraise options for water sector reform. With the aim of the project to provide a global, overall analysis of groundwater resources for the major population islands of the Maldives, the analyses presented in this study should 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), and Population for the 52 most populous islands of the Maldives (Table S-3).

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Table 1. Observed fresh groundwater volumes for islands in the Maldives, based on groundwater investigation reports.

Island	Atoll	Fresh Groundwater Volume *Million Liters*
Thinadhoo[a]	Gaafu Dhaalu	1,700
Gan[b]	Laamu	14,200
Holhudhoo[c]	Noonu	61
Velidhoo[d]	Noonu	218
Kulhudhuffushi[e]	Haa Dhaalu Atoll	1,104
Dhidhdhoo[e]	Haa Alifu Atoll	137

a: Bangladesh Consultants (2010a)
b: Bangladesh Consultants (2010b)
c: Bangladesh Consultants (2010c)
d: Bangladesh Consultants (2010d)
e: Falkland (2001)

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 and Pleistocene aquifers, typically at a depth of 15-25 m below sea level.

Figure 3. Estimated daily average rainfall for the latitude regions of 5N-10N, 0-5N, and 5S-0 for the Maldives for the years 1998-2011, as tabulated by the TRMM (Tropical Rainfall Measuring Mission). Each region is between the longitudes of 71E and 74E.

Figure 4. Observed vs. simulated comparison for (A) freshwater lens thickness and (B) fresh groundwater volume for islands for which observed groundwater data is available. Data reported by Falkland (2000), Falkland (2001), and Bangladesh Consultants (2010a, b, c, d).

Figure 5. Percent decrease in (A) island width and (B) island surface area for the 52 islands by the year 2030, using the minimum (1.0 mm/yr) and the maximum (6.5 mm/yr) projected rate of sea-level rise.

Figure 6. (A) Estimated lens thickness of the 52 islands for current conditions, and estimated percent decrease in lens thickness by the year 2030 for (B) the two rates of sea-level rise, and (C) the three beach slope values, which dictate the amount of shore-line recession due to sea-level rise. For (C), the maximum rate of sea-level rise (6.5 mm/yr) is used for each beach slope value.

Figure 7. (A) Estimated lens volume of the 52 islands for current conditions, in millions of liters, and (B) estimated percent decrease in lens volume by the year 2030 for the two rates of sea-level rise.

Figure 8. Estimated per capita safe yield of the 52 islands for (A) current conditions and for (B) the year 2030, in liters per day, with the estimate for 2030 based solely on population increase. (C) shows results of including sea-level rise and shoreline recession, with percent decrease in per capita safe yield from the 2030 baseline values shown in (B).