



Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected Islands of Maldives



BASELINE ASSESSMENT REPORT

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1 Executive Summary

This is a baseline assessment report for the consultancy services for Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected Islands of Maldives – Lot 03. The project client is Ministry of Environment, Climate Change and Technology and is funded by the Green Climate Fund (GCF). This report will present the main findings from the baseline groundwater assessment for 06 islands.

This project is undertaken with the distinct objectives to undertake baseline assessment to establish the status of the groundwater system and associated catchment characterization, feasibility study and concept design of managed aquifer recharge (MAR) systems for the islands with a specific emphasis on flood water management and detail design of MAR systems.

The methodology followed in the Baseline Assessment is given in Section 4. The following field surveys and tests were conducted to produce a baseline assessment for each island:

- Topographical Survey
- Social Survey
- Water Quality Survey
- Pumping Test
- Permeability Test
- Soil Profile Survey
- Geophysical Survey

The data obtained from these surveys were used to conduct Soil Water Balance (SWB) modelling and Saturated-unsaturated Transport (SUTRA) modelling to estimate current extraction rate and safe yield.

Topography

Given that previous assessments and projects for groundwater baselines did not state the benchmarks and therefore did not offer reproducibility, efforts were made to include the benchmarks used for each island. Most details are not available on the Maldives Land and Survey website.

Digital Surface Models (DSM) were presented and further processing by removing vegetation, human made objects and buildings were used to produce Digital Terrain models (DTM). GPS spot heights were used to check and validate the accuracy of DTMs. Errors were in a generally acceptable range and no bias correction was carried out. Profiles from the DTM were then used to study the terrain of the islands

Most of the lot 3 islands are relatively low-lying islands, with average elevation roughly 1.15 m above mean sea level.

The following table summarizes the main findings of the topography sections for the islands

Table 1: Lot 3 island topography summary

Island	Average Elevation (m)	Atoll Location	Mean DTM Error (cm)	Shoreline Length (m)
GA. Maamendhoo	1.41	East	-5.18	4342
GA. Nilandhoo	1.17	East	-4.38	4639
GDh. Hoandehdhoo	1.132	Southwest	-4.91	7798
GDh. Nadella	1.132	Southwest	+3.46	3369
GDh. Rathafandhoo	0.899	Southwest	+4.37	3134
GDh. Faresmaathoda	1.16	Southwest	+2.11	5180

The Topographical Survey's detailed methodology is presented in Section 4.2 and the results are presented in Sections 5.2, 6.2, ..., 11.2 for the six islands.

Social Survey

In the social survey component, groundwater usage in households, tourism, agriculture, fisheries, and other economic sectors of the islands were collected through quantitative structured questionnaire. The main purpose of the survey was to quantify groundwater usage across the island and to collect flooding information.

The water consumption on the islands can be summarized as follows:

Table 2: Water Consumption Summary Table

Total island wide daily water consumption (m³)							
Island	Population		Domestic	Commercial	Institutional	Industrial	Total
	Number	Density					
GA. Maamendhoo	1554	31.5	387	4.70	5.72	5.16	403
GA. Nilandhoo	1127	19.6	325	1.47	3.57	91.1	421
GDh. Hoandehdhoo	1317	12.4	315	1.85	3.17	45.0	365
GDh. Nadella	1131	25.9	304	0.046	4.00	-	308
GDh. Rathafandhoo	1382	38.3	406	0.90	3.19	0.43	411
GDh. Faresmaathoda	1849	39	457	1.22	4.83	0.714	463

Domestic water consumption ranges from 239 to 294 LPCD. As the groundwater consumption is very high on these islands, it is recommended to conduct awareness programs to encourage and educate people about the role of the freshwater lens and to reduce their water consumption.

The Social Survey's detailed methodology is presented in Section 4.3 and results are presented in Sections 5.3, 6.3, ..., 11.3 for the six islands.

Water Quality

Water Quality points were taken from 40 different sampling locations on all islands. The table below shows the mean values for all the parameters tested for in all islands. In terms of physiochemical parameters, the water quality of all islands was classified as very good.

Table 3: Water Quality (Physiochemical) Summary Table

	EC ($\mu\text{S}/\text{cm}$)	Turbidity (FNU)	DO (mg/L)	pH	Temp ($^{\circ}\text{C}$)	Sal (ppt)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
GA. Maamendhoo	1060	1.49	3.56	7.44	29.42	0.48	4.06	22.48	0.30
GA. Nilandhoo	874	1.18	3.82	7.53	29.04	0.40	2.90	13.29	0.26
GDh. Hoandehdhoo	775	2.30	3.72	7.32	28.79	0.35	2.49	7.39	0.36
GDh. Nadella	825	0.98	4.23	7.45	28.15	0.38	3.50	16.70	0.48
GDh. Rathafandhoo	1004	1.38	4.50	7.47	28.41	0.66	2.65	6.88	0.40
GDh. Faresmaathoda	1381	1.46	3.62	7.53	28.75	0.65	2.80	9.96	0.29

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH₃= Ammonia, NO₃⁻= Nitrate, PO₄³⁻=Phosphate

Geographic Information Systems (GIS) and Surfer software were used to plot spatial distribution of all parameters for further water quality analysis. Generally, it was found that the Electrical Conductivity of groundwater is higher near the coast of the island and lower in the centre of the island. This co-relates to the findings of the geophysical survey which indicates that the freshwater lens is generally thicker in the centre of all islands. Nitrate concentrations are generally higher in farming areas. Phosphate concentrations in groundwater are generally higher in densely populated areas. No spatial trends were found in the Turbidity, Dissolved Oxygen, pH, Ammonia, and temperature readings.

Correlation matrices between the different parameters were calculated. Water Quality Index (WQI) was calculated for all sampling locations and classified into categories. For all islands in this study, the mean WQI was in the category "Very Good".

Microbiological Samples were taken from 15 different sampling locations on all islands. Widespread microbiological contamination was observed across all islands resulting from effluent leakage from septic tanks and local outfall pipes. Results are shown below.

Table 4: Water Quality (Microbiological) Summary Table

	Total Coliform (MPN/100mL)		Faecal Coliform (MPN/100mL)	
GA. Maamendhoo	898	15/15	25	10/15
GA. Nilandhoo	1795	15/15	763	15/15
GDh. Hoandehdhoo	673	15/15	2	9/15
GDh. Nadella	210	14/15	5	6/15
GDh. Rathafandhoo	718	15/15	172	12/15
GDh. Faresmaathoda	1451	15/15	174	4/15

The construction of gravity sewerage systems is either underway or has been planned for all islands which upon commissioning is expected to prevent microbiological contamination provided that the existing septic tanks and outfall pipes are decommissioned according to standard.

The Water Quality Survey methodology is presented in Section 4.4 and results are presented in Sections 5.4, 6.4, ..., 11.4 for the six islands.

Pumping Test, Permeability Test and Soil Profile

Pumping tests were carried out to obtain the properties of the aquifer such as the Transmissivity and Storativity. 1 pumping test was carried out in each of the 6 islands. The average value of Aquifer Transmissivity is 40.7 m²/day, with values ranging from 13.86 m²/day to 405.5 m²/day. The average value of Aquifer Storativity is 0.16, with values ranging from 0.008 to 0.2191.

The Pumping Test's detailed methodology is presented in Section 4.5 and results are presented in Sections 5.5, 6.5, ..., 11.5 for the six islands.

Permeability is a measure of the rate of the flow of water through the soil and estimating the rate is important to develop conservation strategies and aquifer management plans. 5 permeability tests were carried out in each of the 6 islands. The average Permeability value for Lot 03 islands is 21.466 m/day, with values ranging from 0.952 m/day to 113.8 m/day (Figure 1). These permeability values are consistent with the range of permeability values typically obtained for sands (Robertson (2010)) and it was observed that the islands' soil profiles were predominantly sands, thus confirming the obtained values are in the expected range.

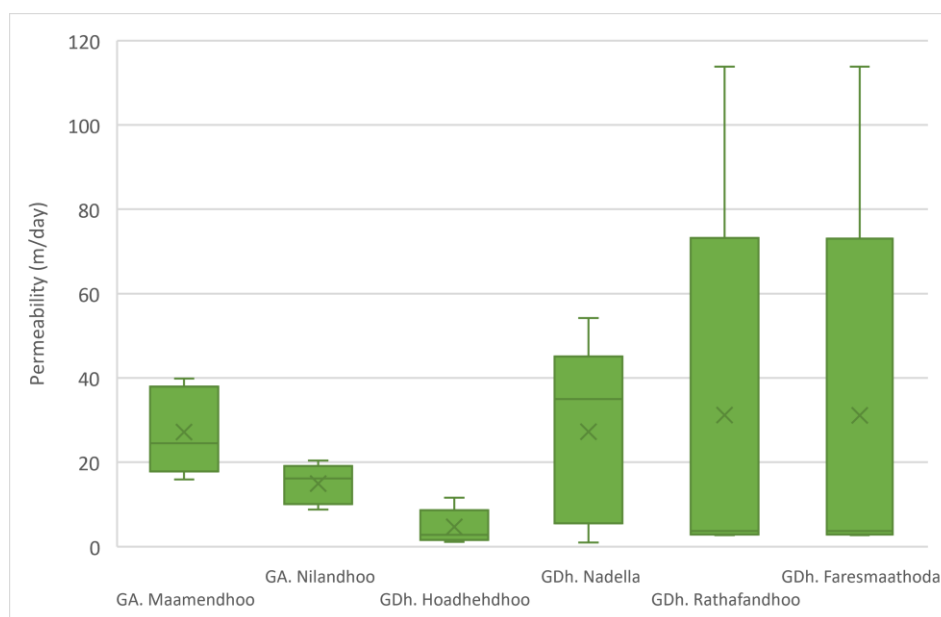


Figure 1: Permeability values across project islands

The Permeability Test's detailed methodology is presented in Section 4.5 and results are presented in Sections 5.6, 6.6, ..., 11.6 for the six islands.

The soil profiles of the islands help further the understanding of the aquifers. Hence, the soil profiles of the islands were obtained by drilling boreholes at 7 locations of each island and taking samples of the different soil layers to identify the soil type and colour. The island soil profiles were observed to be predominantly Uniformly Graded Sands, with variances in colour.

The Soil Profile's detailed methodology is presented in Section 4.7 and results are presented in Sections 5.7, 6.7, ..., 11.7 for the six islands.

Flood Assessment

For the flood assessment survey, perceived flood impacts in the selected islands were surveyed upon individual and community social characteristics with their experiences on significant historical flooding events and recent flooding events. The data sets available in this survey is a combination of local information collected through social survey and secondary rainfall data from Kaadehdhoo weather station.

As per collected information, flood inundation mainly takes place at road stretches and at a few low-lying areas. Table 5 below summaries flood frequency, inundation extent and inundation depth.

Table 5: Flood occurrence and inundation details

Island	Flood Frequency (Annual events)	Avg. depth (m)	Avg. Area (ha)	Avg. Duration (hr)
GDh. Faresmaathoda	34	0.238	1.4	2-4 hr
GDh. Hoandehdhoo	28	0.207	2.7	2-4 hr
GA. Maamendhoo	89	0.305	0.7	2-4 hr
GDh. Nadella	63	0.314	1.1	2-4 hr
GA. Nilandhoo	28	0.167	0.7	2-4 hr
GDh. Rathafandhoo	50	0.229	1.1	2-4 hr

A common feature in all six project islands is absence of storm water drainage system which helps part of inundated water on roads and low-lying areas to infiltrate into ground. Therefore, when there is heavy rain or flooding part of storm water is being drained to sea through natural drainage ditches on the ground while the other part is stagnated or roads and low-lying areas. This stagnated water is later released to atmosphere or sea, infiltration into ground and sub-surface flow during low tide.

Use of stormwater to recharge freshwater aquifer has been considered via MAR designs like infiltration pit, infiltration trench, and infiltration basin and they are to be further studied during feasibility study of the project.

The flood assessment detailed methodology is presented in Section 4.8 and results are presented in Sections 5.8, 6.8, ..., 11.8 for the six islands.

Geo-physical Survey and Assessment

Geo-physical investigations using Electrical Resistivity (ER) method was carried out to measure approximate depth to groundwater table and freshwater-saline water interface at number of locations and they were used to identify the spatial extent of freshwater lens and to estimate volumetric quantity of the same. Tools available in ArcGIS and QGIS were used to develop contours of freshwater top level and bottom level (saline water level) and they were also used to develop a 3-dimensional view of freshwater-saline mixing surface. The comparison of these contours with EC (Electrical Conductivity) measurements show that EC values are less and within potable water range in islands where average freshwater lens thickness is high. Also, from this comparison it was identified that EC values are inversely related with freshwater lens thickness (lesser EC value with higher thickness and vice versa).

For estimation of freshwater lens volume at the time of taking ER measurement, two methods were used; one is "Triangle method" and the other one is use of a set of tools in ArcGIS. In the former method, a triangular mesh was basically established by connecting all ER survey locations and few dummy locations which were placed near shoreline where freshwater layer thickness becomes zero. Freshwater lens volume estimated at project islands and average thickness of freshwater lens are summarized below.

Table 6: Freshwater Lens (FWL) Volume and aquifer stress level summary

Island Name	GDh. Faresmaathoda	GDh. Hoandehdhoo	GA. Maamendhoo	GDh. Nadella	GA. Nilandhoo	GDh. Rathafandhoo
Area (ha)	45	108	51.7	45.4	58.2	38.4
Avg. thickness of FWL (m)	1.11	1.33	2.19	1.31	3.70	1.09
Max thickness of FWL (m)	2.0	2.8	4.5	2.0	7.8	2.0
FW volume (m ³) – Triangle method	75,539	183,811	164,370	89,483	311,426	71,541
FW volume (m ³) – ArcGIS	75,625	195,722	169,196	94,109	314,472	70,419
Aquifer stress level	Highly stressed	Slightly Stressed	Slightly stressed	Highly stressed	Not stressed	Highly stressed

A relationship was built between freshwater lens volume and ground water withdrawal amount and it was found that the freshwater aquifer is already highly stressed in some islands whereas some are not stressed at the existing condition. Aquifer stress levels are indicated in the above table.

ER survey results were also used to adjust SUTRA model parameters and predict the salt-water concentration contours that represent site condition and observations of the project islands.

The Geo-physical Survey and Assessment detailed methodology is presented in Section 4.9 and results are presented in Sections 5.9, 6.9, ..., 11.9 for the six islands.

Soil Water Balance (SWB) Modelling

- Soil Water Balance (SWB) modelling was carried out by defining the project islands using 20m x 20m grids and assigning climate data, flow direction, land use data soil type, and soil water storage capacities. SWB model was run on daily time step for 20 years period starting from Jan 2001 to Dec 2019 and model results were used to check water balance on annual basis and extract recharge values on land use wise.
- Annual recharge estimated by the SWB model ranges from 272 mm/yr to 352.8 mm/yr and they are summarized below.

Table 7: Annual recharge for project islands

Island Name	Annual Rainfall (mm)	Annual Recharge (mm)	Recharge/Rainfall (%)
GDh. Faresmaathoda	2270	311.7	13.0
GDh. Hoandehdhoo	2270	366.5	15.4
GA. Maamendhoo	2270	364.2	16.0
GDh. Nadella	2270	351.6	15.5
GA. Nilandhoo	2270	413.6	15.4
GDh. Rathafandhoo	2270	272.0	12.0

- The reliability of model estimated recharge rates and evapotranspiration values were cross-checked with information from different literatures and found to be reasonable and acceptable.
- Plot of estimated recharge Vs residential & commercial area percentage shows that recharge amount is exponentially reducing with increase of paved areas.

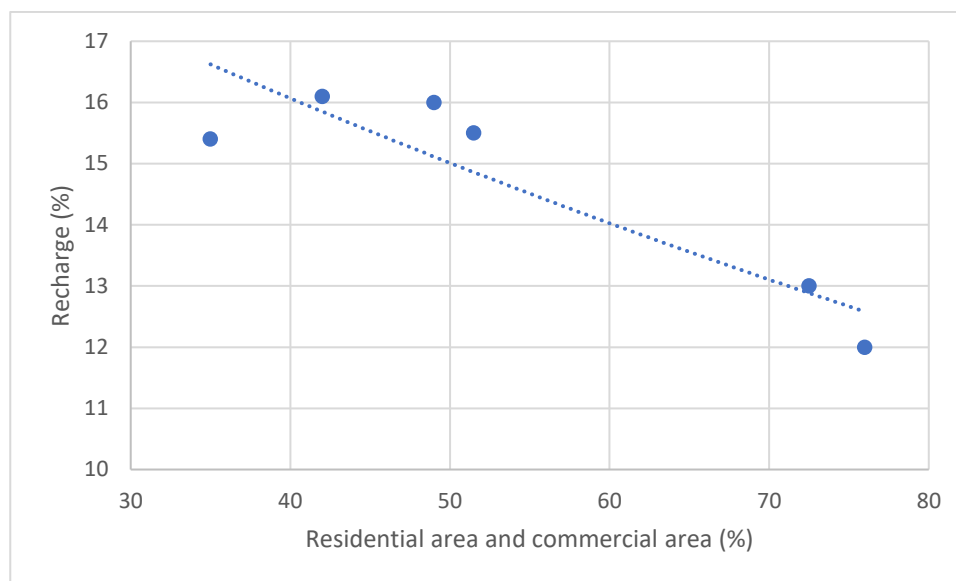


Figure 2: Recharge Vs Residential and commercial area

- Comparison of estimated monthly recharge and monthly pumping quantity over 20 years period reveals that percentage of months where pumping exceeds recharge rate is 32.1% in GDh. Hoandehdhoo island (lowest) and 67.9% in GDh. Faresmaathoda island (highest). These deficit amounts are being compensated from ground water storage.

Table 8: Pumping deficit for project islands

Island Name	Percentage of months with pumping exceedance of recharge (%)
GDh. Faresmaathoda	67.9%
GDh. Hoandehdhoo	32.1%
GA. Maamendhoo	56.3%
GDh. Nadella	52.9%
GA. Nilandhoo	43.8%
GDh. Rathafandhoo	72.5%

- Annual safe yields were computed and compared with annual ground abstraction amount and found that withdrawal amount exceeds safe yield in four islands.

Table 9: Safe yield and pumping quantity for project islands

Island Name	Safe yield (m ³ /yr)	Pumping (m ³ /yr)	Pumping exceedance of safe yield (%)	Impacts on freshwater lens due to pumping
GA. Maamendhoo	65,659	141,235	115%	High
GA. Nilandhoo	73,914	118,470	60%	Slightly high
GDh. Hoandehdhoo	137,160	114,888	-16%	No impact
GDh. Nadella	57,658	111,047	93%	High
GDh. Rathafandhoo	48,768	148,302	204%	Very High
GDh. Faresmaathoda	57,150	166,697	192%	Very High

The SWB Modelling detailed methodology is presented in Section 4.10 and results are presented in Sections 5.10, 6.10, ..., 11.10 for the six islands.

Saturated-unsaturated Transport (SUTRA) Modelling

- Saturated-unsaturated Transport (SUTRA) model has been used to predict saltwater intrusion into the island from sea and this model was set up by defining the island geological features into 3 zones or layers: Unsaturated zone, Holocene and Pleistocene.
- Average monthly recharges estimated by SWB model were extracted and assigned to SUTRA model as source/supply data and the existing pumping rate for non-potable use was another sink data. Hydrogeological parameters for this model were extracted from literatures and they were further adjusted during model simulation to predict the reasonable saltwater concentration that was matching with field observations.

Island	Recharge (mm/month)							Pumping (m ³ /month)
	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture	
GDh. Faresmaathoda	48.1	9.1	38.9	20.9	38.6	43.6	0	13,891
GDh. Hoandehdhoo	70.5	18.5	77.3	60.7	71.7	47.6	78	9,574
GA. Maamendhoo	41.4	6.7	32.6	26.8	33.8	0	35.4	11,770
GDh. Nadella	41	33.9	8.5	32.1	37.4	5.4	0	9,254
GA. Nilandhoo	35.3	5.9	6.9	27	32.4	6.9	27.8	9,873
GDh. Rathafandhoo	43.9	7.1	35.9	19.5	45.9	38.5	0	12,359

- Saltwater intrusion pattern and concentration contours were predicted for all six project islands by simulating the model for 20 years period on monthly time step in the existing condition. Potable water is represented by model concentration of 0.001 or lesser and it is equal to 1g/litter salt. Figure 3 highlights the aforementioned details.

Concentration contours in Figure 3 show that freshwater lens is fairly deep in GA. Nilandhoo and GDh. Hoandehdhoo islands, it is shallow in GA. Maamendhoo and GDh. Nadella islands and it is very shallow in GDh. Rathafandhoo and GDh. Faresmaathoda islands on long term period in the

baseline condition. Since SUTRA model predictions are reasonable and matching with site observations this model can be used later to identify benefits of introducing MAR design.

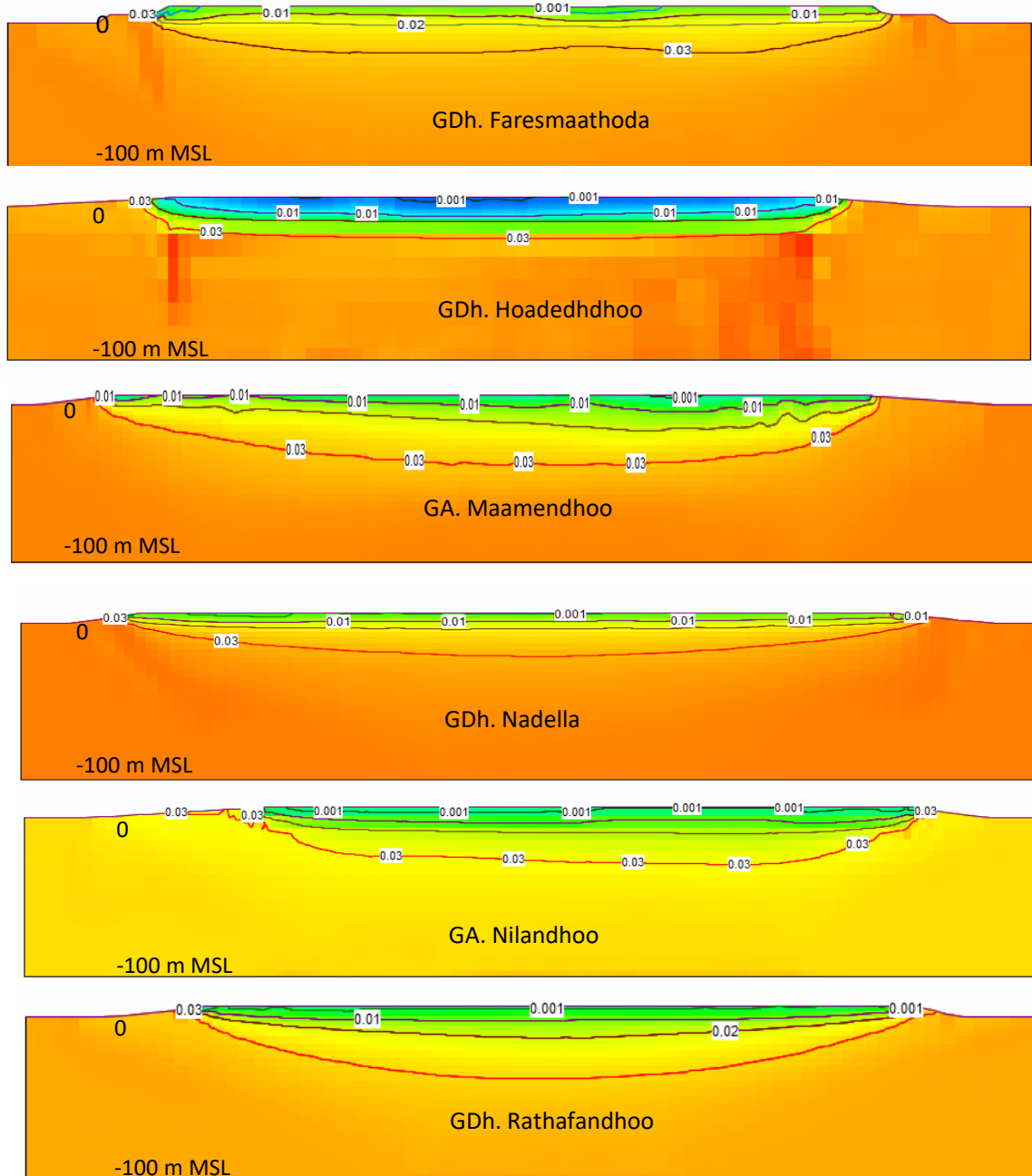


Figure 3: Salt concentration contours predicted by SUTRA Model form 20 yr simulation

The SUTRA Modelling detailed methodology is presented in Section 4.11 and results are presented in Sections 5.11, 6.11, ..., 11.11 for the six islands.

Island	Maamendhoo	Nilandhoo	Faresmaathoda	Rathafandhoo	Nadella	Hoandedhdhoo
Atoll	Gaafu Alifu	Gaafu Alifu	Gaafu Dhaalu	Gaafu Dhaalu	Gaafu Dhaalu	Gaafu Dhaalu
Shape of the island						
General Overview of Island and Demography						
Area (Ha)	52	58	45	38	45	108
Length (m)	1400	1540	1070	870	880	1650
Width (m)	510	550	790	560	560	1120
Population	1554	1127	1849	1382	1131	1317
Pop. density (per /hectar)	31.5	19.6	39	38.3	25.9	12.4
Land cover and Built-up Area (As a percentage of total land area)						
Roof area (%)	13%	8%	13%	11%	8%	7%
Thick Vegetation (%)	36%	39%	19%	22%	22%	34%
Thin Vegetation (%)	30%	20%	42%	52%	33%	38%
Bare lands (%)	20%	15%	26%	15%	34%	9%
Farmlands (%)	1%	18%	-	-	-	8%
Wetlands (%)	-	-	1%	1%	2%	3%
Socio-economic Condition						
Overview	Fast developing island nearby airport with developing guesthouse industry	Large scale farming island with 9.75 hectares dedicated for farming	Two separate islands joined by reclamation; airport being developed adjacent to island	Slow developing island with large percentage of vegetated area	Slow developing island with wetland	8 hectares dedicated for farming and 15 hectares commercially leased for fish processing.
Number of restaurants	4	2	1	2	1	3
No. of Guesthouses	4	1	1	-	-	1
Present Sanitation and Water-use Characteristics						
Presence of Sewer Network	None	None	None	None	None	None
Presence of Water Supply	None	None	None	None	None	None
Households with RW tanks	93%	90%	94%	93%	90%	97%
Rainwater use for drinking	67%	87%	65%	84%	76%	76%
Groundwater non-potable use	100%	100%	100%	100%	100%	100%
RW Storage Capacity (m³)	840	316	595	474	446	595
Water Quality Aspects (Selected Parameters; please refer to respective chapters for other details and data)						
WQI	9.43 ±5.55	6.75 ± 5.29	8.22 ± 5.89	7.58 ± 8.82	7.12 ± 3.89	5.71 ± 3.68
Elect. Conductivity (µS/cm)	1,060 ± 662	874 ± 780	1,381 ± 1,283	1,376 ± 1,816	1,349 ± 1,105	775 ± 252
Ammonia (mg/L)	4.06 ± 7.99	2.90 ± 4.74	2.80 ± 3.45	2.65 ± 4.90	4.96 ± 7.73	2.49 ± 3.68
Faecal Cont	Yes	Yes	Yes	Yes	Yes	Yes
Groundwater Availability, Usage, Water Balance and Recharge Potential						
Freshwater Lens Volume (m³) & Thickness (m)	169,196 m³ & 2.19 m	314,472 m³ & 3.70 m	75,625 m³ & 1.11 m	70,419 m³ & 1.09 m	94,109 m³ & 1.31 m	195,722 m³ & 1.33 m
Rainwater Harvesting (m³)	10,200	7,500	12,500	9,500	7,600	9,000
Groundwater Extraction (m³/yr)	141,235	118,470	166,697	148,302	111,047	114,888
Safe Yield (m³/year)	65,659	73,914	57,150	48,768	57,658	137,160
Usage / Safe Yield (%)	115%	60%	192%	204%	93%	-16%
Present Aquifer Condition	Slightly stressed	Not stressed	Highly stressed	Highly stressed	Highly stressed	Slightly Stressed
Priority for GW Improvement	4	6	1	2	3	5

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List of Abbreviations

AHP	Analytical Hierarchical Process
ADB	Asian Development Bank
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
CIRIA	Construction Industry Research and Information Association
CN	Curve Number
DCP	Dynamic cone penetrometer
DEM	Digital Elevation Models
DO	Dissolved Oxygen
DSM	Digital Surface model
DTM	Digital Terrain model
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EM	Electro-Magnetics
EPA	Environmental Protection Agency
ER	Electrical Resistivity
ERT	Electrical resistivity tomography
EWRI	Environmental & Water Resources Institute
GCF	Green Climate Fund
GCP	Ground Control Points
GDP	Gross Domestic Product
GIS	Geographical Information Systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IFD	Intensity frequency and Duration
LPCD	Litres per capita per day
LPM	Litres per minute
MAR	Managed Aquifer Recharge
MLSA	Maldives Land and Survey Authority
MSL	Mean Sea Level
MTCC	Maldives Transport and Contracting Company
MWSC	Male' Water & Sewerage Company
NBS	National bureau of Statistics
PPK	Post-Processed Kinematic
QA	Quality Assurance
QC	Quality Control
RTK	Real-time kinematic
SuDs	Sustainable Drainage Systems

SUTRA	Saturated-Unsaturated Transport
SWB	Soil Water Balance
TOR	Terms of Reference
UAV	Unmanned Aerial Vehicle
UNDP	United Nations Development Program
URA	Utility Regulatory Authority
USGS	United States Geological Survey
VES	Vertical Electrical Sounding
WHO	World Health Organisation
WQI	Water Quality Index

2 Introduction

2.1 About the project, client, consultancy Kick-off and status

This is a baseline assessment report for the consultancy services for Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected Islands of Maldives – Lot 03. The project client is Ministry of Environment, Climate Change and Technology and is funded by the Green Climate Fund (GCF). This report will present the main findings from the baseline groundwater assessment for 06 islands.

2.2 Background

The Republic of Maldives is a low lying, atoll based, archipelagic nation in the central Indian Ocean. It comprises 1,190 islands grouped into 26 atolls that together occupy a land area of 298 km² and form a chain over 820 km in length, spread over an area of around 90,000 sq. km. With a total population of 341,256, it is the smallest Asian country in terms of area and population. The country has an average elevation of 1 meter above sea- level. The two most important sectors of the economy are tourism and fisheries which contribute nearly 80% of the country's Gross Domestic Product (GDP). Maldives is among the most susceptible and vulnerable to climate change.

The outer islands of the Maldives experiences drinking water shortages during the dry season. These shortages have had significant adverse human, environmental and social impacts on the outer islands. The key problems pertaining to freshwater security relate to the increasingly variable rainfall patterns induced by climate change and sea-level rise induced salinity of groundwater. The Government faces constraints in responding to the challenge at hand without assistance, especially in the context of anticipated impacts of climate change.

In response to this climate challenge, the 5-year Green Climate Fund (GCF) funded project targeting 'Supporting Vulnerable Communities in Maldives to Manage Climate Change-Induced Water Shortages' was launched by the Government of Maldives in the year 2015. The accredited entity for the project is the United Nations Development Programme (UNDP) and the implementer is the Ministry of Environment, Climate Change and Technology. The project has the objective to deliver safe and secure freshwater to 105,000 people in the islands of Maldives in the face of climate change risks. This will be achieved by delivering the following results:

- a. Scaling up integrated water supply system to provide safe water to vulnerable households (at least 32,000 people, including 15,000 women);
- b. Decentralized and cost-effective dry season water supply system introduced benefiting 73,000 people across 7 Northern Atolls.
- c. Groundwater quality improved to secure freshwater reserves for long term resilience on 49 islands.

The freshwater lens underlying each island in the Maldives has historically been the most important water source for the islands. Better understandings of freshwater lens, its protection and proper

This assignment is with 3 distinct objectives and they are as follows.

- Undertake baseline assessment to establish the current status of the groundwater system and associated catchment characterization
- Feasibility study and concept design of managed aquifer recharge (MAR) systems for the islands with a specific emphasis on flood water management
- Detail design of MAR systems.

The location of the project islands is shown in Figure 4.

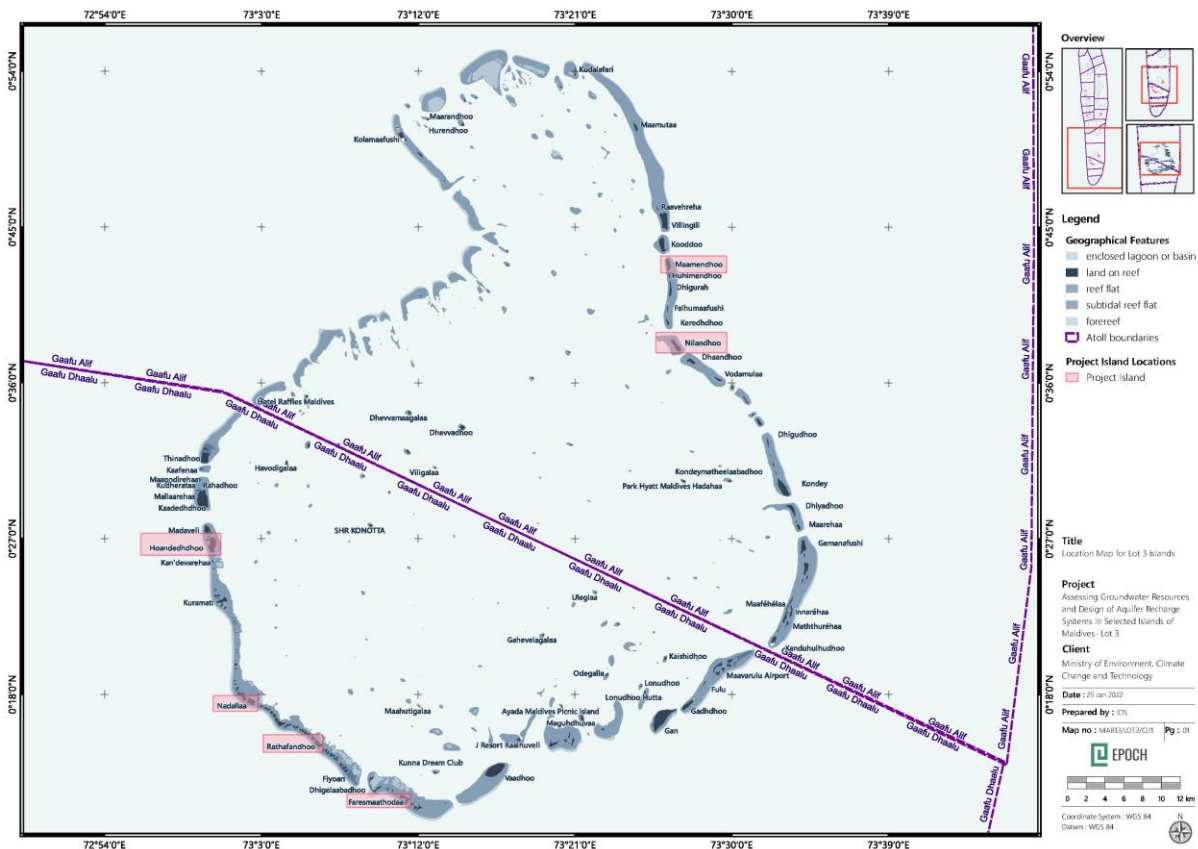


Figure 4: Project Island Locations

2.2.1 General Environment and hydro-metrological aspects of the proposed islands

The general climate of the Maldives is characterized as tropical monsoon climate with two distinctive monsoon seasons. The Southwest (SW) monsoon is regarded as the dry season which extends from May to November while the wet-season or the Northeast monsoon extends from January to March. In both seasons, the temperature varies only slightly despite the considerable differences in rainfall.

2.2.1.1 Temperature

Daily temperature varies slightly during both the monsoons. The annual mean is 28°C and the daily temperatures can fluctuate between 31°C in daytime and 23°C at night. The daily maximum temperature for the central region is 31.5°C while the minimum temperature is recorded as 26.7°C for the central region in 2019. The highest temperature recorded in Maldives was on 19th May 1991 recorded at Kadhdhoo Meteorological office at 36.8°C. The lowest temperature recorded was on 11th April 1978 recorded at the National Meteorological Center at 17.2°C. The Figure 5 below shows the yearly average of daily maximum and minimum temperature for the year 2019 across various regions of the Maldives

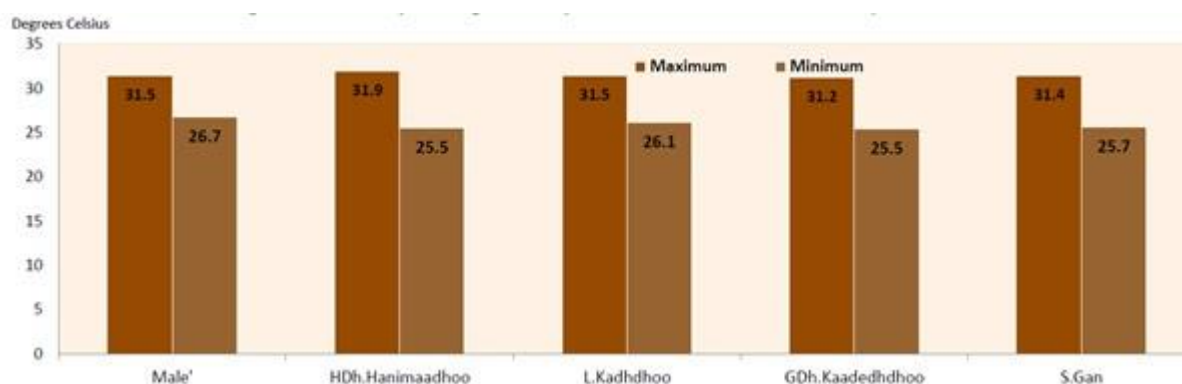


Figure 5: Yearly average of daily maximum and minimum temperature, 2019 (Source: NBS, 2020)

Observations of the monthly data indicate that the daily temperature is highest during March to May, where the peak is during April as evident for 2019 records in Figure 6. There is a very small fluctuation in the maximum and minimum temperatures throughout the year.

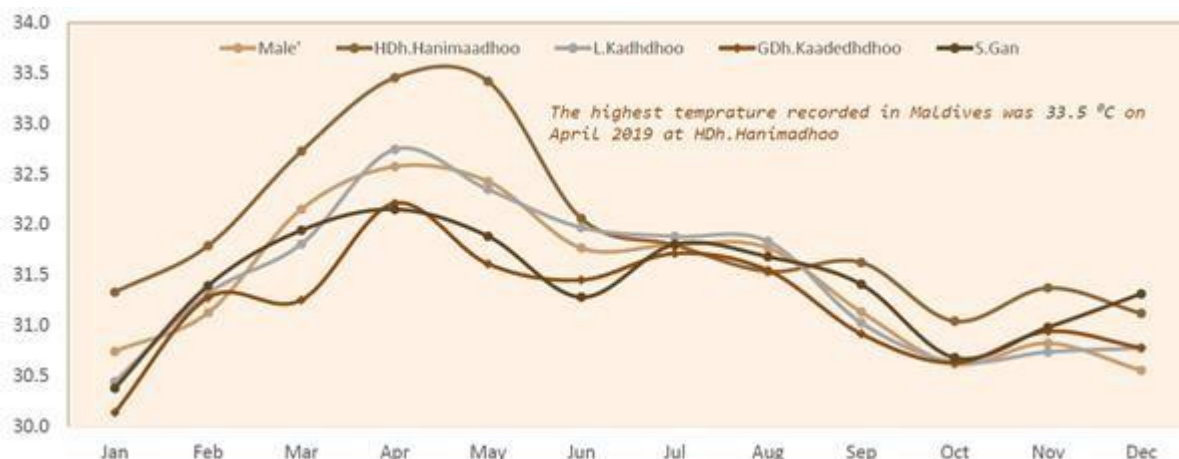


Figure 6: Monthly maximum daily temperature by locality (Source: NBS 2020)

2.2.1.2 Rainfall

During the South-West monsoon, from mid-May to December, heavy rainfall is experienced (between 200mm and 250mm of rainfall) in all atolls. The highest rainfall ever recorded during a 24-hour period was on 9th July 2002 at Kaadedhdhoo Meteorological office, which was 219.8 mm of rainfall. Lowest rainfall is between February and March, where rainfall is between 25mm and 80mm.

There is a considerable difference in the rainfall pattern between the North and the rest of Maldives during May to July and October to December. In the North, rainfall is higher during May to July at 250mm while other areas get 170mm of rainfall. During October to December, rainfall in the North declines from 225mm to 100mm while rainfall for other areas remains between 210mm and 240mm.

Long term records of rainfall over the Hulhule' shows peak rainfall is in May and October for the region. During these months, an approximate average of 260mm of rainfall is recorded. Rainfall is lowest towards the end and beginning of the year that recedes with the NE monsoon.

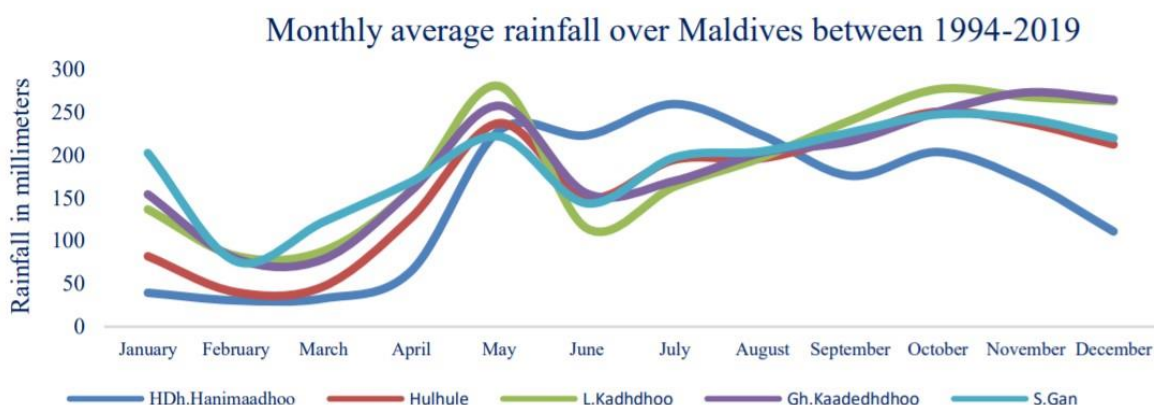


Figure 7: Monthly average rainfall over Maldives between 1994-2019 (Source: MMS, 2020)

The highest rainfall recorded over Hulhule' was 2711.2mm in 2007. Long-term annual rainfall observations indicate a declining trend for the whole country with 0.02mm per year for Male' region. However, future projections show an increase of rainfall over northern and central regions of Maldives for the year 2021-2025 (MEE, 2016).

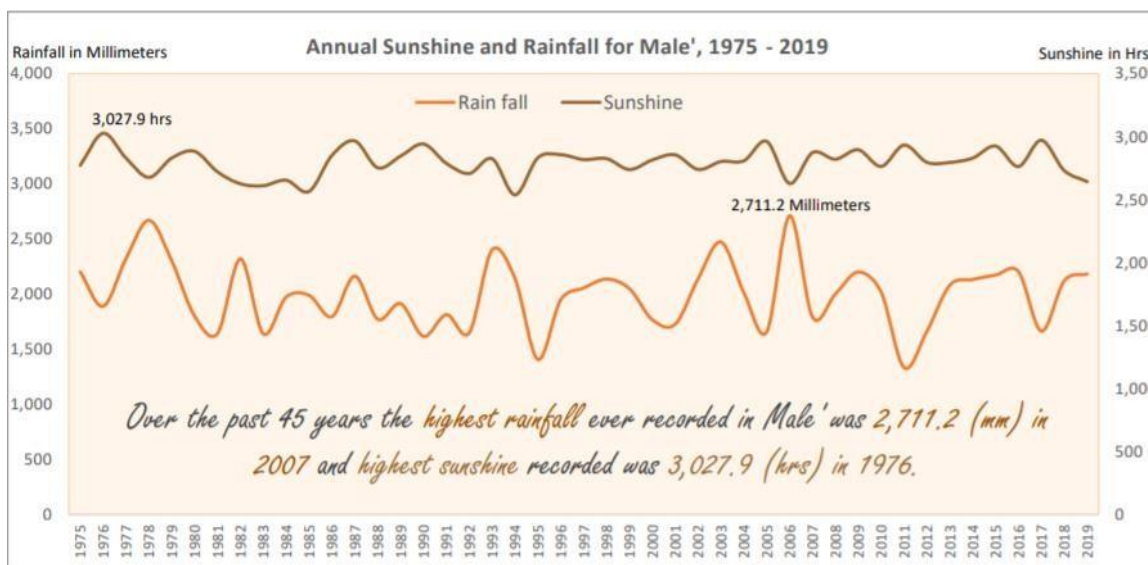


Figure 8: Annual sunshine and Rainfall for Male'. 1975 - 2019 (Source: NBS, 2020)

2.2.1.3 Wind

Long Term records of wind data indicate that the country experiences west to northwest winds during SW monsoon with an average wind speed of 5.1 m/s while during NE period, the winds blow from east-northeast with an average speed of 4.9 m/s.

However, the transition period from NE to SW is distinctively different where the winds show variability. The table below shows the wind directions during the monsoons and transition period.

Table 10: General wind conditions over Maldives (Maldives Meteorological Services)

Monsoon	Month	Wind
NE- Monsoon	December to February	Predominantly from NW-NE., High Speeds from W
Transition Period	March to April	From all directions. Mainly W. High Speeds from W.
SW-monsoon	May to September	Mainly from W. High Speeds from W.
Transition period	October to November	Mainly from W. High Speeds from W

2.2.1.4 Hydrography/hydrodynamics

2.2.1.4.1 Tidal ranges and tidal currents

The tidal pattern of the Maldives indicates a mix of semidiurnal and diurnal tides occurring daily. Tidal patterns record a maximum spring variation of about 1.1m indicating that the tidal range varies slightly in the Maldives. The Table 11 below shows Tidal variation observed at Hulhule Station.

Table 11: Tidal variation observed at Hulhule Station (Mean levels reported by the Maldives Meteorological Services)

Tide Levels	Referred to MSL
Highest Astronomical Tide (HAT)	+0.64
Mean Higher High Water (MHHW)	+0.34
Mean Lower High Water (MLHW)	+0.14
Mean Sea Level (MSL)	0.0
Mean Higher Low Water (MHLW)	-0.16
Mean Lower Low Water (MLLW)	-0.36
Lowest Astronomical Tide (LAT)	-0.56

The maximum tidal range recorded is 1.2m. The highest astronomical tide level from mean sea level was recorded at + 0.64m while the lowest astronomical tide level is - 0.56m. Seasonal variations also exist where high sea levels are seen in NE monsoon.

Tides are accompanied by the horizontal water movement resulting in tidal currents. Generally, the tidal currents are flowing eastward in flood and westward in ebb. However, the nature of the tidal current depends on the speed of the current and the cross-sectional area of the channels through which they pass (CUSP, 2011). Currents are also influenced by the monsoon characteristics, where it flows westward during the northeast monsoon period from December and April and eastward during the southeast monsoon period from May to August.

It should be noted that tidal variations induce groundwater level fluctuations which will have a significant impact on the geophysical surveys.

2.2.1.4.2 Wave Climate

Waves play a crucial role in modifying the coastal environment by influencing the accretion and erosion patterns around the islands. Wave driven flooding can also result in salinization of the freshwater lens. The major types of waves found in Maldives are wind generated waves and swell waves. Wind waves are generated by the monsoon winds and hence show the monsoonal wind patterns and generally last for 3-8 seconds. In contrast, swell waves are attributed to the swells generated by distant storms and last longer than wind waves for about 14-20 seconds (Kench et. al 2006, Binnie Black & Veatch 2000; Lanka Hydraulics 1988a & 1998b). Studies done on wave patterns around Maldives shows a predominant South west to a southerly direction for swell waves (Kench et. al, 2006).

2.2.1.4.3 Wind induced seasonal currents

The ocean surface currents flowing by the Maldives are driven by the prevailing winds from the monsoons. During the SW monsoon currents flow from west to east and during NE monsoon the currents flow from east to west. The transition between the two current systems occurs during March/April and October/November.

2.2.2 Groundwater and flooding vulnerabilities of the proposed islands

2.2.2.1 Flooding

Floods are mainly caused by the heavy rainfall and swell surge events in this region. Extreme rainfall events are the most frequent climate extreme experience in Maldives and the major cause of floods in the islands. Based on the past records, it is estimated that the northern and central region is more prone to extreme flooding due to rain compared to the southern atoll of the country (Zahid, 2011).

Abnormal swell waves and gravity waves are also known to cause floods in the islands and contaminate the freshwater lens. The intensity and impacts of gravity waves are usually very low with flooding occurring within 10m of coastline at less than 0.3 m height above the ground (UNDP, 2007).

Table 12 below shows the rain induced flood risk as well as other hazard levels of the project islands as per the latest Multihazard Risk Atlas of Maldives published by Asian Development Bank in 2020. The rain induced flood risk is high for GA. Maamendhoo, medium for GA. Nilandhoo and GDh. Faresmaathoda and low for the rest of the islands.

Table 12: Hazard levels as per Multihazard Risk Atlas (ADB, 2020)

Name of Island	Hazard Categories and Index Ranges					
	Rain induced Flood Risk	Udha* Hazard	Wind and Wave Hazard	Hydrometeorological multihazard	Multihazard physical risk index	Tsunami Hazard Rank
GA. Maamendhoo	High	Medium	Medium	High	Moderate	Very High
GA. Nilandhoo	Medium	Low	Medium	Medium	Moderate	Very High
GDh. Faresmaathoda	Medium	Low	Medium	High	Moderate	Very High
GDh. Rathafandhoo	Low	Low	High	High	Low	Moderate
GDh. Nadella	Low	Medium	High	High	Low	Moderate
GDh. Hoandedhdhoo	Low	Low	Medium	Medium	Low	Moderate

*Udha=big wave

2.2.2.2 Storm Surge

The occurrence of storm surges in the islands depends on factors such as wave height, origin of the storm event in the ocean, tide level and reef geometry. Figure 9 shows the Storm surge Hazard zones according to the Disaster Risk Assessment report (UNDP, 2006). The Table 13 below shows in which storm surge hazard zone the project islands are located in as per Figure 9. All the islands are in very low surge hazard zone.



Figure 9: Storm surge Hazard zones (UNDP, 2006)

Table 13: Surge Hazard Zone of Project Islands (UNDP, 2006)

Name of Island	Surge Hazard Zone
GA. Maamendhoo	Very Low
GA. Nilandhoo	Very Low
GDh. Faresmaathoda	Very Low
GDh. Rathafandhoo	Very Low
GDh. Nadella	Very Low
GDh. Hoandedhdhoo	Very Low

2.2.2.3 Groundwater Vulnerabilities

Varying perceived groundwater quality was observed in 45 islands as per the document “A Screening Approach for Assessing Groundwater Quality for Consumption in Small Islands: Case Study of 45 Inhabited Islands in the Maldives” published by Jaleel et. al., (2020). The 06 islands in the scope of this assignment were included in the 45 islands. Figure 10 extracted from this document shows the perceived varying salinity odor, color and debris levels in the islands. It was observed that salinity increased with population density and decreased with the area of the island as well as the latitude.

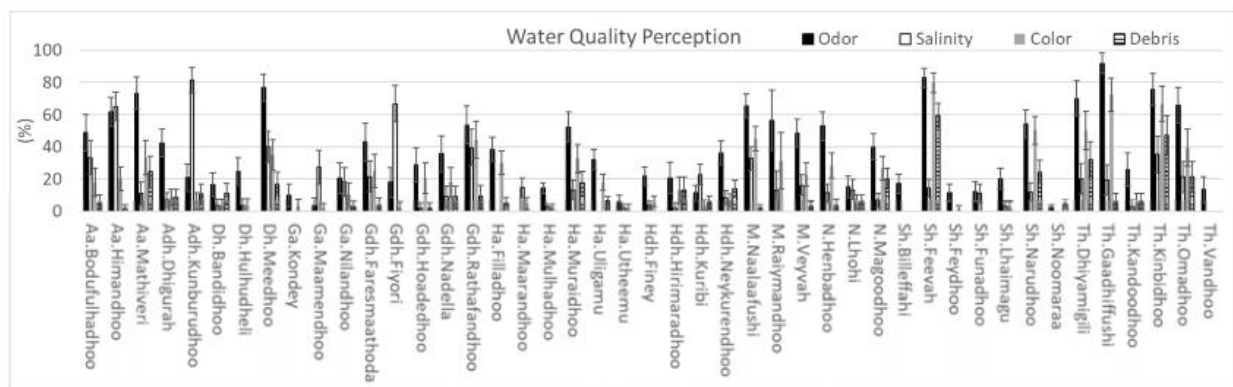


Figure 10: Groundwater quality perception of the respondents (Jaleel et. al, 2020)

2.3 Objectives and Scope

The scope of the project consultancy work is planned based on the tasks stipulated in the ToR and the proposed methodology to be implemented is included in this section.

As per the TOR, baseline assessment will be undertaken, feasibility of implementing managed aquifer recharge systems will be assessed and their conceptual/detailed design, implementation, and BOQ preparation/ tender documents will be submitted to manage the valuable water resource of groundwater. The scope of works is mainly as follows:

2.3.1 Inception

This phase includes conducting a desk review and carrying out the necessary investigations required to produce the Inception Report which will identify technical requirements, give methodology for works to be carried out for concept and detailed design and identify potential risks and constraints. This will be based on prior consultation with the PMU and other key stakeholders to ensure the proper understanding of the context.

2.3.2 Baseline Assessment

This phase includes conducting a detailed assessment to establish current status of the groundwater system and catchment characterization. The present impacts on the freshwater lens will be assessed and rates of groundwater recharge and discharge will be estimated. The sustainable groundwater yield and flood prone zones of the island will also be determined.

2.3.3 Survey, Feasibility and Concept Design

This phase will include concept design of three options for flood mitigation and groundwater recharge options for each island and feasibility study to determine the best option for each island. In this phase, the consultant will carry out the required surveys to obtain the required data for the formulation of the feasibility, concept design and detailed design.

2.3.4 Video Development

A video will be developed suited for online publication which will cover the details of the surveys carried out and their findings as well as show how the proposed Marine Aquifer Recharge System would work and its foreseen impact.

2.3.5 Detailed Design

Detailed engineering design and drawings for the most feasible option from the concept design will be developed and detailed design report will be compiled

The Detailed Design Report will contain three parts:

- Part 1 (Main report) – will include basic data and interpretation of the detailed design, brief description of calculations and hydraulic and structural calculation notes section, general justification and description of the proposed rehabilitated or new structures, identification of different construction lots and works schedule with introduction to material nature and quality and construction methods.
- Part 2 (Bill of Quantities and Cost Estimate) – Bill of Quantities for each structure and then by type of works with unit costs and percentage considered for miscellaneous and contingencies carried out on the basis of quantities and unit costs.
- Part 3 (Technical Report) – will include a drawings section with a first sub-section related to the existing structures ('reference drawings') and a second sub-section related to rehabilitation or construction of new structures (including general layouts, civil structures and electromechanical equipment's).

2.3.6 Tender Documents

Tender documents will be developed for construction tendering of the final approved design which will include:

- **Volume 1: Tender and Administrative Documents**
- **Volume 2: Technical Specifications and Schedules**
- **Volume 3: Drawings and Layouts**

2.4 Organization of the report

This Baseline Assessment Report is the second deliverable of the project and it consists of the following sections.

- Executive Summary
- Introduction
- Literature Review
- Methodology
- Baseline Assessment of 6 islands
- Conclusion and Recommendations

3 Literature Review

A careful review of all available literature was made to gather critical information pertaining to the study area and to find out whether any of the historical studies overlap the intended work.

Some of the studies and documents that were reviewed in the Literature Review phase of this study are presented below:

❖ **Baseline Assessment Report for Groundwater Resource Management and Aquifer Protection in Maldives (ME, 2020)**

The most important document used in the literature review is the Baseline Assessment Report for Groundwater Resource Management and Aquifer Protection in Maldives published by Ministry of Environment (2020). This report presented the results of a robust assessment on the impacts on the freshwater lens based on geo-physical, hydrological and social investigations, with an estimation of rates of groundwater recharge and discharge and safe yield for extraction in 13 islands following a freshwater lens water balance approach. The data and methodologies published in this report was taken as a main reference and used to plan the surveys that needed to be conducted to obtain the data to build the hydrological models for the concept designs. A summary of the baseline assessment is shown in Table 14.

Table 14: Baseline Assessment Summary

Island	Elect. Conductivity ($\mu\text{S/cm}$)	Freshwater Lens		GW Extraction (m^3/day)	Safe Yield M1 & M2 (m^3/day)	Drainage (m^3/day)	Recharge (m^3/day)
		Volume (m^3)	Thickness (m)				
HA. Utheemu	1,744 $\pm$ 2,683	250,231	5.90	112	572 & 234	644	684
HDh. Nolphivaranfaru	2,240 $\pm$ 3,522	335,176	4.52	305	1196 & 830	1828	1501
Sh. Funadhoo	7,547 $\pm$ 9,712	5,473	2.70	488	1694 & 594	1701	2182
N, Henbadhoo	4,239 $\pm$ 1,631	21,989	2.87	90	129 & 66	253	218
R. Maduvvari	3,689 $\pm$ 4,155	40,316	4.96	284	169 & 114	518	453
B. Dharavandhoo	1,008 $\pm$ 399	285,925	4.86	256	1455 & 340	1052	1712
AA. Bodufulhadhoo	6,182 $\pm$ 3,748	10,298	1.51	239	54 & 68	271	293
ADh. Dhigurah	2,725 $\pm$ 4,347	145,149	5.34	199	824 & 314	765	1022
M. Raimandhoo	5,039 $\pm$ 8,474	45,368	3.41	53	403 & 159	331	456
Th. Kinbidhoo	939 $\pm$ 271	113,029	8.46	316	535 & 241	660	851
Dh. Meedhoo	952 $\pm$ 498	117,827	4.11	324	798 & 189	700	1122
GA. Kon'dey	636 $\pm$ 119	601,600	4.18	132	1495 & 720	1073	1998
GDh. Fiyoari	997 $\pm$ 405	123,878	2.03	307	1690 & 501	1268	1627

The results of this study indicates that the freshwater aquifers in islands with high population densities were found to be highly stressed and overexploited with the groundwater extraction rates exceeding their safe yield. The stress level of the aquifer is reflected by the observed, localized drawdown and up-coning effects in the groundwater table and freshwater-saline interface and severe irregularities and significant deviations observed along cross sections and longitudinal sections aligned intercepting such densely populated areas where the aquifers were overstressed due to incessant pumping for household

and community water uses. The aquifer condition and recharging potential of these islands as a result of this study are shown in Table 15.

Table 15: Baseline Assessment Aquifer Condition and Recharging Potential

Name of the island	Aquifer Condition	Recharging potential
Ha. Utheem	Good	High
HDh. Nolvivaranfaru	Good	Moderate
Sh. Funadhoo	Stressed	Low
N. Henbadhoo	Stressed	Moderate to Low
R. Maduvvari	Highly Stressed	Moderate to Low
B. Dharavandhoo	Good	High
AA. Bodufolhudhoo	Highly Stressed	Low
ADh. Dhigurah	Good	Moderate
M. Raiymandhoo	Good	High
Th. Kinbidhoo	Stressed	High
Dh. Meedhoo	Stressed	High
GA. Konday	Good	High
GDh. Fiyoari	Good	High

The microbiological investigations of this study indicated that groundwater aquifers in all 13 islands are exposed to faecal contamination. Extremely high Electrical Conductivity (EC in $\mu\text{S}/\text{cm}$) and Salinity (PPT) were recorded mostly in shoreline samples presumably due to pumping induced seawater intrusion with centrally located wells recording lower Electrical Conductivity (EC in $\mu\text{S}/\text{cm}$) and Salinity (PPT). The overburden soil permeability was found to vary significantly over the landscapes in the islands both depending on the soil-geological type and land use combinations where relatively high permeable sandy soils were encountered in most locations while very low permeable humic clayey sands were found in thick vegetation areas leading to very low infiltration and long period ponding during storm events.

❖ **Estimating Transient Freshwater Lens Dynamics for Atoll Islands of the Maldives (Bailey, R.T., Khalil, A., Chatikavanij, V., 2014)**

In this study the dynamics of the freshwater lens were simulated during an extended (1998–2011) time period to determine the fluctuation of lens thickness of islands of the Maldives in response to annual and long-term changes in rainfall. Numerical model simulations were performed for a variety of island sizes, corresponding to the range of sizes of the islands of the Maldives, and for the various climatic regions of the Maldives, using the variable-density groundwater flow and salt transport code SUTRA. Results indicated that many of the atoll islands are expected to have a measurable freshwater lens during the majority of a long-term climatic period, although significant decreases in thickness can occur during the months of the dry season, with complete depletion occurring for small islands.

A general decrease in lens thickness, approximately 2 to 4 cm/yr, was observed over the 14-year period for the northern regions of the Maldives. If continued at current rates, these trends can have a significant impact on groundwater resources for the Maldives.

The overall results of this study indicate the importance of this assignment and the necessity of protecting groundwater and recharging the freshwater lens for long-term sustainability and use.

❖ **Final Report on Water Resources Assessments in Addu Atoll and sustainable water supply and sanitation strategies for Maldives Water and Sanitation Authority (GWP Consultants, 2006)**

This report provided details of water resources assessments carried out in five islands in Addu Atoll. Piezometer salinity profiling, electromagnetic surveys and household surveys (social surveys, well water and rainwater sampling and testing) were carried out to determine the extent, thickness and volume of freshwater lens. This data was combined with rainfall estimates and population data to determine sustainable yield of islands.

The results indicated adequate groundwater on Hithadhoo and Gan, and inadequate groundwater on Maradhoo, Maradhoo-Feydhoo and Feydhoo. Microbiological contamination was observed from poorly constructed and maintained septic tanks for all islands. High chlorine concentrations due to local over-exploitation and saline up-coning were also observed. However, land reclamation and groundwater recharge from rainfall roof run-off showed evidence of groundwater resources improvement.

This study also presented sustainable water supply and sanitation options for the islands. Rainwater harvesting was presented as the preferred source of potable water. For non-potable water usage, it was recommended to develop groundwater using infiltration galleries. The authors of this report advocated for septic tanks to be connected to small bore sewerage systems for sanitation disposal.

The method of electromagnetic survey presented in this report was not preferred for geophysical investigations for this assignment due to the relatively small dimensions and extents of the islands involved in comparison to the ranges of detectable depths and the specific need for differentiating saline groundwater from fresh groundwater to identify saline-freshwater interphase to detect lens thickness. The Social Survey questionnaire presented in this report was also reviewed in the formulation of the Social Survey questionnaire for this assignment.

❖ **Water and Sewerage Act (8/2020):**

The purpose of the Water and Sewerage Act (8/2020) is to regulate the water and sewerage facilities in the island and ensure the access of safe water and sewerage to the current and future generations of Maldivians. It enables the participation of more sectors in the area and helps in harmonizing the sector with other industries.

The Act ensures that every citizen of the Maldives has the right and access to safe and potable water and safe management of sewage. The relevant clauses of the act to this assignment are detailed below.

- Clause 18 states that the freshwater lens in all uninhabited islands without exception is protected under this Act. and unless otherwise stated in any other Act, these aquifers should be maintained as

per the guidelines and regulations made under this Act. However, this does not obstruct the use of freshwater lens for personal use.

- (raa) states that boreholes should be constructed in such a way that it does not cause any significant impact on the freshwater lens of the island.
- Clause 19 states that water from the freshwater lens or from any natural freshwater body cannot be used for any industrial purposes in islands leased out for industrial purposes or in uninhabited islands.
 - (noonu) states that for inhabited islands, this clause would apply to those doing farming/agricultural activities in lands exceeding 10,000 sqft.
 - (raa) states that it is the responsibility of the owner of the industrial area or development to establish water network/systems for industrial use purposes.
- Clause 20 deals with the contamination of freshwater lens in islands.
 - (haa) and (shaviyani) states that no persons should do any activity that contaminates the freshwater lens in island. However, using of fertilizers that are compulsory to be used or use of septic tanks does not fall under this.
 - (noonu) anything that may spill on the road and contaminate ground water aquifer should be transported after properly sealing it and ensuring that it doesn't spill as per the regulations and guidelines to be made under this Act.
 - (raa) oil or chemical or any related material that may contaminate ground water should be transported in enclosed containers and it should be made sure that they do not spill during transportation
 - (baa) If oil or chemical or any related material that may contaminate ground water is spilled on the road during transportation, the person transporting the material will be held responsible for cleaning and decontaminating the area
 - (lhaviyani) Transporting oil or chemical or any related material that may contaminate ground water by not following the Clauses and guidelines and regulations is illegal.
 - (kaafu) Spilling oil or chemical to the ground or to groundwater intentionally or by negligence is illegal
 - (alifu) If a spill occurs during the storage of oil or chemical or any related material that may contaminate ground water, the owner of the products should be held responsible
 - (vaavu) the water that's mixed with oil or chemicals during cleaning of equipment or engines should not be disposed to the ground or discharged to the sea.
- Clause 22 is on Desalination Plants
 - (haa) water cannot be sourced from freshwater lens or from any freshwater body
- Clause 23 is regarding Disasters and Crisis.
 - The Authority has the right to issue permit for the use of water from water bodies that have been regarded as protected under this Act as per the regulations and guidelines in the case of disasters and crisis.
- Clause 28: states to promote Integrated Water Resource Management System and to harvest rainwater to the highest potential possible

❖ **The Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22)**

The Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22) published in the Maldivian gazette on 11th February 2021 was reviewed in the Literature Review phase of this study. This regulation was published under the clause 58(haa) of the Water and Sewerage Act (8/2020). The purpose of this regulation is to determine and enforce the principles to protect, conserve and develop available water resources such that they can be used in a sustainable manner to get the maximum benefit possible. The relevant clauses of the act to this assignment are detailed below.

