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A Review of Water Resources of Maldives

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WATER RESOURCES OF THE REPUBLIC OF MALDIVES

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Abstract

The Republic of Maldives encompasses around 1200 Islands of which 200 are inhabited by the local Maldivians. Except in a few islands, the Maldives is not endowed with surface water resources, such as streams or natural/man-made lakes. The spatial and temporal distribution rainfall is a critical determinant of the water deficit or surplus in the Maldives. Rainfall is the primary source which is captured directly using rainwater catchments and stored in rainwater tanks or infiltrated into the ground and stored in an aquifer. Both these sources are used in the Maldives as freshwater sources. Groundwater has been the traditional source of potable water until recently.

According to the Government of Maldives and UNICEF, in the year 2000 estimates show that 75% of the Maldivian population use rainwater for drinking and groundwater for other purposes. The Maldives, despite receiving ample rains most of the year, faces water shortages during the dry season because of the limited capacity of the aquifer. The rainwater tank capacity is inadequate to last for the dry period. During the dry season the rainwater tanks go dry and the groundwater is lens gets depleted in most islands. The other islands resort, industrial, agricultural and other uninhabited islands are not currently facing any serious water issues.

Today, on most densely populated islands, groundwater is highly polluted. The government has abandoned relying on groundwater as a source of potable water because of the low water quality on inhabited islands. Groundwater exists in unconfined aquifers of extremely limited capacity and a high level of fragility. A few islands that have surface water bodies are not used as potable water. It is noted that all existing storage systems, including the superficial aquifer are not capable of storing enough water to last a dry period of two months or more. The solution for this is to turn to desalinization option which is expensive and environmentally not attractive.

This paper is an attempt to further review the state of water resources in the Republic of Maldives, in order to identify a sustainable solution to the growing problem of the availability of limited water resources to an ever growing population.

The report gives a general overview of the water resources in Maldives such as rainwater and groundwater. A discussion of the rainwater harvesting methods, quality of the rain water and surface water, threats to water security and scarcity of water. The report concludes that a decline in the rainfall as a result of global climate change becomes a reality in the Maldives and careful management of the existing groundwater resources will be a necessity. Like many other SIDS, the Maldives has a serious water scarcity problem which is bound to aggravate with time with the increasing population, the declining rainfall and incident of drought. A part of the solution would be a combination of improved desalination systems powered by clean energy, sound management of groundwater resources, groundwater recharge wells, good sanitation practices and carful harvesting of ground water from uninhabited islands.

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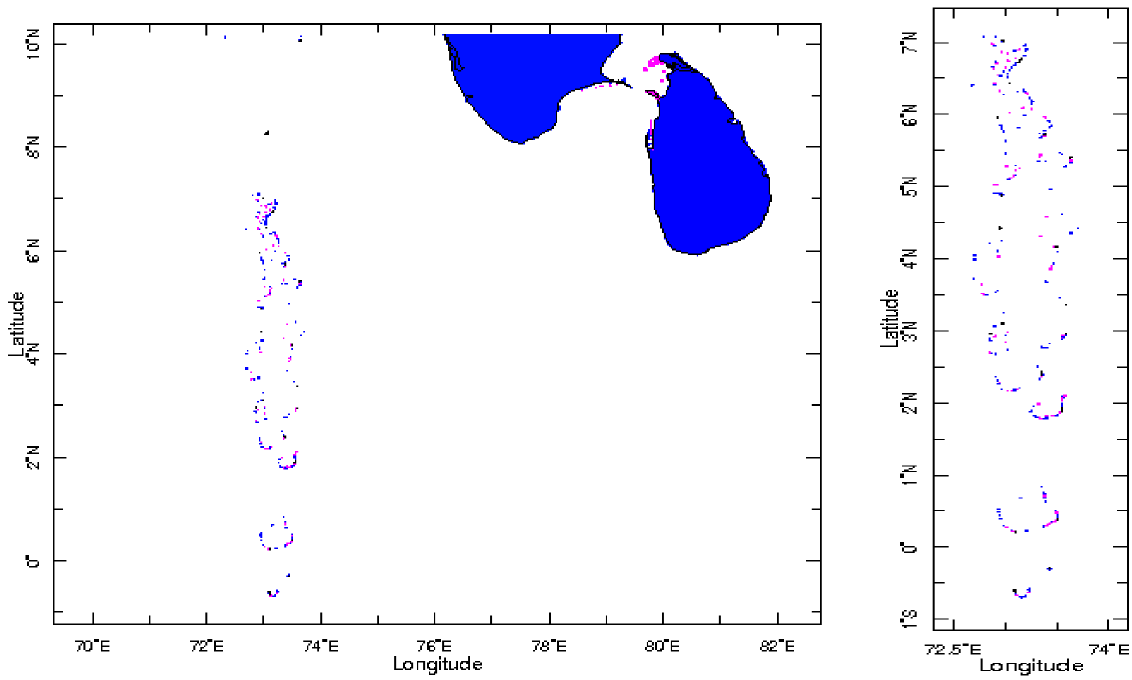
1.0 Introduction

The Maldives falls into the category of Small Island Developing States (SIDS) on the basis of its size and the status of development. The Republic of Maldives is not one island but is made up of about 1200 small islands, of which the number of inhabited islands is 188. The sizes of these islands determine the volume of freshwater available. The size of the inhabited islands ranges from about 4 ha to nearly 700 ha. A large number of uninhabited islands are not more than a few hectares and may or may not be covered with vegetation. The maximum elevation is about 2.5m and 80% of the islands are below 1m from MSL (Mean Sea Level). The surface area of each island determines the volume of rainwater it receives. The percentage of this water can be stored in a small island aquifer according to its capacity. Some small islands have disappeared or amalgamated to other islands. The usable water resource is limited to the replenishable portion of the groundwater resource and this puts a cap on the maximum extractable volume over a given period of time. On the other hand, the quality of the resource determines the suitability of that water for human consumption. Thus, Maldives, like many other SIDs face the problem of scarcity of two most basic natural resources, land and water, that are functionally related. The scarcity of water is not due to a lack of rainfall, but because of the small size of the islands and the low elevation. These small islands are clustered into 26 atolls spread over an area of about 90,000 km^2 (130 km X 820 km) in the Western Indian Ocean. The total land area of the Maldives is about 300 km^2. The only freshwater resource on these islands is a groundwater lens which floats atop a denser salt water layer. Because of the size of the islands and the low elevation, the aquifer capacity is limited and can support only a modest population on each island. This limit has long past on the most of densely populated island of Malé. It has enough water to support only about 10,000 people, but the current population has reached 153,000 including migratory workers and visitors according to 2014 census (National Bureau of Statistics, 2015). Traditionally, the people of the Maldives depended on groundwater for their daily water needs under low population densities. As the population grew, three problems arose. First is the inadequacy of the freshwater lens to support a large population with increased per capita water consumption. The second problem is the diminishing groundwater lens volume due to reduced recharge caused by increased impervious surfaces and capture of rainwater by rainwater harvesting systems and increased pumping. The third is the pollution of the groundwater lens mainly from sewerage from septic tanks. Groundwater lens becomes almost depleted on about 50% of the inhabited islands towards the end of the dry season, prompting the population to seek water from the government to meet their daily needs.

(Shakeela, 2015) Groundwater pollution caused a series of epidemics in the 1970s forcing the government and people to look for alternative sources of freshwater. In the absence of surface water resources, such as rivers and lakes, only viable options were rainwater harvesting and desalinization supplemented by imported bottled water. Of the three, the most economical option is rainwater harvesting. From the beginning of the 20th century rainwater harvesting was practiced in a small scale, but the popularity of rainwater began to increase from the 1970s onwards. A further expansion can be observed in the 1990s to-date. This has increased the access to real or perceived safe water to the increasing numbers of Maldivians. Only 40% of the population had access to safe drinking water in 1977, but it went up to 61% in 1990 and 91% in 1998 (Millar, 2002). WHO and UNICEF (2014, 2015) have reported that 99% of the people of Maldives had access to improved sanitation facilities and safe drinking water by 2012. The same report cited that the government's target was 100% for both by 2013. The government's main focus has been to improve rainwater harvesting infrastructure and expansion of desalination capacity. Now Malé, the capital, is provided with pipe-borne desalinized water to all its residents. The government also undertook to provide public rainwater harvesting tanks free of charge and individual household tanks on cost-recovery basis to the residents of other islands. Under the Science and technology Master Plan (2000) 2,914 tanks with the total capacity of 1,520 cubic metres were distributed free of charge for communal use and another 1,588 household tanks on a cost-recovery basis. But this perceived safety of the rainwater is also problematic. The picture emerging from the scanty data available shows that this source may also be contaminated to a certain extent. It is essential that more interest is shown to determine the rainwater quality and to take remedial measures if necessary.



Regional map showing the southern tip of India, the Maldives islands to the east and Sri Lanka to the west. The Maldivian region is shown in detail in the map to the right.

Figure 1 Location Map of Maldives

2.0 Water Resources of the Maldives

Water resources can be categorized as conventional and non-conventional (Falkland, 1999). The conventional resources include rainwater, groundwater and surface water and non-conventional water includes imported bottled water, desalinized water and treated waste water. In the Maldives the conventional water is limited to groundwater and rainwater. Except in a few islands, the Republic of Maldives is not endowed with surface water resources, such as streams or natural/man-made lakes. Rainfall is the primary source which is captured directly using rainwater catchments (rooftops) and stored in rainwater tanks or infiltrated into the ground and stored in an aquifer. Both these sources are used in the Maldives as freshwater sources. Groundwater has been the traditional source of potable water until recently. Today, on most densely populated islands, groundwater is highly polluted. The government has abandoned relying on groundwater as a source of potable water because of the low water quality on inhabited islands. Groundwater exists in unconfined aquifers of extremely limited capacity and a high level of fragility. A few islands that have surface waterbodies are not used as potable water. The densely populated islands are becoming increasingly dependent on desalinated water due to the high level of pollution and/or contamination with salt water. The resort islands produce their own desalinated water and this is supplemented by rainwater and groundwater for specific functions. Desalination is available to the high population centres like the island of Malé and all resort islands. A limited quantity of water is also imported from neighbouring countries, mostly to be used as drinking water for tourists. Both these options come with a substantial price tag. Desalination at present has a large carbon footprint, which may be reduced by using sustainable energy technologies, such as solar power or ocean power.

The Maldives, despite receiving ample rains most of the year, faces water shortages during the dry season because of the limited capacity of the aquifer. During the dry season the freshwater lens shrinks on most islands. The other islands such as resort, industrial, agricultural and other uninhabited islands are not currently facing any serious water issues. The resort islands do not depend on the freshwater lens for most of their water needs and also they have modern sanitation infrastructure that prevents groundwater pollution. The water needs of the resort islands are met by several sustainable sources. Drinking water for tourists is imported bottled water. Water used for cooking and bathing is desalinized water, which comes from an inexhaustible source, except that the brine from desalinization plants may be a cause for concern if not discharged properly.   Rainwater is used for drinking and other needs of the resort staff and groundwater is used only for watering gardens. Seawater is used directly for flushing toilets.   The industrial islands also do not seem to have a serious water issues at present and agricultural islands as well as the inhabited islands use groundwater for irrigation. Drought periods and the dry season are the main concerns of the islands which depend on groundwater even for a small but essential part of their water needs.

At the time of the 2004 tsunami, about 137,275 islanders were depending on ground water for domestic use completely or partially (Table 1). This was more than half of the population of the Maldives at that time. The situation today is much improved. Fewer people use GW as potable water because of poor water quality.   About 75% of the people of the inhabited islands were drinking untreated groundwater for some part of the year prior to 2004. Estimated total annual volume of GW use was 10.3 million m^3/yr. The statistics in Table 1 paint an alarming picture. Despite the expansion of rainwater harvesting capacity and supply of desalinated water, a significant number of islanders still depend on poor quality groundwater for some part of their water needs. Fifteen islands completely depend on groundwater for their water requirements. Groundwater is a valuable resource and can be exploited in a sustainable manner if managed properly.

