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Estimating transient freshwater lens dynamics for atoll islands of the Maldives

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SUMMARY

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 2–4 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.

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 and 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

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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, 2001; GWP Consultants, 2005; Bangladesh Consultants, Ltd., 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 (Fig. 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 Fig. 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 °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, 1974), 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 Fig. 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 (Fig. 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