- Clause 6 – Conserving and managing the freshwater lens
- Clause 7 – Usage of water resources in emergencies
- Clause 8 – Recharging the freshwater lens:
 - Rainwater overflow from rainwater harvesting tanks should be connected to wells or drained to ground. Examples of rainwater recharge designs are shown.
 - All existing buildings should be changed to allow for rainwater harvesting and rainwater recharge into the ground.
 - Connection of rainwater overflow to sewerage system is prohibited.
 - Connection of rainwater overflow to sewerage system is allowed only during flooding crises and with the permission from respective utility.
- Clause 9 – Drainage of floodwater into the ground:
 - Drainage systems for islands should be designed such that the flood water collected on roads should drain into the ground.
 - Road Gutters should be connected to drainage system such that the water drains into the ground.
 - Reclamation for islands should be carried out such that the reclamation does not exacerbate any existing flooding problems in islands or cause flooding problems.
 - Community areas with wide open space such as football fields and parks should have water drainage systems underground.
- Clause 10 – Preventing Contamination of groundwater from any activities (industrial or otherwise)
- Clause 11 – Preventing Contamination of groundwater from sewage effluent:
 - Connection of all buildings to sewer main line
 - Desludging and decommissioning of septic tanks.
 - Prevent sewage effluent leaking into the ground (utility responsibility)
 - Treated wastewater drained into ground according to guidelines
 - Wastewater draining into ground should be monitored according to monitoring plan with monitoring reports submitted.
 - Septic Tanks should be constructed according to guidelines (Detailed guidelines for the construction, operation and maintenance of wastewater tanks and septic tanks are given)

- Clause 12 – Preventing Contamination of groundwater from oil and chemicals used for multiple purposes
- Clause 13 – Preventing Contamination of groundwater from industrial activities
- Clause 14 – Preventing Contamination of groundwater from agricultural activities
- Clause 15 – Preventing Contamination of groundwater from waste management activities
- Clause 16 – Preventing Contamination of groundwater from medical hazardous waste
- Clause 17 – How to repair and rectify groundwater contamination situations
- Clause 18 – Economizing residential groundwater usage
- Clause 19 – Economizing agricultural groundwater usage
- Clause 20 – Groundwater usage for industrial and economical activities
- Clause 21 – Extraction and Sale of groundwater
- Clause 22 – Accounting for groundwater conservation in Land Use Planning Practices

The details of clauses 3,4 and 5 are given as they are considered to be the most relevant to the scope of the current assignment.

This regulation includes the individual responsibilities of the Utility Regulation Authority and Island Council in the enforcement of this rule. It also details legal and financial action that will be taken against those violating the terms in this document.

This regulation doesn't contain much information about MAR design and structures relative to the scope of the project, but it does serve as an important guideline for island councils to optimize their groundwater usage in low-cost manners without the construction of engineering structures. It also includes Infiltration gallery template, rainwater recharge design template, standards for recharging treated wastewater into the ground and Standards for construction and maintenance of wastewater tanks and septic tanks.

❖ **The regulation regarding Provision of Water and Sewerage System Services in the Maldives (Regulation number: 2021/R-23)**

The regulation regarding Provision of Water and Sewerage System Services in the Maldives (Regulation number: 2021/R-23) published in the Maldivian gazette on 11th February 2021 was reviewed in the Literature Review phase of this study. The purpose of this regulation is to determine guidelines for the following:

- Design and operation of water and sewerage systems,
- Testing and certifying the materials used,
- Preparing the plan for water and sewerage systems,
- Protecting water and sewerage systems.

This regulation states that rainwater that cannot be harvested should be drained into the ground. It also states that after the establishment of a piped conventional sewerage system, previously used septic tanks should be decommissioned in a manner so as to prevent further damage to the freshwater lens.

❖ **National Water and Sewerage Strategic Plan 2020–2025 (NWSSP 2020–2025)**

The National Water and Sewerage Strategic Plan (NWSSP 2020–2025) was formulated under the Water and Sewerage Act (Act No.8/2020). This Strategic Plan provides the strategic framework for the development of the water and sanitation sector. This Plan also addresses flooding, drainage issues and managing their societal, environmental and financial impacts. NWSSP 2020–2025 will also contribute to improve hygiene, health and wellbeing of the population through improved water and sewerage services leading to positive economic growth and development to meet the aspirations of the people of Maldives. The Government's target is to continue this momentum and provide access to safe water supply and adequate sewerage services in all inhabited islands by end of 2023.

The mission of this plan is to

- Provide efficient, effective and reliable water supply and sewerage services.
- Promote conservation and management of the water resources.
- Develop sector capacity for sustainable management of resources and services.

NWSSP 2020–2025 contains six policy goals with detailed strategies, actions, time framework and implementing agencies. Of primary relevance to the scope of this project are policy goal 5 and 6.

Policy 5 is to protect and conserve natural water resources. The first strategy under this policy is to reduce vulnerability of the island freshwater resources. The actions under this strategy are as follows:

- Action 5.1a: Carry out a baseline assessment on water resources in all islands in Maldives
- Action 5.1b: Develop and implement water resource conservation and management plan in all the islands
- Action 5.1c: Incorporate and implement groundwater recharge mechanisms in land use plans of all inhabited islands

The baseline assessment scope of this assignment achieves the purposes of Action 5.1a.

The second strategy under policy 5 is to improve freshwater quality testing and monitoring. The actions under this strategy are as follows:

- Action 5.2a: Conduct national data collection and monitoring of the quality of freshwater resources
- Action 5.2b: Develop and standardize parameters for groundwater quality and quantity in all monitoring activities.
- Action 5.2c: Conduct climate modelling under different emission scenarios for natural water resources

Policy goal 6 is to build flood resilient island communities. The singular strategy under this policy is to seek community protection from flooding incidents. The actions under this strategy are as follows:

- Action 6.1a: Accurately map and identify flood prone areas in islands
- Action 6.1b: Develop design criteria and technical specifications for sustainable flood management systems in the islands

- Action 6.1c: Incorporate flood mitigation and minimization measures in public infrastructure such as roads, reclamation projects, harbours, coastal protections, high rise buildings etc.

Action 6.1a will be carried out for 06 islands under the scope of this assignment.

❖ **National Water and Sewerage Policy (MEE, 2017)**

The National Water and Sewerage Policy (NWSP) published by Ministry of Environment and Energy in 2017 presents a set of 9 goals and associating objectives and strategies that give precedence to ensuring access to safe water and sewerage services for all. The NWSP sets out the government's plans for water and sewerage services in the future and the steps that will be taken to ensure provision of appropriate and sustainable water and sewerage services to all.

Of primary relevance to the scope of this project is policy goal 9. Policy goal 9 is to protect and conserve water resources. The policy objective is to adopt a holistic approach to water resources protection, conservation, management and pollution control. The strategies under this policy objective are as follows:

- Establish an effective research-based monitoring program and information platform of inhabited islands' water resources.
- Develop and implement evidence-based water resource management plans taking into consideration the sustainability and vulnerability of the island freshwater resources, wastewater reclamation, water reuse and minimize impact from pollution.
- Encourage water conservation, water reclamation and water reuse, water demand management and minimize the impact of pollution on water resources.

This policy goal relates to the government manifesto (2014-2018) of establishing properly constructed sewerage systems to reduce groundwater pollution. It also relates to the following Sustainable Development Goal targets:

- 6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
- 6.6: By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes
- 6.b: Support and strengthen the participation of local communities in improving water and sanitation management

❖ **A Guide to Groundwater Protection & Improvement Measures in Maldives (ME, 2021)**

A Guide to Groundwater Protection & Improvement Measures in Maldives published by Ministry of Environment (2021) indicates how urbanisation has changed the landscape of the islands causing increased impermeable land surfaces from increasing density of buildings and paved roads. This has caused increased occurrence of small-scale flooding during rainstorms and depletion of the groundwater due to lack of recharge. This guide indicates the importance of implementing suitable

methods of infiltration drainage techniques to manage stormwater runoff and increase recharge of groundwater in developing islands. It also discusses and illustrates various options and types of sustainable infiltration-based solutions for the drainage of stormwater from roofs and road surfaces that are suitable to be adopted in the Maldives.

❖ **SuDS Manual (CIRIA, 2015)**

The Sustainable Drainage Systems (SuDS) Manual published by CIRIA (2015) indicates the importance of integrating surface water management into the design of towns and cities to protect the environment and create high quality places for future generations. However, the solutions presented in this guide are targeted more for large urban areas and big towns with deep freshwater lens and is mostly unsuitable for small island developing states such as Maldives. However, the principle of Sustainable Urban Drainage Systems presented in this guide will be used in developing the MAR designs within the scope of this project. The principles of SuDS include the following:

- Control the quantity of runoff to support the management of flood risk and maintain and protect the natural water cycle
- Manage the quality of runoff to prevent pollution
- Create and sustain better places for people
- Create and sustain better places for nature

❖ **ASCE Standard Guidelines for Artificial Recharge of Ground Water**

The EWRI/ASCE 34-01 Standard Guidelines for Artificial Recharge of Ground Water provides provide a standardized set of guidelines to describe the many steps required to develop, operate, and maintain a project for artificial recharge of ground water. The main sections presented in this guideline are listed below:

- Planning
- Field Investigation and Testing
- Design
- Regulatory and Water Rights
- Environmental Issues
- Economics
- Construction
- Start-up
- Operation, Maintenance and Closure

Similar to the SuDS Manual, the solutions presented in this text are not very suitable for small island developing states such as Maldives with its flat topography and shallow freshwater lens. However, the more practical guidelines presented here were especially useful in determining the methodology for field investigations and will be helpful to the client during the construction and implementation of the MAR design.

❖ **Application of the USGS soil-water-balance (SWB) model to estimate spatial and temporal aspects of groundwater recharge in north-central Iowa (Day, 2019)**

It is a thesis and dissertation by a student from Iowa State University in 2019. Study area is north-central Iowa and the objective of the study was to estimate spatially-distributed recharge using SWB model. The domain of the SWB modelling is 5960 km² and 100m x 100m grids have been used to define the soil, land use, hydrological and hydrogeological properties.

The study area has a mean annual precipitation of about 914 mm and most of the precipitation falls during the summer months. Land use for the SWB model had been obtained from the Multi-Resolution Land Characteristics Consortium, National Land Cover Database and climate data was from DAYMET database and National Oceanic and Atmospheric Administration for a 20-year period (1996 to 2005). Soil data for grids had been collected from the U.S. Department of Agriculture and National Resource Conservation Service. Model had been simulated for the 20-year period and it was found that mean annual potential recharge was 159mm/yr which is around 17% of mean annual precipitation. The reliability of model estimated recharge was checked with the value from groundwater modelling studies in the region and it was found that the results were consistent.

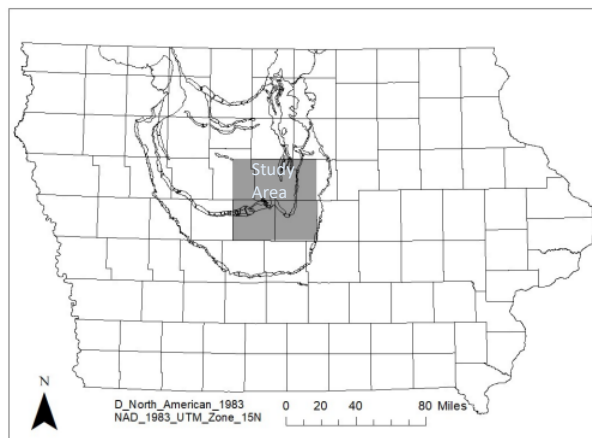


Figure 11: Location Map (Day, 2019)

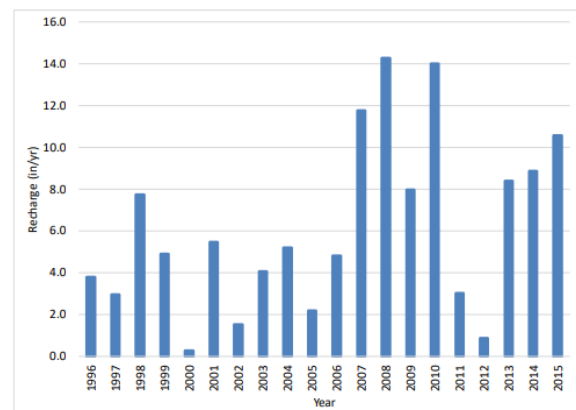


Figure 12: Estimated Annual Recharge by SWB Model (Day, 2019)

❖ **Numerical Simulation of Groundwater Availability in Central Molokaʻi, Hawaiʻi (Oki, D.S., Engott, J.A., and Rotzoll, K., 2020)**

It is a groundwater study carried out using SUTRA model (3 dimensional) for central Molokaʻi, Hawaiʻi. The purpose of this study was to describe an evaluation of groundwater availability in the study area for selected withdrawal scenarios.

Groundwater recharge from the soil zone, which is one of the inputs to the SUTRA model, had been estimated using a daily water budget of each decade during 1940–2012 and other available data including the distributions of monthly rainfall and potential evapotranspiration. A two-dimensional, sharp-interface groundwater-flow model covering the entire island was used to estimate subsurface inflows at the boundaries of the central Moloka‘i groundwater model. Aquifer hydraulic properties for the numerical groundwater model were estimated using available water-level and salinity information. Simulated withdrawal scenarios were selected in consultation with water managers and stakeholders. The model mesh used in this study consists of 520,821 nodes and 495,388 variably sized elements and 64 vertical layers. The lateral extent of the model domain has been defined by boundaries that are either no-flow, recharge, or specified-pressure boundaries.

For calibration of the model both water level and chloride concentrations were used and found that simulated values were in general reasonable agreement with observed values.

SUTRA model had been simulated for four distinguished scenarios.

- 1) a baseline scenario using average recharge
- 2) a scenario using average recharge and withdrawals from existing wells
- 3) Four options using average recharge and selected withdrawals from existing and proposed new wells:
and
- 4) a scenario using reduced recharge and selected withdrawals from existing and proposed new wells.

From the analysis of model results, this study concluded that the rate of groundwater recharge would be a controlling factor for the quality of water withdrawn from production wells in the Kualapu‘u aquifer system. A reduction in groundwater recharge in the future (all other factors remaining equal) would tend to cause increased salinity of water withdrawn from production wells.

In conclusion, relevant Maldivian guidelines and regulations, previous groundwater studies done in the Maldives and technical manuals were reviewed for the formulation of the methodology of the baseline assessment which include planning field works as well as data processing. The methodology based on Literature Review is presented in the next section.

4 Methodology

4.1 Data Collection

4.1.1 Climate data

Historical meteorological data was collected with finest available resolution to assess the state of the existing environment, fill information gaps, to obtain most up to date information and for the assessment of extreme rainfall depths. Following data for the past 20–30 years has been received from five weather stations (Gan, Hanimaadhoo, Hulhule, Kaadedhdhoo and Kadhdhoo) from the Maldives Meteorological Service:

- Hourly Rainfall Data: Most possible discretized information
- Maximum, minimum, and mean temperature – daily points
- Relative humidity – daily points
- Sunshine duration – daily points
- Wind Velocity – daily points

Literature review also covered existing studies undertaken for all of the islands with respect to hazard vulnerability, specifically flooding and any historical and current data on flooding associated with storm surges.

4.1.2 Maps/Plans/Etc.

Literature review also covered any existing survey maps and data from Environmental Impact Assessment (EIA) reports, and other relevant documents. The following reports were reviewed:

- MoEnv. (2020). Groundwater Resource Management and Aquifer Protection in Maldives, Baseline Assessment Report. Ministry of Environment, Male', Maldives
- Land Use Plans for GDh. Faresmaathoda and GDh. Rathafandhoo
- Multihazard Risk Atlas of Maldives, Volume 1–5, March 2020
- National Water and Sewerage Strategic Plan, 2020
- Water and Sewerage Act (8/2020)
- The Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22)
- National Water and Sewerage Policy (MEE, 2017)
- A Screening Approach for Assessing Groundwater Quality for Consumption in Small Islands: Case Study of 45 Inhabited Islands in the Maldives, Jul 2020
- A Guide to Groundwater Improvement Measures in Small Low-lying Islands – Maldives, Jan 2021.

4.1.3 Water quality standards

WHO Drinking Water Guidelines were used as a main reference for water quality standards. Additionally, the Drinking Water Guidelines published by Utility Regulatory Authority (2021) was also referred to in the analysis of groundwater parameters.

4.2 Topographical Survey

4.2.1 General/objective

Topographic survey primarily relied on Unmanned Aerial Vehicle (UAV) mapping using ground control points supplemented with Global Navigation Satellite System (GNSS) Real-time Kinematic (RTK) Surveys. Maldives Land and Survey Authority (MLSA) currently only specifies guidelines for Land Registration Survey of Islands, Control Surveys, Reclamation and Dredging. There are no relevant guidelines for surveys carried out for infrastructure projects in the water and sanitation sector including sewerage, water supply and groundwater recharge projects and the requirements are usually set by the design engineer.

The topographic survey using GNSS RTK surveys as determined by the design engineer provided road levels required due to the nature of design works and served as an important source to provide ground control points and validate the vertical accuracy of UAV mapping. Along with this, the High-Water Line (HWL) and Low-Water Line (LWL) was mapped (this includes any coastal features which would have an effect on the boundary line (for example groynes, jetties, quay wall, etc). The extent of the vegetation canopy, except fallen or dead trees was also recorded using the topographic survey. In addition to this, permanent structures such as roads, buildings, land parcels, and fences were represented.

There are three different methods that can be used to carry out UAV mapping to provide accurate and absolute XYZ measurements.

1. Ground Control Points (GCPs)- technique which uses several ground control points or locations with known coordinates
2. Real time Kinematic (RTK) -technique used to correct GNSS position of images in real time
3. Post-Processed Kinematic (PPK) -technique to correct geotagged data after data collection by processing it in the cloud

The pros and cons of these methods are discussed below.

Table 16: Comparison of drone-based survey methods (<https://www.sensefly.com/blog/gcps-rtk-ppk-when-what-why/>)

	Advantages	Disadvantages
Ground Control Points (GCP)	• Most widely used method • Highest level of precision and accuracy	• Requires additional equipment such as GNSS receiver, GCP targets • Takes much longer time and personnel • Unsafe areas may need to be accessed
Real time Kinematic (RTK)	• Saves time • No need to consider inaccessible areas of the island	• Requires special equipment • No post processing required • Dependant on GPS signal
Post-Processed Kinematic (PPK)	• very high level of precision and accuracy • Time spent onsite is reduced	• Post processing required • Very high level of precision and accuracy • Less control over workflow and more mistakes

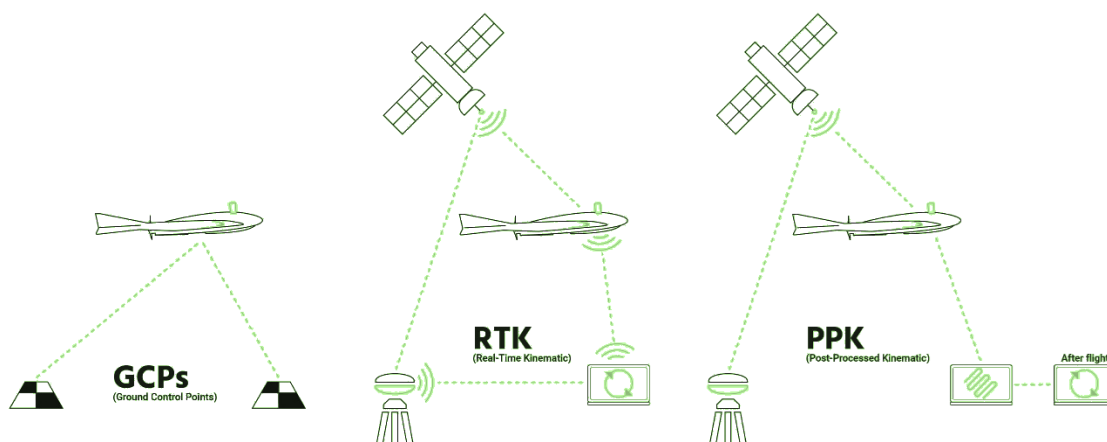


Figure 13: Different methods to carry out accurate UAV mapping

Drone based UAV surveying was used in this project to produce Digital Surface Models (DSM) of the surface, Digitized layers to be used for Geographical Information Systems (GIS) and orthomosaic photos of the islands. For the purposes of this project a survey grade UAV (Unmanned Aerial Vehicle) that incorporates an internal RTK (Real time kinematic) GPS was used to obtain highly accurate elevations.

This provided centimetre level accuracy (less than 10 cm vertical accuracy specified in the contract) and the basis to assess groundwater resources and the design of aquifer recharge systems.

4.2.1.1 Proposed methodology

This section presents the methodology used to carry out UAV mapping in the islands. The equipment that was used for UAV mapping is the DJI phantom 4 Real Time Kinematic (RTK) UAV. The image below indicates the activities that were carried out for UAV surveying with details provided in following subsections.

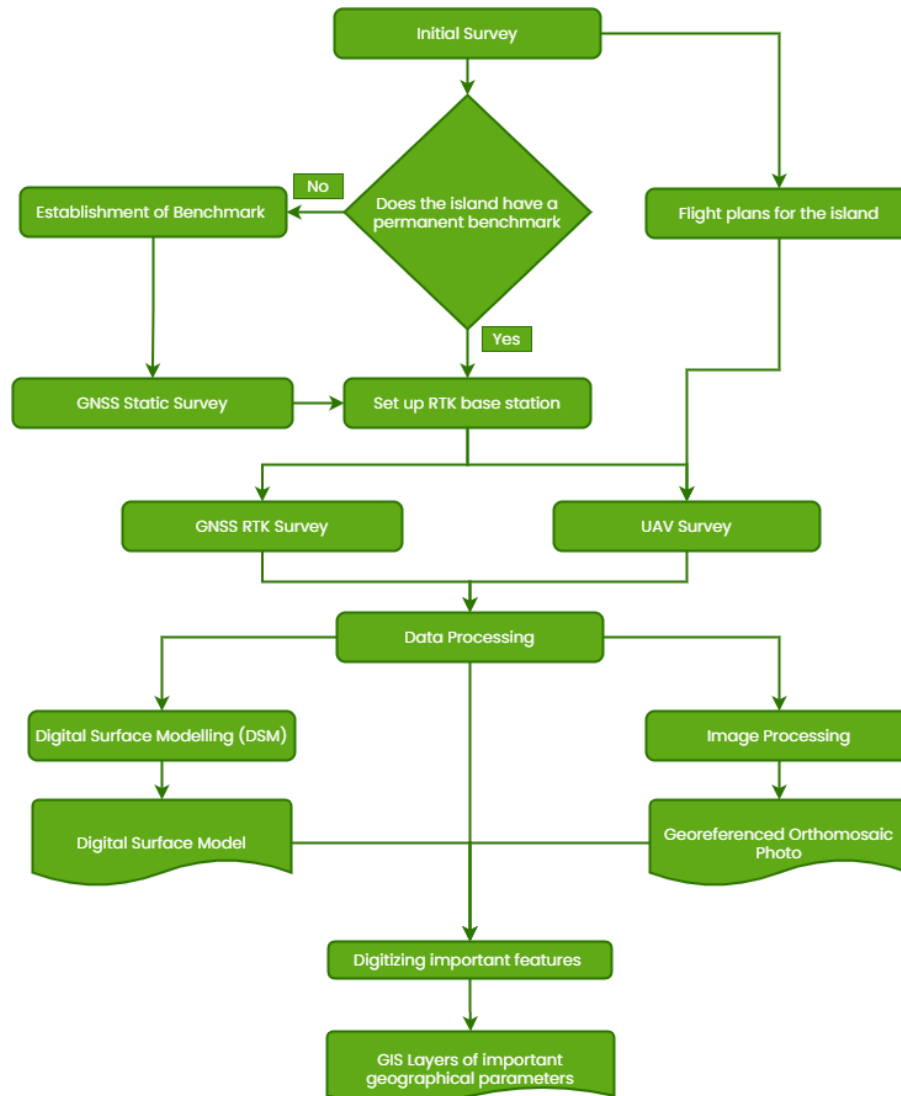


Figure 14: Flowchart for proposed methodology

❖ Initial Survey

Initial surveys were done during the site visit to plan out the UAV surveys. All areas of the island were visited to seek ideal locations and coordinates for the Ground control Points. Furthermore, permanent

benchmarks (if any) on the island were located to gauge their status. Disturbance to established permanent benchmarks are a common occurrence in Maldives especially on islands where Harbours have been constructed recently.

❖ Static GPS Survey

Static GPS survey was carried out to provide the accurate ground control point for the base station in islands where no previous benchmark exists.

❖ Pre-programmed Flight plans for the islands

Pre-programmed flight plans were produced using flight planning applications for mobile phones. The flight height for the islands was determined along with overlap and sidelap to obtain a ground sampling distance of 2 cm/pixel with approximately 20 minutes of flight duration (operational battery life is usually lower with wind and payload affecting battery discharge times). For larger islands battery swaps were required and this was accounted for manually as shown in the figure below.

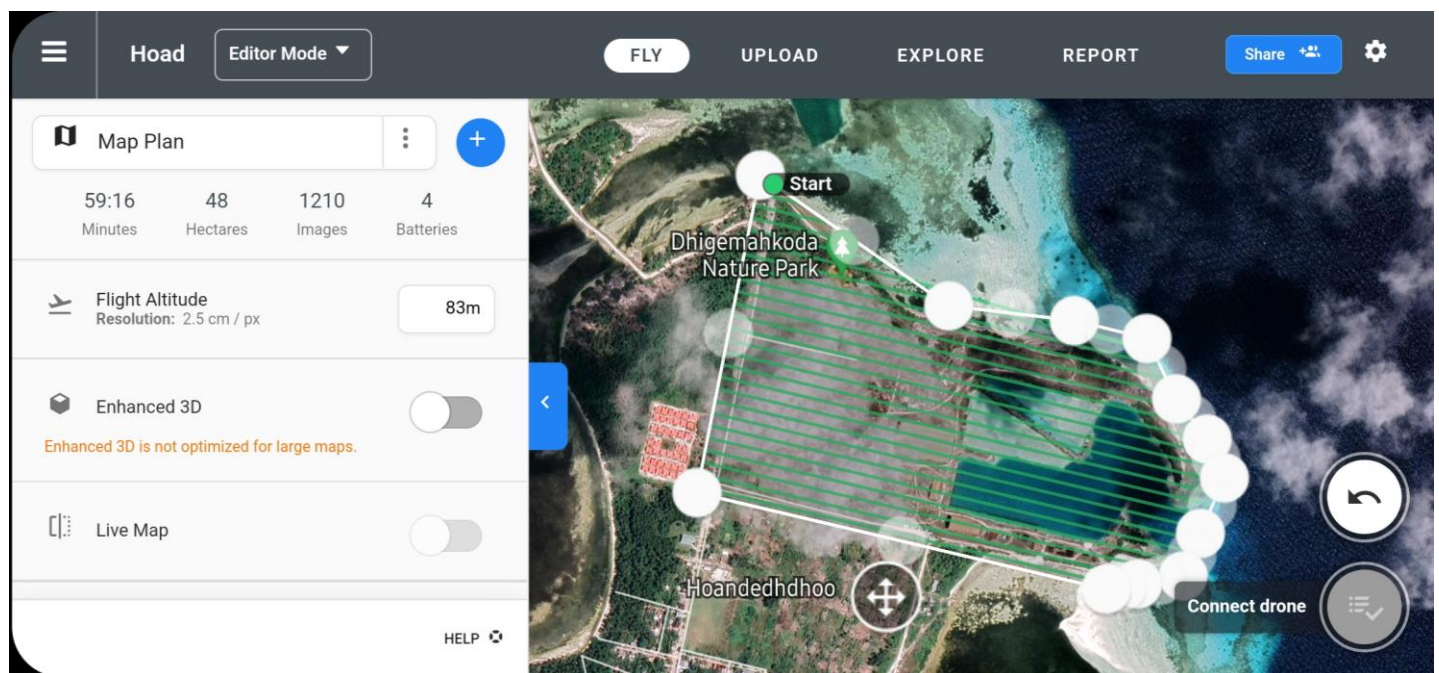


Figure 15: An example of the flight plan produced for a drone that allows the altitude and flight direction to be determined and gives estimates of the flight duration and resolution

❖ Setting up RTK Base station

The base station for the RTK drone was a physical one rather than a Continuously Operating Reference Station (CORS) Network Station using a 4G sim. This option allowed calculation of the drone position (while capturing images).

❖ UAV mapping

As a general rule, drone imagery was captured early in the morning to reduce sun glint but depended on the field conditions such as tide and access to the site. Optimal flight directions were decided during

the field timing of drone surveys to fly the drone in the direction of the sun azimuth. Camera angles were also adjusted to ensure that if any sun glint exists it was towards the edge of the image.

The proposed ground sampling distance as achieved by flying the DJI Phantom RTK drone at a height range of 70–150 m based on the camera parameters given in the table below.

Table 17: Camera parameters for the Phantom 4 RTK drone

Camera Parameters	
Image Width	5472 px
Image Height	3648 px
Sensor Width	13.2 mm
Sensor Height	8 mm
Focal Length	8.8 mm

❖ Data Processing

UAV data was downloaded and processed using photogrammetric and image processing software Pix4D Mapper or Agisoft Metashape. The reader is referred to the software manual for information regarding the workflow to produce georeferenced orthomosaics (<https://support.pix4d.com/hc/en-us/articles/204272989-Offline-Getting-Started-and-Manual-pdf>). GCP coordinates were entered into the software to georeference the produced orthomosaic.

❖ UAV mapping outputs

The drone (ortho) photos were stitched together to make the Orthomosaic photo. The resolution of the orthomosaic was produced at 2cm per pixel as mentioned in the *Groundwater Resource Management and Aquifer Protection in Maldives, Baseline Assessment Report* conducted by Ministry of Environment in 2020.

Orthomosaic data was utilized to extract data regarding:

- Rainwater catchment areas such as roofs
- Vegetation line and areas including coastal fringes, pond fringes, mangrove bay fringes, mangrove forests and inland forests
- Shoreline dynamics including the low tide line and high tide line
- Infrastructure, road areas and zonation at block level

These digitized layers are presented in a GIS format for the use of the Client.

Digital elevation models (DEMs) were produced by filtering out non ground points (such as trees). After filtering of objects such as vegetation in islands, Digital Terrain Models (DTM) were produced but the accuracy of such a model at the scale of islands in Maldives where canopies can extend from the shoreline to large areas, remains questionable.

The results of the Topographical Survey are presented in Sections 5.2, 6.2, ..., 11.2 for the six islands.

4.3 Social Survey

4.3.1 General/objective

1. Quantify groundwater usage in households, tourism, agriculture, fisheries, and other economic sectors of the islands at present
2. Collecting information related to shortage of groundwater (amount and time), water borne diseases and other issues
3. Collect supporting information regarding flooding depths, frequency, and causes

4.3.2 Questionnaire Survey + Items covered

The methodology for the social survey is proposed based on existing literature and in particular, the *Groundwater Resource Management and Aquifer Protection in Maldives, Baseline Assessment Report* conducted by Ministry of Environment in 2020. This was done to ensure repeatable and scalable sampling and analysis for comparison across projects.

An additional element to this survey was the collection of information regarding flooding on the islands surveyed.

The social survey was conducted in three parts:

1. Desk review of existing literature
2. Structured surveying
3. Comparing survey results with field investigation reports

The below sections describe the structured surveying methodology.

❖ Categories and proposed sample size

The sample size (n) is calculated according to the formula:

$$n = [z^2 * p * (1 - p) / e^2] / [1 + (z^2 * p * (1 - p) / (e^2 * N))]$$

Where:

N = population size = as per table

p = population proportion = 0.5

z = confidence level = 1.96

e = margin of error = 0.05

Assumptions made: Household numbers for each island were obtained from the island councils.

Table 18: Percentage of households proposed to be sampled per island

Island	No. of Households (Island Council, 2021)	Minimum Sample Percentage (MOE 5%)
GA. Maamendhoo	250	151
GA. Nilandhoo	105	82
GDh. Hoandehdhoo	173	119
GDh. Nadella	152	109
GDh. Rathafandhoo	150	108
GDh. Faresmaathoda	235	146

Based on previous studies done for Water-Usage Surveys, this survey adapted the categories used for surveying for future comparative studies as per the following Table 19.

Table 19: Social Survey Categories

Category	Description	Sample Size
Households	Households to be chosen at random and interviewed	As per the table above
Café/ Restaurant	Café's, Restaurants to be chosen at random and interviewed.	100% of all entities
Guesthouses	Guesthouses, City Hotels, to be chosen at random and interviewed.	100% of all entities
Institutions	Hospitals, health centres, offices, schools	100% of all institutions
Farming and Industrial	Farms, fisheries activities, mariculture, etc	25% of all farms

❖ Sampling methodology

A quantitative, structured questionnaire was administered face to face for all islands. The surveys were created on Google Forms and input by trained facilitators.

All social surveys were undertaken at 95% confidence interval and the sampling points were geo-coordinated.

The structured questionnaires included:

1. Demographic questions to segment data and conduct correlation studies
2. Nominal Yes/No level questions
3. Multiple choice questions
4. Open ended questions (to capture unique no. of use in households)

The following categories of questions were included in the survey to analyse usage and perception of water

1. Drinking water
2. Ground water

3. Sanitation Facilities
4. Flooding

Social Survey Questionnaire is attached in Annex IV: Social survey questionnaires.

❖ **Data Entry and Analysis**

Data collected from questionnaire was entered and recorded into excel spreadsheets and calculations were performed for individual islands. For each island, the water usage for each category were analysed separately.

4.3.3 Methodology used to estimate water consumption by different user/usage

For domestic water usage seven main categories were considered in calculating water usage:

- Showering
- Water Closet Flushing
- Laundry
- Gardening
- Household cleaning
- Dishwashing
- Water used by bathroom faucets

The following information was obtained from the social survey for the water consumption calculation:

- The average number of showers per person
- Duration of shower
- The average number of times toilet is flushed per day
- Type of flush tank used
- The number of times laundry is done daily
- Type of washing machine used
- Total time garden hose is used daily
- Number of watering cans used daily for watering plants
- Number and size of water buckets used in household cleaning
- Time spent washing dishes
- Total duration in minutes bathroom faucet is used daily

For institutional water usage, four main categories were considered in calculating water usage:

- Water Closet Flushing
- Laundry
- Gardening
- Cleaning

For Café/ Restaurant water usage, five main categories were considered in calculating water usage:

- Water Closet Flushing
- Laundry
- Gardening
- Cleaning
- Dishwashing

For Guesthouse water usage, four main categories were considered in calculating water usage:

- Water used in rooms
- Laundry
- Gardening
- Cleaning

Average occupancy rates were used to calculate water consumption. Average discharge rates were used.

For Farming usage, one category was considered which is the irrigation techniques used by the farming were used to calculate the total water consumption.

4.3.4 Limitations

All the surveys undertaken in GA. Maamendhoo, GA. Nilandhoo, GDh. Hoandehdhoo and GDh. Nadella maintained 95% confidence interval with an error margin of 5%. GDh. Faresmaathoda and GDh. Rathafandhoo maintained 95% confidence interval with an error margin of 6.5% and 9% respectively. The error margin for these two islands were relatively high because households were unresponsive and not willing to take part in the survey because of unavailability. There were also other challenges such as Covid-19 restrictions and some islands going under monitoring during the social survey period. Despite the challenges, a maximum of three attempts were made on different occasions to determine unavailability of the participant.

On the same note, farming plots in this batch of islands were relatively high and thus was decided to undertake 25% of all farms in the island.

4.3.5 Future Water Demand

The Population Projection carried out by National Bureau of Statistics (2014) was used to obtain the population figures for the years 2036 and 2054. The population projection was based on assumptions about mortality, fertility, and migration. These population figures were used to calculate the future water demand. Future water demand was calculated only considering the domestic water demand using the present domestic water demand obtained from the social survey.

The establishment of water supply services in islands are expected to decrease groundwater usage. Average per capita demand for water supply water was estimated approximately 50 LPCD for the 15-year projections and 75 LPCD for 33-year projections. This is assumed by considering the current water usage patterns in other islands with Water Supply systems such as GDh. Thinadhoo and HDh.

Kulhudhuffushi and also Male'. Therefore, to calculate groundwater usage, the water supply water usage (50 and 75 LPCD) was deducted from the total domestic water demand

The results of the Social Survey are presented in Sections 5.3, 6.3, ..., 11.3 for the six islands.

4.3.6 Stakeholder Consultancy

Meetings were held with Ministry of National Planning, Housing and Infrastructure to obtain details of any planned significant infrastructure projects in the 06 islands to ensure that any proposed MAR design aligns with future road development and drainage plans.

Initially online meetings were held with the island councils and physical meetings were held during the field investigation period. Additionally, representatives from the island utility authority, health center, school and other institutions were also consulted during the field investigation period.

Stakeholder Consultation attendance sheets and minutes of meetings are attached to Annex I.

4.4 Water Quality Survey

4.4.1 Physiochemical + instrument/equipment used

Sampling locations for physiochemical parameters of groundwater were selected in a way that represents the whole island with its various land use areas including residential areas, commercial areas, agricultural areas, and vegetated areas. Sampling locations were chosen in close proximity to Electrical Resistivity (ER) survey locations for validation of ER survey results. Sampling locations were evenly distributed throughout the island and included points from the centre of the island as well as around the coastal ridge of the island.

The geographical coordinates of the sampling location were marked using Global Positioning System (GPS). As per the Terms of Reference (TOR), 40 samples were taken from each island.

For the measurement of the physiochemical properties of groundwater, a YSI ProDDS water quality meter was used. This device is a portable, handheld multi-parameter probe/meter with a digital sampling system. The ProDDS is suitable for data collection in surface water, groundwater, coastal, and even wastewater. The ProDSS water quality meter uses smart sensor technology that allows sensors to be automatically recognized by the handheld device while retaining calibration data.

The following physiochemical parameters were measured for each island:

- **pH** – The instrument was calibrated using a two-point or three-point calibration with buffers of known pH.
- **Dissolved Oxygen (DO)** – The amount of dissolved oxygen in a sample can vary with depth, temperature, and biological demand. Care was taken to avoid turbulence and sample aeration in groundwater sampling.
- **Electrical Conductivity (EC)** – Electrical conductivity (EC) is a term used to describe a measurement unit of salinity. Calibration of conductivity meters was performed using standards of a known concentration that are appropriate to the anticipated range of conductivity of the water to be sampled.
- **Turbidity** – A measure of the quantity of suspended material in a water body.
- **Temperature** – The temperature of the water to be sampled was generally the mean temperature of the region that the well is located. Temperature will move toward ambient upon sampling, so it was recorded as soon as a stable reading was obtained after collection.
- **Salinity** – The salinity of the water is a measure of the concentration of dissolved salts in the water.
- **Ammonia** – Ammonia was measured in NH₃-N form using the molecular weight of only the nitrogen atoms. Relevant conversion charts were used to convert NH₃-N to NH₃ (ammonia).
- **Nitrate** – Nitrate is measured in NO₃-N form using the molecular weight of only the nitrogen atoms. Relevant conversion charts were used to convert NO₃-N to NO₃ (Nitrate).
- **Phosphate** – Naturally, phosphate concentration in surface water is very low. However, usage of fertilizers, detergents and leaching of wastewater has caused an increase in Phosphate

concentrations and widespread eutrophication. Groundwater samples were taken and sent to MWSC laboratory for phosphate concentration testing.

The following Table 20 shows the details for the physiochemical parameters that were tested.

Table 20: Physiochemical parameters details

Parameter	Test Method	Unit	Accuracy	Resolution	Reference
pH	In-situ Multi-probe	Standard Units	±0.2 pH units	0.01 pH units	YSI ProDDS Multi-probe
DO	In-situ Multi-probe	mg/L or %	- 0 to 200%: ±1% of reading or 1% saturation, whichever is greater - 200 to 500%: ±8% of reading - 0 to 20 mg/L: ±0.1 mg/L or 1% of reading, whichever is greater - 20 to 50 mg/L: ±8% of reading	0.01 mg/L and 0.1%, or 0.1 mg/L and 1% (user selectable)	YSI ProDDS Multi-probe
EC	In-situ Multi-probe	mS/cm	0 – 100 mS/cm: ±0.5% of reading or .001 mS/cm, whichever is greater 100 – 200 mS/cm: ±1.0% of reading	0.001, 0.01 or 0.1 µS/cm (range dependent)	YSI ProDDS Multi-probe
Turbidity	In-situ Multi-probe	FNU	0 to 999 FNU: 0.3 FNU or ±2% of reading, whichever is greater 1000 to 4000 FNU: ±5% of reading	0.1 FNU	YSI ProDDS Multi-probe
Temperature	In-situ Multi-probe	°C	±0.2 °C	0.1 °C or 0.1 °F (user selectable)	YSI ProDDS Multi-probe
Salinity	In-situ Multi-probe	mg/L or PPT	±1.0% of reading or ±0.1 ppt, whichever is greater	0.01 ppt	YSI ProDDS Multi-probe
Ammonia	In-situ Multi-probe	mg/L as NH ₃ -N	-	0.01 mg/L	YSI ProDDS Multi-probe
Nitrate	In-situ Multi-probe	mg/L as NO ₃ -N	±10% of reading or 2 mg/L, whichever is greater	0.01 mg/L	YSI ProDDS Multi-probe
Phosphate	Laboratory	mg/L as P			HACH DR5000 Spectrophotometer procedure Manual

When the water quality was checked from existing wells, the probes were dipped straight into the well and measurement was taken at the top of the well first and then at the bottom of the well to compare how the water quality parameters change with depth. Care was taken to ensure minimal disturbance

to the water as the probe was inserted into the well. At the top of the well, it was ensured that the probe is completely immersed in the water.

If wells are lidded and probe cannot be inserted, depending on availability of pumps, water was pumped straight into the collection container of the instrument and the sensors was flushed with the sample water at least twice before taking readings.

No-purge sampling was carried out with the underlying assumption that the water within the well is equilibrated with the groundwater in the associated formation.

As physical and chemical changes to groundwater can occur following removal from the aquifer through exposure to the atmosphere, changes in temperature, and changes in pressure, importance was given to using equipment which can take in-situ readings, with minimal disturbance.

Quality assurance (QA) and quality control (QC) procedures were integral to ensure representativeness and integrity of water samples and resulting data to be used in review, analysis and concept and detailed design. The following QA/QC measures were followed to minimize errors and provide accurate results for the physiochemical survey:

- Equipment to be used to collect samples were appropriately cleaned and decontaminated
- The water quality equipment was calibrated according to the manufacturer's requirements.
- Water of a known low analyte concentration was used as a 'blank' sample to detect whether sample contamination occurs during the sampling process.
- No samples were collected before there is no significant variation in the physical parameters. That is changes of less than $\pm 10\%$ for pH, conductivity, or dissolved oxygen or less than $\pm 0.2^\circ\text{C}$
- If groundwater was pumped from wells for sampling, the sensors of the probe were flushed with the sample water at least twice before readings were taken.
- The water level probes were decontaminated between each sampling point by wiping or scrubbing off soil or other foreign material and rinsing with tap water.

All groundwater sampling and water quality testing was conducted following US EPA SESDPROC-301-R4, Groundwater Sampling, (US EPA, 2017) or ASTM D4448: Standard Guide for Sampling Ground-Water Monitoring Wells (ASTM, 2007/2019).

4.4.1.1 Correlation Matrix

A Correlation matrix was produced which provides the assessment of the correlation coefficients "r" between groundwater quality elements. These coefficients were applied to suppress the strength of the linear relationship between the variables. It has been used to estimate both positive and negative correlations. A colour bar is provided along with correlation matrix which indicates the strength of the correlation.

4.4.1.2 Water Quality Index

Water quality index (WQI) is one of the most effective tools to communicate information on the quality of water. The WQI is a mathematical instrument used to transform large quantities of water quality data

into a single number which is easily expressible and understandable. It thus, becomes an important parameter for the assessment and management of groundwater.

WQI is a rating reflecting the composite influence of different water quality parameters. In this study, a simple methodology based on multivariate analysis is developed to create a WQI.

For computing WQI the following steps are followed:

- 1) Parameters with comparable standards (S_i) are identified and assigned a weight (w_i) according to its relative importance in the overall quality of water.
- 2) The relative weight (W_i) is computed from the following equation:

$$W_i = \frac{w_i}{\sum_{i=1}^n w_i}$$

Where, W_i = the relative weight, w_i = weight of each parameter, n = number of parameters

- 3) A quality rating scale (q_i) for each parameter is assigned by dividing its concentration in each water sample by its respective standard and the result multiplied by 100 as follows:

$$q_i = \frac{C_i}{S_i} * 100$$

Where q_i = quality rating, C_i = concentration of each parameter in the water sample,
 S_i = water quality standard.

The following Table 21 shows the different values used in the WQI calculations.

Table 21: WQI Calculation parameters

	Turbidity (FNU)	EC (μS/cm)	NH₃ (mg/L)	NO₃⁻ (mg/L)
S_i	5	2500	35	50
w_i	1	3	2	2
W_i	0.125	0.375	0.25	0.25

- 4) WQI is then calculated using the following equations:

$$SI_i = W_i * q_i$$

$$WQI = \sum SI_i$$

Where SI_i = subindex of i th parameter, q_i = quality rating, WQI= Water Quality Index

The computed WQI values are classified into the following four categories:

Table 22: WQI Categories

WQI	Category
0 to 10	Very Good
10 to 20	Good
20 to 50	Poor
>50	Very Poor

The WQI is then mapped such that the areas with high and low water quality can easily be distinguished by researchers as well as policymakers or the general public.

However, their application should always involve the necessary care and prudence, as standardization and aggregation of the variables are subjective procedures accompanied by a loss of information. Therefore, the index can never be considered as a final quantitative assessment of capability of groundwater to be used as a reliable source of water but should be applied as a purpose-specific water management tool.

4.4.2 Microbiological + instrument/equipment used

Microbiological surveys were conducted at each island where total coliform and faecal coliform was measured at sampling locations. As per the TOR, 15 samples were taken from each island.

The minimum distance between septic tanks and groundwater wells where samples for microbiological analysis were taken from, was measured and any resulting microbiological contamination was analysed. This analysis was supplemented by septic tank usage and maintenance information provided by the Social Surveys.

The water samples were collected using Whirl-Pak® Thio-Bags® which contain 25 mg of active sodium thiosulfate to neutralize chlorine at the time of collection. To ensure the integrity of the water samples, they were kept with ice inside cool boxes to maintain temperatures between 4 and 10 degree Celsius. These samples were transported to the Male' Water & Sewerage Company Pvt. Ltd. (MWSC) laboratory within 24 hours for faecal and coliform testing. The following Table 23 shows the details of the microbiological testing that was carried out.

Table 23: Microbiological Test Details

Parameter	Test Method	Unit
Total coliform	Laboratory	MPN/100 mL
Faecal coliform	Laboratory	MPN/100 mL

Quality assurance (QA) and quality control (QC) procedures were integral to ensure representativeness and integrity of water samples and resulting data to be used in review, analysis and concept and

detailed design. The following QA/QC measures were followed to minimize errors and provide accurate results for the microbiological survey:

- The person collecting the sample washed their hands thoroughly with soap and water before collecting samples.
- If wells were sampled, care was taken to ensure the sterility of all sampling equipment and all other equipment entering the well.
- There was no flushing of Whirl-Pak® Thio-Bags® with sample water to prevent removal or disintegration of the preservatives in the bag.
- The bags were handled with care and were only opened at the time of collecting the sample and filling the bag.
- To avoid contamination of sample, Care was taken by all sample collecting staff to not touch the lip or inside of the sampling bag.
- The bag was sealed tightly immediately after collecting sufficient amount of water and labelled.
- The bags were kept in ice inside cool boxes at temperatures between 4 and 10 degree Celsius to ensure the integrity of the sample.

4.4.3 Limitations

For islands with large farming areas, information about fertilizer and pesticide usage was not obtained within the social survey. As the usage of fertilizers correlates to Nitrate contamination of groundwater, this information would be useful in the groundwater physiochemical results analysis. For future studies, it is recommended to include this information in the Social Survey questionnaire.

There were limitations in the microbiological analysis as information about sewerage disposal methods for institutions and commercial entities were not obtained in the Social Survey. Information about sewerage disposal methods were only obtained for households. This additional information would have enabled a more complete analysis of microbiological contaminations.

The results of the Water Quality Survey are presented in Sections 5.4, 6.4, ..., 11.4 for the six islands.

4.5 Pumping Test

4.5.1 General/objective

In order to obtain the aquifer properties which are essential to groundwater models, a Multi-Well pumping test was proposed during the inception phase. However, during field visit it was observed that such tests were not practical due to limited space and lack of observation wells within the proximity of the test well. Additionally, a multi well approach was studied in one of the islands where observation wells within 6m and 12m radius of the test well were constructed in an open land. There were no significant observations in changes in water level that can be utilized to understand the aquifer properties. As such a step draw down test on single well was carried to investigate the performance of a pumping well under controlled variable discharge conditions. In a step-drawdown test, the discharge rate in the pumping well is increased from an initially low constant rate through a sequence of pumping intervals (steps) of progressively higher constant rates. Each step is typically of equal duration, lasting from approximately 30 minutes to 2 hours (Kruseman and de Ridder 1994). Each step should be of sufficient duration to allow dissipation of wellbore storage effects.

The hydraulic properties such as transmissivity and Storativity of the aquifer were estimated by carrying out the pumping test.

One pumping test was carried out in each island in a manner and during a period so that it does not impact the groundwater use in the island. The test was carried out in accordance with the dewatering regulation number 2021/R-20.

4.5.2 Instrument/equipment used

The equipment used in the pumping test are as follows:

- i. Rotary drill or Auger (where observation wells were made).
- ii. PVC pipes, fittings and 50m flexible hose to discharge the pumped water into the sea or an empty plot.
- iii. Pump with sufficient capacity
- iv. Water meter to measure discharge rates.
- v. Measuring guides for water level measurements
- vi. Water quality probe to measure Electrical Conductivity

4.5.3 Approach/methodology

A well without a base (or if not available on the island, a well without a fully enclosed base) was chosen for the pumping test. As the wells tested for pumping are existing dug wells within the island, the selection process also ensured that no other extraction will be ongoing from the well during the pumping test.

The methodology used in the pumping test are as follows:

- Pump and rising main was inserted into the well and drawdown is carried out at a known flow rate. The rate of flow from the pump was measured by a flow meter. The water levels were measured by placing a measuring tape at a marked location of the well.
- Water level measurements were recorded in both pumping and observation wells (where applicable) continuously and a typical drawdown time and pumping response curve is generated.
- Electrical conductivity values were also recorded at a set time interval, using a digital water quality probe.
- Pumping is carried out until one of the following conditions are met; either 50% or 75% drop in water level, sudden surge in electrical conductivity (EC) value, 180 minutes each of pumping phase or recovery phase has been carried out.
- The raw data from the test was analyzed using the software AQTESOLV. The Cooper-Jacob Solution for Unconfined Aquifer Models was used for this analysis.
- The type of well, the diameter of the well, total depth of water, as well as the time, flowrate, and water level measured at set interval were the input parameters required for the software.
- The software generated displacement-time graphs using the input data and using curve fittings the Transmissivity and Storativity were calculated as the output parameters.

The pumping test set-up is shown in Figure below.

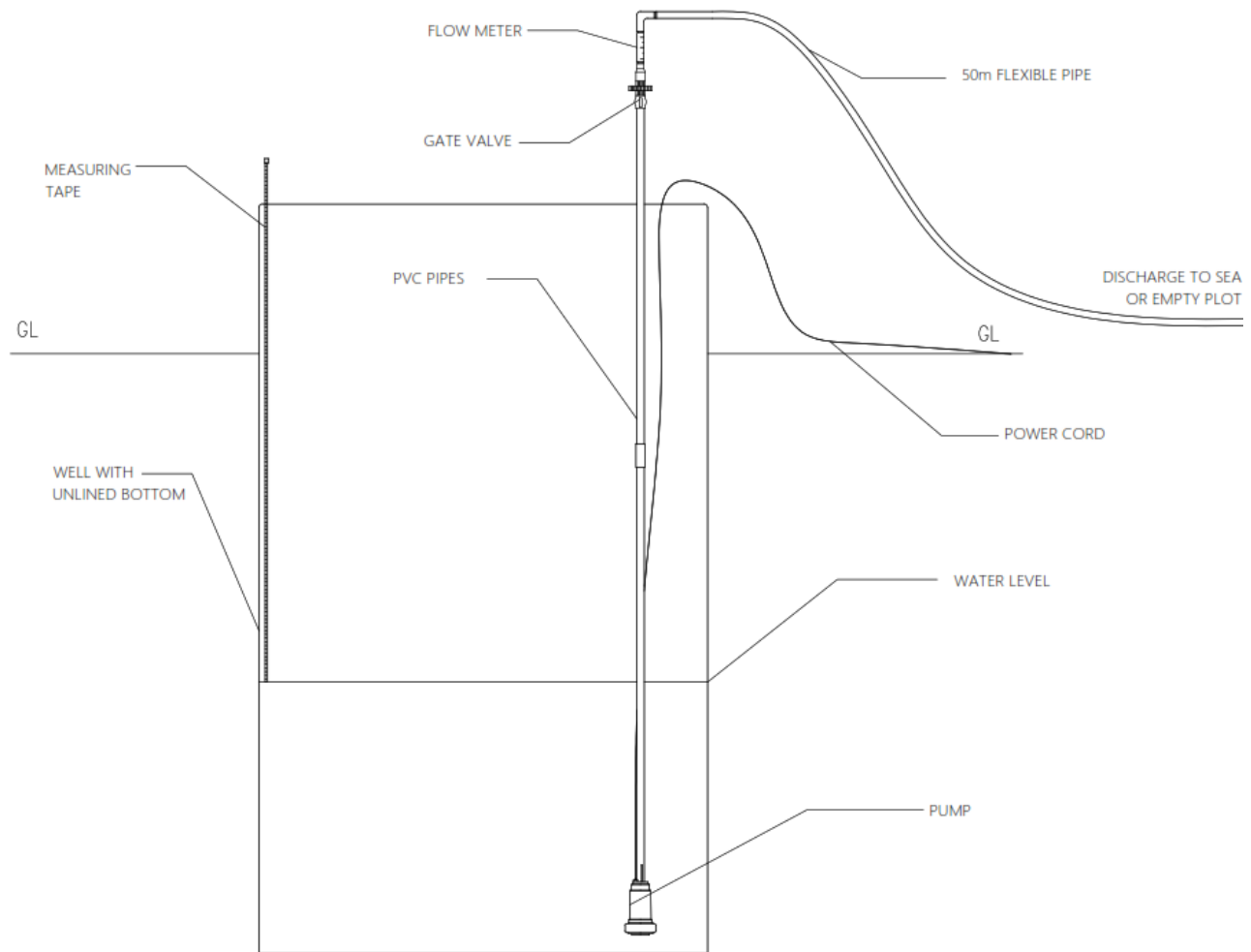


Figure 16: Pumping Test Setup

4.5.4 Limitations

The multi-well pumping test initially proposed in the methodology was changed to a single-well pumping test, as observation wells were not available nearby, and limitations on site did not allow boreholes to be drilled.

The results of the Pumping Test are presented in Sections 5.5, 6.5, ..., 11.5 for the six islands.

4.6 Permeability Test

4.6.1 General/objective

Permeability is a measure of the rate of the flow of water through the soil and estimating the rate is important to develop conservation strategies and aquifer management plans.

Sample locations were chosen to cover geological features encountered during the site visit. Five permeability tests were carried out on each island.

4.6.2 Instrument/equipment used

The equipment used in the permeability test are as follows:

- i. Auger
- ii. 4-inch diameter PVC pipe with 3mm holes made at a 0.5m section. (Interval between holes were kept at 1-2 inches. A drill was used to make the holes)
- iii. Plastic barrel (with capacity of 200 Liters)
- iv. Timer
- v. A pump with a maximum flowrate of 120 LPM.
- vi. PVC Pipes and fittings to connect the pump to the flowmeter, and the flowmeter to the perforated pipe.
- vii. Water flow meter.
- viii. Aggregates (10-20 mm)
- ix. An 8-inch diameter PVC pipe to be used as casing.
- x. Measuring tape.

4.6.3 Approach/methodology

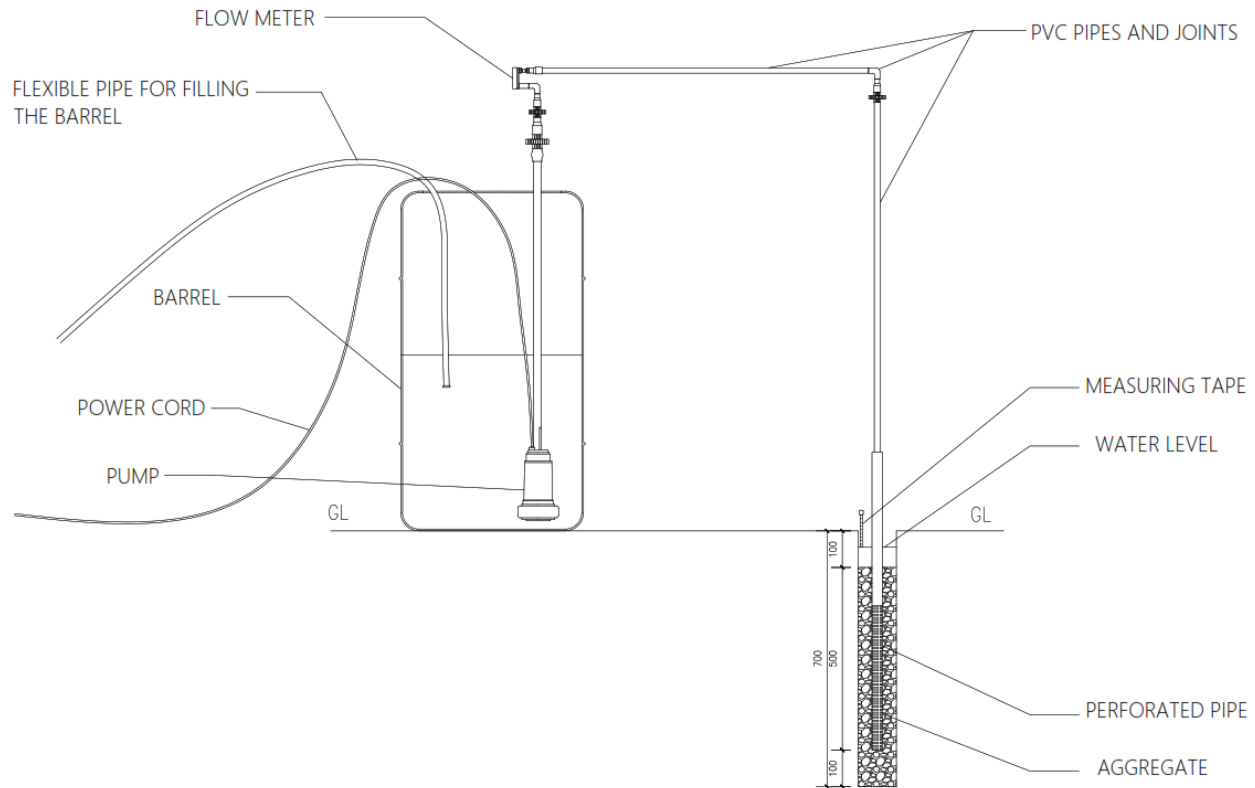


Figure 17: Field set up of a typical constant head permeability test

Constant Head Gravity Permeability Tests were carried out to obtain permeability by measuring water absorbance of unconsolidated materials. Permeability tests were carried out following Gravity Permeability Test Method 1 (Engineering Geology Field Manual, vol. II, 2001). The methodology for the test is as follows:

- A 4-inch (100-mm) or larger hole was drilled or augered to the test depth and then carefully developed. A constant test depth of 700mm was used for all islands.
- A cushion of coarse gravel was placed at the bottom of the hole, setting a bed of approximately 100mm in depth, and the perforated feed pipe (I) was set in position (Figure 17).
- After the pipe is in position, the hole was filled with medium gravel to a depth at least five times the diameter of the hole. This depth was set as 500mm for all islands.
- Water was pumped into the casing and the flowrate was controlled by adjusting the valves connected to the flowmeter. A stabilized water level was observed for 5 minutes. The water supply

was controlled so that the stabilized water level was not within the casing and was located more than five times the hole diameter above the bottom of the hole. The water flow generally had to be adjusted to obtain the required stabilized level.

- The readings that were taken from this test are:

Q = Steady flow into well (m^3/s),

H = Height of water in well (m),

l = length of perforated section (m), [$l=H$ for this test]

r = radius of test section (m),

C_s = Conductivity Coefficients (Figure 18) and

T_u = distance from water level in casing to water table (m).

- Coefficient of permeability, K (m/s under Q unit gradient) was obtained using the following equation:

$$K = \frac{2Q}{(C_s + 4)rT_u}$$

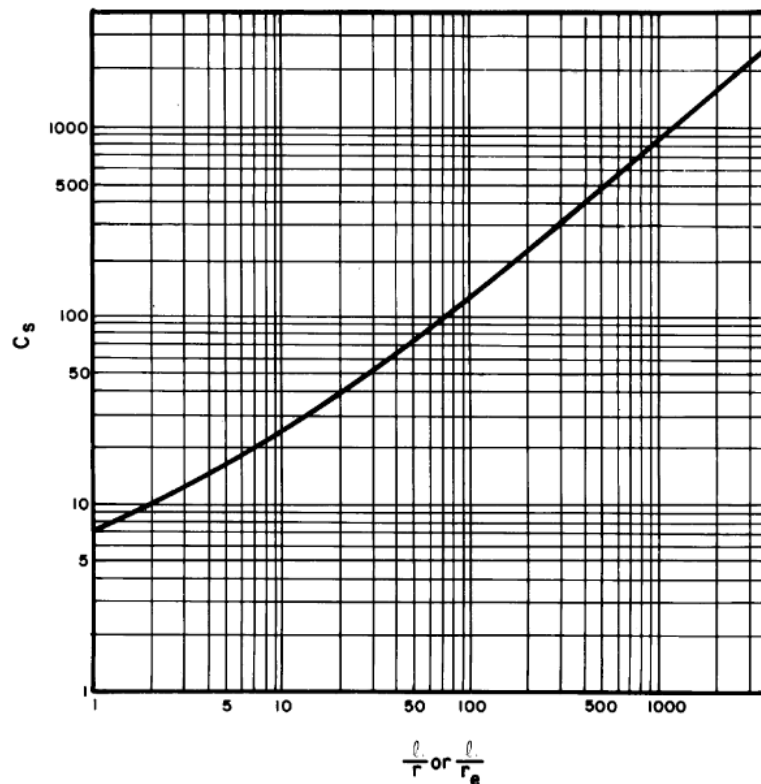


Figure 18: Conductivity coefficients for semispherical flow in saturated materials through partially penetrating cylindrical test wells (Engineering Geology Field Manual, vol. II, 2001)

4.6.4 Limitations

The originally proposed locations had to be changed due to difficulties in obtaining water and electricity for the test, as well as to utilize public spaces which are more ideal for the implementation of the design solutions.

The results of the Permeability Testing are presented in Sections 5.6, 6.6, ..., 11.6 for the six islands.

4.7 Soil Profile Survey

4.7.1 General/objective

Soil profiles were determined by drilling boreholes at the test location using the Auger. A small sample of soil was taken from each of the visibly identifiable layer and placed in a sample bag. The layer start depth and end depth were also recorded on the respective sample bags. These samples were later used to identify the type and colour of the soil in order to establish a soil profile for each of the test locations. Soil profile survey was carried out to a depth of 0.7 meters, as the boreholes for soil profile were also used in the permeability test which required a hole depth of 0.7 meters. Moreover, the ground water levels were encountered around this depth, hence drilling further with the auger was not possible due to the soil caving in on the hole.

The visible soil profile was further verified by carrying out dynamic cone penetrometer (DCP) tests up to depths of up to 1 meter at the selected location. The average displacement (mm/blow) values from the DCP test results were used to verify the depths at which the soil layers start/end. The DCP tests are described in ASTM D3441 – 16 (Standard Test Method for Mechanical Cone Penetration Testing of Soils) and ASTM D 6951 – 03 Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications. The setup involved driving a steel cone with extension rod assembly to determine the number of blows required for the cone to penetrate a certain depth. Tests were carried out to a depth well below the water levels which are encountered typically shallow. The DCP tests were carried out near or adjacent to the locations of sample collection in order to provide a comprehensive data set which can be used with geophysical surveys to parameterize and quantify the underground water aquifer.

Sample locations were chosen to cover geological features encountered during the site visit. Seven Soil Profile Surveys were carried out on each island.

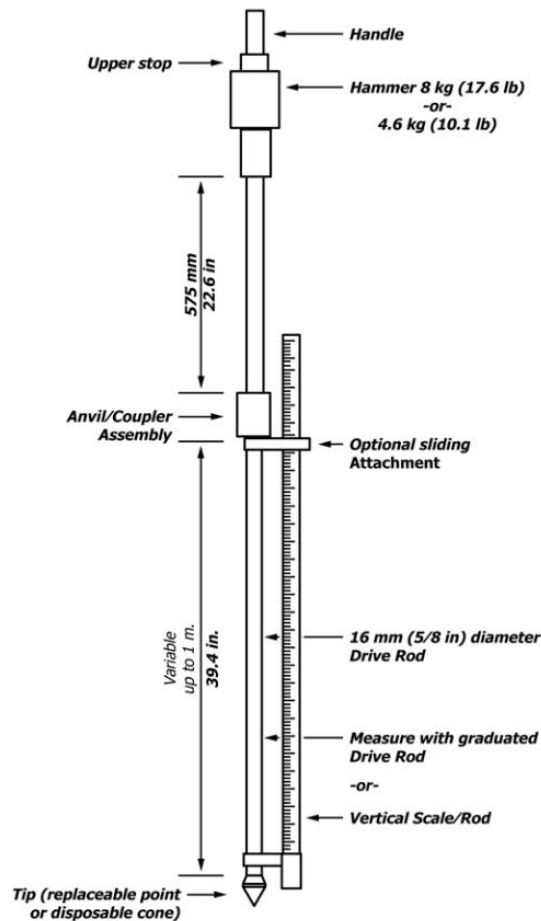


Figure 19. Schematic of Dynamic Cone Penetrometer apparatus (ASTM D 6951 – 03)

4.7.2 Instrument/equipment used

The equipment used in Soil Profile are as follows:

- i. DCP Hammer and anvil
- ii. Extension rods of 1 m
- iii. A vertical scale graduated using increments of 1.0-mm (0.04-in.), or measuring rod longer than the longest drive rod if the drive rod(s) are not graduated,
- iv. Tools for assembling the DCP,
- v. Lubricating Oil,
- vi. Thread Locking Compound, and
- vii. Extraction jack, recommended if disposable cone tips are not used
- viii. Auger
- ix. Sample bags for soil profiling.
- x. Measuring tape.

4.7.3 Approach/methodology

Soil sampling was carried out as follows:

- A borehole was drilled at the test location using the Auger. A small sample of the first layer of soil was then placed into a sample bag and labelled with the necessary details.
- After drilling for approximately 100 millimeters, the soil was checked to see if a different type/colour of soil have been encountered. This process was repeated up to a depth 0.7 meters, and samples of all the different layers were obtained and the layer depths recorded.



Figure 20: Soil profile collected

Dynamic cone penetrometer (DCP) tests were carried out as follows:

- The setup is assembled with the cone tip centred on the location to be tested (Figure 19) with an 8 kg driving hammer at the upper stop position.
- The operator releases the hammer and the raises it subsequently to the upper stop position before releasing again.
- The distance penetrated after 5 blows is recorded before continuing.
- If after 5 blows, the device has not advanced more than 2-mm (0.08-in.) or the handle has deflected more than 75-mm (3-in.) from the vertical position, the test shall be stopped.



Figure 21: Dynamic Cone Penetrometer Testing on-site

The results of the Soil Profile Survey are presented in Sections 5.7, 6.7, ..., 11.7 for the six islands.