Table 1 Pattern of GW Water Usage

Total number of inhabited islands in 2014	188
Total number of islands with fresh groundwater	132
Total number of islands with salty groundwater	17
Total islands drinking GW all the time	15
Total islands drinking GW when no rainwater	146
Total no. of Wells	38,476
Average depth of well below ground surface(m)	1.1 – 2.1
Average no. Pers/well	5.2
No. people drinking GW all the time	32,300
No. people drinking GW some of the time	104,975
No. of people drinking untreated GW	95,815
Estimated total annual volume of GW use (m^3/y)	10,269,637

Source: White, Falkland and Bari (2013); National Bureau of Census (2015)

This valuable freshwater resource should not be abandoned in favour of other expensive options. The largest threat to groundwater lens is the sewerage pollution. To reduce contamination, it may be necessary to equip the islands with proper sanitation facilities. Since no water is extracted in the uninhabited islands, the shallow groundwater lens can be assumed to be adequate for ecological needs and some of these islands and also large sparsely populated islands may have groundwater resources to be used by the inhabited islands. Some part of the available water can be supplied at least as bottled water if stringent measures are adopted to prevent anthropogenic pollution. For this, it may be necessary to examine the aquifer capacity of the uninhabited islands.

3.0 Rainwater

The primary source of drinking water in the Maldives is the rainfall. The rainfall is either directly intercepted by rainwater harvesting system or allowed to go into the aquifer and then extracted as groundwater. The spatial and temporal distribution rainfall is a critical determinant of the water deficit or surplus in the Maldives. Spatially, rainfall declines from

2,320 mm at *Gan* (Airport Island) in the South to about 1,700mm in the North. That means more water is available to islanders in the South than to those in the North. The Maldives has a humid tropical climate which ensures a high rate of evapotranspiration throughout the year. Another important feature of the rainfall of the Maldives in terms of water availability is the seasonal distribution. The Maldives has two seasons, southwest monsoon (SWM) and northeast monsoon (NEM) seasons. The former is the wet period that extends from September to November and the latter is the dry period from December to April. During this dry period (Dec-Mar) most islands have water shortages and government supplies desalinized water free of charge on request. The length of the dry season also varies from south to north. In the South, the Dry Season is limited to 2 months, February and March (Figure 2). Compared to the South *(Gan)* dry season rainfall in the North is lower *(Hanimaadhoo).* In the North, the dry season spans over 4 months from December to March.

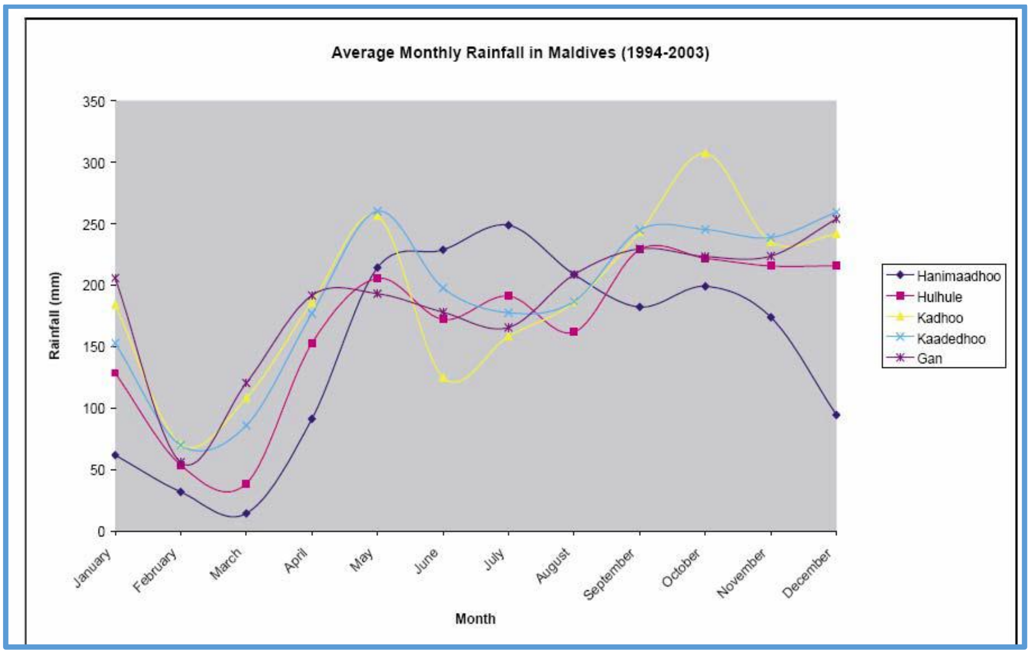


Figure 2 Seasonality of Rainfall in the Maldives

The Maldives has experienced downward trends in rainfall in the last few decades starting from late 1970s (Figure 3). The trend at *Gan* (South) is steeper than that in the north as exemplified by Malé. A drop of 5mm in the annual rainfall and 4 mm during the wet season has been observed in the Maldives. Parallel reduction in rainfall during the SWM has been observed in the core monsoon areas of India and Sri Lanka during the same period. The downward trend in the rainfall will have serious implications for the water security of the Maldives. This is perhaps far more serious than the projected sea level rise. However, global climate models predict enhanced rainfall in the Maldives (Deng, 2016) resulting in increased availability of groundwater. On the contrary, the statistical data shows a declining rainfall.

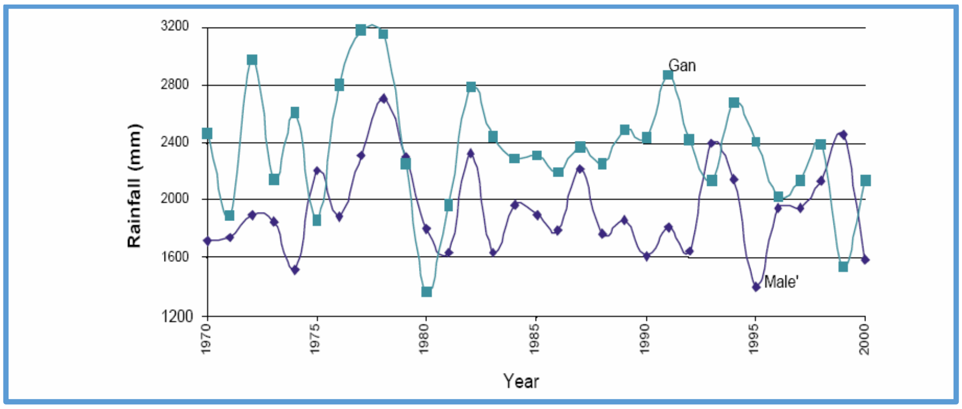


Figure 3 Long-Term Rainfall at Gan (South) and Malé (North)

Water security in the Maldives is directly controlled by the seasonal regime and long-term trends. Rainfall determines the amount of freshwater the people of the Maldives can utilize as directly captured rainwater and extraction from the freshwater lens which has traditionally been the source of potable water. Availability of both fresh groundwater and rainwater that can be captured depends on the rainfall amount and seasonal regime. Possible adverse effects of climate change on water scarcity cannot be ruled out.

4.0 Groundwater

Rainwater is infiltrated into the highly permeable soil and recharges the water table. On atoll islands the aquifer that stores this water has a limited capacity and therefore the volume of water remaining in the aquifer at any given time depends on rainfall and the size of the island. The water recharged during the wet season is lost during the dry season due to water extraction and evapotranspiration losses. Groundwater (GW) in small islands exists as a lens floating atop saline groundwater (Figure 4). This very same situation exists in coastal dune areas and hydrologists call this ‘dune problem’ (Eeman, et al 2011). At the freshwater saline water interface the flow lines turn horizontal. Freshwater entering the aquifer flows out into the sea at the edges of the islands. It is generally conceptualized that there exists a sharp transition from freshwater to saline water (Eeman, et al., 2011). But a modelling study carried out by Deng (2016) shows that there is a transitional mixing zone between the two layers. The amount of freshwater available is limited and the resource is extremely vulnerable to over use and pollution from land surface sources.

Groundwater lenses have been the main source of potable water since historical times for the people living on numerous small islands of the Maldives archipelago. In the past, the GW resource was adequate and the risk of pollution was low. As the population grew, living standards improved and the economy diversified putting more stress on groundwater. This effect increased on islands that received population through migration and decreased on islands which lost population or depopulated completely.

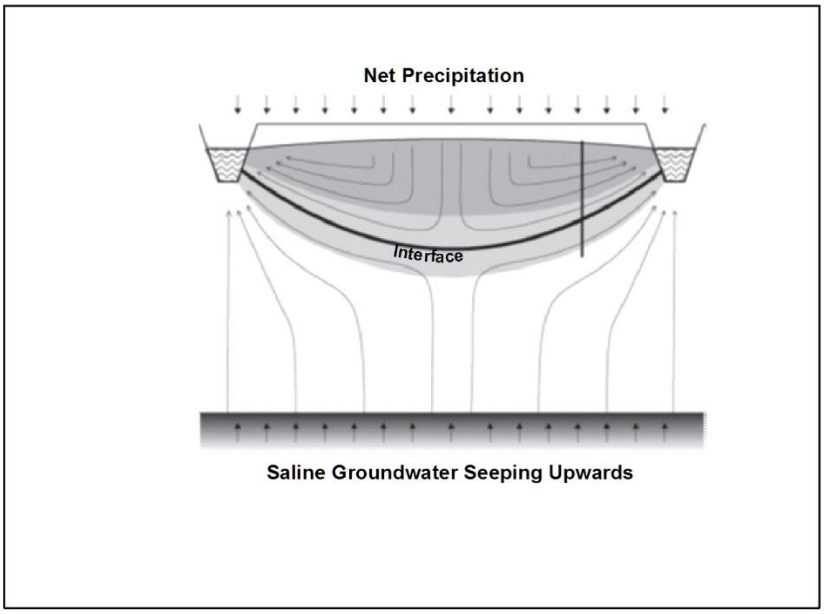


Figure 4 Freshwater Lens atop Saline Water (After Eeman, et al, 2011)

A series of water related epidemics were recorded in the recent history of the Maldives. The very nature of the superficial material in the atoll islands is such that both rainwater and pollutants are transmitted to the GW. The first rainwater harvesting tank for public use was installed in Malé in 1906 and this followed by installing another tank in 1908 (Ibrahim, Bari and Miles, 2002). The two tanks had the total capacity of nearly 97,000 litres. However, Maldivians continued to depend on groundwater for all their water needs until recently.

4.1 Aquifer

The unique character of the hydrogeology of atoll islands is the dual aquifer system, the lithic Pleistocene aquifer and the unconsolidated Holocene aquifer overlying it (Figure 5). The freshwater lens is found within the Holocene aquifer which is made up of sedimentary coral sand and mud derived from the nearby reefs. The contact between the two is at a depth about 9.5-25m below the sea level (Wheatcraft and Buddemeier, 1981, Falkland, 2000 & 2001). Rainfall is absorbed into the sandy soil until the water table rises to the ground level and surface runoff is very limited.

