CLIMATE VULNERABILITY ASSESSMENT – ISLANDS OF DHIDHDHOO AND HINNAVARU, THE MALDIVES

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Climate Vulnerability Assessment –
Islands of Dhidhdhoo and Hinnavaru, The Maldives

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ACRONYMS

AR4	Fourth Assessment Report, IPCC
CCTF	MHE's Climate Change Trust Fund (CCTF)
CGCM	Canadian Centre for Climate Modelling and Analysis Coupled General Circulation Model, Canada
CMIP3	Coupled Model Inter-comparison Project phase 3
ECRWS	Enhance Climate Resiliency and Water Security
EPA	Environmental Protection Agency, regulatory agency within MHE
MPI ECHAM	Max Planck Institute for Meteorology (MPI), European Centre/Hamburg Model (ECHAM), Germany
GCM	General Circulation Model
GCM	Global Climate Model
GEF/UNDP	Global Environmental Facility/United Nations Development Program
GFDL	Geophysical Fluid Dynamics Lab
GHG	Greenhouse gas
GIS	Geographic Information System
GMSL	Global Mean Sea Level
GOM	Government of the Maldives
GPS	Global Positioning System
HadCM3	Hadley Centre Coupled Model, Version 3, United Kingdom
ICCRIP	Integrating Climate Change Risks into Resilient Island Planning
IPCC	Intergovernmental Panel on Climate Change
IPRC	International Pacific Research Center
ISM	Indian Summer Monsoon
JJAS	Southwest monsoon months (June, July, August and September)
MEMP	Maldives Environmental Management Project
MHE	Ministry of Housing and Environment
MMS	Maldives Meteorological Service
MRI CGCM	Meteorological Research Institute, Coupled General Circulation Model, Japan
MWSA	Maldivian Water and Sewage Agency (no longer exists)
MWSC	Male' Water and Sewerage Company
M&E	Monitoring and Evaluation
NASA	National Aeronautics and Space Administration, USA
NCAR	National Center for Atmospheric Research, USA
NCEP	National Center for Environment Protection, USA
NDMC	National Disaster Management Center
NGO	Non-Governmental Organization

NOAA	National Oceanic and Atmospheric Administration, USA
NOC	National Oceanography Centre
NRW	non-revenue water
NUL	Northen Utilities Ltd.
O&M	operations and maintenance
OND	Northeast monsoon months (October, November, and December)
PSMSL	Permanent Service for Mean Sea Level
RCM	Regional Climate Models
RegCM	Regional Climate Models
RIMES	Regional Integrated Multi-Hazard Early Warning System for Africa and Asia
SDSM	Statistical Down Scaling Model
SRES	Special Report on Emission Scenarios, IPCC
SST	Sea Surface Temperature
STELCO	State Electric Company
SWRO	seawater reverse osmosis
TRMM	Tropical Rainfall Measuring Mission
UNUL	Upper North Utilities Ltd
USAID	United States Agency for International Development
V&A	Vulnerability and Adaptation
WB	World Bank
WCRP	World Climate Research Programme
WDCC	World Data Center for Climate

EXECUTIVE SUMMARY

BACKGROUND AND PURPOSE

The Maldives program to Enhance Climate Resiliency and Water Security is intended to demonstrate the process and outcomes needed to allow island communities to maximize their opportunity to overcome impacts from global climate change. The program will provide assistance to the Government of the Maldives (GOM), and island and atoll councils; the private sector; and residents of two islands in the northern part of the country that will be targeted with United States Agency for International Development (USAID) assistance to become "climate resilient islands." The underlying purpose and intended outcome of the program is to develop the knowledge, skills, and attitudes that island residents will need to become stewards of their island environment and to make rational and informed decisions on key climate change adaptation issues. This report concerns the islands of Dhidhdhoo and Hinnavaru.

The Climate Vulnerability Assessment uses available climate data to assess the vulnerability of water, sanitation, solid waste management services to the impacts of climate change, and feeds into the Utility Service Delivery Assessment, which is documented in a separate report (CH2M HILL, 2012). During a 2 week field effort, a consultant team worked with relevant Ministry of Housing and Environment (MHE) officials, island council members, community groups, and representatives from utilities to evaluate the current state of services, vulnerability of services to climate-related impacts, and priorities to improve the resiliency of services in light of likely climate-related impacts.

Dhidhdhoo (Dhivehi:) is the capital of Haa Alif Atoll administrative division in the Maldives. The island lies on the northwestern tip of Tiladummati Atoll. Originally, the island was 52 hectares, but after land reclamation in 2010, the island is now around 85 hectares. There are some estimated 3,740 people in Dhidhdhoo (2009-Registered-Statistical Year book 2010) and it is the largest population in the Atoll. Population on Dhidhdhoo has increased at a steady rate in recent years of about 2.0 percent per year.

Hinnavaru (Dhivehi:) is one of the inhabited islands of the Lhaviyani Atoll. Originally, the island was 22 hectares, and after land reclamation in 2010, the island is now 55 hectares. It has a population of approximately 4,500 people with 715 registered households. Population data and growth rates available for the past decade through 2010 shows a slow rate of increase with an annual average growth rate of about 0.6 percent.

WATER RESOURCES AND CURRENT CLIMATE ON DHIDHDHOO

The 1992 to 2010 long-term average temperature at Hanimaadhoo weather station, which is closest to Dhidhdhoo, is 28.5°C. Rainfall varies significantly throughout the year, with a long-term annual average of 1826 mm per year. A distinct dry season occurs from

December through April, with rainfall dropping to almost zero in January through March in some years.

Dhidhdhoo relies mostly on harvested rainfall and groundwater to supply most of its water demands, with rainwater and bottled water being the primary source of drinking water and cooking water demands, and groundwater being used for toilet flushing and cleaning. Of the roughly 1,050 properties in Dhidhdhoo, it is believed that all have rainwater harvesting facilities, consisting typically of one 2,500 L tank and sometimes two for residences, and several more for mosques, the school, and hospital. The average roof drainage area draining to cisterns was 46.5 square meters (m^2), with a range of 8 to 77 m^2.

On Dhidhdhoo, no desalination facilities are currently operational, though a 10-ton facility was installed after the 2004 tsunami. This facility is not currently operating (see Utility Service Delivery Assessment documented in separate report [CH2M HILL, 2012]).

WATER RESOURCES AND CURRENT CLIMATE ON HINNAVARU

Hinnavaru is roughly equidistant between the Hulhule weather station at the airport in the capitol of Male' and the Hanimaadhoo weather station. The 1980 to 2010 long-term average temperature at Hulhule, which is closest to Hinnavaru, is 28.4°C and at Hanimaadhoo it is 28.5°C, with a minimum of 24.2°C and a maximum of 32.5°C. Rainfall varies significantly throughout the year, with a long-term annual average of 1826 mm per year. A distinct dry season occurs from December through April, with rainfall dropping to almost zero in January through March in some years.

Hinnavaru relies mostly on harvested rainfall and groundwater to supply most of its water demands, with rainwater and bottled water being the primary source of drinking water and cooking water demands, and groundwater being used for toilet flushing and cleaning. Of the roughly 700 properties in Hinnavaru, it is believed that all have rainwater harvesting facilities, consisting typically of one 2,500 L tank and sometimes two for residences, and several more for mosques, and the school. The average roof drainage area was 54 m^2, with a range of 10 to 78 m^2.

In addition Hinnavaru has a 30 ton desalination plant used primarily for some 50 households, community taps (see Utility Service Delivery Assessment [CH2M HILL, 2012]).

NON-CLIMATIC AND CURRENT CLIMATIC STRESSORS ON FRESHWATER RESOURCES.

Population growth and water pollution are key stressors on freshwater resources. For the most part, drinking water comes from rainwater harvesting and bottled water. Access to freshwater is of particular concern during drought, as the duration of dry season gets more erratic and rainwater harvesting systems are not always well managed to ensure full capacity at the end of the rainy season.

Pollution of freshwater resources is a major concern in the Maldives, including Dhidhdhoo and Hinnavaru. Bird and animal feces, sea spray, dust, urban pollution, and other contaminants can pollute rainwater from residential and commercial rooftops. Storage tanks and the rooftop collection systems are usually not maintained and cleaned regularly to eliminate numerous kinds of bacteria.

Freshwater groundwater lenses underly the densely populated cores of Dhidhdhoo and Hinnavaru. Until the recent installation of sewerage systems, the pollution sources included:

- Privies (latrines) – nitrates, ammonium, and bacteria
- Saltwater intrusion due to overpumping
- Co-disposal of hazardous waste with solid waste

The following water resources management issues were identified as key areas of vulnerability under current climate and institutional conditions:

- Poorly Designed and Maintained Rooftop Collection (Rainwater Harvesting) Systems
- Inoperable Emergency Desalination Systems
- Poor Coverage and Leaky Distribution Pipes
- "Safe Yield" Management of the Freshwater Groundwater Lens

CLIMATE CHANGE IMPACTS ON FRESHWATER RESOURCES

Three factors were investigated to assess vulnerability to climate change:

- Sea level rise that affects potential for inundation, coastal erosion, and saltwater intrusion to groundwater aquifers.
- Changes in rainfall that affect the reliability of rainwater harvesting systems.
- Changes in rainfall that affect groundwater recharge.

The SimCLIM tool was used to estimate climate change impacts using 13 GCM models and 3 possible future scenarios of greenhouse gases. In the next 20 years an increase in relative sea level of about 110 mm is expected relative to 2010 levels, with a range of 65 mm to 115 mm. By 2100, the estimated increases compared to 2010 are 495 mm, with a range from 300 mm to 760 mm.

The current groundwater recharge on Dhidhdhoo is estimated to be over 1 million L/day on an annual average basis, but as little as zero during the critical dry months of December through April. The current groundwater recharge on Hinnavaru is estimated to be over 400,000 L/day on an annual average basis, but as little as zero during the critical dry months of December through April.

Total annual precipitation is projected to go up by between 175 and 225 mm by the year 2100. Conversely, average precipitation in the dry months, is projected to go down for

January through March. As a result, the groundwater recharge and resulting safe yield is expected to go down in those dry months leading to high chance of saltwater intrusion.

The reliability of rainwater tanks was evaluated for a range of demands, and for two tank sizes (2,500 L and 5,000 L) and two rooftop areas (46.5 m^2 and 8 m^2), which represent the average and low end of the roof areas found in the informal survey of homes conducted in Dhidhdhoo and Hinnavaru. A 2,500 L tank can reliably meet a demand of about 20 L/day for a household with a 46.5 m^2 contributing area, but that drops down to 15 L/day with a roof area of 8 m^2. Adding a second tank increases the demand that can be met to 40 L/day and 30 L/day. Projected climate changes barely have any impact on the projected reliability of the rainwater harvesting systems, as far out as 2100 and regardless of GHG scenarios. The survey of rainwater harvesting systems noted a high percentage of homes did not have full storage tanks at the end of the rainy season, when the survey was conducted, which suggests that there is some need for retraining on the optimal use of rainwater harvesting systems.

CONCLUSIONS

In the next 20 to 100 years, significant sea level rise is projected, imperiling the islands themselves. In the next 20 years, the sea level is projected to increase above 2010 levels by approximately 110 mm (projected increase ranges from 65 to 115 mm). By 2100, the sea level is projected to increase above 2010 levels by approximately 495 mm (projected increase ranges from 300 to 760 mm). The projected sea level rise will increase shoreline erosion, increase the chances of inundation (particularly in association with storm surges or possible future tsunami events), and increase saltwater intrusion, which will imperil groundwater supply systems.

By the year 2100, the total annual precipitation is projected to increase by 175 to 225 mm. Conversely, average precipitation in the dry months, is projected to decrease moderately: by 5 mm in January, 5 mm in February, and 10 mm in March. As a result, the dry season will be more pronounced and the rainwater harvesting systems will be less likely to meet water supply needs through the dry season. Additionally, groundwater recharge will be further reduced during this season, thereby increasing the likelihood of saltwater intrusion. It should be noted, however, that the impacts of these projected changes in rainwater harvesting reliability and saltwater intrusion potential are small compared to challenges Dhidhdhoo and Hinnavaru face in providing reliable rainwater-fed supplies under existing conditions.

Because of the interdependency of the island water management systems and land use decisions, it is important to develop a water management strategy for the whole island that recognizes the linkages between systems, and their dependence on climate and land use decisions. For example, groundwater quality depends on both wastewater management approaches, as well as on recharge from rainwater infiltration, pumping levels, and sea level. Therefore, climate change impacts groundwater quality directly through impacts on recharge and sea level rise. Similarly, wastewater treatment affects groundwater quality if it eliminates sources of contamination from latrines. Finally, the availability of rainwater harvesting as a source of supply varies based on climate

uncertainty, which in turn drives the need for improved rainwater harvesting methods and for alternate sources of supply such as desalination.

RECOMMENDATIONS

1. To address increased risk of inundation and saltwater intrusion due to sea level rise, the following recommendations are offered:

A. Protect critical infrastructure by raising it or otherwise insulating it from inundation; for example, by providing higher platform levels and dikes.

B. Promote vegetated shoreline protection measures, for example by working with the island councils and community groups to plant and maintain vetiver, other hardy grasses or mangrove species, as appropriate to the specific locations These initiatives could be implemented through the project grants program or through voluntary community awareness building activities regarding climate vulnerability and adaptation.

C. Promulgate emergency management and evacuation plans for each island, including training and drills.

D. Promulgate long-term land use plans that factor in sea level rise in conjunction with recent land reclamation efforts on Dhidhdhoo and Hinnavaru (for example, relocation of facilities including housing and critical infrastructure, and controlling total number of residents/households).

2. To address saltwater intrusion threats due to rising sea levels and reduced groundwater recharge, it is recommended that enhanced groundwater recharge measures be adopted, including linking impervious surfaces (rooftops) to below ground recharge wells or infiltration galleries, instead of allowing surface ponding that leads to higher evaporation losses.

3. To address historic sources of groundwater contamination from latrines, promote connection to the collection system, and develop a program to decommission cess pits.

4. To address reduced reliability of rainwater harvesting systems, it is recommended that significant capacity building and institutional strengthening be targeted at increasing the optimal use of existing rainwater harvesting systems to ensure that they are full at the end of the rainy season, and to consider implementation of centralized rainwater harvesting and storage systems for islandwide emergency and routine water supply.

5. To address periodic drought conditions and increasingly unpredictable rainfall patterns, it is recommended that there is improved coordination and planning between the Northern and Upper Northern Utilities, the Hinnavaru and Dhidhdhoo island councils and the Maldives National Disaster Management Centre (NDMC). This improved coordination should have as its objective assuring water security for the target islands while at the same time minimizing costly emergency water transport to the islands in favor of improved integrated water resources management.

These recommendations are further detailed in the Utility Service Delivery Assessment (CH2M HILL, 2012).

SECTION 1
Overview

1.1 BACKGROUND

The Maldives program to Enhance Climate Resiliency and Water Security is intended to demonstrate the process and outcomes needed to allow island communities to maximize their opportunity to overcome impacts from global climate change. The program will provide assistance to the Government of the Maldives (GOM), and island and atoll councils; the private sector; and residents of two islands in the northern part of the country that will be targeted with United States Agency for International Development (USAID) assistance to become "climate resilient islands." The program's focus is based on climate-related risk-reduction associated with the development, use, and conservation of water resources in ways that are responsive to the environmental, social, cultural, economic, and governance context of the atolls. The provision of selected water, sanitation, and solid waste services and infrastructure will be designed and implemented. However, the underlying purpose and intended outcome of the program is to develop the knowledge, skills, and attitudes that island residents will need to become stewards of their island environment and to make rational and informed decisions on key climate change adaptation issues.

1.2 PURPOSE

The Climate Vulnerability Assessment uses available climate data to assess the vulnerability of key services (e.g., water, sanitation, solid waste management) to the impacts of climate change, and feeds into the Utility Service Delivery Assessment (CH2M HILL, 2012), including preliminary evaluation of alternatives and recommendations. This report documents the Climate Vulnerability Assessments for the Islands of Dhidhdhoo and Hinnavaru.

1.3 ASSESSMENT METHODOLOGY

The Climate Vulnerability Assessment methodology follows the first two steps in the six-step Vulnerability and Adaptation (V&A) approach laid out by USAID (2007) (shown in Figure 1-1).