4.8 Flood Assessment and Inundation Survey

4.8.1 General/objective

Catchment of the flood water includes rooftops, paved & compacted roads, compacted & interlocked brick earth & compacted soils in houses. Flood plains are lands subject to recurring floods located adjacent to the marshlands, water bodies and low elevated grounds. Most flood prone zones of studied Islands are associated with roads & flood plain zones and these zones are more vulnerable to flood events. The unplanned development activities make the situation further hazardous. However, the flood prone zones can be potentially used for storing and recharging the groundwater during extreme events and flooding conditions. Therefore, it is necessary to identify and map these zones for the potential benefits of both recharging into groundwater and thereby reducing the risk of flooding in the regions.

Processing of available precipitation data was key in establishing the flood zones. As there are no rainwater gauges in each of the islands under the study, rainfall data taken from the nearest weather station would be utilized. Based on the information collected, 20–30 years of historical weather data was processed to provide Intensity frequency and Duration (IFD) curves.

The causes & effects of the small to large scale floods and flash floods are very important to the design & management purpose of the flood mitigation. Topographic information is required for finding the flood depth and volumes. The approach to map these flood prone zones was based on topographic surveys carried.

The flood prone zone mapping done through topography and weather data was verified with field surveys as discussed in the social survey. The field data for flood depth and extents was assessed from social survey, literature, and other existing project reports.

4.8.2 Approach/methodology

4.8.2.1 Flood occurrence & Draining period

The survey utilized water indicators and socio-economic status of households, institutions, commercial units, and industrial areas on determining the flood causes and frequency. This includes reported and observed data on causes of flooding, draining period and discharge of rainwater overflow in the households. A number of quantitative indicators were also used to express the form of proportions (for example, percentages to indicate the cohort of responses for flooding causes, discharge of rainwater overflow and draining period). This is to facilitate perception of the magnitude observed in the set data. As most of the islands did not have much historical data, available limited information was used to present the flood frequency and occurrences of the island.

4.8.2.2 Flood impact

For the flood assessment survey, social impact and perceived flood assessment in the selected islands were surveyed upon individual and community social characteristics with their experiences on significant historical flooding events and recent flooding events.

This method is more salient in identifying people's actual risks of experiencing environmental hazards and recovering from the impacts of it. The survey also sought to understand whether a broad sample of selected households from each island would perceive flood risk and adaptation differently. Therefore, several plausible scenarios and options were given while determining the severity and impact of the affected households; damage indexes were explained for accurate reporting. For the flood damage assessment, it only involves the physical damages which are rated into four brackets: (minor, moderate, severe and no damage).

- Minor - Damages to outside properties of the household, (example, inaccessible roads, broken fences & trees etc)
- Moderate - Content damages to the household which are fixable. (Content damage refers to damage to personal property kept inside the building that is not permanently affixed to the building)
- Extreme - Structural damages which are not fixable. (Example, damages to fittings, fixtures, and appliances)
- No damages (No damages caused by flooding)

For the problem rating aspect, three brackets (acceptable, mild and severe) were given to assess the impact of flooding. The flood data also covers a series of potential impacts which the community may be subjected to during major infrastructure projects or natural disasters. The classification of data sets in this element was determined based on individual responses while evaluating how they have experienced long term impacts of the project/event over time. However, it must be considered that the two events may not have a direct cause and effect relationship as this was solely for predicting potential social impact and providing a basis to mitigate flooding causes over time.

4.8.2.3 Flood depth & Inundation

In order to gather necessary information related to flood inundation areas, Digital Elevation Model data and flood inundation periods from social survey was collated and analysed in the report. The data was then analysed and overlaid by GIS techniques and presented in GIS maps. The maps also presented potential and significant flood zones including the identification of flood depth. The measurements calculated were based on average flood depths reported by the households.

The mitigation measures and flood reports are limited to specific incidents and were analysed on a case by case basis.

4.8.3 Limitations

One of the limitations of flood survey are the assumptions made regarding rain induced flooding. The inundation and draining periods reported by households simply vary depending on magnitudes of rainfall and is only limited to the most recent rainfall the respondent has experienced. For future

research, it is important to monitor inundation and draining periods for a longer time frame to have significant estimates of flood risk and impact in the community. The mitigation measures and flood reports are also limited to implications where consistency varies from the most recent memory of the surveyed individual. Therefore, when determining social impact, the survey did consider external factors and available data on disaster risk level, environmental risks and as well as access to natural environment and resources in the islands.

The results of the Flood Assessment and Inundation Survey are presented in Sections 5.8, 6.8, ..., 11.8 for the six islands.

4.9 Geophysical Survey

4.9.1 General/objective

A prime objective of the study is to assess the baseline condition of the project islands with respect to water quality and water quantity and to use the findings for developing strategies to conserve the groundwater and manage the aquifer. Under this objective, TOR instructs to conduct an ER survey to identify the variation of freshwater lens thickness and to estimate the freshwater quantity being stored in those lenses. These data and information are to be used for

- a) identifying the impact on freshwater lens with respect to water quality
- b) comparing with freshwater lenses predicted by the SUTRA model
- c) developing protocols for groundwater extraction and recharge system
- d) designing MAR system

This baseline assessment report addresses items (a) and (b) and remaining items will be covered under Feasibility Study.

4.9.2 Instrument/equipment used

GD-10 instrument which is a product of Geomative Ltd was used for ER Survey and it is a multi-functional direct current (D.C.) method instrument, based on the latest digital and analog circuitry technology. GD-10 has facility to carry out 1D and 2D/3D ER survey and it has advantages of data logging and processing.



Figure 22: ER Survey Instrument

Left: GD-10 connection to power supply, Center: GD-10 mainframe, Right, GD-10 Power cables (Source: geomative.com)

4.9.3 Approach/methodology

1D Vertical electrical sounding (VES) method was used to measure the resistivity of the soil in the project islands and this method was selected as it was relatively faster while giving intended results with adequate accuracy. The Schlumberger array method was used to estimate resistivity using measured voltage difference for a known current. Descriptions of Schlumberger array methods are given below.

4.9.3.1 Schlumberger Array Method

Figure 23 shows the typical configuration of the measurement setup. The electrodes A and B are current electrodes, and they are connected to a current source whereas M and N are potential electrodes which are used to measure the voltage difference. As source, the direct current or low frequency alternating current is sent through electrodes A and B.

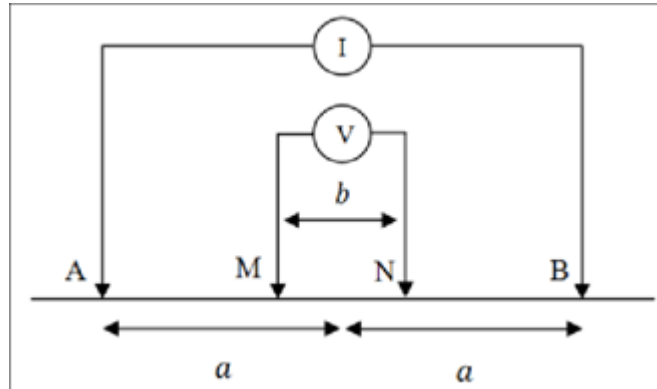


Figure 23: Diagram for the Schlumberger Array

Geometric factor calculation for Schlumberger Array (K) is defined as

$$K = \frac{\pi(a^2 - \frac{b^2}{4})}{b}$$

where,

a : half of distance between Current electrodes (m)
 b : distance between Potential electrodes (m)

Apparent resistivity is equal to (ρ)

$$\rho = K \frac{(\Delta V)}{I}$$

where,

ρ Apparent Resistivity
 (ΔV) Potential voltage difference
 I Current passing through the soil

4.9.3.2 Survey Procedure

Procedure adopted for ER survey in the field are given below.

- I. A map showing transect lines together with shoreline and other landmarks was prepared and tentative ER measurement locations were marked. Locations close to shoreline were chosen around 20–30 m away from it as the water is usually saline at this region. When choosing other locations, a distance of 100 m – 200 m was maintained. However, these locations were further adjusted on following occasions.
 - If the accessibility to the measurement location was not possible.
 - EC values of groundwater samples taken under water quality survey showed sudden change in a particular location
 - Island coverage of ER measurement was adequate to make reliable estimation of freshwater volumes using the same.

Refer Annex IX: ER Locations for ER survey location map.

- II. Current electrodes were placed at smaller intervals to larger intervals so that unsaturated soil thickness and start and end of freshwater lens can accurately be identified by analysing the measured resistivity data and change in the geological formation within 20 to 30 m depth of the soil layer can be recognized. Minimum spacing between electrodes was 1 m and maximum was 60 m. A script representing electrode spacing was entered into GD-10 equipment prior to commencement of the ER survey in the field.
- III. Step (ii) was followed at each ER measurement location. However, at few locations taking ER measurements at larger intervals could not be done due to access difficulty and at such locations maximum distance between electrodes were limited to 30 – 40 m which was adequate to identify freshwater lens thickness. Also, since freshwater depth thickness is lesser in areas near to the shore, maximum spacing between electrodes were limited to 40 m.
- IV. Coordinates of ER measurement locations were taken using handheld-GPS in addition to marking the location in the map prepared in (i).
- V. Figure 24 shows the photographs taken during ER survey together with equipment used for the same.



Figure 24: ER survey equipment and measurements taking in the field

4.9.4 Estimation for freshwater volume

As noted previously the objective of the ER survey is to identify the freshwater layer underneath of the island and estimate volume of the same at the time of the measurement. This data will later be used to model the freshwater variation over in the future and to design the MAR system.

Steps followed in carrying volumetric calculations are given below.

- I. Survey data stored in the GD-10 equipment was copy-pasted into GeoVES 1.5 – GeoElectrical Model and they were used to identify the variation of the resistivity over depth via plotting the data on log scale. Below table shows the resistivity values used to differentiate freshwater and saline water depths.

Table 24: Resistivity values used for freshwater characterization

Zone	Resistivity (Ohm, m)
Unsaturated sand	> 30
Freshwater	10 – 30
Saline water	<5

- II. The estimated depth for start and end of the freshwater layer was converted to level with respect to mean sea level using the ground level of ER surveyed location.
- III. Step (I) and (II) were repeated for other data set locations of ER survey and hence a table consisting of ER survey location/co-ordinates, ground level, freshwater level and saltwater level were prepared and used in ArcMap and ArcScene to create a 3D view of freshwater layer underneath the island and the same data was used for volumetric calculation as described below.

- IV. A triangular mesh (Figure 25) was established by connecting ER measurement locations and they were used to estimate the spatial extent of freshwater lenses by summing areas of these triangles in the mesh. Average height/depth to water level and freshwater – saline water interface computed for each triangle in the mesh was multiplied by the area of the respective triangular to calculate freshwater volume in it and volume of freshwater lens was estimated by summing the volume of each triangles in the mesh and multiplying it by porosity of the soil.

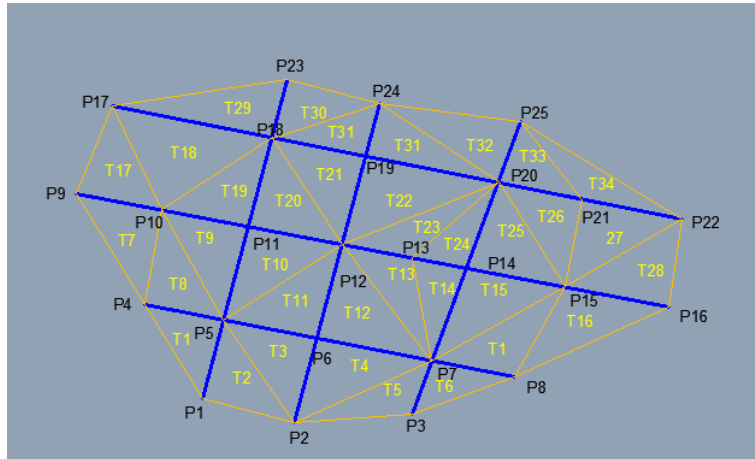


Figure 25: Triangular mesh of ER measurement locations

The other alternative method used for freshwater volume estimation is transferring freshwater levels and saline water levels from ER measured locations to 20m x 20m grids prepared for SWB modelling using interpolation techniques available in ArcGIS and multiplying depth or height of freshwater lens by grid area to calculate freshwater volume underneath the grid. Such computed volumes at grids were summed to estimate the total volume of the freshwater lens volume of the island.

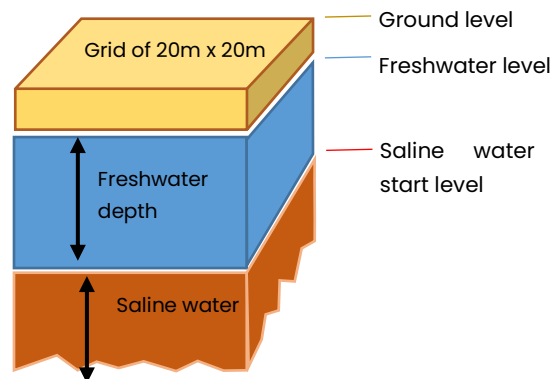


Figure 26: Grids for freshwater volume estimation

The freshwater lens volume estimated through triangular mesh computation method was compared with that of the interpolation method of 20m x 20m grids for project islands and found that they were tallying closely.

Falkland (1994) has suggested the use of an empirical formula to a quick and crude estimation of freshwater lens thickness in the absence of other data. This formula was originally developed by Oberdorfer & Buddemeier (1988) and they formulated a relationship relating island width (m), annual rainfall (m) and freshwater lens thickness to mid-point of the transition zone. The developed equation is given below:

$$\text{Freshwater lens Thickness (m)} = (6.94 * \text{LOG (width of the island)} - 14.38) * \text{Avg. Annual rainfall}$$

The above equation was used to estimate the maximum freshwater lens thickness and compared with the measured maximum thickness via ER survey.

The estimated freshwater thickness is expected to differ from the measured thickness. Reasons for the difference is mainly attributed to the empirical formula since only two factors are included in this formula. However freshwater thickness depends on many other factors such as soil type, permeability, ground water abstraction, land use, rainfall pattern, temperature variation etc. Also, the above said formula gives 0.1m thickness for 120m width and 3.61m thickness for 200m width. It is unlikely that maximum freshwater thickness suddenly rises by 3.5 m when island width increases just by 80m. Since Falkland (1994) noted some of these drawbacks in the same publication, it is necessary to modify the above said empirical formula based on site conditions and laboratory test before utilizing the equation for the given project scope.

The results of the Geophysical Survey are presented in Sections 5.5, 6.5, ..., 11.5 for the six islands.

4.10 SWB Modelling

4.10.1 General/objective

The proposed project is to start with assessing the groundwater quality and recharge rates in-depth and to end with designing aquifer recharge systems to increase present recharge rate by 50%. Therefore, estimating the recharge rate at the baseline condition is a key activity of the project and as proposed in the inception report, the model chosen for recharge estimation is Soil Water Balance (SWB). Once the recharge rate is estimated it will be transferred to the hydraulic model known as SUTRA to estimate the freshwater lens profile underneath the ground.

The prediction of the freshwater lens profile is to be done for two distinct cases; one is before incorporating MAR design (baseline condition) and the other is after incorporating MAR design to the project islands. Figure 27 shows the flow-chart that shows the relationship between SWB modelling and freshwater lens profile estimation.

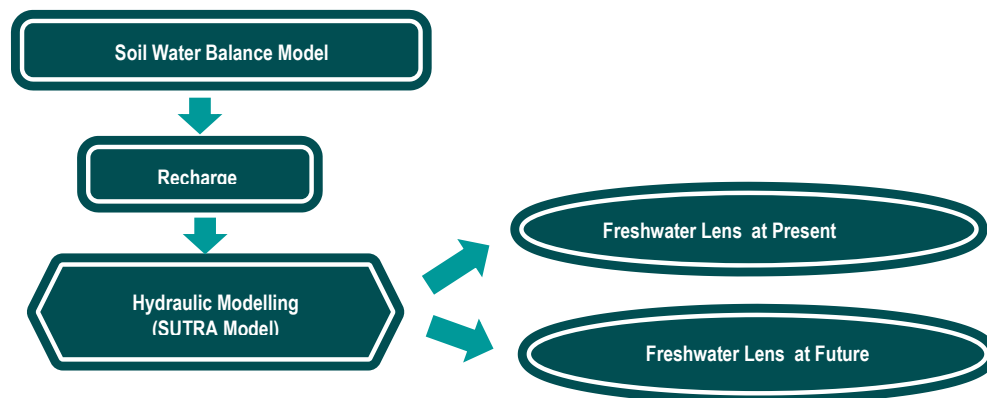


Figure 27: Flow-chart showing relationship between SWB model and freshwater lens estimation

General Features and Model Background

The Soil-Water-Balance (SWB) model is a numerical model developed by United States Geological Survey (USGS) which is a scientific agency of the United States government and this model has been developed to allow estimates of potential recharge to be made quickly and easily. The code incorporated in this model calculates components of the water balance at a daily time step by means of a modified version of the Thornthwaite-Mather soil-moisture-balance approach.

Data requirements for SWB model include several commonly available tabular and gridded data such as;

- A. Precipitation, and minimum and maximum air temperature (tabular or gridded)
- B. land-use classification (gridded)
- C. hydrologic soil group (gridded)
- D. flow direction (gridded)
- E. soil-water capacity (gridded)

The data and formats required are designed to take advantage of widely available GIS datasets and file structure.

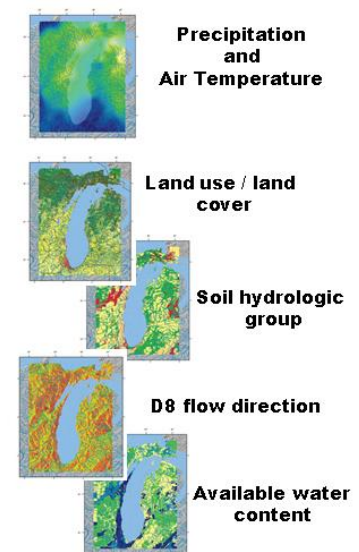


Figure 28: Data Requirements for SWB Model (Westenbroek et al, 2010)

SWB model considers multiple components for the estimation of recharge and it includes precipitation, interception, evapotranspiration, inflow, outflow, and storage change.

The first step in SWB modelling is defining the modelling area using grid cells and these cells will then be populated with landscape data, soil characteristics data and flow direction data which is to be generated using topography. Once these data are assigned, SWB model calculates recharge values on each grid cells separately based on climate data.

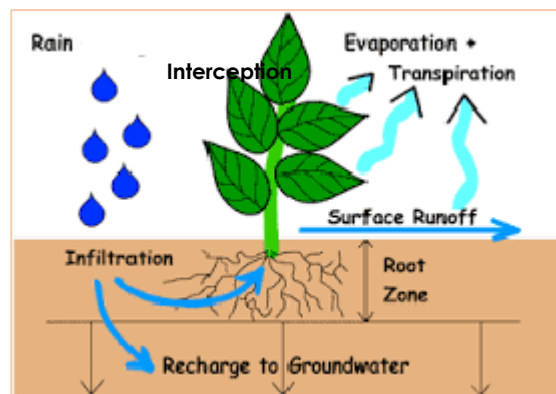


Figure 29: Components for estimation of recharge (Westenbroek et al, 2010)

Water balance components and relationship defined in the SWB model is given below.

$$\text{Recharge} = (\text{Precipitation} + \text{Snowmelt} + \text{Inflow}) - (\text{Interception} + \text{outflow} + \text{Evapotranspiration}) - \Delta \text{Soil Moisture}$$

Precipitation:

daily values in time series format

Snowmelt:

melting amount on a daily basis. The daily mean, maximum and minimum temperature are used by the model to determine precipitation takes the form of rain or snow.

Inflow:

It is calculated by use of a flow-direction grid derived from a digital elevation model to route outflow to adjacent downslope grid cells.

Outflow :

Outflow from a cell is calculated by use of the U.S. Department of Agriculture, Natural Resources Conservation Service (curve number rainfall-runoff relation.)

Interception :

It is treated simply by means of a “bucket” model approach

Evapotranspiration :

Thornwaite-Mather (1957) method or Jensen-Haise (1963) method or Turc (1961) and other commonly applied methods are available to estimate evapotranspiration.

Δ Soil Moisture:

Change in soil moisture amount is tabulated by means of the soil-water-balance methods published in Thornwaite (1948) and Thornwaite and Mather (1955, 1957).

4.10.2 Input data preparation and model set up

Model domain and grid size

As noted previously, the first step in the SWB modelling is defining grid cell size of the domain area that is to be considered by the model for the estimation of recharge and other water balance components. In this regard, after several test simulations, a grid size of 20m x 20m was selected to define the model domain of all six study islands and domain area of an island was selected so that the entire island can be included within it.

Table 25 shows grid cells and island area.

Table 25: Grids in model domain and island area

Island	No. of column in the domain	No. of row in the domain	Island Area (ha)
GA. Maamendhoo	34	76	53
GA. Nilandhoo	62	71	58.5
GDh. Hoandehdhoo	83	96	94
GDh. Nadella	52	44	45
GDh. Rathafandhoo	46	51	37
GDh. Faresmaathoda	65	63	45

Climate data

SWB model categorizes climate data into 2; essential and optional. Precipitation, average temperature, minimum temperature, and maximum temperature fall on the former category and wind speed, relative humidity and sunshine duration falls under the latter category. All data must be presented as daily data and required units. Table 26 below shows sample climate data, their units and format.

Table 26: Climate data for SWB model

Month	Day	Year	T _{AVE} (F)	Precipitation (inch)	T _{MAX} (F)	T _{MIN} (F)
1	6	2000	84.40	0.00	87.08	79.52
1	7	2000	84.70	0.00	87.80	74.12
1	8	2000	83.50	0.00	87.44	73.04
1	9	2000	82.00	0.05	86.90	76.28
1	10	2000	83.30	0.00	86.36	75.02
1	11	2000	82.00	0.04	86.36	77.72
1	12	2000	82.00	0.04	86.72	74.66
1	13	2000	78.10	0.84	82.40	72.32
1	14	2000	82.40	0.26	85.64	72.68
1	15	2000	82.90	0.00	87.80	74.30

Climate data for all 6 project islands were collected from Kaadedhdhoo regional weather station for 20yr period starting from 2000 to 2019 and this is the only one weather station closer to Lot 3 study islands.

Figure 30 shows locations of Kaadedhdhoo weather station and Lot 3 study islands.



Figure 30: Kaadedhdhoo regional weather station and Lot 3 study islands

Climate data recorded at Kaadedhdhoo weather stations were screened and checked for gaps and unrealistic values. They were also subjected to simple statistical analyses of examining annual total/average, annual maximum and monthly variation and checking consistency. From these screening and checking methods, it was concluded that the collected data are in good quality and reliable.

Figure 31 shows daily variation of rainfall, maximum temperature, and minimum temperature over 20 years period (from 2000 to 2019).

Annual mean rainfall and temperature estimated from Kaadhedhoo weather station data are 2269mm and 28.4° C.

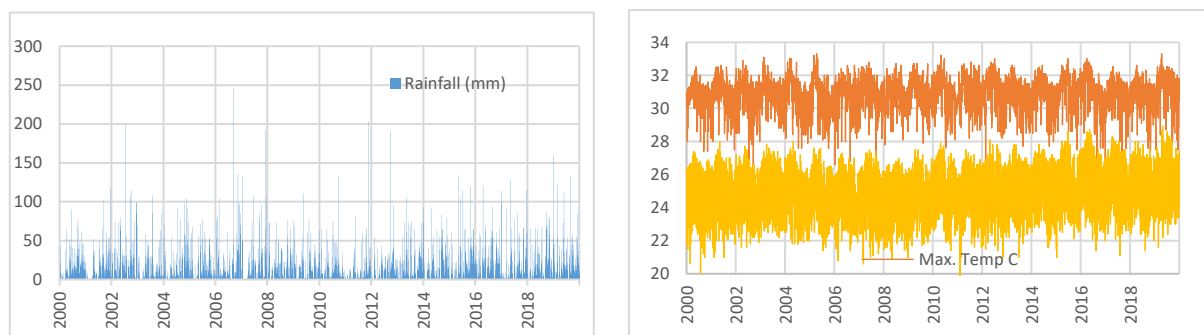


Figure 31: Rainfall and Temperature variation at Kaadedhdhoo weather station

Land use data

Land use at the study islands were initially identified by studying Google Earth satellite images and they were then categorized and assigned to grid cells of the model domain. The identified land use from

satellite images were later slightly modified based on observations during field visits to study islands. Classification applied to land use of the Lot 3 study island falls into the 7 categories and they are summarized in Table 27.

Table 27: Land use category for Lot 3 islands

Land use	Description
Residential area	Area which are mainly covered by houses
Commercial area	Harbor and surrounding areas (harden surface due to vehicle movement)
Tree covered or forest	Shaded area with trees
Ground	Pasture covered
Bare land	No structure located including road with larger width
Wetland	Marsh area
Agriculture area	Area where agricultural activities are taking place in large scale

Curve Number (CN) appropriate to land use listed in the Table 27 was assigned in the SWB model to estimate the runoff from each category.

Hydrological soil group

Four hydrologic soil groups namely Group A, Group B, Group C and Group D are considered in the SWB model.

Group A: having low runoff potential when thoroughly wet. Water is transmitted freely through the soil. Group A soils typically have less than 10 percent clay and more than 90 percent sand or gravel and have gravel or sand textures.

Group B—Soils in this group have moderately low runoff potential when thoroughly wet. Water transmission through the soil is unimpeded. Group B soils typically have between 10 percent and 20 percent clay and 50 percent to 90 percent sand and have loamy sand or sandy loam textures

Group C—Soils in this group have moderately high runoff potential when thoroughly wet. Water transmission through the soil is somewhat restricted. Group C soils typically have between 20 percent and 40 percent clay and less than 50 percent sand and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures.

D—Soils in this group have high runoff potential when thoroughly wet. Water movement through the soil is restricted or very restricted. Group D soils typically have greater than 40 percent clay, less than 50 percent sand, and have clayey textures.

Table 28 shows the infiltration rate of all 4 soil groups.

Table 28: Soil group and infiltration rate

Hydrologic soil group	Characteristics	Texture	Infiltration rate (inches per hour)
A	Low runoff potential and high infiltration rates, consisting primarily of deep, well- to excessively-drained sand or gravel.	Sand, loamy sand, sandy loam	>0.30
B	Moderate infiltration rates when wetted consisting of moderately deep to deep, moderately well-drained to well-drained soils of moderately fine to coarse texture.	Silt loam or loam	0.15–0.30
C	Low infiltration rates when wetted consisting primarily of (1) soils that have an underlying layer impeding downward movement of water and (2) soils with moderately fine to fine texture.	Sandy clay loam	0.05–0.15
D	Very low infiltration rates and high runoff potential when wetted, consisting primarily of clay soils with (1) high swelling potential, (2) high permanent water table, (3) clay or claypan near the surface, or (4) shallow soils over nearly impervious material.	Clay loam, silty clay loam, sandy clay, silty clay, or clay	<0.05

Hydrologic soil group	Curve Number		
	Minimum	Central	Maximum
A	25	51–68	77
B	48	62–77	86
C	65	70–84	91
D	73	77–88	94

Source: SWB model manual

According to observation on soil samples taken during permeability test, Group B soil is more representative for Lot 3 islands. It is of note that there are few patches in the island that represent Class A soil groups.

Flow Direction

Flow direction is basically generated from the topographical data and it decides flow direction from each cell to its downslope neighbor, or neighbors. Topographical data collected through drone survey and level survey were used to assign ground elevation to each grid cell in the model domain and then they were used to generate flow direction using tools in ArcGIS. The results of this exercise are attached to Annex XIV: Groundwater flow direction.

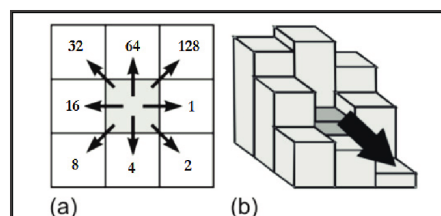


Figure 32: Cell flow direction in ArcGIS

Soil-water capacity

Soil water capacity is defined as the total amount of water that is stored in the soil within the plant's root zone. The soil texture and the crop rooting depth determine this. A deeper rooting depth means there is a larger volume of water stored in the soil and therefore a larger reservoir of water for the crop to draw upon between irrigations or water infiltration.

Table 29 shows typical soil textures and their water storage capacities.

Table 29: Soil texture and water capacity

Soil Texture	Available Water Capacity (inches per foot of thickness)	Available Water Capacity (mm/m of thickness)
Sand	1.2	100
Loamy sand	1.4	117
Sandy loam	1.6	133
Fine sandy loam	1.8	150
Very fine sandy loam	2	167
Loam	2.2	183
Silt loam	2.4	200
Silt	2.55	213
Sandy clay loam	2.7	225
Silty clay loam	2.85	238
Clay loam	3	250
Sandy Clay	3.2	267
Silty Clay	3.4	283
Clay	3.6	300

For lot 3 islands, soil water capacities were changing between 1.2 inch per foot and 1.6 inch per foot.

4.10.3 Model simulation

SWB model was simulated on daily time steps for a 20-year period (from 2000 to 2019) and model results were saved on both daily and monthly time steps. The former is for water balance analysis and latter was for SUTRA model which can successfully be simulated with monthly recharge rate.

SWB model has the capacity to produce results in both grid format and graphical format. However, only grid format was selected to save the results as it was adequate to estimate the average recharge rate over a long period of time. It is important to note that water budget components of SWB model are registered in inch and therefore, it must be converted into required units (millimeter or cubic meter) before using the relevant components for analysis. Also, since results are registered on each grid cell, appropriate technique should be used for summing the values from grids and making them as island average value.

4.10.4 Water Balance Analysis

Water balance analysis was carried out to understand how precipitation on the island is distributed above the ground and below the ground. It also helps to recognize the importance of managing freshwater storage underneath the ground and controlling water abstraction. Below are different components considered for water balance checking.

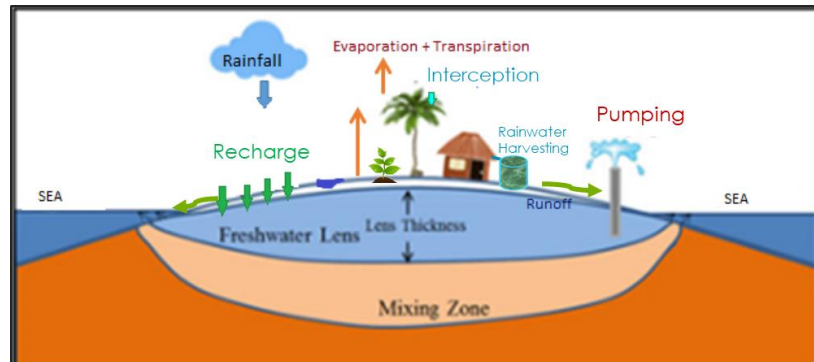


Figure 33: Components of water balance

- Precipitation: rainfall from Hulhule and Kahdhoo station
- Rainwater Harvesting: obtained from social survey
- Recharge, and evapotranspiration: from SWB model
- Pumping: estimated from the amount of water usage in different sectors such as residential, restaurants, institutes, agriculture etc.

The results of the SWB Modelling are presented in Sections 5.10, 6.10, ..., 11.10 for the six islands.

4.11 SUTRA Modelling

As stated in Section 4.10, this project is aiming to increase groundwater availability by implementing MAR design and therefore, there is a requirement to predict and compare the freshwater lens before and after the implementing the MAR design. Saturated-unsaturated transport (SUTRA) – a hydraulic model has been selected to estimate the groundwater levels and assess the sustainable yield or calculate the total groundwater storage in freshwater lens for both in the existing condition and in the design condition. Further descriptions on SUTRA modelling are given below.

4.11.1 General Features and Model Background

SUTRA is a saturated-unsaturated variable density groundwater flow with solute or energy transport developed by United States Geological Survey (Voss and Provost, 2010) and this model uses finite element method to solve the coupled density dependent groundwater flow and solute transport governing equations. This model requires the model parameters, boundary conditions, and forcing variables to simulate the flow and transport in the unsaturated-saturated aquifer systems. The model parameters needed to develop the SUTRA model include porosity, permeability, specific yield, porous matrix compressibility, and dispersivity. The model parameters will be obtained from field measurements, previously conducted project reports, and from literature studies. The output from this model includes nodal pressure, saturation, and solute concentration. Salt concentration could also be used as solute in the solute transport model that simulates salt concentration across the model domain and its variation over the time simulated.

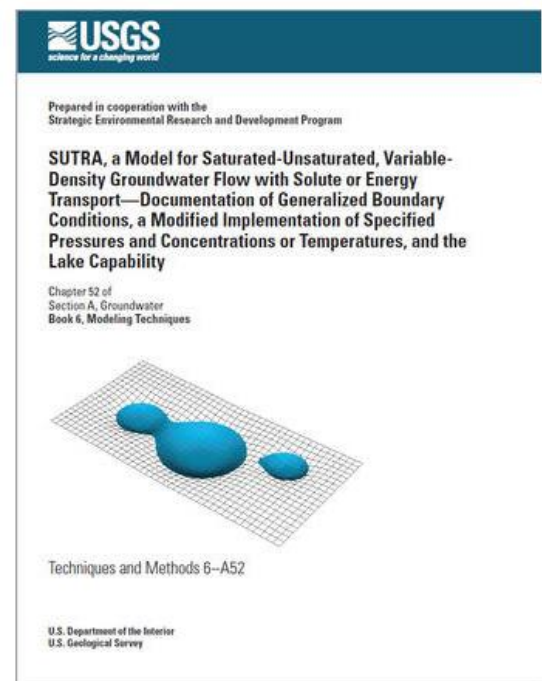


Figure 34: Cover image from the SUTRA 3.0 manual

SUTRA modelling can be performed on 2D or 3D basis and users have freedom to choose appropriate model dimensions based on the objective of the modelling work and level of details required. In general, compared to a 2D vertical cross-section model, which has often been used to simulate freshwater lens dynamics of atoll islands, a 3D model has the advantage of being able to specify natural boundary conditions, represent the actual shape of the coast or island surface area, simulate the effect of groundwater pumping in all aquifer dimensions, and provide an estimate of lens volumes. Therefore, for this project, SUTRA 3D was selected as a freshwater lens that can be estimated at any location within the island using it.

4.11.2 Input data preparation and model set up

Setting up the SUTRA model requires two types of data; one is related to layer definition and the other one is related to hydrology.

Layer definition data

This is to define elevation of island surface (ground), unsaturated zone and other geological features. For this project 3 zones or layers were defined.

- (1) Upper zone: layer between ground top level and average ground water level
- (2) Middle zone: layer between average ground water level and bottom of the Holocene geological layer
- (3) Bottom zone: layer between bottom of the Holocene and Pleistocene

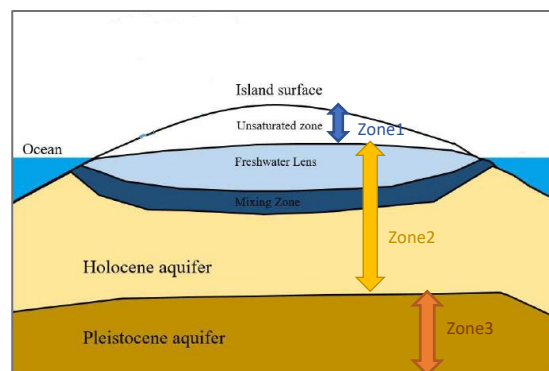


Figure 35: Layer definition for SUTRA modelling purposes

The outer boundary of the upper zone was defined so that it covers the entire island plus surrounding ocean area that influences saline water intrusion into the island. Irregular mesh was produced to define the inner part of the island, shoreline and area between shoreline and ocean boundary

Hydrological data

There are 18 parameters in SUTRA Model, and they can be grouped into 5 or 6. Of them, flow direction, permeability, porosity, longitudinal dispersivity and transverse dispersivity are important for 3D modelling. Values for these parameters were initially extracted from literatures and they were later adjusted during the model calibration/simulation process. Table 30 below shows aquifer properties given for Maldives islands in Abdullah A. A's PhD thesis (2017).

Table 30: Holocene and Pleistocene aquifer properties

Parameter [units]	Value	Source
General aquifer properties		
Compressibility of porous matrix [m^2/N]	1×10^{-9}	Peterson and Gingerich, 1995
Specific yield [m^3 / m^3]	0.20	Griggs and Peterson, 1993
Longitudinal dispersivity, α_L [m]	6.0	
Transverse dispersivity, α_T [m]	0.05	Griggs and Peterson, 1993
Upper Holocene aquifer		
Porosity [m^3 / m^3]	0.2	Anthony, 1996
Thickness [m]	15	Hamlin and Anthony, 1987
Horizontal K [m/d]	75	Bailey et al., 2014
Vertical K [m/d]	15	Bailey et al., 2014
Lower Pleistocene aquifer		
Porosity [m^3 / m^3]	0.3	Swartz, 1962
Thickness [m]	105	
Horizontal K [m/d]	5000	Oberdorfer et al., 1990
Vertical K [m/d]	1000	Oberdorfer et al., 1990

Source: Abdullah A.A, 2017, The sustainability of atoll islands freshwater lenses under nonstationary climatic and anthropogenic stresses, Colorado State University

ModelMuse – a graphical user interface for constructing numerical models for USGS-based codes such as modular finite-difference flow model (MODFLOW) and SUTRA was used to construct the 3D finite element mesh and to generate the necessary input files containing node-by-node aquifer properties, boundary conditions, initial conditions, and fluid source/sink terms such as recharge and pumping (i.e., extraction).

4.11.3 Model simulation and result extraction

SUTRA model can be simulated on various time steps from hourly to years. However, for the prediction of saline concentration in Lot 3 islands, a large time step is adequate. Therefore, both model simulation and result storing were set on a 2-month time step and the model was simulated for a 20-year period (from 2000 to 2019).

Pressure on model nodes and salt concentration were chosen to store for each time step and they were exported as ASC files for analysis and preparing plots.

The results of the SUTRA Modelling are presented in Sections 5.11, 6.11, ..., 10.11 for the six islands.

Baseline assessment outcomes of individual islands are presented in the following sections.

5 GA. Maamendhoo

5.1 Island Overview and Location

The Island of GA. Maamendhoo, belonging to Huvadhoo Atholhu Uthuruburi Atoll, is in the Southern region of Maldives at 0°42'55.7"N and 73°26'20.5"E. It is approximately 384 km South of the capital Male'.

Table 31: Island Geographical Data

Island	GA. Maamendhoo
Atoll	Huvadhoo Atholhu Uthuruburi Atoll
Location	0°42'55.7"N and 73°26'20.5"E

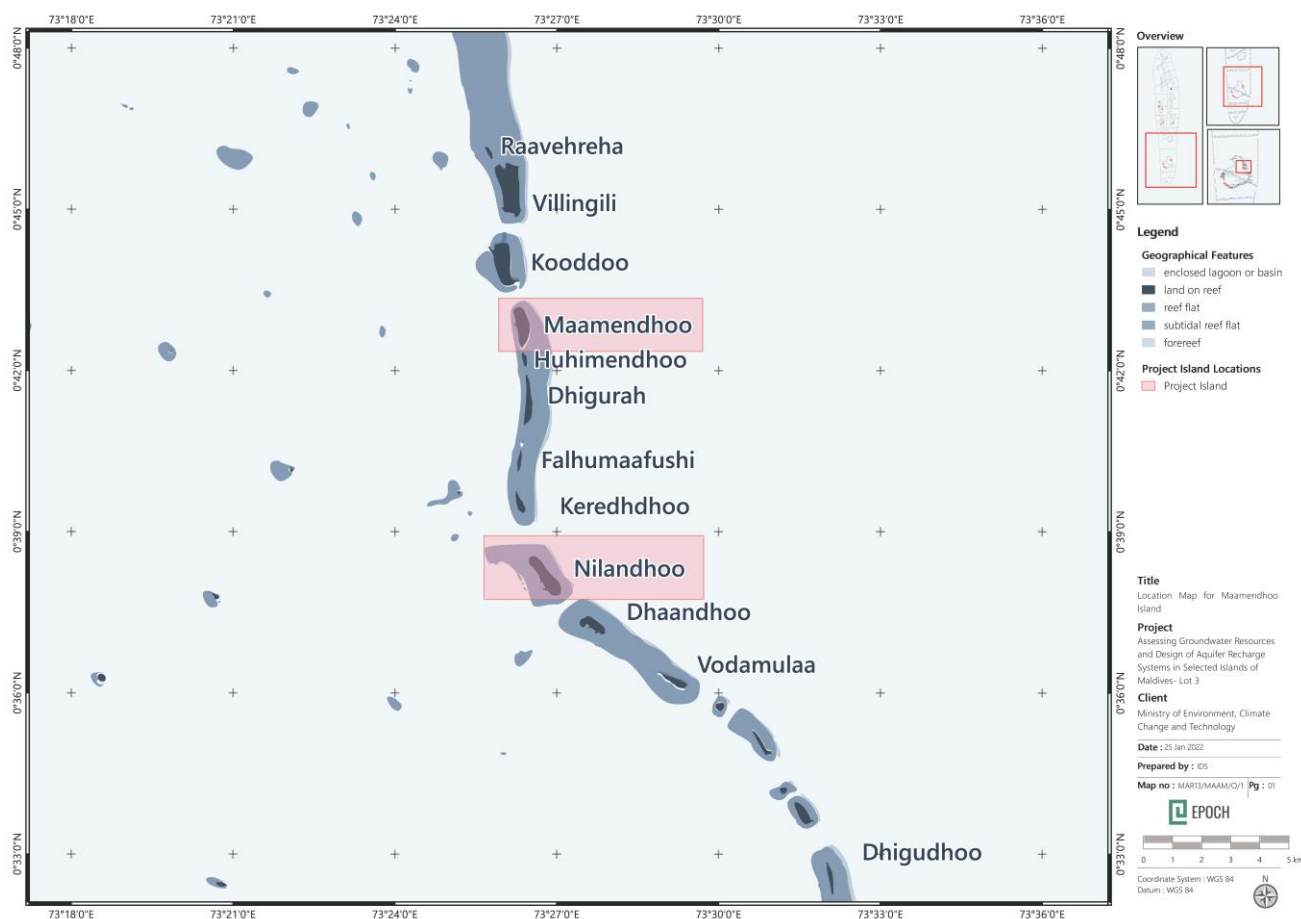


Figure 36: Location Map – GA. Maamendhoo

5.1.1 Island features

The island is approximately 1.4 km long and 0.51 km wide, giving it a total area of about 49.3 Hectares. Four uninhabited islands and one resort are in the same reef system as GA. Maamendhoo. Northern end of the island is tapered with a small beach and moderate erosion is observed in that part of the island. In the southern side of the island, a designated waste centre is also built for waste management.

The island has a harbour at its Northwest side. About two-third of the island's surface is vegetation. This vegetation is mostly located at the outer edges around the island. The southern part of the island is covered mostly by thick vegetation. Farming takes place on the southern east side of the island. Only about one-third of the island is populated, which is mostly the northern part of the island. The Land Use Characterization map is attached to Annex II.

Table 32: Area Distribution in GA. Maamendhoo

Area	49.3ha	
Length	1.4 km	
Width	0.49 km	
	Area (m²)	% of total area
Roof cover	66,222	13%
Vegetation (Thick)	176,025	36%
Vegetation (Thin)	146,188	30%
Bare Lands	98,389	20%
Farmlands	6,557	1%
Total	493,380	100%



Figure 37: GA. Maamendhoo Land Use Characterization

5.2 Topographical Features

Permanent Survey Marks PSM 0078 and PSM 0077 were used as benchmarks for GA. Maamendhoo topographical survey and drone survey with benchmark details available at <https://www.mlsa.gov.mv/psm>. Digital Surface Models and Orthomosaic were derived in Pix4D Mapper using 2497 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.22 cm per pixel. 12 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 33 GCP Statistics for GA. Maamendhoo

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	0.00134	-0.000614	-0.00272
Sigma [m]	0.0276	0.0347	0.311
RMS Error [m]	0.0276	0.0347	0.311

The Digital Surface Model (DSM) in *Annex III: Topography Maps* indicates that the northern region of the island (Average Elevation 1.5 m) is higher than the southern region (Average elevation of 1 m). This trend is particularly visible along the long main road that goes from north to South in GA. Maamendhoo. The Harbour was rehabilitated recently in 2020/2021 but the regions near the quay wall remain around the same elevation as the island average. In contrast, elevations are much lower than the island average for the waste region located in the South.

Roof elevations generally do not exceed 5–7 m and very few houses have multistorey buildings in GA. Maamendhoo. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Thick vegetation with heights greater than 10 m are primarily seen on the eastern periphery of the island. It is also noteworthy that despite the Southern region having dense thick and thin vegetation the elevations are generally lower than 10m.

The Digital terrain model (DTM) was produced at a resolution of 0.1 m spatial resolution for the purposes of analysis. The scatter plot for sampled Unmanned Aerial Vehicle (UAV) Elevations vs GPS Spot heights is presented below along with statistics for the regression line. The error statistics for sampled elevations are given in the table below and indicate that the drone survey slightly underestimates the elevation with a mean of -5.18 cm. It should be noted that the DTM does not contain any elevation information related to the detached sand filled breakwater of GA. Maamendhoo.

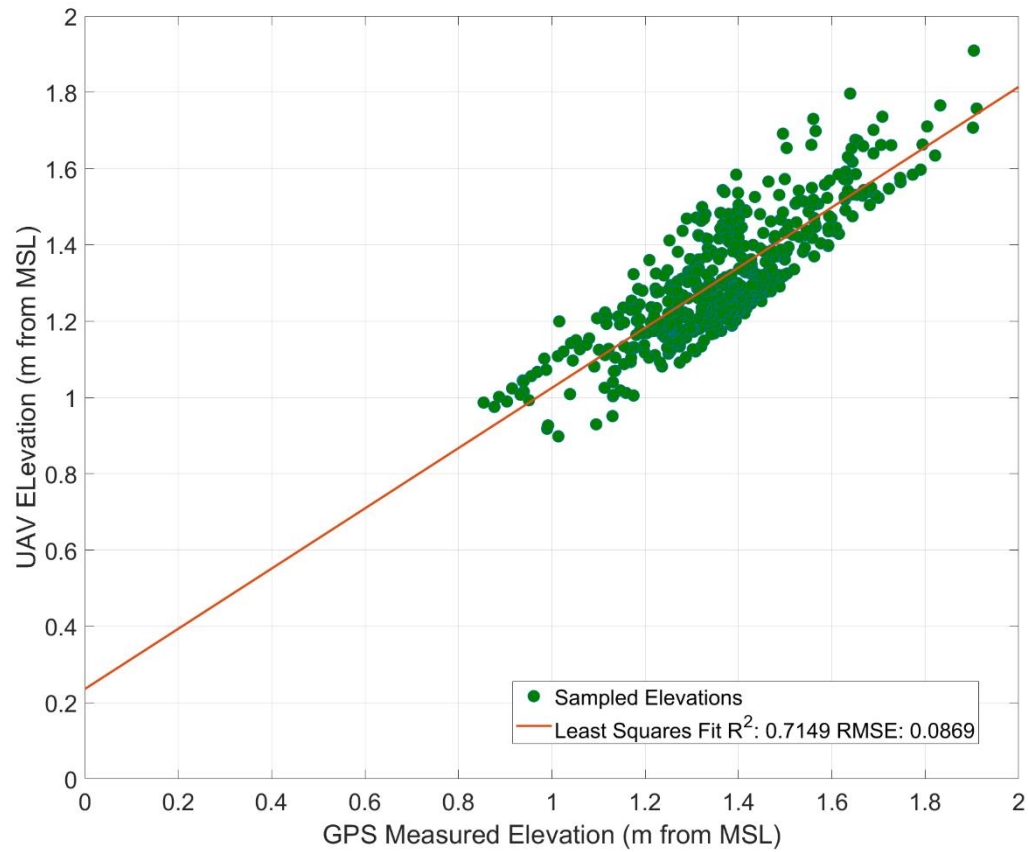


Figure 38 Linear Regression Plot for GA. Maamendhoo Sample UAV elevations

Table 34 Error Statistics for DTM sampled elevations for GA. Maamendhoo

Statistical Parameter	Value (cm)
Mean	-5.18
Standard Error	0.45
Median	-6.65
Mode	#N/A
Standard Deviation	9.73
Sample Variance	94.62
Kurtosis	-0.71
Skewness	0.49
Range	39.42
Minimum	-19.79
Maximum	19.63
Sum	-2446.04
Count	472.00

5.2.1 Level changes

GA. Maamendhoo has an average elevation of 1.41 m with a standard deviation of 0.521. Digital Terrain Model elevations range from -0.6 to 2 m from MSL. The distribution of elevations is negatively skewed with 1.8m being the highest frequency for elevations.

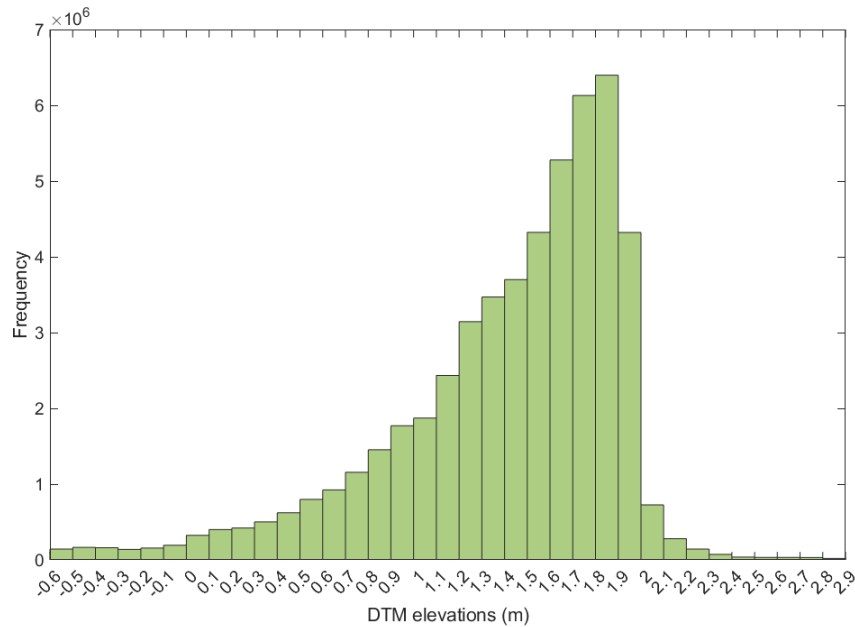


Figure 39 Histogram of DTM Elevations for GA. Maamendhoo Island

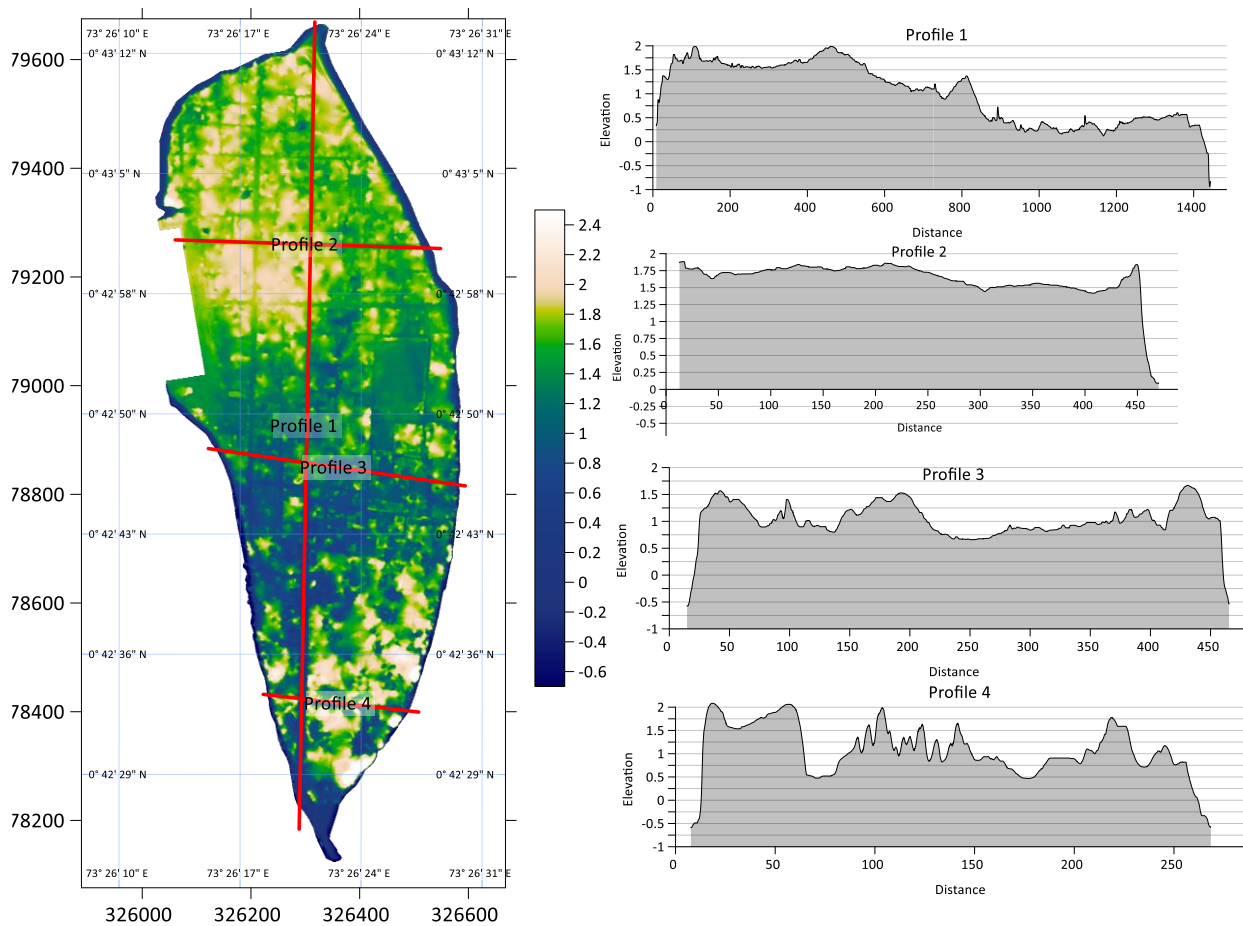


Figure 40 Digital Terrain Model Elevations and Profiles for GA. Maamendhoo Island

Level changes are apparent for the road which goes from the North to South along the entire length of GA. Maamendhoo in Profile 1. Elevation drops from an average of 1.5 m to below 1m from MSL for Profile 1 at 500 m before becoming constant around 900 m. Profile 2 begins from the harbour and a constant elevation of 1.75 m continues till 250 m where a slightly lower elevation of 1.5 m is found before the island's sandy ridge on the west.

Profile 3 illustrates two average ridges on the east and west of the island with a central region around 250 m metres with an elevation below 1 m. Profile 4 illustrates the change in elevation where the low main road appears around 75 m before another low elevation region (Waste area) is seen at 175 m. Other regions in profile 4 are higher and influenced by low vegetation.

5.2.2 Shoreline

GA. Maamendhoo shoreline is 4342 m long without accounting for the detached sand filled breakwater. Both the north and southern tips have sandy areas locally known as Thundi which form nice white sandy beaches. Significant changes in the GA. Maamendhoo shoreline have occurred near the Northern Area

adjacent to Kooddoo Airport leading to the felling of several coconut palms. This was reported by the council and evidenced by the drone images below.



Figure 41 GA. Maamendhoo Orthomosaic illustrating the eroding area (pink), detached breakwater (red)



Figure 42 Drone Images taken of GA. Maamendhoo North Eroding area

5.2.3 Reef

The reef that houses GA. Maamendhoo is also occupied by the 5 resort islands and 2 uninhabited islands.

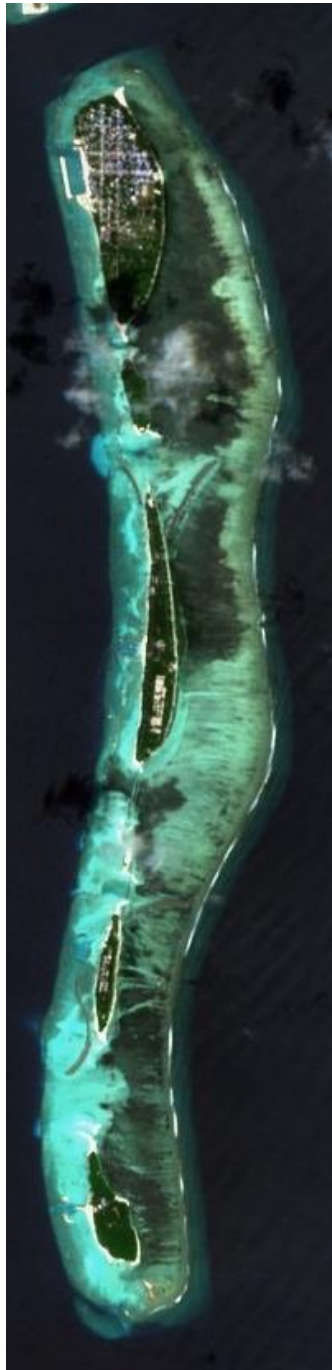


Figure 43 Sentinel 2 Imagery of GA. Maamendhoo reef taken in January 2022. GA. Maamendhoo is shown at the top

5.3 Socio Economic Status

5.3.1 Demography

The Island has a registered population of 1137 as per the 2014 census, with a total of 544 males and 509 females. The island population density is 31.52 people per hectare as per the year 2021. The population figures have drastically increased over the past years where the total registered local population climbed up to 1554. The following table and graph illustrate the demographic breakdown of GA. Maamendhoo.

GA. Maamendhoo Population

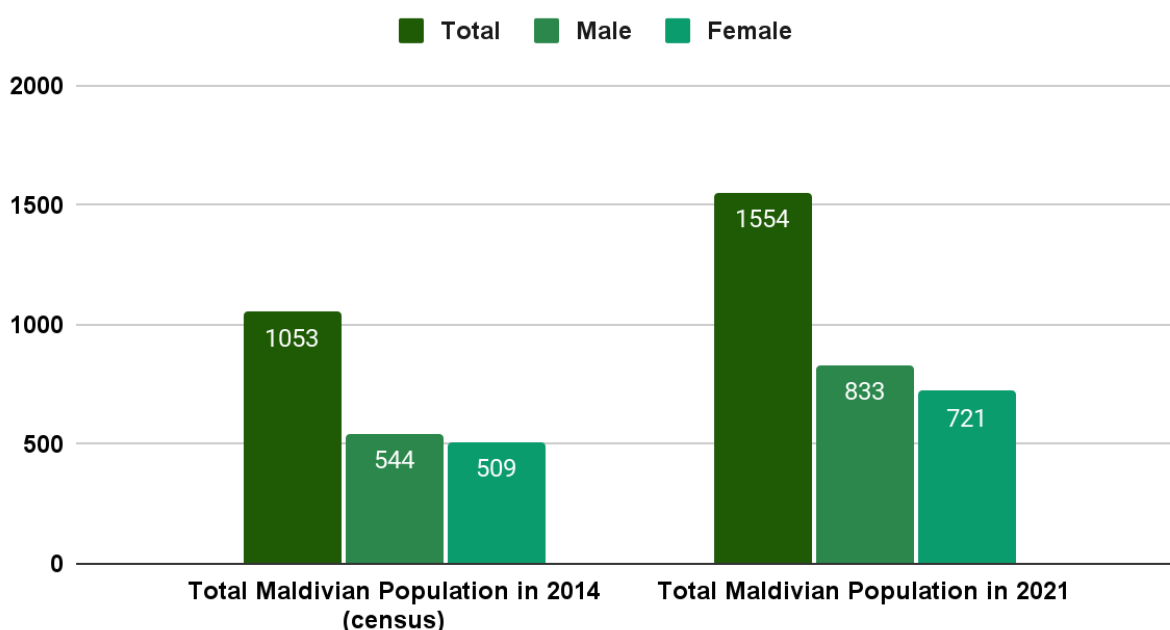


Figure 44: GA. Maamendhoo Population

Table 35: GA. Maamendhoo Population (Census, 2014)

Resident Population according to Census 2014										
Atoll	Locality	Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
GA	Maamendhoo	1,137	614	523	1053	544	509	84	70	14

5.3.2 Socio-Economic Activities

GA. Maamendhoo is an inhabited island in Gaafu Alifu Atoll's administrative unit and physically part of Huvadhu Atholhu Uthuruburi Atoll in the Maldives'. This island is well-known for its fisheries activities. The people in the island are well known for fishing. The island also has 4 operational cafes/restaurants and 16 guesthouse beds that provide for the tourism industry. The island also has a slipway for boat building work. Currently, a Land Use Plan is being made for the island.

5.3.3 Facilities available

5.3.3.1 Health Care

GA. Maamendhoo Health Center currently has 1 doctor, 6 nurses and 5 beds. The health facilities in the island are bare minimum and many island residents find that the health center needs to be upgraded and service hours need to be extended.

5.3.3.2 Education

The sole education facility found in GA. Maamendhoo is Maamendhoo school. The school has 270 students, 37 teachers and 12 administrative staff. The island school offers education up to grade 10 standard.

5.3.3.3 Utilities

Electricity on the island is provided by state-owned utility company FENAKA Corporation. The island has an ongoing Sewerage Network Construction project which is expected to finish by April 2022. GA. Maamendhoo Water Supply System project is also expected to start by 2022.

5.3.3.4 Transportation

The island has a harbor. The transportation between GA. Maamendhoo island and other islands is by sea. The island has Maldives Transport and Contracting Company (MTCC) ferry services, the island also has other private speed launches.

5.3.4 Water resources, water usage and water consumption

In GA. Maamendhoo there are a total of 250 households. 153 out of 250 households were surveyed, while maintaining a 95% confidence interval and geo-coordinated sampling points. A map of households surveyed is attached in Annex V.

Table 36: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	153/250 households = 61%
Percentage of wells fitted with pumps	97%
Ground water	Usage in percentage
Source of drinking	1%
Source of cooking	3%

5.3.4.1 Existing water and sanitation

The main form of sanitation is via the use of septic tanks. Each household has one or two septic tanks, and the septic tanks are cleaned periodically by disposing the septic waste into the sea. the Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22) annex 4 states that the households should keep a 15 meters (49.2 ft) distance between septic tank and nearest well. The main reason for the adoption of this standard is to negate any possible causes of contamination in the groundwater. This being the recommended standard, majority of the surveyed households were reported with less than 49ft distance between septic tank and water well. In GA. Maamendhoo 75 percent reported to have less than 49ft distance between septic tanks and water well. While remaining 21% reported to have more than 49ft distance between septic tanks and water well.

Rainwater is primarily used for cooking. Many homes use rainwater from neighbouring houses or bottled water when rainwater is not readily available during the dry season. Rainwater collected from rooftops is stored mostly in water tanks, whether at home or communal rainwater tanks.

In GA. Maamendhoo, 13 houses have connected rainwater to the well and have reported improvement in groundwater. On the same note, 88% of the households have rainwater overflow drained to the ground.

5.3.4.2 Water usage and resources

Based on the survey conducted in GA. Maamendhoo, 143 houses have HDPE rainwater tanks for rainwater storage. 67% of the households use rainwater for drinking and 94% use rainwater for cooking. While groundwater is mainly used for gardening, household cleaning with all the houses fitted with water pumps. The following sections outline further details about various groundwater usage and consumption scenarios in the island.

5.3.4.3 Domestic water usage

Based on household water usage surveys in GA. Maamendhoo, **386,946** Liters of groundwater is used daily in the households. A total of **249** Liters of groundwater are consumed per capita per day.

Table 37: Domestic groundwater use data for GA. Maamendhoo

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
138.44	28.03	11.21	40.07	2.31	25.03	4.25	249

*All units are in Liters per capita per day

5.3.4.4 Commercial water usage

Based on the survey conducted in GA. Maamendhoo, there are currently four operational café/restaurants and 4 guesthouses on this island. A total of **4696** Liters of groundwater are used by commercial entities and their detailed breakdown is given in the tables below.

Table 38: Café/ Restaurant groundwater use data for GA. Maamendhoo

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Laundry	Total
Atige	135	273	156	10	151	725
Maakean	67.5	218	360	20	303	968
Engaa Coffee	36	0	25	20	0	81
The Village Cafe and Restaurant	270	303	160	20	0	753
						2,527

*All units are in Liters per day

Table 39: Guesthouse groundwater use data for GA. Maamendhoo

Guesthouse	Average Occupancy	Total (L/day)
Sunny Side	25%	567
Village Life	25%	457
Mercary	25%	361
Island Guesthouse	25%	784
		2,169

5.3.4.5 Industrial water usage

In GA. Maamendhoo, 5 out of 30 farming plots were surveyed to determine the industrial groundwater usage. Majority of the farms have pumpkin, cucumber and chillies and they are produced throughout the year. An average of **172** Liters of groundwater is used by each farm and the breakdown for 30 farms are given in the table below. A total of **5160** Liters of groundwater is used for industrial purposes.

Table 40: Industrial groundwater use data for GA. Maamendhoo

Total farms	No. of farms surveyed	Average usage	Total usage for all the farms (Liters)
30	5	172	5160

5.3.4.6 Institutional water usage

Based on the survey conducted in GA. Maamendhoo, there are currently five institutions that have groundwater well facilities and use groundwater. A total of **5723** Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 41: Institutional groundwater use data for GA. Maamendhoo

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Magistrate Court	109.03	240	1.4	–	350
GA. Maamendhoo School	1,455.64	1,480	214.3	–	3,150
GA. Maamendhoo Council	187.82	360	20	–	568
Powerhouse	219.13	300	20	–	539
Health Center	266.51	300	30	519.3	1,116
					5,723

*All units are in Liters per day

5.3.5 Present & Future water demand

In GA. Maamendhoo, the present water demand is at **402,525** Liters per day and groundwater usage is expected to decrease with the establishment of water supply services in the island. The year 2021 figures are as per the latest island council data. For the figures in year 2036 and 2054, it is as per Maldives Populations Projections Report published by the National Bureau of Statistics.