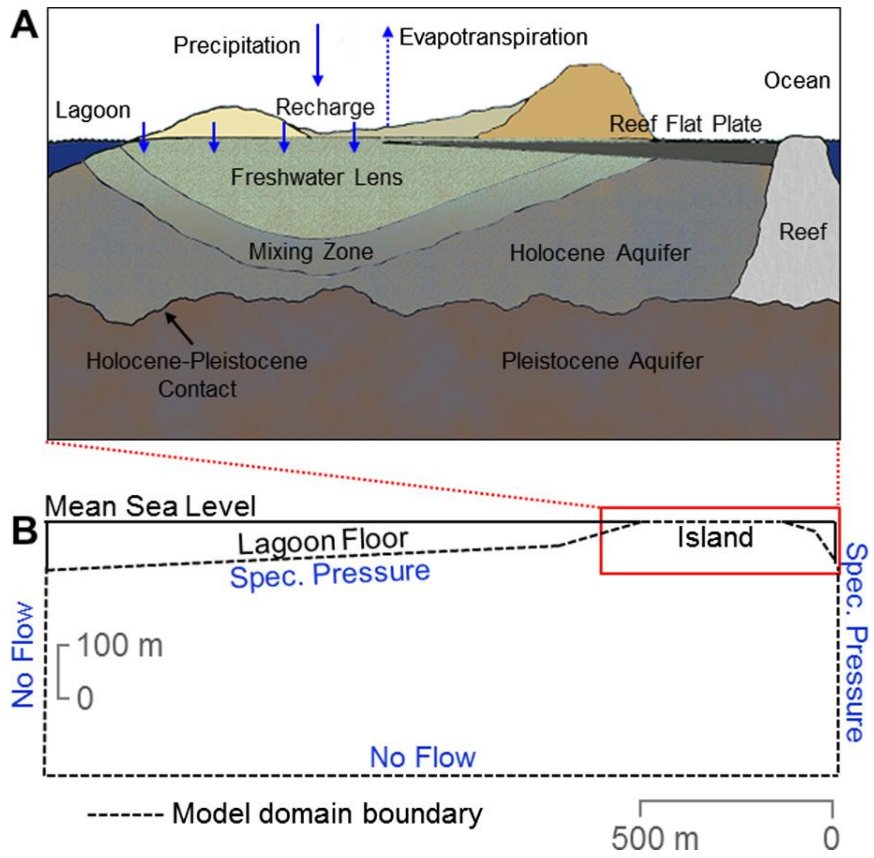


Figure 5 Generalized Aquifer System of Maldives (after Bailey et al., 2015)

The water table is shallow near the surface within 1-1.5m from the surface, particularly during the rainy season. During the dry season the freshwater lens shrinks or is completely depleted on smaller islands. In addition to the natural variation in line with the rainfall regime, the rate of extraction and the rate of recharge also affect the freshwater lens.

Permeability of the Pleistocene aquifer is greater than the Holocene aquifer. Its hydraulic conductivity (K = 5 – 10 m/day) is one to two orders of magnitude (50 – 1000 m/day) greater than the Holocene aquifer (Falkland, 2000; Bailey, Khali and Chatikavanij, 2015). Underwater studies have revealed the presence of sink holes in the lithified Pleistocene aquifer. They would have been formed by subaerial weathering during the low Pleistocene sea level stands. At the last glacial maximum (LGM) around 18,000 BP, the sea level was about 120-150m below the present level exposing much of the carbonate platform. The carbonate platform evolution took place while the sea level also fluctuated. Thickness of this limestone layer is up to 2-3 km (Kench, et. al. 2009, Aubert, 1994). According to Aubert these neritic carbonates were laid down during the Eocene (53-37 Ma ago) on a subsiding volcanic basement. When the volcanism stopped, the islands and the oceanic plate moved towards the deeper areas of the ocean subsiding the islands. Growth of the carbonate system took place as the sea level rose during the Eocene. Reef growth occurs within a narrow depth range of the existing sea level. The volcanic platform highs were aggraded with carbonate deposition (Belopolsky, 2000). In the Maldives, these platform highs were "separated by two deep, narrow and continuous graben systems" according to Belopolsky. The overlying Holocene aquifer began to form about 8,000 years ago while the sea level was rising from the LGM low stand. The reef growth kept up with the rising sea level. The islands formed on reef flats with sediment from the nearby reefs. These unconsolidated sedimentary deposits formed the Holocene aquifer system. The GW layer is confined to the upper part of the Holocene aquifer on small islands. It may increase in thickness on large islands but the Holocene-Pleistocene aquifer contact limits its vertical extent. The boundary between the upwelling salt water and percolating freshwater is a mixing zone (Deng, 2016). The mixing zone thickness is not clear from the available data. The thickness of the freshwater body reaches the maximum towards the centre of the island. The geometry of the freshwater layer resembles a lens and therefore it is referred to as freshwater lens. On the island of Malé, a 10-15m thick succession of shell and coral debris overlies a highly permeable coral rock 'basement' (Edworthy, 1985). The shell coral aquifer has 10-15% porosity. The vertically transmitted rainwater (infiltration) outflows from the edges of the islands. This is the reason for increasing depth of the lower boundary of the freshwater lens towards the centre of the island despite the fact that the island surface is less than a few metres above MSL. It appears that even on larger islands no sustained surface runoff exists to form perennial streams. The amount of freshwater each island can hold is dependent on the capacity of the aquifer.

The horizontal extent of aquifers is limited by the surface area and the width of islands. Most islands are elongated or oval shaped. The size distribution of the islands is given in Figure 6. More than half of the islands are less than 5 ha. The percentage of islands larger than 50 ha is only 4.5%. About 83% of the islands are below 100 ha and only 3 islands have an area above 400ha. The largest island is *Gan* (Lhavini Atoll) and has only about 3,000 inhabitants according to 2014 census. The great majority of inhabited islands are small in size creating tremendous stress on the groundwater resources.

The vertical extent of the islands also affects the aquifer capacity. The vertical dimension of the islands varies from a few metres above sea level to a depth of about 20-25 m below the MSL at which the Holocene aquifer meets the Pleistocene aquifer. Although there is a dry season, it is not the dry season that limits the volume of freshwater in each island. The surface area of the islands on one hand limits the volume of rain intercepted and the storage capacity of the Holocene aquifer controls how much of the intercepted rainwater can be retained. The excess water drains to the sea. The dry season only makes things worse.

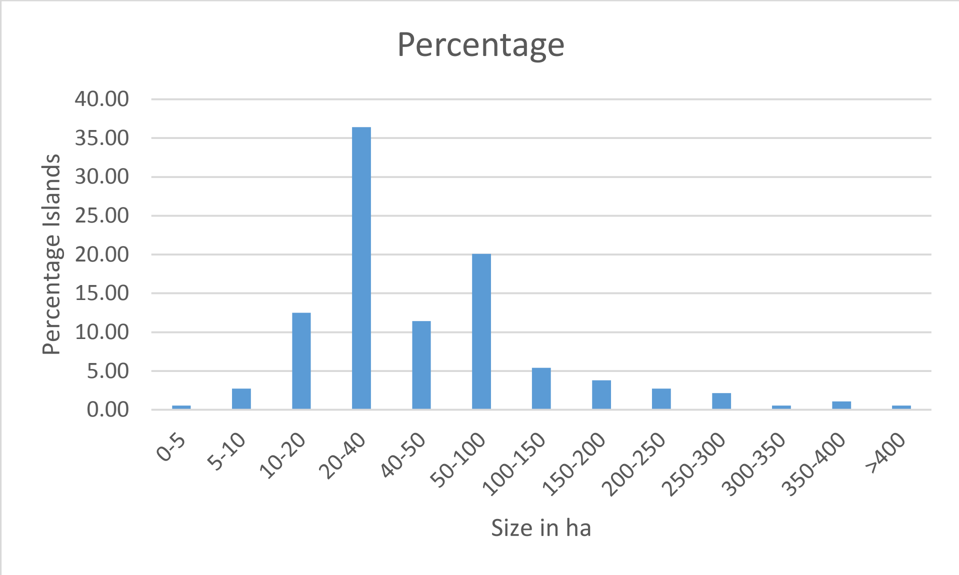


Figure 6 Size distribution of Islands

4.2 Width of island and Freshwater Lens

The thickness of the groundwater lens has been used by many as a measure of the available volume of freshwater. The factors that affect the lens thickness are the width of the island, volume and temporal distribution of rainfall, rate of groundwater recharge, hydraulic conductivity of the Holocene aquifer, aquifer dispersity, and the depth to the Pleistocene-Holocene contact. These factors can be divided into two categories as static and dynamic. The static factors are the permeability, size of the islands (width), depth to the Pleistocene-Holocene contact, etc. They may vary over space but not over short time scales. The dynamic factors are hydrometeorologic and social and economic. Hydrometeorologically important dynamic factors are rainfall, evapotranspiration, climate change, groundwater recharge, and outflows into the sea. Social and economic factors are growth of population, increased per capita water demand, water extraction rates, construction of impervious surfaces, diversification of economic activity, capture of rainwater before reaching the ground, anthropogenic pollution, etc.

The size of the islands, particularly the width, is known to be related to the thickness of the freshwater lens on small atoll islands (Falkland, 2000). A number of detailed studies on the groundwater potential of the Maldives were carried out in the past (Falkland, 2000 and 2001; Bangladesh Consultants Ltd., 2010). The data collected by Falkland was published as a supplement to a paper published by Baily, Khalil and Chatikavanij, (2014). Reanalysis of this data was done for this paper in order to examine the groundwater potential of all the inhabited islands of the Maldives. The data set includes the width of 201 islands, observed freshwater lens thickness of 20 islands, and groundwater lens volume for 11 islands. The island width was plotted against the observed thickness of the freshwater lens for 20 islands and linear regression equation was fitted to the data (Figure 7).

Where multiple measurements of island width and freshwater lens thickness were done for a given island the maximum width and average lens thickness were used. The strength of the correlation is statistically significant (r^2 = 0.57, n= 20). Where island widths are less than 600m, the lens thickness is < 5m. This demonstrates that the island width is a major determinant of the thickness of the freshwater lens. The island width in turn is related to the size of an island. However, the islands used for this estimate range in width from 300m to 1,400m and the relationship outside this range is likely to be different. If smaller islands and larger than 1,400m were added to the data set the relationship may become non-linear. As the width increases the depth to the bottom of the lens is limited by the Holocene-Pleistocene contact (Bailey, Barnes and Wallace, 2016). Linear regression equation shows negative values when the width is less than about 180m. The spread of the points in the scatter plot suggests that there are other important factors that need to be considered for a more accurate estimate of the lens thickness.

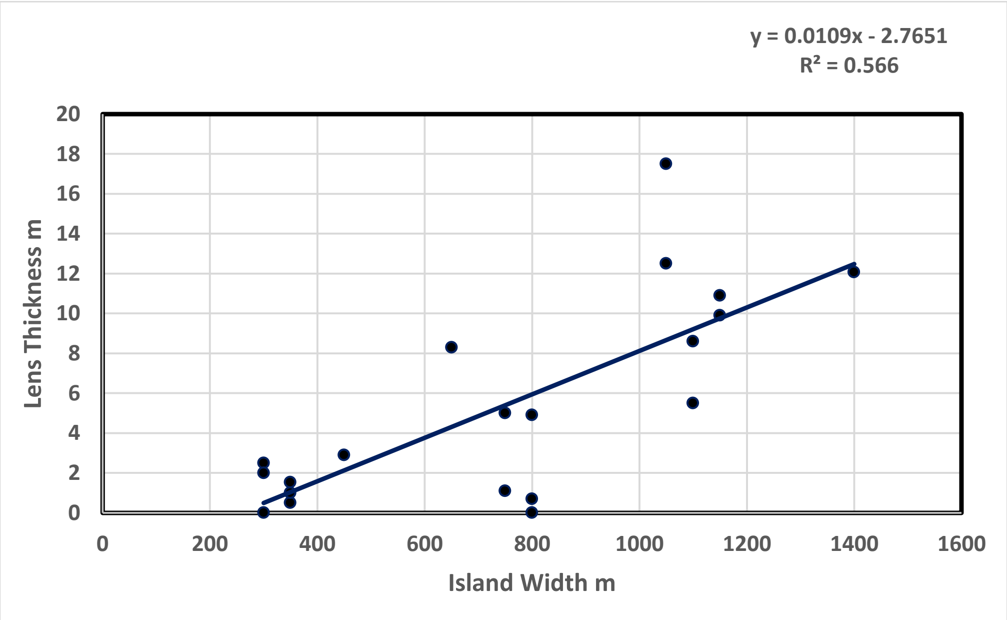


Figure 7 Relationship between Island Width and Lens Thickness (Based on data from Falkland, 2000)

The following regression equation was obtained for the data set:

$$y = 0.0109\,x - 2.7651$$

Where y is the lens thickness (m) and x is the width of an island (m). Only 170 islands (width > 170m) out of 201 islands in the data set gave positive lens thickness values. In the absence of lens thickness observations, for islands having a width less than 170m, no estimate of their lens thickness is possible. The lens thickness increases with increasing width of the islands in the full data range from 300m to 1600m. The lens thickness varies from 0.1m to 16.7m. The distribution of lens thickness values is given by the Figure 8. The highest numbers of islands are in the 0.5-1.0 m lens thickness range. This is because the majority of the islands are small in size. The distribution of the surface area of the islands, island width and lens thickness are positively skewed. Figure 8 shows the distribution of the surface area of 186 inhabited islands.