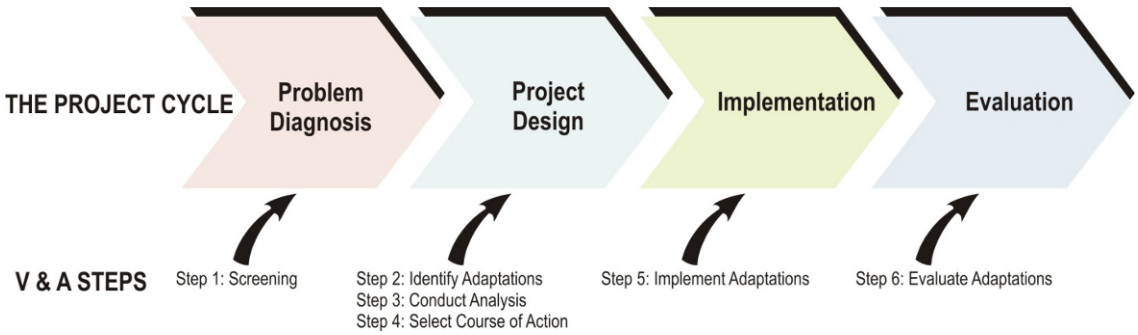


Figure 1-1: Vulnerability and Adaptation Approach

The V&A approach is a six-step process developed by USAID to help project and program planners account for and integrate climate concerns into designs, plans, and strategies. As indicated in Figure 1-1, the V&A approach involves a similar set of steps as project cycles and policy reform processes. The major differences relate to the scope of problem diagnosis (screening) in the V&A approach, which considers the typical set of development stressors as well as vulnerability to climate change and variability. The Utility Service Delivery Assessment further develops the adaptation measures for each island, and develops a recommended course of action (Steps 2, 3, and 4).

During a 2 week field effort, a consultant team worked with relevant Ministry of Housing and Environment (MHE) officials, island council members, community groups, and representatives from utilities to evaluate the current state of services, vulnerability of services to climate-related impacts, and priorities to improve the resiliency of services in light of likely climate-related impacts. The consultant team consisted of a Climate Vulnerability Assessment Specialist and a Utility Service Delivery Specialist from CH2M HILL, accompanied by a Maldivian utility specialist from Riyan, both of whom are subcontractors and supported by Chemonics.

The Climate Vulnerability Assessment Specialist completed the following tasks associated with this assignment:

- Review USAID six-step climate vulnerability assessment methodology described in *Adapting to Climate Variability and Change: a Guidance Manual for Development Planning*, USAID, 2007, and relevant updates.
- Obtain and analyze relevant climate data available from secondary sources.
- Review ongoing work of the Global Environmental Facility/United Nations Development Program (GEF/UNDP) funded program called Integrating Climate Change Risks into Resilient Island Planning (ICCRIP) in the Maldives.
- Consult with officials at the GOM MHE and Maldives Metrological Service (MMS) regarding climate issues, climate resilient island concept, and service delivery priorities on Hinnavaru and Dhidhdhoo.
- Conduct consultation sessions with relevant stakeholder groups on Hinnavaru and Dhidhdhoo, including island councils, women, local NGOs, business interests (e.g., fisherman) and representatives from each utility (and/or obtain information from Social and Community Development Assessment team if feasible).
- Work with Utility Service Delivery Assessment team to obtain information of current and planned service levels/capacity, and operations and maintenance for water supply (from all sources) and sanitation and solid waste management.
- Assess island-specific climate vulnerability for targeted services.
- Develop recommendations to address vulnerability and enhance climate resiliency.

The Utility Service Delivery Assessment Specialist completed the following tasks associated with this assignment:

- Obtain and review available information regarding water supply (groundwater, desalination, rain water harvesting), sanitation and solid waste management for Hinnavaru and Dhidhdhoo.
- Consult with officials at the GOM MHE regarding climate issues, climate resilient island concept, and service delivery priorities on Hinnavaru and Dhidhdhoo.
- Conduct consultation sessions with relevant stakeholder groups on Hinnavaru and Dhidhdhoo, including island councils, women, local NGOs, business interests (e.g., fisherman) and representatives from each utility.
- Consult with Upper Northern Utility (Dhidhdhoo) and Northern Utility (Hinnavaru) regarding current and planned service delivery capacity, and operations and maintenance for water supply, sanitation and solid waste management
- Assess condition and capacity of current utility assets.
- Assess utility institutional capability and related training needs.
- Make recommendations for enhancing utility service delivery capability, including both physical assets and institutional capacity, paying special attention to the deployment of renewable energy applications (e.g., solar powered reverse osmosis desalination).
- Assess non-utility water supply capacity on each island (e.g., household rainwater harvesting systems).
- Make recommendations for enhancing non-utility water supply capacity on each island.
- Make recommendations for an integrated approach to improving service delivery for water supply, sanitation and solid waste management, and enhancing water security.

1.4 CONSULTATIONS WITH GOVERNMENT OF THE MALDIVES AND STAKEHOLDER GROUPS

The following consultations were conducted:

- MHE's Permanent Secretary, the chief civil servant for all Ministry projects.
- MHE's Project Manager for ICCRIP.
- MHE's Water Section Chief, in charge of planning for water supply and sewerage facilities.
- MHE's Engineering Section Chief, in charge of engineering for water supply projects.
- Environmental Protection Agency (EPA), Water and Sewerage Head.
- MHE's Climate Change Trust Fund (CCTF), project manager.

- Upper North Utilities, Engineering Manager in Male', in charge of Dhidhdhoo's water, sewerage, and solid waste services.
- North Utilities, Engineering Manager in Male', in charge of Hinnavaru's water, power, sewerage, and solid waste services.
- Male' Water and Sewerage Company (MWSC).
- MHE's Maldives Environmental Management Project (MEMP), project manager and waste coordinator.
- Dhidhdhoo Island Council and Hinnavaru Island Council.
- Upper North Utilities, Engineering Manager in Dhidhdhoo, in charge of water, sewerage, and solid waste services.
- North Utilities, Engineering Manager in Hinnavaru, in charge of water, power, sewerage, and solid waste services.
- Haa Alif Atoll (H.A.) Education Center School Principal.
- Dhidhdhoo Hospital Administrator.
- Shin Nippon, Contractor for the Sewage Treatment Plant in Hinnavaru, currently operating the facility as part of defects liability period.
- Hinnavaru School Principal.
- Residents of five houses on Dhidhdhoo.
- Residents of five houses on Hinnavaru.
- A mosque was visited to observe rainwater harvesting systems, but Imam was not available.
- Ahmed Rasheed, assistant director for Island Council, and former island chief.

Meeting notes from each of these consultations are provided in Annex A.

SECTION 2
Water Resources in Dhidhdhoo and Hinnavaru, the Maldives

2.1 TOPOGRAPHY AND DEMOGRAPHICS

The Republic of the Maldives is an island nation in the Indian Ocean (see Figure 2-1), composed of 1,192 islands in 26 atolls, oriented north-south over 860 kilometers (km), spread over roughly 90,000 square km (35,000 square miles), making it one of the world's most dispersed countries in geographic terms. Its population of 313,920 (2010) inhabits 358 of its 1,192 islands. With an average ground level of 1.5 meter (m) (4 feet 11 inches) above sea level, it is the planet's lowest country.

Figure 2-1: Location of the Maldives

2.1.1 Dhidhdhoo

Dhidhdhoo (Dhivehi:) is the capital of Haa Alif Atoll administrative division in the Maldives. The island lies on the northwestern tip of Tiladummati Atoll, as shown in Figure 2-2.

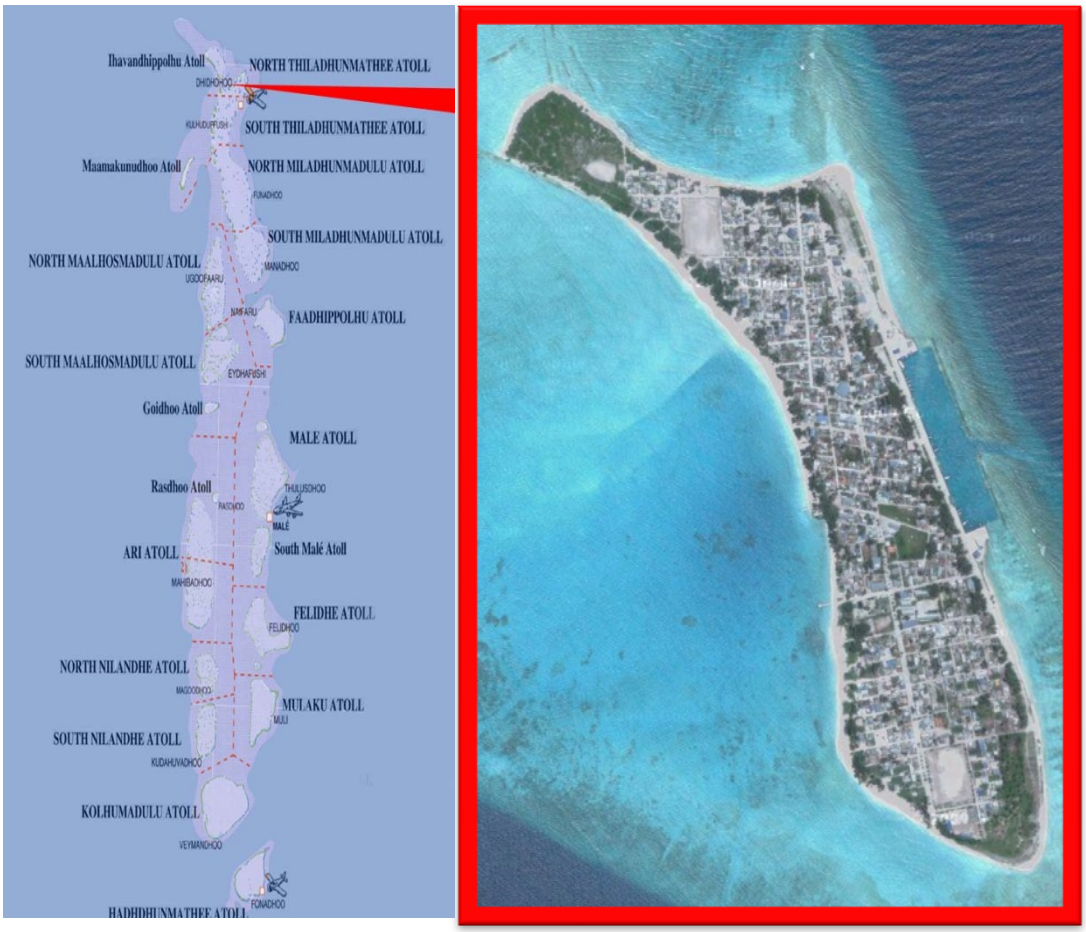


Figure 2-2: Location of Island of Dhidhdhoo in the Maldives, and Aerial Photo before Land Reclamation

Originally, the island was 52 hectares, but after land reclamation in 2010, the island is now around 85 hectares. Reclaimed area is shown in Figure 2-3. Land was reclaimed to cater the growing population and industries. There are some estimated 3,740 people in Dhidhdhoo (2009-Registered-Statistical Year book 2010) and it is the largest population in the Atoll.

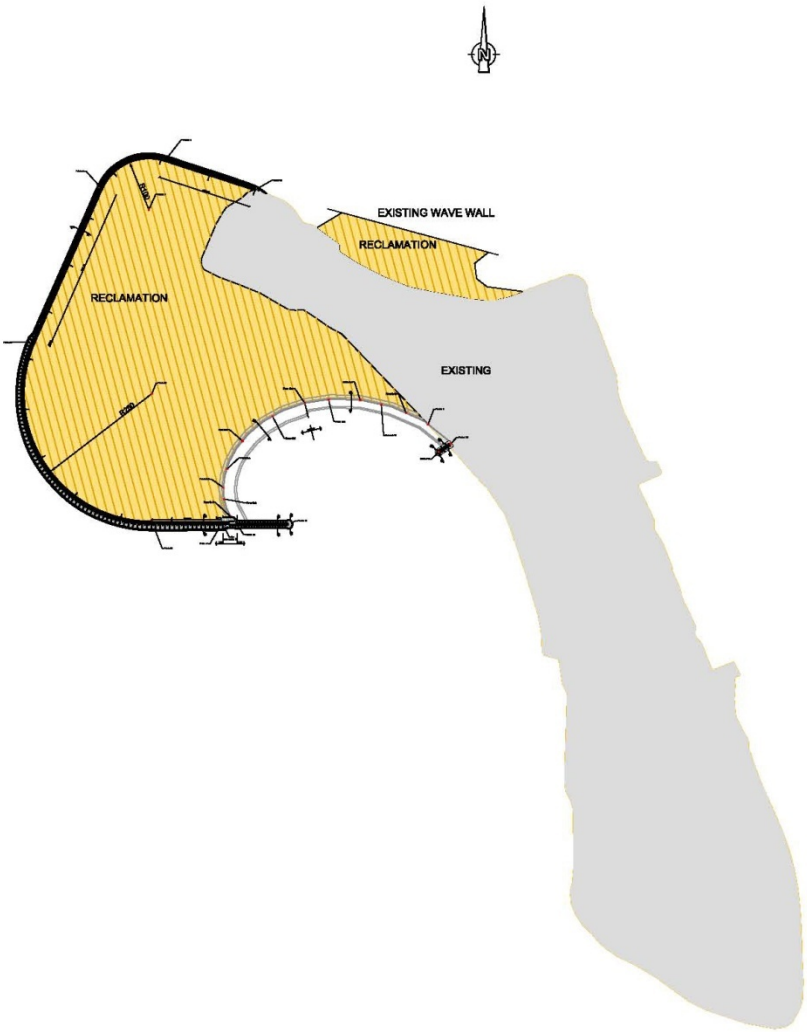


Figure 2-3: Reclaimed Area of Dhidhdhoo

Estimated population growth rates for Dhidhdhoo are listed in Table 2-1 and show a steady rate of increase with annual increases in recent years of about 2.0 percent.

Table 2-1. Dhidhdhoo Population Growth Rates

Number of Births from 2000 to December 8, 2011[a]					
Year	Female	Male	Total	Total Population	Growth Rate
2000	27	21	48	3,210	
2001	27	27	54	3,264	1.7%
2002			48	3,312	1.5%
2003	23	31	54	3,366	1.6%
2004	23	28	51	3,417	1.5%
2005	29	30	59	3,476	1.7%
2006	28	20	48	3,524	1.4%
2007	28	32	60	3,584	1.7%
2008	30	46	76	3,660	2.1%
2009	34	46	80	3,740[b]	2.2%
2010	42	35	77	3,817	2.1%
2011	34	43	77	3,894	2.0%

[a]Data provided by Haa Alif Atoll Dhidhdhoo Island Council.
[b]Total population in 2009 from registered total in 2010 Statistical Yearbook. Population in other years estimated from given number of births.

2.1.2 Hinnavaru

Hinnavaru (Dhivehi: □□□□□□□□□□□) is one of the inhabited islands of the Lhaviyani Atoll. Originally, the island was 22 hectares, and after land reclamation in 2010, the island is now 55 hectares (see Figure 2-4). It has a population of approximately 4,500 people living in 715 registered households. Land use is shown in Figure 2-5.