Population Projection - GA. Maamendhoo

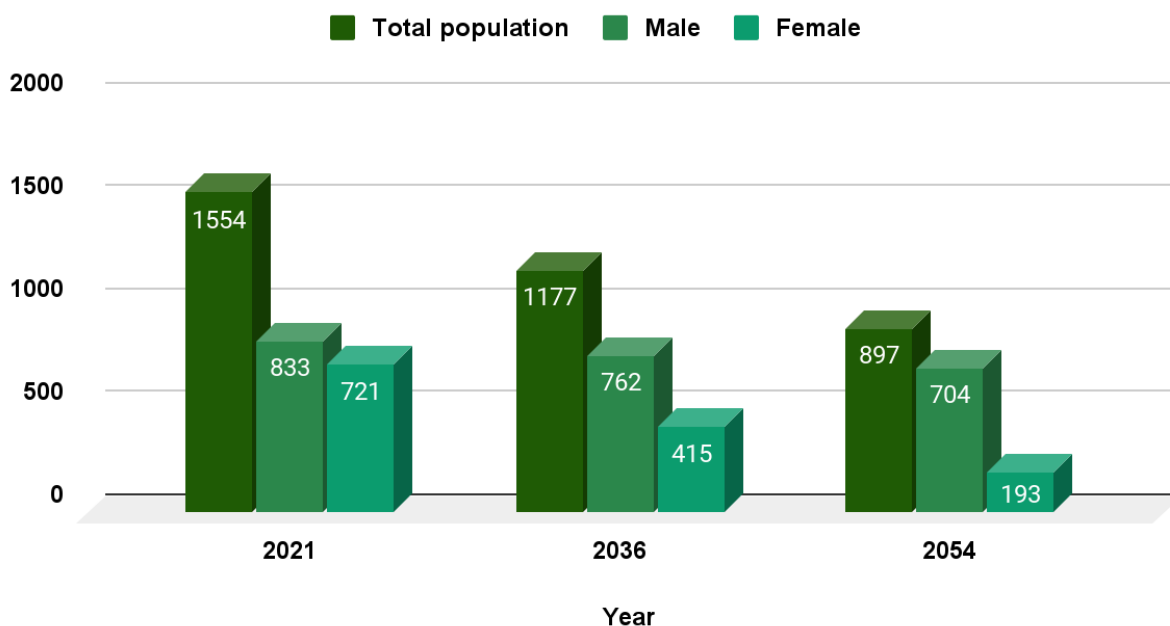


Figure 45: Population Projection – GA. Maamendhoo

Table 42: Present groundwater demand - GA. Maamendhoo

Year	Total Population	Domestic water demand	Commercial water demand	Institutional water demand	Industrial water demand	Groundwater usage
2021	1,554	386,946	4,696	5,723	5,160	402,525

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 249 Liters per day. For the year 2036, water supply usage is expected to be 50 Liters per capita per day. After deducting 50 Liters from 247 Liters, the groundwater demand is expected to be 199 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 1,177 is expected to be **234,223** Liters per day.

For the year 2054, water supply usage is expected to be 75 Liters per capita per day. After deducting 75 Liters from 249 Liters, the groundwater demand is expected to be 174 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 897 is expected to be **156,078** Liters per day.

Table 43: Future domestic water demand - GA. Maamendhoo

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	1,177	249	50	199	234,223
2054	897	249	75	174	156,078

5.3.6 Water related issues

From 153 households surveyed in GA. Maamendhoo, most houses reported unpleasant smells (54%) and milky and cloudy texture (10%) in their respective wells. Only 35% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gasses such as hydrogen sulfide which causes unpleasant smells. Some residents also believe groundwater has become worse after the Tsunami.

Table 44: Signs of contamination reported by households

Types of contamination	Data in % out of 153 households surveyed
Smell	54%
Milky	10%
Foul taste	20%
Salty	0%
None	9%

The following table details out the changes in groundwater quality reported by the households during tidal or seasonal changes.

Table 45: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 153 households surveyed
Changes with tidal variations	24%
Groundwater quality is better in rainy months (Hulhangu season)	35%
Long periods without rain causes bad smell	33%
Long periods without rain causes bad taste	13%
Rain makes it worse	0%
No change	37%

5.4 Groundwater Quality

5.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 46 summarizes the water quality results. Map of locations where groundwater quality points were taken for physiochemical analysis is attached to Annex VI. The full list of measured parameters is attached to Annex VII.

Table 46: Statistical summary of groundwater physiochemical parameters in GA. Maamendhoo

	EC ($\mu\text{S}/\text{cm}$)	Turbidity (FNU)	DO (mg/L)	pH	Temp ($^{\circ}\text{C}$)	Sal (ppt)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
Standards	<1500 Potable purposes <2500 Non- potable purposes Source ¹	<5 Source ²	 	6.5-8.5 Source ²			<1.5 Odour threshold <35 Taste threshold Source ¹	<50 Source ¹	
Mean	1060	1.49	3.56	7.44	29.42	0.48	4.06	22.48	0.30
Median	880	0.76	2.86	7.42	29.33	0.39	1.36	11.73	0.25
SD	662	2.46	2.11	0.27	1.26	0.32	7.99	23.42	0.17
Min	321	0.00	1.60	7.02	27.50	0.14	0.17	1.99	0.07
Max	3626	14.14	11.39	8.20	33.44	1.76	48.77	87.83	0.89
CV	0.62	1.65	0.59	0.04	0.04	0.67	1.97	1.04	0.56

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH₃= Ammonia, NO₃⁻ = Nitrate, PO₄³⁻=Phosphate, SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source¹ = WHO Drinking Water Guidelines, 2017. Source² = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 1060 $\mu\text{S}/\text{cm}$ is within the WHO Standard for potable water (<1500 $\mu\text{S}/\text{cm}$) and non-potable water (<2500 $\mu\text{S}/\text{cm}$).
- Two samples had higher EC than 2500 $\mu\text{S}/\text{cm}$. Seven samples had EC between 1500 $\mu\text{S}/\text{cm}$ and 2500 $\mu\text{S}/\text{cm}$ while 31 samples had EC lower than 1500 $\mu\text{S}/\text{cm}$. The EC distribution is shown in Figure 47.
- Electrical Conductivity of groundwater is higher near the coast of the island and lower in the centre of the island.
- The mean Turbidity level at 1.49 NTU is within the URA Guidelines for drinking water (5 NTU). Only two samples had a higher Turbidity level than 5 NTU. Turbidity is generally lower in the residential areas
- Dissolved Oxygen ranged from 1.60 mg/L to 11.39 mg/L with a mean of 3.56 mg/L.
- All samples fell within the pH range of 6.5-8.5 as per URA Guidelines for drinking water with a mean pH of 7.44.

- Temperature ranges from 27.50°C to 33.44°C depending on the well characteristics and time of day reading was taken. Mean temperature was 29.42°C.
- Salinity ranged from 0.14ppt to 1.76ppt with a mean of 0.48ppt.
- The mean Ammonia concentration was 4.06 mg/L which is higher than the WHO threshold for odour and lower than the threshold for taste. 52.5% of samples had concentration below 1.5 mg/L, 45% of samples had concentration between 1.5 mg/L and 35 mg/L and 2.5% of samples had concentration higher than 35 mg/L. The Ammonia concentration distribution is shown in Figure 46.
- The mean Nitrate concentration was 22.48 mg/L which is within the WHO Standard for Nitrate concentration (50 mg/L). Five samples had Nitrate concentration higher than the standard.
- Phosphate concentration ranges from 0.07 to 0.89 mg/L with a mean concentration of 0.30 mg/L. There is no WHO guideline value for phosphate concentration. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater. Only one sample tested had phosphate concentration below 0.1 mg/L. Phosphate concentrations are higher in densely populated areas.

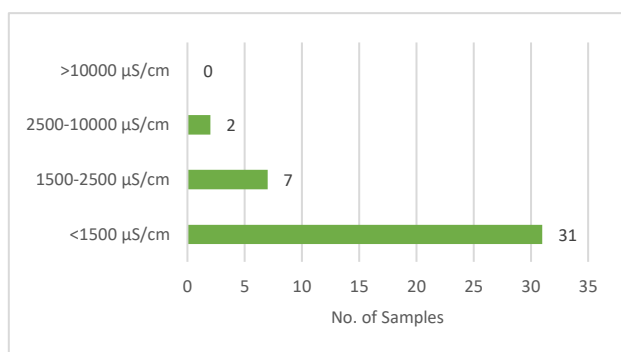


Figure 46: EC Distribution in GA. Maamendhoo

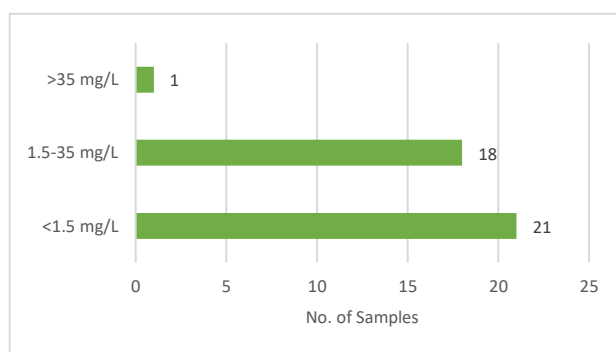


Figure 47: Ammonia Concentration Distribution in GA. Maamendhoo

The spatial distribution of all the parameters measured are shown in Figure 48 (a-i)

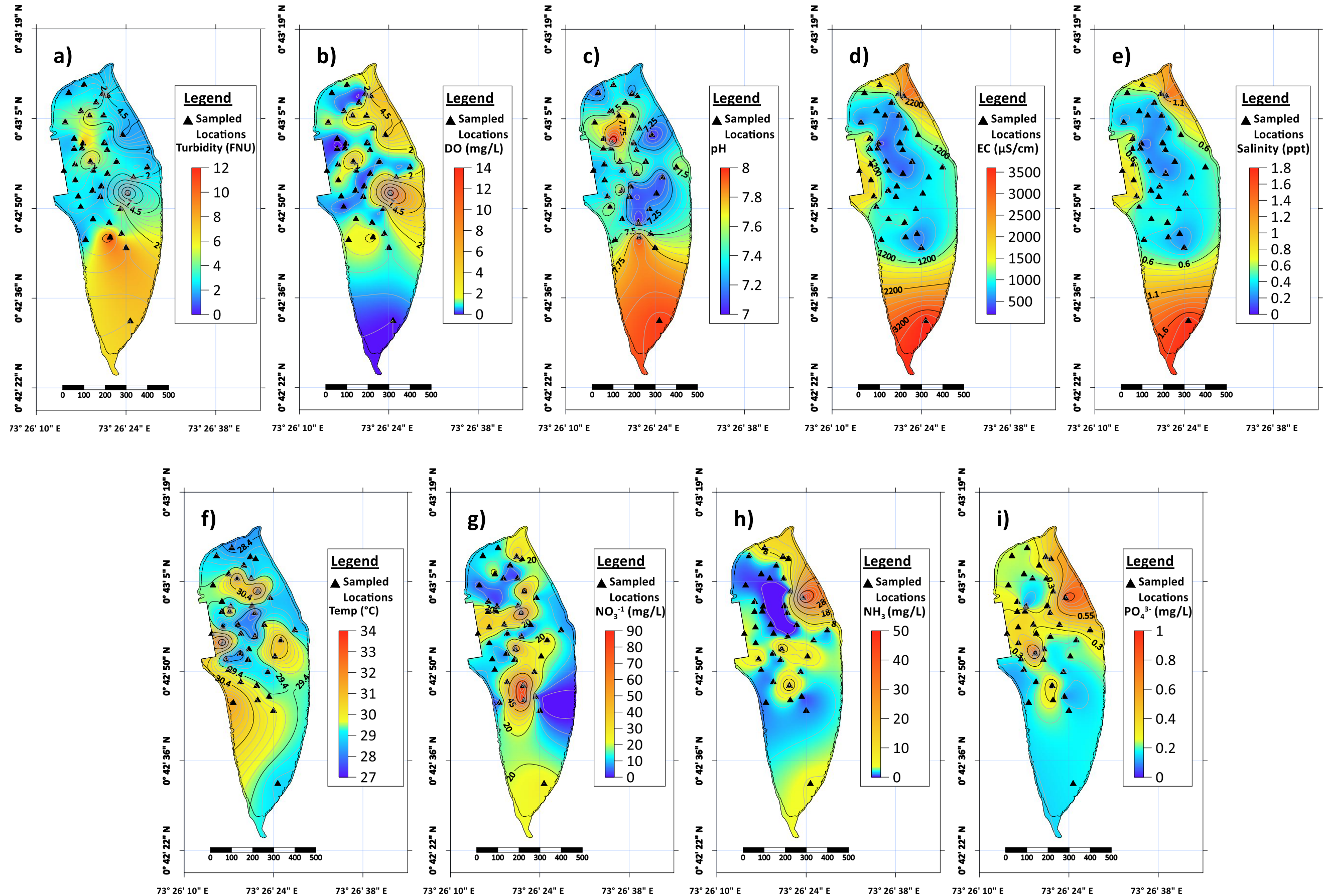


Figure 48: Spatial variation of physiochemical parameters in GA. Maamendhoo

As a principle, excessive groundwater usage leads to overextraction causing salinization of the freshwater lens. The Social Survey findings were used to calculate the daily water consumption at each household, institution, and other commercial entities. The EC values at these locations were plotted against water consumption to check if increasing water usage leads to salinization. The correlation coefficient of EC to Water usage is -0.0513 and the R-squared of the plot is 0.0026 as indicated from the Figure 49. Therefore, there is no significant relationship observed between EC and Water Usage for the island as per the findings from the Social Survey and Water Quality Survey. The Spatial distribution of EC and water usage is shown in Annex VIII.

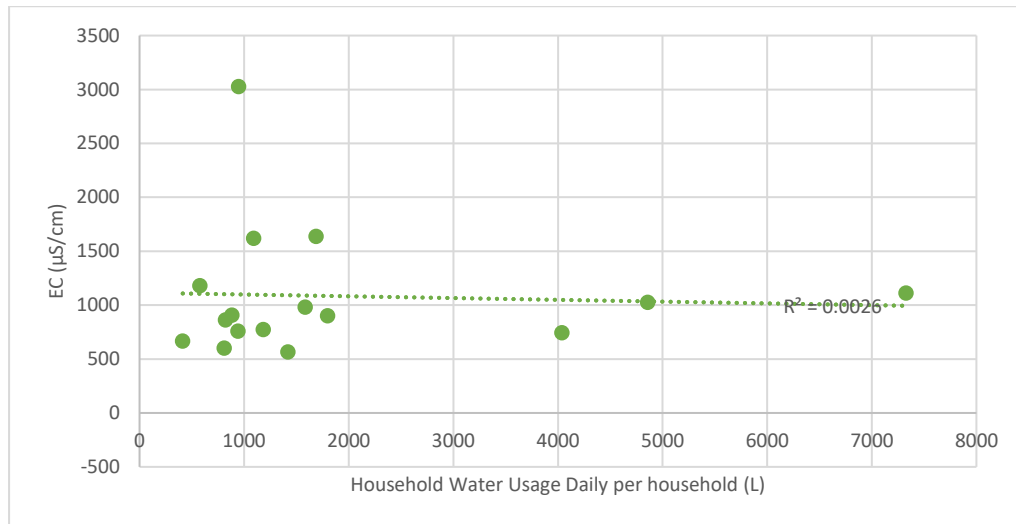


Figure 49: EC against Water Usage in AA. Mathiveri

5.4.1.1 Correlation Matrix

The correlation matrix for GA. Maamendhoo along with the colour bar is given below. Red colour indicates negative correlation while green colour indicates positive correlation.

Table 47: Correlation matrix of the groundwater quality parameters in GA. Maamendhoo

Variables	Turbidity (FNU)	DO (mg/L)	pH	EC (µS/cm)	Sal (ppt)	Temp (°C)	NO ₃ ⁻ (mg/L)	NH ₃ (mg/L)		
DO (mg/L)	-0.01									
pH	-0.16	0.70								
EC (µS/cm)	0.03	-0.08	-0.06							
Sal (ppt)	0.03	-0.07	-0.05	***1.00						
Temp (°C)	0.16	-0.02	-0.07	-0.02	-0.06					
NO ₃ ⁻ (mg/L)	0.00	0.19	-0.21	0.07	0.07	0.01				
NH ₃ (mg/L)	0.29	-0.22	-0.39	0.21	0.21	-0.12	0.11			
PO ₄ ³⁻ (mg/L)	0.15	-0.24	-0.19	0.12	0.12	-0.15	0.12	0.53		
negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation

Table 47 shows a strong positive correlation coefficient between pH/DO ($r=0.70$) and EC/Sal ($r=1.00$). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlations between salinity and conductivity are as expected. There are no strong negative correlations between parameters observed.

5.4.1.2 Water Quality Index

In this study, the computed Water Quality Index (WQI) ranges from 2.03 to 21.9, with a mean of 9.43. The WQI was divided into four categories and Table 48 shows the categorization of samples. 60% of samples were classified as "Very Good", 35% of samples were classified as "Good", 5% of samples were classified as "Poor" and 0% of samples were classified as "Very Poor". The high value of WQI at few locations have been found to be mainly from the high Nitrate concentration at these locations. The spatial distribution of WQI is shown in Figure 50.

Table 48: WQI Categorization for GA. Maamendhoo

WQI	Category	No. of samples	Percentage
0 to 10	Very Good	24	60%
10 to 20	Good	14	35%
20 to 50	Poor	2	5%
>50	Very Poor	0	0%

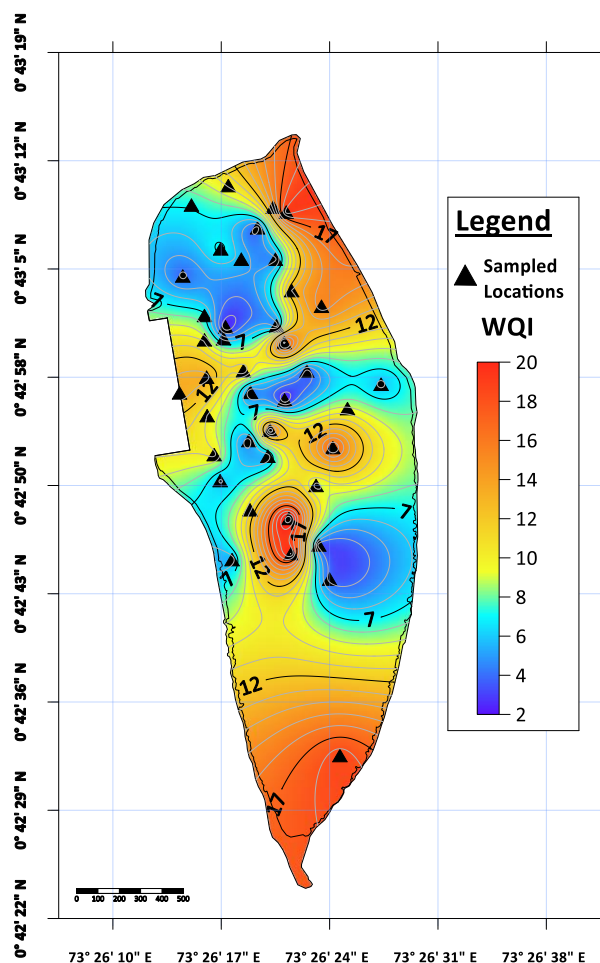


Figure 50: Spatial Distribution of WQI in GA. Maamendhoo

5.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following table summarizes the results.

Table 49: Microbiological Parameters of groundwater in GA. Maamendhoo

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq01	579	2	50	Septic Tank. Septic Tank cleaned once a year and waste buried in household
wq04	75	1	50	Septic Tank. Not cleaned yet.
wq07	150	Not detected	20	Septic Tank.
wq09	>2420	2		Location does not fall within the coverage of social survey
wq12	1414	Not detected		Location does not fall within the coverage of social survey
wq15	81	Not detected	20	Septic Tank. Not cleaned yet.
wq16	>2420	Not detected	22	Septic Tank. Septic Tank cleaned once a year and waste buried in household
wq17	36	Not detected	48	Septic Tank. Not cleaned yet.
wq20	28	1		Location does not fall within the coverage of social survey
wq21	>2420	152		Location does not fall within the coverage of social survey
wq29	>2420	179	30	Septic Tank. Not cleaned yet.
wq32	435	3	50	Septic Tank. Septic Tank cleaned once every 2 years and waste buried in household
wq35	308	25		Health Center
wq38	517	10		Location does not fall within the coverage of social survey
wq40	172	6	50	Location does not fall within the coverage of social survey

*Distance between water well and nearest septic tank (feet)

Faecal Coliform was detected in 10 samples. Total Coliform was detected in all 15 samples with 4 samples containing Total Coliform count greater than 2400 MPN/100mL.

The effects of effluent leakage from septic tanks and local outfall pipes are evident in the microbiological survey results. On average, there is an approximate distance of 35 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Faecal Coliform and Total Coliform is given in Figure 51. On average, Faecal Coliform is not detected in the center and East side of the island while it was detected on the West and North-East side of the island. Lower count of Total Coliform was observed near the centre of the island adjacent to the harbour, while extremely high levels of total coliform count was observed on the rest of the island.

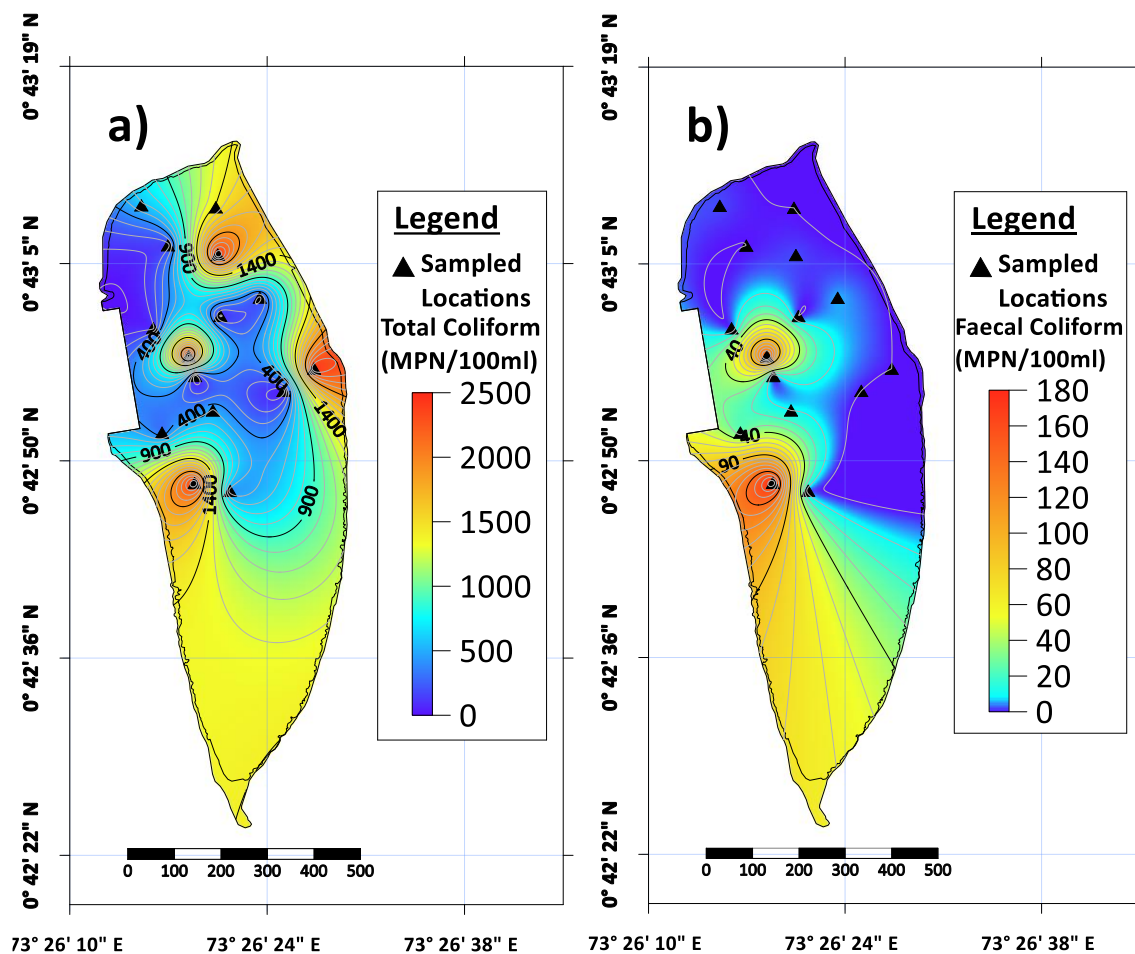


Figure 51: Total (a) and Faecal (b) Contamination Distribution in GA. Maamendhoo

The Total Coliform and Faecal Coliform Contamination was plotted against the distance between septic tank and well, to identify the correlation between these two variables. The graphs are given below.

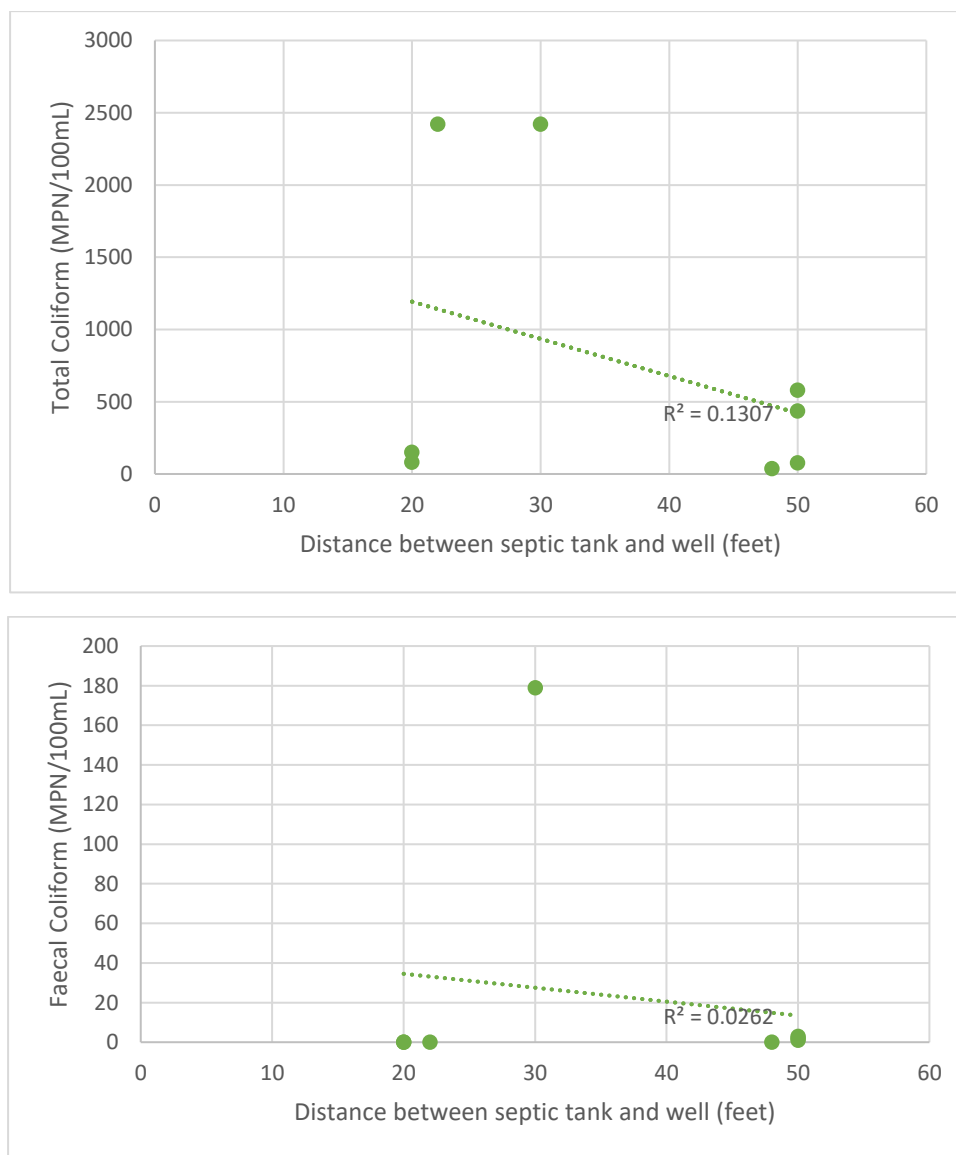


Figure 52: Microbiological Contamination against Septic Tank distancing - Maamendhoo

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.362 and the R-squared of the plot is 0.131. The correlation coefficient of Faecal Coliform to distance between septic tank and well is -0.162 and the R-squared of the plot is 0.026. Therefore, there is no significant relationship observed between the parameters.

5.5 Pumping Test

5.5.1 Test location

A well in construction, with a gravel bed base was available from a private land in GA. Maamendhoo and hence, it was selected to be used for the pumping test. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 53 below shows the location for the pumping test at GA. Maamendhoo.



Figure 53: Pumping test location – GA. Maamendhoo

5.5.2 Pumping rate, pumping hours and collected data

A step-drawdown pumping test was carried out at GA. Maamendhoo. The test began at 1601 hours on 12 November 2021 and lasted for 153 minutes. A flowrate of 20 LPM was maintained for 0–55th minute of the test. The flow was then gradually increased to 25 LPM for 56th–90th minute, and 45 LPM for 91st–118th minute. The recovery phase of the test lasted from 119th–153rd minute for more than a 96% recovery.

5.5.3 Hydrogeological parameter estimation

The Cooper-Jacob Solution for Unconfined Aquifer Models was used to process the data from the pumping test. The analysis was carried out using the software, AQTESOLV. The Aquifer Transmissivity (T) value was estimated to be $9.74 \times 10^{-4} \text{ m}^2/\text{s}$ (84.16 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.1335 for GA. Maamendhoo. The full data set of the pumping test at GA. Maamendhoo has been annexed at Annex XII.

5.6 Permeability Test

5.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 54 below. The originally proposed locations were changed as necessary due to unavailability of water and electricity for testing, inaccessibility of proposed locations, as well as the prioritizing of public lands that can be used for potential design solutions over private lands.

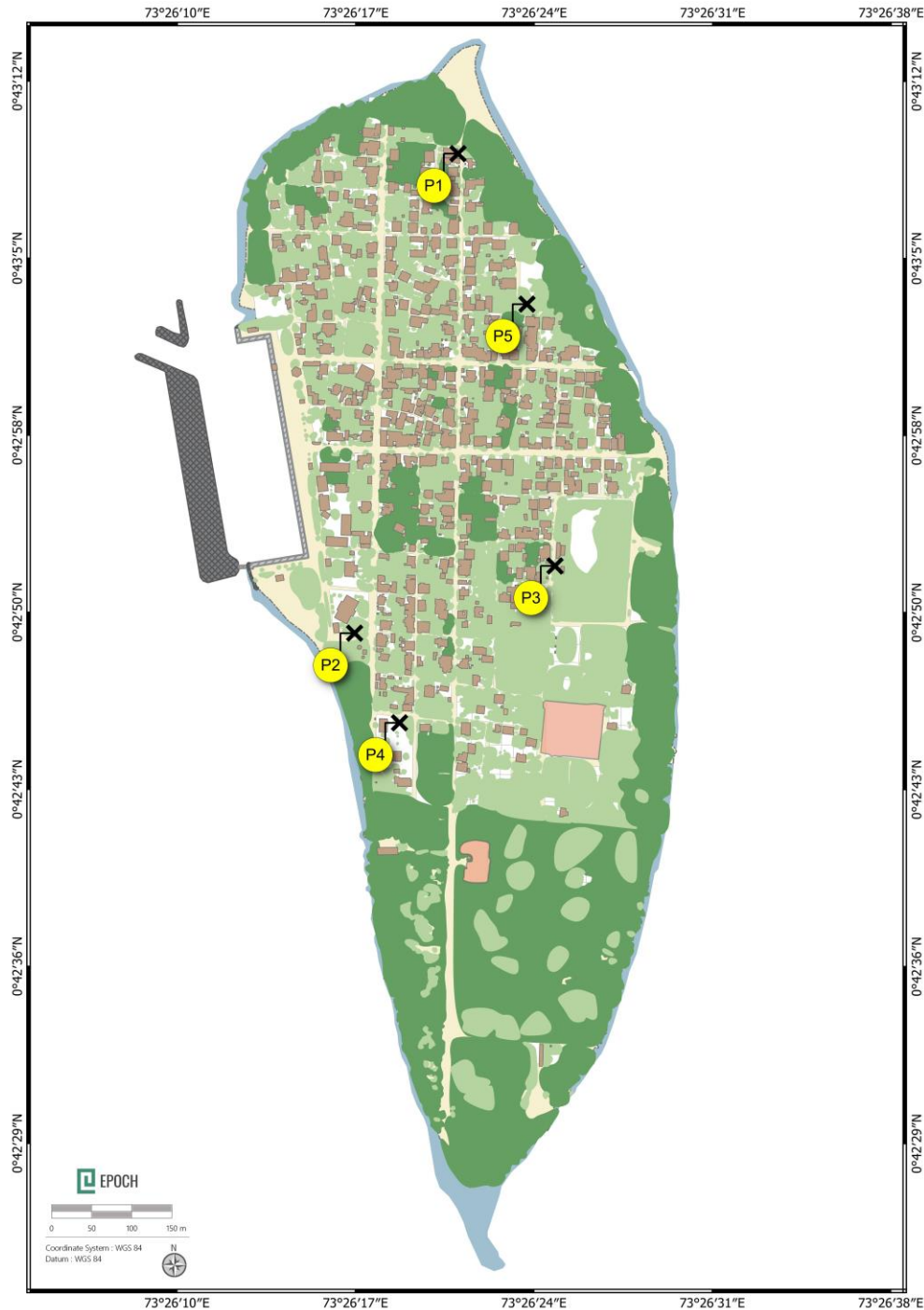


Figure 54: Permeability Test Locations – GA. Maamendhoo

5.6.2 Measured data

Table 50: Permeability Test Measured Data - GA. Maamendhoo

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m ³ /s)	K (m/s)	K (m/day)
MMD-PMB1	0.6	1.660	35	12	18.00	0.000300	1.84E-04	15.92
MMD-PMB2	0.6	0.780	35	12	13.00	0.000217	2.83E-04	24.48
MMD-PMB3	0.6	0.700	35	12	19.00	0.000317	4.61E-04	39.86
MMD-PMB4	0.6	1.045	35	12	14.00	0.000233	2.28E-04	19.67
MMD-PMB5	0.6	0.815	35	12	20.00	0.000333	4.17E-04	36.04

Note: H = Height of water in well (m),
 Tu = distance from water level in casing to water table (m),
 Cu = Conductivity Coefficient,
 r = borehole radius,
 Q = Steady flow into well,
 K = Coefficient of permeability.

5.6.3 Permeability estimation and identified features

The average permeability value for GA. Maamendhoo is 27.19 m/day, with permeability values ranging from 15.92 m/day to 39.86 m/day. As highlighted in Section Soil Profile Survey, the island soil profile is predominantly Sands, and the K values above are consistent with the range of K values obtained for Sands (Robertson (2010)).

5.7 Soil Profile Survey

5.7.1 Test locations

Soil Profile surveys were carried in 7 locations across the island, as outlined in Figure 55 below. Out of the 7 locations, 5 points were permeability test locations, and the remaining 2 points were chosen in a way that ensured a uniform coverage of the entire island.



Figure 55: Soil Profile Survey Locations – GA. Maamendhoo

5.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 56 below. Even though there are variances in the colour due to environmental factors, the island soil profile is made up of Uniformly Graded Sand for the observed depth.

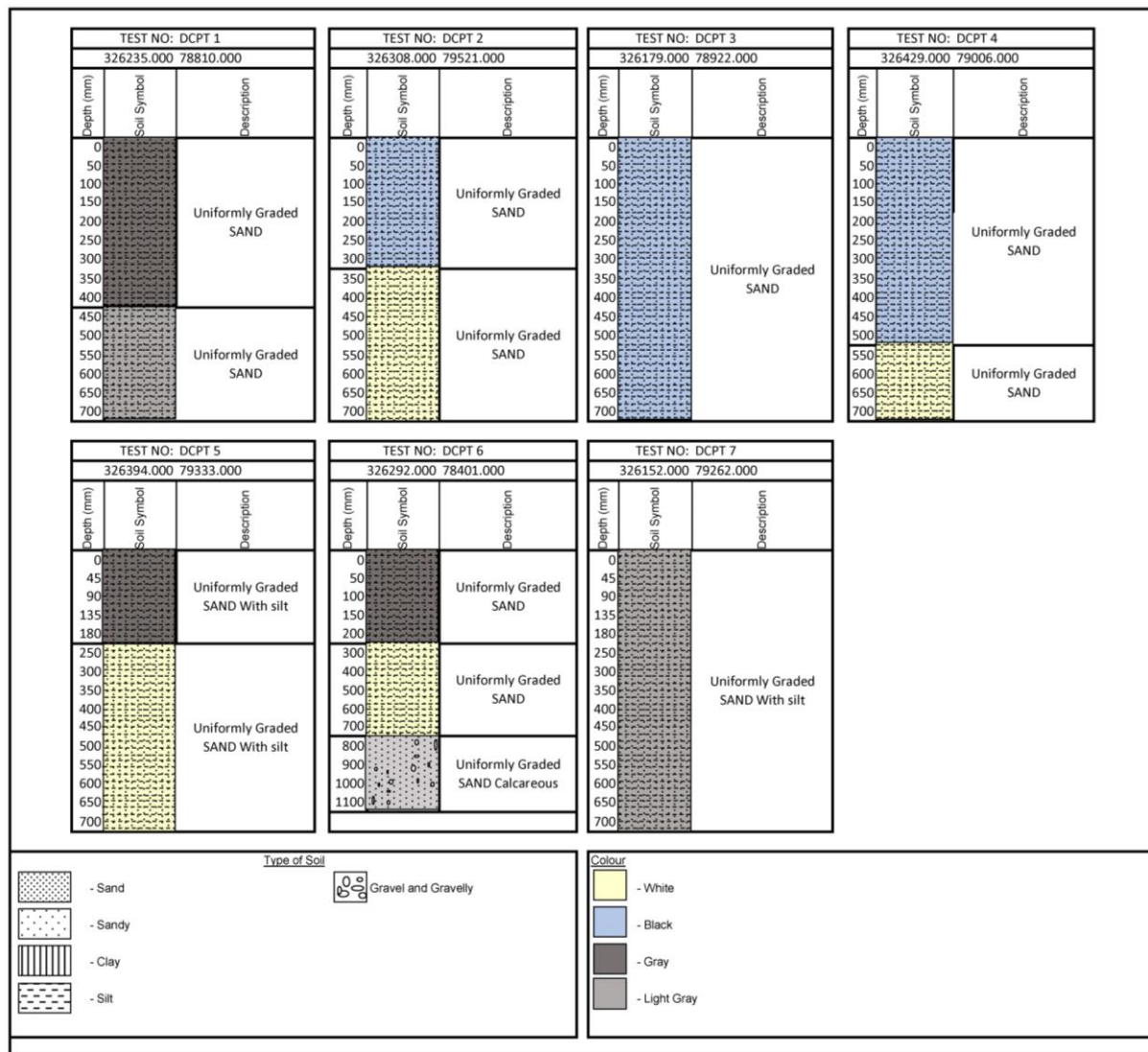


Figure 56: Soil Profile - GA. Maamendhoo

5.8 Flood Assessment and Inundation Survey

5.8.1 Flood occurrence and flood impact

As per Social Survey, 44% reported that flooding occurs every time it rains. Flood events in the Maldives are referred to as small inundation events which may cause damage to property but are not large-scale life-threatening events. On the same note 53% of the households reported that flooding does not happen in the island. Many respondents also reported that harbour construction and Tsunami had a major impact on the flooding pattern of the island. The island also experiences significant soil erosion on the North side of the island.

As per the social survey, 20 households reported rain induced flood incidents in 2019, 2020, and 2021. In the three incidents, 11 houses reported complete damages of furniture and household appliances while, 7 houses reported with damages that are fixable. The remaining 2 households only reported minor damages to their household. On the same note, 82% of the households reported that they experienced no damages by recent flooding events.

Despite the flooding events, 69% households report flooding as an acceptable problem. (refer to flood severity component of Annex XIII: Flood Maps).

The flooding originates mostly from roof runoff (44%) as per the Social Survey. Most responses state multiple sources for the flooding within their properties such as from neighbours' roof, off the road, and general run off in the area. Perceived causes of flooding as per social survey are given in table below.

Table 51: Perceived causes of flooding - GA. Maamendhoo

Perceived causes of flooding				
Roof run off	Neighbours' roof	Off the road	General run off in the area	No flooding within the plot
44%	14%	22%	28%	50%

From the social survey, 88% of households report that they drain rainwater overflow from storage and roofs to the ground. Most responses state multiple ways for the discharge of rainwater overflow such as to the ground, roads, open areas within the plot and to the well. Details of discharge of rainwater overflow are given in the table below.

Table 52: Discharge of rainwater overflow - GA. Maamendhoo

Discharge of rainwater overflow			
Ground	Roads	Open area within the plot	Drained to well
93%	1%	1%	4%

5.8.2 Flood Depth and Inundation area identification

Common flooding areas are the empty plots and houses in the east of the island and one road, commonly known as 'Ranhadhaa Goalhi' was reported as significant flooding zones (refer to Annex XIII: Flood Maps). Many households reported that it takes 2 to 4 hours to inundate the area once heavy rain starts and an average of 1.00 ft is estimated to be the flooding depth when there is a heavy rainfall.

5.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 73% observe that the water drains during the rainfall itself, 15% observe that the water drains in less than 4 hours, 7% observe that the water drains in less than 4-24 hours and 5% observe that it takes more than 24 hours for water to drain.

Table 53: Draining period - GA. Maamendhoo

Draining period			
only while raining	drains less than 4hrs	takes 4-24 hrs	more than 24hrs
73%	15%	7%	5%

In GA. Maamendhoo, the flooded water is usually pumped out and sandbags are used to reduce water level in the vicinity and negate any further damages caused by flooding.

5.9 Geophysical Survey

5.9.1 Surveyed locations

Locations where ER sounding measurement taken at GA. Maamendhoo island are shown in Figure 57 together with transect lines. There are 40 ER measurement locations and 14 transect lines.

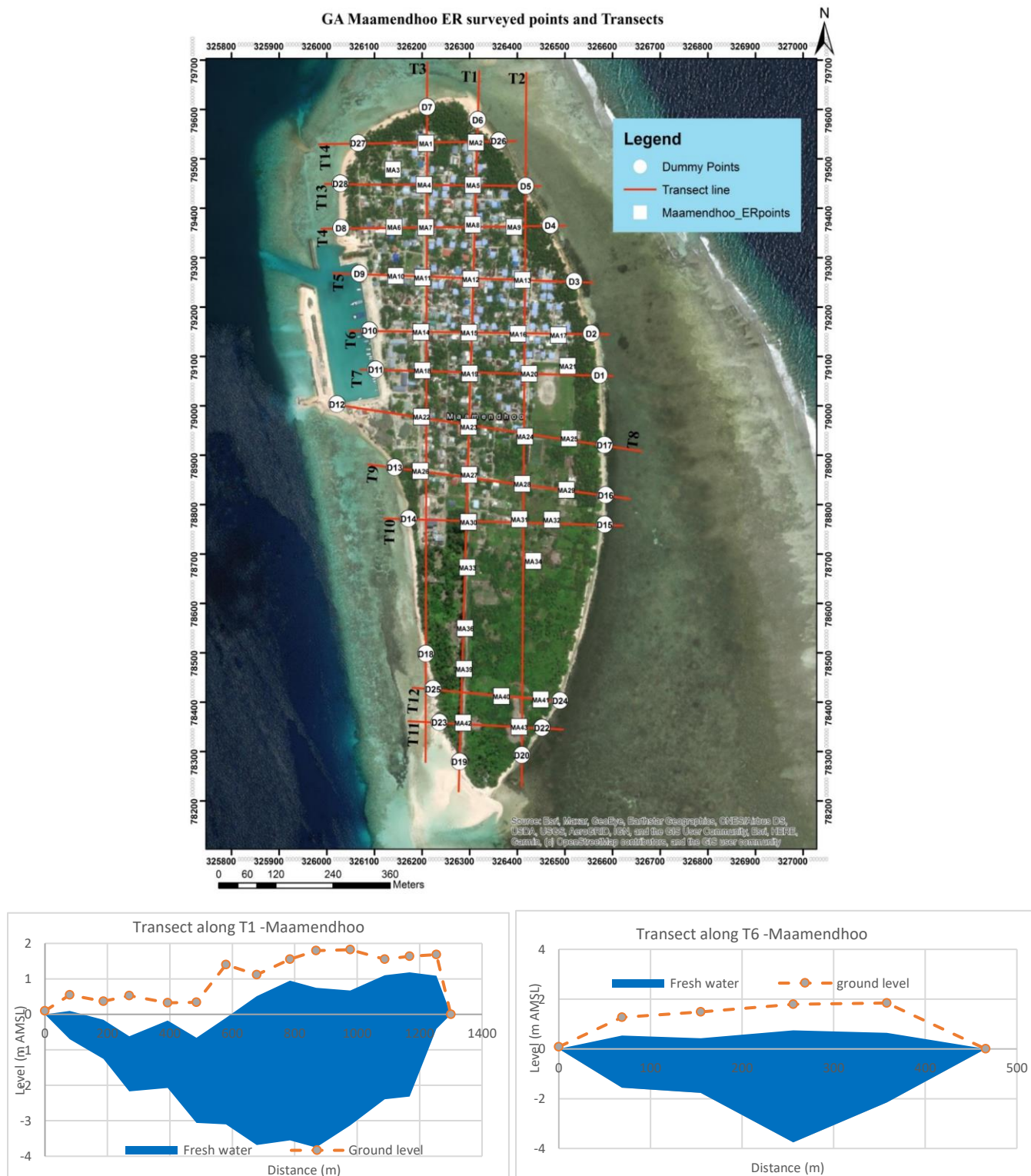


Figure 57: ER surveyed locations and transect lines – GA. Maamendhoo Island

5.9.2 Freshwater levels and saline water levels

From processed ER data using GeoVES 1.5 – GeoElectrical Model depth to freshwater starting level and depth to freshwater lens bottom level (saline water start level) were determined and they were converted to elevation with respect to mean sea level using ground collected through drone survey. Table 54 below shows the estimated levels at ER surveyed locations of GA. Maamendhoo Island and freshwater lens thickness.

Table 54: Freshwater lens levels and thickness – GA. Maamendhoo island

No	Map ID	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	MA01	1.67	0.92	-0.88	1.80
2	MA02	1.69	1.09	-0.41	1.50
3	MA03	1.74	1.14	-0.86	2.00
4	MA04	1.60	0.50	-1.70	2.20
5	MA05	1.63	1.18	-2.32	3.50
6	MA06	1.83	1.13	-1.07	2.20
7	MA07	1.70	1.10	-1.30	2.40
8	MA08	1.55	1.10	-2.40	3.50
9	MA09	1.57	0.57	-0.63	1.20
10	MA10	1.71	1.11	-0.99	2.10
11	MA11	1.79	0.79	-1.71	2.50
12	MA12	1.82	0.67	-3.13	3.80
13	MA13	1.49	0.39	-2.61	3.00
14	MA14	1.84	0.64	-2.16	2.80
15	MA15	1.80	0.75	-3.75	4.50
16	MA16	1.48	0.43	-1.77	2.20
17	MA17	1.27	0.54	-1.56	2.10
18	MA18	1.46	0.36	-1.34	1.70
19	MA19	1.55	0.95	-3.55	4.50
20	MA20	1.42	0.32	-2.28	2.60
21	MA21	1.32	0.22	-1.98	2.20
22	MA22	1.15	0.35	-1.30	1.65
23	MA23	1.11	0.51	-3.69	4.20
24	MA24	1.79	0.49	-2.01	2.50
25	MA25	1.14	-0.06	-2.06	2.00
26	MA26	0.91	0.01	-1.49	1.50
27	MA27	1.40	-0.10	-3.10	3.00
28	MA28	0.95	-0.10	-2.40	2.30
29	MA29	1.26	0.06	-1.74	1.80
30	MA30	0.34	-0.66	-3.06	2.40
31	MA31	0.91	0.01	-2.19	2.20
32	MA32	1.05	0.15	-1.15	1.30

Average freshwater thickness of GA. Maamendhoo island is 2.19m.

Data in Table 54 were used to plot freshwater lens cross sections along 14 transects and they are given in Annex IX. Of these sectional plots 2 were given in Figure 57 and they represent the transect plot along the longitudinal section and cross section of the island that passes through island middle. Dotted lines in these plots indicate ground level variation with respect to mean sea level along the transect lines.

5.9.3 Freshwater lens spatial extent

For the purpose of identifying spatial distribution of upper and lower level of freshwater lens the computed freshwater levels and saline water levels at ER points were exported to ArcGIS and used to generate contours with help of interpolation tools available in the same software. The generated contours are shown in Figure 58 and the processed ER data were also used to develop a 3D view of the freshwater lens and it is also shown in Figure 58.

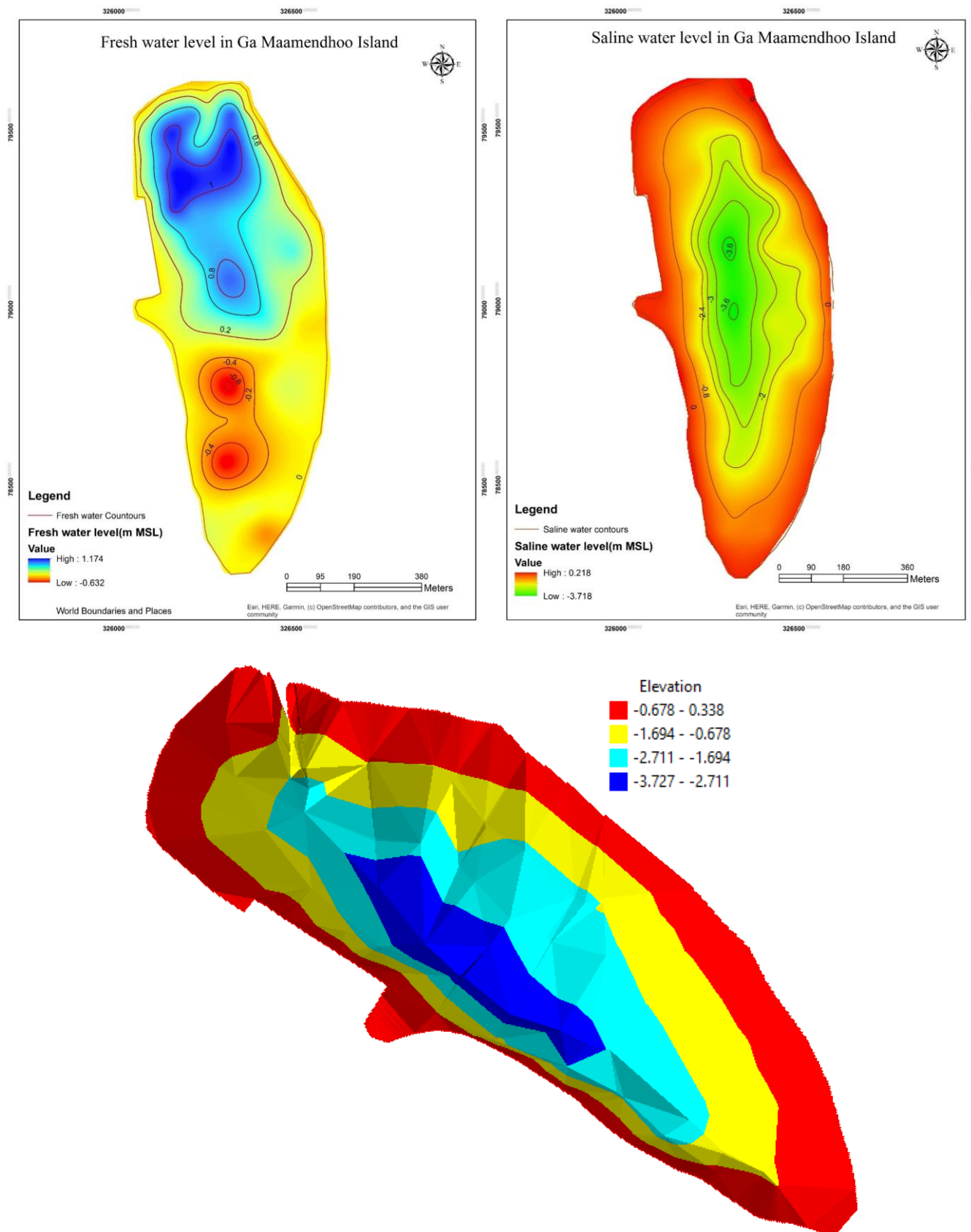


Figure 58: Top Left: Contours of Freshwater lens upper level, Top Right: Contours of Freshwater lens lower level, Bottom: 3D view of Freshwater lens bottom level

5.9.4 Freshwater lens storage volume and stress level

For the estimation of freshwater volume, the depth difference between freshwater-saline water interface and freshwater upper level was computed at each ER measurement points and they were then used to determine freshwater volume stored in the ground at time of taking ER measurements. Both “Triangle method” and Tools in ArcGIS software were used to perform this computation. Figure 59 shows triangles considered for the above said computation and refer Annex X for detailed calculations.

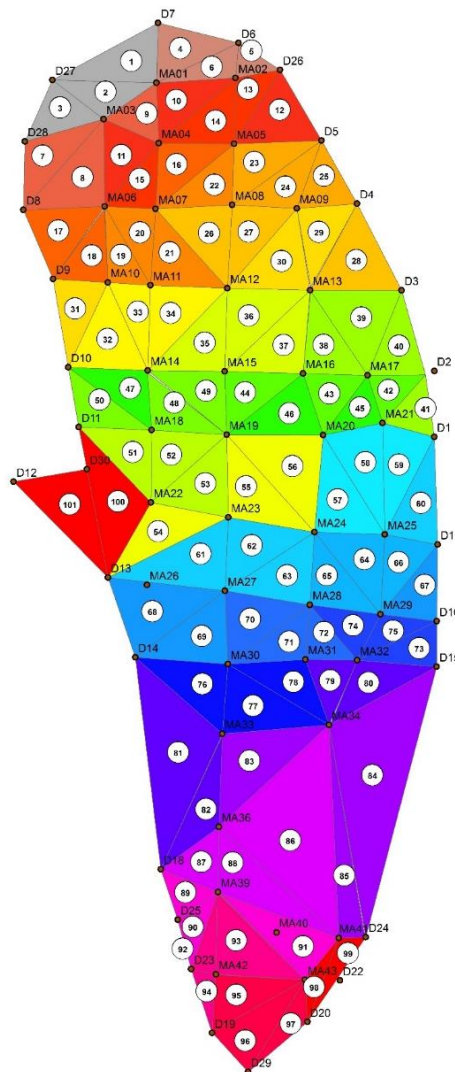


Figure 59: Triangles for freshwater volume computation – GA. Maamendhoo island

Stress level on freshwater aquifer of GA. Maamendhoo island was determined by computing ratio between freshwater lens volume and annual groundwater abstraction for non-potable water usage at present. When this ratio was more than 1.5, the island was treated as “not stressed” and if it was between 1.5 and 1 the aquifer was assumed to be “stressed” and any other lower ratio was taken as “highly stressed” aquifer. This criterion was developed based on saline water issues collected from

the project islands during field work. The computed freshwater volume, water abstraction and aquifer stress level are given in Table 55.

Table 55: Freshwater lens volume and aquifer stress level – GA. Maamendhoo island

Item	Value	Unit
Freshwater lens volume – Triangle method	164,370	m ³
Freshwater lens volume – ArcGIS	169,196	m ³
Groundwater abstraction	141,235	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	1.2	-
Aquifer stress level	Slightly stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation amounts to 9.2m. This deviates by 104% from the maximum measured value of 4.5m, which is more reliable as it results from a more comprehensive, site-specific methodology.

5.10 SWB Modelling

5.10.1 Topography for flow direction

Topographical data assigned to model grids for computation of D8 flow directions is shown in Figure 60 and according to this figure elevation of the island is changing from -0.675 mAMSL to 2.627 mAMSL and average elevation is 1.412 mAMSL.

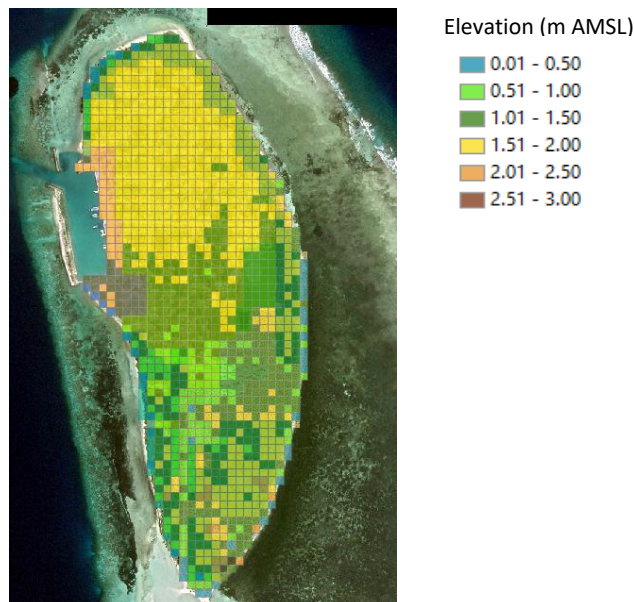


Figure 60: Elevation data assigned for SWB modelling - GA. Maamendhoo Island

5.10.2 Land use categorization and area estimation

Land use map prepared for SWB modelling of GA. Maamendhoo island is shown in Figure 2 together with table a showing land classification and their respective areas. It could be noted from the Figure 61 that 20m x 20m grids are adequate to represent the island land use for SWB modelling purpose.



Land use	Symbol	Area (m ²)	Area (%)
Residential		226400	43.8%
Forest		146400	28.3%
Commercial		29200	5.7%
Ground		16800	3.3%
Bare land		90800	17.6%
Wetland		0	0%
Agriculture		7200	1.4%

Figure 61: Land use for SWB model - GA. Maamendhoo Island

5.10.3 Recharge estimation and distribution

Monthly recharge values estimated at grid cells of the SWB model were extracted and used to identify its variation over years and months (refer Figure 62 and Table 56). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 147.6, 364.2 and 537.4 respectively over a 20 year period.
- There is a good relationship between annual rainfall and annual recharge, it is not linear but inverse exponential.
- Annual average rainfall is around 2270 mm but for 5 consecutive years (from 2008 to 2012) annual rainfall was below average. It indicates that there would be serious issue of saline water intrusion into the freshwater lens during such period as the recharge value would be considerably lower than annual average recharge value (inverse exponential relationship).
- Variation among the monthly average recharge value is very high. It is lowest on month of March and highest in November.
- Water consumption (pumping) for non-potable use on 6-month period is less than the recharge value on the respective months. It indicates that GA. Maamendhoo island is heavily depending on groundwater storage and there would be serious issues of saline water intrusion into this island.

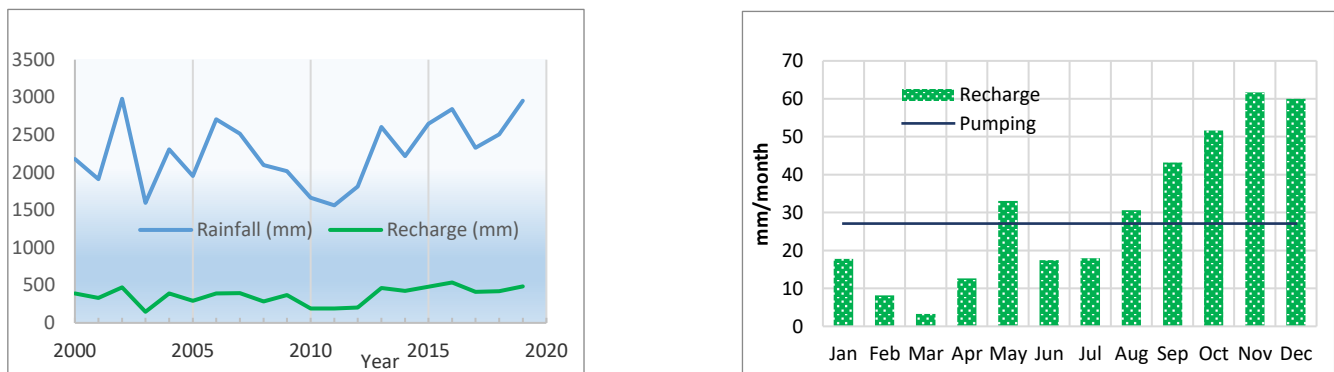


Figure 62: Monthly and annual recharge distribution – GA. Maamendhoo island

Table 56: Monthly recharge estimated by SWB model – GA. Maamendhoo Island

Year	Monthly Recharge (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	4.8	0.0	0.1	7.8	10.9	48.1	27.4	31.3	115.9	34.3	71.1	36.3
2001	0.0	0.0	0.0	33.5	8.8	0.0	11.4	47.0	69.7	55.7	68.7	42.0
2002	6.0	17.0	13.8	21.5	37.2	64.9	31.3	12.1	33.3	85.2	62.6	93.6
2003	2.5	0.0	0.0	7.7	33.1	27.6	27.8	15.9	0.1	8.8	33.3	16.7
2004	35.9	0.0	0.0	12.4	0.5	0.4	26.4	39.5	56.2	57.4	98.1	55.1
2005	28.9	11.8	0.0	0.1	35.3	47.7	36.3	20.4	17.5	99.4	3.2	0.0
2006	38.6	49.7	0.0	4.2	0.1	5.6	9.9	9.6	44.9	8.4	134.2	76.4
2007	58.5	0.0	0.0	3.1	16.5	36.6	26.7	4.5	32.3	92.5	10.1	112.0
2008	28.4	0.0	0.0	27.9	23.4	15.9	27.1	6.3	0.0	53.1	65.4	48.2
2009	33.9	19.4	0.0	0.1	51.6	0.0	5.9	87.4	23.0	43.6	51.7	51.2
2010	11.3	0.0	0.0	29.9	14.7	0.1	39.5	57.6	40.8	15.6	0.3	0.0
2011	0.0	0.0	0.0	5.8	22.6	0.0	0.0	8.9	0.0	57.1	16.0	85.7
2012	0.0	15.1	0.1	0.0	22.7	7.9	15.5	13.0	13.6	90.1	31.1	15.1
2013	0.0	0.1	10.5	16.2	69.8	10.5	28.0	43.5	12.1	27.6	123.5	115.2
2014	0.0	0.0	8.9	14.2	106.4	0.0	5.8	17.9	129.6	30.1	68.0	40.7
2015	9.0	12.0	0.0	0.0	23.4	22.2	11.6	97.6	29.1	77.4	92.1	100.2
2016	57.4	4.3	22.3	47.1	56.9	6.2	24.7	112.9	21.6	52.7	71.9	51.9
2017	2.3	0.0	13.7	0.0	87.8	0.0	28.1	23.0	83.7	0.0	57.6	122.6
2018	0.0	5.7	0.3	34.6	50.3	48.8	30.3	0.0	57.9	95.7	51.2	37.3
2019	62.3	25.4	7.5	14.3	45.6	55.9	13.3	18.5	72.1	45.1	56.1	72.9

5.10.4 Water Balance

As per estimation, annual recharge estimated by the SWB model is 188,104 m³ and it is 16% of annual average rainfall (refer Figure 63).

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	1,172,717	4,710	10,153	624,455	188,104	345,295	141,235
%	100.0%	0.4%	0.9%	53.2%	16.0%	29.4%	12.0%

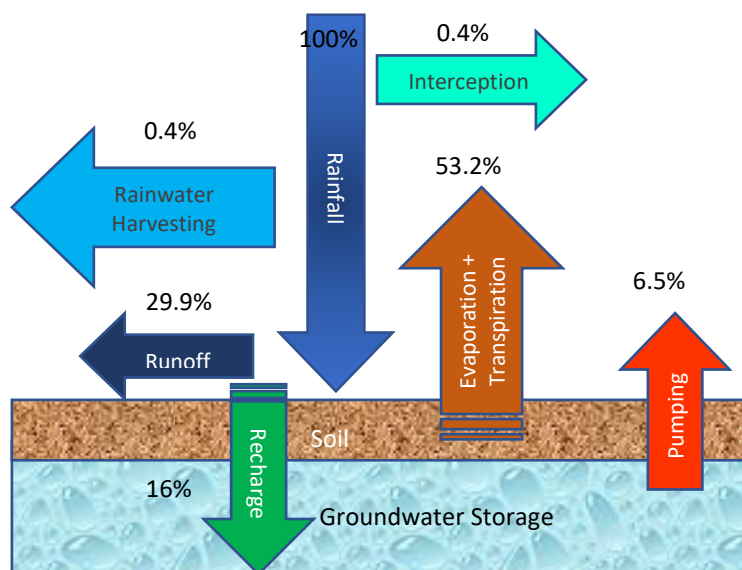


Figure 63: Annual water balance - GA. Maamendhoo Island

5.10.5 Deficit estimation, dry month identification and safe yield

Deficit calculation was carried out to identify whether recharge over a month period is smaller than or larger than the pumping quantity in the island. Monthly recharge time series estimated by the SWB model was compared with total pumping quantity of the island (14,004 m³/month) and if recharge exceeds the pumping quantity it was taken as "no deficit" and on other hand if pumping quantity exceeds the recharging value it was taken as "deficit".

Table 57: Deficit percentage - GA. Maamendhoo

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	142	59.2

It is to be noted that "deficit" doesn't mean failure or inadequate freshwater for pumping, but it is to be interpreted as the number of months where pumping is to be supported by groundwater storage in addition to recharging quantity. As per estimation, pumping at GA. Maamendhoo island is 59.2% dependent on the groundwater storage.

Determining safe yield which is defined as the attainment and maintenance of a long-term balance between the annual amount of groundwater withdrawn by pumping and the annual amount of recharge is important for small islands and there are various methods to estimate this amount. One simple method is checking whether ground water abstraction is less than or equal to 10% of average annual rainfall (MoEnv. 2020). The comparison of the estimated ground water withdrawal (168,046 m³/yr) with safe abstraction volume (67,310 m³/yr) shows that present withdrawal is 156% higher than the safe yield.

5.11 SUTRA Modelling

5.11.1 Model representation and mesh production

SUTRA modeling requires model domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island (refer Figure 64). The other boundary defined in the model was island outline which can be taken as the shoreline for most of the cases except at harbor area and the inner part of the island which was subdivided to several polygons representing different types of land use and it was accomplished by importing GIS shape files of island land use and then drawing a polygon on the shape files. Some other boundaries were also defined to represent island features such as lake and elevation change in the middle of the reef. Mesh with irregular quadrilateral elements were produced for all closed boundaries. Mesh size defined for outer boundaries (area between shoreline and model domain) were 3 to 4 times larger than the size defined for the inner part of the island. Elevation at shoreline was defined as zero whereas elevations for inner part of the island was assigned from topographical data used for SWB modelling. Figure 64 shows model domain and SUTRA model mesh with topographical changes.