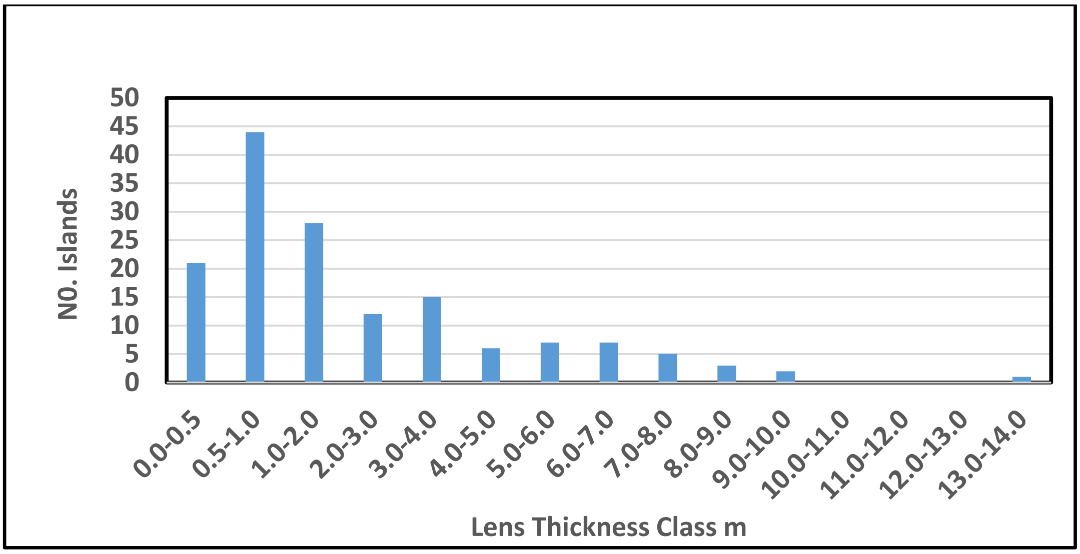


Figure 8 The Frequency Distribution of Lens Thickness

The limiting factor for the lens thickness of small islands is the width of the island not the Holocene-Pleistocene contact because the freshwater-saline water interface is located closer to the surface on such islands. The freshwater input is not enough to counteract the upwelling salt water from below in small island (at the lower end of the scale) aquifers.

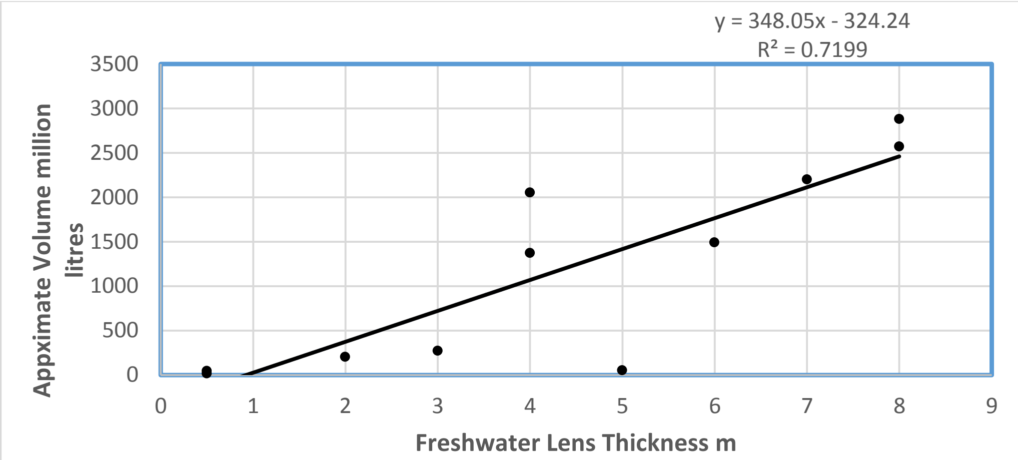


Figure 9 Freshwater Lens thickness and Water Volume

Falkland (2001) estimated the parameters relating to the freshwater lenses of 11 islands (Table 2). The freshwater lens thickness varied from 0.5m to 8.0 m (Figure 9). The freshwater volume was calculated from the lens parameters. The calculated aquifer volume is positively correlated with the lens thickness for 11 islands ($r^2 = 0.72$, n=11). The freshwater volumes estimated varied from 15 million litres to 2,888 million litres (Figure 9). These estimates at best are approximate. More data is required to test the validity of these estimates. Although these are approximate values, still they can be used as important indicators of the groundwater potential of the Maldivian islands.

Table 2 Freshwater Lens Characteristics of 11 Islands in the Maldives

Island Name	Population 2000	Av. Freshwater Lens Thickness (m)	Freshwater Lens Area ha	Approx.Volume (Million litres)	Est. Sustained Yield (litres/person/day)
Hoarafushi	2,767	0.5	31	45	50
Ihavandhoo	2,306	3	30	270	60
Dhidhdhoo	3,349	2	34	200	60
Kelaa	1,892	8	107	2,570	255
Filladhoo	883	0.5	11	15	40
Baarah	1,570	6	83	1,490	240
Hanimaadhoo	1,240	4	171	2,050	620
Nolhivaramfaru	615 0.	5	33	50	200

Nolhivaram	1,873	4	114	1,370	275
Kulhudhuffushi	7,242	7	105	2,200	65
Kumundhoo	1,245	8	120	2,880	440

(Source: Falkland, 2001)

Another factor affecting the thickness of the freshwater lens is the rainfall amount and its seasonal distribution. Rainfall in the Maldives is both spatially and temporally variable. It also shows a long-term decline. Baily, Khalil and Chitikavanij (2014) arbitrarily divided the Maldives chain into 3 geographic regions or latitudinal zones—South (5oS to 0), Central (0 to 5oN and North (5^{o}N to 10^{o}N). The Southern geographic region receives the highest rainfall. Rainfall declines towards the North (Figure 10). The South receives an annual rainfall of nearly 2,400mm, while the North geographic region receives only just over 1,700 mm of spatially averaged rainfall. In addition to this spatial variation, the rainfall regime shows a marked seasonality with a short dry season coinciding with the NE monsoon (January to April). The rest of the year brings a sufficient rainfall to all the geographic regions. The length of the dry season is shorter in the south and longer in the North. The central region shows a transitional character in terms of all the main characteristics of the rainfall.

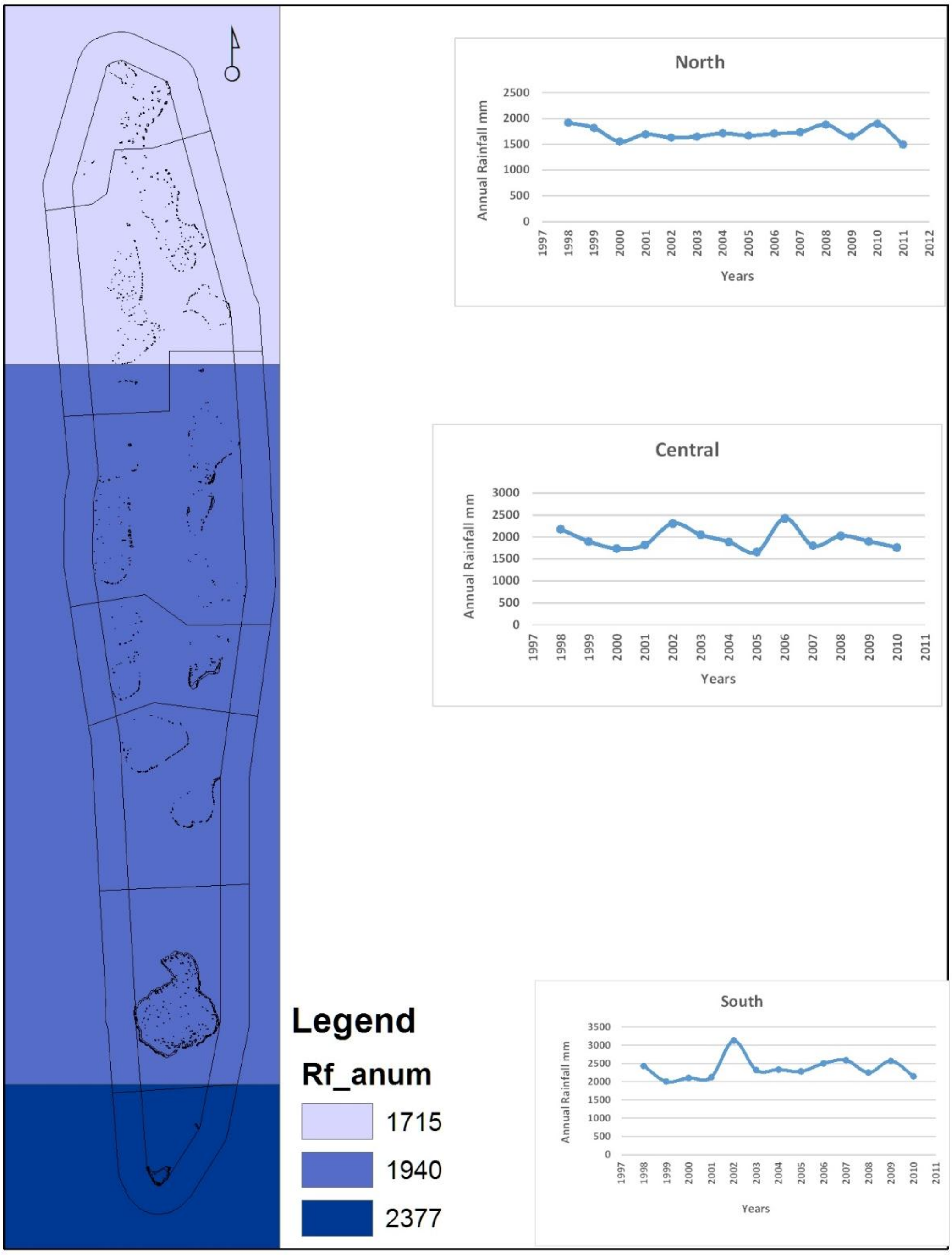


Figure 10 Rainfall Variations from South to North

There seems to be a slight decline in the rainfall since 1998, but the length of the time series is not enough to arrive at a firm conclusion. However, its effect is felt in the groundwater table as shown by Figure 10, and Table 3. In response to the fluctuating rainfall, the freshwater lens thickness also varies. Figure 10 shows the variation of the annual rainfall in each of the 3 geographic regions of the Maldives from 1998 to 2011. The island width plays a significant role on the behaviour of the lens thickness in response to rainfall. The minimum lens thickness coincides with the dry weather period.

The islands having a width of about 200m in all geographic regions experienced complete or near complete depletion of groundwater lens during some time of the year most of the study period from 1998 to 2011. In the central and northern geographic regions, the islands having widths of 300m and 400m also experienced this problem during the dry season. The rate of depletion of the water table is under natural conditions is dependent on the rainfall. Water extraction rates, introduction of impervious surfaces and interception of rain by rainwater harvesting systems may complicate this. The Southern geographic region receives the highest rainfall, while the Northern region the lowest. The central region is a transitional region as far as the rainfall is concerned. The behaviour of the freshwater lens thickness in all three regions is consistent with the seasonal regime of the rainfall.