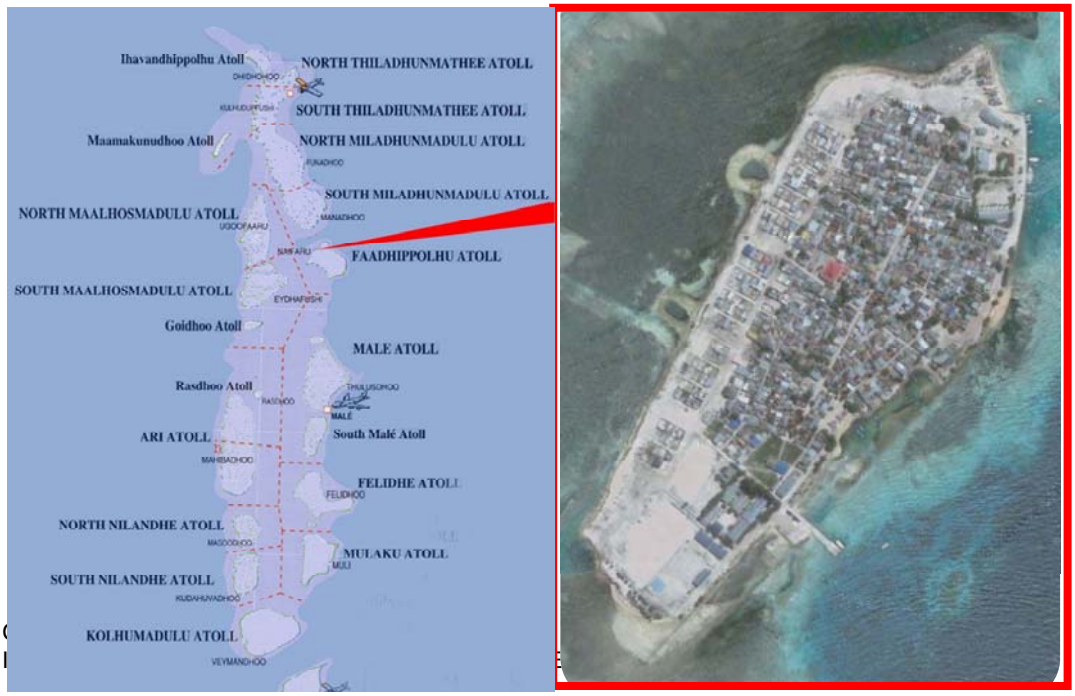


Figure 2-4: Location of Island of Hinnavaru in the Maldives, and Aerial Photos Before and After Land Reclamation

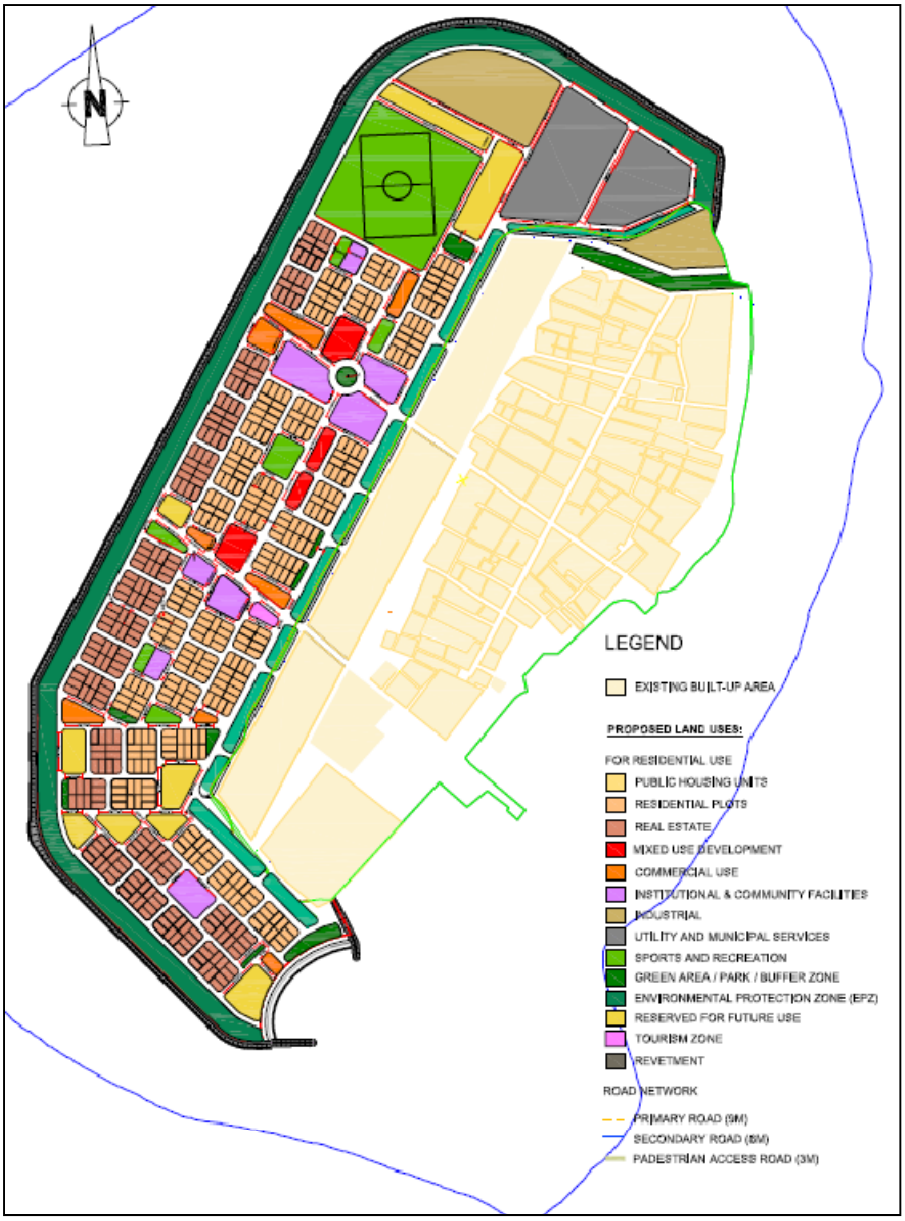


Figure 2-5: Land Use Plan for Reclaimed Area of Hinnavaru

Population data and growth rates are listed in Table 2-2 for the past decade through 2010. Table 2-2 shows a slow rate of increase with an annual average growth rate of about 0.6 percent.

Table 2-2: Hinnavaru Population Growth Rates

Year	Population	Annual Growth Rate (%)
2000	4,269	
2001	4,303	0.8%
2002	4,319	0.4%
2003	4,323	0.1%

Table 2-2: Hinnavaru Population Growth Rates

Year	Population	Annual Growth Rate (%)
2004	4,333	0.2%
2005	4,367	0.8%
2006	4,403	0.8%
2007	4,452	1.1%
2008	4,446	-0.1%
2009	4,520	1.7%
2010	4,539	0.4%

Data provided by Lh Atoll Hinnavaru Island Council.

2.2 GEOLOGY

The geology of the Maldives is composed of coral reefs and sand. The islands are low-lying and began forming between 3,000 and 5,500 years ago. They represent the most recent deposition along a submarine plateau that is underlain by approximately 2,100 meters of mostly shallow-water carbonates resting on a slowly-subsiding volcanic foundation. The islands are composed primarily of reef-derived carbonate sediment that has been deposited by waves and currents. In simple terms, the islands tend to have taken one of three forms:

- Seaward-edge islands on the peripheral atoll rim, formed of sand and gravel with steep, coarse beaches along their seaward margins and sand beaches along their lagoon shores.
- Lagoon-edge islands composed mostly of sand with minor amounts of gravel.
- Sand-cay type islands that form on peripheral rims and within lagoon, reef-top settings.

The reef foundations have been in existence for millions of years. The islands, however, are some of the youngest land surfaces on earth. Because of their unconsolidated nature, the islands should be considered ephemeral from the perspective of geologic timescales.

Island shorelines consist of sand, gravel, and a variety of engineering structures. The country's beach systems are highly dynamic and subject to seasonal conditions, especially from monsoons.

Although Maldives is located away from the main pathways of tropical cyclones, the presence of gravel beach ridges and cemented conglomerates attest to the fact that storm waves are an important element in the development of the islands.

No geologic data were identified specific to Dhidhdhoo. But observations suggest the western shoreline is largely sand, with minor amounts of gravel, while the eastern shoreline consists of steeper sand and gravel beaches, and reinforced shoreline in the port area.

No geologic data were identified specific to Hinnavaru. But observations showed that the western shoreline is now entirely reinforced by large boulders protecting the newly installed reclamation area, while the eastern shoreline consists of steeper sand and gravel beaches, and reinforced shoreline in the port area.

2.3 CLIMATE

Maldives has a tropical monsoon climate. The southwest monsoon is from May to November and the northeast monsoon is from January to March. Daily temperature varies between 31 degrees Celsius (°C) and 23°C. The mean daily maximum temperature is 30.4°C and the mean daily minimum temperature is 25.7°C. Humidity ranges from 73 to 85 percent (MEC, 2004; Meteorology, 2006). The annual average rainfall for Maldives is 2,124 millimeters (mm). Southern atolls on average receive 2,277 mm, while northern atolls receive 1,786 mm of rainfall annually.

2.3.1 Dhidhdhoo Climate

The 1992 to 2010 long-term average temperature at Hanimaadhoo weather station, which is closest to Dhidhdhoo, is 28.5°C, with a minimum of 24.2°C and a maximum of 32.5°C. Rainfall varies significantly throughout the year, as shown in the long-term record (Figure 2-6), and in the average monthly records (Figure 2-7). A distinct dry season occurs from December through April, with rainfall dropping to almost zero in January through March in some years. Local residents provided anecdotal evidence that the return of the rainy season in April is getting more erratic, but the long-term records do not show a trend from year to year.

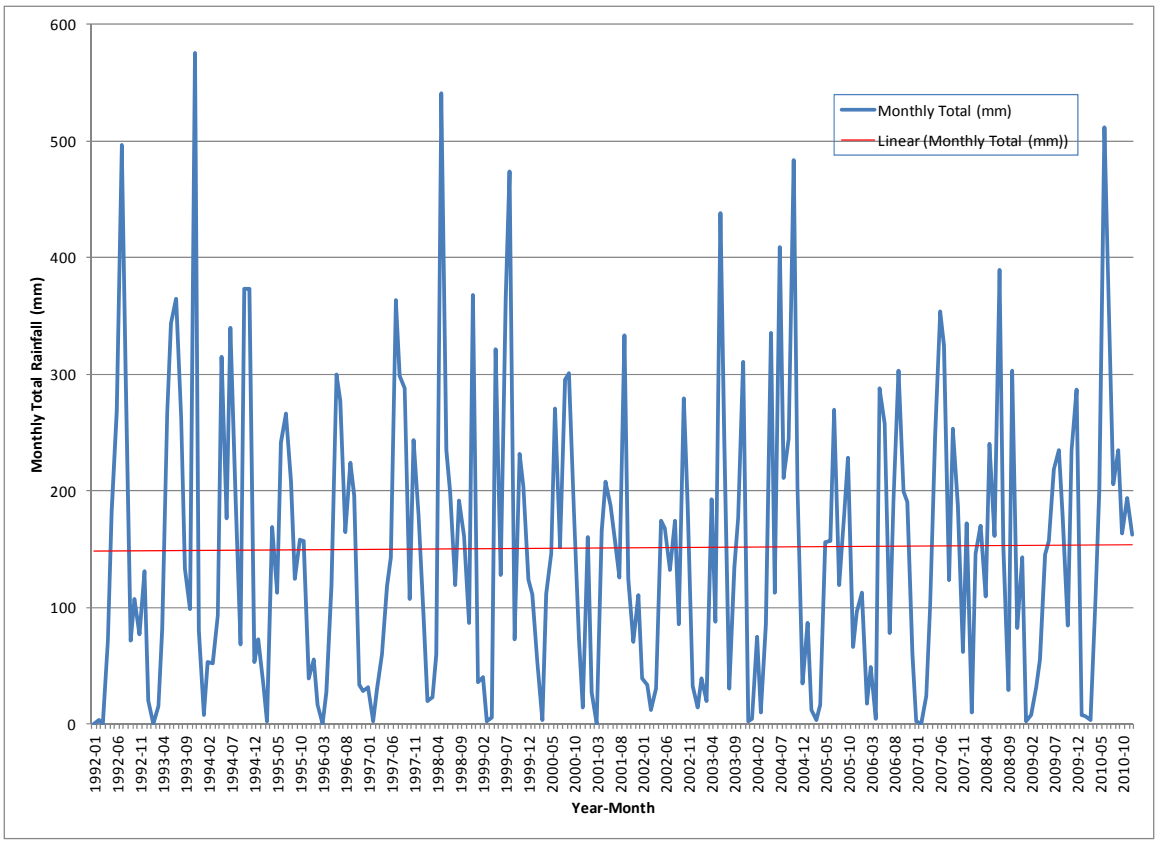


Figure 2-6: Long-Term Rainfall Record at Hanimaadhoo, near Dhidhdhoo.

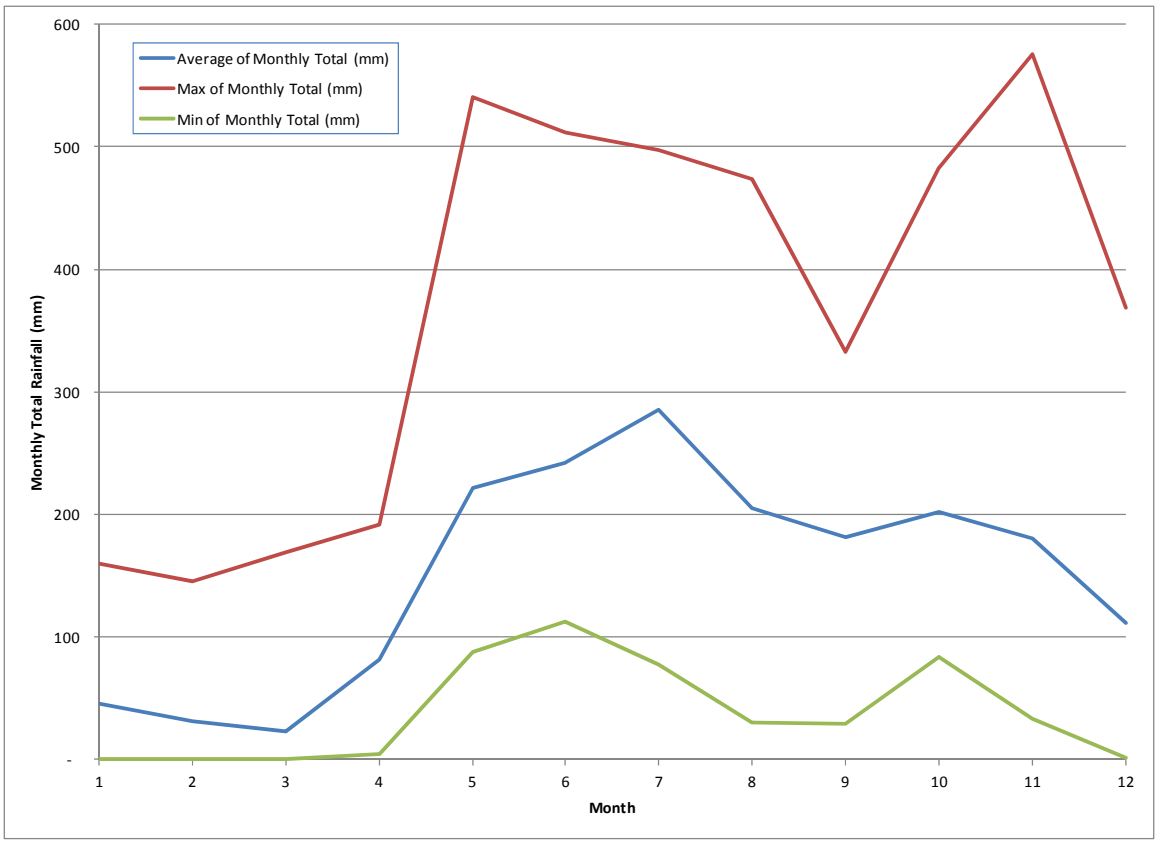


Figure 2-7: Average Monthly Rainfall Records at Hanimaadhoo, near Dhidhdhoo.

2.3.2 Hinnavaru Climate

Hinnavaru is roughly equidistant between the Hulhule weather station at the airport in the capitol of Male' and the Hanimaadhoo weather station. The 1980 to 2010 long-term average temperature at Hulhule, which is closest to Hinnavaru, is 28.4°C, with a minimum of 24.4°C and a maximum of 31.2°C. The 1992 to 2010 long-term average temperature at Hanimaadhoo weather station, which is next closest to Hinnavaru, is 28.5°C, with a minimum of 24.2°C and a maximum of 32.5°C. Rainfall varies significantly throughout the year, as shown in the long-term record at Hulhule and Hanimaadhoo (Figure 2-8), and in the average monthly records (Figure 2-9). A distinct dry season occurs from December through April, with rainfall dropping to almost zero in January through March in some years. Local residents provided anecdotal evidence that the return of the rainy season in April is getting more erratic, but the long-term records do not show a trend from year to year.