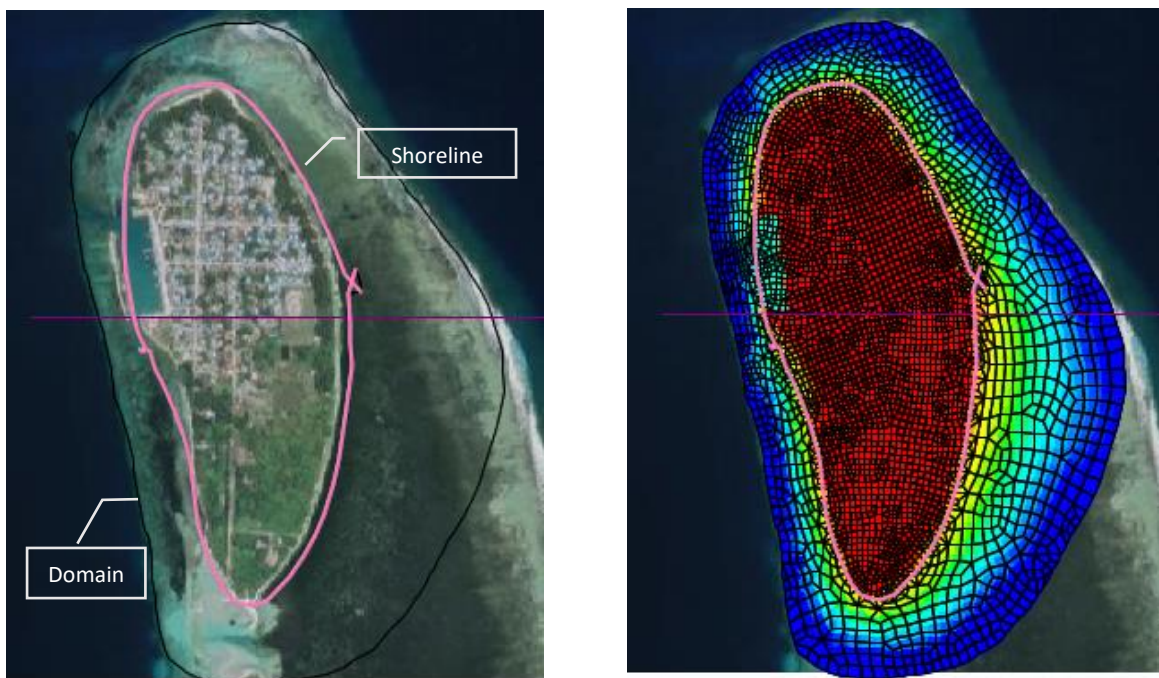


Figure 64: Model boundaries and model mesh - Maamendhoo island

5.11.2 Pressure boundaries

Specified pressure boundary was defined along the model domain so that it would cause saline water intruding into the island when pressure along the outer boundary of freshwater lens is less due to lower recharge and/or groundwater abstraction is high. Figure 65 shows the pressure boundary defined for GA. Maamendhoo island.

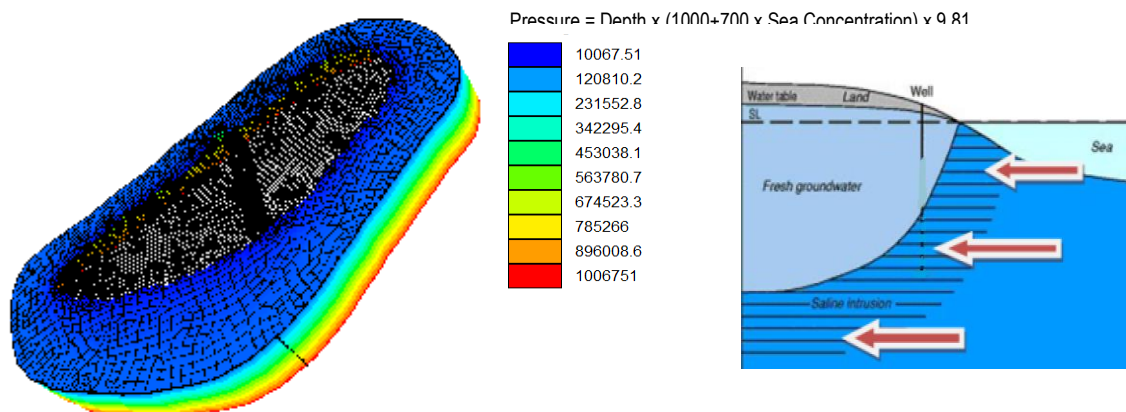


Figure 65: Pressure boundary at SUTRA model - Maamendhoo island

5.11.3 Assigning recharge on land use basis

Recharge rates estimated by the SWB model for each grid cells were lumped on land use basis using VB program and ArcGIS tool and were then used to estimate the monthly average recharge rate on residential area, commercial area, and other land use areas. Table 58 shows monthly recharge rate estimate for GA. Maamendhoo island.

Table 58: Recharge for SUTRA model - GA. Maamendhoo island

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	41.4	6.7	32.6	26.8	33.8	0.0	35.4

5.11.4 Groundwater abstraction

Groundwater pumping takes place at individual houses, restaurants, and institutes. Since all well locations are not available and abstraction rate would also have spatial variation, a simplified approach was adopted by defining a polygon around the residential area (area highlighted in blue in Figure 66) and assigning average pumping rate of 14,004 m³/month.



Figure 66: Pumping region at SUTRA model - GA. Maamendhoo island

5.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20-year period is shown in Figure 67. The orange-coloured component in the 3D view represents sea water concentration around the island and the section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0375 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top. As shown in Figure 4, depth to freshwater lens is deeper in the residential area and it could be due to pumping of freshwater for non-potable water use.

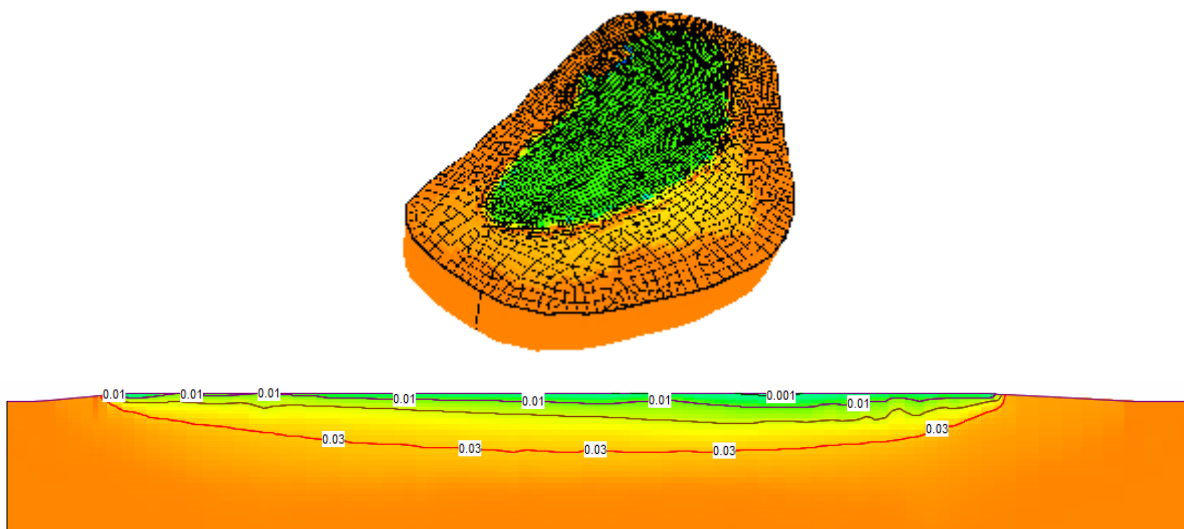


Figure 67: Saltwater distribution - GA. Maamendhoo island

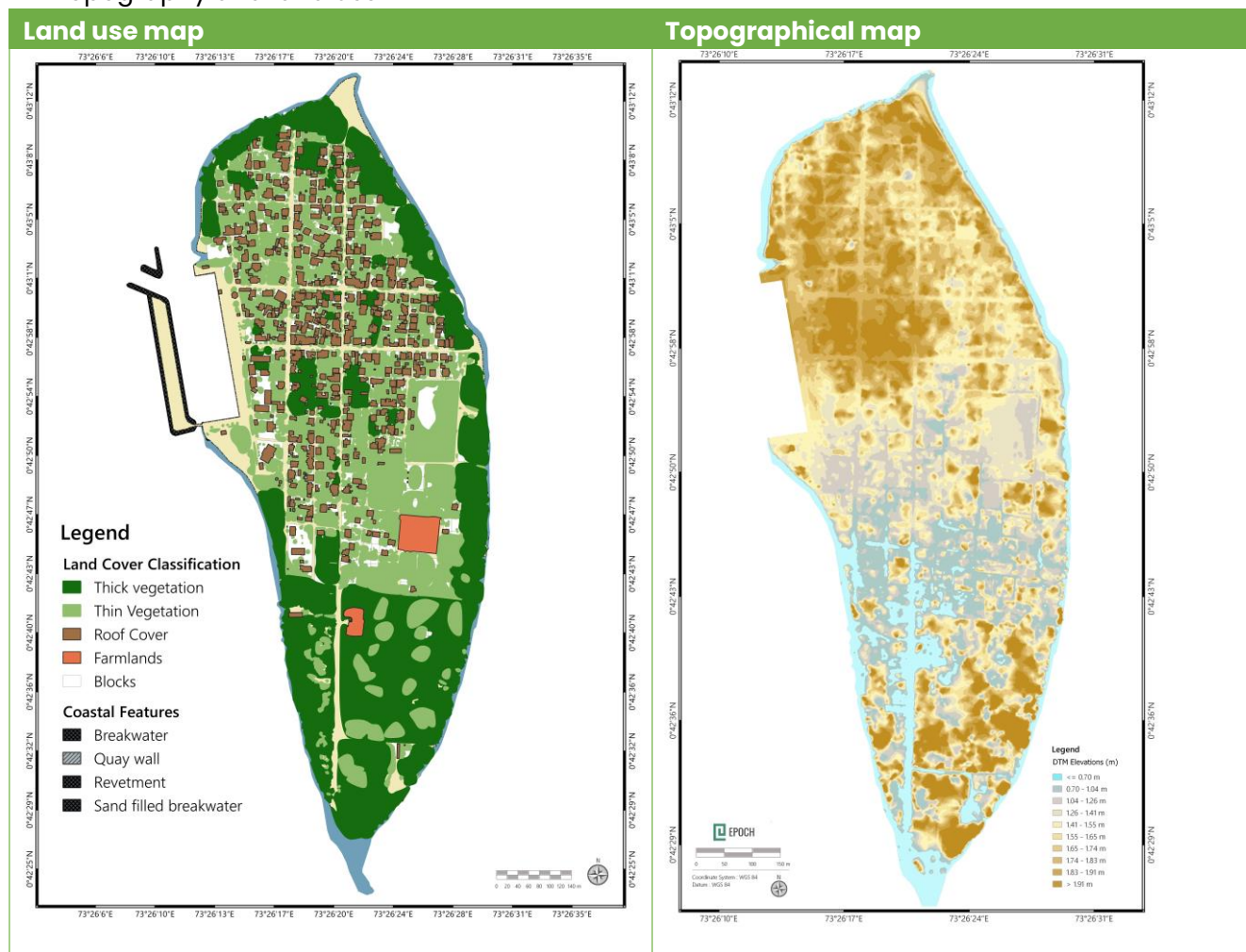
5.12 Summary of Baseline Assessment

Summary of findings extracted from field works, laboratory test, modelling and analysis are presented below.

- General overview, demography, and climatology

Item	Details
Atoll	Huvadhoo Atholhu Uthuruburi Atoll
Length	1.4 km
Width	0.51 km
Area	49.3 ha
Population	1554
Population/area	31.52 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use



Average elevation = 1.41 m above MSL Shoreline length = 4342 m	% of total area	
	Roof cover	13%
	Vegetation (Thick)	36%
	Vegetation (Thin)	30%
	Bare Lands	20%
	Farmlands	1%
	Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Institutional	Industrial	Total
Rate (m³/d)	387	4.70	5.72	5.16	403

- Water quality parameters – Physiochemical

Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	1060 ± 662	1500
Turbidity (FNU)	1.49 ± 2.46	5
DO (mg/L)	3.56 ± 2.11	
pH	7.44 ± 0.27	6.5–8.5
Temp (°C)	29.42 ± 1.26	
Sal (ppt)	0.48 ± 0.32	
NH₃ (mg/L)	4.06 ± 7.99	1.5 (Odour Threshold)
NO₃⁻ (mg/L)	22.48 ± 23.42	50
PO₄³⁻ (mg/L)	0.30 ± 0.17	

- Water quality parameters – Microbiological

Number of samples tested = 15

Parameter	Value range	Average value	Remarks (<i>on permit limit</i>)
Total Coliform (MPN/100ml)	28– >2420	898	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not Detected – 179	25	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	84.16	m ² /day
Storativity	1	0.1335	–
Permeability	7	15.92 – 39.86 Average – 27.19	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m ²)	Inundation depth (m)
89	7000	0.305

- Electric Resistivity survey

- Measurement taken at 40 locations and number of transect is 14.
- Average freshwater thickness in the island is 2.19 m.
- Freshwater lens volume and aquifer stress level

Item	Value	Unit
Freshwater lens volume - Triangle method	164,370	m ³
Freshwater lens volume - ArcGIS	169,196	m ³
Groundwater abstraction	141,235	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	1.2	-
Aquifer stress level	Slightly stressed	-

- SWB modelling

- Annual recharge is 188,104 m³ and it is 16% of annual rainfall (2270 mm)
- Annual water balance

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	1,172,717	4,710	10,153	624,455	188,104	345,295	141,235
%	100.0%	0.4%	0.9%	53.2%	16.0%	29.4%	12.0%

- Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 59.2% in an average year, and it is compensated by ground water storage.
- Ground water withdrawal (168,046 m³/yr) is 156% higher than the safe abstraction (67,310 m³/yr).

- SUTRA modelling

- Average monthly recharge assigned to SUTRA model

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	41.4	6.7	32.6	26.8	33.8	0.0	35.4

- Freshwater lens prediction (allowable concentration for potable use is 0.001)

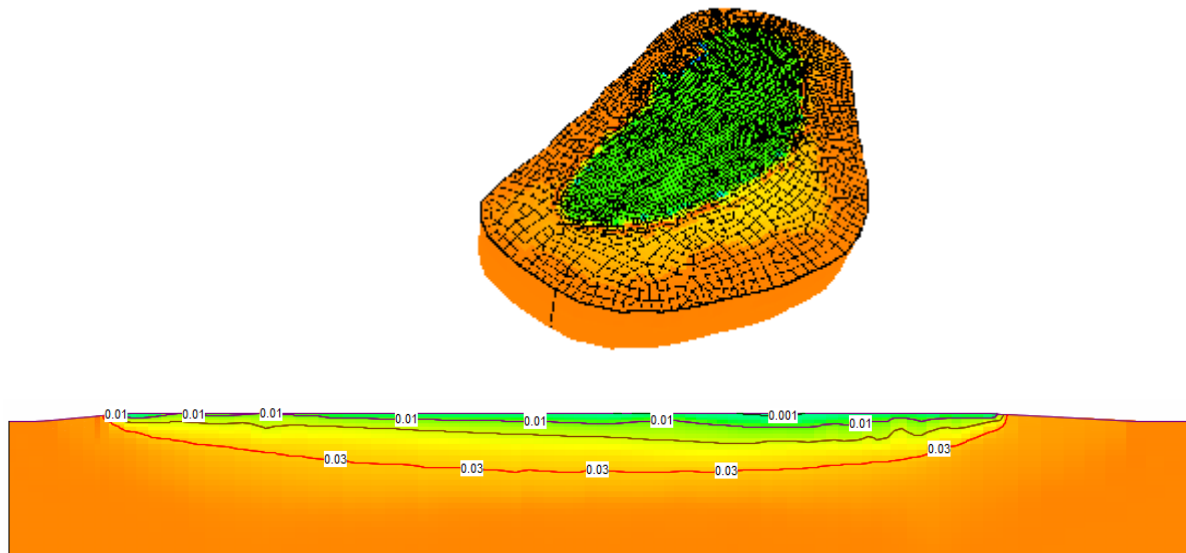


Figure 68: Saltwater distribution – Maamendhoo island

6 GA. Nilandhoo

6.1 Island Overview and Location

The Island of GA. Nilandhoo, belonging to Huvadhoo Atholhu Uthuruburi Atoll, is in the Southern region of Maldives at 0°38'14" N and 73°26'48" E. It is approximately 729 km South of the capital Male'.

Table 59: Island Geographical Data

Island	GA. Nilandhoo
Atoll	Huvadhoo Atholhu Uthuruburi Atoll
Location	0°38'14"N and 73°26'48"E

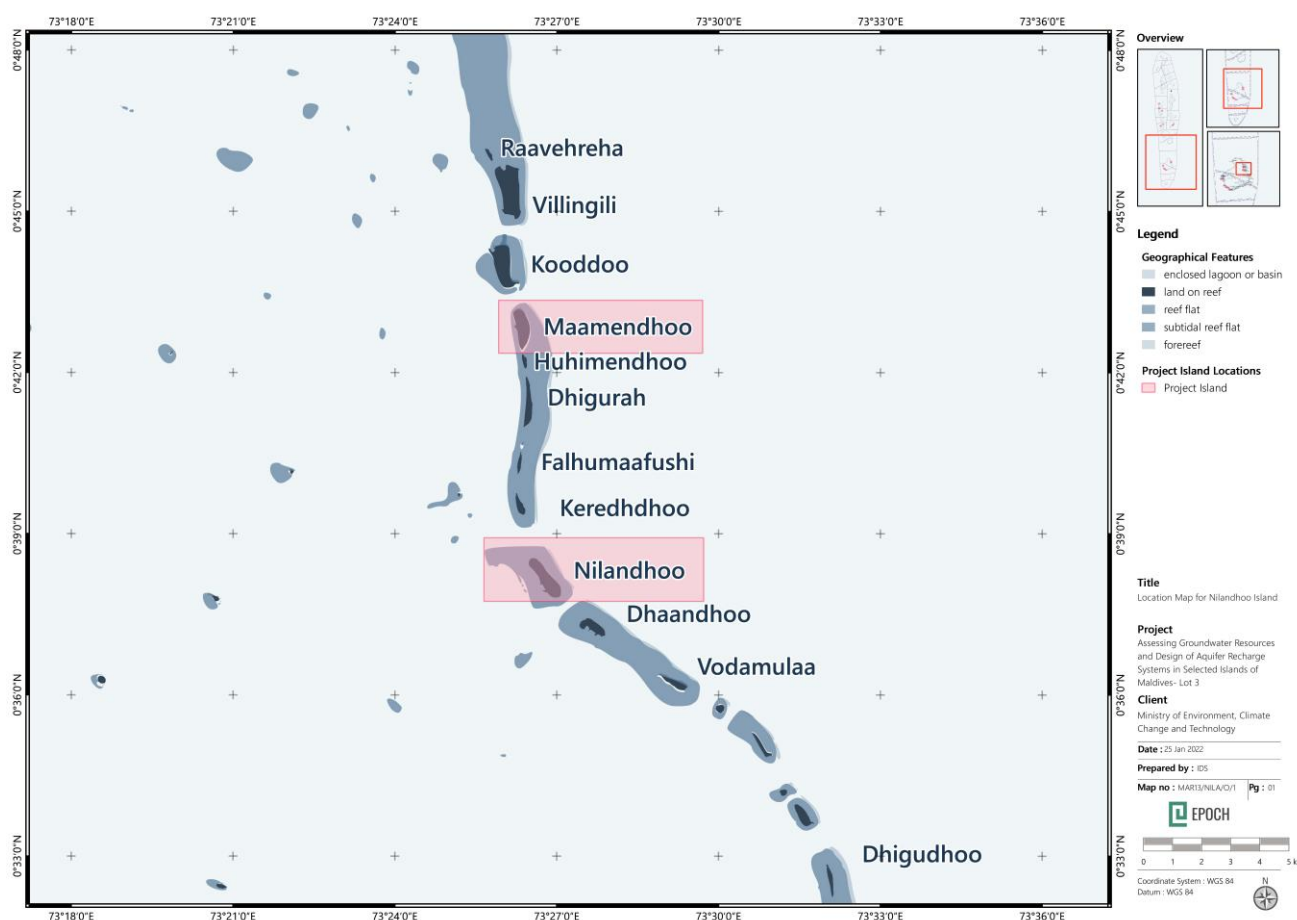


Figure 69: Location map – GA. Nilandhoo

6.1.1 Island features

The island extends up to 1.54 km in length from toe to toe and a width of 0.55 km from toe to toe. The reef system which holds the island is small and only holds the island itself. A large part of GA. Nilandhoo is reported to have muddy soil which is good for agriculture. Evidently, more than half of the island is allocated for agricultural purposes with a total of 210 dedicated farming plots.

The island has a harbour at its Southern west side of the island. About two-third of the island's surface is vegetation. Thick vegetation is mostly located in the North western and South eastern parts of the

island. Farming takes place on the Northern side of the island. Only about one-third of the island is populated, which is mostly the Southern part of the island.

Table 60: Area Distribution in GA. Nilandhoo

Area	57.4ha	
Length	1.54 km	
Width	0.55 km	
	Area (m²)	% of total area
Roof cover	44,515	8%
Vegetation (Thick)	226,218	39%
Vegetation (Thin)	112,625	20%
Bare Lands	85,729	15%
Farmlands	104,866	18%
Wetlands	-	0%
Total	573,955	100%

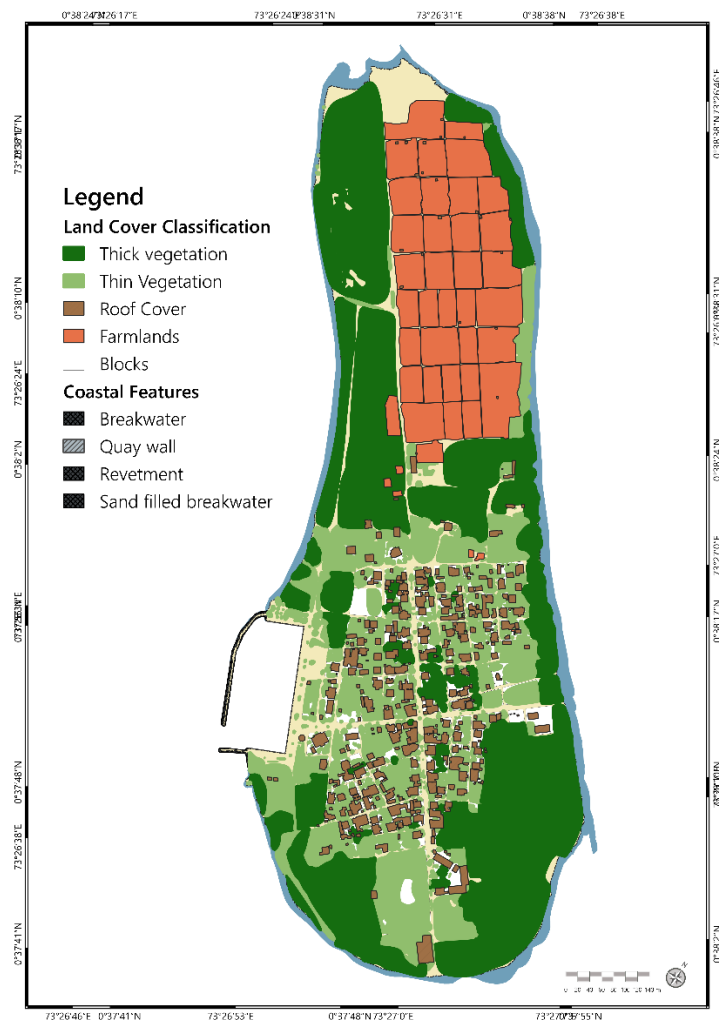


Figure 70: GA. Nilandhoo Land Use Characterization

6.2 Topographical Features

6.2.1 Topographical Features

Permanent Survey Marks Permanent Benchmark 1 and Permanent Benchmark 2 were used as benchmarks for GA. Nilandhoo topographical survey and drone survey. However, benchmark details are not registered and therefore not available at <https://www.mlsa.gov.mv/psm>. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 1930 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.22 cm per pixel. 11 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 61 GCP Statistics for GA. Nilandhoo

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	0.00323	-0.000297	-0.00274
Sigma [m]	0.0163	0.0186	0.0195
RMS Error [m]	0.0164	0.0186	0.0197

The Digital Surface Model in Annex III indicates that island has a constant elevation of 1m above MSL throughout its entire length. In contrast, at the southern tip, the elevations (average 0.7 m from MSL) are much lower than the island average.

Roof elevations generally do not exceed 5–7 m and very few houses have multistorey buildings in GA. Nilandhoo. For visualisation purposes all elevations above 10 were given the same colour in the DSM. As the north of the island is primarily used for farming the DSM does not illustrate these plants clearly as they tend to blend in with ground levels. Thick vegetation with heights greater than 10 m are primarily seen on the Southern periphery of the island. It is also noteworthy that despite the South-eastern region having dense thick and thin vegetation the elevations are generally lower than 10m. There is a wetland region where the elevations are generally around MSL but are not indicated in the DSM or GPS survey due to difficulties encountered in the field in accessing the area.

The Digital terrain model was produced at a resolution of 0.1 m spatial resolution for the purposes of analysis. scatter plot for sampled UAV Elevations vs GPS Spot heights is presented below along with statistics for the regression line. The error statistics for sampled elevations are given in the table below and indicate that the drone survey slightly underestimates the elevation with a mean of -4.38 cm

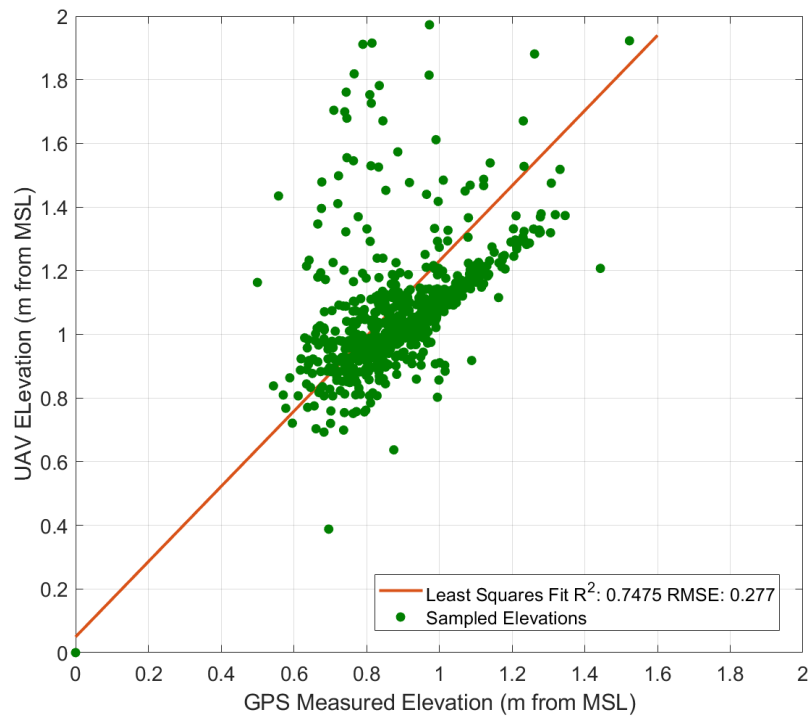


Figure 71 Linear Regression Plot for GA. Nilandhoo Sample UAV elevations

Table 62 Error statistics for GA. Nilandhoo Sampled elevations from DTM

Parameter	Value(cm)
Mean	-4.38
Standard Error	0.45
Median	-7.23
Mode	#N/A
Standard Deviation	11.02
Sample Variance	121.34
Kurtosis	2.21
Skewness	1.21
Range	68.96
Minimum	-29.02
Maximum	39.94
Sum	-2599.11
Count	594.00

6.2.2 Level changes

GA. Nilandhoo has an average elevation of 1.17 m with a standard deviation of 0.48. Digital Terrain Model elevations range from -0.6 to 3m from MSL. The distribution of elevations has a 'bell curve' with 1.1 m being the highest frequency for elevations. An additional peak is also observed around -0.2 for the low tide regions.

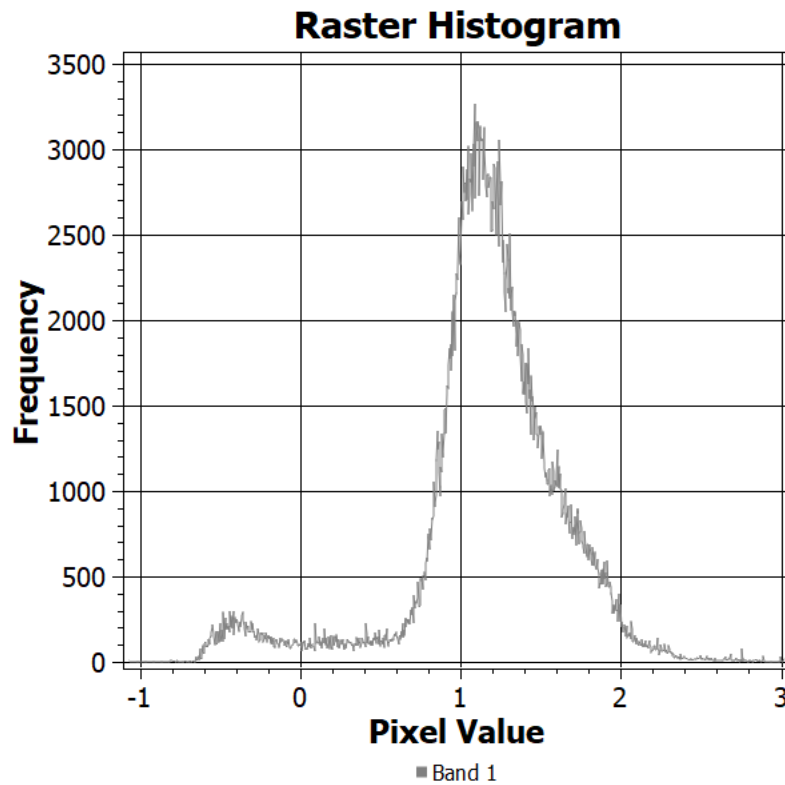


Figure 72 Raster Histogram created for GA. Nilandhoo DTM through QGIS for the Elevation Band 1

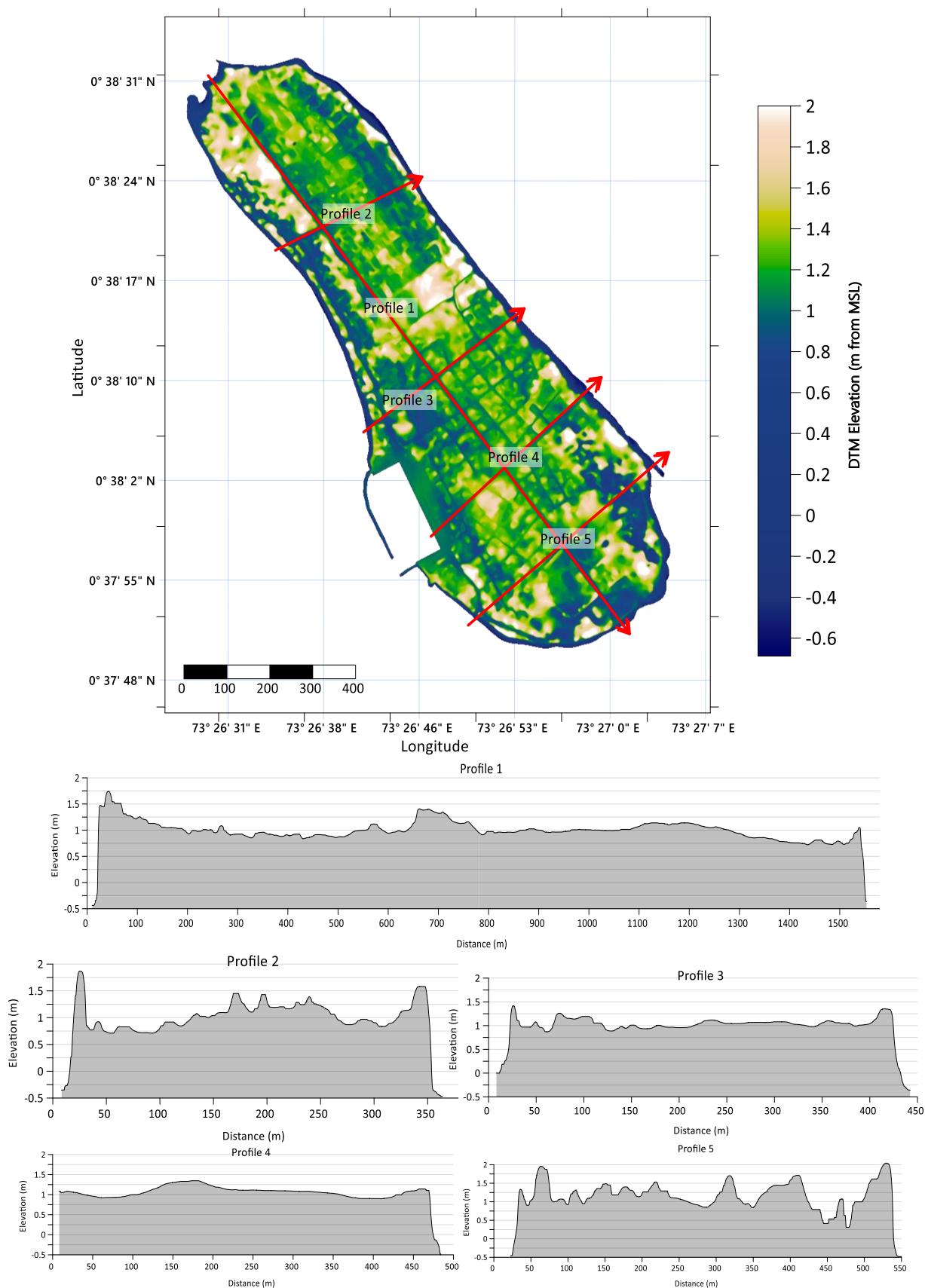


Figure 73 Digital Terrain Model Elevations and Profiles for GA. Nilandhoo Island

Analysis of the GA. Nilandhoo Terrain revealed that the island is generally flat (average elevation 1.0 m) in the centre except for small ridges (average elevation 1.5 m). The southern region specifically in profile 1 is at a lower elevation (0.75 m). The eastern and western ridges are more pronounced in profile 2. Areas next to these ridges are slightly lower and they are used for farming, but the central region of the Profile 2 is higher with an average elevation of 1.25 m.

Profile 3 near the school area shows an average island profile with small ridges on either side. Profile 4 which begins from the harbour shows very gradual and smooth changes from 1 m from MSL to 1.25 m MSL throughout the entire profile except for the steep ridge at the end.

Profile 5 has several peaks and troughs as it does not go through just one road, but it shows the very low elevated wetland area at 475 m in the profile.

6.2.3 Shoreline

GA. Nilandhoo shoreline is 4639 m long and does not have sandy areas extending from the north and southern tips of the island like most islands on the eastern rim of Huvadho Atoll. However interesting coastal features including lithified beach rock is found at the northern tip which forms bay like features.



Figure 74 Orthomosaic of Nilandhoo with distinctive beachrock features (orange)

6.2.4 Reef

In contrast to other islands of this Project, GA. Nilandhoo is the only island found in the reef. The tidal pass to the south is slightly narrower and shorter than the one in the north.



Figure 75 Sentinel 2 imagery of GA. Nilandhoo Reef taken in January 2022

6.3 Socio Economic Status

6.3.1 Demography

The Island has a registered population of 500 as per the 2014 census, with a total of 265 males and 235 females. The island population density is 19.63 people per hectare as per the 2021 figures. The population figures have drastically increased over the past years where the total registered local population climbed up to 1127. The following table and graph illustrate the demographic breakdown of GA. Nilandhoo.

GA. Nilandhoo Population

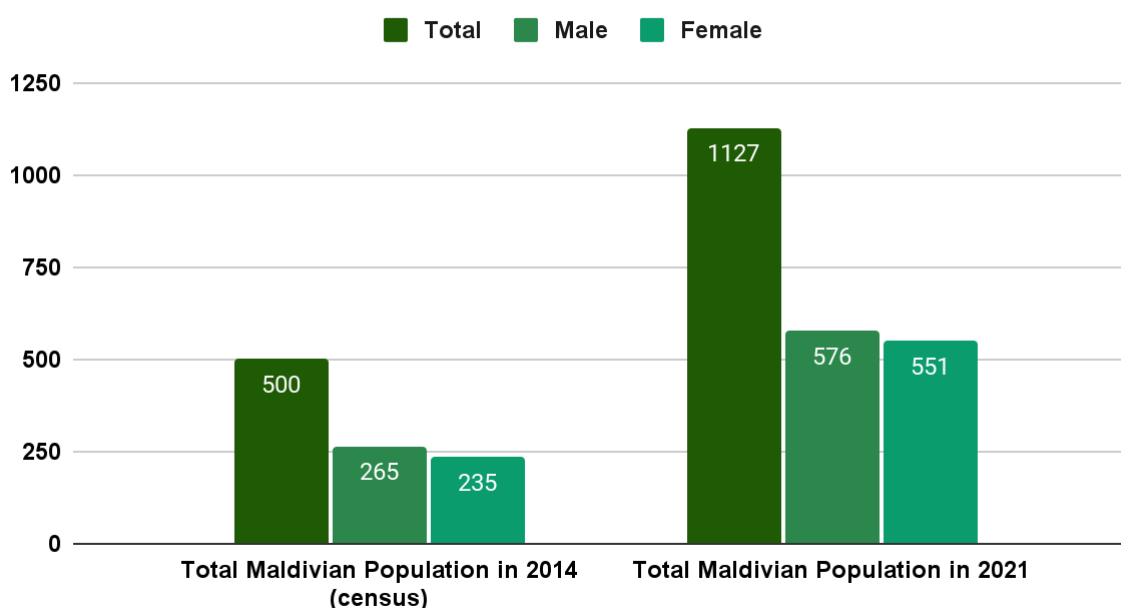


Figure 76: GA. Nilandhoo Population

Table 63: GA. Nilandhoo Population (Census, 2014)

Resident Population according to Census 2014										
Atoll	Locality	Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
GA	Nilandhoo	600	359	241	500	265	235	100	94	6

6.3.2 Socio-Economic Activities

GA. Nilandhoo is an inhabited island in Gaafu Alifu Atoll's administrative unit and physically part of Huvadhu Atholhu Uthuruburi Atoll in the Maldives'. This island is well-known for its fisheries and

agricultural activities. The island also has 2 cafes/restaurants, 5 guesthouse beds and 6 shops. The island also has 2 boat building units.

6.3.3 Facilities available

6.3.3.1 Health Care

GA. Nilandhoo Health Center currently has 1 doctor, 2 nurses and 3 beds. The health facilities in the island are bare minimum and many island residents find that the health center needs to be upgraded and service hours need to be extended.

6.3.3.2 Education

GA. Nilandhoo School has 126 students, 24 teachers and 8 administrative staff. The island school offers education up to grade 10 standard.

6.3.3.3 Utilities

Electricity and water on the island are provided by FENAKA. The island currently does not have a sewerage and sanitation system.

6.3.3.4 Transportation

The island harbour was constructed by Maldives Transport and Contracting Company (MTCC) on 26th February 2010. The transportation between GA. Nilandhoo and other islands is by sea.

6.3.4 Water resources, water usage and water consumption

In GA. Nilandhoo there are a total of 119 households. 89 out of 105 households were surveyed, while maintaining a 95% confidence interval and geo-coordinated sampling points. A map of households surveyed is attached in Annex V.

Table 64: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	89/105 households = 85%
Percentage of well fitted with pumps	97%
Ground water	Usage in percentage
Source of drinking	0
Source of cooking	2.25

6.3.4.1 Existing water and sanitation

The main form of sanitation facility is via the use of septic tanks and local outfall pipes. Based on the survey, 100 percent of the surveyed households have connected their sanitation to septic tanks.

In GA. Nilandhoo, 96 percent reported to have less than 49ft distance between septic tanks and groundwater well. While the remaining 4% reported to have more than 49ft distance.

According to the Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22), annex 4 states that the households should keep a 15-meter (49.2126 ft) distance

between septic tank and nearest well. The main reason for the adoption of this standard is to negate any possible causes of contamination in the groundwater.

Rainwater is also the primarily used for cooking. Many homes use rainwater from neighbouring houses or bottled water when rainwater is not readily available during the dry season. Rainwater collected from rooftops is stored mostly in water tanks, whether at home or communal rainwater tanks.

In GA. Nilandhoo, 4 houses have connected rainwater to the well and have reported improvement in groundwater. On the same note, 93% of the households have rainwater overflow drained to the ground.

6.3.4.2 Water usage and resources

Based on the survey conducted, out of 89 houses surveyed in GA. Nilandhoo, 80 houses have HDPE rainwater tanks for rainwater storage. 92% of the households use rainwater for cooking and 87% use rainwater for drinking. While groundwater is mainly used for gardening and household cleaning with 98% of the houses fitted with water pumps. The following sections outline further details about various water usage and consumption scenarios in the island.

6.3.4.3 Domestic water usage

Based on household water usage surveys in GA. Nilandhoo, **324,576** Liters of groundwater is used daily in the households. A total of **288** Liters of groundwater are consumed per capita per day. In GA. Nilandhoo, 71% of the surveyed households shower more than 3 times daily and take 16 minutes to shower on an average. This is a factor for high groundwater usage.

Table 65: Domestic groundwater use data for GA. Nilandhoo

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
172.65	33.11	14.55	33.81	2.75	23.21	7.76	288

*All units are in Liters per capita per day

6.3.4.4 Commercial water usage

Based on the survey conducted in GA. Nilandhoo, there are currently two operational café/restaurants and 1 guesthouse on this island. A total of **1470** Liters of groundwater are used by commercial entities and their detailed breakdown is given in the tables below.

Table 66: Café/ Restaurant groundwater use data for GA. Nilandhoo

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Wooden Cafe	0	7.5	212	0	6
Icicle	151.4	180	12.11	0	20
					589

*All units are in Liters per day

Table 67: Guesthouse groundwater use data for GA. Nilandhoo

Guesthouse	Average Occupancy	Total (L/day)
Thigo Business	25%	881
		881

6.3.4.5 Industrial water usage

In GA. Nilandhoo, 72 out of 210 farming plots were surveyed to determine the industrial groundwater usage. Majority of the farms have pumpkin, cucumber, watermelon and chillies and they are produced throughout the year. An average of 433 Liters of groundwater is used by each farm. GA. Nilandhoo also has one fish processing unit where 80 Liters of groundwater is used daily for fish processing activities. A total of **91,067** Liters of groundwater is used for industrial purposes and detailed breakdown for 210 farms and fish processing unit is given in the tables below.

Table 68: Groundwater use for farming in for GA. Nilandhoo

Total farms	No. of farms surveyed	Average usage	Total usage for all the farms (Liters)
210	72	433.27	90,987

Table 69: Groundwater use for fish processing in for GA. Nilandhoo

No. of fish processing unit	Fish processing activities	Number of days in a week	Total groundwater usage daily (Liters)
1	Cutting and Cleaning, Cooking and Smoking, Rihaakuru Production	1	80

6.3.4.6 Institutional water usage

Based on the survey conducted in GA. Nilandhoo, there are currently six institutions that have groundwater well facilities and use groundwater. A total of **3,566** Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 70: Institutional groundwater use data for GA. Nilandhoo

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Fenaka	206	80	20	-	306
Police desk	24	190	0.1	519	734
GA. Nilandhoo Council	884	15	3.6	74	977
Magistrate Court	61	124	0.6	-	185
GA. Nilandhoo School	743	420	43	-	1206
Health Center	157	-	-	-	158
					3,566

*All units are in Liters per day

6.3.5 Present & Future water demand

In GA. Nilandhoo, the present water demand is at **375,542** Liters per day and groundwater usage is expected to decrease with the establishment of water supply services in the island. The year 2021 figures are as per the latest island council data. For the figures in year 2036 and 2054, it is as per Maldives Populations Projections Report published by the National Bureau of Statistics.

Population Projection - GA. Nilandhoo

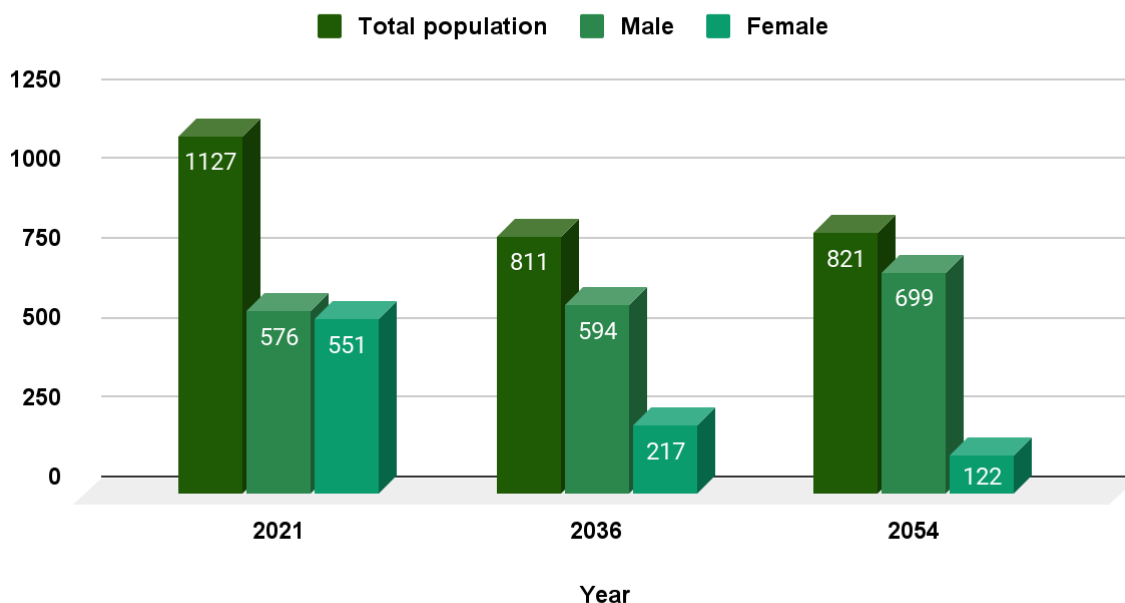


Figure 77: Population Projection – GA. Nilandhoo

Table 71: Present groundwater demand – GA. Nilandhoo

Year	Total Population	Domestic water demand	Commercial water demand	Institutional water demand	Industrial usage	Groundwater usage
2021	1,127	324,576	1470	3566	45,930	375,542

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 288 Liters per day. For the year 2036, water supply usage is expected to be 50 Liters per capita per day. After deducting 50 Liters from 288 Liters, the groundwater demand is expected to be 238 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 811 is expected to be **193,018** Liters per day.

For the year 2054, water supply usage is expected to be 75 Liters per capita per day. After deducting 75 Liters from 288 Liters, the groundwater demand is expected to be 213 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 821 is expected to be **174,873** Liters per day.

Table 72: Future domestic water demand – GA. Nilandhoo

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	811	288	50	238	193,018
2054	821	288	75	213	174,873

6.3.6 Water related issues

From 89 households surveyed in GA. Nilandhoo, most houses reported no contamination in the groundwater (71%). Only 1% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gasses such as Hydrogen Sulfide which causes unpleasant smells.

Table 73: Signs of contamination reported by households

Types of contamination	Data in % out of 79 households surveyed
Smell	28%
Milky	1%
Foul taste	0%
Changes in color	0%
Salty	3%
None	71%

The following table details the changes in groundwater quality reported by the households during tidal or seasonal changes.

Table 74: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 79 households surveyed
Changes with tidal variations	17%
Groundwater quality is better in rainy months (Hulhangu season)	0%
Long periods without rain causes bad smell	4%
Long periods without rain causes bad taste	0%
Rain makes it worse	0%
No change	79%

6.4 Groundwater Quality

6.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 75 summarizes the water quality results. Map of locations where groundwater quality points were taken for physiochemical analysis is attached to Annex VI. The full list of measured parameters is attached to Annex VII.

Table 75: Statistical summary of groundwater physiochemical parameters in GA. Nilandhoo

	EC ($\mu\text{S}/\text{cm}$)	Turbidity (FNU)	DO (mg/L)	pH	Temp ($^{\circ}\text{C}$)	Sal (ppt)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
Standards	<1500 Potable purposes <2500 Non- potable purposes Source ¹	<5 Source ²		6.5-8.5 Source ²			<1.5 Odour threshold <35 Taste threshold Source ¹	<50 Source ¹	
Mean	874	1.18	3.82	7.53	29.04	0.40	2.90	13.29	0.27
Median	660	0.39	3.51	7.46	29.00	0.30	1.24	5.89	0.20
SD	780	1.84	1.45	0.30	1.16	0.38	4.74	19.03	0.21
Min	246	0.00	1.64	7.10	26.22	0.11	0.26	1.64	0.05
Max	3887	7.88	7.36	8.31	33.06	1.87	21.58	95.09	1.07
CV	0.89	1.56	0.38	0.04	0.04	0.95	1.64	1.43	0.80

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH₃= Ammonia, NO₃⁻= Nitrate, PO₄³⁻=Phosphate, SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source¹ = WHO Drinking Water Guidelines, 2017. Source² = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 874 $\mu\text{S}/\text{cm}$ is lower than both the WHO Standard for potable water (<1500 $\mu\text{S}/\text{cm}$) and the WHO Standard for non-potable water (<2500 $\mu\text{S}/\text{cm}$).
- 3 samples had higher EC than 2500 $\mu\text{S}/\text{cm}$. 1 sample had EC between 1500 $\mu\text{S}/\text{cm}$ and 2500 $\mu\text{S}/\text{cm}$ while 36 samples had EC lower than 1500 $\mu\text{S}/\text{cm}$. The EC distribution is shown in Figure 78.
- As expected, the EC of the groundwater in the centre of the island is lower than the coastal areas of the island which indicate saltwater intrusion at the periphery of the island, especially on the North-East side of the island.
- The mean Turbidity level at 1.18 NTU falls within the URA Guidelines for drinking water (5 NTU). 1 sample had a higher Turbidity level than 5 NTU. Generally, the samples taken from the farming area of the island on the North-West side of the island have a higher turbidity than the samples taken from the inhabited areas of the island.
- Dissolved Oxygen ranged from 1.64 mg/L to 7.36 mg/L with a mean of 3.82 mg/L.
- All samples fell within the pH range of 6.5–8.5 as per URA Guidelines for drinking water with a mean pH of 7.53.

- Temperature ranges from 26.2°C to 33.1°C depending on the well characteristics and time of day reading was taken. Mean temperature was 29.04°C.
- Salinity ranged from 0.11ppt to 1.87ppt with a mean of 0.40ppt.
- The mean Ammonia concentration was 2.90 mg/L which is higher than the WHO threshold for odor but well below the threshold for taste. 55% of samples had concentration below 1.5 mg/L, 45% of samples had concentration between 1.5 mg/L and 35 mg/L and none of the samples had concentration higher than 35 mg/L. The Ammonia concentration distribution is shown in Figure 79.
- The mean Nitrate concentration was 13.29 mg/L which falls below the WHO Standard for Nitrate concentration (50 mg/L). 3 samples had Nitrate concentration higher than the WHO standard. The Nitrate concentration of samples taken from the farming area are higher than inhabited areas, with 2 samples having higher Nitrate concentration than the WHO Standard. This is as expected as application of nitrogenous fertilizers and manure for agriculture can result in Nitrate infiltrating into the groundwater.
- Phosphate concentration ranges from 0.08 to 1.07 mg/L with a mean concentration of 0.27 mg/L. There is no WHO guideline value for phosphate concentration. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater. 4 samples tested were below 0.1 mg/L. The phosphate concentration in inhabited areas is higher than in the farming areas.

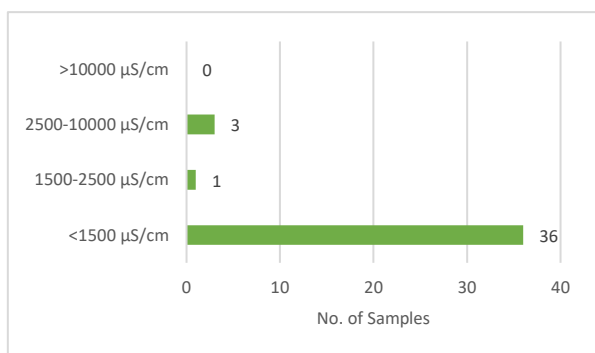


Figure 78: EC Distribution in GA. Nilandhoo

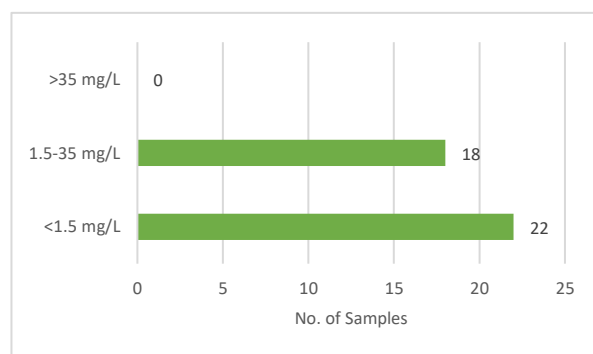


Figure 79: Ammonia Concentration Distribution in GA. Nilandhoo

The spatial distribution of all the parameters measured are shown in Figure 80 (a-i).

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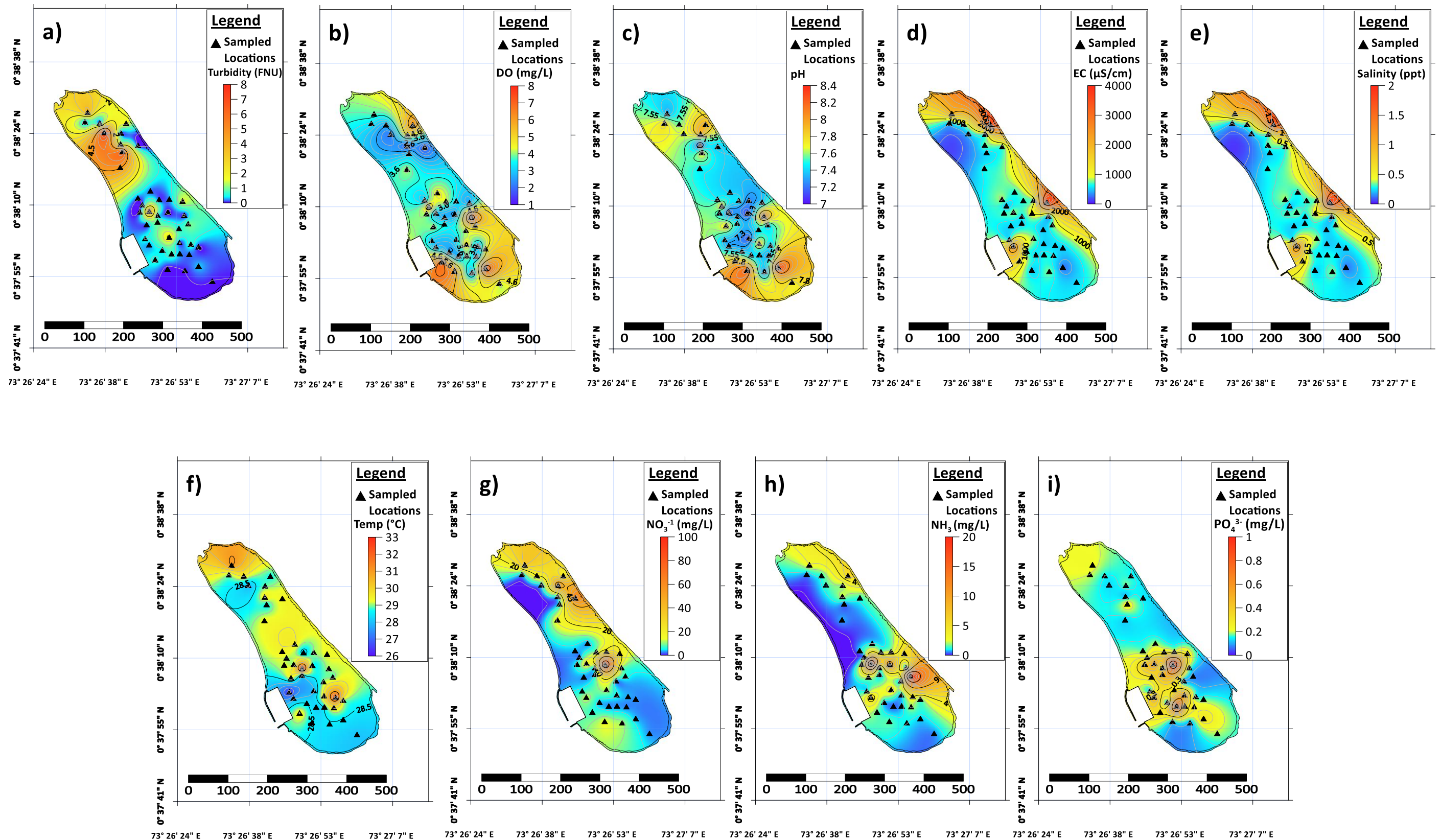


Figure 80: Spatial variation of physiochemical parameters in GA. Nilandhoo

As a principle, excessive groundwater usage leads to overextraction causing salinization of the freshwater lens. The Social Survey findings were used to calculate the daily water consumption at each household, institution, and other commercial entities. The EC values at these locations were plotted against water consumption to check if increasing water usage leads to salinization. The correlation coefficient of EC to Water usage is -0.168 and the R-squared of the plot is 0.0282 as indicated from the Figure 81. Therefore, there is no significant relationship observed between EC and Water Usage for the island as per the findings from the Social Survey and Water Quality Survey. The Spatial distribution of EC and water usage is shown in Annex VIII.

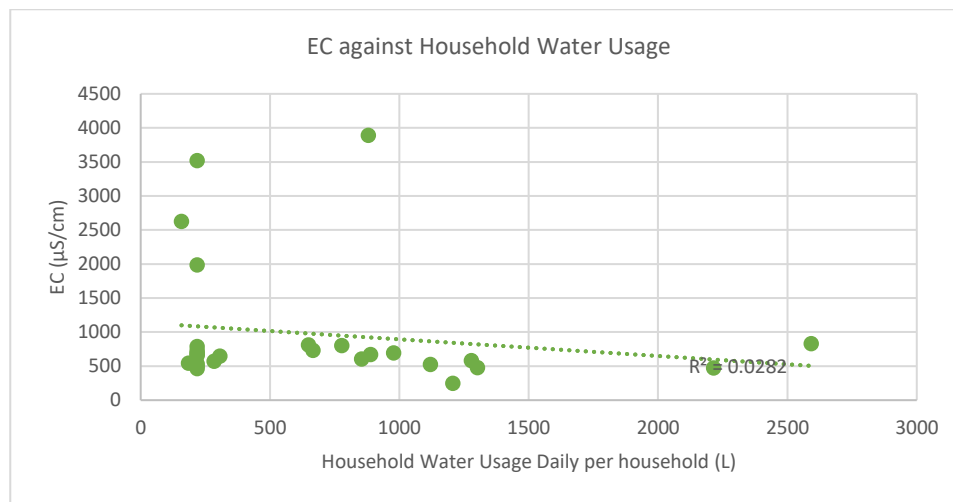


Figure 81: EC against Water Usage in GA. Nilandhoo

6.4.1.1 Correlation Matrix

The correlation matrix for GA. Nilandhoo along with the colour bar is given below. Red colour indicates negative correlation while green colour indicates positive correlation.

Table 76: Correlation matrix of the groundwater quality parameters in GA. Nilandhoo

Variables	Turbidity (FNU)	DO (mg/L)	pH	EC ($\mu\text{S/cm}$)	Sal (ppt)	Temp ($^{\circ}\text{C}$)	NO_3^- (mg/L)	NH_3 (mg/L)
DO (mg/L)	-0.21							
pH	-0.10	0.79						
EC ($\mu\text{S/cm}$)	0.11	-0.04	-0.13					
Sal (ppt)	0.11	-0.04	-0.12	1.00				
Temp ($^{\circ}\text{C}$)	-0.06	-0.08	-0.09	0.02	0.00			
NO_3^- (mg/L)	-0.04	-0.18	-0.19	0.22	0.21	0.01		
NH_3 (mg/L)	0.17	-0.08	-0.32	0.24	0.24	-0.01	0.29	
PO_4^{3-} (mg/L)	-0.07	-0.13	-0.20	0.06	0.06	-0.16	0.36	0.24

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation
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Table 76 shows a strong positive correlation coefficient between DO/pH ($r=0.79$) and EC/Sal ($r=1.00$). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlations between salinity and conductivity are as expected. There are no strong negative correlations between parameters observed.

6.4.1.2 Water Quality Index

In this study, the computed WQI ranges from 1.96 to 22.41, with a mean of 6.75. The WQI was divided into four categories and Table 77 shows the categorization of samples. 80% of samples were classified as "Very Good", 15% of samples were classified as "Good", 5% of samples were classified as "Poor" and 0% of samples were classified as "Very Poor". The high value of WQI at the "Poor" locations have been found to be from the high Nitrate concentration at one location and high EC at one location. The spatial distribution of WQI is as per Figure 82.

Table 77: Water Quality Classification based on WQI – GA. Nilandhoo

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	32	80%
10 to 20	Good	6	15%
20 to 50	Poor	2	5%
>50	Very Poor	0	0%

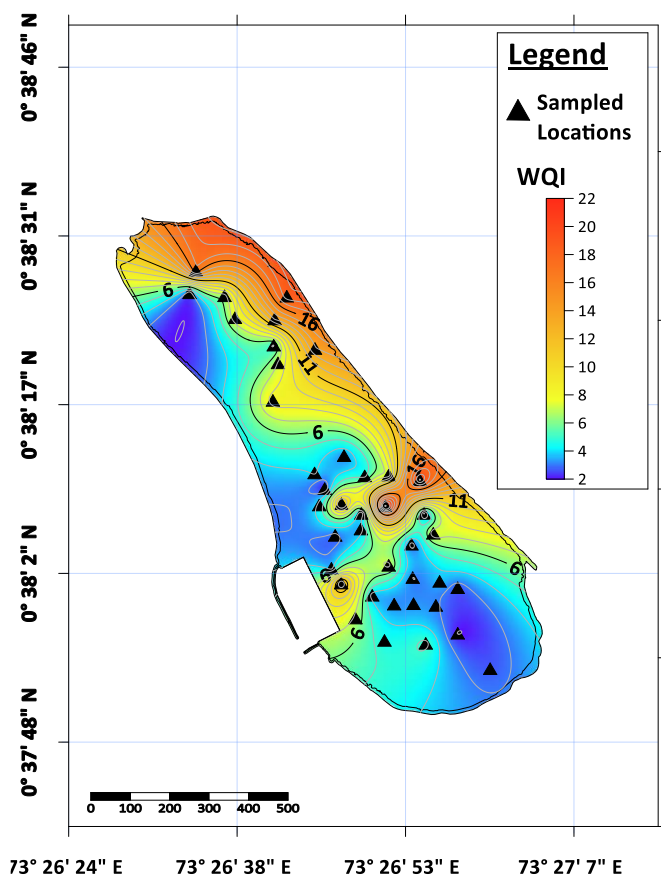


Figure 82: Spatial Distribution of WQI in GA. Nilandhoo

6.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 78 summarizes the results.

Table 78: Microbiological Parameters of groundwater in GA. Nilandhoo

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq01	>2420	1553		Preschool
wq05	>2420	2420		Location does not fall within the coverage of social survey
wq06	816	214	35	Septic Tank. Septic Tank cleaned once every 2 years and waste buried in household
wq07	920	273		Location does not fall within the coverage of social survey
wq09	1414	258	10	Septic Tank. Septic Tank cleaned every 6 months and waste pumped out to sea
wq12	1299	250	20	Septic Tank. Not cleaned yet.
wq15	1203	372	30	Septic Tank. Not cleaned yet.
wq17	1732	273		Location does not fall within the coverage of social survey
wq18	>2420	1120		Location does not fall within the coverage of social survey
wq30	1986	151		Health Center
wq33	>2420	980	20	Septic Tank. Not cleaned yet.
wq34	1732	1046	20	Septic Tank. Septic Tank cleaned every 2 years and waste pumped out to sea
wq35	>2420	1413	30	Septic Tank. Not cleaned yet.
wq38	>2420	547	15	Septic Tank. Not cleaned yet.
wq40	1300	579		Location does not fall within the coverage of social survey

*Distance between water well and nearest septic tank (feet)

Both Faecal and Total Coliform was detected in all the samples. Total Coliform count higher than 2400 MPN/100mL were detected in 6 samples.

The effects of effluent leakage from septic tanks and local outfall pipes are evident in the microbiological survey results. On average, there is an approximate distance of 22 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Faecal Coliform and Total Coliform is given in Figure 83. Low count of faecal coliform was observed in the South side of the island while most samples on the Northern side showed zero count of Faecal Coliform. Total Coliform was observed for all samples with similar trend of South side of the island having a higher count of Total Coliform.

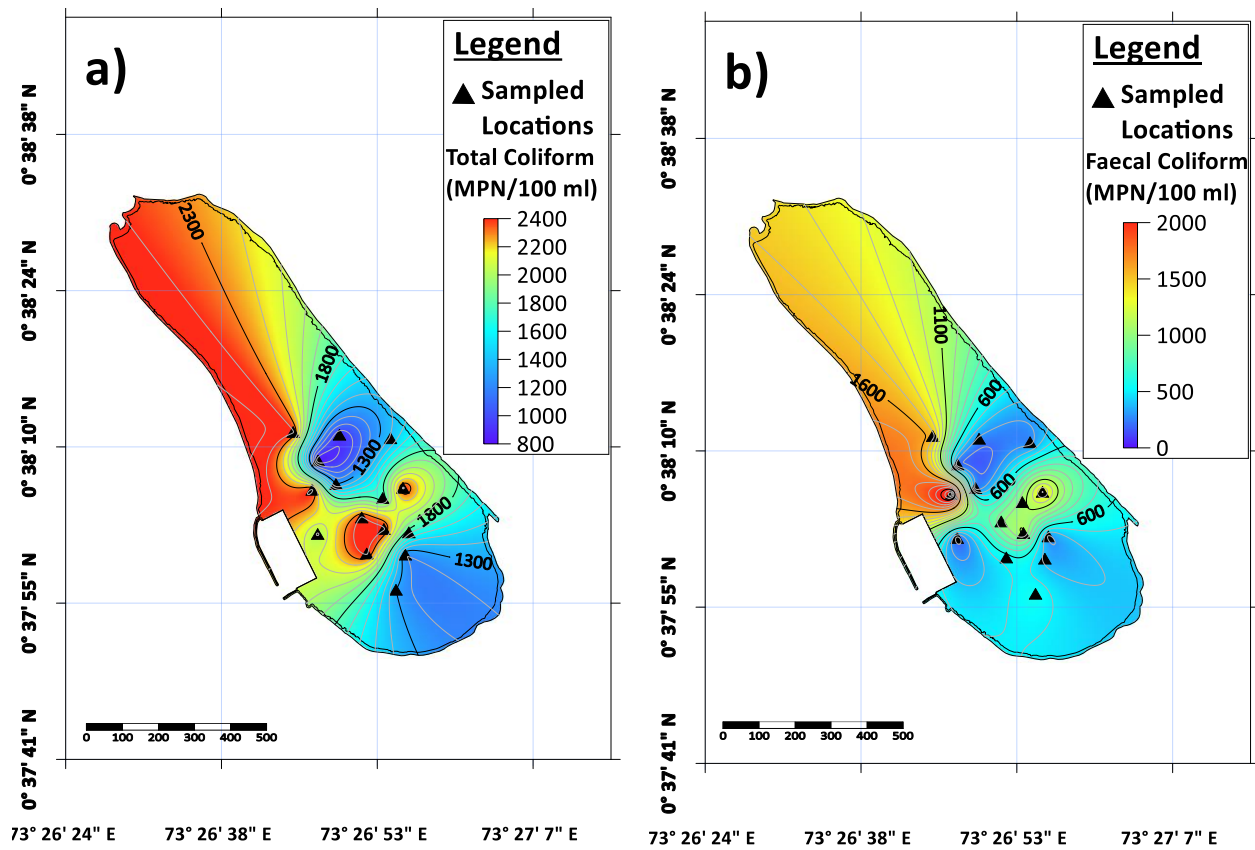


Figure 83: Total (a) and Faecal (b) Contamination Distribution in GA. Nilandhoo

The Total Coliform and Faecal Coliform Contamination was plotted against the distance between septic tank and well, to identify the correlation between these two variables. The graphs are given below.