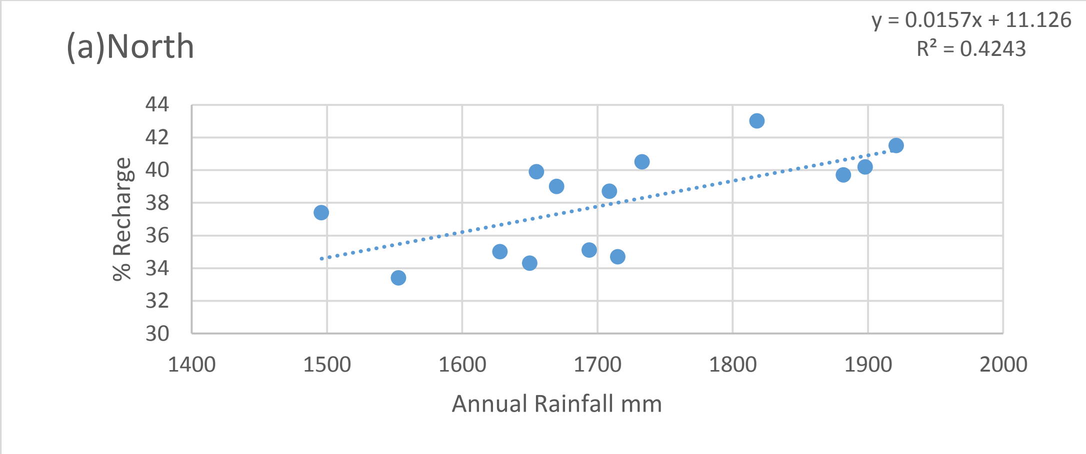
Table 3 Effect of the Island Width on the Freshwater Lens Thickness

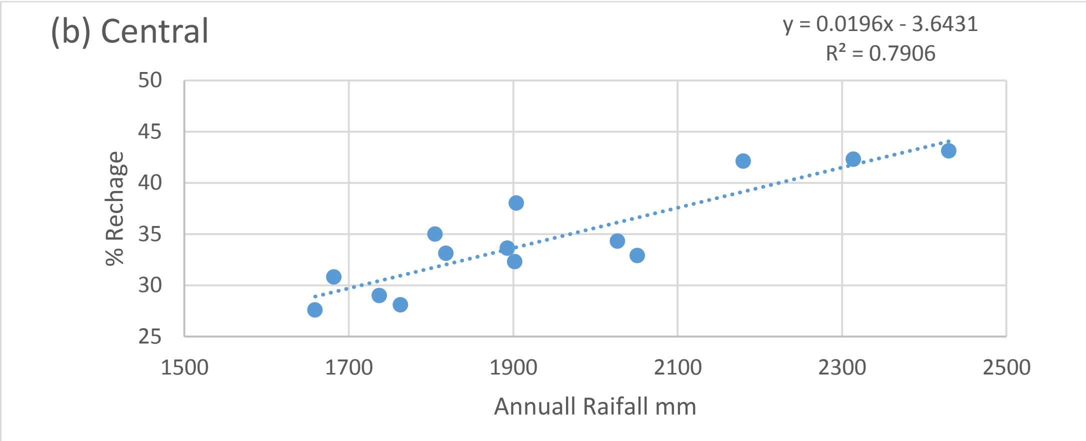
	South			Central			North		
Width(m)	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
200	0.3	0.0	1.4	0.1	0.0	1.0	0.0	0.0	0.4
300	1.2	0.1	2.8	0.6	0.0	1.8	0.5	0.0	1.2
400	2.5	1.0	4.4	1.5	0.5	2.9	1.4	0.5	2.4
500	4.3	2.5	6.8	2.8	1.2	4.4	2.6	1.3	3.9
600	5.9	3.7	7.8	4.1	2.7	5.9	3.8	2.5	5.2
1100	11.9	10.2	13.4	10.8	9.3	12.8	10.5	9.0	12.3

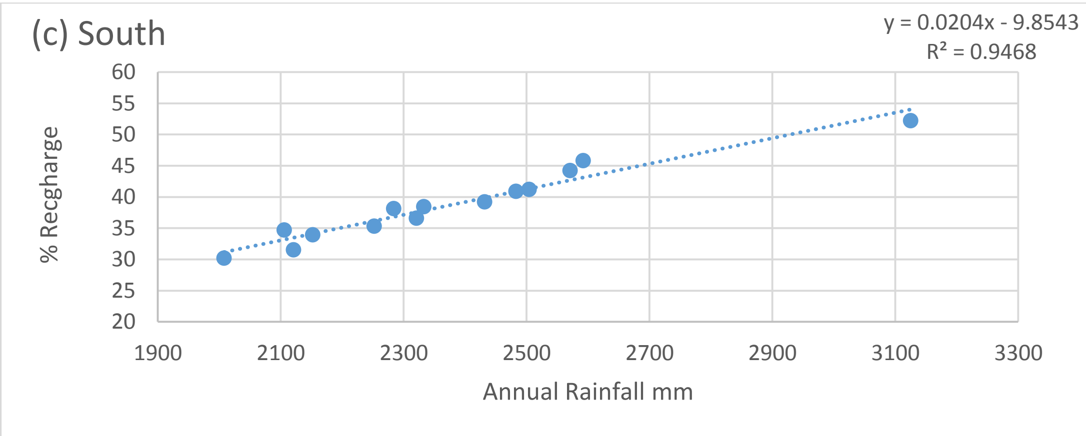
Data Source: Baily et al (2014)

4.3 Replenishable Groundwater Resources

Because the top soil is highly permeable recharge rates can be expected to be rapid. In the Maldives it has been estimated that it is around 40% of the rainfall. Baily, Khalil and Chitikavanij (2014) provide data on the groundwater recharge rates for the 3 geographic regions over a time period from 1998 to 2011. This data shows a variation of groundwater recharging rates with the variation of annual rainfall. When the data is plotted separately for the 3 geographic regions, strong linear relationships between the rainfall and the rate of recharge are shown (Figure 11, a, b and c). The r^2 values vary from 0.4 to 0.9 from North to South. When all the data are plotted together the relationship appears to be curvi-linear (Figure 11d).


(a)North
y = 0.0157x + 11.126
R² = 0.4243
% Recharge
44
42
40
38
36
34
32
30
1400
1500
1600
1700
1800
1900
2000
Annual Rainfall mm


(b) Central
y = 0.0196x - 3.6431
R² = 0.7906
% Rechage
50
45
40
35
30
25
1500
1700
1900
2100
2300
2500
Annuall Raifall mm


(c) South
y = 0.0204x - 9.8543
R² = 0.9468
% Recgharge
60
55
50
45
40
35
30
25
20
1900
2100
2300
2500
2700
2900
3100
3300
Annual Rainfall mm

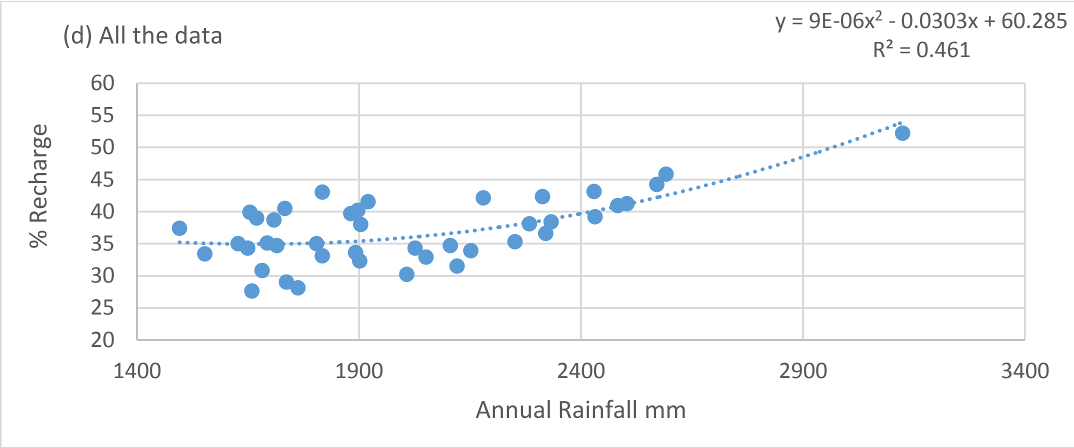


Figure 11 Relationships between Rainfall and Groundwater Recharge

Baily, Khalil and Chitikavanij (2014) found that the average freshwater lens thickness of a sample of 52 islands was 4.5m and it is confined to the Holocene aquifer. They also observed that the freshwater lens thickness declined in the Central (0-5^{o}N) and Northern (5-10^{o}N) geographic regions, while it increased in the Southern (5-0^{o}S) geographic region during the study period from 1998 to 2011. This they attributed to the decline in the rainfall in the former two regions and the increase in rainfall in the South region. Thus, it can be concluded that the thickness of the freshwater lens responds to the decline in rainfall as well. The implication of this is that climate change would have a significant impact on the freshwater availability of the atoll islands depending on whether the long-term trend is positive or negative. The latter will cause severe problems to the groundwater users.

Depletion of the freshwater lens in small islands is faster than in large islands (Bailey, Khalil and Chakitavajin, 2014). During the study period, a complete depletion of the freshwater lens was observed during the dry months from January to April. This is particularly severe in small island aquifers creating a water shortage. The data from 11 islands show that the depth of the water table rarely exceeds 12m. This they considered typical of all 200 inhabited islands. However, the largest island in the Gandhu atoll (Southernmost) recorded a 20m thick freshwater lens.

FAO estimated the total renewable groundwater resources of the Maldives to be about 30,000 m^3 assuming a 0.1 m rate of recharge from a mean annual rainfall of about 1970 mm. This is a highly conservative estimate. A recharge rate of about 38-40% has been estimated as discussed above. But the evapotranspiration losses and outflows into the sea cannot be estimated from the available data. The total amount of groundwater extraction in 1987 was

3.20 MCM of which 98% is for domestic (including municipal) use. Only 2% was used by industries. There is no information about how much is used to irrigate crops lands.

4.4 Groundwater Quality

A survey of household dug wells in seven islands (Vilufushi, Thimarafushi, Veymandoo, Burunee, Fenfushi, Thimarafushi,Veymandoo, Burunee, Thoddoo, Daravandhoo and Daravandhoo) of the Maldives found a very high levels of faecal contamination (FC) in 51% of the wells (Barthiban and Lloyd, 2011; Barthiban, Lloyd, Maier, 2012). This study revealed that only 6.4% of the sample satisfied the WHO standards for drinking water. The most common level of FC was 36% for FC Grade D (101-1000 cfu/100ml). It was also found that water quality improves with continuing rainfall due to dilution.

5.0 Rainwater Harvesting

Rainwater harvesting plays a major role in the domestic water supply today more than ever before. There is a major improvement in the rainwater harvesting capacity in the Maldives since the 2004 tsunami (Figure 12). The tsunami destroyed most of the rainwater harvesting capacity that existed at that time. However, with donor assistance not only replaced what was destroyed, but also expanded the capacity substantially. GOM and UNICEF (2000) estimates show that 75% of the Maldivian population use rainwater for drinking before the tsunami. This figure is as high as 87% if Malé which provides desalinized drinking water to all homes is removed from the calculation (Falkland, 2001). The average per capita water use in the Maldives has been estimated to be at 50 – 100 l/day, of which rainwater is only 5-10 litres per capita. The balance is obtained from groundwater to be used for such purposes as washing, flushing toilets, bathing, etc. However, WHO estimates are lower than this amount. The water requirement per person is given as 20 litres per day (WHO (2009). During the dry season, the rainwater storage tanks go dry and the water needs of the people in the remote islands are supplied from mosque wells which are supposed to be relatively safe, being located some distance from septic tanks, unlike domestic wells which are within a distance less than 10m from the toilet pits. In some case it can be as close as a metre.