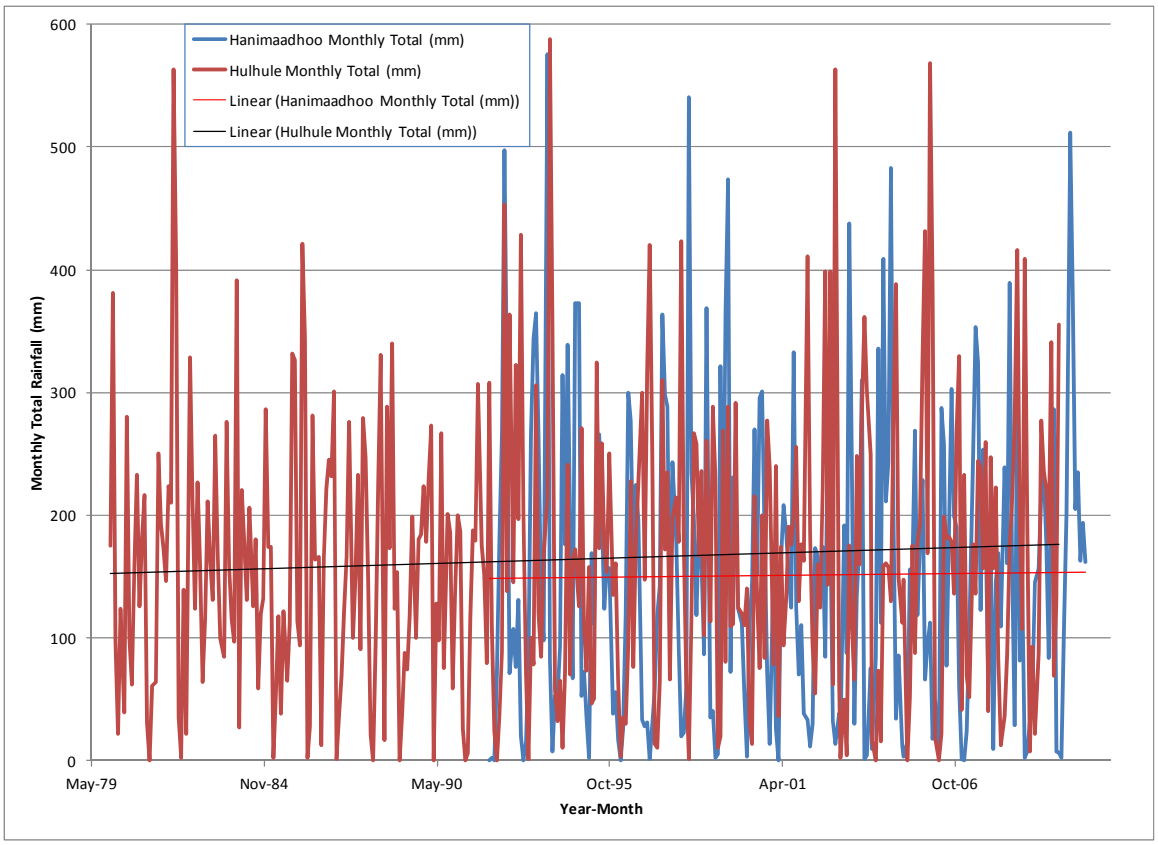


Figure 2-8: Rainfall at Hulhule and Hanimaadhoo

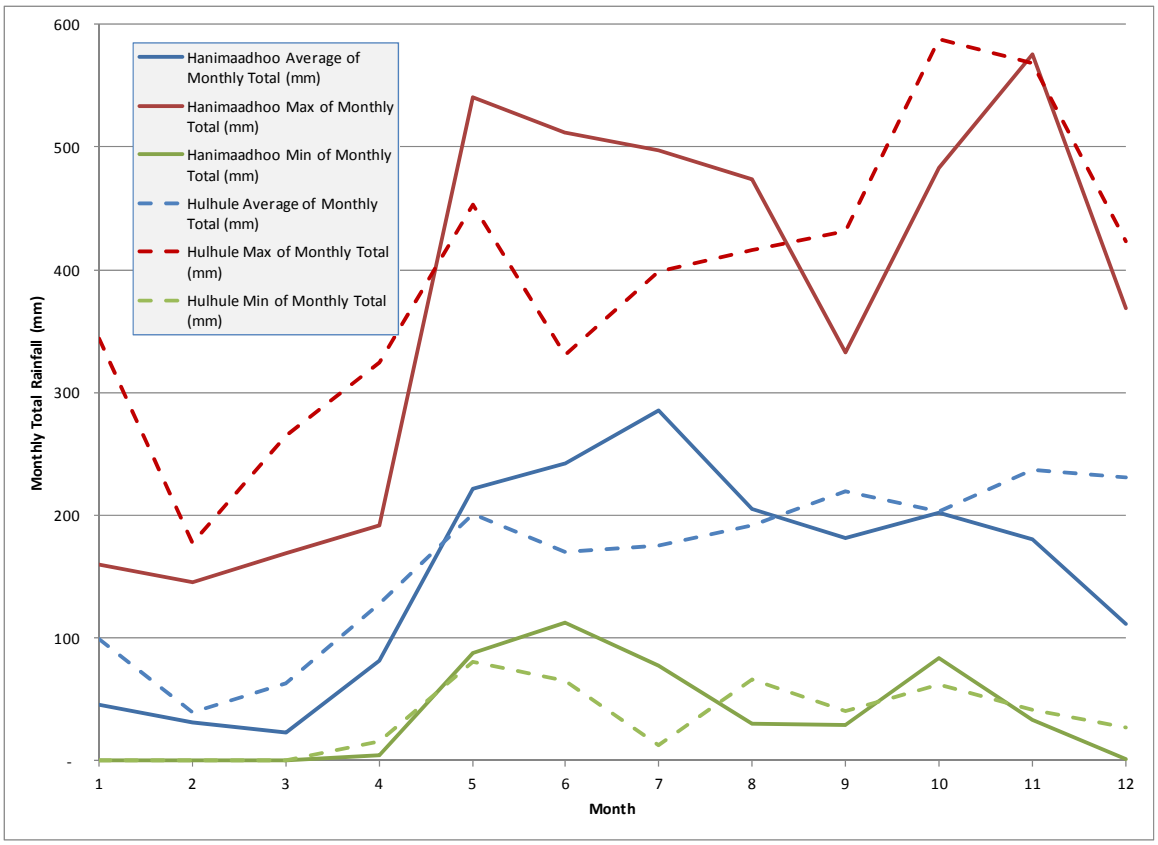


Figure 2-9: Average Monthly Total Rainfall at Hulhule and Hanimaadhoo

2.4 WATER RESOURCES

2.4.1 Dhidhdhoo Water Resources

Dhidhdhoo relies mostly on harvested rainfall and groundwater to supply most of its water demands. A rainfall harvesting system is shown in Figure 2-10, and a groundwater well is shown in Figure 2-11.

Figure 2-10: Typical Rainwater Harvesting System with First flush Valve Allowing Diversion. Most households have only one 2,500-liter (L) tank, instead of two shown here.

Figure 2-11. Wells were located either in a courtyard or inside the house, adjacent to the toilet. Well water is generally used for toilet flushing, but occasionally also for washing.

Groundwater is a scarce resource because of the hydrogeology of the country (Figure 2-12). The freshwater aquifer lying beneath the islands is a shallow lens, 1 to 1.5 meters below the surface and no more than a few meters thick.

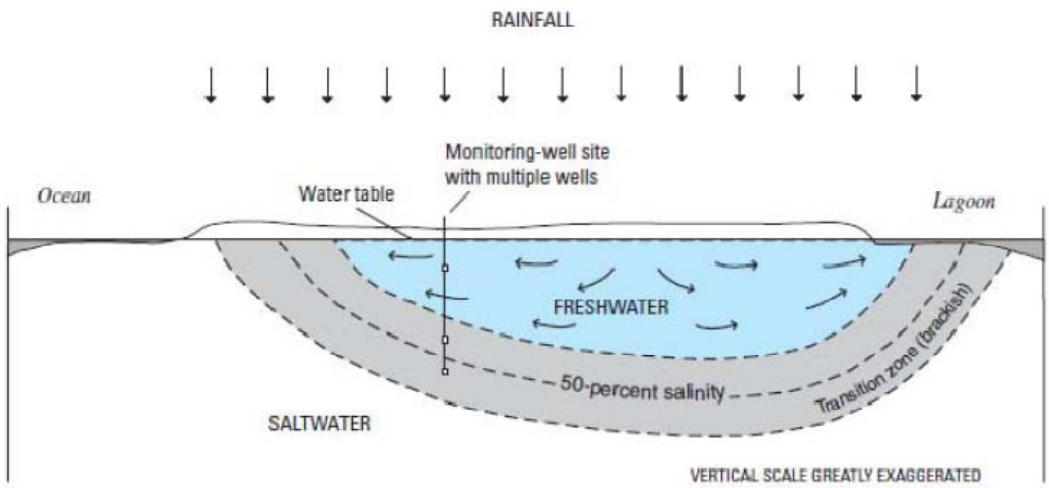


Figure 2-12: Area Hydrology

Surface freshwater is lacking on Dhidhdhoo. Traditionally, people depend on shallow wells to get access to the groundwater lens for nonpotable water uses. However, 90 percent of the atoll households now use rainwater as the principal source of drinking water. Following the tsunami, 38 islands have been provided with desalination plants that are being operated daily or on an emergency basis. On Dhidhdhoo, no desalination facilities are currently available, though a 10-ton facility was installed after the 2004 tsunami. See the Utility Assessment for further details. Note that in Male', 100 percent of the population has access to piped desalinated water, a level of service to which the people on Dhidhdhoo aspire.

Thickness of the groundwater aquifer in the islands is determined by net rainfall recharge, size of the island, and permeability of the soil column. The freshwater aquifers already stressed from over-extraction face the risk of total depletion if dry periods extend. As the islands have a precarious hydrological system, with the predicted sea level rise and during periods of wave-induced flooding, there is a very high risk of saltwater intrusion into the freshwater lens. Salinization of groundwater would affect the quality of life in the islands as people depend on groundwater for washing, bathing, and other non-potable uses. Saltwater intrusion would also affect soil and vegetation, causing impacts on agriculture and terrestrial ecosystems. As indicated in Figure 2-11, in addition to saltwater intrusion, until the recent introduction of wastewater collection systems, groundwater had also been contaminated by the common use of cesspools for wastewater disposal, often in close proximity to groundwater wells. No recent groundwater quality data are available to document the groundwater quality improvements that are expected as a result of the elimination of cesspools.

Rainwater is the main source of drinking water in the atolls. The lowest rainfall is during February and March (Meteorology, 2006). In 2010, the island-wide lack of drinking water resulted in the need to import 180 cubic meters (m^3) of desalinated water from Male'.

Of the roughly 1,050 properties in Dhidhdhoo, it is believed that all have rainwater harvesting facilities, consisting typically of one 2,500 L tank and sometimes two for residences, and several more for mosques, the school, and hospital. An informal survey was taken of five houses, one mosque, the school and the hospital, including measurements of number of cisterns, roof area, depth to groundwater and groundwater salinity. Data are compiled in Annex C. The average roof drainage area was 46.5 square meters (m^2), with a range of 8 to 77 m^2.

The Dhidhdhoo Island Council provided information on the number and distribution of rainwater tanks on the island, as follows:

- Number of water tanks provided by the inhabitants: 319 (each 2,500 L)
- Number of tanks permitted to be distributed to the inhabitants: 774 (each 2,500 L)
- Total number of tanks: 1,093 (each 2,500 L)

The number of public water tanks is shown in Table 2-3. Information based on land plots is shown in Table 2-4.

Table 2-3: Number of Public Tanks on Dhidhdhoo

	2,500 Liters per tank	5,000 Liters per tank
Total	23	11

Table 2-4: Information Based on Land Plots for Residential Areas and for Other Services on Hand in Haa Alif Dhidhdhoo

Permitted for	Total Number of Rainwater Storage Tanks
Residential areas	582
Land permitted to be used before 30th September 2006	210
Land permitted to be used after 30th September 2006	192
Office building	15
Mosque	09
Leased land	34
Residents building	12
Civil Society Organizations	02
Total	1,056

2.4.2 Hinnavaru Water Resources

Hinnavaru relies mostly on harvested rainfall and groundwater to supply most of its water demands, though it also has a 30 ton desalination plant. A rainfall harvesting system is shown in Figure 2-13, and a groundwater well is shown in Figure 2-14.

Figure 2-13: Typical Rainwater Harvesting System with first flush valve allowing diversion. Note: Most households have only one 2,500 liter (L) tank. The three shown in this photograph are for three households supplied by one roof.

Figure 2-14: Wells were located either in a courtyard or inside the house, adjacent to the toilet. Well water is generally used for toilet flushing, but occasionally also for washing.

As on Dhidhdhoo, groundwater is a scarce resource on Hinnavaru because of the hydrogeology of the country (Figure 2-12). The hydrogeology for Hinnavaru is the similar to that described above for Dhidhdhoo.

Surface freshwater is also lacking on Hinnavaru. Traditionally, people depend on shallow wells to get access to the groundwater lens for nonpotable water uses. However, 90 percent of the atoll households now use rainwater as the principal source of drinking water. On Hinnavaru, a 30 ton desalination facility was installed after the 2004 tsunami. The people on Hinnavaru would like the same level of service as is provided in Male' where 100 percent of the population has access to piped desalinated water.

Of the roughly 700 properties in Hinnavaru, it is believed that all have rainwater harvesting facilities, consisting typically of one 2,500 L tank and sometimes two for residences, and several more for mosques, and the school. An informal survey was taken of five houses, one mosque, and the school, including measurements of number of cisterns, roof area, depth to groundwater, and groundwater salinity. Data are compiled in Annex C. The average roof drainage area was 54 square meters (m^2), with a range of 10 to 78 m^2.

SECTION 3
Problem Diagnosis for Existing Conditions

This section provides an assessment of problems related to the sustainable provision of freshwater of the desired quantity and quality. The section is divided into two parts. The first part focuses on an overview of non-climatic stressors and the second part focuses on climatic stressors. The vulnerability of freshwater resources to climate change and variability is assessed in Section 4.

3.1 NON-CLIMATIC STRESSORS ON FRESHWATER RESOURCES

3.1.1 Population

As shown in Tables 2-1 and 2-2, population increases over the last 10 years have placed greater stress on the existing sources of freshwater on Dhidhdhoo and Hinnavaru. To some extent, the land reclamation areas, as shown in Figures 2-3 and 2-5, will eventually add groundwater resources, as freshwater lenses develops below these newly reclaimed lands.

Access to freshwater is of particular concern during drought, as the duration of dry season gets more erratic and rainwater harvesting systems are not always well managed to ensure full capacity at the end of the rainy season. Theoretically, water rationing, rainwater storage, groundwater, and desalinated water can extend the supply of water for a few months.

3.1.2 Pollution

Pollution of freshwater resources is a major concern in the Maldives, including Dhidhdhoo. For the most part, drinking water comes from rainwater harvesting and bottled water. However, lower income households that cannot afford bottled water may drink water directly from their storage tanks, or wells. Bird and animal feces, sea spray, dust, urban pollution, and other contaminants can pollute rainwater from residential and commercial rooftops. Storage tanks and the rooftop collection systems are usually not maintained and cleaned regularly to eliminate bacteria.

Freshwater lenses underly the densely populated cores of Dhidhdhoo and Hinnavaru. Until the recent installation of sewerage systems, the pollution sources included:

- Privies (latrines) – nitrates, ammonium, and bacteria
- Saltwater intrusion due to overpumping
- Co-disposal of hazardous waste with solid waste

The main cause of increased salinity relates to management practices – specifically, to overpumping. In Dhidhdhoo and Hinnavaru, until recently, privies posed the greatest pollution risk to the freshwater lenses. However, with the installation of a sewer system in 2010, it is expected that groundwater quality will improve. But not all toilets are connected to the sewer system. Previously, toilet facilities mainly consisted of privies

constructed over hand dug or excavated pits. Wastes from these pits were not removed and seepage of contaminated water from these is a concern.

3.1.3 Management Issues

Water resource management issues are addressed in greater detail in the Utility Delivery System Assessment (CH2M HILL, 2012). During the case study, the four most important management issues associated with the public supply of water concerned inefficient use of rainwater harvesting systems, inoperability of desalination systems, poor coverage by the emergency water distribution, and extractions from the freshwater lens.

Poorly Designed and Maintained Rooftop Collection (Rainwater Harvesting) Systems

The vast majority of households in Dhidhdhoo and Hinnavaru depend on rainfall collection systems for the majority of their water. For private catchment systems, the main concerns are:

- Maintenance and cleaning of rooftops, gutter, and storage tanks
- Storage capacity
- Concerns about water quality, leading to diversion of water instead of storing it for the dry season

In Dhidhdhoo and Hinnavaru, many rooftop systems are poorly designed, with roof top drainage areas that are either insufficient for the 2,500 L tank, or tanks that are insufficient to maximize storage handling capacity for the rainfall from the roof. In addition, rooftop systems may not be maintained and cleaned; or more commonly, misconceptions about the benefits of first flush diversion systems leads to the overuse of manually operated first flush bypass valves (up to 3 days) to divert allegedly contaminated roof runoff . See Figure 2-10 for picture of rainwater harvesting system, including bypass valve,

There is currently lack of public education about maintaining systems – very little information is available for public outreach in the Maldivian language, Dhivehi (▯▯▯▯▯▯ Divehi), to instruct owners of the proper use, and maintenance of rainwater harvesting systems, and guidelines on the need for and proper application of first flush systems, and other personal water filtration and disinfection systems to improve the quality and public health benefits of using harvested rainwater for drinking water and cooking needs.