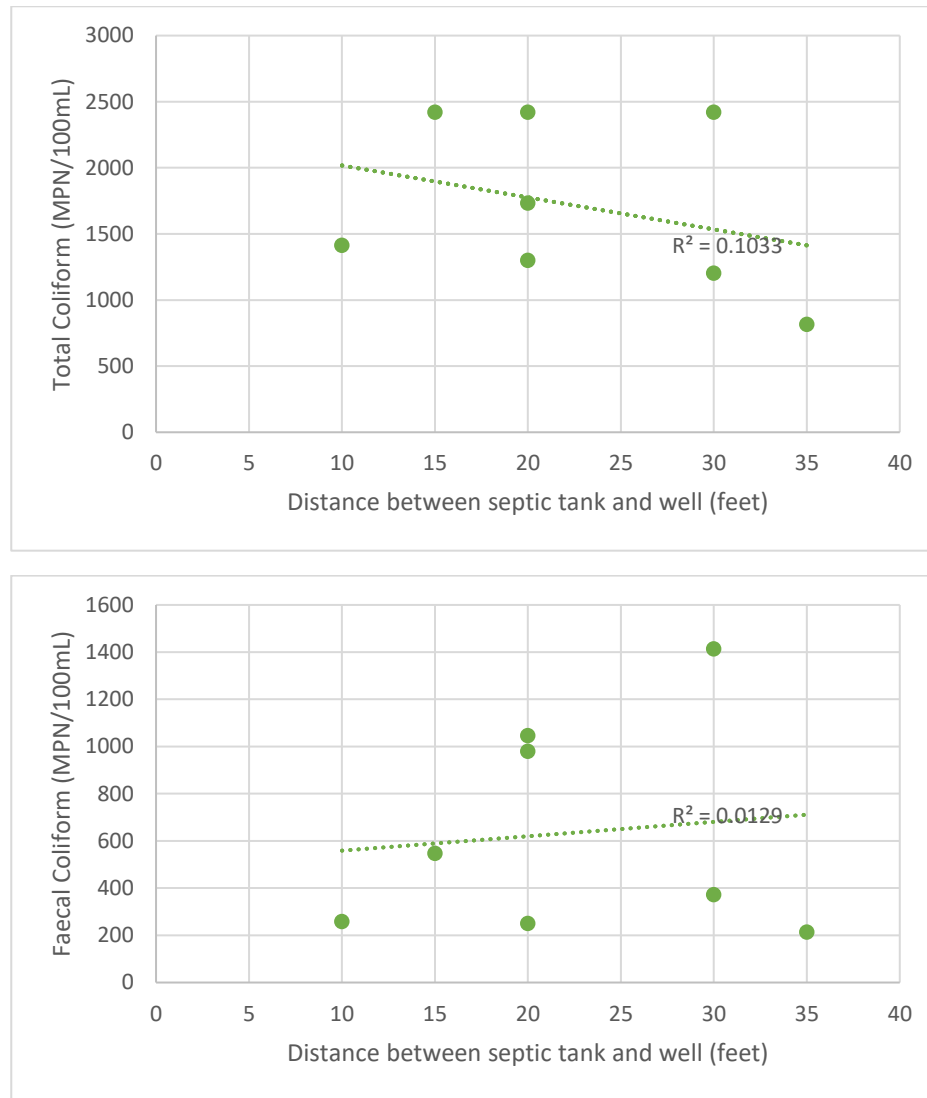


Figure 84: Microbiological Contamination against Septic Tank distancing - Nilandhoo

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.321 and the R-squared of the plot is 0.103. The correlation coefficient of Faecal Coliform to distance between septic tank and well is 0.114 and the R-squared of the plot is 0.0129. Therefore, there is no significant relationship observed between the parameters.

6.5 Pumping Test

6.5.1 Test location

A well in construction, with a sand bed base was available from a private land in GA. Nilandhoo and hence, it was selected to be used for the pumping test. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 85 below shows the location for the pumping test at GA. Nilandhoo.

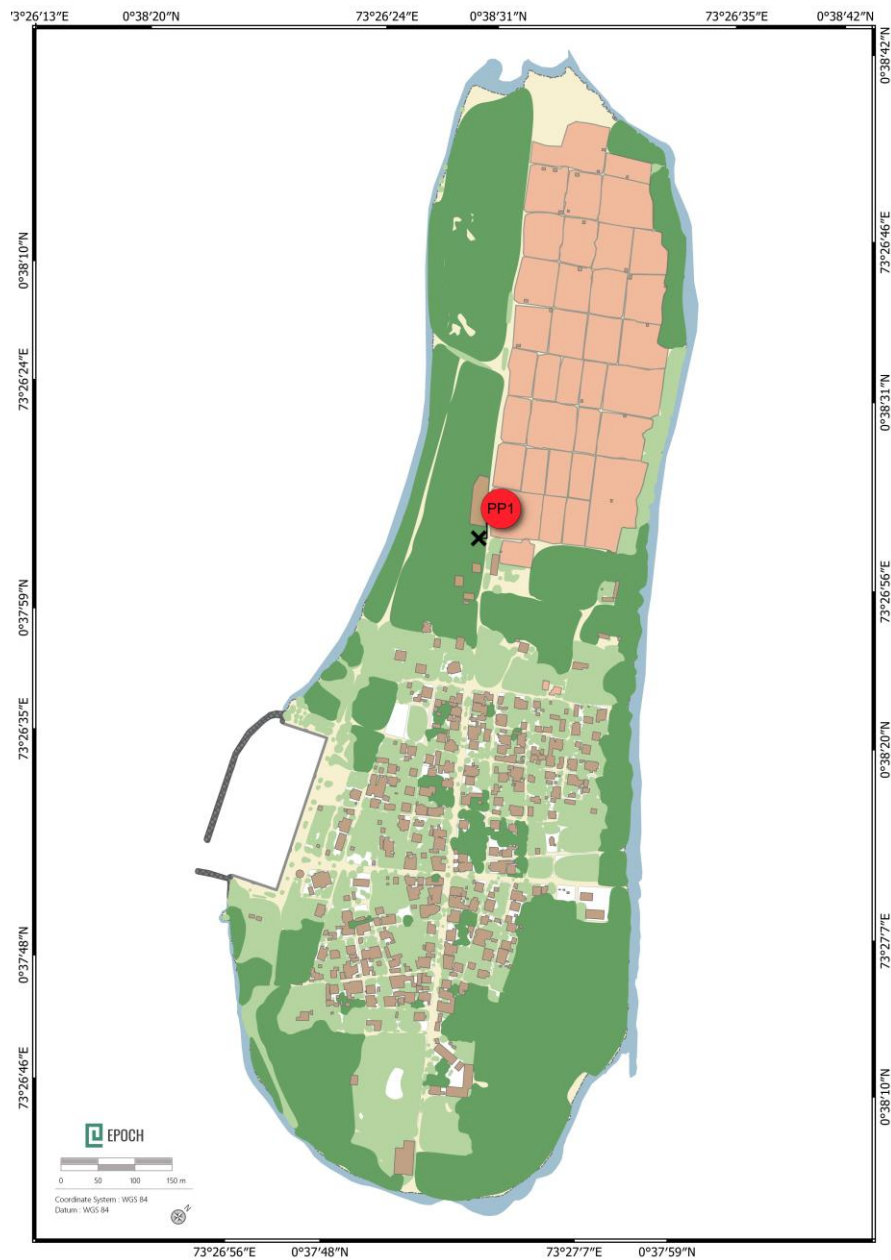


Figure 85: Pumping test location – GA. Nilandhoo

6.5.2 Pumping rate, pumping hours and collected data

A step-drawdown pumping test was carried out at GA. Nilandhoo. The test began at 1200 hours on 16 November 2021 and lasted for 190 minutes. A flowrate of 20 LPM was maintained for 0–45th minute of the test. The flow was then gradually increased to 30 LPM for 46th–95th minute, 45 LPM for 96th–130th minute, and 55 LPM for 131st–150th minute. The recovery phase of the test lasted from 151st–190th minute for more than a 92% recovery.

6.5.3 Hydrogeological parameter estimation

The Cooper-Jacob Solution for Unconfined Aquifer Models was used to process the data from the pumping test. The analysis was carried out using the software, AQTESOLV. The Aquifer Transmissivity (T) value was estimated to be $6.88 \times 10^{-4} \text{ m}^2/\text{s}$ (59.47 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.2042 for GA. Nilandhoo. The full data set of the pumping test at GA. Nilandhoo has been annexed at Annex XII.

6.6 Permeability Test

6.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 86 below. The originally proposed locations were changed as necessary due to unavailability of water and electricity for testing, inaccessibility of proposed locations, as well as the prioritizing of public lands that can be used for potential design solutions over private lands.

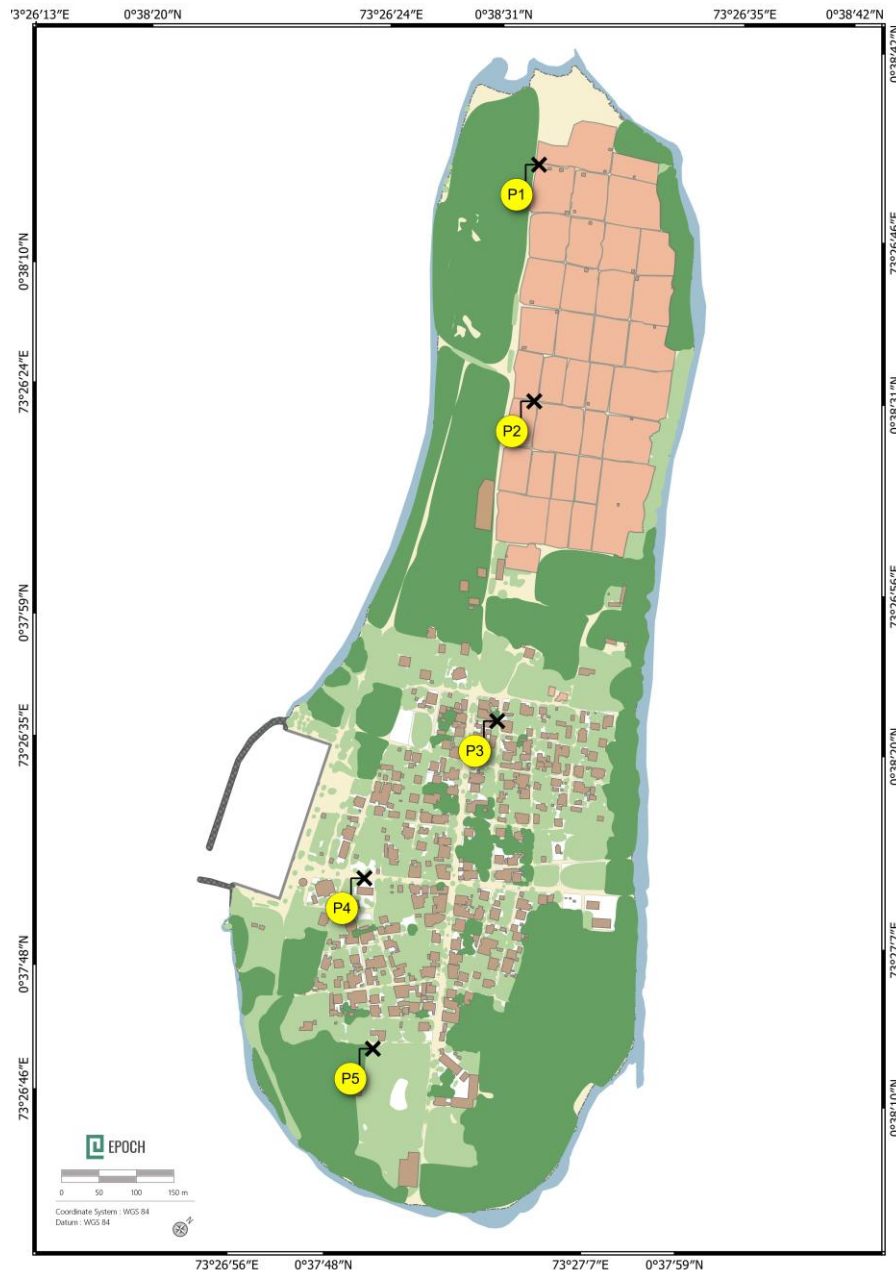


Figure 86: Permeability Test Locations – GA. Nilandhoo

6.6.2 Measured data

Table 79: Permeability Test Measured Data - GA. Nilandhoo

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m ³ /s)	K (m/s)	K (m/day)
NIL-PMB1	0.6	0.780	35	12	6.00	0.000100	1.31E-04	11.30
NIL-PMB2	0.6	1.090	35	12	12.00	0.000200	1.87E-04	16.17
NIL-PMB3	0.6	1.250	35	12	7.50	0.000125	1.02E-04	8.81
NIL-PMB4	0.6	1.150	35	12	14.00	0.000233	2.07E-04	17.88
NIL-PMB5	0.6	1.080	35	12	15.00	0.000250	2.36E-04	20.40

Note: H = Height of water in well (m),
 Tu = distance from water level in casing to water table (m),
 Cu = Conductivity Coefficient,
 r = borehole radius,
 Q = Steady flow into well,
 K = Coefficient of permeability.

6.6.3 Permeability estimation and identified features

The average permeability value for the GA. Nilandhoo is 14.91 m/day, with permeability values ranging from 8.81 m/day to 20.40 m/day. As highlighted in Section Soil Profile Survey, the island soil profile is predominantly Sands, and the K values above are consistent with the range of K values obtained for Sands (Robertson (2010)).

6.7 Soil Profile Survey

6.7.1 Test locations

Soil Profile surveys were carried in 7 locations across the island, as outlined in Figure 87 below. Out of the 7 locations, 5 points were permeability test locations, and the remaining 2 points were chosen in a way that ensured a uniform coverage of the entire island.



6.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 88 below. Even though there are variances in the colour due to environmental factors, the island soil profile is made up of Uniformly Graded Sand for the observed depth.

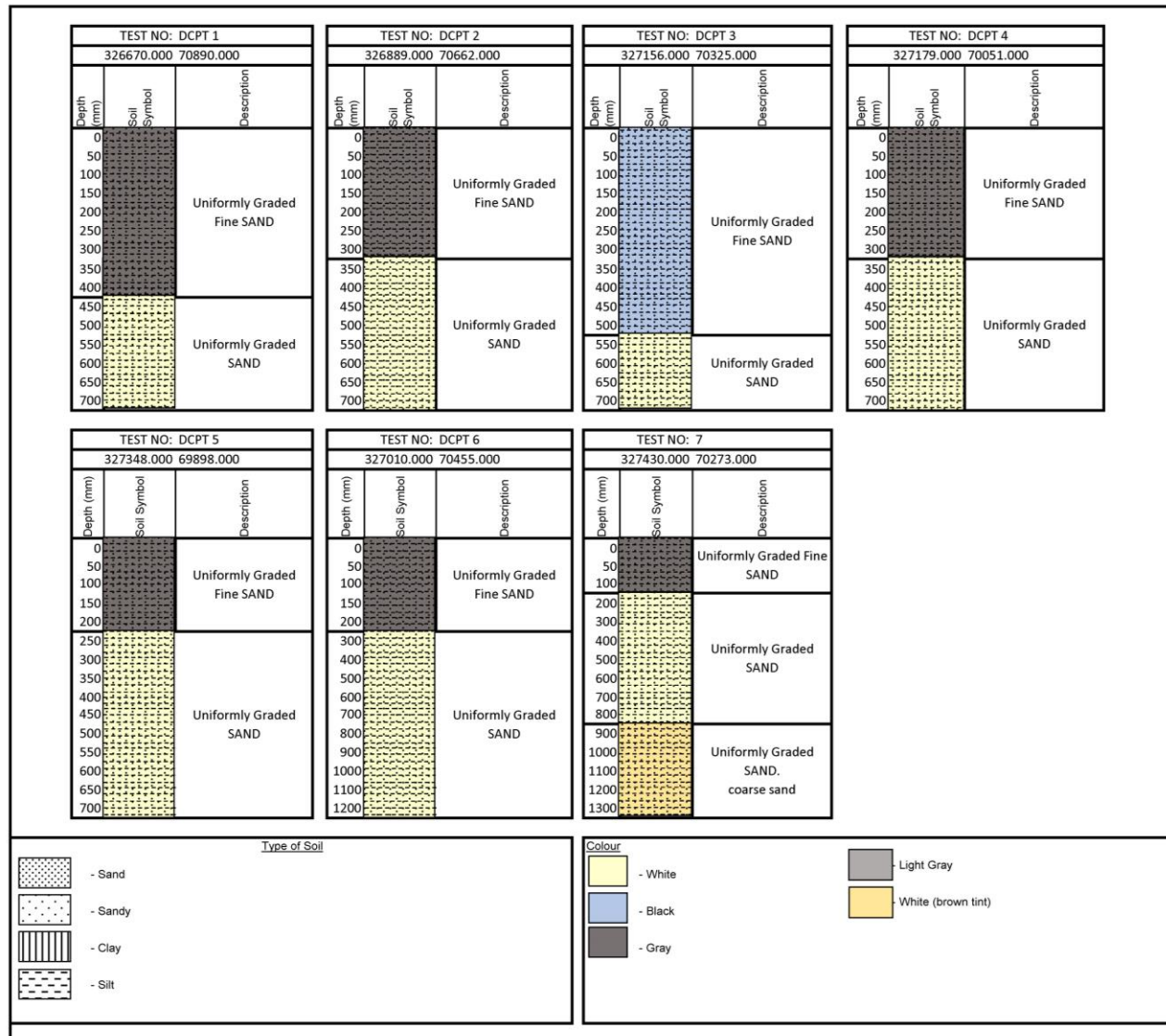


Figure 88: Soil Profile – GA. Nilandhoo

6.8 Flood Assessment and Inundation Survey

6.8.1 Flood occurrence and flood impact

The island does not usually report severe seasonal flooding as such events are rare. For GA. Nilandhoo, around 55% of the houses reported that flooding occurs mostly when it rains heavily. There is significant flooding observed in the main road of the island. According to the survey, 34% of the houses reported that the Island reclamation work for harbour construction had a major impact on the flooding pattern of the island.

The flooding originates mostly from roof runoff (70%) as per the Social Survey. Most responses state multiple sources for the flooding within their properties such as from neighbours' roof, off the road, and general run off in the area. Perceived causes of flooding as per social survey are given in table below.

Table 80: Perceived causes of flooding – GA. Nilandhoo

Perceived causes of flooding				
Roof run off	Neighbours' roof	Off the road	General run off in the area	No flooding within the plot
70%	12%	19%	0%	25%

From the social survey, 93% of households report that they drain rainwater overflow from storage and roofs to the ground. Most responses state multiple ways for the discharge of rainwater overflow to the roads, open areas within the plot and to the well. Details of discharge of rainwater overflow are given in the table below.

Table 81: Discharge of rainwater overflow – GA. Nilandhoo

Discharge of rainwater overflow			
Ground	Roads	Open area within the plot	Drained to well
93%	1%	1%	4%

In the social survey, 63% of the respondents rated flooding as an acceptable problem. This can be due to continuous flood mitigation efforts by the island council and residents. (refer to flood severity component of Annex XIII: Flood Maps).

6.8.2 Flood Depth and Inundation area identification

Based on the social survey responses, an average of 0.6 ft is estimated as the flooding depth when there is a heavy rainfall. Also, 47% reported that it takes 2 to 4 hours to inundate the area once the heavy rain starts. The common flooding areas are the main road and roads adjacent to it (refer to Annex XIII: Flood Maps).

6.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 22% observe that the water drains during the rainfall itself, 24% observe that the water drains in less than 4 hours and 17% observe that the water drains in less than 4-24 hours.

Table 82: Draining period - GA. Nilandhoo

Draining period			
only while raining	drains less than 4hrs	takes 4-24 hrs	more than 24hrs
35.7%	37.5%	26.8%	0%

6.9 Geophysical Survey

6.9.1 Surveyed Locations

Locations where ER sounding measurement taken at GA. Nilandhoo island are shown in Figure 89 together with transect lines. There are 32 ER measurement locations and the number of transects in this island is 10.



6.9.2 Freshwater levels and saline water levels

From processed ER data using GeoVES 1.5 – GeoElectrical Model depth to freshwater starting level and depth to freshwater lens bottom level (saline water start level) were determined and they were converted to elevation with respect to mean sea level using ground collected through drone survey. Table 83 below shows the estimated levels at ER surveyed locations of GA. Nilandhoo Island and freshwater lens thickness.

Table 83: Freshwater lens levels and thickness – GA. Nilandhoo island

No	Map ID	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	NI01	1.11	0.11	-2.69	2.80
2	NI02	1.34	0.14	-2.06	2.20
3	NI03	0.60	-0.20	-2.00	1.80
4	NI04	1.02	0.02	-3.78	3.80
5	NI05	1.11	0.11	-3.09	3.20
6	NI06	0.77	0.07	-1.63	1.70
7	NI07	0.89	0.09	-4.01	4.10
8	NI09	1.03	0.23	-1.67	1.90
9	NI13	0.88	-0.02	-4.52	4.50
10	NI14	1.32	0.12	-2.88	3.00
11	NI17	1.42	0.02	-4.88	4.90
12	NI18	1.05	0.15	-3.85	4.00
13	NI19	0.96	0.16	-2.04	2.20
14	NI20	0.95	0.20	-7.60	7.80
15	NI21	1.08	0.18	-2.02	2.20
16	NI22	0.77	-0.23	-1.93	1.70
17	NI23	0.97	0.37	-6.63	7.00
18	NI24	1.09	-0.01	-1.51	1.50
19	NI25	0.95	-0.05	-1.45	1.40
20	NI26	1.06	0.06	-1.14	1.20
21	NI29	0.92	-0.28	-2.38	2.10
22	NI30	0.95	-0.25	-2.55	2.30
23	NI31	1.11	0.21	-6.29	6.50
24	NI32	1.07	0.07	-7.43	7.50
25	NI33	1.03	0.13	-2.37	2.50
26	NI34	1.07	-0.13	-6.13	6.00
27	NI35	1.03	0.03	-6.17	6.20
28	NI36	1.03	-0.47	-5.87	5.40
29	NI37	0.84	-0.46	-6.26	5.80
30	NI38	1.15	0.35	-5.25	5.60
31	NI39	0.69	0.24	-2.26	2.50
32	NI40	0.81	-0.04	-3.24	3.20

Average freshwater thickness of GA. Nilandhoo island is 3.70m.

Data in Table 83 were used to plot freshwater lens cross sections along 10 transects and they are given in Annex IX. Of these sectional plots, 2 were given in Figure 89 and they represent the transect plot along the longitudinal section and cross section of the island that passes through island middle. Dotted lines in these plots indicate ground level variation with respect to mean sea level along the transect lines.

6.9.3 Freshwater lens spatial extent

For the purpose of identifying spatial distribution of upper and lower level of freshwater lens the computed freshwater levels and saline water levels at ER points were exported to ArcGIS and used to generate contours with help of interpolation tools available in the same software. The generated contours are shown in Figure 90 and the processed ER data were also used to develop a 3D view of the freshwater lens and it is also shown in Figure 90.

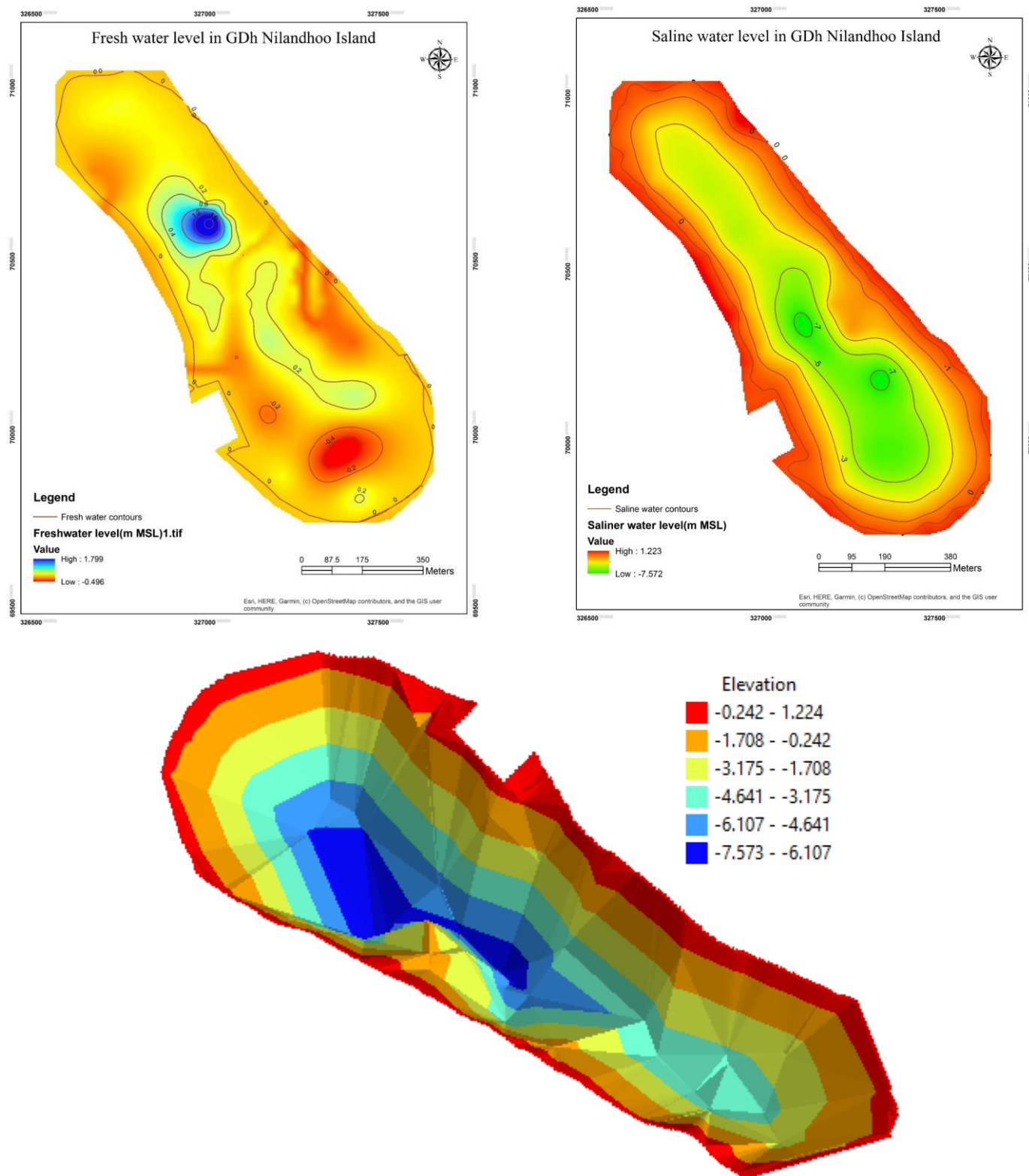


Figure 90: Top Left: Contours of Freshwater lens upper level, Top Right: Contours of Freshwater lens lower level, Bottom: 3D view of Freshwater lens bottom level – GA. Nilandhoo

6.9.4 Freshwater lens storage volume and stress level

For the estimation of freshwater volume, the depth difference between freshwater-saline water interface and freshwater upper level was computed at each ER measurement points and they were then used to determine freshwater volume stored in the ground at time of taking ER measurements. Both “Triangle method” and Tools in ArcGIS software were used to perform this computation. Figure 91 shows triangles considered for the aforementioned computation. Detailed calculations can be found in Annex X: Freshwater Lens volume calculations.



Figure 91: Triangles for freshwater volume computation – GA. Nilandhoo island

Stress level on freshwater aquifer of GA. Nilandhoo island was determined by computing ratio between freshwater lens volume and annual groundwater abstraction for non-potable water usage at present. When this ratio was more than 1.5, the island was treated as “not stressed” and if it was between 1.5 and 1 the aquifer was assumed to be “stressed” and any other lower ratio was taken as “highly stressed” aquifer. This criterion was developed based on saline water issues collected from the project islands during field work. The computed freshwater volume, water abstraction and aquifer stress level are given in Table 84.

Table 84: Freshwater lens volume and aquifer stress level – GA. Nilandhoo island

Item	Value	Unit
Freshwater lens volume – Triangle method	311,426	m ³
Freshwater lens volume – ArcGIS	314,472	m ³
Groundwater abstraction	153,548	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	2.0	-
Aquifer stress level	Not stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 6.9m. This deviates by 11.5% from the maximum measured value of 7.8m, which is more reliable as it results from a more comprehensive, site-specific methodology.

6.10 SWB Modelling

6.10.1 Topography for flow direction

Topographical data assigned to model grids for computation of D8 flow directions is shown in Figure 92 and according to this figure, elevation of the island is changing from -0.489 mAMSL to 2.315 mAMSL and average elevation is 1.229 mAMSL.

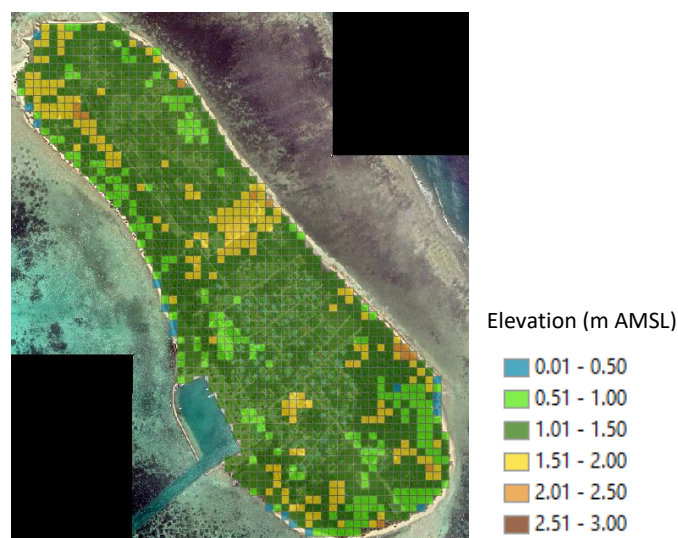


Figure 92: Elevation data assigned for SWB modelling - GA. Nilandhoo Island

6.10.2 Land use categorization and area estimation

Land use map prepared for SWB modelling of GA. Nilandhoo island is shown in together with a table showing land classification and their respective areas. It could be noted from the Figure 93 that 20m x 20m grids are adequate to represent the island land use for SWB modelling purposes.



Land use	Symbol	Area (m ²)	Area (%)
Residential		172800	29.7%
Forest		204000	35.1%
Commercial		32400	5.6%
Ground		22000	3.8%
Bare land		16000	2.8%
Wetland		4400	0.8%
Agriculture		130000	22.4%

Figure 93: Land use for SWB model - GA. Nilandhoo Island

6.10.3 Recharge estimation and distribution

Monthly recharge values estimated at grid cells of the SWB model were extracted and used to identify its variation over years and months (refer Figure 94 and Table 85). The Following were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 195.4, 413.6 and 601.4 respectively over a 20-year period.
- There is a good relationship between annual rainfall and annual recharge, it is not linear but inverse exponential.
- Annual average rainfall is around 2270 mm but for 5 consecutive years (from 2008 to 2012) annual rainfall was below average. It indicates that there would be serious issue of saline water intrusion into the freshwater lens during dry periods as the recharge value would be considerably lower than annual average recharge value (inverse exponential relationship).
- Variation among the monthly average recharge value is very high. It is lowest on month of March and highest in November.
- Water consumption (pumping) for non-potable use on only 3-month period is less than the recharge value on the respective months. It indicates that GA. Nilandhoo island is slightly depending on groundwater storage and there would be serious issues of saline water intrusion into this island.

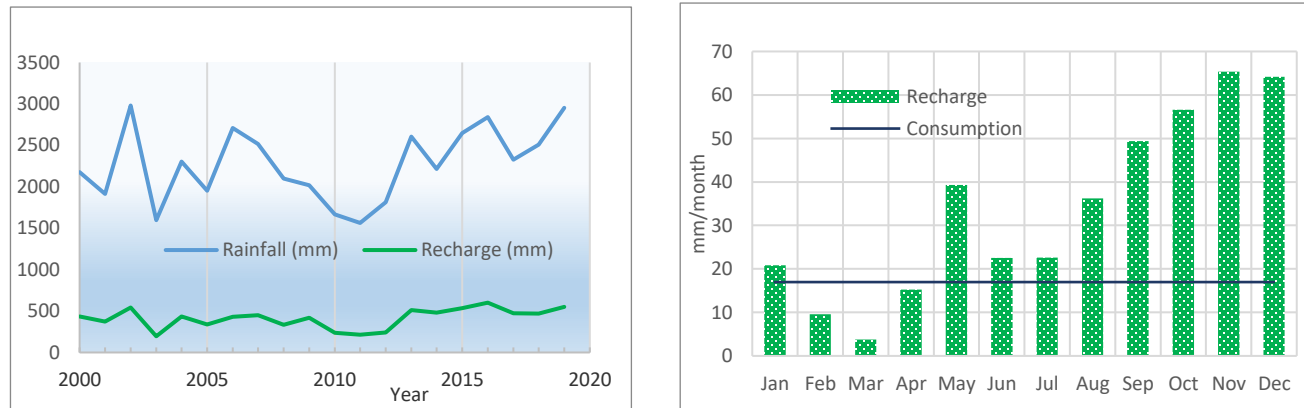


Figure 94: Monthly and annual recharge distribution – GA. Nilandhoo island

Table 85: Monthly recharge estimated by SWB model – GA. Nilandhoo Island

Year	Monthly Recharge (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	4.4	0.0	0.0	7.8	10.7	54.5	30.8	36.2	132.2	37.3	79.2	40.0
2001	0.0	0.0	0.0	34.8	10.4	0.0	10.9	52.5	80.8	62.3	75.6	45.8
2002	5.9	18.9	15.2	26.1	42.3	71.0	36.5	13.1	38.0	99.9	69.1	108.1
2003	2.2	0.0	0.0	7.5	39.2	29.6	33.1	18.6	0.0	7.8	37.3	20.1
2004	42.2	0.0	0.0	12.2	0.1	0.1	29.9	45.4	65.5	66.4	110.2	61.9
2005	31.1	14.0	0.0	0.0	35.5	56.0	40.3	23.4	18.7	115.0	3.7	0.0
2006	44.3	59.0	0.0	3.7	0.0	5.5	9.9	9.5	53.3	7.9	149.4	88.9
2007	69.5	0.0	0.0	2.7	18.0	42.9	29.4	4.4	38.9	105.4	10.9	128.4
2008	32.6	0.0	0.0	32.8	27.6	17.5	29.7	5.5	0.0	61.1	73.6	54.1
2009	38.5	21.4	0.0	0.0	59.8	0.0	5.7	100.7	25.4	49.9	57.2	59.2
2010	13.6	0.0	0.0	31.6	15.9	0.0	44.0	66.9	47.6	18.5	0.1	0.0
2011	0.0	0.0	0.0	5.3	23.0	0.0	0.0	8.8	0.0	64.9	17.9	93.5
2012	0.0	15.0	0.0	0.0	21.4	8.1	14.8	12.0	14.7	102.1	35.7	16.6
2013	0.0	0.0	10.1	17.8	79.5	12.4	30.3	48.3	13.8	30.7	139.1	129.0
2014	0.0	0.0	8.3	14.5	125.1	0.0	5.5	17.2	152.1	33.9	77.4	46.5
2015	8.4	14.1	0.0	0.0	24.2	26.7	14.0	113.0	33.3	86.4	103.2	113.3
2016	64.5	4.4	24.6	54.1	66.3	5.7	25.4	130.1	24.0	59.6	82.2	60.4
2017	2.6	0.0	13.6	0.0	103.9	0.0	28.6	22.9	97.9	0.0	67.4	137.2
2018	0.0	5.4	0.1	38.3	57.8	55.7	34.7	0.0	67.1	111.2	57.2	42.5
2019	71.3	29.0	6.8	15.2	52.1	65.2	13.0	20.5	84.2	49.3	61.2	80.8

6.10.4 Water Balance

As per estimation, annual recharge estimated by the SWB model is 205,115 m³ and it is 15.54% of annual average rainfall (refer Figure 95).

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	1,319,761	8,347	7,487	685,811	205,115	377,924	153,548
%	100.0%	0.6%	0.6%	52.0%	15.54%	28.6%	11.63%

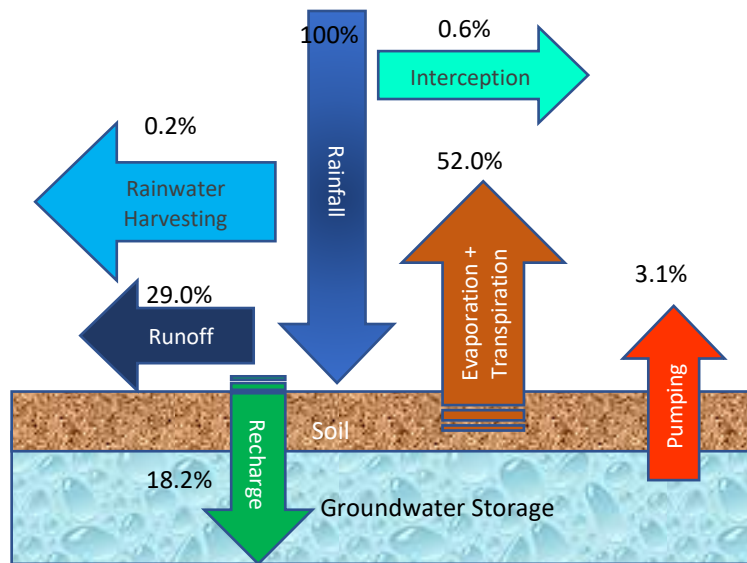


Figure 95: Annual water balance - GA. Nilandhoo Island

6.10.5 Deficit estimation, dry month identification and safe yield

Deficit calculation was carried out to identify whether recharge over a month period is smaller than or larger than the pumping quantity in the island. Monthly recharge time series estimated by the SWB model was compared with total pumping quantity of the island (12,796 m³/month) and if recharge exceeds the pumping quantity it was taken as "no deficit" and on other hand if pumping quantity exceeds the recharging value it was taken as "deficit".

Table 86: Deficit percentage - GA. Nilandhoo

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	103	43.8%

It is to be noted that "deficit" doesn't mean failure or inadequate freshwater for pumping, but it is to be interpreted that the number of months when pumping is to be supported by groundwater storage in addition to recharging quantity. As per estimation, pumping at GA. Nilandhoo island 43.8% dependent on the groundwater storage.

Determining safe yield which is defined as the attainment and maintenance of a long-term balance between the annual amount of groundwater withdrawn by pumping and the annual amount of recharge is important for small islands and there are various methods to estimate this amount. One simple method is checking whether ground water abstraction is less than or equal to 10% of average annual rainfall (MoEnv. 2020). The comparison of the estimated ground water withdrawal (153,548 m³/yr) with safe abstraction volume (73,914 m³/yr) shows that present withdrawal is 108% higher than the safe yield.

6.11 SUTRA Modelling

6.11.1 Model representation and topographical features

SUTRA modelling requires model domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island (refer Figure 96). The other boundary defined in the model was island outline which can be taken as the shoreline for most of the cases except at harbour area and the inner part of the island which was subdivided into several polygons representing different land use areas, and it was accomplished by importing GIS shape files of island land use and then drawing polygons on the shape files. Some other boundaries were also defined to represent island features such as lake and elevation change in the middle of the reef. Mesh with irregular quadrilateral elements were produced for all closed boundaries. Mesh size defined for outer boundaries (area between shoreline and model domain) were 3 to 4 times larger than the size defined for the inner parts of the island. Elevation at shoreline was defined as zero whereas elevations for inner part of the island was assigned from topographical data used for SWB modelling. Figure 96 shows model domain and SUTRA model mesh with topographical changes.

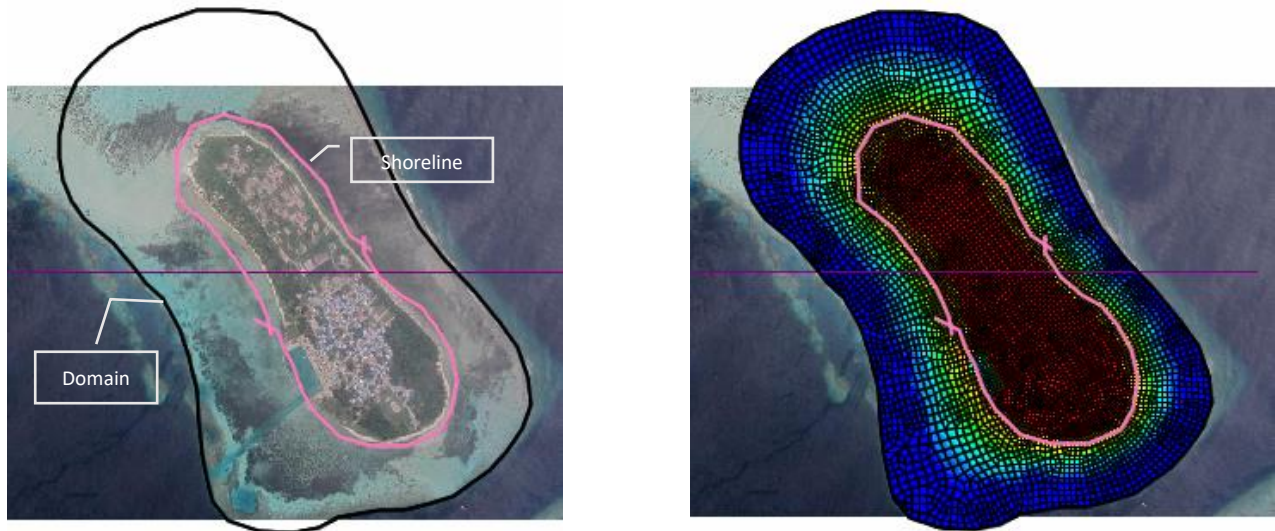


Figure 96: Model boundaries and model mesh – GA. Nilandhoo island

6.11.2 Pressure boundaries

Specified pressure boundary was defined along the model domain so that it would cause saline water intruding into the island when pressure along the outer boundary of freshwater lens is less due to lower recharge and/or groundwater abstraction is high. Figure 97 shows the pressure boundary defined for GA. Nilandhoo island.

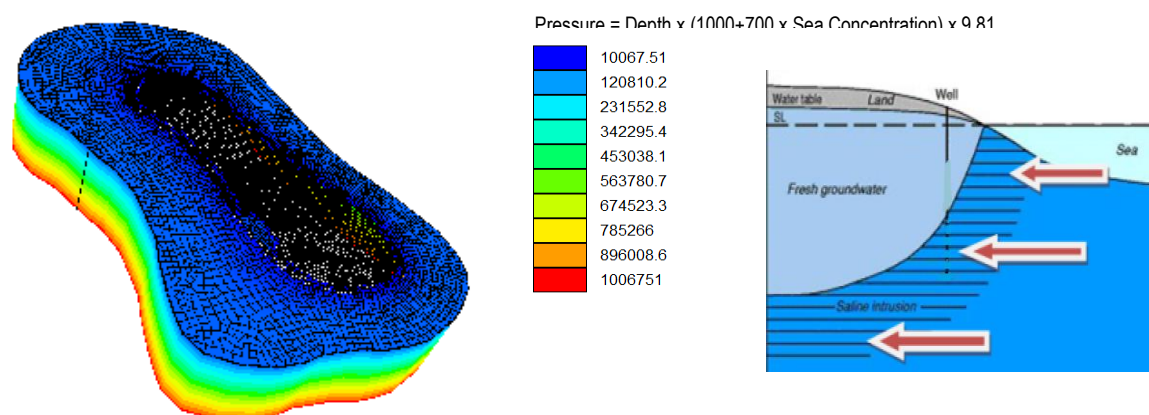


Figure 97: Pressure boundary at SUTRA model - GA. Nilandhoo island

6.11.3 Assigning recharge on land use basis

Recharge rates estimated by the SWB model for each grid cells were lumped on land use basis using VB program and ArcGIS tool and they were then used to estimate the monthly average recharge rate on residential area, commercial area and other land use areas. Table 88 shows monthly recharge rate estimate for GA. Nilandhoo island.

Table 87: Recharge for SUTRA model - GA. Nilandhoo island

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	35.3	5.9	6.9	27.0	32.4	6.9	27.8

6.11.4 Groundwater abstraction

Groundwater pumping takes place at individual houses, restaurants, and institutes. Since all well locations are not available and abstraction rate would also have spatial variability, a simplified approach was adopted by defining a polygon around the residential area (area highlighted in blue in the below map) and assigning average pumping rate of 12,976 m³/month.

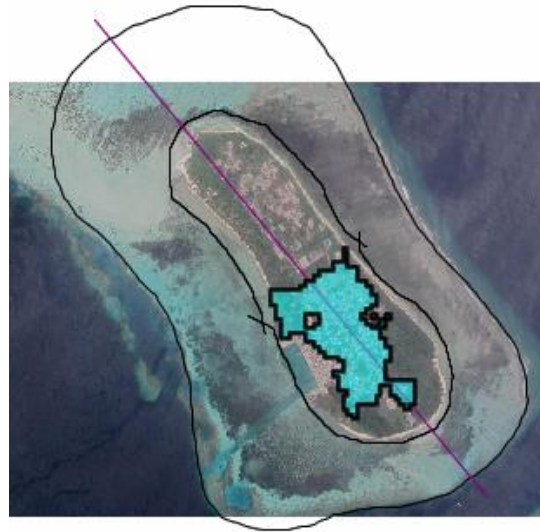


Figure 98: Pumping region at SUTRA model - GA. Nilandhoo island

6.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20-year period is shown in Figure 99. The orange-coloured component in the 3D view represents sea water concentration around the island and the section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0375 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top and at relatively deeper depth compared to freshwater depth in other Lot 3 study islands.

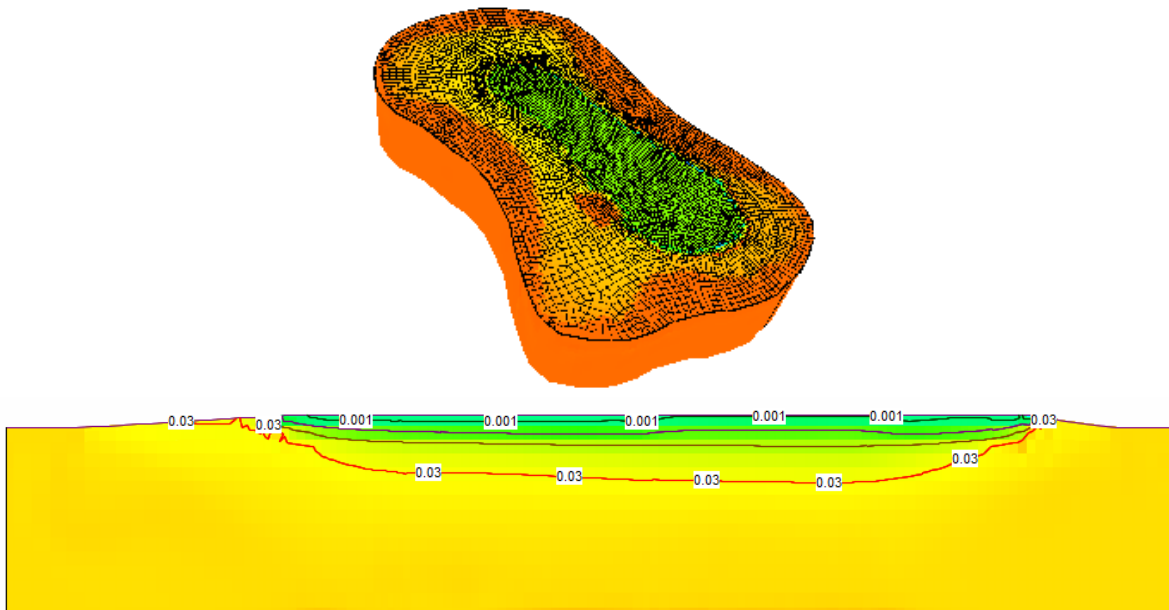


Figure 99: Saltwater distribution - GA. Nilandhoo island

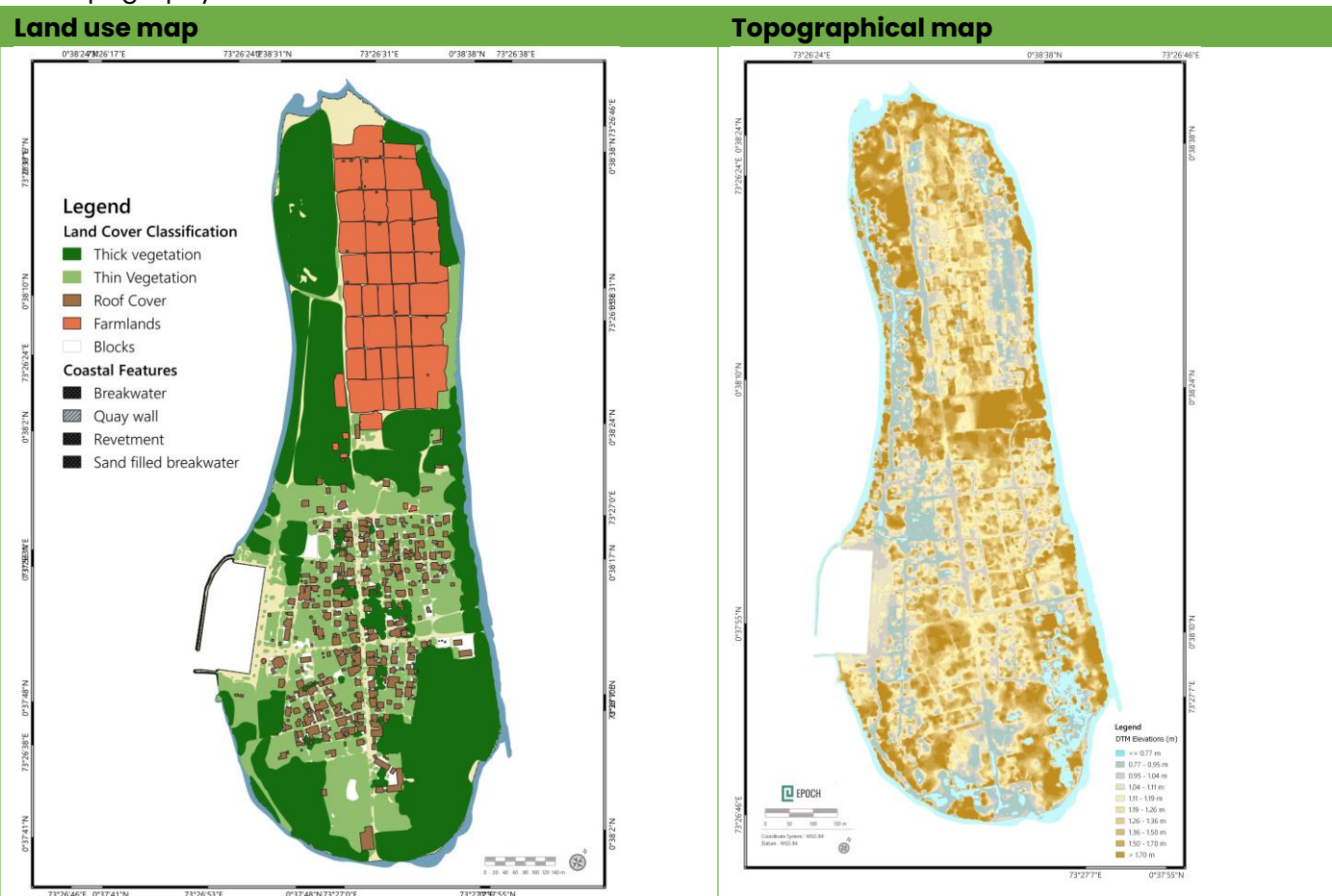
6.12 Summary of Baseline Assessment

Summary of findings extracted from field works, laboratory test, modelling and analysis are presented below.

- General overview, demography, and climatology

Item	Details
Atoll	Huvadhoo Atholhu Uthuruburi Atoll
Length	1.54 km
Width	0.55 km
Area	57.4 ha
Population	1,127
Population/area	19.63 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use



Average elevation = 1.17 m above MSL Shoreline length = 4639 m	% of total area	
	Roof cover	8%
	Vegetation (Thick)	39%
	Vegetation (Thin)	20%
	Bare Lands	15%
	Farmlands	18%
	Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Institutional	Industrial	Total
Rate (m ³ /d)	325	1.47	3.57	91.1	421

- Water quality parameters – Physiochemical

Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	874 ± 780	1500
Turbidity (FNU)	1.18 ± 1.84	5
DO (mg/L)	3.82 ± 1.45	
pH	7.53 ± 0.30	6.5-8.5
Temp (°C)	29.04 ± 1.16	
Sal (ppt)	0.40 ± 0.38	
NH ₃ (mg/L)	2.90 ± 4.74	1.5 (Odour Threshold)
NO ₃ ⁻ (mg/L)	13.29 ± 19.03	50
PO ₄ ³⁻ (mg/L)	0.27 ± 0.21	

- Water quality parameters – Microbiological

Number of samples tested = 15

Parameter	Value range	Average value	Remarks (on permit limit)
Total Coliform (MPN/100ml)	816 - >2420	1794.8	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	151 - 2420	763.2	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	59.47	m ² /day
Storativity	1	0.2042	-
Permeability	7	8.81 – 20.40 Average – 14.91	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m ²)	Inundation depth (m)
28	7000	0.167

- Electric Resistivity survey

- Measurement taken at 32 locations and number of transect is 10.
- Average freshwater thickness in the island is 3.70 m.
- Freshwater lens volume and aquifer stress level

Item	Value	Unit
Freshwater lens volume – Triangle method	311,426	m ³
Freshwater lens volume – ArcGIS	314,472	m ³
Groundwater abstraction	153,548	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	2.0	-
Aquifer stress level	Not stressed	-

- SWB modelling

- Annual recharge is 205,115 m³ and it is 15.5% of annual rainfall (2270 mm)
- Annual water balance

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	1,319,761	8,347	7,487	685,811	205,115	377,924	153,548
%	100.0%	0.6%	0.6%	52.0%	15.54%	28.6%	11.63%

- Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 43.8% in an average year, and it is compensated by ground water storage.
- Ground water withdrawal (153,548 m³/yr) is 108% higher than the safe abstraction (73,914 m³/yr).

- SUTRA modelling
 - Average monthly recharge assigned to SUTRA model

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	35.3	5.9	6.9	27.0	32.4	6.9	27.8

- Freshwater lens prediction (allowable concentration for potable use is 0.001)

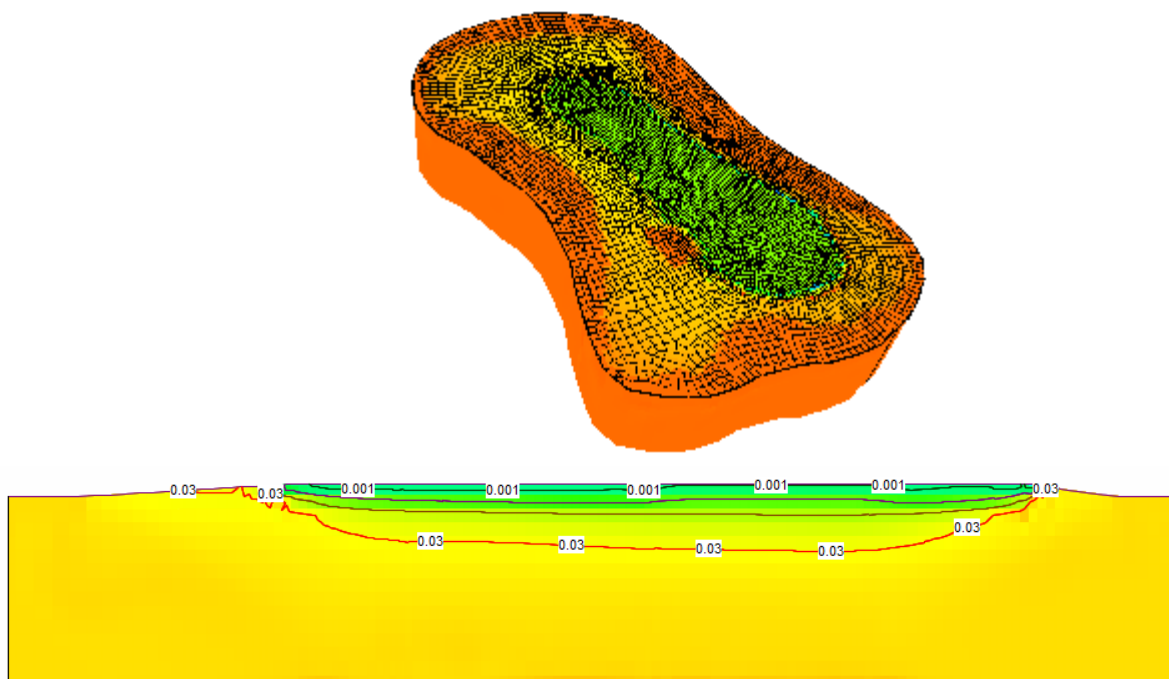


Figure 100: Saltwater distribution - GA. Nilandhoo island

7 GDh. Hoandehdhoo

7.1 Island Overview and Location

The Island of GDh. Hoandehdhoo, belonging to Huvadhoo Atholhu Dhekunuburi Atoll, is in the Southern region of Maldives at 0°26'39.1"N and 73°00'12.6"E. It is approximately 418 km South-West of the capital Male'.

Table 88: Island Geographical Data

Island	GDh. Hoandehdhoo
Atoll	Huvadhoo Atholhu Dhekunuburi Atoll
Location	0°26'39.1"N and 73°00'12.6"E

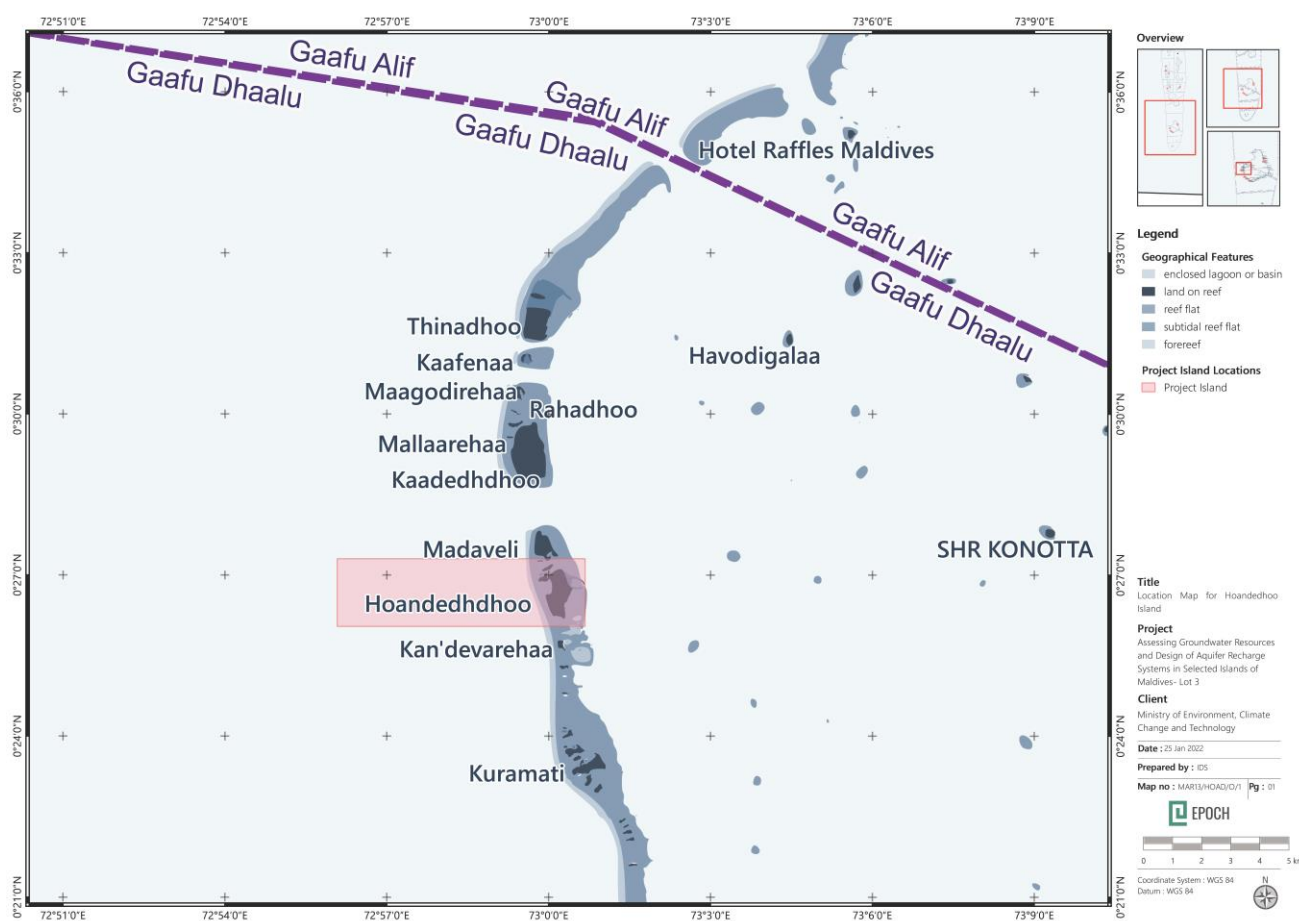


Figure 101: Location map - GDh. Hoandehdhoo

7.1.1 Island features

The island extends up to 1.65 km in length from toe to toe and a width of 1.12 km from toe to toe. There is a reclaimed area of approximately 15 hectares on the North East side of the island, in addition to the land

that was reclaimed on the South East side of the island for harbour construction (between 1999–2005). The island has multiple wetlands on the South and South-West side of the island.

The island has a harbour at its Southern east side of the island. About two-third of the island surface is vegetation. Thick vegetation is mostly located in Northern west and Southern west parts of island. Farming takes place on the east side of the island. Only about one-third of the island is populated, which is mostly the Southern part of the island.

Table 89: Area Distribution in GDh. Hoandehdhoo

Area	106.4ha	
Length	1.65 km	
Width	1.12 km	
	Area (m²)	% of total area
Roof cover	77,288	7%
Vegetation (Thick)	365,746	34%
Vegetation (Thin)	405,589	38%
Bare Lands	97,813	9%
Farmlands	80,858	8%
Wetlands	36,809	3%
Total	1,064,104	100%

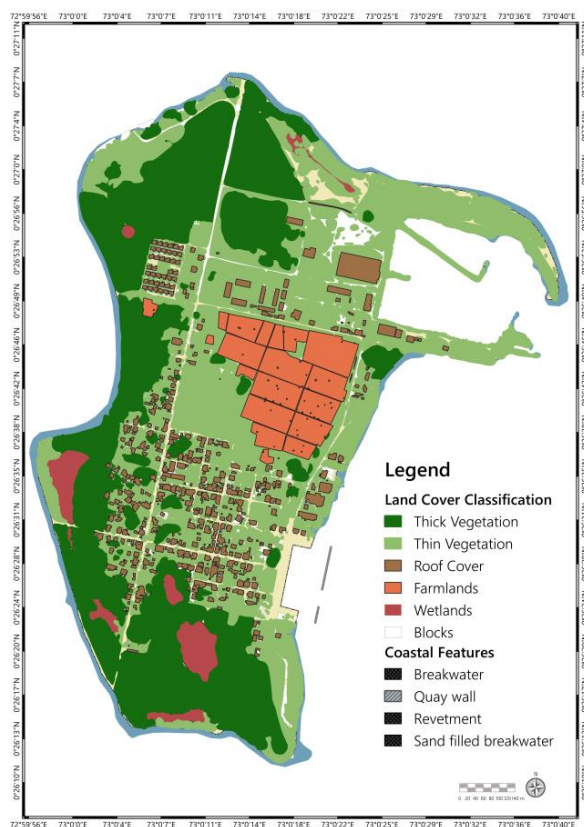


Figure 102: Land Use Characterization – GDh. Hoandehdhoo

7.2 Topographical Features

Permanent Survey Marks PSM 0371 and PSM 0372 were used as benchmarks for GDh. Hoandehdhoo topographical survey and drone survey with benchmark details available at <https://www.mlsa.gov.mv/psm>. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 4958 calibrated UAV photos at an altitude of 83 m resulting in an Average Ground Sampling Distance (GSD) of 2.48 cm per pixel. 17 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 90 GCP Statistics for GDh. Hoandehdhoo

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	0.00612	-0.000592	-0.00272
Sigma [m]	0.0456	0.266	0.187
RMS Error [m]	0.0459	0.2744	0.187

The Digital Surface Model in Annex III indicates that the northern region of the island (Average Elevation 1.0 m) is the same as southern region (Average elevation of 1 m). The Horizon fisheries complex area was reclaimed around 18 years ago and remains the highest area of the island with an average elevation of 1.8 m. Ground elevations near the old harbour are much higher than nearby residential area. In contrast, the Southern region, the elevations are much lower than the island average. The southern areas are surrounded by three wetlands that are assumed to serve as flood defences where water can be routed.

Roof elevations generally do not exceed 5–7 m and very few houses have multistorey buildings in GDh. Hoandehdhoo. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Thick vegetation with heights greater than 10 m are primarily seen on the on the south-eastern periphery of the island. It is also noteworthy that despite the entire island region having dense vegetation the elevations are generally lower than 10m.

Drone surveys were carried out during rainy days in November 2021 so the flooding that followed are likely to have an impact on the accuracy of the produced DTM. The Digital terrain model was produced at a resolution of 0.1 m spatial resolution for the purposes of processing. The scatter plot for sampled UAV Elevations vs GPS. The DTM does not contain any elevation information related to the new harbour that is under construction at GDh. Hoandehdhoo.