Rainwater harvesting capacity data is available for 2004 and 2010 by atoll. A survey of 164 inhabited Islands of Maldives, except Malé, provides data on the rainwater harvesting capacity as of 2010 (Ministry of Housing and Infrastructure, 2011). The total installed capacity was 113,483 cubic metres. There is a marked improvement in per capita and total rainwater harvesting capacity between 2004 and 2010 (Figure 12). The average per capita capacity in 2004 was 100 litres and it went up to 540 litres in 2010. This is a fivefold increase. But there is a considerable geographic variation in both these variables. The highest per capita capacity (798 litres) in 2010 is in the Gnaviyani Atoll and the lowest (413 litres) is in Gaafu Dhalu Atoll. The total capacity consists of household and communal storage systems. The former is by far the largest making up of 955,672 litres. The average household rainwater harvesting tank capacity is around 2000 – 3000 litre. After the tsunami, with the help of International donors, households were supplied with 2500 litre (2.5 m^3) rainwater tanks, larger community rainwater tanks, and 52 desalination plants with a total capacity of 3,260 m^3/d and 32 sewerage systems with 15 treatment plants. The situation in 2013 was as follow

- Household rainwater tank capacity increased from 1.1 to 2.9 m^3
- Total community tank capacity increased from 13,800 to 17,200 m^3
- Only 40% if the desalinization plants are still operational (1,410 m^3/day)
- Only 30% sewerage treatment plants are in operation
- Groundwater is officially abandoned.

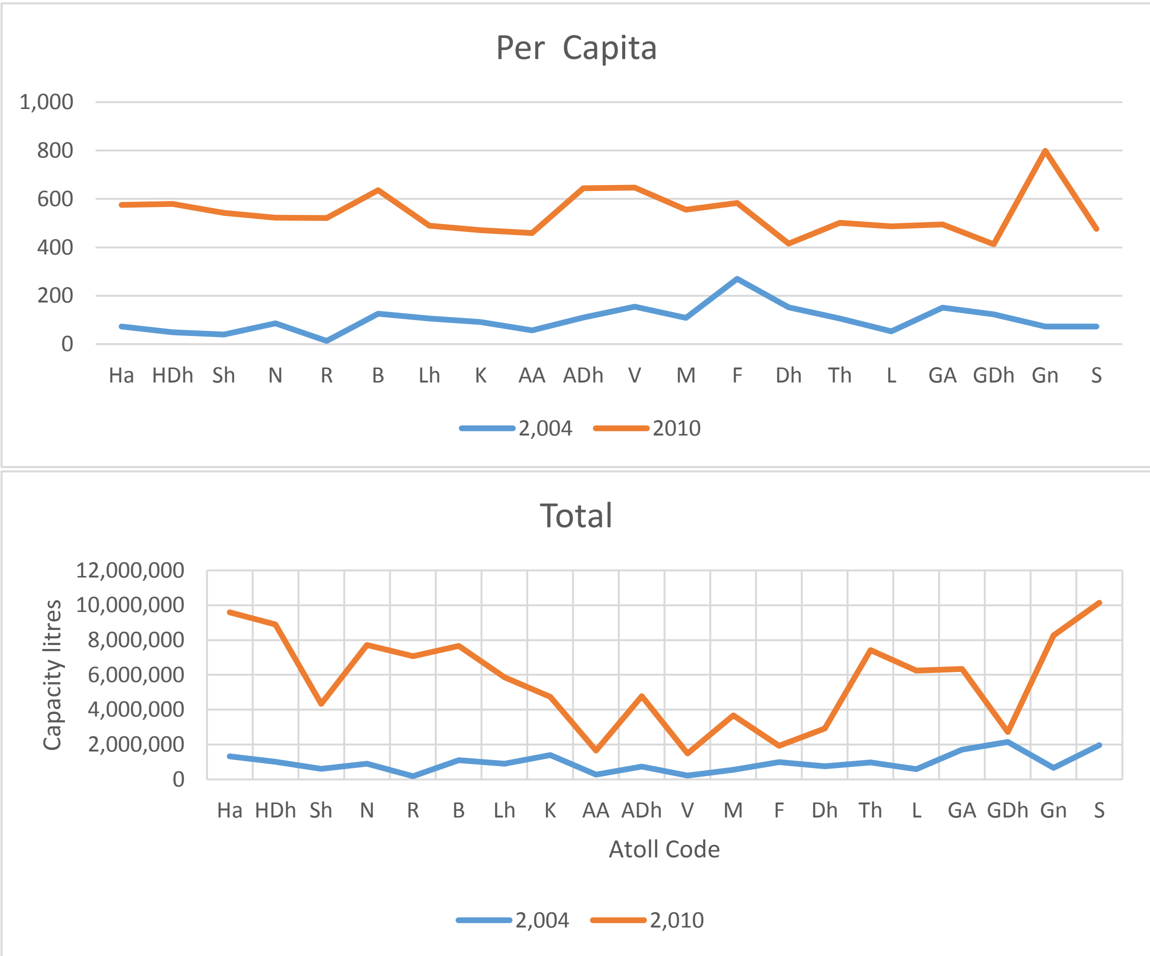


Figure 12 Per Capita and Total Rainwater Harvesting Capacity in 2004 and 2010

Dependency on rainwater for potable water has shifted from groundwater to rainwater or desalinated water because of the dangerously high levels of pollution of the groundwater in most densely populated islands. About 90% of the households of Dhidhdhoo depend on rainwater for drinking (USAID, 2012). The island has 1093 rainwater tanks with the storage capacity of 2500 litre each. It also has 34 tanks with storage capacities 2500 litre (23 tanks) and 5,000 litres (11 tanks). Thus the total storage capacity is 2,845,000 litres. If rainfall is evenly distributed without a marked dry season, then the rainwater harvesting can meet year round water demand. But rainfall during the dry season (Northeast monsoon period) from December to April is so low that most household tanks go dry towards the end of the dry season. Number of reasons can be identified for this scenario. There is a large variation in the efficiency of the rainwater harvesting systems currently used and the efficiency of the rainwater catchments. Ibrahim, Bari and Miles (2014) estimated the roof area and tank size needed to supply 10 litres of rainwater per person per day for different family sizes from 4 to 8. They also estimated the percentage of rainwater intercepted by the rainwater catchment and the tank combinations (Table 4, Figure 13). As the tank size increases the interception efficiency also goes up. This is also affected by the roof size. Roof area is a function of the family's economic status and also the family size. For the same catchment size (roof area), the capture efficiency depends on the tank size. Larger tanks can capture more water from a rainfall event.

Table 4 Rainwater Tank Size

HH Size	Roof Area m2	Tank Volume (litres)	Supply (litres/p/d)	Supply Caught %
4	24	2000	10	42
6	24	2500	10	61
8	24	5000	10	86
8	36	4000	10	55
10	36	4500	10	67

Source: Ibrahim, Bari, and Miles

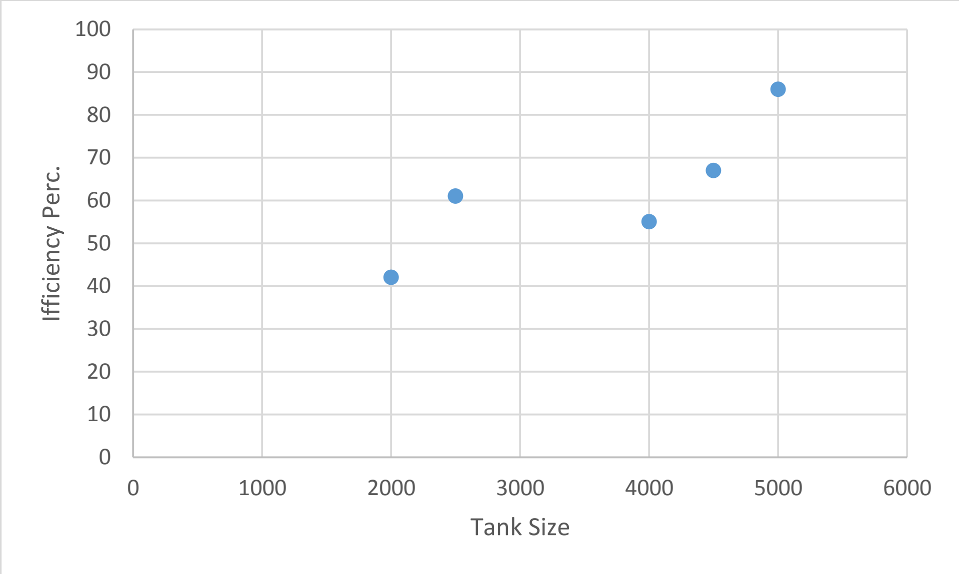


Figure 13 Tank Size and Catching Efficiency

Roof material also affects the efficiency of rainwater capture. The low income households may not have the required roof area (rainwater catchment), roof material with high efficiency or a place to keep a large tank. These limitations put an effective limit on how much water can be captured from a given rainfall event. To last for the dry season, a large store of water may be required. This requires more capacity at household and communal level facilities.

In 2004, the total rainwater harvesting capacity of the Maldives was about 19 million litres and was distributed among 20 atolls (Table 5). It increased to 113.5 million litres by 2010 serving a population of 210,036 of 33,164 housing units (Table 6). That is nearly a six-fold increase. At the same time, the per capita capacity has also increased substantially from 85 litres to 536 litres and rainwater systems were distributed over 162 islands. Theoretically this is a significant improvement in the capacity. But some information shows that in some outer islands, most of the rainwater tanks are not in use. "Although rainwater storage tanks have been distributed in many instances by governmental agencies, in many cases, these tanks have remained unconnected due to a lack of essential components, such as catchments and connective materials, including gutters, pipes, overflows, filters, valves and taps. Consequently, large numbers of rainwater tanks sit idle." (Water Charity, 2012). Data on the addition of more rainwater harvesting systems after 2010 is not available. Judging by the rate of increase between 2004 and 2010, it can be considered substantial. The rapid increase after 2004 tsunami was mainly due to donor assistance as part of the tsunami recovery effort.
If rainfall is evenly distributed and no marked dry season, then the rainwater harvesting can meet the water demand. Beswick (2000) (Quoted by Ibrahim, Bari and Miles, 2014) estimated the roof area and tank size needed to supply 10 l of rainwater per person per day for

different family sizes from 4 to 8. He also estimated the percentage of rainwater intercepted by the rainwater catchment and the tank combination (Table 4, Figure 13). As the tank size increases the interception efficiency also goes up. This is also affected by the roof size. Roof area is a function of the family's economic status and also the family size.

Rainwater Quality

Although rainwater is widely used for drinking and food preparation, quality of the water is a concern, because rainwater is used in the raw state. Boiling or chlorination is not done (UNEP 2002). A pilot survey conducted in the island Gan (Laamu Atoll) found only 15% of the households treated their rainwater, 45% of the water samples collected from household rainwater tanks were tested positive for faecal coliform, 65% of houses had cats (UNEP, 2002). In recent years, the government of the Maldives adopted a policy to encourage migration to the capital due to the difficulty in delivering the public services to all inhabited islands distributed right across the Maldives. This has aggravated the pollution problem. Islands receiving population have undergone the deterioration of the freshwater lens.

Surface Water

The Maldives has only a limited amount of surface water as lakes of freshwater wetlands. Small wetlands are present on 29 islands belonging to 9 atolls. The total area of wetlands is 175.2 ha. Two lakes (*Kilhi*) are located in the interior of the island of Fuvahmulah in Gaafu Alifu Atoll (Figure 14 and Plate 1). The largest of the two is called Dhadimagu Kilhi is located in the middle of the island towards the north. The local people are engaged in thilapia fishing, but the water is not used for human consumption. The quality of the water is also unknown. This is a settled island.