Desalination Systems

In Dhidhdhoo during droughts, the availability of desalination units to provide emergency water could reduce the risk of overpumping and cause irreversible damage to the groundwater system. As an emergency measure following the 2004 tsunami, one 10 ton reverse osmosis (RO) system was donated and installed in Dhidhdhoo by the International Federation of Red Cross/Red Crescent for use in these types of water emergencies. During the assessment, however, this system was found to be inoperable

and reportedly it was only used for 209 hours before failing. Improper training and lack of spare parts seemed to be the primary reason for failure.

Hinnavaru has a 30 ton seawater reverse osmosis (SWRO) facility that was installed in 2008 as part of USAID's Maldives Tsunami Reconstruction Project. This system is currently being operated by the Northern Utilities Ltd. (NUL) approximately 8 hours per day, 6 days per week, producing on average 10 tons per day. There are 57 households, businesses, and government facilities in Hinnavaru that are connected to the distribution system; however, NUL does not have an effective metering and billing system so it does not receive revenue from a significant portion of the water being used

Poor Coverage and Leaky Distribution Pipes

All water distribution pipelines leak. Leakage represents technical non-revenue water (tNRW), that is, water produced by the water company but is lost in the system or is used in the plant for treatment requirements (filter backwash, etc). A water system can also have financial non-revenue water (fNRW), which is water that is produced by the water company, but cannot be billed to customers due to contractural obligations, broken water meters, etc. The total non-revenue water (NRW) is the sum of these two values and is typically 25 to 30 percent in well-managed water companies. When NRW exceeds 50 percent, the financial situation of a water company is significantly worsened – it may be difficult to recover operating costs and maintain an effective maintenance program and replace depreciated capital.

"Safe Yield" Management of the Freshwater Groundwater Lens

The lens of freshwater on top of the groundwater system underlying the island is sensitive to overpumping and its size can contract dramatically during droughts when it is pumped at a significantly higher rate during times when recharge is minimal. The concern during droughts is that overpumping can alter the size of the aquifer and limit recovery to its former size (see additional discussion in Section 3.2).

At present, in Dhidhdhoo the freshwater lens is pumped at an estimated rate of roughly between 95,000 and 131,000 L per day, far below the "safe yield" calculation of 1,015,000 L/day (see Groundwater Recharge section below). Similarly, in Hinnavaru the freshwater lens is pumped at an estimated rate of roughly between 68,000 and 94,000 L per day (90 to 125 L/day/household), far below the "safe yield" calculation of 411,000 L/day.

However, on both islands the groundwater recharge drops to low levels for 3 or 4 months in the dry season, which given the high soil transmissivities can lead to rapid saltwater intrusion into the freshwater aquifers. Improved management of both rainwater harvesting systems, and of groundwater recharges, through drainage wells, drainage galleries, and recharge basins could reduce the need to extract water from the freshwater groundwater lens.

In particular, enhanced groundwater recharge from rooftop drainage should be a priority. Water is typically discharged to the street, which is compacted sand and therefore has

reduced infiltration capacity, leading to water losses to evaporation. Some localities, such as the Island Council of Hinnavaru, are now requiring drainage wells for new buildings, largely because of ponding and flooding. But the additional benefit of promoting groundwater recharge should be recognized and encouraged in local drainage design standards. Figure 3-1 shows a Hinnavaru shop with a roof drain to groundwater recharge.

Figure 3-1: Hinnavaru Shop With Roof Drain Groundwater Recharge

During droughts in Hinnavaru, the availability of desalination units or centralized large storage reservoirs for rainwater to provide emergency water could reduce the risk of overpumping that might cause irreversible damage to the groundwater system.

3.2 CURRENT CLIMATE IMPACTS ON FRESHWATER RESOURCES

Current climate can impact freshwater resources in a variety of ways. In combination with the stressors discussed in the previous section, climate presents a formidable challenge to the Maldives in meeting the water needs of its people. As discussed below, the most immediate climate stressors are drought in the form of extended dry seasons and severe storms. Over a longer time horizon, changes in precipitation patterns, temperature, and sea level rise will affect the management of rainfall and groundwater. Climate change impacts on freshwater resources are discussed in Section 4.

Without question, drought is the number one concern in meeting demand for freshwater for Dhidhdhoo and Hinnavaru on a sustainable basis. Two drought issues have distinct risks to the water supply in Dhidhdhoo and Hinnavaru:

- Extended dry seasons, during which reliance on storage from rainwater harvesting systems for drinking water are vulnerable to depletion.
- Reduced overall recharge during the wet season, affecting the availability of groundwater.

Because of these factors, rainfall patterns are as important as total annual rainfall amounts.

Dry Season Precipitation

The four longest lasting dry seasons, each lasting 4 to 5 months, are highlighted in Table 3-3. For Dhidhdhoo, these drought periods were identified based on having consecutive months with less than 55 mm per month. That threshold was picked for illustrative purposes because 55 mm would replenish a 2,500 L rainwater storage tank from the average roof top drainage area of 46.5 m^2. For Hinnavaru, these drought periods were identified based on having consecutive months with less than 46 mm per month. That threshold was picked for illustrative purposes because 46 mm would replenish a 2,500 L rainwater storage tank from the average rooftop drainage area of 54 m^2.

Note also that 2,500 L represents an average consumption over 4 months of 20 L per day per household, which is within the guidelines used by MHE for drinking and cooking needs. Therefore, any dry period that does not replenish rainwater tanks within 4 months, will severely stress basic drinking water needs on Dhidhdhoo, assuming tanks are full at the beginning of the dry season (which the recent survey indicated was not a good assumption).

The drought in 1996-1997 lasted 5 months, during which time recorded precipitation was 123 mm, or 25 mm/month. The droughts in 1992 and 1993 had average monthly precipitation levels of 29 and 26 mm/month, respectively. However, several 3 month dry periods had lower average monthly precipitation, including 2007, 2009, and 2010, at 9, 14, and 6 mm/month, respectively.

Groundwater Recharge

Groundwater recharge from infiltration of rainwater is one of the four primary sources of freshwater available to Dhidhdhoo, with rainwater harvesting, desalinated water, and imported bottled mineral water. Groundwater recharge replenishes the thin freshwater lens that sits on top of brackish salt water beneath the island, and is tapped through shallow wells at individual household levels.

Estimating groundwater recharge is fairly complex calculation that combines the following factors:

- Seasonally variable rainfall.
- Evapotranspiration, though with limited vegetation on most of Dhidhdhoo and Hinnavaru, the transpiration component is limited to some trees with deep rooting systems, and some scrub vegetation in open spaces and along the waterfront.
- Soil infiltration capacity, which might be assumed to be large for most of the coral sand and limestone soils. But observation and anecdotal evidence of significant

ponding suggests soil compaction and reduced infiltration capacity in areas of dirt roads and inner courtyards of residences and businesses.

- Land use, primarily determining what percentage of land is impervious versus pervious.

Seasonally variable rainfall was derived from the records at Hanimaadhoo, for which daily rainfall was available from the Maldives Meteorological Service from 1992 through 2010. Hanimaadhoo is near Dhidhdhoo, in the Ha Atoll.

Evapotranspiration was estimated using the RefET software developed by the University of Idaho, using daily maximum and minimum temperature, barometric pressure, and wind speed data from Hanimaadhoo.

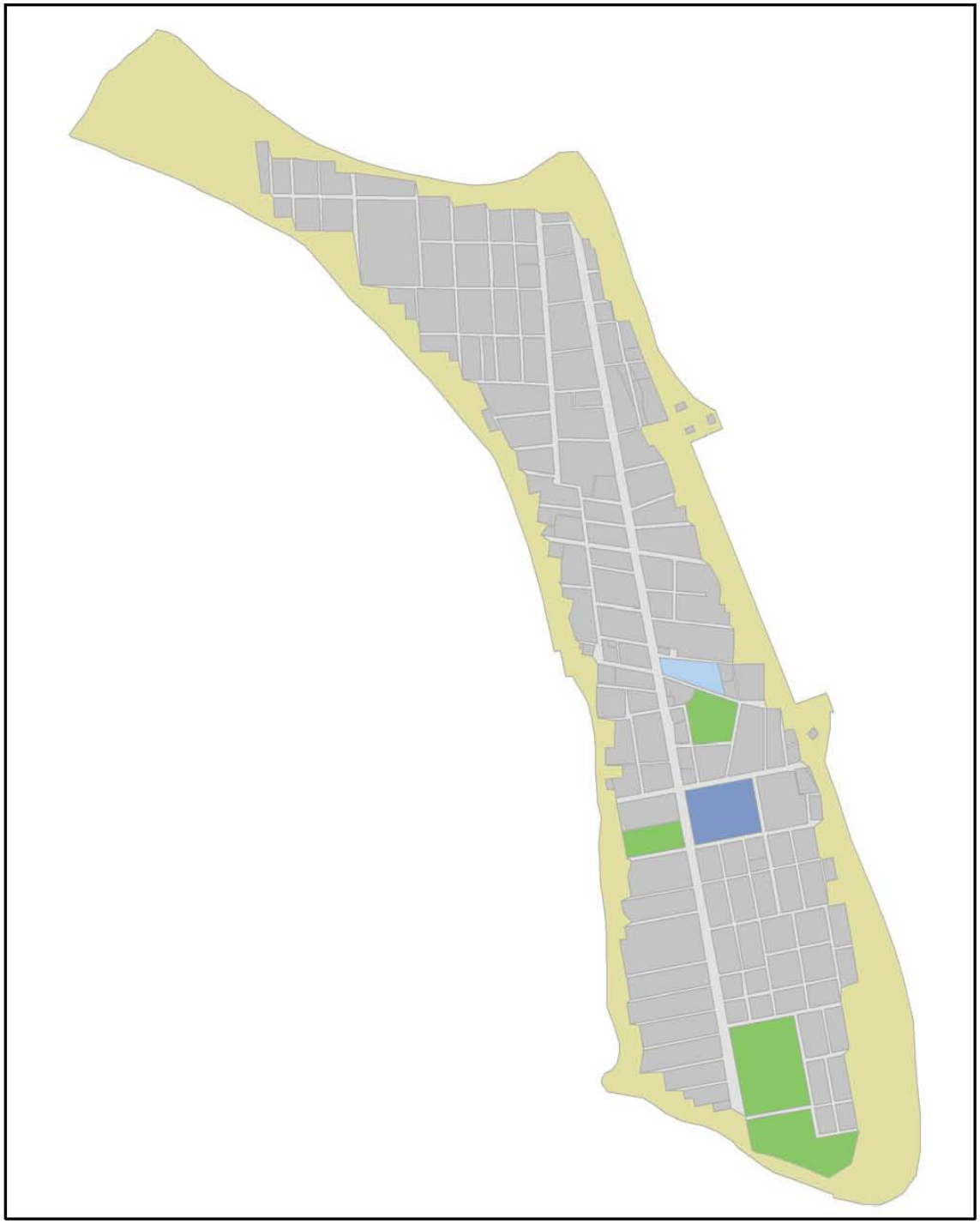
Soil infiltration capacity was assumed to be in Soil Conservation Service (SCS) Type A good condition category for open space areas, and in Type B poor condition category for roads and pervious portion of residential areas.

For Dhidhdhoo, land use was estimated using geographical information service (GIS) interpretation of aerial photography coupled with on the ground observations, and using computer aided drafting (CAD) files of road layers. The resulting land use map is shown in Figure 3-1. The assumptions shown in Table 3-1 were used for impervious percentages, in each of the categories listed.

Table 3-1: Land Use Assumptions for Dhidhdhoo

Land Use Category	Area (hectares)	Assumed Percent Impervious
Residential/Mixed Use	25.05	70%
Pervious (Ocean Front Open Space)	18.85	0%
Road	6.70	0%
Open Space	2.74	5%
School	0.73	30%
Cemetery	0.27	10%
Total	54.34	33%

Based on these data, the following average annual recharge rate was computed for the long-term Dhidhdhoo record from 1992 to 2010. On an annual average, groundwater recharge is about 1,016,000 L/day, or 680 mm/year. Figure 3-2 shows the seasonal and annual variability of that recharge for Dhidhdhoo. This shows that for the dry season, the recharge rate drops down to very low levels, during which time groundwater pumping can lead to saltwater intrusion if there is insufficient storage and high soil transmissivities lead to depletion of the freshwater lens on top of the groundwater system.



LEGEND
- Road
- Impervious
- Cemetery
- School
- Open Space
- Pervious

N

0 100 200 400
Meters

FIGURE 3-1
Dhidhdhoo Land Use Map
CLIMATE CHANGE VULNERABILITY ASSESSMENT

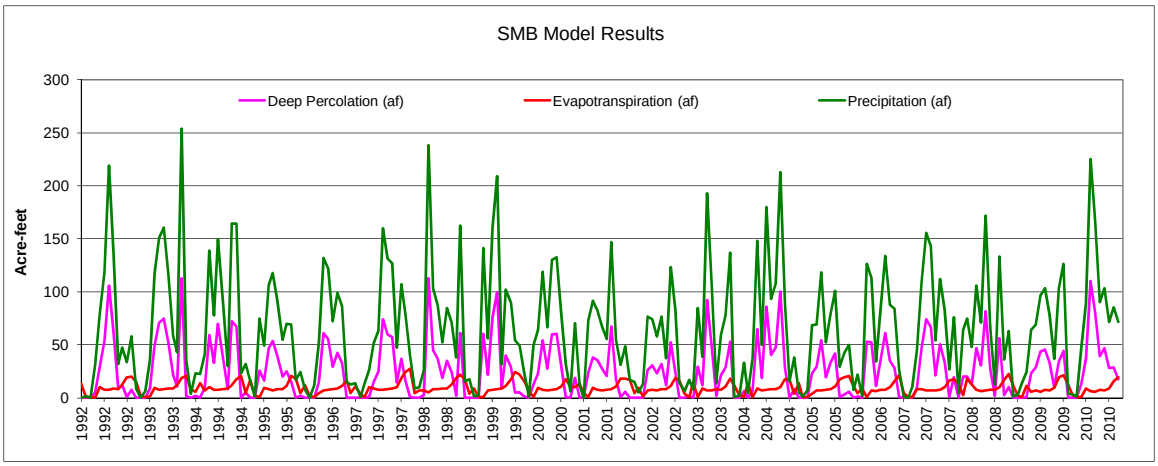


Figure 3-2: SMB Model Results for Dhidhdhoo

Table 3-2 summarizes average monthly groundwater recharge for Dhidhdhoo. In January, February, and March, the estimated average groundwater withdrawals of between 95,000 and 131,000 L/day exceed the estimated recharge rate. With highly transmissive sandy soils, this could lead to saltwater intrusion by the end of the dry season. Anecdotal evidence from interviews of residents of Dhidhdhoo confirms that well water does get substantially saltier at the end of the dry season, particularly for properties closer to the coast line. Precipitation data are summarized in Table 3-3.