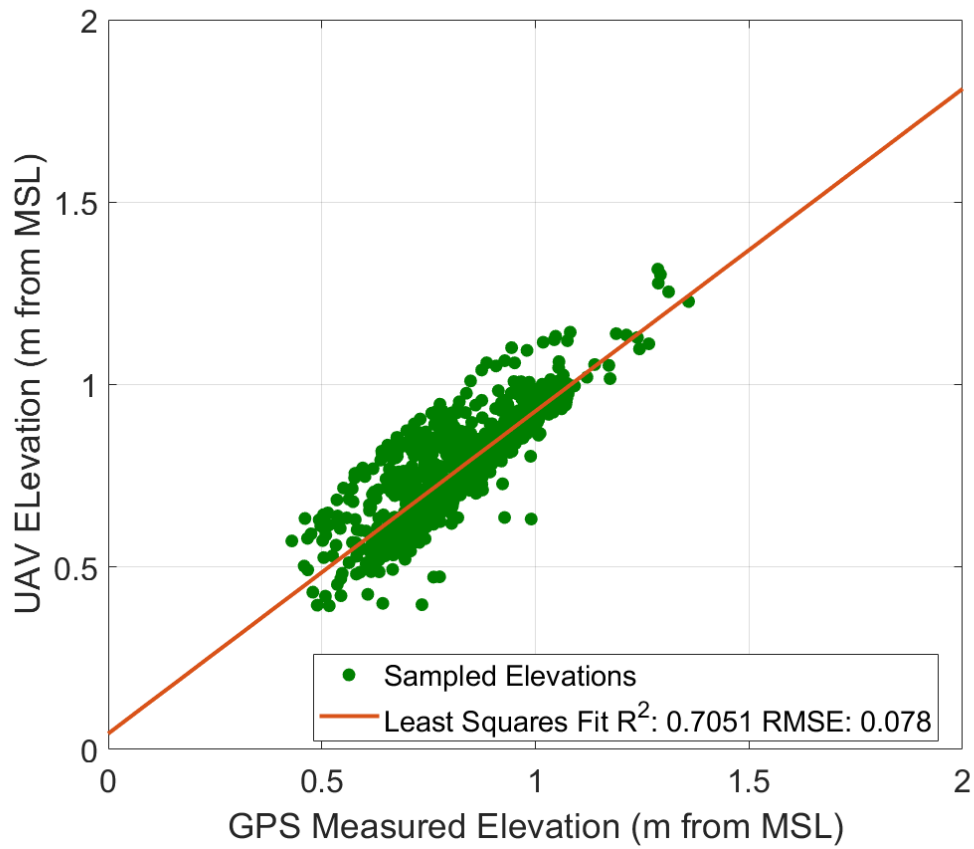


Figure 103 Linear Regression Plot for GDh. Hoandehdhoo Sample UAV elevations

Table 91: Error statistics for GDh. Hoandehdhoo sampled elevations from DTM

Parameter	Value (cm)
Mean	-4.91
Standard Error	0.25
Median	-7.50
Mode	-7.50
Standard Deviation	7.98
Sample Variance	63.69
Kurtosis	1.12
Skewness	0.98
Range	53.90
Minimum	-35.90
Maximum	18.00
Sum	-4949.60
Count	1008.00

7.2.1 Level changes

GDh. Hoandehdhoo has an average elevation of 1.132 m with a standard deviation of 0.628. Digital Terrain Model elevations range from -0.6 to 3 m from MSL. The distribution of elevations has a distribution with a very large spread from 0.9-1.8 m which are the highest frequencies for elevations. A second peak is observed near 0.1 m from MSL.

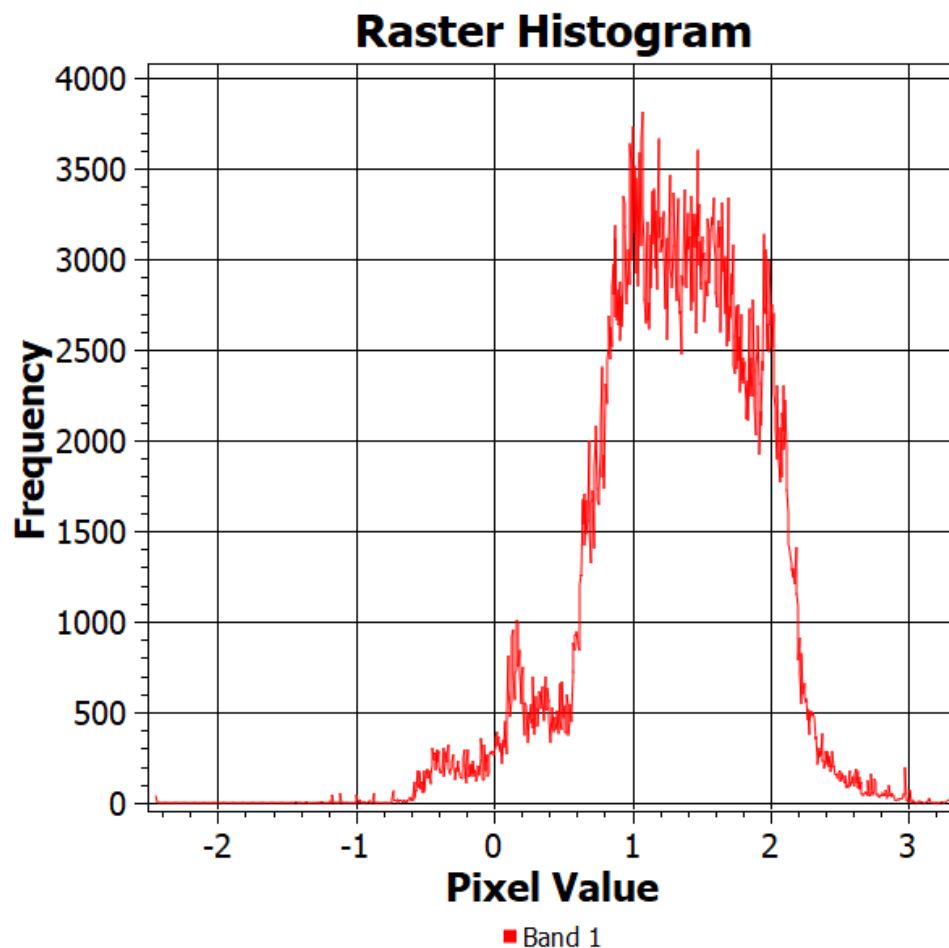


Figure 104 Raster Histogram created for GDh. Hoandehdhoo DTM through QGIS for the Elevation Band 1

Analysis of the GDh. Hoandehdhoo terrain revealed that the island elevation does not change that much from north to south. Specifically, profile 1 running along the main road shows an average elevation of 1 m and a 2m high vegetated ridge at the end of the road which form due to wave action. Profile 2 shows several peaks and troughs where the peaks are for vegetated areas on the road and troughs show areas on the road where puddling was observed during the field visit. The elevation gradually decreases to the east in profile 2 to 0m above MSL.

Profile 3 also shows several troughs and peaks for the region that goes through the football field. The constant elevation area is the farming area which has an average elevation of 0.75 m from MSL. A small

ridge can be observed next to this farming constant elevation area before the connecting road. Profile 4 has a small ridge of 1.25 m and decreases for the wetland area to rise to the average island level which is low for this region. At the end of profile 4, the elevation difference between the harbour area and residential areas adjacent to it can be observed.

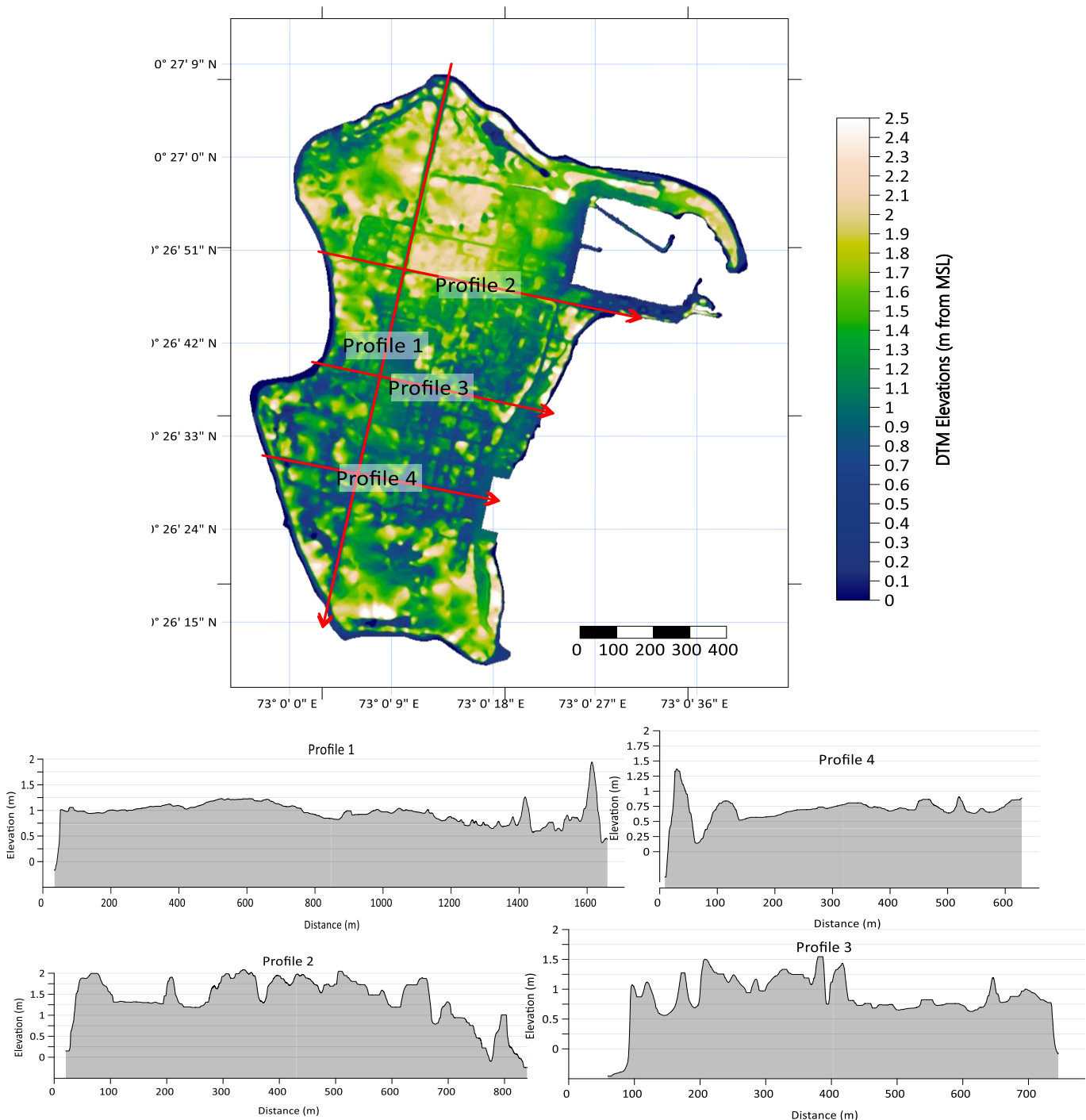


Figure 105 Digital Terrain Model Elevations and Profiles for GDh. Hoandehdhoo Island

7.2.2 Shoreline

GDh. Hoandehdhoo shoreline is 7798 m long and has the longest shoreline for this project like other islands on the Western ridge. Harbor construction was underway during field work, so the processed data does not capture the change in shorelines in the new harbour area. This area is significantly large and has several fanned-out sediment regions that are exposed during low tide.



Figure 106 GDh. Hoandehdhoo Orthomosaic



Figure 107 New Harbour Construction progress indicating large changes in the shoreline of the island

7.2.3 Reef

GDh. Hoandehdhoo is found of a reef with hundreds of islands. Most notably GDh. Hoandehdhoo is located next to Kudhehulhehdhoo, Kannigilla, Dhinmanaa and Haadhoo. The causeway to Madaveli connects both islands through the island of Kannigilla. This causeway has resulted in higher tidal velocities and regular wave-driven flooding of the north region resulting in Mangrove die off.



Figure 108 Sentinel 2 imagery of GDh. Hoandehdhoo reef taken in January 2022

7.3 Socio Economic Status

7.3.1 Demography

The Island has a registered population of 800 as per the 2014 census, with a total of 404 males and 396 females. The island population density is 12.38 people per hectare as per the year 2021. The population figures have drastically increased over the past years where the total registered local population climbed up to 1317. The following table and graph illustrates the demographic breakdown of Hoandedhdhoo.

GDH.Hoandedhdhoo Population

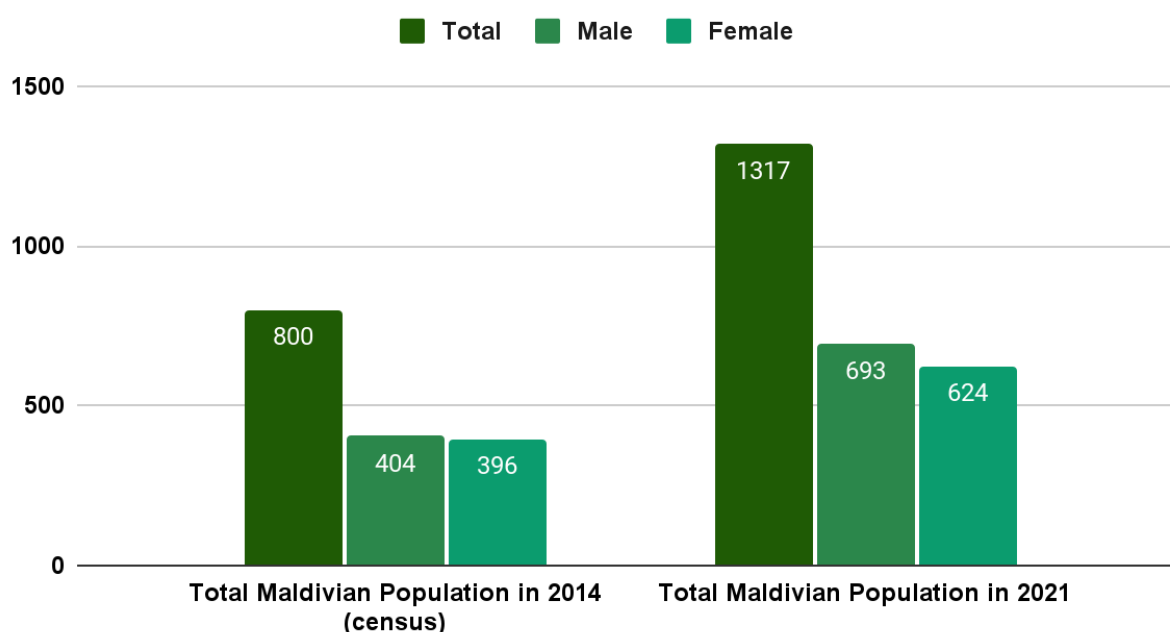


Figure 109: GDh. Hoandedhdhoo Population

Table 92: GDh. Hoandedhdhoo Population (Census, 2014)

Resident Population according to Census 2014										
Atoll	Locality	Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
GDh	Hoandedhdhoo	861	454	407	800	404	396	61	50	11

7.3.2 Socio-Economic Activities

Hoandedhdhoo is an inhabited island in Gaafu Dhaalu Atoll's administrative unit and physically part of Huvadhu Atholhu Dhekunuburi Atoll in the Maldives'. This island is well-known for its fishery, agricultural and tourism activities. The island also has 3 cafes/restaurants, 6 shops and 60 guesthouse beds that contribute to the tourism industry.

7.3.3 Facilities available

7.3.3.1 Health Care

Hoandedhdhoo Health Centre currently has 1 doctor, 4 nurses and 3 beds. The health facilities in the island are bare minimum and many island residents find that the health centre needs to be upgraded and service hours need to be extended.

7.3.3.2 Education

Hoandedhdhoo school has 256 students, 36 teachers and 13 administrative staff. The island school offers education up to grade 10 standard.

7.3.3.3 Utilities

Electricity on the island is provided by state owned utility company FENAKA. The island currently does not have a sewerage and sanitation system.

7.3.3.4 Transportation

The island has an outer islands harbour project which is expected to finish by 2025. The transportation between Hoandedhdhoo island and other islands is by sea.

7.3.4 Water resources, water usage and water consumption

In Hoandedhdhoo there are a total of 173 households inhabited currently. 119 out of 173 households were surveyed, while maintaining a 95% confidence interval and geo-coordinated sampling points. A map of households surveyed is attached in Annex V.

Table 93: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed		119/173 households = 69%
Percentage of well fitted with pumps		99%
Ground water		Usage in percentage
Source of drinking		0
Source of cooking		0.84

7.3.4.1 Existing water and sanitation

The main form of sanitation is via the use of septic tanks. Each household has one or two septic tanks, and the septic tanks are cleaned periodically by disposing the septic waste into the sea. According to

the Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22), annex 4 states that the households should keep a 15 meters (49.2126 ft) distance between septic tank and nearest well. The main reason for the adoption of this standard is to negate any possible causes of contamination in the groundwater. This being the recommended standard, majority of the surveyed households were reported with less than 49ft distance between septic tank and water well. In Hoandedhdhoo 93 percent reported to have less than 49ft distance between septic tanks and water well. While remaining 7% reported to have more than 49ft distance between septic tanks and water well. Rainwater is also the primarily used for cooking. Many homes use rainwater from neighbouring houses or bottled water when rainwater is not readily available during the dry season. Rainwater collected from rooftops is stored mostly in water tanks, whether at home or communal rainwater tanks.

In GDh. Hoandedhdhoo, 3 houses have connected rainwater to the well and have reported improvement in groundwater. On the same note, 52% of the households have rainwater discharged to an open area within the plot.

7.3.4.2 Water usage and resources

Based on the survey conducted in Hoandedhdhoo, 1116 houses have HDPE rainwater tanks for rainwater storage. 98% of the households use rainwater for cooking and 76% use rainwater for drinking. While groundwater is mainly used for gardening, household cleaning, with all the houses fitted with water pumps. The following sections outline further details about various groundwater usage and consumption scenarios in the island.

7.3.4.3 Domestic water usage

Based on household water usage surveys in Hoandedhdhoo, **314,763** Liters of groundwater is used daily in the households. A total of **239** Liters of groundwater are consumed per capita per day.

Table 94: Domestic groundwater use data for GDh. Hoandedhdhoo

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
113	39	29.28	22	4.47	24	7	239

*All units are in Liters per capita per day

7.3.4.4 Commercial water usage

Based on the survey conducted in GDh. Hoandedhdhoo, there are currently three operational café/restaurants and 1 guesthouse on this island. A total of **1,851** Liters of groundwater are used by commercial entities and their detailed breakdown is given in the tables below.

Table 95: Café/ Restaurant groundwater use data for GDh. Hoandehdhoo

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Mina Cafe	1.5	151	0	10	163
Raabadaa	18	182	180	21	401
LalooPy	90	0	0	10	100
					664

*All units are in Liters per day

Table 96: Guesthouse groundwater use data for GDh. Hoandehdhoo

Guesthouse	Average Occupancy	Total (L/day)
Vaaruge Residence	25%	1187

7.3.4.5 Industrial water usage

In Hoandedhdhoo, 82 out of 203 farming plots were surveyed to determine the industrial groundwater usage. Majority of the farms have pumpkin, cucumber, watermelon and chillies and they are produced throughout the year. An average of **221.69** Liters of groundwater is used by each farm and the breakdown for 203 farms are given in the table below. A total of **45,003** Liters of groundwater is used for industrial purposes.

Table 97: Groundwater use for Farming in for GDh. Hoandehdhoo

Total farms	No. of farms surveyed	Average usage	Total usage for all farms
203	82	221.69	45,003

7.3.4.6 Institutional water usage

Based on the survey conducted in Hoandedhdhoo, there are currently six institutions that have groundwater well facilities and use groundwater. A total of **3,172** Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 98: Institutional groundwater use data for GDh. Hoandehdhoo

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Magistrate Court	72.7	–	8.6	–	81.3
Powerhouse	206	–	2.9	–	209
GDh. Hoandehdhoo School	1755	15	8.6	–	1779
Council office	206	12	4.3	–	222
Health Center	110	180	30	519	839
Youth Center	36.3	–	5.7	–	42
					3,172

*All units are in Liters per day

7.3.5 Present & Future water demand

In Hoandedhdhoo, the present water demand is at **353,106** Liters per day and groundwater usage is expected to decrease with the establishment of water supply services in the island. The year 2021 figures are as per the latest island council data. For the figures in year 2036 and 2054, it is as per Maldives Populations Projections Report published by the National Bureau of Statistics.

Population Projection - GDH.Hoandedhdhoo

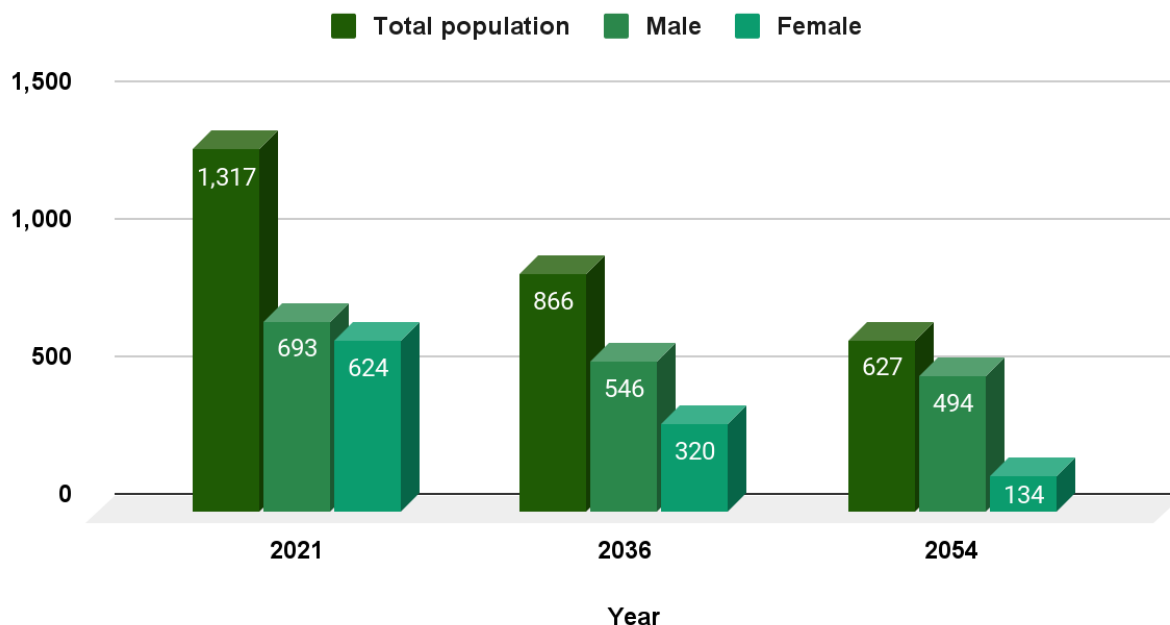


Figure 110: Population Projection - GDh. Hoandedhdhoo

Table 99: Present groundwater demand - GDh. Hoandedhdhoo

Year	Total Population	Domestic water demand	Commercial water demand	Institutional water demand	Industrial water demand	Groundwater usage
2021	1,317	314,763	1,851	3,172	33,320	353,106

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 239 Liters per day. For the year 2036, water supply usage is expected to be 50 Liters per capita per day. After deducting 50 Liters from 239 Liters, the groundwater demand is expected to be 189 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 866 is expected to be **163,674** Liters per day.

For the year 2054, water supply usage is expected to be 75 Liters per capita per day. After deducting 75 Liters from 239 Liters, the groundwater demand is expected to be 164 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 627 is expected to be **102,828** Liters per day.

Table 100: Future domestic water demand – GDh. Hoandedhdhoo

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	866	239	50	189	163,674
2054	627	239	75	164	102,828

7.3.6 Water related issues

From 119 households surveyed in Hoandedhdhoo, most houses reported unpleasant smells (42%) and milky and cloudy texture (23%) in their respective wells. There were four houses having reddish brown color changes in the groundwater. Only 10% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gasses such as Hydrogen Sulfide which causes unpleasant smells.

Table 101: Signs of contamination reported by households

Types of contamination	Data in % out of 57 households surveyed
Smell	42%
Milky	23%
Foul taste	10%
Changes in color	3%
Salty	3%
None	0%

The following table details out the changes in groundwater quality reported by the households during tidal or seasonal changes.

Table 102: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 57 households surveyed
Changes with tidal variations	13%
Groundwater quality is better in rainy months (Hulhangu season)	18%
Long periods without rain causes bad smell	22%
Long periods without rain causes bad taste	3%
Rain makes it worse	0.84%

No change

66%

7.4 Groundwater Quality

7.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 103 summarizes the water quality results. Map of locations where groundwater quality points were taken for physiochemical analysis is attached to Annex VI. The full list of measured parameters is attached to Annex VII.

Table 103: Groundwater physiochemical parameters statistical summary - GDh. Hoandehdhoo

	EC ($\mu\text{S}/\text{cm}$)	Turbidity (FNU)	DO (mg/L)	pH	Temp ($^{\circ}\text{C}$)	Sal (ppt)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
Standards	<1500 Potable purposes <2500 Non-potable purposes Source ¹	<5 Source ²		6.5-8.5 Source ²			<1.5 Odour threshold <35 Taste threshold Source ¹	<50 Source ¹	
Mean	775	2.30	3.72	7.32	28.79	0.35	2.49	7.39	0.36
Median	739	0.55	3.20	7.24	28.65	0.33	0.98	4.83	0.28
SD	252	4.53	1.99	0.35	1.33	0.12	3.68	7.96	0.31
Min	160	0.00	1.27	6.88	26.80	0.07	0.16	2.20	0.05
Max	1870	20.92	8.83	9.17	33.70	0.86	16.33	48.23	1.62
CV	0.33	1.98	0.54	0.05	0.05	0.33	1.48	71.08	0.87

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH₃= Ammonia, NO₃⁻= Nitrate, PO₄³⁻=Phosphate, SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source¹ = WHO Drinking Water Guidelines, 2017. Source² = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 775 $\mu\text{S}/\text{cm}$ is lower than the WHO Standard for potable water (1500 $\mu\text{S}/\text{cm}$) and non-potable water (2500 $\mu\text{S}/\text{cm}$).
- All the samples had EC lower than 1500. The Electrical Conductivity distribution of tested samples is presented in Figure 112.
- Electrical Conductivity of groundwater is higher near the coast of the island and lower in the centre of the island.
- The mean Turbidity level at 2.3 NTU fall below the URA Guidelines for drinking water (5 NTU). Only four samples had higher Turbidity level than 5 NTU.
- Dissolved Oxygen ranged from 1.27 mg/L to 8.83 mg/L with a mean of 3.72 mg/L.
- All samples fell within the pH range of 6.5-8.5 as per URA Guidelines for drinking water with a mean pH of 7.32.

- Temperature ranges from 26.8°C to 33.7°C depending on the well characteristics and time of day reading was taken. Mean temperature was 28.79°C.
- Salinity ranged from 0.07ppt to 0.86ppt with a mean of 0.35ppt.
- The mean Ammonia concentration was 2.49 mg/L which is higher than the WHO threshold for odour but well below the WHO threshold for taste. 60% of samples had concentration below 1.5 mg/L, 40% of samples had concentration between 1.5 mg/L and 35 mg/L and 0% of samples had concentration higher than 35 mg/L. The ammonia concentration distribution is shown in Figure 111.
- The mean Nitrate concentration was 7.39 mg/L which falls below the WHO Standard for Nitrate concentration (50 mg/L). No samples had Nitrate concentration higher than the standard.
- Phosphate concentration ranges from 0.05 to 1.62 mg/L with a mean concentration of 0.36 mg/L. There is no WHO guideline value for phosphate concentration. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater. Four samples tested had Phosphate concentration below 0.1 mg/L. Phosphate concentrations are higher in densely populated areas.

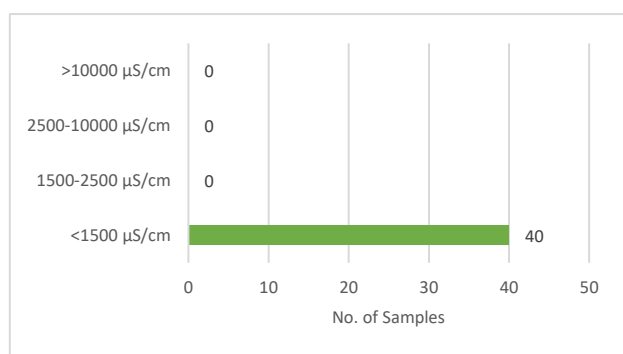


Figure 111: EC Distribution in GDh. Hoandehdhoo

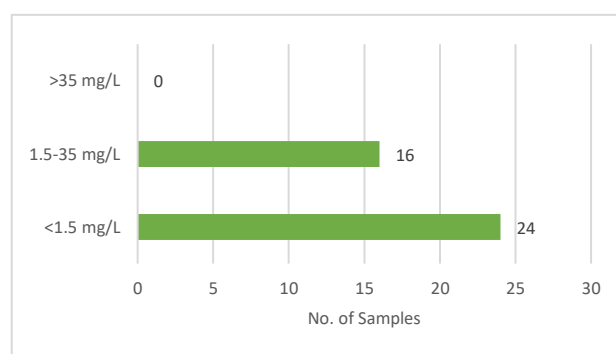


Figure 112: Ammonia Concentration Distribution in GDh. Hoandehdhoo

The spatial distribution of all the parameters measured are shown in Figure 113(a-i).

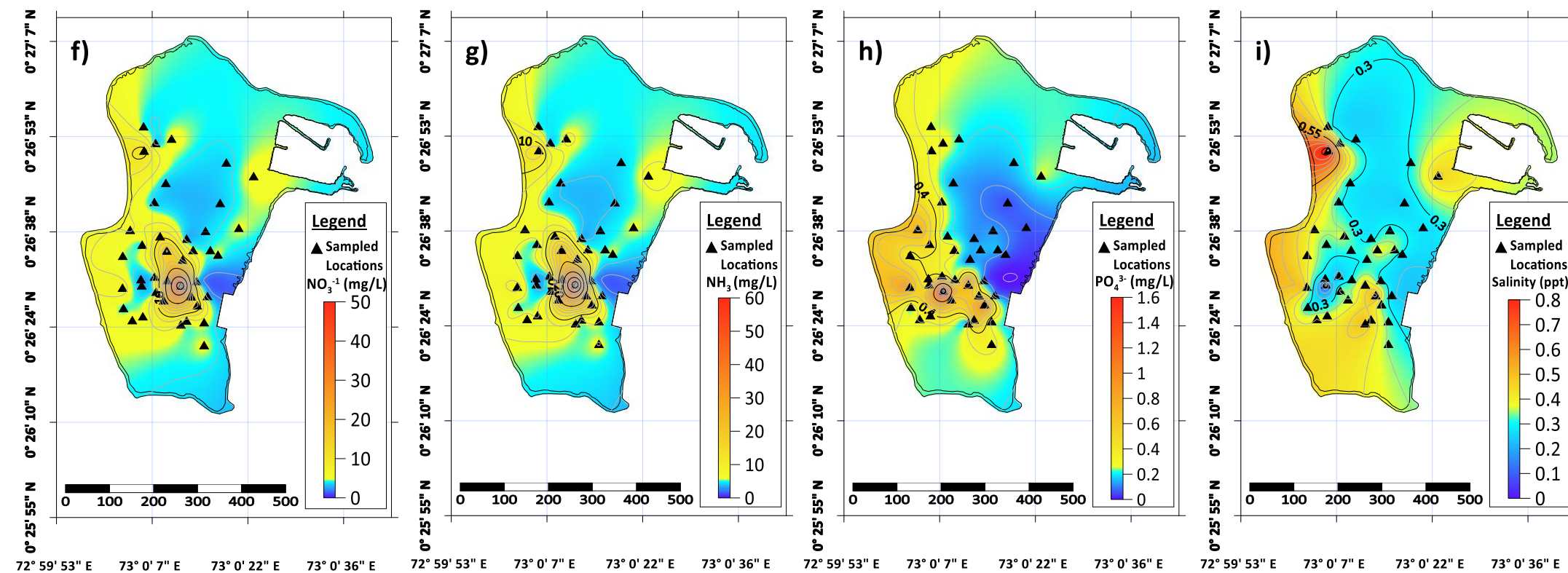
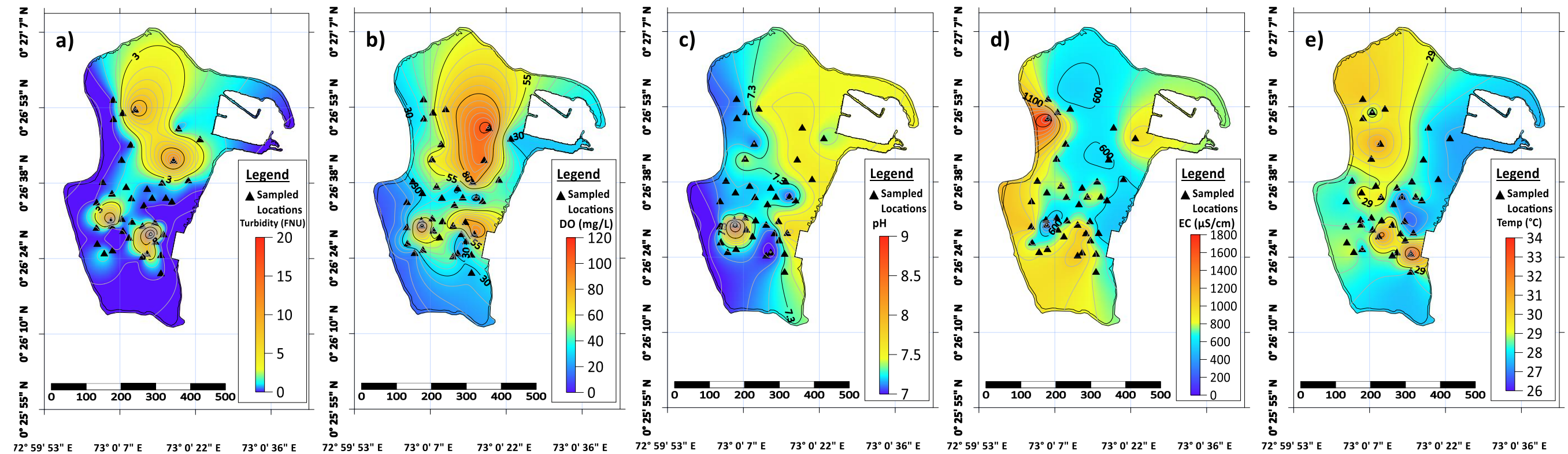


Figure 113: Spatial variation of physiochemical parameters in GDh. Hoandehdhoo

As a principle, excessive groundwater usage leads to overextraction causing salinization of the freshwater lens. The Social Survey findings were used to calculate the daily water consumption at each household, institution, and other commercial entities. The EC values at these locations were plotted against water consumption to check if increasing water usage leads to salinization. The correlation coefficient of EC to Water usage is 0.452 and the R-squared of the plot is 0.204 as indicated from the Figure 114. Therefore, there is a positive correlation observed between EC and Water Usage for the island as per the findings from the Social Survey and Water Quality Survey. However, this correlation is not very significant. The Spatial distribution of EC and water usage is shown in Annex VIII.

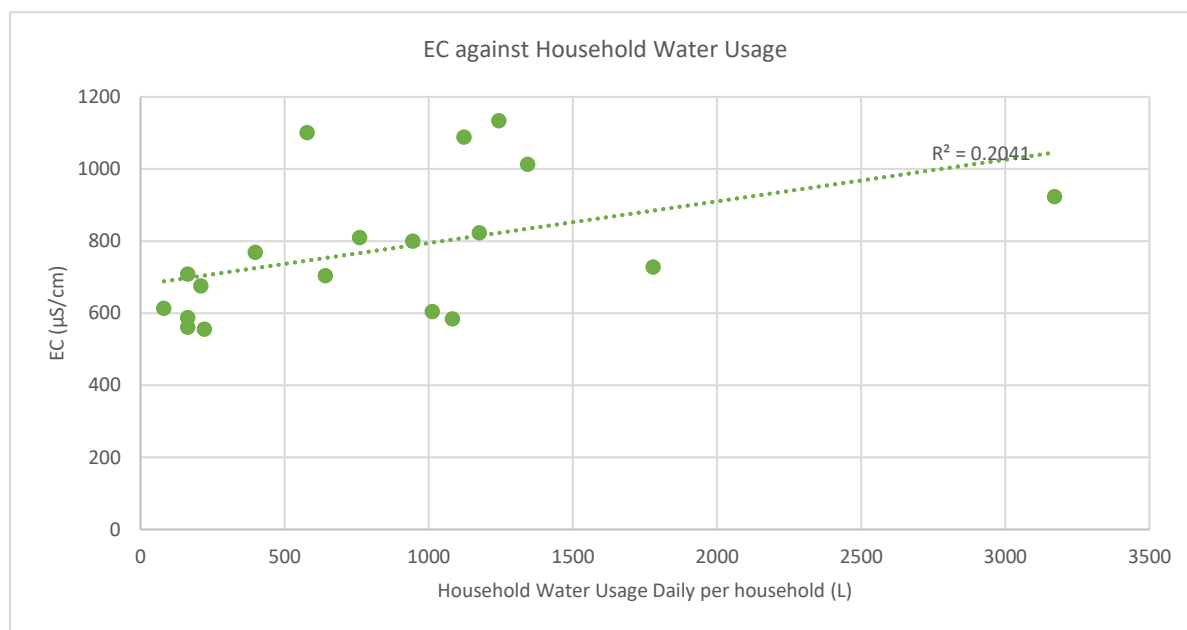


Figure 114: EC against Water Usage in GDh. Hoandehdhoo

7.4.1.1 Correlation Matrix

The correlation matrix for GDh. Hoandehdhoo along with the colour bar is given below. Red colour indicates negative correlation while green colour indicates positive correlation.

Table 104: Correlation matrix of the groundwater quality parameters in GDh. Hoandehdhoo

Variables	Turbidity (FNU)	DO (mg/L)	pH	EC (µS/cm)	Sal (ppt)	Temp (°C)	NO ₃ ⁻ (mg/L)	NH ₃ (mg/L)
DO (mg/L)	0.09							
pH	-0.05	0.69						
EC (µS/cm)	0.07	-0.48	-0.58					
Sal (ppt)	0.08	-0.47	-0.56	1.00				
Temp (°C)	-0.08	-0.14	-0.13	0.12	0.04			
NO ₃ ⁻ (mg/L)	0.05	-0.06	-0.19	0.26	0.24	0.23		
NH ₃ (mg/L)	0.42	-0.40	-0.34	0.46	0.46	0.00	0.19	
PO ₄ ³⁻ (mg/L)	0.01	-0.25	-0.03	0.20	0.19	0.11	0.31	0.14

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation
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Table 104 shows a strong positive correlation coefficient between DO/pH ($r=0.69$) and EC/Sal ($r=1.00$). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlations between salinity and conductivity are as expected. There are no significant negative correlations observed.

7.4.1.2 Water Quality Index

In this study, the computed WQI ranges from 1.27 to 22.1, with a mean of 5.71. The WQI was divided into four categories and Table 105 shows the categorization of samples. 87.5% of samples were classified as "Very Good", 10% of samples were classified as "Good", 2.5% of samples were classified as "Poor" and 0% of samples were classified as "Very Poor". The high value of WQI at one location was found to be mainly from the high turbidity at that location. The spatial distribution of WQI is as per Figure 115.

Table 105: Water Quality Classification based on WQI – GDh. Hoandehdhoo

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	35	87.5%
10 to 20	Good	4	10%
20 to 50	Poor	1	2.5%
>50	Very Poor	0	0%

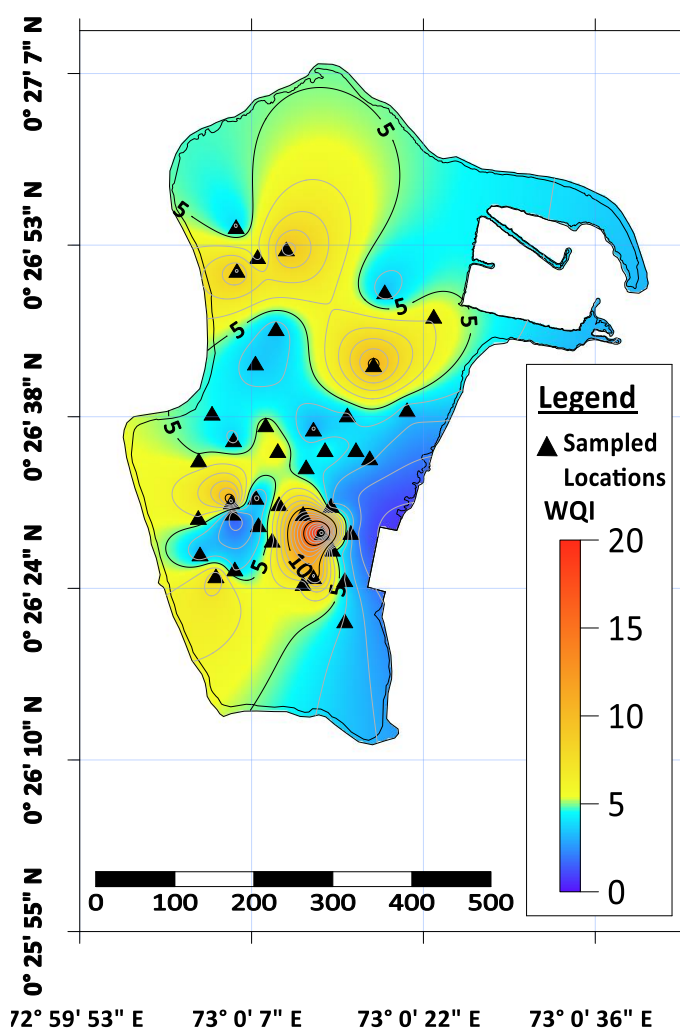


Figure 115: Spatial Distribution of WQI in GDh. Hoandehdhoo

7.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 106 summarizes the results.

Table 106: Microbiological Parameters of groundwater in GDh. Hoandehdhoo

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq02	142	3		Location does not fall within the coverage of social survey
wq03	248	1	50	Septic Tank. Septic Tank cleaned once every 5 years and waste pumped out to sea.
wq07	1733	2	12	Septic Tank. Septic Tank cleaned once every 5 years and waste buried in household
wq08	73	1	20	Septic Tank. Septic Tank cleaned once a year and waste buried in household
wq10	411	1	40	Septic Tank. Septic Tank cleaned once a year and waste buried in household
wq13	112	Not detected		Location does not fall within the coverage of social survey
wq18	184	Not detected	30	Septic Tank. Septic Tank cleaned once every 5 years and waste buried in household
wq19	461	1		Location does not fall within the coverage of social survey
wq21	548	Not detected		Location does not fall within the coverage of social survey
wq22	22	22	20	Septic Tank. Septic Tank cleaned once every 8 years and waste buried in household
wq23	1203	Not detected		Location does not fall within the coverage of social survey
wq34	>2420	Not detected	35	Septic Tank. Not cleaned yet.
wq35	77	Not detected	60	Septic Tank. Septic Tank cleaned once every 8 years and waste buried in household
wq38	39	2		Location does not fall within the coverage of social survey
wq39	>2420	1		Horizon Area

*Distance between water well and nearest septic tank (feet)

Faecal Coliform was detected in 9 samples and Total Coliform was detected in all 15 samples with 2 samples detecting Total Coliform count higher than 2400 MPN/100mL.

On average, there is an approximate distance of 25 feet between septic tanks and the nearest water well as observed from social survey.

The spatial distribution of Faecal Coliform and Total Coliform is given in Figure 116. On average, Faecal Coliform is not detected on the East side of the island while small amounts of Faecal Coliform were detected in the West side of the island. Moderately even spatial distribution of Total Coliform was observed with higher count detected on the South West side of the island. Generally lower count was detected on the North side of the island.

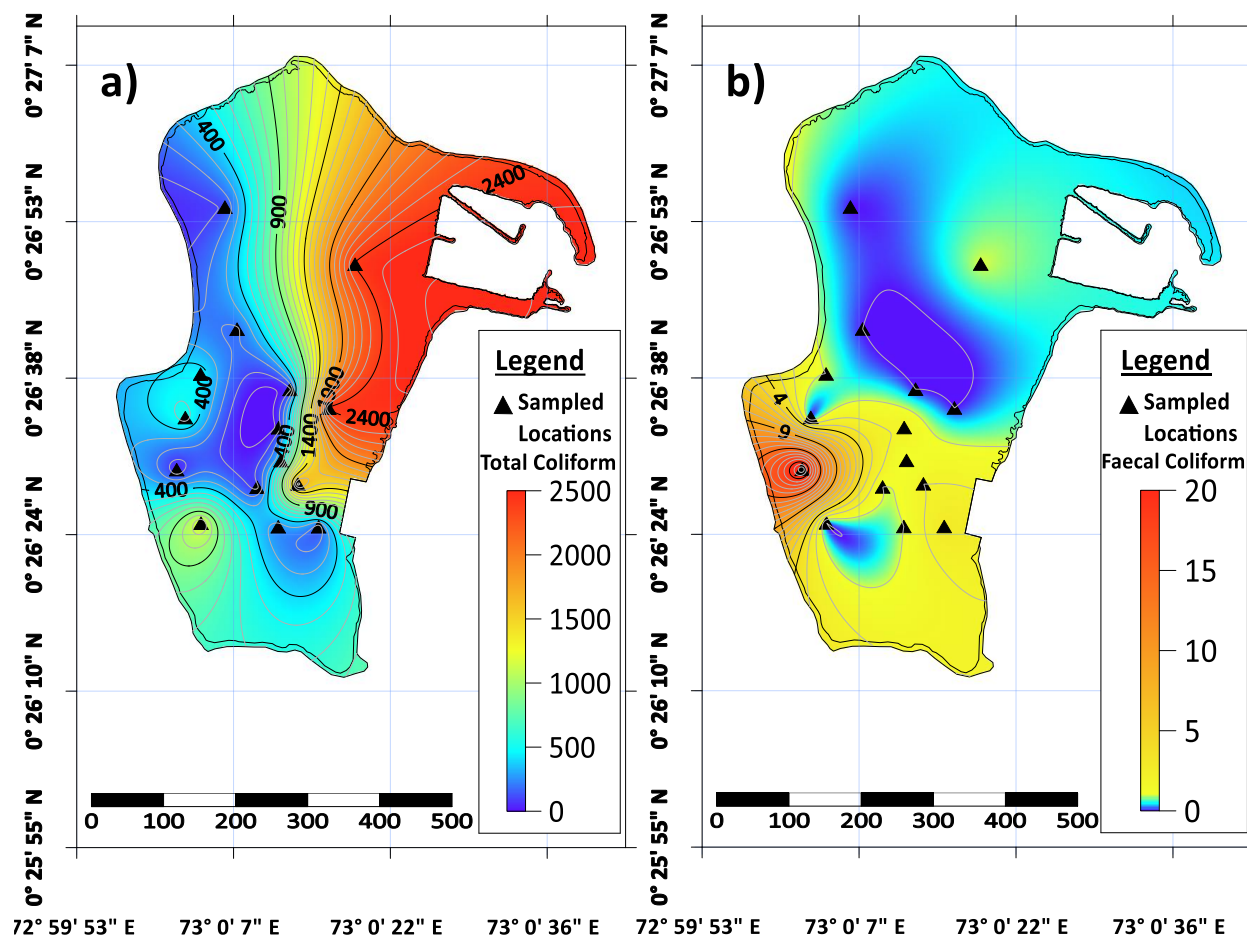


Figure 116: Total (a) and Faecal (b) Contamination Distribution in GDh. Hoandehdhoo

The Total Coliform and Faecal Coliform Contamination was plotted against the distance between septic tank and well, to identify the correlation between these two variables. The graphs are given below.

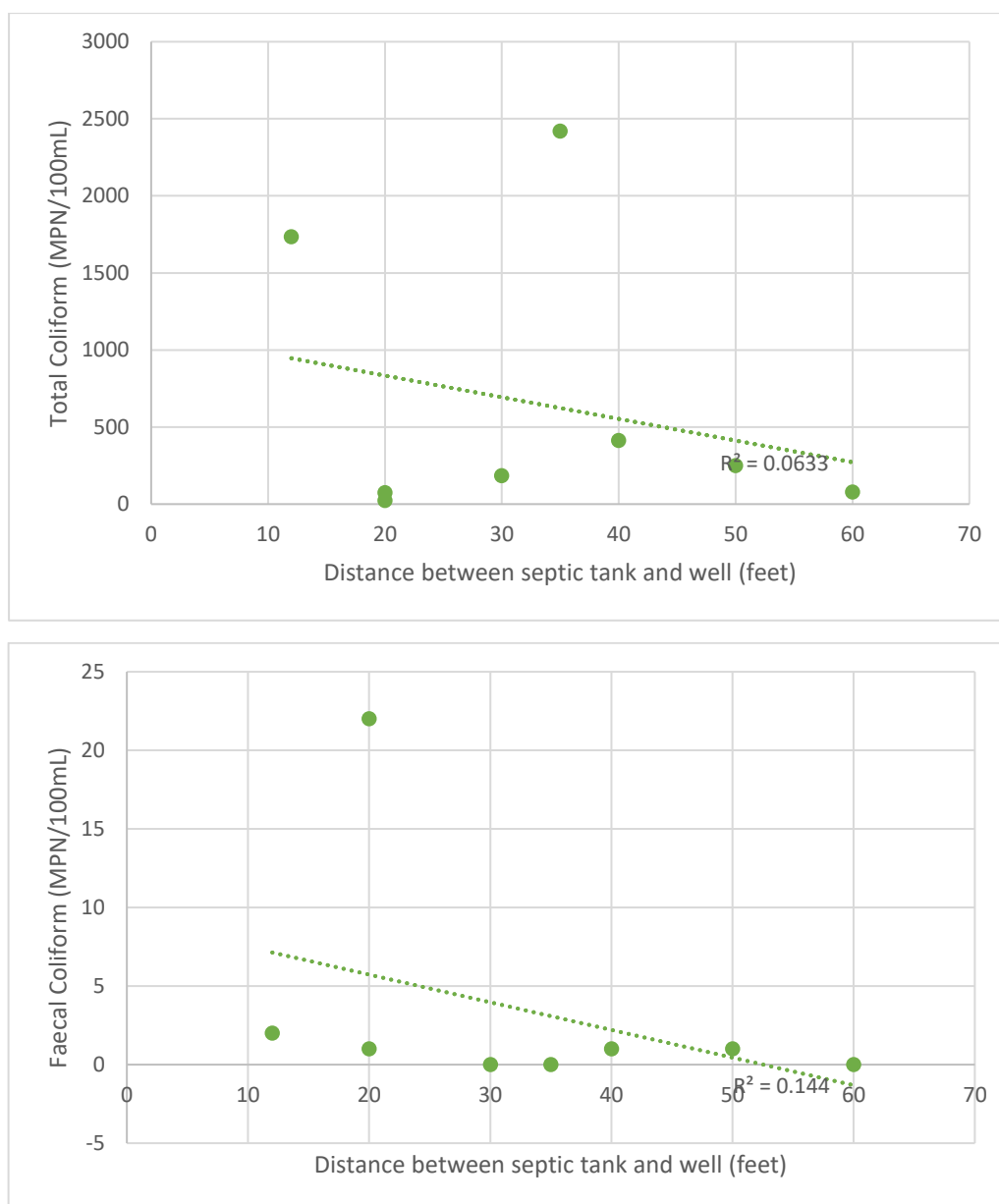


Figure 117: Microbiological Contamination against Septic Tank distancing - Hoandehdhoo

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.252 and the R-squared of the plot is 0.063. The correlation coefficient of Faecal Coliform to distance between septic tank and well is -0.38 and the R-squared of the plot is 0.144. Therefore, there is no significant relationship observed between the parameters.

7.5 Pumping Test

7.5.1 Test location

A suitable well without a base was not available from GDh. Hoandedhdhoo. The old mosque well had a placed flat coral stone bed and was not fully enclosed, hence it was selected to be used for the pumping test. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 118 below shows the location for the pumping test at GDh. Hoandedhdhoo.

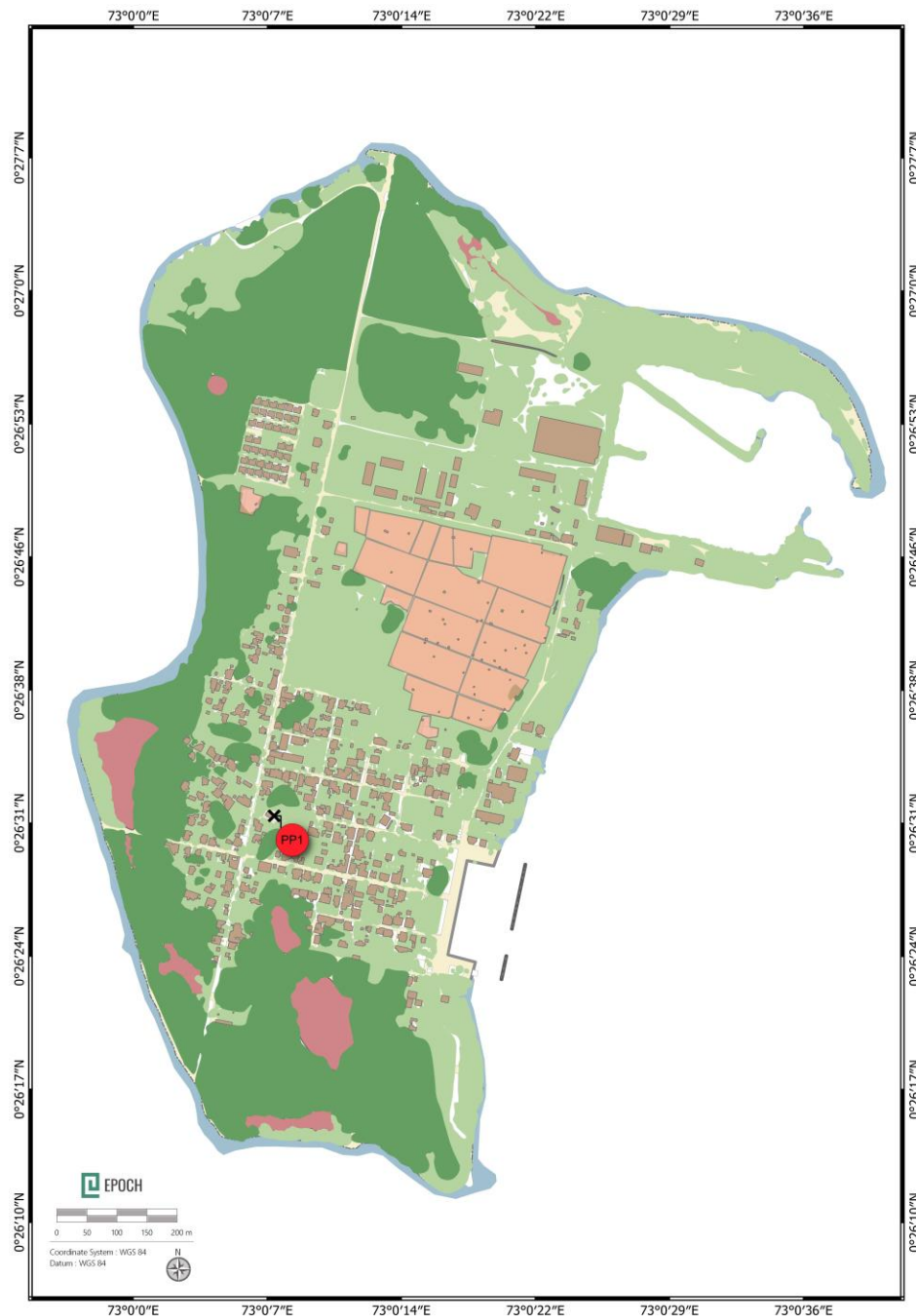


Figure 118: Pumping test location - GDh. Hoandedhdhoo

7.5.2 Pumping rate, pumping hours, and collected data

A step-drawdown pumping test was carried out at GDh. Hoandedhdhoo. The test began at 10:58 hours on 20 November 2021 and lasted for 155 minutes. A flowrate of 20 LPM was maintained for 0–70th minute of the test. The flow was then gradually increased to 30 LPM for 71st–115th minute, and 35 LPM for 116th–130th minute. The recovery phase of the test lasted from 131st–155th minute for more than a 100% recovery, due to incremental tide.

7.5.3 Hydrogeological parameter estimation

The Cooper-Jacob Solution for Unconfined Aquifer Models was used to process the data from the pumping test. The analysis was carried out using the software, AQTESOLV. The Aquifer Transmissivity (T) value was estimated to be $3.50 \times 10^{-4} \text{ m}^2/\text{s}$ (30.22 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.2191 for GDh. Hoandedhdhoo. The full data set of the pumping test at GDh. Hoandedhdhoo has been annexed at Annex XII.

7.6 Permeability Test

7.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 119 below. The originally proposed locations were changed as necessary due to unavailability of water and electricity for testing, inaccessibility of proposed locations, as well as the prioritizing of public lands that can be used for potential design solutions over private lands.

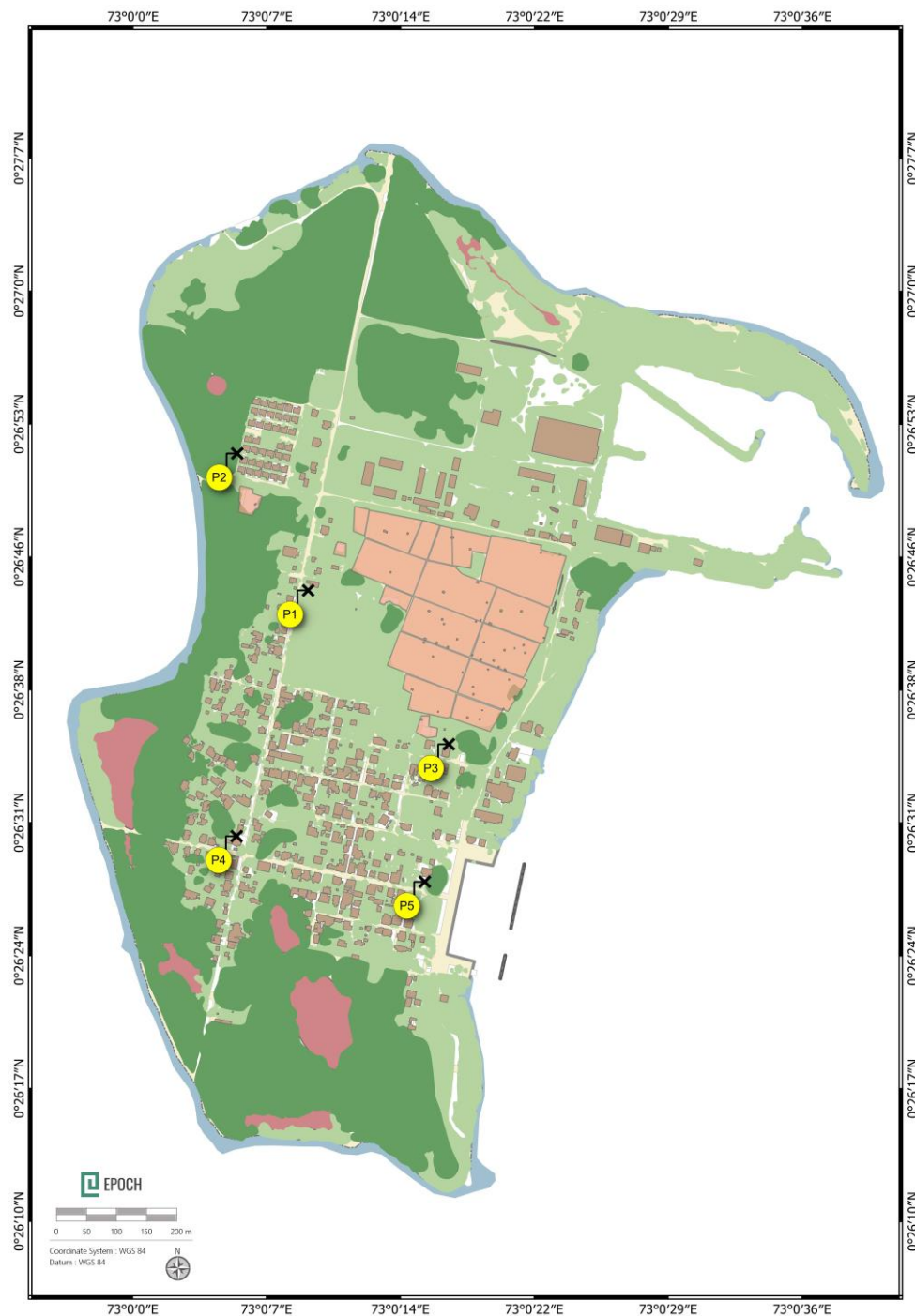


Figure 119: Permeability Test Locations – GDh. Hoandedhdhoo

7.6.2 Measured data

Table 107: Permeability Test Measured Data - GDh. Hoandedhdhoo

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m ³ /s)	K (m/s)	K (m/day)
HDD-PMB1	0.6	0.260	35	12	0.50	0.000008	3.27E-05	2.82
HDD-PMB2	0.6	0.650	35	12	0.50	0.000008	1.31E-05	1.13
HDD-PMB3	0.6	0.360	35	12	2.84	0.000047	1.34E-04	11.59
HDD-PMB4	0.6	0.640	35	12	2.50	0.000042	6.64E-05	5.74
HDD-PMB5	0.6	0.360	35	12	0.50	0.000008	2.36E-05	2.04

Note: H = Height of water in well (m),
 Tu = distance from water level in casing to water table (m),
 Cu = Conductivity Coefficient,
 r = borehole radius,
 Q = Steady flow into well,
 K = Coefficient of permeability.

7.6.3 Permeability estimation and identified features

The average permeability value for the GDh. Hoandedhdhoo is 4.66 m/day, with permeability values ranging from 1.13 m/day to 11.59 m/day. As highlighted in Section 7.7 **Soil Profile Survey**, the island soil profile is predominantly Sands, and the K values above are consistent with the range of K values obtained for Sands (Robertson (2010)).

7.7 Soil Profile Survey

7.7.1 Test locations

Soil Profile surveys were carried in 8 locations across the island, as outlined in Figure 120 below. Out of the 7 locations, 5 points were permeability test locations, and the remaining 3 points were chosen in a way that ensured a uniform coverage of the entire island. An 8th point was added to account for the large island size, even though the methodology proposed was for 7 points.

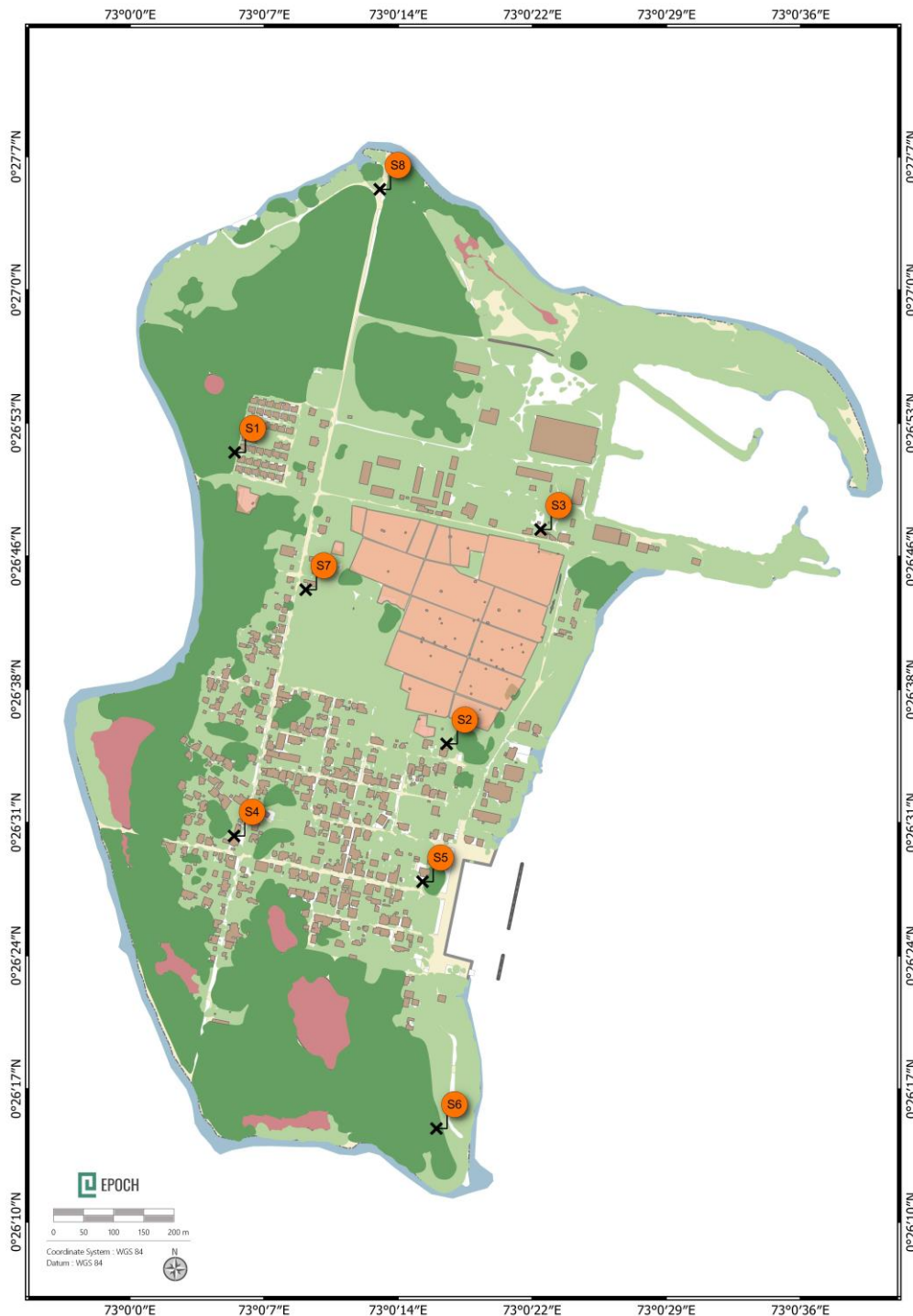


Figure 120: Soil Profile Survey Locations - GDh. Hoandedhdhoo

7.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 121 below. Even though there are variances in the colour due to environmental factors, the island soil profile is predominantly made up of Uniformly Graded Sand for the observed depth. Gravel was observed in some sand layers in a few areas of the island.