Table 5 Wetlands in Maldives

Atoll Name	Island Name	Wetland Area (ha)	Total (ha)
Haa Alifu	Filladhoo	3.6	
	Thakandhoo	1.8	
	Baarah	5	
	Mulhadhoo	-	
	Maafari	0.8	11.2
Haa Dhaalu	Nolhivaranfaru	0.35	
	Neykurendhoo	-	
	Finney	-	
	Nolhivaramu	4	
	Kulhuduffushi	16.1	20.45
Shaviyani Atoll	Maakandoodhoo	8.28	
	Feydhoo	-	
	Funadhoo	-	
	Maroshi	-	
	Nalandhoo	2.49	
	Milandhoo	1.6	
	Medukuburudhoo	7.88	
	Farukolhu	1.3	
	Eriadhoo	1.1	
	Ekasdhoo	29	51.65
Noon Atoll	Bomasdhoo	2.3	
	Kedhikolhusdhoo	31.1	
	Tholhendhoo	3.7	
	Medufaru	5.9	
	Karinmavattaru	0.3	43.3
Lhaviyani Atoll	Kuredhdhoo	2.4	2.4

Meemu Atoll	Kohufushi	5.3	5.3
Laamu Atoll	Gan	-	
	Ishdhoo	-	
	Gaadhoo	-	0.0
Gaafu Alifu Atoll	Viligili	-	
	Kadulhudhoo	-	
	Madaveli	4	
	Nadallaa	3.7	
	Thinadhoo	3	
	Fuahmulah	8.5	19.2
Seenu	Hithadhoo	11.9	
	Hulhudhoo	2.8	
	Meedhoo	-	
	Herethere	4.7	
	Viligili	2.3	21.7

(Source: MHAHE, 2002)

Plate: 1 People move around the bank of a kilhi (lake) in this March 2000 dated picture. The nearly1.5 kilometre long lake, located in Dhadimagi district of Fulah Mulaku is a place frequented by anglers who game for tilapia fish

Figure 14 Freshwater Lakes on Fuvahmulah, Maldives

Desalinized Water

Desalinization plays a major role in the water supply in the Maldives. The greater part of the water needs of the resort islands are met by desalinized water. Except for drinking, all other needs of the tourists are met by desalinized water. Drinking water is imported from neighbouring countries as bottled water. On inhabited islands desalinized water is used for human consumption, particularly in urban areas as a supplementary source to rainwater. Male completely depends on desalinized water. All households are provided with pipe-borne desalinized water. Most of the drinking water demand is met by desalinized water and rainwater, while the groundwater serves such purposes as washing, cleaning, and sometimes bathing and agriculture. Still the people in rural islands use rainwater for drinking and food preparation, while groundwater is used for washing and cleaning. All inhabited islands do not have desalination facilities or the facilities established are not operational. For example, Dhidhdhoo does not have a desalination plant and people use rainwater and groundwater. Table 5 shows the estimated water consumption in the Maldives.

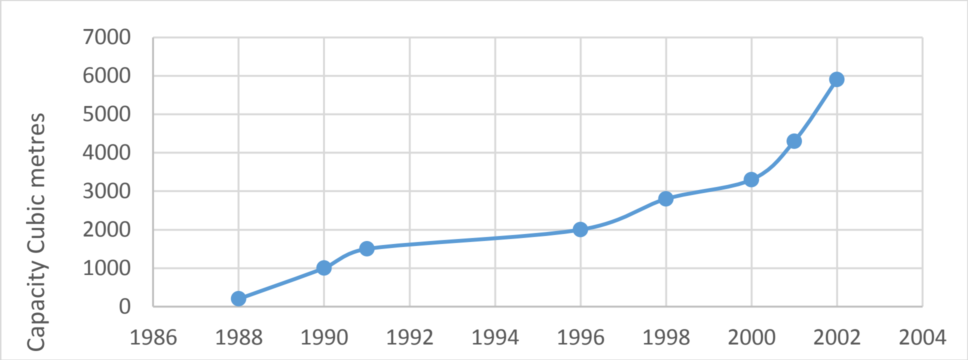


Figure 15 Development of Desalination Capacity (MWSA and MWSC 2002)

Desalination rapidly increased over the years (Figure 15) before the tsunami in 2004. There is circumstantial evidence showing further improvement but no reliable data could be accessed to determine the rate of change.

Table 6 Annual Water Consumption in the Maldives

	Annual Mean Rainfall (mm)	Total	
Renewable Freshwater Resources			
Area of Inhabited Islands		300 km2	
Area of Inhabited Islands		130 km2	
Average Rainfall Volume per year	1972	590 (MCM)	
Internal Renewable Water Resources (Whole Country)		30 (MCM)	Assuming 0.1m / year recharge rate
Internal Renewable Water Resources (Inhabited Islands)		12.9 (MCM)	
Per capita total renewable water resources		96 (m^3)	
Water withdrawal in 2008			
Total Groundwater withdrawals		5.9 (MCM)	
Municipalities		5.6 (MCM)	

Industry		0.3 (MCM)	
Per Capita		19 (m^3)/year	
Non-Conventional Sources			
Desalinated Water		1.225 (MCM)/year	
Total withdrawals		7.125 (MCM)	

Source: FAO

Current water withdrawal statistics are not available. The figures in Tables also do not include the rainwater harvesting amounts. The total renewable groundwater resource is substantial when the whole country is taken into consideration. At present no water extraction takes place on uninhabited islands. A total renewable groundwater resource on the inhabited islands is roughly about 12.9 MCM at the current level of rainfall. From that 5.9 MCM is withdrawn per year. This is well below sustainable level. But the quality of the water is the main barrier to its use. If the projected implementation of 100% access to sanitation was realized by 2013, water quality of the inhabited islands should improve. The other islands also have groundwater lenses which are currently not used. If proper safeguards are imposed this might present a viable source of good quality water for the people of the Maldives.

The country has 7,000 ha of agricultural land, of which 4000 ha are under annual crops and the balance under perennial crops. The former needs irrigation at least for some part of the growth cycle. This water comes from the groundwater resource.

Threats to Water Security

At present 4 main sources of water is used in the country. They are rainwater, ground water, desalinized sea water and imported bottled water. The demand for water comes from the fast growing population and also the tourism sector.

All atoll islands are extremely vulnerable to water shortage due to the population increase, climate change effects, saltwater intrusion, and pollution. In the Maldives, some islands experienced a rapid rise in population well beyond the carrying capacity of water resources. Over 80% of the land area of the Maldives is below 1.0 m from the MSL. The threat of sea level rise (SLR) has been recognized as an existential threat to the Maldives. Lack of long-term sea level data hampers correct estimation of the rate of sea level rise. As a result, there is no general agreement on the SLR or its impact. One estimate shows that the average sea level rise (SLR) in the region between 40o S to 40o N and 30o E to 120o E is 4 mm/year

(Church, White and Hunter, 2006). However, SLR at Maldives based on short-term tidal observation, and satellite altimetry show a rise of only about 0.4 mm/yr for the period 1960 to1989 (Church, White and Hunter, 2006). This is consistent with the results obtained from the geological record by Woodroffe (2005). Malé, the capital, is the best example to illustrate this problem. The groundwater lens of Malé, with a land area of only 2.08 km2, can support 10,000 people with a modest per capita consumption without depleting the resource. But the current population of Malé stands at 153,000 according to the 2014 census. This has contributed to pollution of groundwater lens from anthropogenic sources and sea water intrusion due to excessive extraction. Groundwater is not suitable even for washing purposes. It has become saline due to excessive extraction. Malé alone has over 4000 wells. Today almost all Malé's potable water needs are met by desalination and rainwater harvesting.

Allan (2002) Estimated per capita water requirement as follow: Which means a population of 402,000 requires 443 million cubic metres or 443,000 million litres. The rainwater harvesting capacity in 2011 was 112 million litre capacity has to be filled

Demand for Freshwater

The freshwater demand comes from the population for domestic needs, tourism industry, Industries, and agriculture. The islands of the Maldives are grouped into inhabited islands (188 in 2014), Resorts (109), and industrial islands (128). The uninhabited islands are not affected by water shortage like the other three categories. Some tourists and temporary visitors and also migratory workers stay on the inhabited islands. Malé is the most densely populated island with a population of 153,904 (2014 census) in an area of about 2.08 km2. The population density is 74,000 per km2. This is among the highest in the world. After Malé, there is only one other island with a population above 10,000. It is Hithadhoo with a population of 11,129. It has an area of 5.13 km2 and population density of 2169 per km2. About 40% of the Maldives population is urban. The population grows at about 1.65% on average, while the urban growth is about 4.2%.

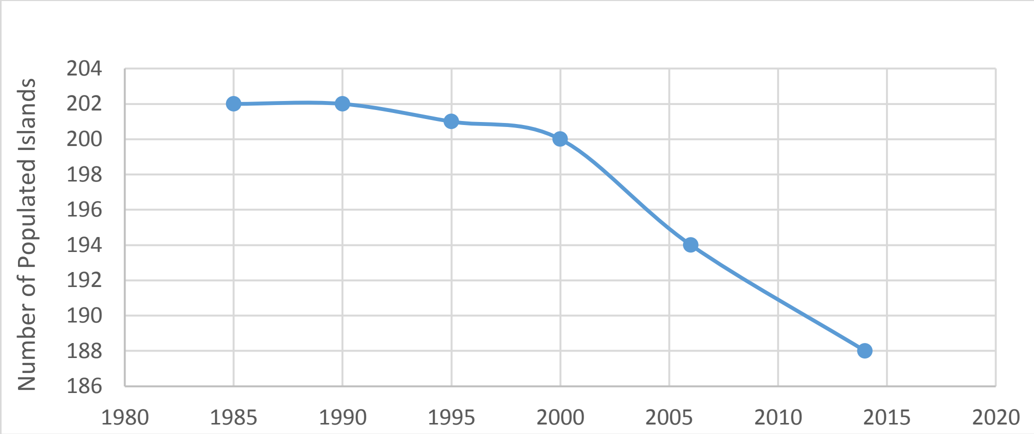


Figure 16 Decline of Inhabited Islands from 1985 to 2014

The number of inhabited islands have decreased slowly from 1985 to 2000 and thereafter rapidly (Figure 16). This is a result of outmigration of people from infrastructure poor islands. The highest number of islands suffered from depopulating is those that had a population less than 300 persons (Figure 17), while the islands that had more than 500 persons gained population. This is shown by the increase in the number of islands with population above 500 persons. Most increase is in the number of islands in the population range 700 – 799. That probably shows the preference is for the islands with a moderate population, because of high land prices and land shortage on densely populated islands. Out migration from islands that have low population frees the islands from human occupation and perhaps will lead to the restoration of the islands back to the original state. Certainly, this will improve the groundwater quality by increased recharge and by removing the sources of pollution. At the same time water scarcity increases in the receiving islands.

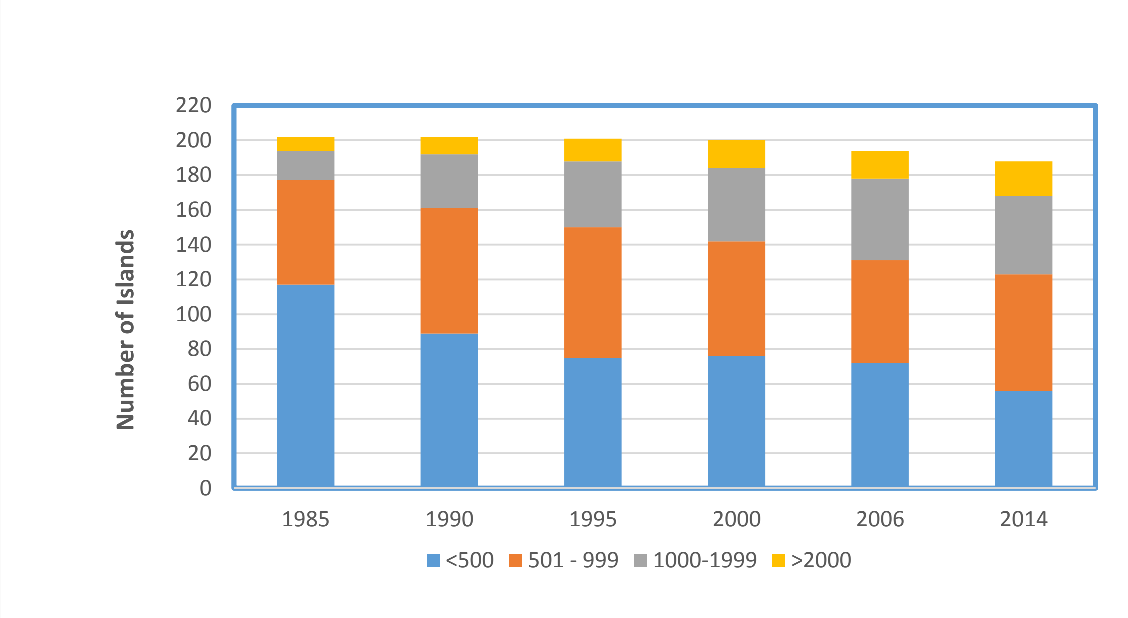


Figure 17 Decline of Number of Islands in Specific Population Ranges

The largest islands are not the most populous islands in the Maldives. The ten largest islands in the Maldives are listed with the population and population density in Table 6. Gan is the largest island but has only 3080 people. In the whole of Maldives, the island which has the second largest population and the second largest area is Hithadhoo (Laamu Atoll) with a population of 11,129 of which is about 1000 are foreign nationals. This Island is 5.13 km2 in extent, nearly two and half times the size of Malé . About 40% of the Maldives population is urban. The average rate of population growth in the Maldives is 1.78% (2004). This is a significant slowing down of the population growth rate from 3.3% in 1990. The urban growth rate is however about 4.2%. This can be attributed to rural to urban migration. Of the largest islands, two islands are uninhabited. They are Gan of seenu Atoll, and Gan of Gaafu Dhaalu atoll. Gan of Laamu atoll is the largest inhabited island but the population density ranks 4th.

