

1 **Estimating Transient Freshwater Lens Dynamics for Atoll Islands of the Maldives**

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6 Ryan T. Bailey^{1*}, Abedalrazq Khalil², Vansa Chatikavanij²

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10 ¹ Department of Civil and Environmental Engineering, Colorado State University, 1372 Campus

11 Delivery, Fort Collins, CO, 80523-1372, United States

12 ² The World Bank Group, Washington D.C., 20433, United States

13

14 Emails: rtbailey@engr.colostate.edu, akhalil@worldbank.org, vchatikavanij@worldbank.org

15 * Corresponding author. Tel: 970-491-5045; Fax: 970-491-7727

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24 **Abstract**

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

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

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50 **1. Introduction**

51 Water resources of the Republic of the Maldives are under serious immediate and future
52 threat due to changing rainfall patterns, sea-level rise and associated coastal degradation
53 (Pernetta, 1992; Lal et al., 2002; Mörner et al., 2004; Woodworth, 2005; Woodroffe, 2008), an
54 increasing urban population for many of the islands, limited rainwater harvesting capacity, and
55 contamination due to seawater intrusion, overwash events (Woodroffe, 2008; Barthiban et al.,
56 2012), and land surface derived pollution. The nation, located in the Indian Ocean, comprises
57 about 200 inhabited small coral atoll islands and has a total population of approximately
58 320,000. Communities on atoll islands are considered some of the most vulnerable worldwide in
59 terms of freshwater scarcity and depletion of water resources due to small land surface, low
60 elevations, geographic remoteness, and expected changes in climate (Nurse et al., 1998; IPCC,
61 2001; Carpenter, 2002; White et al., 2007; White and Falkland, 2010; Yamamoto and Estaban,
62 2013).

63 Of particular concern for the islands of the Maldives is the potential depletion of fresh
64 groundwater, a historically important source of potable water for island communities of the
65 Maldives. The body of fresh groundwater in the near-surface island sediments, termed the
66 “freshwater lens” due to its volumetric shape, floats atop underlying seawater-saturated
67 sediments and is naturally a fragile resource for atoll islands (White et al., 2007; White &
68 Falkland, 2010) due to extremely small land surface area ($< 1 \text{ km}^2$) and resulting thinness of the
69 lens. As such, this resource is acutely affected by short-term and long-term changes in rainfall

70 patterns, such as annual dry seasons and potential decrease in annual rainfall rates, respectively,
71 as well as contamination from the land surface that is rapidly advected through the thin (< 2-3 m)
72 unsaturated zone to the water table (Dillon, 1999).

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

84 In this study, a general assessment of freshwater lens fluctuation over a decadal time period
85 is performed for the most populous islands in the Republic of the Maldives to analyze the
86 influence of annual and long-term rainfall patterns on groundwater resources. Specific objectives
87 are first, to identify ranges and trends of lens thickness that result from decadal trends in rainfall
88 patterns across the geographic region of the Maldives, with particular attention given to
89 minimum lens thickness that occurs during periods of low rainfall rates; and second, to provide
90 month-by-month estimates of freshwater lens thickness for the 201 most populous islands of the
91 Maldives during the 14-year time period of 1998-2011. These objectives are accomplished in the
92 two-step process of first, using a variable-density groundwater flow and salt transport numerical

93 model to simulate time-dependent fluctuations of lens thickness for a variety of island widths
94 during the years 1998-2011; and second, projecting these results to individual islands. All model
95 simulations use daily-calculated recharge derived from daily rainfall data for the geographic
96 regions encompassing the Maldives, and the range of island widths corresponds to those of the
97 atoll islands of the Maldives. The models are corroborated using observed time-dependent lens
98 thickness values from a number of islands of the Maldives. Results provide water resource
99 managers and policy makers within the Republic of the Maldives with reliable lens fluctuation
100 evaluations that can be taken into account for current and future water resource planning and
101 management.

102

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

104 **2.1 Geography, Land, and Population**

105 The Republic of the Maldives is located in the Indian Ocean to the southwest of India (Figure
106 1), and comprises approximately 2000 coral islands, many of which are administered as 20 atolls
107 covering a geographic area of approximately 90,000 km². The coral islands have extreme low
108 elevations and small land surface areas. Average and maximum ground surface elevation of 1.5
109 m and 2.4 m, respectively, and many of the inhabited islands have a land surface area of less than
110 1 km². More than 90% of the country's land has an elevation of less than 1 m above mean sea
111 level. Total actual land area of the Maldives is approximately 300 km² (MEE, 2011), with 84%
112 occupied by miscellaneous infrastructure and native vegetation, 10% by cultivated land, 3% by
113 forested land, and 3% by pastures. A detailed map of Laamu Atoll in the southern Maldives is
114 presented in Figure 1, showing the typical land surface structure of atolls, with a circular or
115 quasi-circular chain of small coral islands surrounding a shallow lagoon.