Table 3-2: Average Monthly Groundwater Recharge for Dhidhdhoo

Month	Average of Deep Percolation (L/day)
January	97,000
February	65,500
March	47,000
April	342,000
May	1,604,000
June	1,946,000
July	2,343,000
August	1,575,000
September	1,357,500
October	1,418,000
November	992,000
December	407,000
Annual Total	1,016,000

Table 3-3: Precipitation Data from Hanimaadhoo, Near Dhidhdhoo and Hinnavaru

Year	Month (mm)												Total Annual Precipitation (mm)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	
1992		2.9	-	71.0	181.5	268.4	497.0	305.4	71.8	107.3	76.9	130.9	1,713.1
1993	19.5	-	14.7	80.6	267.2	343.7	364.6	263.3	132.8	98.2	575.5	80.4	2,240.5
1994	8.0	52.9	51.5	92.8	314.6	176.7	339.1	197.3	67.7	373.4	372.7	52.6	2,099.3
1995	72.2	34.9	2.4	169.1	112.0	241.7	266.3	207.3	124.3	157.6	156.8	38.6	1,583.2
1996	55.5	16.7	-	27.0	119.1	299.9	277.0	164.2	224.2	196.3	33.5	27.9	1,441.3
1997	30.9	1.8	29.3	59.1	117.6	142.3	363.3	298.7	288.1	107.1	243.0	178.9	1,860.1
1998	90.9	19.4	22.5	59.1	541.0	234.6	197.4	119.2	191.6	160.7	86.8	368.3	2,091.5
1999	35.7	40.1	2.4	5.6	321.0	127.8	364.6	474.2	72.6	231.3	202.9	123.6	2,001.8
2000	111.7	53.1	3.4	111.5	145.9	270.0	151.5	295.7	300.4	181.8	72.4	13.8	1,711.2
2001	159.8	26.5	-	165.2	208.2	187.1	152.1	125.2	333.2	124.5	70.1	110.6	1,662.5
2002	38.9	33.3	12.0	30.0	173.6	167.5	131.6	173.9	85.1	279.4	188.6	32.6	1,346.5
2003	14.0	38.4	19.0	192.0	87.9	438.1	243.9	30.7	134.2	176.7	310.5	1.8	1,687.2
2004	4.3	75.1	9.8	85.1	335.5	113.0	408.7	211.3	244.4	483.5	203.8	34.8	2,209.3
2005	86.1	11.8	3.3	16.2	155.8	156.6	268.9	119.1	179.7	228.7	66.5	96.2	1,388.9
2006	112.6	17.4	48.9	4.1	287.2	257.7	77.4	191.8	303.3	199.0	190.1	59.6	1,749.1
2007	1.9	-	23.9	101.1	247.6	353.2	324.2	123.2	253.6	187.6	61.5	171.9	1,849.7
2008	9.4	145.7	169.3	109.3	239.6	161.1	389.1	152.2	28.9	302.9	82.1	142.4	1,932.0
2009	2.6	7.6	31.5	55.5	145.4	156.6	218.7	234.8	177.3	83.9	234.4	286.9	1,635.2
2010	8.0	6.9	2.8	107.7	201.7	511.7	378.4	205.3	234.9	163.1	194.1	161.9	2,176.5
Average	45.4	30.8	23.5	81.2	221.2	242.5	284.9	204.9	181.5	202.3	180.1	111.2	1,809.4
Maximum	159.8	145.7	169.3	192.0	541.0	511.7	497.0	474.2	333.2	483.5	575.5	368.3	2,240.5
Minimum	-	-	-	4.1	87.9	113.0	77.4	30.7	28.9	83.9	33.5	1.8	1,346.5

Land use data were not available for Hinnavaru. However, because Hinnavaru is similar to Dhidhdhoo, the imperviousness on Dhidhdhoo was used to estimate the imperviousness on Hinnavaru. The average percent imperviousness for the non-reclaimed area of Dhidhdhoo was calculated at 33 percent. That same 33 percent was assumed to approximate the impervious percentage of Hinnavaru's 22 hectares, not including the reclaimed land area.

Based on these data, the following average annual recharge rate was computed for the long-term Hinnavaru record from 1992 to 2010. On an annual average groundwater recharge is about 411,000 L/day, or 680 mm/year. Figure 3-3 shows the seasonal and annual variability of that recharge. This shows that for the dry season, the recharge rate drops down to very low levels, during which time groundwater pumping can lead to saltwater intrusion if there is insufficient storage and high soil transmissivities lead to depletion of the freshwater lens on top of the groundwater system. Table 3-4 summarizes average monthly groundwater recharge. In January, February, and March, the estimated average groundwater withdrawals of between 68,000 and 94,000 L/day exceed the estimated recharge rate. With highly transmissive sandy soils, this could lead to saltwater intrusion by the end of the dry season. Anecdotal evidence from interviews of residents of Hinnavaru confirms that well water does get substantially saltier at the end of the dry season, particularly for properties closer to the coast line.

Table 3-4: Average Monthly Groundwater Recharge for Hinnavaru

Month	Average of Deep Percolation (L/day)
January	39,000
February	27,000
March	19,000
April	138,000
May	649,000
June	788,000
July	948,000
August	638,000
September	550,000
October	574,000
November	401,000
December	165,000
Annual Total	411,000

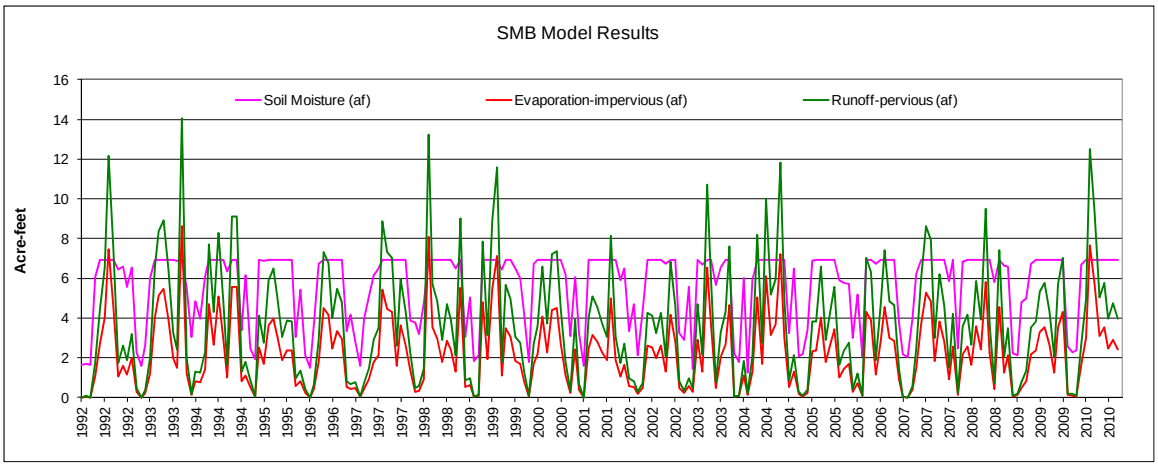


Figure 3-3: SMB Model Results for Hinnavaru

SECTION 4
Climate Change Impacts on Freshwater Resources

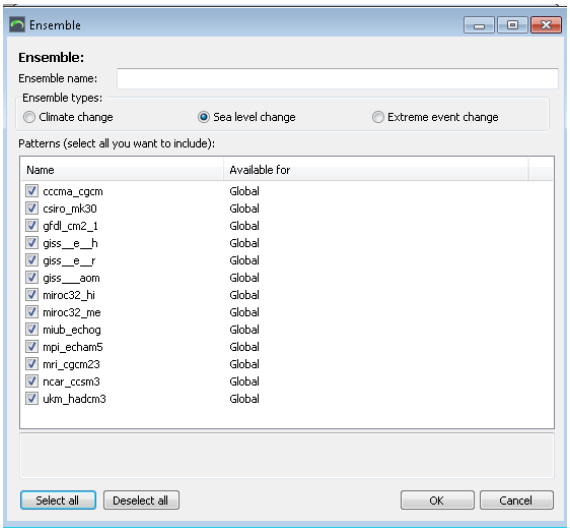
4.1 CLIMATE CHANGE

The process of predicting future climate is considered an extremely daunting task. As described by USAID (2009) and RIMES (2011), it requires an assessment of the future state of a wide array of complex climatic components—including the atmosphere, the ocean, land surfaces, the stratosphere, and the sun, as well as the interactions among these components—with the only practical method to make such projections the use of mathematical models (derived from weather forecasting) to represent the earth's energy and water cycles.

The most sophisticated of these models, general circulation models (GCMs), use a three-dimensional grid overlaying the surface of the earth, coupled to atmosphere-ocean general circulation models, to simulate the earth's climatic system and facilitate prediction of changes in key climate parameters into the future. The development and parameterization of these models is coordinated through the United Nations' Intergovernmental Panel on Climate Change (IPCC). This section provides a brief overview of climate changes that are expected to occur for Dhidhdhoo and the Maldives and the potential impacts of these changes on freshwater resources.

The climate projections presented in this section were done using the SimCLIM tool, developed by CLIMsystems, and were done in parallel with more detailed analyses done by RIMES (2011), which tap into regional circulation models (RCMs).

SimCLIM uses either individual GCMs or can look at ensemble averages of multiple GCMs. The ensemble average from the following 13 GCMs from the IPCC 4th Assessment Report (AR4) was used for this analysis, as listed in Figure 4-1.



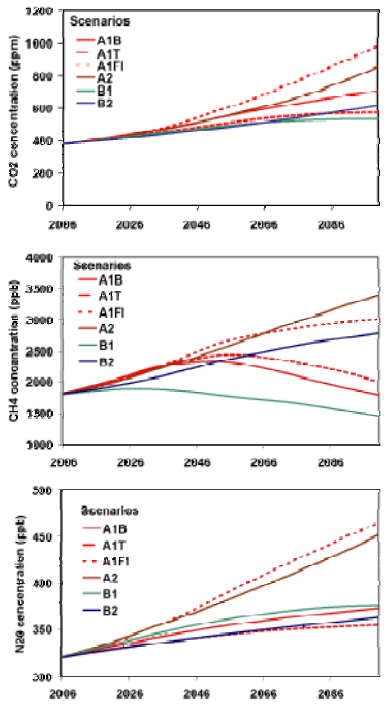


Figure 4-1: IPCC Assessment Report 4 GCMs

Projections were developed to the year 2100, using three greenhouse gas (GHG) emission scenarios from the IPCC Special Report on Emission Scenarios (SRES): A2, A1FI, and A1B, which represent the high, and moderate range, of the IPCC emission scenarios.

4.2 VULNERABILITY TO CLIMATE VARIABILITY AND CHANGE: FRESHWATER RESOURCES

Three factors were investigated to assess vulnerability to climate change:

- Sea level rise that affects potential for inundation, coastal erosion, and saltwater intrusion to groundwater aquifers.
- Changes in rainfall that affect the reliability of rainwater harvesting systems.
- Changes in rainfall that affect groundwater recharge.

4.2.1 Sea Level Rise

Sea level rise projections developed with SimCLIM are shown in Figure 4-2, with the first graph showing relative to absolute sea level and the second graph showing relative to the start of available historical records (Male-B, Hulule). These projections do not include the effects of storm surge that might result from more extreme or more frequent tropical cyclones. These projections show a relative sea level rise, assuming a vertical land movement of -1.1 mm/year (± 0.6).

The second graph of Figure 4-2 shows that in the next 20 years an increase of about 110 mm is expected relative to 2010 levels, with a range of 65 mm to 115 mm. By 2100, the estimated increases compared to 2010 are 495 mm, with a range from 300 mm to 760 mm. With average ground surface elevations only about 1.5 meters, these longer term sea level rise projections suggest that the sustainability of Dhidhdhoo and Hinnavaru is in jeopardy.

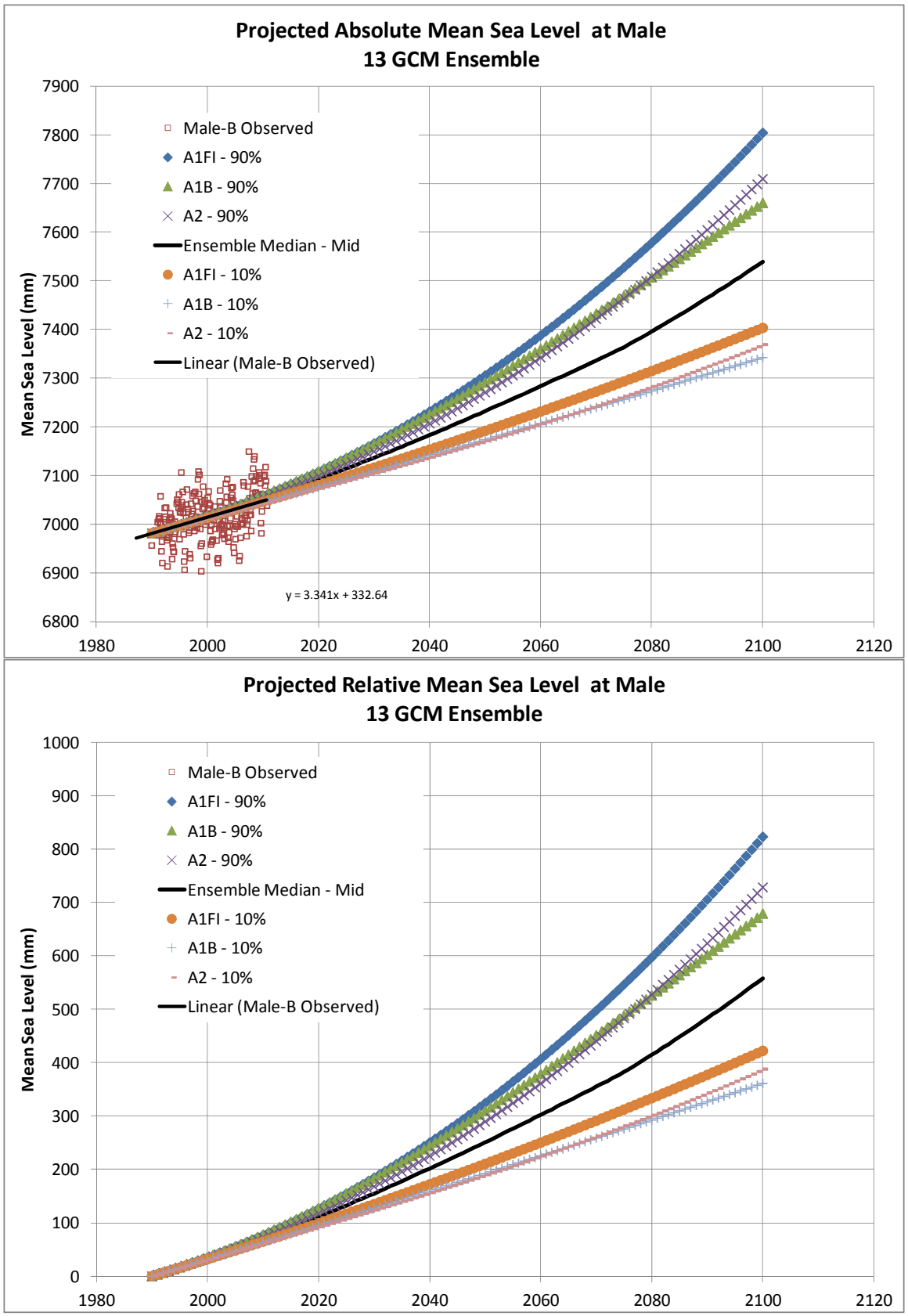


Figure 4-2: SimCLIM Sea Level Projections

4.2.2 Groundwater Recharge under Climate Change

As previously shown, the current groundwater recharge is estimated to be over 1 million L/day on an annual average basis, but as little as zero during the critical dry months of December through April.

As shown in Figure 4-3, total annual precipitation is projected to go up by between 175 and 225 mm by the year 2100. Conversely, average precipitation in the dry months, is projected to go down, as shown in Figures 4-4, 4-5, and 4-6 for January through March. As a result, the groundwater recharge and resulting safe yield is expected to go down in those dry months.