Table 7 Ten Largest Islands with Population in 2014

Atoll	Island Name	Area (km2)	Population (2014)	Density (sqkm)
1. Laamu	Gan	5.166	3,080	596
2. Seenu	Hithadhoo	4.673	11,129	2381
3. Gnaviyani	Fuvah Mulah	4.200	8,510	2026

4. Laamu	Isdhoo	2.937	958	326
5. Kaafu	Kaashidhoo	2.765	521	188
6. Seenu	Gan*	2.649	0	
7.Gaafu Dhaalu	Gan**	2.636	0	
8. Haa Dhaalu	Hanimaadhoo	2.595	1951	751
9. Haa Alifu	Baarah	2.488	1215	488
10. Haa Alifu	Filladhoo	2.256	584	259

* Airport/industrial ** Uninhabited

The ten islands with the largest population are listed in Table 4.4. Malé is way above all the islands and has the highest population density (74473). The island, Villin'gili has the second highest population density because of its small size compared to the population. Among the ten islands with the highest population, Villin'gili is the smallest. The second largest population is on Hithadhoo and has a population density of 2111. Gan is the largest of the ten islands has a population just over 3000 and a relatively low population density (517). Because of its large size the island has a larger reserve of freshwater. Such islands can utilize this resource productively if better sanitation practices are adopted.

Table 8 Islands by Population

Island	Atoll	Area km2	Population	Pop Density/km2
Malé	K	2.08	154903	74473
Hithadhu	Addu	5.27	11129	2111
Fuvahmulah	Gnaviyani	5.13	8510	1659
Kulhudhufushi	Haa Dhaalu	1.99	8440	4241
Vilin'gili	Gaaafu	0.27	7790	28852
Thinadhoo	Gaafu Dhaalu	1.19	5230	4395
Naifru	Faadhipolu	0.56	4103	7327
Feydhoo	Addu	0.67	3431	5121
Gan	Addu	5.96	3080	517
Dhuvafaru	Raa	0.54	3016	5585

The islands that received population from other islands will have more stress on the groundwater resources. Construction of more buildings means more impervious surfaces. More rainwater interception is less groundwater recharge. Even with improved sanitation infrastructure, the thickness and quality of the renewable groundwater resource is likely to decline further on inhabited islands. Lower recharge means lower thickness of the freshwater lens. The increased water demand has to be met by desalinization and rainwater harvesting. Both these options have their own problems. Densely populated islands may not have enough area in the household premises to keep rainwater tanks. On the other hand the household rainwater harvesting systems do not have facilities for water treatment, without which the safety of the rainwater cannot be guaranteed.

Table 9 Populated Island by Island Type

Island Type	Number of Islands
Administrative Islands	188
Resorts	109
Industrial Islands	128
Total	424

Table 8 gives the figures on tourist resorts, industrial islands and populated islands (Administrative islands). Altogether 424 islands out of about 1192 small islands have human activity and they all are water users. However, no data is available on water demand for industries and agriculture. There are also resident foreign nationals living in many parts of the Maldives as well.

Table 10 Inhabited Islands with the Given Ranges of Population

Population	1985	1990	1995	2000	2006	2014	Change
< 100	2	1	1	0	5	2	-3
100-199	17	13	11	11	11	5	-6
200-299	29	20	10	15	18	10	-8
300-399	39	30	26	22	18	18	0

400-499	30	25	27	28	20	21	1
500-599	19	24	23	19	18	17	-1
600-699	13	19	16	14	12	15	3
700-799	10	14	16	12	11	15	4
800-899	6	7	9	13	12	11	-1
900-999	12	8	11	8	6	9	3
1000-1999	17	31	38	42	47	45	-2
2000-4999	6	7	9	12	12	16	4
5000-9999	1	2	3	3	3	2	-2
>10000	1	1	1	1	1	2	1
Total	202	202	201	200	194	188	

The highest number of islands suffered from depopulating is those that had a population less than 300 persons (Table 9) while the islands that had more than 500 persons gained population. This is shown by the increase in the number of islands with population above 500 persons. Most increase is in the number of islands in the population range 700 – 799 per/km2. That probably shows the preference is the islands with a moderate population, because of high land prices and land shortage on densely populated islands. Depopulated islands will lead to the restoration islands back to the original state. Certainly, this will improve water quality and quantity.

Table 11 Ten Largest Islands with Population in 2014

Atoll	Island Name	Population (2014)
1. Laamu	Gan	3,080
2. Seenu	Hithadhoo	11,129
3. Gnaviyani	Fuvah Mulah	8,510

4. Laamu	Isdhoo	958
5. Kaafu	Kaashidhoo	521
6. Seenu	Gan*	0
7.Gaafu Dhaalu	Gan**	0
8. Haa Dhaalu	Hanimaadhoo	1951
9. Haa Alifu	Baarah	1215
10. Haa Alifu	Filladhoo	584

* Airport/industrial ** Uninhabited

Of the largest islands, two islands are uninhabited. They are Gan of seenu Atoll, and Gan of Gaafu Dhaalu Atoll. Gan of Laamu atoll is the largest but the population density is 4th. Potential for using groundwater on some of these islands should be explored.

Table 12a Islands by Population

Island	Atoll	Population	Pop Density/km2
Malé	K	154903	74473
Hithadhu	Addu	11129	1659
Fuvahmulah	Gnaviyani	8510	4241
Kulhudhufushi	Haa Dhaalu	8440	28852
Vilin'gili	Gaaafu	7790	4395
Thinadhoo	Gaafu Dhaalu	5230	7327
Naifru	Faadhipolu	4103	5121
Feydhoo	Addu	3431	517
Gan	Addu	3080	5585
Dhuvafaru	Raa	3016	2112

The ten islands with the largest population are listed in Table 4.3a. Malé is way above all the islands and has the highest population density (74473). The island, Villin'gili has the second highest population density because of its small size compared to the population. Among the ten islands with the highest population, Villin'gili is the smallest. The second largest population is on Hithadhoo and has a population density of 2111. Gan is the largest of the ten islands has a population just over 3000 and a relatively low population density (517). Because of its large size the island has a larger reserve of freshwater. Such islands can utilize this resource productively if better sanitation practices are adopted.

The islands that received population from other islands will have more stress on water resources. Construction of more buildings means more impervious areas and more rainwater interception reducing groundwater recharge. Even with improved sanitation infrastructure, the thickness and quality of the renewable groundwater resource is likely to decline further. Lower recharge means lower thickness of the freshwater lens. The increased water demand has to be met by desalinization and rainwater harvesting. The latter has its own problems. Densely populated islands may not have enough area in the household premises to keep rainwater tanks. On the other hand the household rainwater harvesting systems do not have facilities for water treatment, without which the safety of the rainwater cannot be guaranteed. Only a few studies have been done on rainwater quality. It is possible to improve the groundwater quality by increased recharge and by removing the sources of pollution.

Current Water Consumption Pattern

Rainwater harvesting accounts for a significant portion of domestic water supply of the outer islands. GOM and UNICEF (2009) estimates show that 90% of the Maldivian population use rainwater for drinking. This figure is as high as 87% if Malé which provides desalinized drinking water to all homes is removed from the calculation (Falkland, 2001). The average per capita water consumption in the Maldives has been estimated to be at 50 – 100 l/day, of which consumption of rainwater is only 5-10 l per capita. That means the balance used for other purposes, such as washing, flushing toilets, bathing, etc. is obtained from groundwater. During the dry season, the rainwater storage tanks go dry and the water demand of the people in remote islands is met from mosque wells which are supposed to be relatively safe being located some distance much greater distance away from soakage pits, unlike domestic well which are as close as a one to a few metres. Most of the domestic dug wells are within a distance less than 10m from the toilet pits.In 2004, the total rainwater harvesting capacity of the Maldives was about 19 million litres and was distributed among 20 atolls (Table 4.5).

This is about 2008 litres per person. A large part of rainwater harvesting infrastructure was damaged by the 2004 tsunami. However, with donor assistance, not only the damaged facilities were repaired and also new systems were added to the pre-tsunami infrastructure. With this assistance and government interventions, the rainwater harvesting capacity of the Maldives increased to 112.5 million litres by 2010 serving a population of 210,036 of 33,164 housing units (Table 4.6). That is nearly a six-fold increase. At the same time, the per capita capacity has also increased substantially from 85 litres to 536 litres. There is a considerable variation of the per capita capacity between islands from 85 litres to 1400 litres. The distributed over 162 islands. This is a significant improvement. Data on the addition of more rainwater harvesting systems after 2011 is not available. Judging by the rate of increase between 2004 and 2011, it can be considered substantial. The rapid increase after 2004 tsunami was mainly due to donor assistance as part of the tsunami recovery effort.

Water Scarcity

During the dry season, 42-50% of the outer islands request desalinized water from Malé every year (Shakeela, 2015). The rainwater tank capacity is inadequate to last for the dry period. During the dry season the rainwater tanks go dry and the groundwater is lens gets depleted. "From the year 2005 to 2011, more than about 70 islands out of 200 inhabited islands reported water scarcity every year, ranging from 2.1 ML to 7.5 ML" (MEE, 2011 quoted by Deng, 2016).

In 2015 42% of the inhabited island communities faced water stress towards the end of April (end of dry season) (Shakeela, 2015). This is not due to lack of rainfall. All existing storage systems, including the superficial aquifer are not capable of storing enough water to last a dry period of two months or more. Groundwater lens is also depleted during the dry season on most islands or is too polluted to use as potable water. Only option available under these circumstances is to turn to desalinization option. It is too expensive and environmentally not attractive. The government policy of providing safe sanitation to all the islands will improve the quality of groundwater. The groundwater option is viable on large but sparsely populated island. The groundwater resources of the uninhabited islands might be another source of good quality freshwater. It is possible to have a well-planned groundwater harvesting system on these islands. Water can be sent to inhabited islands using barges or as bottled water. A decline in the rainfall as a result of global climate change becomes a reality in the Maldives, careful management of the existing groundwater resources will be a necessity. Desalination together with groundwater might solve the problem water scarcity in the Maldives.

Conclusions

Like many other SIDS, the Maldives has a serious water scarcity problem which is bound to aggravate with time with the increasing population, the declining rainfall and incident of drought. A part of the solution would be a combination of improved desalination systems powered by clean energy, sound management of groundwater resources, groundwater recharge wells, good sanitation practices and carful harvesting of ground water from uninhabited islands. Selected uninhabited islands should be protected as hydrological reserves and water harvesting can be done during the rainy period.

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