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

122 **2.2 Climate and Water Resources**

123 The climate experienced by the Maldives is warm and tropical year round, with mean annual
124 temperature and average relative humidity of 28.0 °C and 80%, respectively. Annual rainfall is
125 highest in the southern Maldives, with the southern atolls receiving approximately 2350 mm/yr
126 on average, and lowest in the northern region, with the northern atolls receiving approximately
127 1700 mm/yr on average. Average intra-annual changes in rainfall rate occur according to a dry
128 season-wet season pattern, with the dry season occurring from January to April and the
129 remaining annual rainfall depth typically distributed evenly throughout the remaining months of
130 the year.

131 The inhabitants of the Maldives rely on a combination of rain catchment water, desalinated
132 seawater, and groundwater from the freshwater lens to meet freshwater demands for domestic
133 and manufacturing needs. Due to the high permeability of land surface sediments the small land
134 surface area, streams and lakes do not form on the islands, typical of atoll islands (Urish, 1951),
135 and hence the freshwater lens is the only natural storage of freshwater. Desalinated seawater is
136 typically used on high-urbanized islands such as Male', whereas the outer atoll islands use a
137 combination of stored rainwater and groundwater. Rainwater, which is captured using individual
138 household or communal roof catchment systems, typically is the primary source of drinking

139 water, while groundwater is used for secondary purposes including bathing, washing, and toilet
140 flushing. Similar patterns of water use are followed in other atoll island communities, such as
141 within the Federated States of Micronesia (SOPAC 2007a), the Republic of Marshall Islands
142 (SOPAC, 2007b), and the Republic of Kiribati (White et al., 1999).

143 A general representation of the groundwater system for atoll islands (Ayers and Vacher,
144 1986) is shown in Figure 2A. Due to the differences in density between freshwater and seawater
145 and resulting variable-density groundwater flow, the fresh groundwater floats atop the denser
146 seawater within the island subsurface sediments. Rainwater that is not intercepted by vegetation,
147 captured by rooftop catchment systems, evaporated, or transpired by plants, percolates through
148 the thin soil profile and recharges the freshwater lens at the water table. The aquifer has two
149 distinct units, the surficial particulate Holocene aquifer and the high-permeable, limestone
150 Pleistocene paleo-karst, with a solution discontinuity forming the contact between the two units.
151 The contact typically is located approximately 15-25 m below sea level (Wheatcraft and
152 Buddemeier, 1981), and the hydraulic conductivity (K) of the Pleistocene aquifer is estimated to
153 be one to two orders of magnitude higher than K of the Holocene aquifer (Woodroffe and
154 Falkland, 1997).

155 The thickness of the freshwater lens, which controls the available volume of extractable
156 fresh groundwater in the subsurface, is controlled by island width, the rate of precipitation and
157 associated infiltration and recharge, K of the Holocene aquifer (Figure 2A), aquifer dispersivity,
158 which controls the thickness of the mixing zone between the freshwater and seawater, and the
159 Holocene-Pleistocene contact. Depending on these factors, lens thicknesses for islands in the
160 Pacific and Indian Ocean basins range from less than a few meters to 25-30 m (Falkland, 1994;
161 Anthony, 1997; Hunt, 1997; Falkland, 2000; Falkland 2001; Bailey et al., 2009), with drought

162 conditions typically causing a complete depletion of fresh groundwater (Bailey et al., 2013). For
163 islands in which rainfall rate is high enough and the island width is large enough for a thick (> 10
164 m) freshwater lens to develop and the base of the lens to reach the Holocene-Pleistocene contact,
165 freshwater moving below the contact mixes with underlying seawater, thereby creating a sharp
166 transition between freshwater and seawater and resulting truncation of the lens (Hunt, 1997;
167 Woodroffe and Falkland, 1997).

168

169 **3. Methodology**

170 **3.1 Quantifying Time-Dependent Lens Thickness**

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

184 Six different finite-element meshes are used to represent infinite-strip islands with widths of
185 200 m, 300 m, 400 m, 500 m, 600 m, and 1100 m, with the cross-section assumed to occupy the
186 transect orthogonal to the island axis. These widths were chosen to span the range of island
187 widths observed in the Maldives. Mesh discretization varies throughout the extent of the model
188 domain, with finely-resolved discretization required within the vicinity of expected freshwater
189 lens development to provide numerical stability during simulations. For the mesh representing
190 the 400-m wide island, the mesh consists of 7,832 elements and 8,055 nodes.