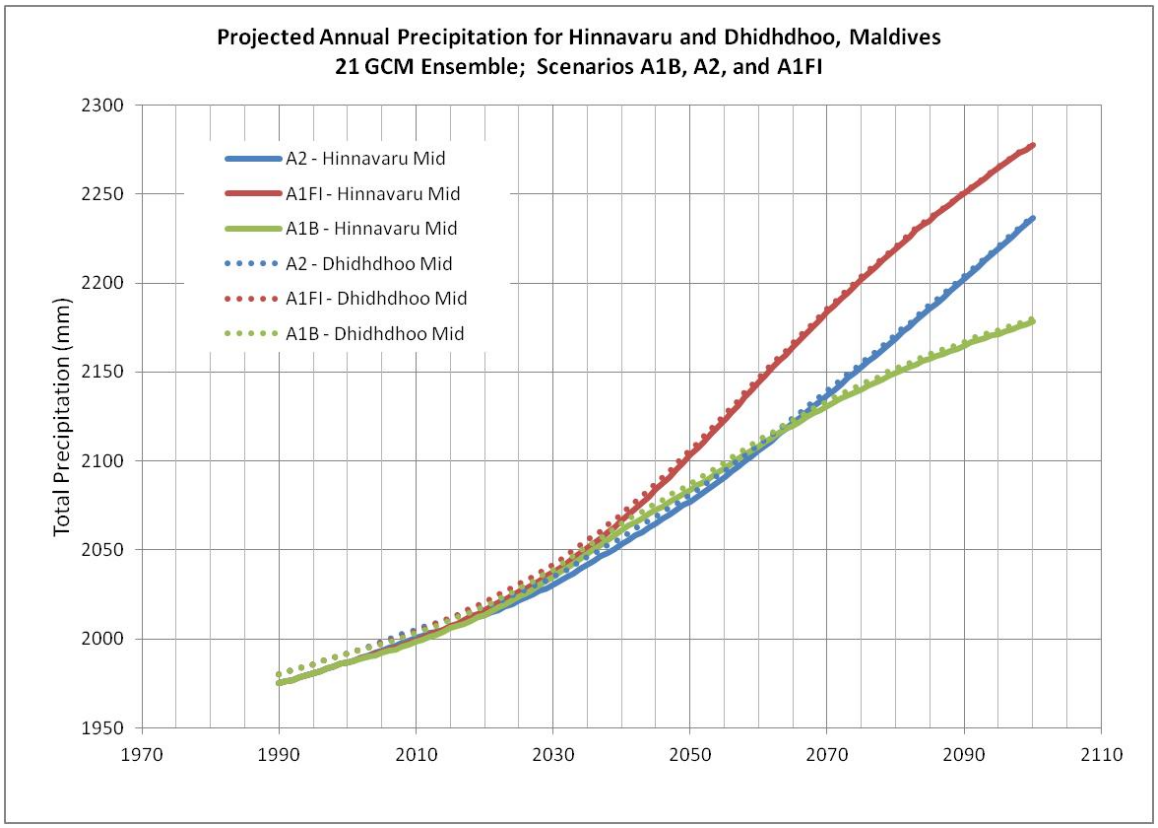


Figure 4-3: Projected Annual Precipitation for Dhidhdhoo and Hinnavaru, Maldives

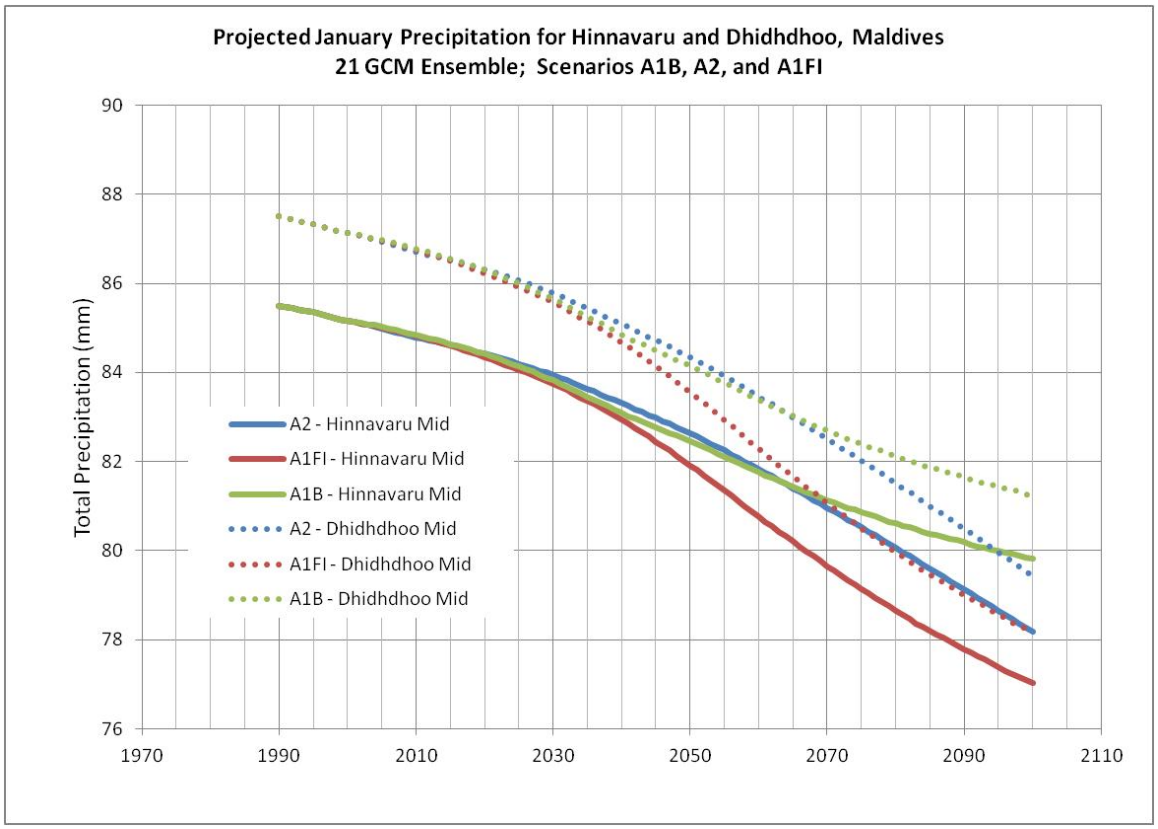


Figure 4-4: Projected January Precipitation for Dhidhdhoo and Hinnavaru, Maldives

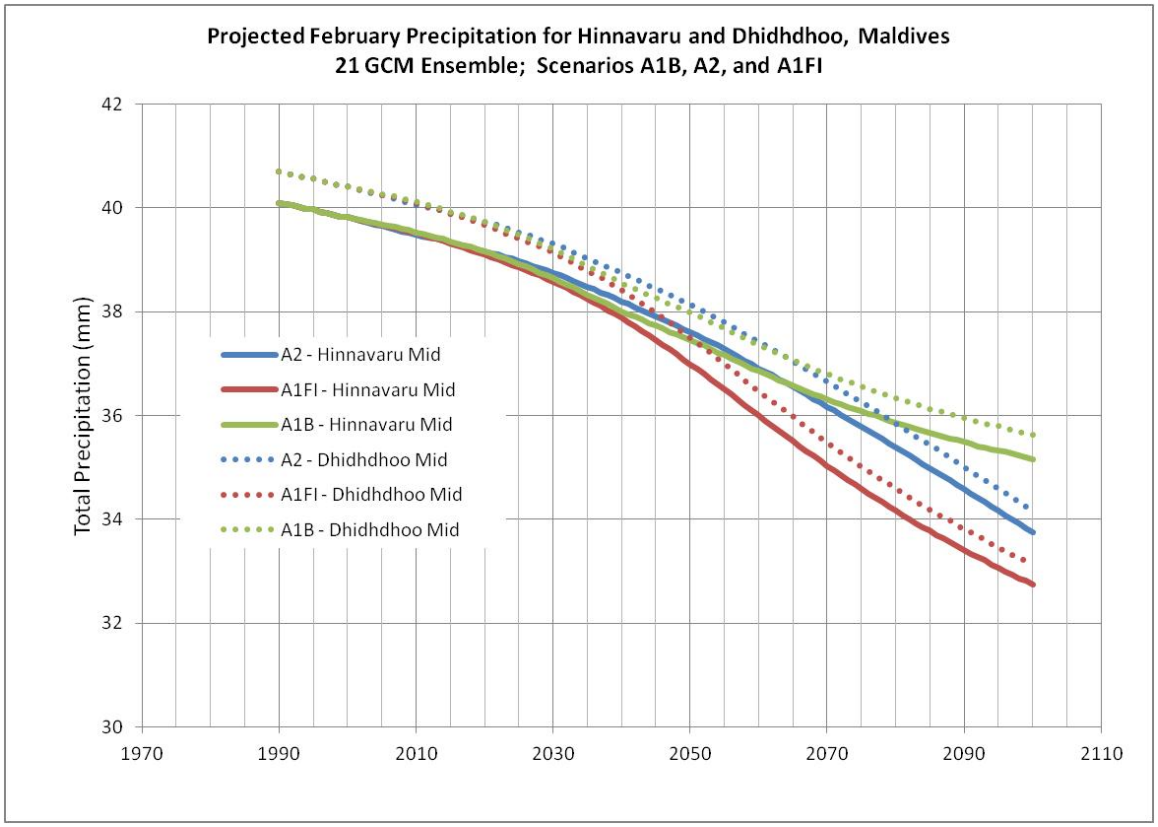


Figure 4-5: Projected February Precipitation for Dhidhdhoo and Hinnavaru, Maldives

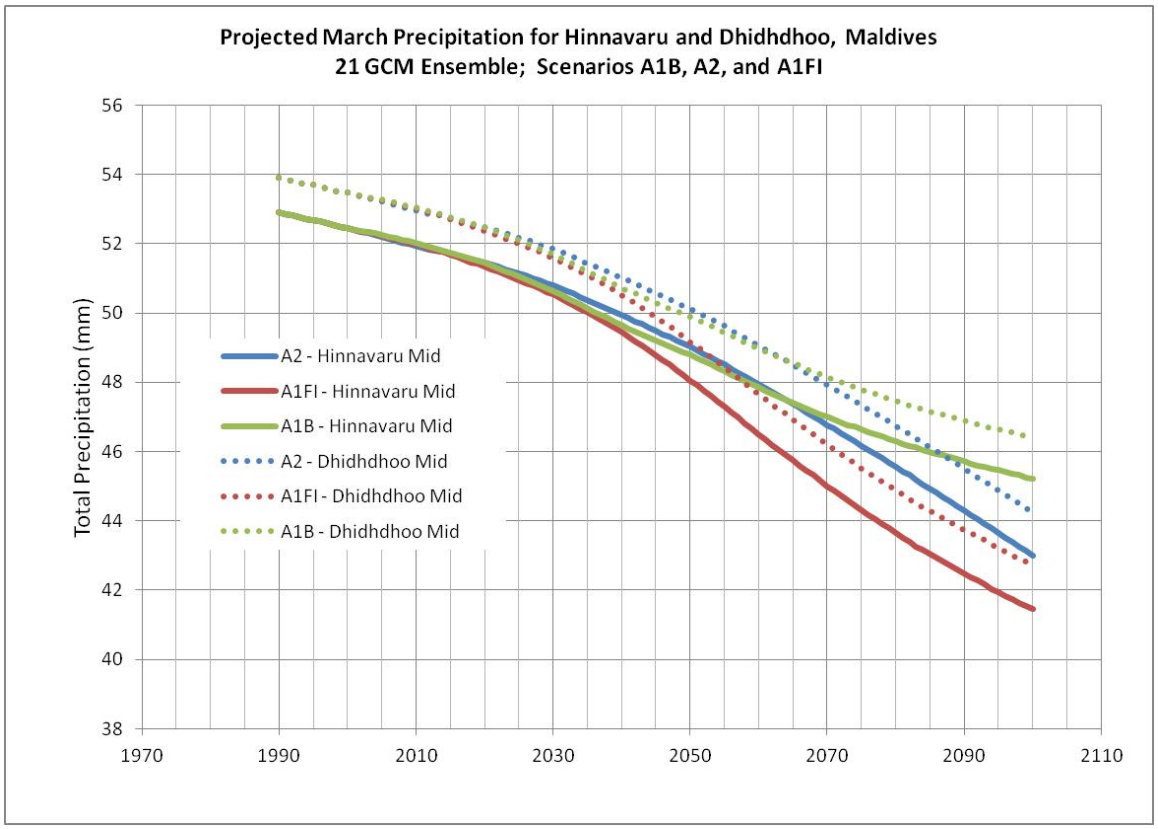


Figure 4-6: Projected March Precipitation for Dhidhdhoo and Hinnavaru, Maldives

4.2.3 Rainwater Harvesting Under Climate Change

The reliability of rainwater harvesting systems can be expressed in terms of the frequency of the tanks being empty in a period of time, such as days that the tank is projected to be empty over a 100 year planning horizon. The SimCLIM tool has a rainwater tank model that allows evaluation of the reliability of rainwater tanks for historical daily precipitation data and projected future daily precipitation data as a function of a number of variables, including (Figure 4-7):

- Tank size
- Rooftop collection area
- Water demand
- Initial storage amount
- Rainfall projection (GCMs and emission scenarios)

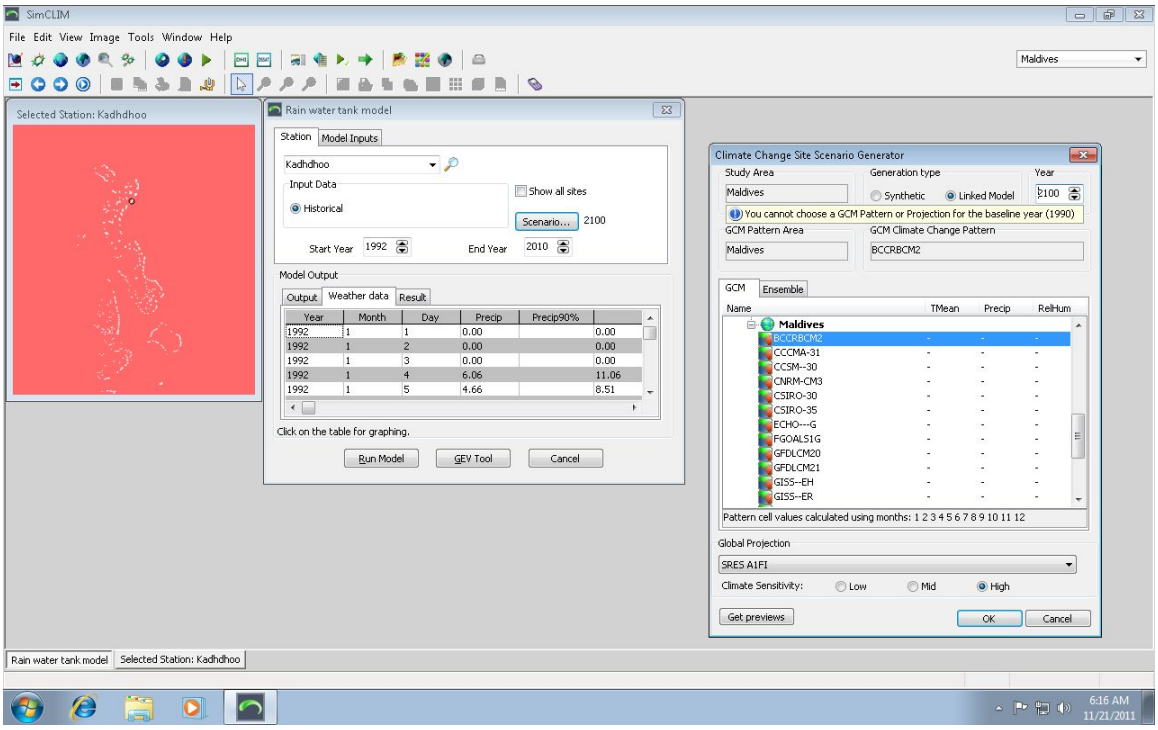


Figure 4-7: SIMClim Rainwater Harvesting Tool

These variables were evaluated for a range of demands, and for two tank sizes (2,500 L and 5,000 L) and two rooftop areas (46.5 m^2 and 8 m^2), which represent the average and low end of the roof areas found in the informal survey of homes conducted in Dhidhdhoo and Hinnavaru. Table 4-1 and Figure 4-8 show these results. From these results, the following conclusions can be drawn.

A 2,500 L tank can reliably meet a demand of about 20 L/day for a household with a 46.5 m^2 contributing area, but that drops down to 15 L/day with a roof area of 8 m^2. Adding a second tank increases the demand that can be met to 40 L/day and 30 L/day.

Projected climate changes barely have any impact on the projected reliability of the rainwater harvesting systems, as far out as 2100 and regardless of GHG scenarios.

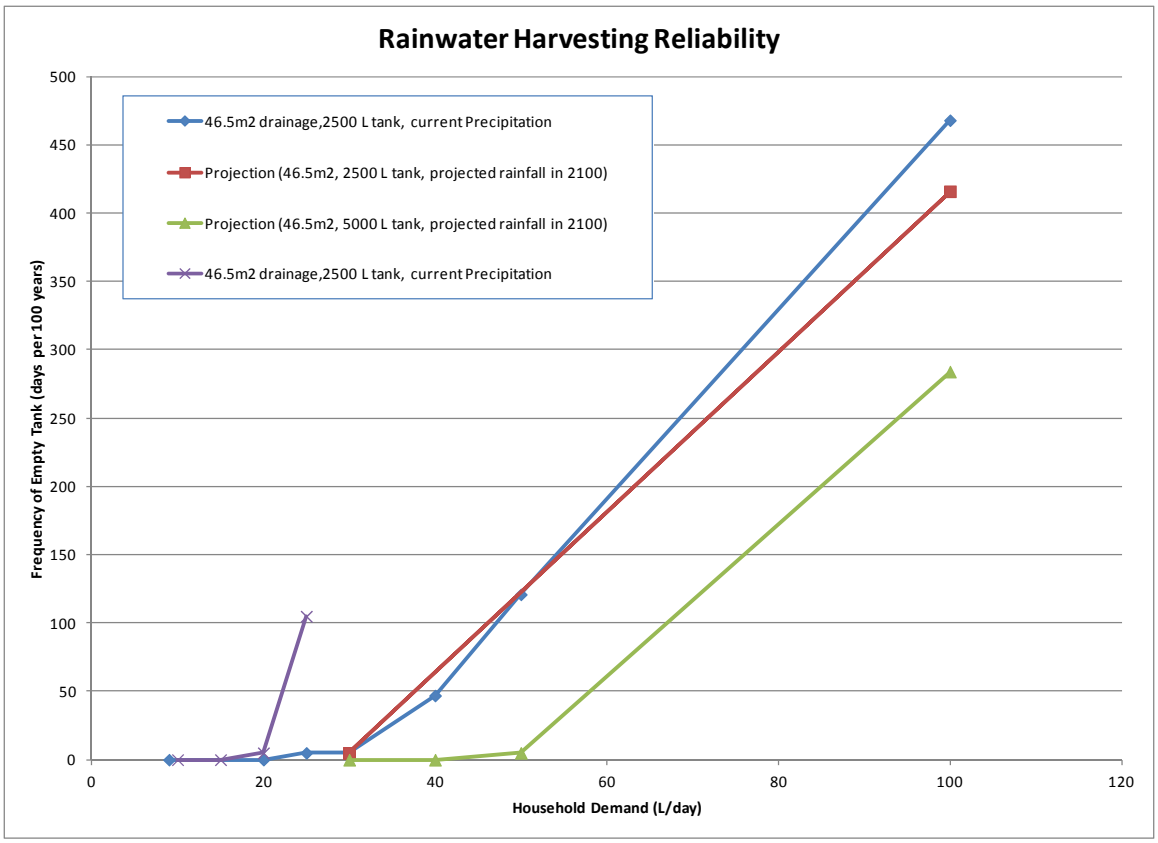


Figure 4-8: Rainwater Harvesting Reliability

Similar to the analysis presented in Table 4-1 for a typical residence, Table 4-2 shows the potential demand that can reliably be met with a large storage tank that could hypothetically be served by large rooftop areas, such as for the school in Dhidhdhoo. The rooftop area of the school was not measured directly, but the area currently served by rainwater harvesting is about 77 m^2, which represents roughly one quarter of the total roof area on one of seven buildings at the school. So analyses were run with a roof area of about 500 m^2 and 2,200 m^2, assuming a larger portion or the entire school roof area could be drained to the potential storage tank. In addition, several simulations were run with larger tanks and drainage areas. From these results, the following conclusions can be drawn. A 500 m^3 storage tank, could reliably meet demands of about 4,400 L/day, assuming a drainage area of 2,200 m^2. A larger drainage area of up to 10,000 m^2 only slightly increases the reliable demand of up to 5,000 L/day. But more storage, coupled with more drainage area, could increase the demand that can be reliably met. For example, a 1,000 m^3 tank, with a 2,200 m^2 drainage can meet a demand of 6,800 L/day, but larger drainage areas of up to 10,000 m^2 could improve the demands met, but not with full reliability.