191 Recharge from rainfall is assigned to nodes located at sea-level along the length of the island
192 transect. Recharge for each day of the 1998-2011 time period is derived from daily rainfall
193 values from the Tropical Rainfall Measuring Mission (TRMM). To account for the differences in
194 rainfall rates across the geographic region encompassing the Maldives, daily rainfall was
195 collected for three regions: the geographic region between the latitudes of 5N to 10N, the region
196 between 0 and 5N, and the region between 5S and 0, with each region between the longitudes of
197 71E and 74E. Daily values for the period of 1998-2011 for each of the three regions are shown in
198 Figure 3, with annual totals of rainfall for each region presented in Table 1.

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

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

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

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

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

252 2001. In total, 152 observed lens thickness values were compiled for model testing. Each
253 observed value is compared to a corresponding simulated value from the applicable model, i.e.,
254 from the island width model that corresponds most closely with the width of the island from
255 which the measurement was taken. Furthermore, observed values are compared to simulated
256 values from the applicable time step, i.e., from the time step during the 1998-2011 simulation
257 time period that corresponds to the date on which the measurement was taken. It should be noted
258 that, in order to avoid bias, no attempt was made to calibrate parameters for specific islands, i.e.
259 the same K values and depth to the Holocene-Pleistocene contact are used for each of the six
260 island width models.

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

269 **3.2 Lens Thickness Estimates for Inhabited Islands**

270 Using the results from the numerical modeling simulations, monthly simulated lens thickness
271 values during 1998-2011 are projected to the inhabited islands of the Maldives based on the
272 average width of each island. For islands with widths in between the widths used for the
273 numerical models (200 m, 300 m, 400 m, 500 m, 600 m, and 1100 m), linear interpolation was
274 used to provide monthly estimates. This efficacy in using linear interpolation is possible due to

275 the linear relationship between island width and lens thickness for each month of the 14-year
276 simulation period, which will be discussed in Section 4. The islands included in this analysis,
277 including population, the atoll on which the island is situated, and the average width (m), is
278 presented in Table S-3 in Supporting Information.

279

280 **4. Results and Discussion**

281 **4.1 Numerical Model Simulations**

282 Results are shown as time series of maximum lens thickness (i.e., lens thickness at the center
283 of the island), cross-section contour plots of salinity to display the delineation of the freshwater
284 lens, and summary statistics for the 201 islands regarding maximum and minimum lens thickness
285 during the 1998-2011 time period. The achieved steady seasonal pattern of lens thickness
286 fluctuation for each of the island widths using the four-year transient spin-up simulations is
287 shown in Figure 4 for each of the three geographic regions. The development of steady-state
288 freshwater lens delineation during the initial steady recharge rate simulations is shown in Figure
289 S1 in Supporting Information for each island width model. In Figure 4, notice that the lens
290 thickness values for the 5S-0 latitude region are the highest among the three climate regions due
291 to the higher magnitude of rainfall, with the average lens thickness for all island widths during
292 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,
293 respectively. In general, the fluctuation of the lens between wet and dry season is most
294 pronounced for the two northern regions.

295 The lens thickness fluctuation during 1998-2011 for each island width model for each of the
296 three geographic regions is shown in Figure 5, and comparison of observed and simulated values
297 of lens thickness shown in Figure 6, with a 1:1 line depicting a perfect match. The match

298 between the observed and simulated values is reasonable ($R^2 = 0.625$), with large observed lens
299 thicknesses generally matched by large simulated lens thicknesses, and small observed
300 thicknesses matched by small simulated thicknesses. Similar to the steady seasonal fluctuation
301 shown in Figure 4, the lens thickness values for the 5S-0 region are the highest among the three
302 geographic regions, with average lens thickness for island widths equal to 4.4 m, 3.3 m, and 3.1
303 m for the 5S-0, 0-5N, and 5N-10N regions, respectively.

304 For the 5N-10N region, minimum lens thicknesses occur in the years 2003-2005 due to
305 below-average rainfall rates and associated recharge rates, with absolute minimums occurring
306 during the dry seasons of these years. For the 0-5N region, minimum lens thicknesses occur in
307 2001 and 2006; and for the 5S-0 region, minimum lens thickness occurs during 2000-2002,
308 followed by a steady increase in lens thickness during the latter months of 2002 and the first
309 months of 2003. The minimum, maximum, and average lens thickness for each island width and
310 for each geographic region is shown in Table 3. For each of the three geographic regions, the 200
311 m island experiences complete or nearly complete depletion of the lens for much of the 14-year
312 time period; the 300 m island experiences depletion during the dry season of many of the years
313 for the 0-5N and 5N-10N regions; and the 400 m island experiences near-depletion during the
314 dry season for the 0-5N and 5N-10N regions. Cross-section contour plots of salinity, depicting
315 the freshwater lens and the transition zone to seawater, are shown in Figure 7 for the models with
316 island widths of 200 m, 400 m, 600 m, and 1100 m at the beginning of the 14-year period
317 (January 1 1998) and at times of minimum and maximum lens thickness for the three geographic
318 regions. For the plot showing the maximum lens thickness of the 1100 m island within the 5S-0
319 region, notice the truncation of the lens due to the base of the lens descending to the Holocene-
320 Pleistocene contact.

321 Results of the 1998-2011 simulations shown in Figure 5 also provide information regarding
322 general long-term trends in groundwater resources for atoll islands in the Maldives. The islands
323 located in the 0-5N and 5N-10N regions experience an overall decrease in lens thickness during
324 the 14-year period, whereas the islands in the 5S-0 region experience an overall increase, due to
325 differences in rainfall patterns. Average rate of change in lens thickness for each island width
326 model for each geographic region is presented in Table 4. The rates of increase in the 5S-0
327 region range from 0.39 cm/yr (200 m island) to 8.82 cm/yr (600 m island), with an average rate
328 of increase of 4.0 cm/yr. The rates of decrease in the 0-5N region range from 0.24 cm/yr (200 m
329 island) to 5.61 cm/yr (600 m island), and the rate of decrease in the 5N-10N region range from
330 0.23 cm/yr (200 m island) to 4.65 cm/yr (1100 m island). Overall, rates of decrease in lens
331 thickness are most pronounced for the islands in the 0-5N region with an average of 3.75 cm/yr,
332 compared to 1.87 cm/yr for the 5N-10N region. If continued at current rates, these trends can
333 have a significant impact on lens thickness for the islands of the Maldives, particularly since the
334 majority of islands are located in the two northern geographic regions.

335 **4.2 Lens Thickness Estimates for Inhabited Islands**

336 Using results from the 1998-2011 simulations, monthly lens thickness values for each of the
337 201 inhabited islands are estimated. The viability of these projections using linear interpolation is
338 demonstrated in Figure S-2 in Supporting Information, which shows linear trends of lens
339 thickness vs. island width for a number of time steps during the 1998-2011 simulation. R^2 values
340 of the trends are all above 0.98, and typically above 0.99. Figure 8 shows an example of
341 projection results for seven islands of the Maldives, selected to display the difference in lens
342 thickness and fluctuation patterns according to island width and geographic region. Three islands
343 are selected from the 5N-10N region (Kelaa, Haa Alifu Atoll, 1000 m; Vashafaru, Haa Dhaalu

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

347 A summary of the freshwater lens dynamics for all 201 islands is presented in Figure 9.
348 Figures 9A and 9B show the maximum and minimum lens thickness for each island during 1998-
349 2011, as a function of island width and as a histogram, and Figure 9C shows the percent decrease
350 in lens thickness from the maximum to the minimum thickness values for each island. For the
351 latter, values are displayed according to geographic region. From these results, as well as the
352 complete lens fluctuation for selected islands as shown in Figure 8, it is evident that a significant
353 change in lens thickness occurs during the period due to rainfall rate differences between the
354 annual wet season and dry season, as well as during years of low rainfall and preceding or
355 succeeding years of higher annual rainfall. As expected, lens thickness increases with island
356 width, with scatter around this trend due to geographic region and associated rainfall rates for the
357 individual islands. Lens thickness for large islands is limited by the depth to the Holocene-
358 Pleistocene contact (~ 14-15 m). The majority of the islands have an island width of 500 m or
359 less, and hence a relatively thin lens, with a complete depletion of fresh groundwater for at least
360 one month during the 14-year period for islands with widths of less than 300 m.

361 The depletion of the lens for smaller islands also can be seen in Figure 9C as high percent
362 decreases in lens thickness occur for small islands. From the values of percent decrease in lens
363 thickness (Figure 9C), it can be seen that the lens can become completely depleted (100%
364 decrease) for small islands (≤ 300 m in width) for one or more months during the 14-year period.
365 For islands width widths smaller than 500 m, the percent decrease typically is more than 50%.
366 Due to the shape of the freshwater lens, a 50% decrease in lens thickness equates to a much

367 higher percent decrease in groundwater volume, and hence many of the islands can experience
368 drastic changes in fresh groundwater reserves from the wet season to the dry season.