Table 4-1: SimCLIM Rainwater Harvesting Analysis of Household Collection Potential

Property Type	Period/Climate Ensemble	Storage (L)	Initial Storage (%)	Tolerance Threshold (Days with Empty Tank)	Drainage Area (m^2)	Daily Water Consumption (L/day)	Longest Period of Empty Tank (Days)	Frequency of Empty Tank (days per 100 years)
Typical Residence	Historical (1992-2010)	2,500	100%	1	46.5	9	0	0
Typical Residence	Historical (1992-2010)	2,500	100%	1	46.5	20	0	0
Typical Residence	Historical (1992-2010)	2,500	100%	1	46.5	25	4	5
Typical Residence	Historical (1992-2010)	2,500	100%	1	46.5	30	22	5
Typical Residence	Historical (1992-2010)	2,500	100%	1	46.5	40	44	47
Typical Residence	Historical (1992-2010)	2,500	100%	1	46.5	50	57	121
Typical Residence	Historical (1992-2010)	2,500	100%	1	46.5	100	84	468
Typical Residence	Historical (1992-2010)	2,500	50%	1	46.5	25	54	5
Residence with Small Roof	Historical (1992-2010)	2,500	100%	1	8	10	0	0
Residence with Small Roof	Historical (1992-2010)	2,500	100%	1	8	15	0	0
Residence with Small Roof	Historical (1992-2010)	2,500	100%	1	8	20	6	5
Residence with Small Roof	Historical (1992-2010)	2,500	100%	1	8	25	23	105
Residence with Small Roof	2030, GCM Ensemble, A1B	2,500	100%	1	8	15	0	0
Typical Residence	2030, GCM Ensemble, A1B	2,500	100%	1	46.5	30	22	5
Typical Residence	2050, GCM Ensemble, A1FI (High)	2,500	100%	1	46.5	30	22	5
Typical Residence	2100, GCM Ensemble, A1FI (High)	2,500	100%	1	46.5	30	24	5
Typical Residence	2100, GCM Ensemble, A1FI (High)	2,500	100%	1	46.5	100	84	416
Typical Residence	2100, GCM Ensemble, A2 (High)	2,500	100%	1	46.5	30	23	5
Typical Residence	2100, GCM Ensemble, A1FI (High)	5,000	100%	1	46.5	30	0	0
Typical Residence	2100, GCM Ensemble, A1FI (High)	5,000	100%	1	46.5	40	0	0
Typical Residence	2100, GCM Ensemble, A1FI (High)	5,000	100%	1	46.5	50	8	5
Typical Residence	2100, GCM Ensemble, A1FI (High)	5,000	100%	1	46.5	100	59	284

TABLE 4-2: SimCLIM Rainwater Harvesting Analysis of Large Community Storage Tank Collection Potential

Property Type	Period/Climate Ensemble	Storage (L)	Initial Storage (%)	Tolerance Threshold (Days with Empty Tank)	Drainage Area (m^2)	Daily Water Consumption (L/day)	Longest Period of Empty Tank (Days)	Frequency of Empty Tank (days per 100 years)
School in Dhidhdhoo, Potential Rooftop Area	Historical (1992-2010)	500,000	100%	1	500	1,000	0	0
School in Dhidhdhoo, Potential Rooftop Area	Historical (1992-2010)	500,000	100%	1	500	5,000	104	1563
School in Dhidhdhoo, Potential Rooftop Area	Historical (1992-2010)	500,000	100%	1	500	5,000	104	1563
School in Dhidhdhoo, Potential Rooftop Area	Historical (1992-2010)	500,000	100%	1	2,200	5,000	14	53
School in Dhidhdhoo, Potential Rooftop Area	Historical (1992-2010)	500,000	100%	1	2,200	4,500	3	5
School in Dhidhdhoo, Potential Rooftop Area	Historical (1992-2010)	500,000	100%	1	2,200	4,400	0	0
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	2,500	5,000	10	32
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	2,500	4,000	0	0
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	2,500	4,500	0	0
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	2,500	4,700	2	11
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	3,000	5,000	8	11
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	4,000	5,000	7	5
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	10,000	5,000	4	5
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	2,500	10,000	62	432
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	500,000	100%	1	10,000	10,000	57	111
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	1,000,000	100%	1	10,000	10,000	7	5
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	1,000,000	100%	1	2,200	7,000	4	5
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	1,000,000	100%	1	2,200	6,900	1	5
Demands for Potential Additional Rooftop Area	Historical (1992-2010)	1,000,000	100%	1	2,200	6,800	0	0

SECTION 5
Conclusions and Recommendations

5.1 CONCLUSIONS

Three factors were investigated to assess vulnerability to climate change:

- Sea level rise that affects potential for inundation, coastal erosion, and saltwater intrusion to groundwater aquifers.
- Changes in rainfall that affect the reliability of rainwater harvesting systems.
- Changes in rainfall that affect groundwater recharge.

In the next 20 to 100 years, significant sea level rise is projected, imperiling the islands themselves. In the next 20 years, the sea level is projected to increase above 2010 levels by approximately 110 mm (projected increase ranges from 65 to 115 mm). By 2100, the sea level is projected to increase above 2010 levels by approximately 495 mm (projected increase ranges from 300 to 760 mm). The projected sea level rise will increase shoreline erosion, increase the chances of inundation (particularly in association with storm surges or possible future tsunami events), and increase saltwater intrusion, which will imperil groundwater supply systems.

By the year 2100, the total annual precipitation is projected to increase by 175 to 225 mm. Conversely, average precipitation in the dry months is projected to decrease moderately: by 5 mm in January, 5 mm in February, and 10 mm in March. As a result, the dry season will be more pronounced and the rainwater harvesting systems will be less likely to meet water supply needs through the dry season. Additionally, groundwater recharge will be further reduced during this season, thereby increasing the likelihood of saltwater intrusion. It should be noted, however, that the impacts of these projected changes in rainwater harvesting reliability and saltwater intrusion potential are small compared to challenges Dhidhdhoo and Hinnavaru face in providing reliable rainwater-fed supplies under existing conditions.

Because of the interdependency of the island water management systems and land use decisions, it is important to develop a water management strategy for the whole island that recognizes the linkages between systems, and their dependence on climate and land use decisions. For example, groundwater quality depends on both wastewater management approaches, as well as on recharge from rainwater infiltration, pumping levels, and sea level. Therefore, climate change impacts groundwater quality directly through impacts on recharge and sea level rise. Similarly, wastewater treatment affects groundwater quality if it eliminates sources of contamination from latrines. Finally, the availability of rainwater harvesting as a source of supply varies based on climate uncertainty, which in turn drives the need for improved rainwater harvesting methods and for alternate sources of supply such as desalination.

5.2 RECOMMENDATIONS

1. To address increased risk of inundation and saltwater intrusion due to sea level rise, the following recommendations are offered:

E. Protect critical infrastructure by raising it or otherwise insulating it from inundation; for example, by providing higher platform levels and dikes.

F. Promote vegetated shoreline protection measures, for example by working with the island councils and community groups to plant and maintain vetiver, other hardy grasses or mangrove species, as appropriate to the specific locations These initiatives could be implemented through the project grants program or through voluntary community awareness building activities regarding climate vulnerability and adaptation.

G. Promulgate emergency management and evacuation plans for each island, including training and drills.

H. Promulgate long-term land use plans that factor in sea level rise in conjunction with recent land reclamation efforts on Dhidhdhoo and Hinnavaru (for example, relocation of facilities including housing and critical infrastructure, and controlling total number of residents/households).

2. To address saltwater intrusion threats due to rising sea levels and reduced groundwater recharge, it is recommended that enhanced groundwater recharge measures be adopted, including linking impervious surfaces (rooftops) to below ground recharge wells or infiltration galleries, instead of allowing surface ponding that leads to higher evaporation losses.

3. To address historic sources of groundwater contamination from latrines, promote connection to the collection system, and develop a program to decommission cess pits.

4. To address reduced reliability of rainwater harvesting systems, it is recommended that significant capacity building and institutional strengthening be targeted at increasing the optimal use of existing rainwater harvesting systems to ensure that they are full at the end of the rainy season, and to consider implementation of centralized rainwater harvesting and storage systems for islandwide emergency and routine water supply.

5. To address periodic drought conditions and increasingly unpredictable rainfall patterns, it is recommended that there is improved coordination and planning between the Northern and Upper Northern Utilities, the Hinnavaru and Dhidhdhoo island councils and the Maldives National Disaster Management Centre (NDMC). This improved coordination should have as its objective assuring water security for the target islands while at the same time minimizing costly emergency water transport to the islands in favor of improved integrated water resources management.

These recommendations are further detailed in the Utility Service Delivery Assessment (CH2M HILL, 2012).

ANNEX A
References

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ANNEX B
Meeting Notes

ANNEX C
Rainwater Harvesting and Groundwater Quality Data

Rainwater Harvesting Data for Dhidhdhoo and Hinnavaru

USAID Maldives, Climate Resilience and Water Security

House #	No. of Cisterns (2500 L, unless shown)	Roof Area Length (m)	Roof Area Width (m)	Cistern Drainage Area (m^2)	Depth to Ground-water (m)	Conduc-tivity of Well (uS/cm)*	Salinity of Well (mg/L)*	pH of GW	People in House	Water/Day from Drinking Water Storage (L/day)	Ran out of water during 2010 drought?	Water Quality Concerns?	No. of Toilets (all flushed with GW)	Toilets Connected to Sewerage?	Notes	Consumption Details
Dhidhdhoo Island																
1	2	5	7	35.0	2.75	882				9	Yes		2	1 of 2	3hr diversion for first flush at beginning of rain storm. No water quality issues. Groundwater well pump capacity: 24L/min at 9m head (Dan has photo of faceplate on Hitachi pump)	3x1.5 for cooking, 2 x1.5 for drinking. Water in cistern lasts 6 months, but this year ran out.
2	2	4	2	8.0	1.8	1019	0.5		4	9		Yes, see discussion of crows. Also, GW water quality is poor at end of dry season. Smells and poor taste.	1	No	Did not fill cistern due to crows. Have 2/7 remaining in 1 tank and 1/7 in other, at beginning of dry season. Husband goes on roof to clean.	
3	2	5.35	9.8	52.4	1.8	790	0.38		4						One of two cisterns is 3.5x3m, below floor, and second is on roof of 2nd floor. Half of roof area goes to second downspout, which does not drain to cistern. House had a nice water filter.	
4	2	4.8	13.5	64.8	1.4	450	0.21		5 then 1	4.5	No				Practice first flush diversion for 3 hours at beginning of each storm event.	
Mosque	2	2.75	22	60.5	1.4	500	0.24							NA	Roof area is 22x22, assumed 1/8 goes to cisterns. 3 downspouts per side, only 1 to cistern, but 1 to below ground well that's also cistern. Ablution building roof area: 3 m x 11.5 m.	
5	1	10	4.4	44.0	2.6	613	0.29			30	Yes					
School	7@2500, 1@5000	13.3	5.8	77.1	NA	NA	NA		600	NA	Yes, obtained 30-40 tons.		NA	No, but plan to connect	600 students, grades 1-12. School year is January-November. Only one other school on the island, the preschool, which has 245 students. Only one of 7 buildings on the property has rainwater harvesting. A lot more potential. But principal was concerned about giving up above ground playground space, but suggested that below ground might work, say under a new auditorium that's being considered or a new basketball court.	

Rainwater Harvesting Data for Dhidhdhoo and Hinnavaru

USAID Maldives, Climate Resilience and Water Security

House #	No. of Cisterns (2500 L, unless shown)	Roof Area Length (m)	Roof Area Width (m)	Cistern Drainage Area (m^2)	Depth to Ground-water (m)	Conduc-tivity of Well (uS/cm)*	Salinity of Well (mg/L)*	pH of GW	People in House	Water/Day from Drinking Water Storage (L/day)	Ran out of water during 2010 drought?	Water Quality Concerns?	No. of Toilets (all flushed with GW)	Toilets Connected to Sewerage?	Notes	Consumption Details
Hospital	4@5000, plus 2@5000	4.3	7	30.1	NA	NA	NA		25 beds now, plus 35 in new building	167	Yes.	No. Administrator thought that there were no health issues on the island due to WQ.	NA	Yes	Only rainwater used in the operating theater and labor room. Willing to pay for desal water. Even as high as 5000 MRF for 5000 L (1 MRF/1000 L, though that's 10 times what UNUL said their rate would likely be: 0.1 MRF per 1000 L. Additional roof area available for rainwater harvesting: 7 m x 5 m (35 m^2), plus 5.2 x 6.0 (31.2 m^2). Plus have 5x2500L unused tanks sitting on ground behind the 4x5000L tanks.	4 tanks are empty now, and have 2x5000 tanks in reserve. Don't expect to last through this dry season. Estimate have 2 months stock available. So estimated daily demand is 2*5000/60=167 L/day. But administrator estimates 140000 L for 1 year, for everything.
Average				46.5	2.0	709.0	0.3			43.8						
Max				77.1	2.8	1,019.0	0.5			166.7						
Min				8.0	1.4	450.0	0.2			4.5						
Hinnivaru Island																
School	4 (empty)	8.5	7	59.5	NA	NA	NA		700			Yes (stopped using 4 tanks due to cat in tank)			Don't use installed rainwater harvesting on one roof due to concerns about water quality.	
	3 (full)	5.8	13.5	78.3	NA										Do use these 3 tanks that are elevanted and roof is clear of vegetation. Do water quality testing 2 times/yr with help of health office.	
1	3	9.2	5.8	53.4	1.05	630	0.3	8.27	10		Yes, for 2 months	Don't use their roof due to cement fiber board, but RWH supplied by neighbors roof.	5	Yes		
2	1	8.5	9	76.5	NA	NA	NA	N	5	20	Yes.	See first flush process.	2	Yes	Divert first flush for 2 days of rain, and take rain on 3rd day.	
3	2	8	7	56.0	1.00	812	0.47	8.41	8	NA		Only used for cooking and drinking	4	Yes	Rusty corrugated metal roof.	
4A	2	8	6	48.0	0.70	467	0.67	9.00	6	NA	No	House close to water's edge results in more saline water at end of dry season.	3	Yes	Well is connected to roof to supplement, and improve water quality.	
4B	1	4.4	2.3	10.1												
Average				54.5	0.9	636.3	0.5			20.0						
Max				78.3	1.1	812.0	0.7			20.0						
Min				10.1	0.7	467.0	0.3			20.0						

* Water quality in wells is at end of rainy season. So may not be indicative of end of dry season when overpumping leads to high salinity and lack of flushing of cesspool waste.