369

370 **5. Summary and Concluding Remarks**

371 This study presents an overall analysis of freshwater lens fluctuation for the atoll islands of
372 the Maldives during a 14-year period (1998-2011) in an effort to further understand long-term
373 (>10 years) behavior of groundwater resources for the nation. Numerical model simulations were
374 performed using the variable-density groundwater flow and salt transport code SUTRA for a
375 variety of island widths (200 m, 300 m, 400 m, 500 m, 600 m, 1100 m) and for three latitudinal
376 belts (5N to 10N, 0 and 5N, and 5S and 0 between 71E and 74E) covering the Maldives atolls
377 and the associated differences in annual rainfall patterns. The numerical models are constructed
378 after the dual-aquifer atoll island model, with a surficial fine-sediment Holocene aquifer
379 underlain by a highly-permeable limestone Pleistocene aquifer. Daily recharge to the freshwater
380 lens is derived from daily rainfall depths using a water balance model. Simulated lens
381 thicknesses are compared against observed lens thickness values from 22 islands for model
382 corroboration according to island width and date of measurement, and model results are
383 projected to 201 inhabited islands of the Maldives based on average island width and latitudinal
384 belt.

385 Model results indicate that many of the atoll islands are expected to have a measurable
386 freshwater lens during the majority of a long-term climatic period, although significant decreases
387 in thickness can occur during the months of the dry season. For the majority of the islands, the
388 lens is very dynamic, with at least a 50% decrease from the maximum to the minimum lens
389 thickness experienced during the 1998-2011 period. For small islands (≤ 300 m in width),

390 complete depletion of the lens is expected to occur either due to typical dry season rainfall
391 patterns or due to successive years of low annual rainfall rates. Due to higher rainfall totals, the
392 islands in the 5S-0 region experience generally a thicker freshwater lens than the islands located
393 in the 0-5N and 5N-10N regions. Of keen interest is the overall trend in lens thickness, with a
394 general decrease in lens thickness over the 14-year period for islands subject to the rainfall
395 patterns of the 0-5N and 5N-10N regions, and a general increase for the islands located in the 5S-
396 0 belt. Average rates of decrease of lens thickness are 3.75 cm/yr and 1.87 cm/yr for the 0-5N
397 and 5N-10N regions, respectively, and the average rate of increase is 4.0 cm/yr for the 5S-
398 region.

399 It should be noted that groundwater pumping, which occurs on many of the islands of the
400 Maldives, was not taken account in the numerical modeling simulations and analysis. However,
401 as model results generally correspond with observed results, this feature does not impact the
402 general results of the study, particularly since lens thickness is depleted during the dry season for
403 small islands due to rainfall patterns alone. Furthermore, by neglecting human effects, the 14-
404 year trend in lens thickness due to changes in rainfall patterns is able to be elucidated. Also, it is
405 noted that the simulations did not take into account the impacts of the December 26 2004
406 tsunami, which for several islands would result in salinization of the lens due to island overwash
407 events, with about 1.5 years required to achieve pre-overwash lens thickness based on field
408 observations and numerical modeling experiments (Terry and Falkland 2010; Bailey and Jenson,
409 2013). However, only several months of average rainfall would be required to provide potable
410 groundwater at the depths accessed by hand-dug wells (Bailey and Jenson, 2013).

411 Results imply that fresh groundwater, if properly protected from land surface-derived
412 contamination and over-pumping and associated salinization, can be a valuable source of water

413 for the islands of the Maldives, particularly for the larger islands. However, a significant
414 decrease in fresh groundwater occurs between the wet and dry seasons, and hence supplemental
415 sources of water such as rainwater captured and stored by rooftop catchment systems during the
416 wet season should be used where available during the dry season. Furthermore, results indicate
417 that long-term trends in fresh groundwater reserves are occurring due to changes in rainfall
418 patterns, with detrimental trends (i.e., decrease in lens thickness) experienced by the northern (0-
419 5N, 5N-10N) geographic regions. If continued at current rates, these trends can have a significant
420 impact on groundwater resources for the Maldives. Finally, as this study only analyzes lens
421 fluctuation for inhabited islands, likely there are numerous uninhabited islands that also have
422 significant fresh groundwater reserves, which could figure into water resources planning and
423 management. Overall, results provide water resource managers and government officials with
424 valuable data for consideration in water security measures.

425

426 **Supporting Information**

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

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559

560 **Figure Captions**

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

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

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

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

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

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

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

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

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

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