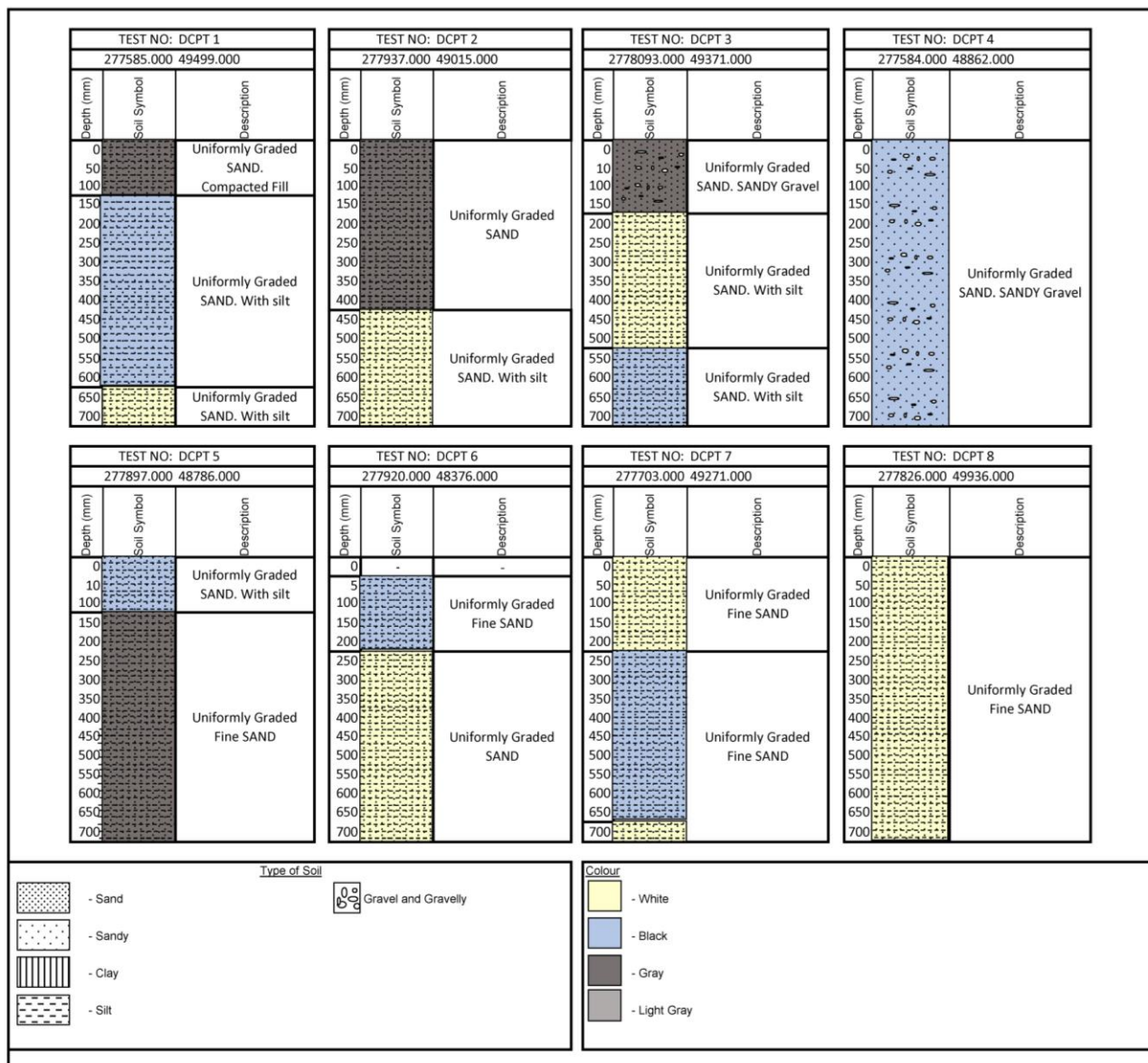


Figure 121: Soil Profile - GDh. Hoandedhdhoo

7.8 Flood Assessment and Inundation Survey

7.8.1 Flood occurrence and flood impact

As per Social Survey, 74% reported that flooding occurs every time it rains. Many houses reported that Harbour construction and Island reclamation work had a major impact on the flooding pattern of the island.

As per the social survey, 27 households reported rain induced flood incidents in October and November in the year 2021 and 9 households reported flooding incidents in 2020. In the two incidents, 30 houses reported complete and partial damages of furniture and household appliances along with broken fences and trees. On the same note, 77% of the households reported that they experienced no damages and only minor inconveniences by recent flooding events.

The flooding originates mostly from roof runoff (77%) as per the Social Survey. Most responses state multiple sources for the flooding within their properties such as the neighbours' roof, off the road, and general run off in the area. Perceived causes of flooding as per social survey are given in the table below.

Table 108: Perceived causes of flooding - GDh. Hoandedhdhoo

Perceived causes of flooding				
Roof run off	Neighbours' roof	Off the road	General run off in the area	No flooding within the plot
77%	12%	34%	59%	18%

From the social survey, 52% of households reported that they drain rainwater overflow from storage and roofs to an open area within the plot. Most responses state multiple ways for the discharge of rainwater overflow to the roads, open areas within the plot and to the well. Details of discharge of rainwater overflow are given in the table below.

Table 109: Discharge of rainwater overflow - GDh. Hoandedhdhoo

Discharge of rainwater overflow			
Ground	Roads	Open area within the plot	Drained to well
41%	5.7%	50.8%	2.5%

Despite the flooding incidents in Hoandedhdhoo, 59% households reported flooding as an acceptable problem. (Refer to flood severity component of Annex XIII: Flood Maps) This can be due to continuous flood mitigation efforts by the island council and residents.

7.8.2 Flood Depth and Inundation area identification

The common flooding zones are mainly the farming area and near the Health Centre (refer to Annex XIII: Flood Maps). Based on the social survey responses, an average of 0.68ft is estimated as the flooding depth when there is a heavy rainfall. Also, 51% reported that it takes 2-4 hours to inundate the area once the heavy rain starts.

7.8.3 Draining flood water

There is a gravity-based drainage system in the farm area of the island. The flooded water is directed to the sea from the east side of the island. As per the social survey, 53% observe that it takes more than 24 hours to drain the flooded water, 22% observe that the water drains during the rain fall, 14% observe that the water drains in less than 4 hours and 11% observe that it drains within 4 to 24 hours.

Table 110: Draining period - GDh. Hoandehdhoo

Draining period			
only while raining	drains less than 4hrs	takes 4-24 hrs	more than 24hrs
22%	14%	11%	53%

7.9 Geophysical Survey

7.9.1 Surveyed Locations

Locations where ER sounding measurement taken at GDh. Hoandehdhoo island are shown in Figure 122 together with transect lines. There are 50 ER measurement locations and the number of transects in this island is 7.

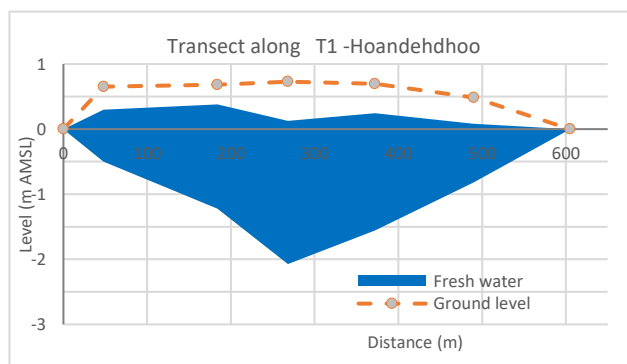
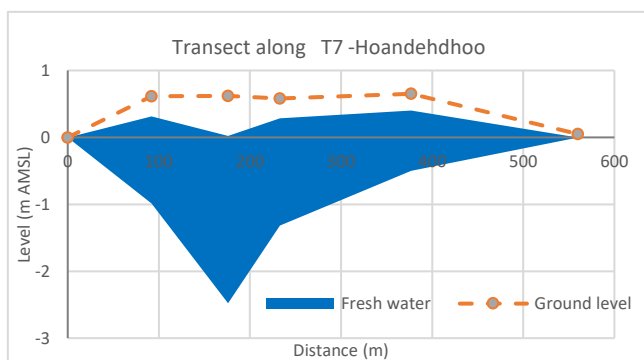


Figure 122: ER surveyed locations and transect lines – GDh. Hoandehdhoo Island

7.9.2 Freshwater levels and saline water levels

From processed ER data using GeoVES 1.5 – GeoElectrical Model depth to freshwater starting level and depth to freshwater lens bottom level (saline water start level) were determined and they were converted to elevation with respect to mean sea level using ground collected through drone survey. Table III below shows the estimated levels at ER surveyed locations of GDh. Hoandehdhoo Island and freshwater lens thickness.

Table III: Freshwater lens levels and thickness – GDh. Hoandehdhoo island

No	Map ID	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	HO01	0.84	0.44	0.21	0.23
2	HO03	0.95	0.55	-0.05	0.60
3	HO08	1.19	0.74	-0.06	0.80
4	HO09	1.12	0.77	-0.13	0.90
5	HO10	1.35	0.95	0.35	0.60
6	HO12	1.23	0.63	-0.17	0.80
7	HO14	1.27	0.92	0.02	0.90
8	HO18	1.54	0.84	-0.96	1.80
9	HO19	0.98	0.08	-1.72	1.80
10	HO20	1.33	1.03	0.03	1.00
11	HO21	1.50	1.05	-0.15	1.20
12	HO22	0.59	-0.01	-1.01	1.00
13	HO23	0.79	0.19	-0.71	0.90
14	HO25	1.62	1.02	-0.78	1.80
15	HO26	1.38	0.78	-0.07	0.85
16	HO28	1.20	0.90	-0.10	1.00
17	HO29	0.92	0.32	-1.68	2.00
18	HO33	1.31	0.71	-0.14	0.85
19	HO34	0.96	0.36	-0.44	0.80
20	HO36	1.67	1.17	-0.63	1.80
21	HO37	0.48	0.08	-0.82	0.90
22	HO38	0.65	0.15	-1.95	2.10
23	HO39	0.55	0.25	-1.95	2.20
24	HO41	0.77	0.17	-1.83	2.00
25	HO42	0.95	0.60	-1.70	2.30
26	HO43	0.82	0.47	-0.33	0.80
27	HO44	0.70	0.25	-1.55	1.80
28	HO45	0.64	0.34	-1.46	1.80
29	HO46	0.85	0.35	-2.45	2.80
30	HO47	0.89	0.51	-1.69	2.20
31	HO49	0.65	0.40	-0.50	0.90
32	HO5	1.27	0.97	0.37	0.60
33	HO51	0.73	0.13	-2.07	2.20
34	HO52	0.90	0.65	-0.25	0.90

35	HO53	0.64	0.19	-2.61	2.80
36	HO55	0.63	0.28	-1.52	1.80
37	HO56	0.72	0.37	-1.23	1.60
38	HO57	0.58	0.28	-1.32	1.60
39	HO58	0.94	0.54	-2.26	2.80
40	HO59	0.65	0.20	-0.25	0.45
41	HO60	0.68	0.38	-1.22	1.60
42	HO61	0.84	0.54	-0.36	0.90
43	HO64	0.62	0.02	-2.48	2.50
44	HO65	0.66	0.30	-0.50	0.80
45	HO66	0.65	0.29	-0.71	1.00
46	HO67	0.61	0.31	-0.99	1.30
47	HO68	1.13	0.83	0.43	0.40
48	HO7	1.33	0.93	0.13	0.80
49	HO71	1.11	0.67	0.07	0.60
50	HO72	1.51	1.01	0.71	0.30

Average freshwater thickness of GDh. Hoandehdhoo island is 1.33m.

Data in Table III were used to plot freshwater lens cross sections along 7 transects and they are given in Annex IX. Of these sectional plots 2 were given in Figure 122 and they represent the transect plot along the longitudinal section and cross section of the island that passes through island middle. Dotted lines in these plots indicate ground level variation with respect to mean sea level along the transect lines.

7.9.3 Freshwater lens spatial extent

For the purpose of identifying spatial distribution of upper and lower level of freshwater lens the computed freshwater levels and saline water levels at ER points were exported to ArcGIS and used to generate contours with help of interpolation tools available in the same software. The generated contours are shown in Figure 124 and the processed ER data were used to develop a 3D view of the freshwater lens and it is also shown in Figure 124.

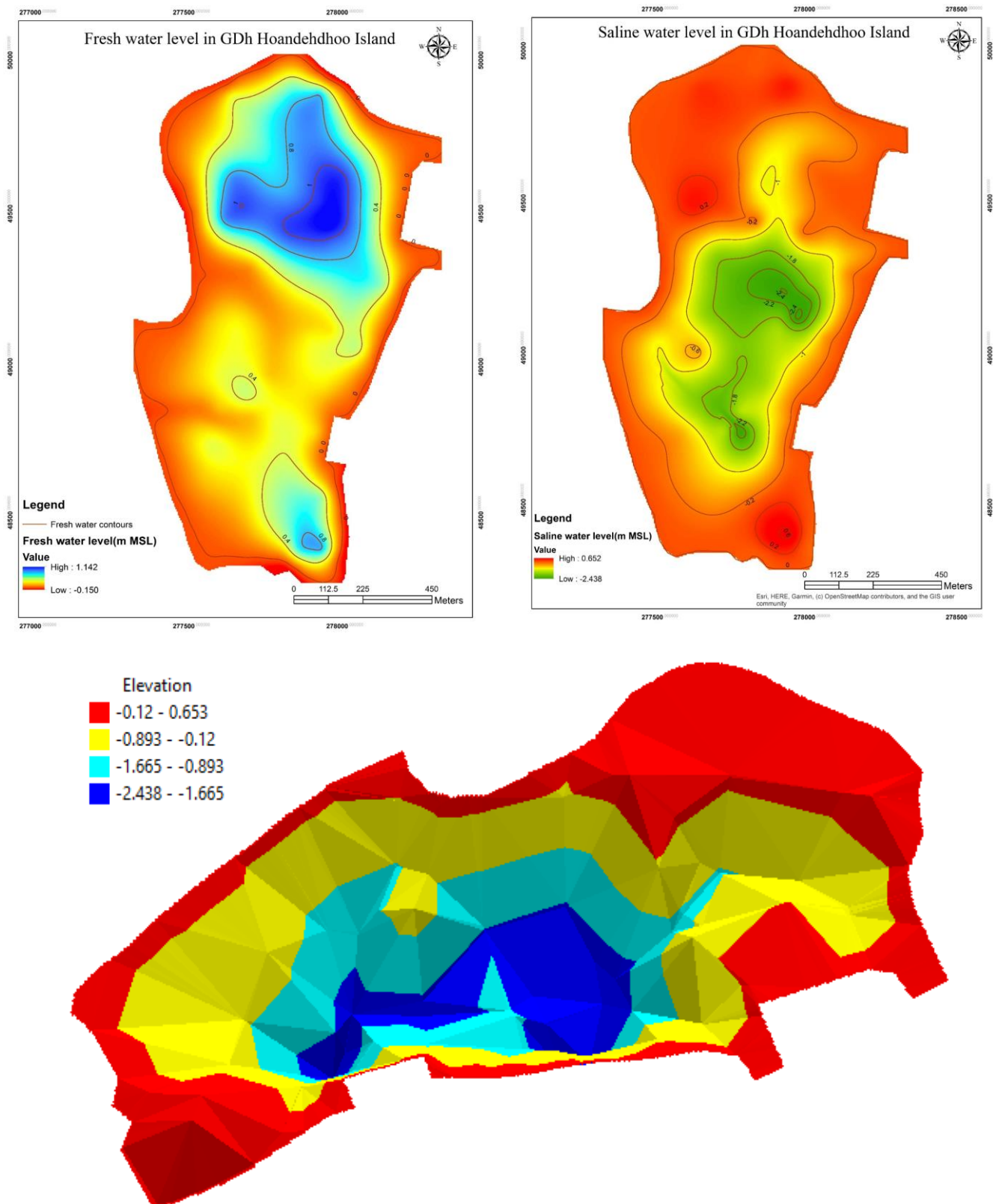


Figure 124: Contours of Freshwater lens upper level – GDh. Hoandehdhoo island

7.9.4 Freshwater lens storage volume and stress level

For the estimation of freshwater volume, the depth difference between freshwater-saline water interface and freshwater upper level was computed at each ER measurement points and they were then used to determine freshwater volume stored in the ground at time of taking ER measurements. Both “Triangle method” and Tools in ArcGIS software were used to perform this computation. Figure 125 shows triangles considered for the aforementioned computation. Detailed calculations can be found in Annex X: Freshwater Lens volume calculations

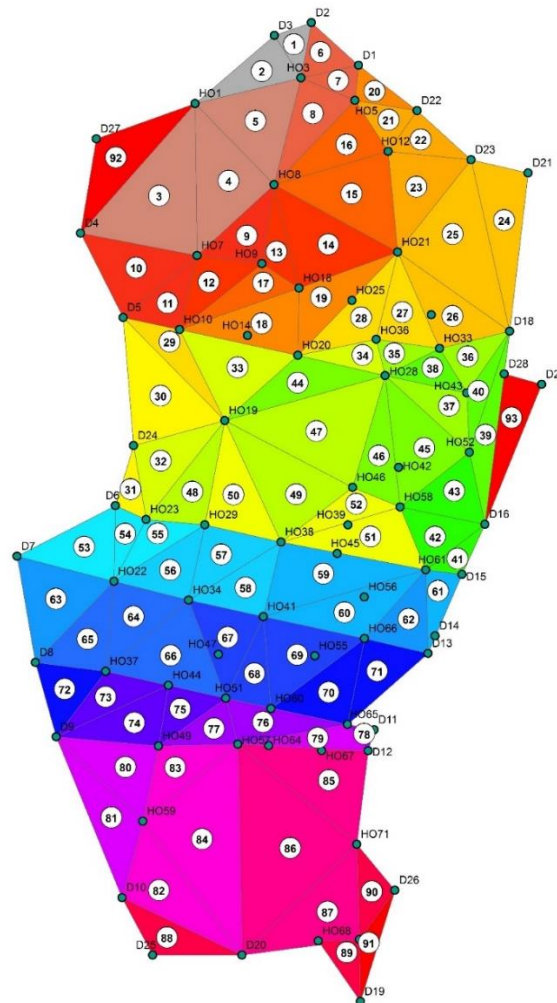


Figure 125: Triangles for freshwater volume computation – GDh. Hoandehdhoo island

Stress level on freshwater aquifer of GDh. Hoandehdhoo island was determined by computing ratio between freshwater lens volume and annual groundwater abstraction for non-potable water usage at present. When this ratio was more than 1.5, the island was treated as “not stressed” and if it was between 1.5 and 1 the aquifer was assumed to be “stressed” and any other lower ratio was taken as “highly stressed” aquifer. This criterion was developed based on saline water issues collected from the project islands during field work. The computed freshwater volume, water abstraction and aquifer stress level are given in Table 112.

Table 112: Freshwater lens volume and aquifer stress level – GDh. Hoandehdhoo island

Item	Value	Unit
Freshwater lens volume - Triangle method	183,811	m ³
Freshwater lens volume - ArcGIS	195,722	m ³
Groundwater abstraction	133,148	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	1.38	-
Aquifer stress level	Slightly Stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 11.7m. This deviates by 146% from the maximum measured value of 2.8m, which is more reliable as it results from a more comprehensive, site-specific methodology.

7.10 SWB Modelling

7.10.1 Topography for flow direction

Topographical data assigned to model grids for computation of D8 flow directions is shown in Figure 126 and according to this figure elevation of the island is changing from -0.538 mAMSL to 2.911 mAMSL and average elevation is 1.348 mAMSL.

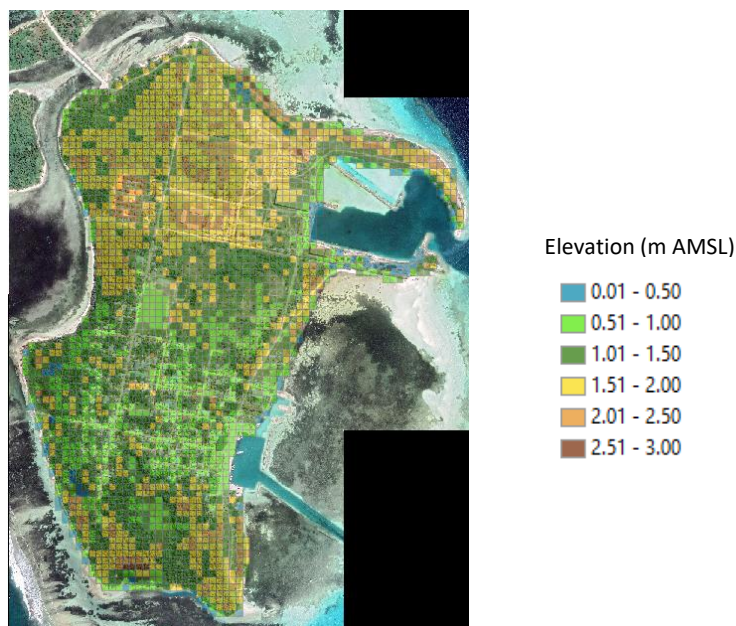


Figure 126: Elevation data assigned for SWB modelling - GDh. Hoandehdhoo Island

7.10.2 Land use categorization and area estimation

Land use map prepared for SWB modelling of GDh. Hoandehdhoo island is shown in together with table a showing land classification and their respective areas. It could be noted from the Figure 127 that 20m x 20m grids are adequate to represent the island land use for SWB modelling purpose.

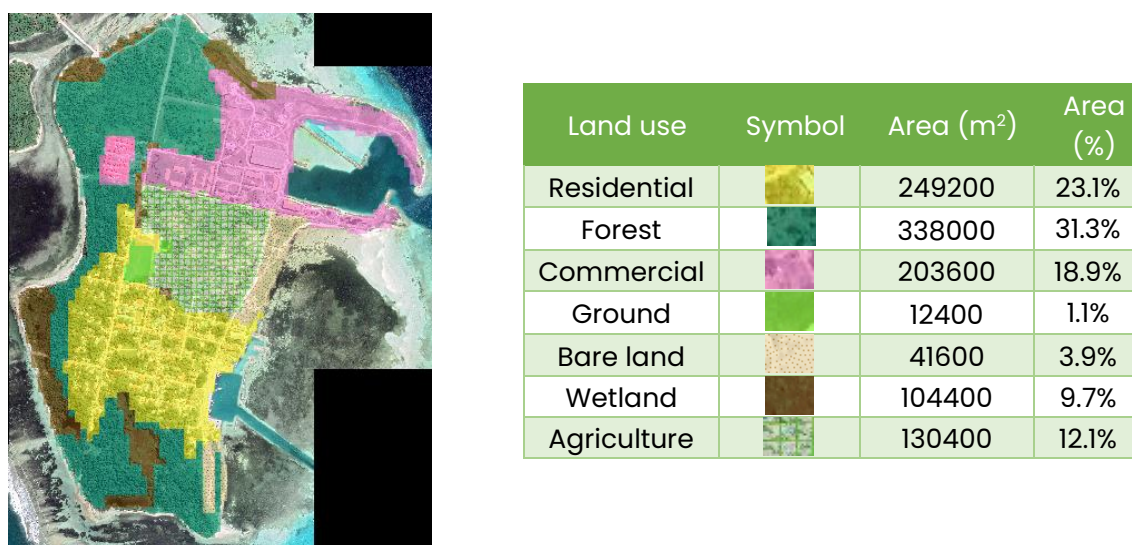


Figure 127: Land use for SWB model - GDh. Hoandehdhoo Island

7.10.3 Recharge estimation and distribution

Monthly recharge values estimated at grid cells of the SWB model were extracted and used to identify its variation over years and months (refer Figure 128 and Table 85). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 173.4, 366.5 and 529.7 respectively over a 20-year period.
- There is a good relationship between annual rainfall and annual recharge, it is not linear but inverse exponential.
- Annual average rainfall is around 2270 mm but for 5 consecutive years (from 2008 to 2012) annual rainfall was below average. It indicates that there would be a serious issue of saline water intrusion into the freshwater lens during dry periods as the recharge value would be considerably lower than annual average recharge value (inverse exponential relationship)
- Variation among the monthly average recharge value is very high. It is lowest on month of March and highest in November
- Water consumption (pumping) for non-potable use on 1-2 month period is less than the recharge value on the respective months. It indicates that GDh. Hoandehdhoo island does not heavily depend on the groundwater storage and hence, saline water intrusion into this island would be restricted to only one or two months.

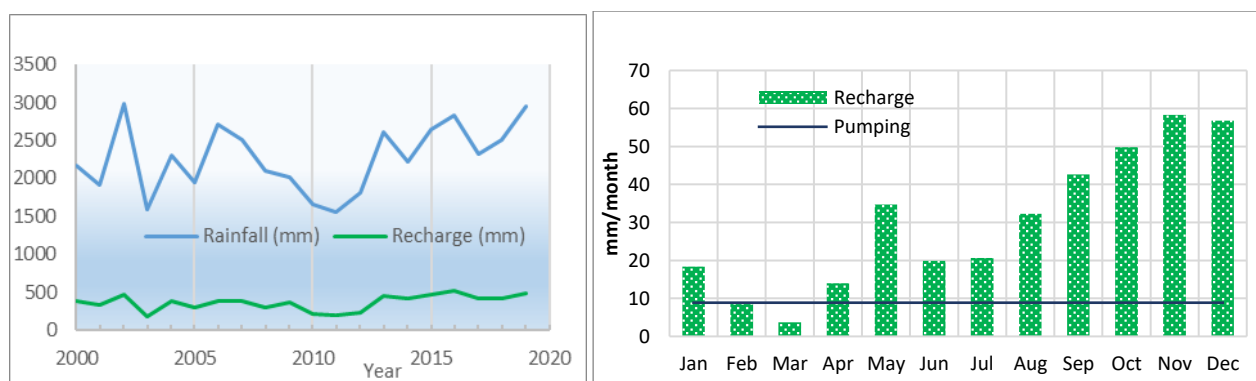


Figure 128: Monthly and annual recharge distribution – GDh. Hoandehdhoo island

Table 113: Monthly recharge estimated by SWB model – GDh. Hoandehdhoo Island

Year	Monthly Recharge (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	4.8	0.0	0.1	7.8	10.9	48.1	27.4	31.3	115.9	34.3	71.1	36.3
2001	0.0	0.0	0.0	33.5	8.8	0.0	11.4	47.0	69.7	55.7	68.7	42.0
2002	6.0	17.0	13.8	21.5	37.2	64.9	31.3	12.1	33.3	85.2	62.6	93.6
2003	2.5	0.0	0.0	7.7	33.1	27.6	27.8	15.9	0.1	8.8	33.3	16.7
2004	35.9	0.0	0.0	12.4	0.5	0.4	26.4	39.5	56.2	57.4	98.1	55.1
2005	28.9	11.8	0.0	0.1	35.3	47.7	36.3	20.4	17.5	99.4	3.2	0.0
2006	38.6	49.7	0.0	4.2	0.1	5.6	9.9	9.6	44.9	8.4	134.2	76.4
2007	58.5	0.0	0.0	3.1	16.5	36.6	26.7	4.5	32.3	92.5	10.1	112.0
2008	28.4	0.0	0.0	27.9	23.4	15.9	27.1	6.3	0.0	53.1	65.4	48.2
2009	33.9	19.4	0.0	0.1	51.6	0.0	5.9	87.4	23.0	43.6	51.7	51.2
2010	11.3	0.0	0.0	29.9	14.7	0.1	39.5	57.6	40.8	15.6	0.3	0.0
2011	0.0	0.0	0.0	5.8	22.6	0.0	0.0	8.9	0.0	57.1	16.0	85.7
2012	0.0	15.1	0.1	0.0	22.7	7.9	15.5	13.0	13.6	90.1	31.1	15.1
2013	0.0	0.1	10.5	16.2	69.8	10.5	28.0	43.5	12.1	27.6	123.5	115.2
2014	0.0	0.0	8.9	14.2	106.4	0.0	5.8	17.9	129.6	30.1	68.0	40.7
2015	9.0	12.0	0.0	0.0	23.4	22.2	11.6	97.6	29.1	77.4	92.1	100.2
2016	57.4	4.3	22.3	47.1	56.9	6.2	24.7	112.9	21.6	52.7	71.9	51.9
2017	2.3	0.0	13.7	0.0	87.8	0.0	28.1	23.0	83.7	0.0	57.6	122.6
2018	0.0	5.7	0.3	34.6	50.3	48.8	30.3	0.0	57.9	95.7	51.2	37.3
2019	62.3	25.4	7.5	14.3	45.6	55.9	13.3	18.5	72.1	45.1	56.1	72.9

7.10.4 Water Balance

As per estimation, annual recharge estimated by the SWB model is 377,159 m³ and it is 15.4% of annual average rainfall (refer

Figure 129).

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	2,449,815	13,569	9,037	1,237,558	377,159	794,232	133,148
%	100.0%	0.6%	0.4%	50.5%	15.4%	32.4%	5.44%

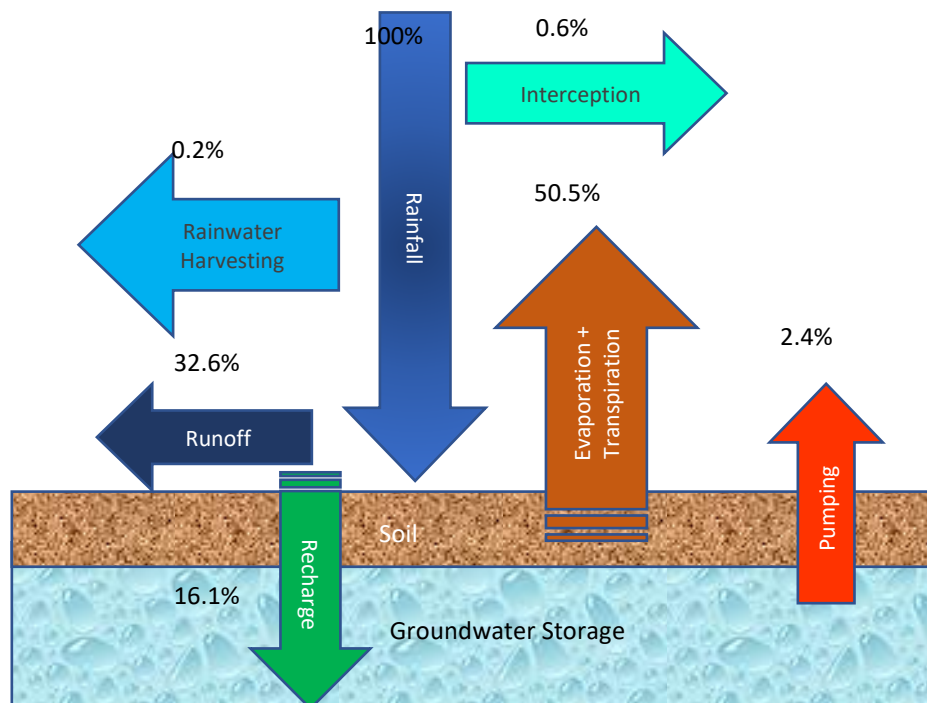


Figure 129: Annual water balance - GDh. Hoandehdhoo Island

7.10.5 Deficit estimation, dry month identification and safe yield

Deficit calculation was carried out to identify whether recharge over a month period is smaller than or larger than the pumping quantity in the island. Monthly recharge time series estimated by the SWB model was compared with total pumping quantity of the island (11,096 m³/month) and if recharge exceeds the pumping quantity it was taken as “no deficit” and on other hand if pumping quantity exceeds the recharging value it was taken as “deficit”.

Table 114: Deficit percentage - GDh. Hoandehdhoo

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	77	32.1%

It is to be noted that “deficit” doesn’t mean failure or inadequate freshwater for pumping, but it is to be interpreted that the number of months when pumping is to be supported by groundwater storage in addition to recharging quantity. As per estimation, pumping at GDh. Hoandehdhoo island has a 32.1% dependency on the groundwater storage.

Determining safe yield which is defined as the attainment and maintenance of a long-term balance between the annual amount of groundwater withdrawn by pumping and the annual amount of recharge is important for small islands and there are various methods to estimate this amount. One simple method is checking whether ground water abstraction is less than or equal to 10% of average annual rainfall (MoEnv. 2020). The comparison of the estimated ground water withdrawal (133,148 m³/yr) with safe abstraction volume (137,160 m³/yr) shows that present withdrawal is -2.93 % lesser than the safe yield.

7.11 SUTRA Modelling

7.11.1 Model representation and topographical features

SUTRA modelling requires model domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island (refer Figure 130). The other boundary defined in the model was island outline which can be taken as the shoreline for most of the cases except at harbour area and the inner part of the island which was subdivided into several polygons representing different land use areas and it was accomplished by importing GIS shape files of island land use and then drawing polygons on the shape files. Some other boundaries were also defined to represent island features such as lake and elevation change in the middle of the reef. Mesh with irregular quadrilateral elements were produced for all closed boundaries. Mesh size defined for outer boundaries (area between shoreline and model domain) were 3 to 4 times larger than the size defined for the inner part of the island. Elevation at shoreline was defined as zero whereas elevations for inner part of the island was assigned from topographical data used for SWB modelling. Figure 130 shows model domain and SUTRA model mesh with topographical changes.

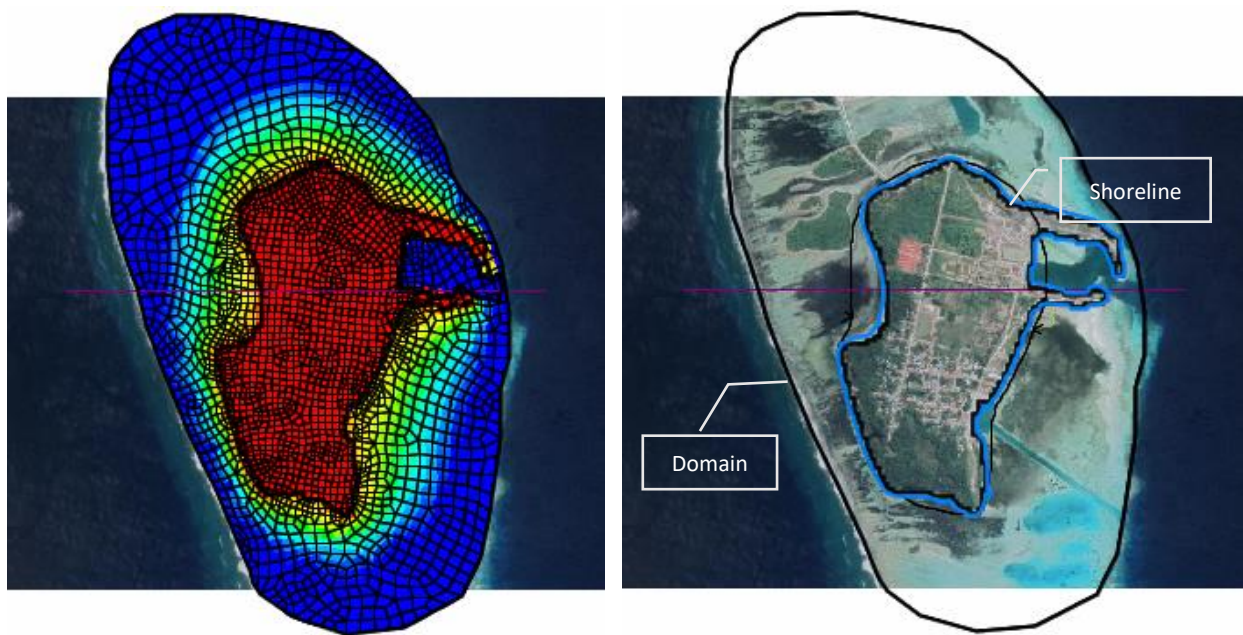


Figure 130: Model boundaries and model mesh – GDh. Hoandehdhoo island

7.11.2 Pressure boundaries

Specified pressure boundary was defined along the model domain so that it would cause saline water intruding into the island when pressure along the outer boundary of freshwater lens is less due to lower recharge and/or groundwater abstraction is high. Figure 131 shows the pressure boundary defined for GDh. Hoandehdhoo island.

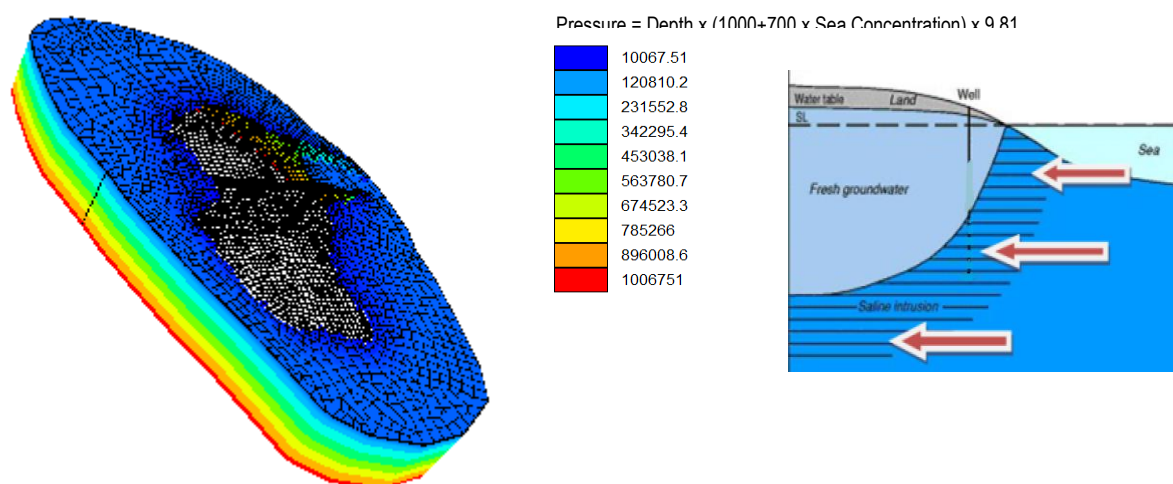


Figure 131: Pressure boundary at SUTRA model - GDh. Hoandehdhoo island

7.11.3 Assigning recharge on land use basis

Recharge rates estimated by the SWB model for each grid cells were lumped on land use basis using VB program and ArcGIS tool and they were then used to estimate the monthly average recharge rate on residential area, commercial area, and other land use areas. Table 115 shows monthly recharge rate estimate for GDh. Hoandehdhoo island.

Table 115: Recharge for SUTRA model - GDh. Hoandehdhoo island

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	35.3	5.9	6.9	27.0	32.4	6.9	27.8

7.11.4 Groundwater abstraction

Groundwater pumping takes place at individual houses, restaurants, and institutes. Since all well locations are not available and abstraction rate would also change place to place a simplified approach was adopted by defining a polygon around the residential area (area highlighted in blue in the below map) and assigning average pumping rate of 9,574 m³/month.



Figure 132: Pumping region at SUTRA model - GDh. Hoandehdhoo island

7.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20-year period is shown in Figure 133. The orange-coloured component in the 3D view represents sea water concentration around the island and the section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0375 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top and at the central portion where there is relatively low abstraction of ground water due to absence of low existence of residential building.

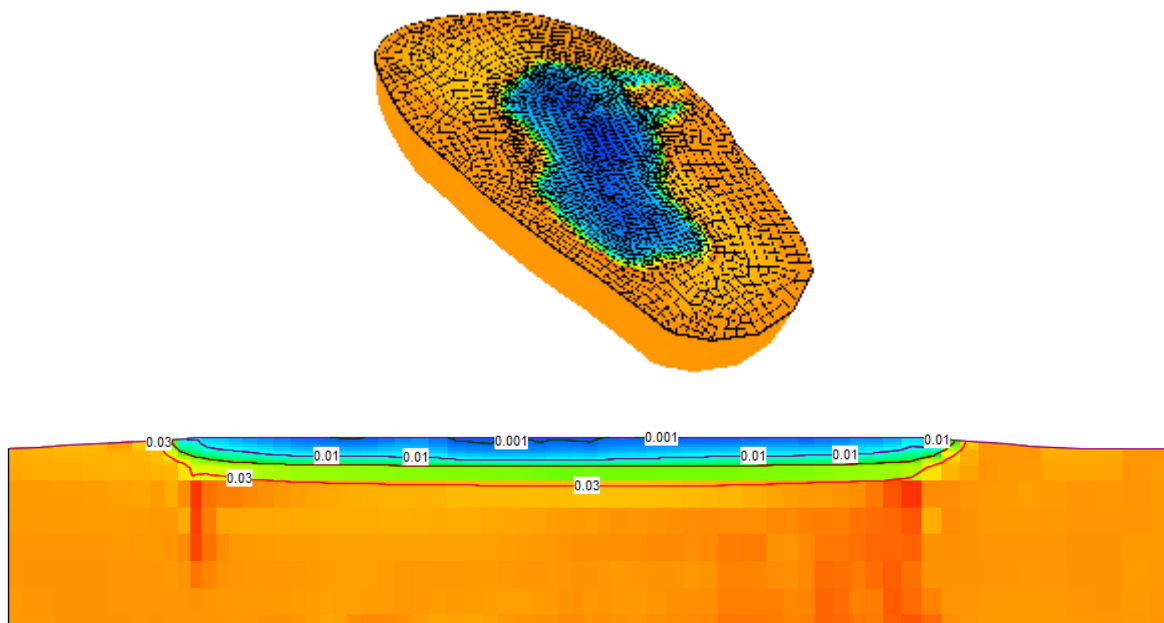


Figure 133: Saltwater distribution - GDh. Hoandehdhoo island

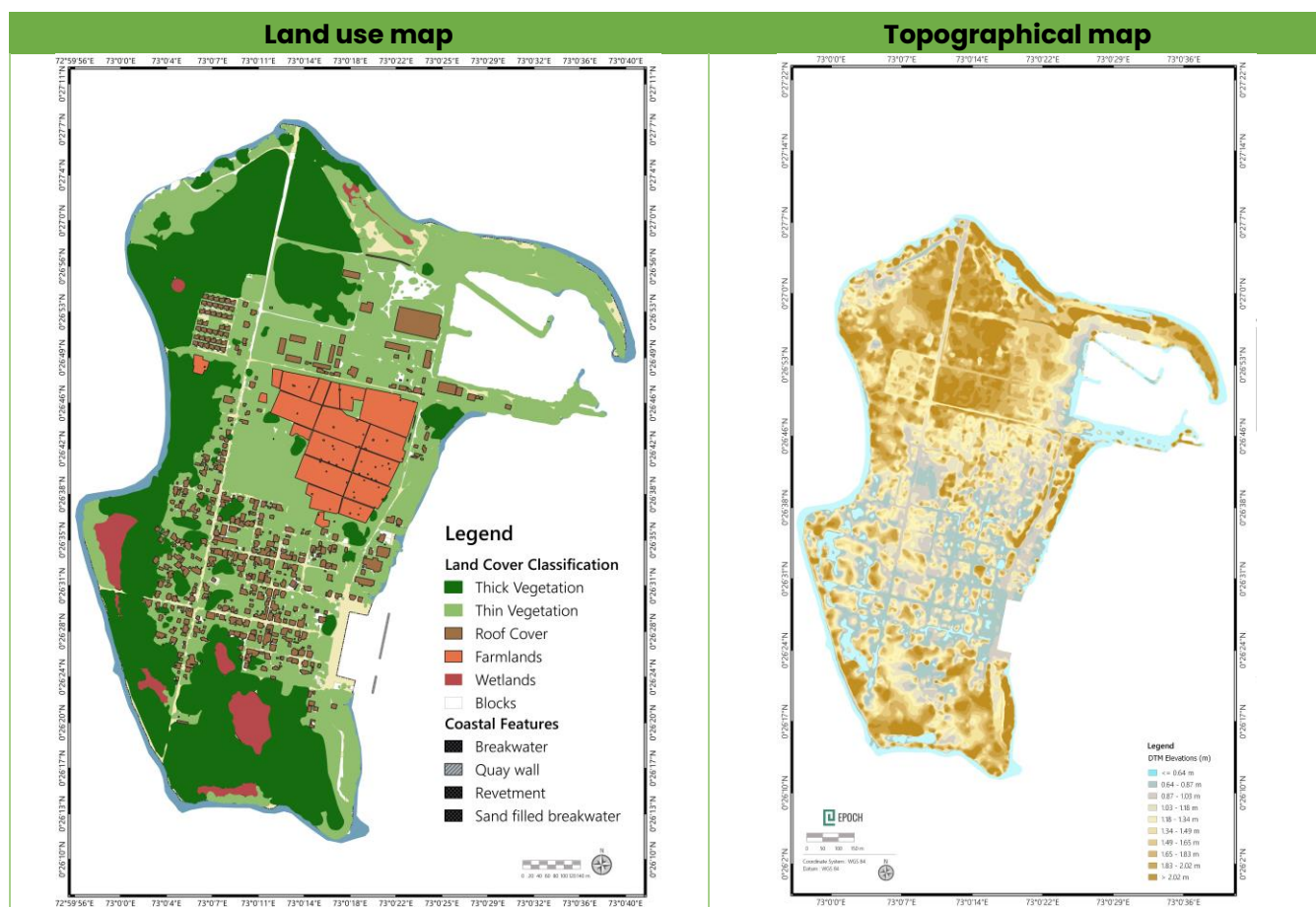
7.12 Summary of Baseline Assessment

Summary of findings extracted from field works, laboratory test, modelling and analysis are presented below.

- General overview, demography, and climatology

Item	Details
Atoll	Huvadhoo Atholhu Uthuruburi Atoll
Length	1.65 km
Width	1.12 km
Area	106.4 ha
Population	1,317
Population/area	12.38 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use



Average elevation = 1.13 m above MSL Shoreline length = 7798m	% of total area	
	Roof cover	7%
	Vegetation (Thick)	34%
	Vegetation (Thin)	38%
	Bare Lands	9%
	Farmlands	8%
	Wetlands	3%

- Water consumption

Category	Domestic	Commercial	Institutional	Industrial	Total
Rate (m ³ /d)	315	1.85	3.17	45.0	365

- Water quality parameters – Physiochemical

Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	775 ± 252	1500
Turbidity (FNU)	2.30 ± 4.53	5
DO (mg/L)	3.72 ± 1.99	
pH	7.32 ± 0.35	6.5-8.5
Temp (°C)	28.79 ± 1.33	
Sal (ppt)	0.35 ± 0.12	
NH ₃ (mg/L)	2.49 ± 3.68	1.5 (Odour Threshold)
NO ₃ ⁻ (mg/L)	7.39 ± 7.96	50
PO ₄ ³⁻ (mg/L)	0.36 ± 0.31	

- Water quality parameters – Microbiological

Number of samples tested = 15

Parameter	Value range	Average value	Remarks (<i>on permit limit</i>)
Total Coliform (MPN/100ml)	22 - >2420	672.87	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not detected - 22	2.27	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	30.22	m ² /day
Storativity	1	0.2191	-
Permeability	7	1.13 – 11.59 Average – 4.66	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m ²)	Inundation depth (m)
28	27000	0.207

- Electric Resistivity survey

- Measurement taken at 50 locations and number of transect is 7.
- Average freshwater thickness in the island is 1.33 m.
- Freshwater lens volume and aquifer stress level

Item	Value	Unit
Freshwater lens volume - Triangle method	183,811	m ³
Freshwater lens volume - ArcGIS	195,722	m ³
Groundwater abstraction	133,148	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	1.38	-
Aquifer stress level	Slightly Stressed	-

- SWB modelling

- Annual recharge is 395,419 m³ and it is 16.1% of annual rainfall (2270 mm)
- Annual water balance

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	2,449,815	13,569	9,037	1,237,558	377,159	794,232	133,148
%	100.0%	0.6%	0.4%	50.5%	15.4%	32.4%	5.44%

- Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 32.10% in an average year, and it is compensated by ground water storage.
- Ground water withdrawal (133,148 m³/yr) is -2.93% lesser than the safe abstraction (137,160m³/yr).

- SUTRA modelling
 - Average monthly recharge assigned to SUTRA model

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	35.3	5.9	6.9	27.0	32.4	6.9	27.8

- Freshwater lens prediction (allowable concentration for potable use is 0.001)

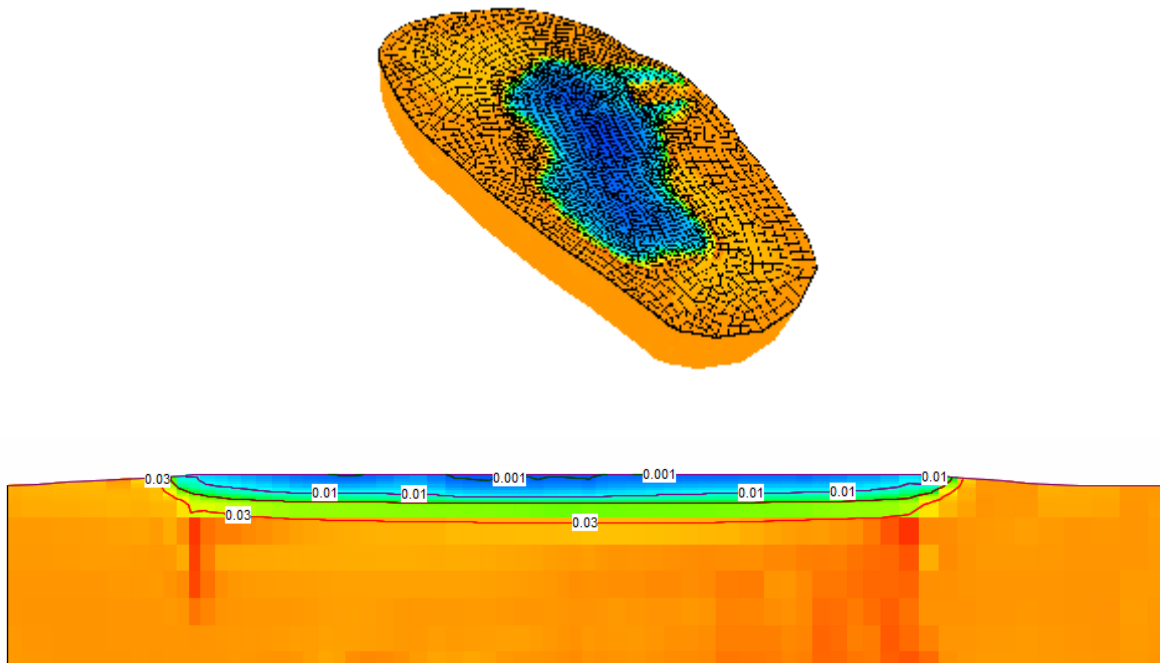


Figure 134: Saltwater distribution - GDh. Hoandehdhoo island

8 GDh. Nadella

8.1 Island Overview and Location

The Island of GDh. Nadella, belonging to Huvadhoo Atholhu Dhekunuburi Atoll, is in the Southern region of Maldives at 0°17'37"N and 73°02'27"E. It is approximately 434 km South of the capital Male'.

Table 116: Island Geographical Data

Island	GDh. Nadella
Atoll	Huvadhoo Atholhu Dhekunuburi Atoll
Location	0°17'37"N and 73°02'27"E

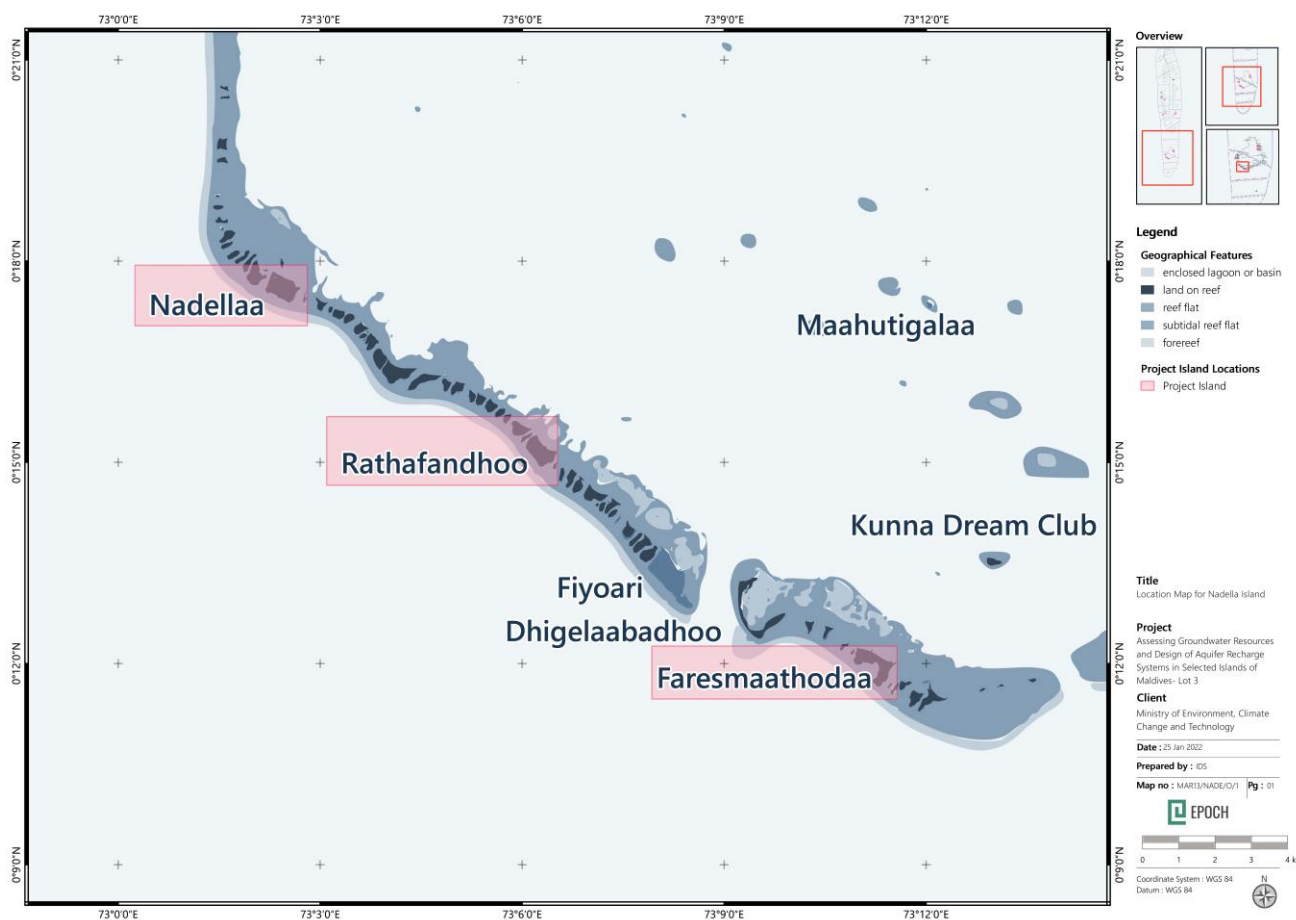


Figure 135: Location map - GDh. Nadella

8.1.1 Island features

GDh. Nadella is found in a huge reef that contains over 85 islands. The island is approximately 0.88 km long and 0.56 km wide, giving it a total area of about 43.7 hectares. The island has a harbour at its east side of the island. About two-third of the island surface is vegetation. Thick vegetation is mostly located in North western and outer edges of south west part of the island. The island has one wetland on the northern side of the island. This indicates that the island has a general slope northward. Only about one-third of the island is populated, which is mostly the Southern part of the island.

Table 117: Area Distribution in GDh. Nadella

Area	43.7ha	
Length	0.88 km	
Width	0.56 km	
	Area (m²)	% of total area
Roof cover	35,852	8%
Vegetation (Thick)	96,568	22%
Vegetation (Thin)	146,463	33%
Bare Lands	149,361	34%
Farmlands	-	0%
Wetlands	9,065	2%
Total	437,308	100%



Figure 136: Land Use Characterization – GDh. Nadella

8.2 Topographical Features

Permanent Survey Marks PSM 0327 and PSM 0325 were used as benchmarks for GDh. Nadella topographical survey and drone survey. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 1930 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.22 cm per pixel. 11 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	0.00323	-0.000297	-0.00274
Sigma [m]	0.016	0.0347	0.0195
RMS Error [m]	0.0276	0.0347	0.0197

The Digital Surface Model in Annex III: indicates that the Southwestern region of the island (Average Elevation 1.7 m) due the existence of a ridge is higher than the north Eastern region (Average elevation of 0.6 m). This trend is particularly visible along the ring road that goes around the western part of the island. The Harbour is notably higher than nearby island regions especially where the council office is located. There is a noticeably lower region to the southwest region near the Health Centre. The lowest regions of GDh. Nadella are found near the wetland including the ring road and football field area and the northern area where elevations are generally 0.6 m or less.

Roof elevations generally do not exceed 5-7 m and very few houses have multi-storey buildings in GDh. Nadella. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Thick vegetation with heights greater than 10 m are primarily seen on the windward periphery of the island. It is also noteworthy that despite the Northern region having dense thick and thin vegetation near the wetland, the elevations are generally lower than 10m.

The Digital terrain model was produced at a resolution of 0.1 m spatial resolution for the purposes of analysis. The figure below the plot of GPS spot heights vs Sampled DTM elevations for the island of GDh. Nadella. The DTM slightly overestimates the elevations with a mean of 3.46 cm

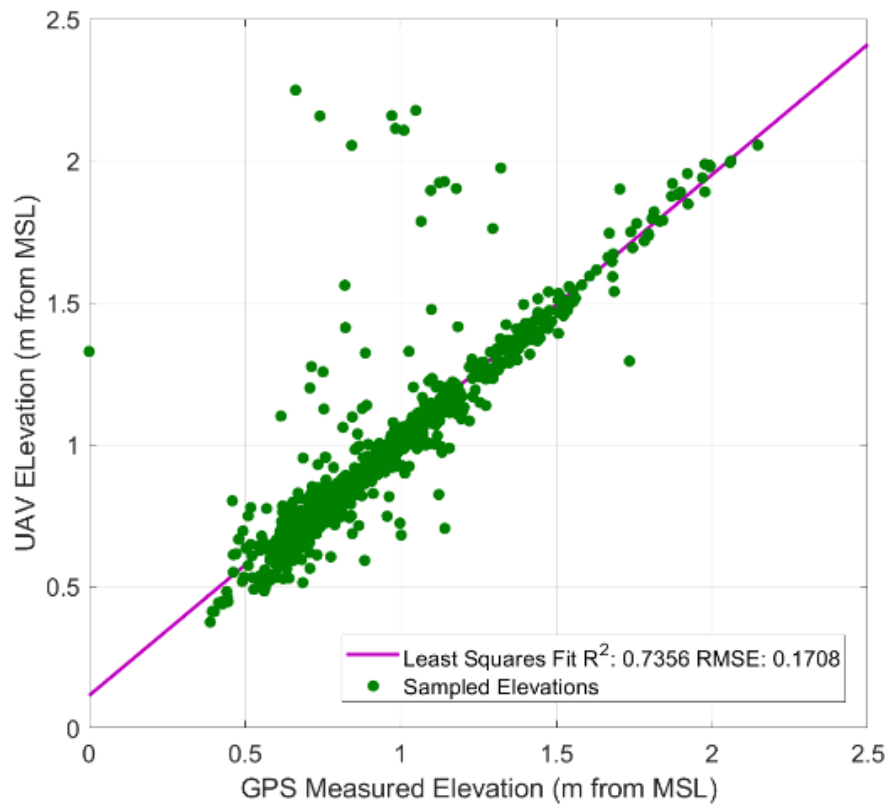


Figure 137 Linear Regression Plot for GDh. Nadella Sample UAV elevations

Table 118: Error Statistics for GDh. Nadella DTM

Parameter	Value (cm)
Mean	3.46
Standard Error	0.57
Median	1.50
Mode	3.50
Standard Deviation	16.61
Sample Variance	275.85
Kurtosis	47.26
Skewness	5.85
Range	240.20
Minimum	-44.10
Maximum	196.10
Sum	2977.20
Count	860.00

8.2.1 Level changes

GDh. Nadella has an average elevation of 1.132 m with a standard deviation of 0.628. Digital Terrain Model elevations range from -0.6 to 2.9 m from MSL. The distribution of elevations has a symmetrical distribution with 1.1 m being the highest frequency for elevations. A second peak is observed near -0.2 m from MSL. This is mainly due to the north-eastern tip where there is fanned out sediment that is exposed during low tide.

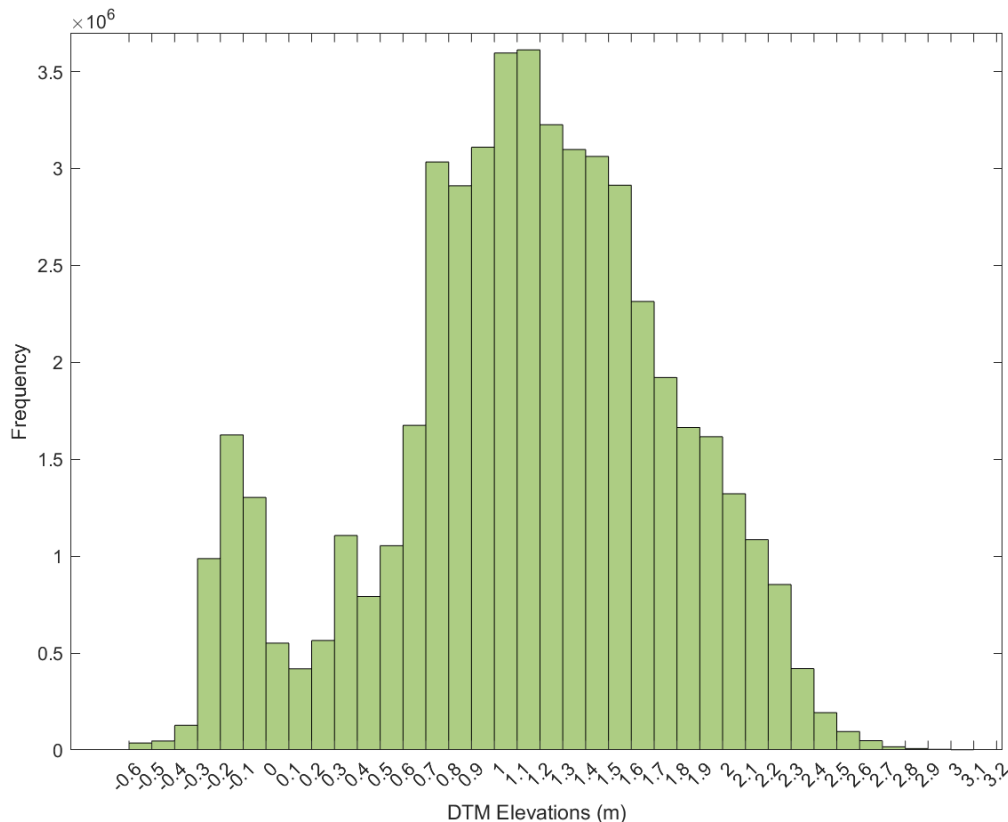


Figure 138 Histogram of Elevations in GDh. Nadella

The image below is an analysis done using Golden Software Surfer checking individual profiles of major roads on GDh. Nadella. Profile 1 shows the profile from the leeward to windward side of the island where the elevations rise from around 0.75 m to 1.6 m. The ring road with a slightly lower elevation than the ride is also captured within this profile at 625 m. Profile 2 alternatively begins from the football field region and therefore the lower ring road is included. The football field region is particularly low and gradually rises to a height of 2.25 m at the windward ridge. The end of profile 2 is a very steep beach ridge with large gravel like sediments.

Profile 3 begins from the harbour and continues the main road to the elevated ridge. At 50 m the lower elevations of the island compared to the harbour can be seen clearly. Before the 1.5 m extended

ridge begins at around 575 m, the island has an average constant elevation of 1m. For this profile the ring road is not that clearly visible as it remains high along this ridge.

Profile 4 exemplifies the profile changes seen on the ring road from the leeward to windward side. An initial vegetated ridge next to the tidal pass region at 125 m is followed by low elevations of 0.75 m before gradually increasing to 1.5 m. The ridge in this profile is steep with elevations above 2m from MSL.

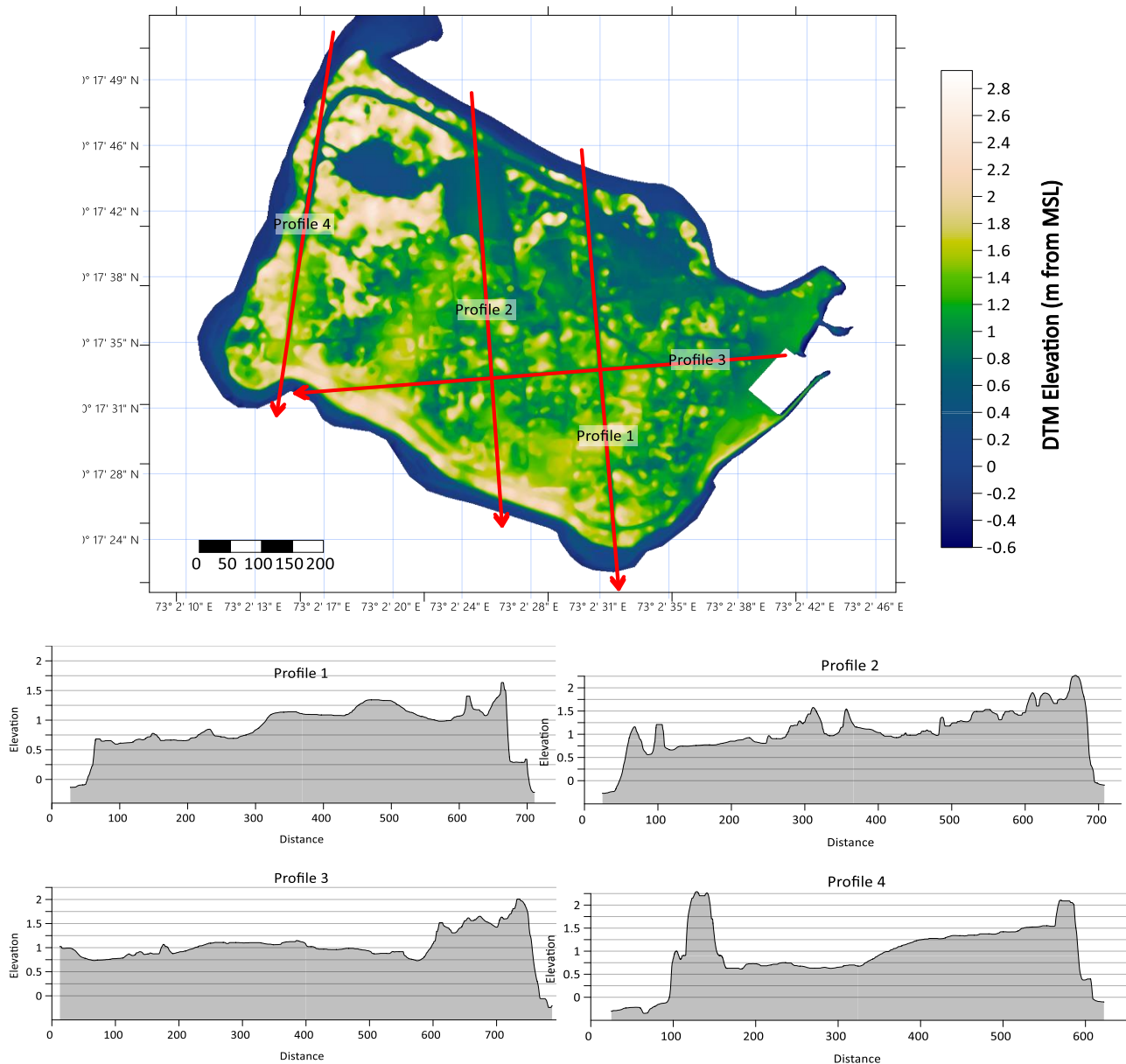


Figure 139 Digital Terrain Model Elevations and Profiles for GDh. Nadella Island

8.2.2 Shoreline

GDh. Nadella shoreline is 3369 m long with gravel like sediment lining the entire windward edge of the island. On the leeward side washed over sediment lie in extended regions and are generally exposed during low tide.



Figure 140 Orthomosaic preview of Nadella with windward region with large gravel sized sediment (orange) and fanned out sediment that are exposed during low tide (yellow)

8.2.3 Reef

GDh. Nadella is found on the same reef as GDh. Hoandehdhoo and GDh. Rathafandhoo along with dozens of uninhabited islands strewn across this reef.



Figure 141 Sentinel 2 imagery taken of GDh. Nadella Reef in January 2022

8.3 Socio Economic Status

8.3.1 Demography

The Island has a registered population of 738 as per the 2014 census, with a total of 375 males and 363 females. The island population density is 25.88 people per hectare as per the 2021 figures. The population figures have drastically increased over the past years where the total registered local population climbed up to 1,131. The following table and graph illustrate the demographic breakdown of GDh. Nadella.

GDH.Nadella

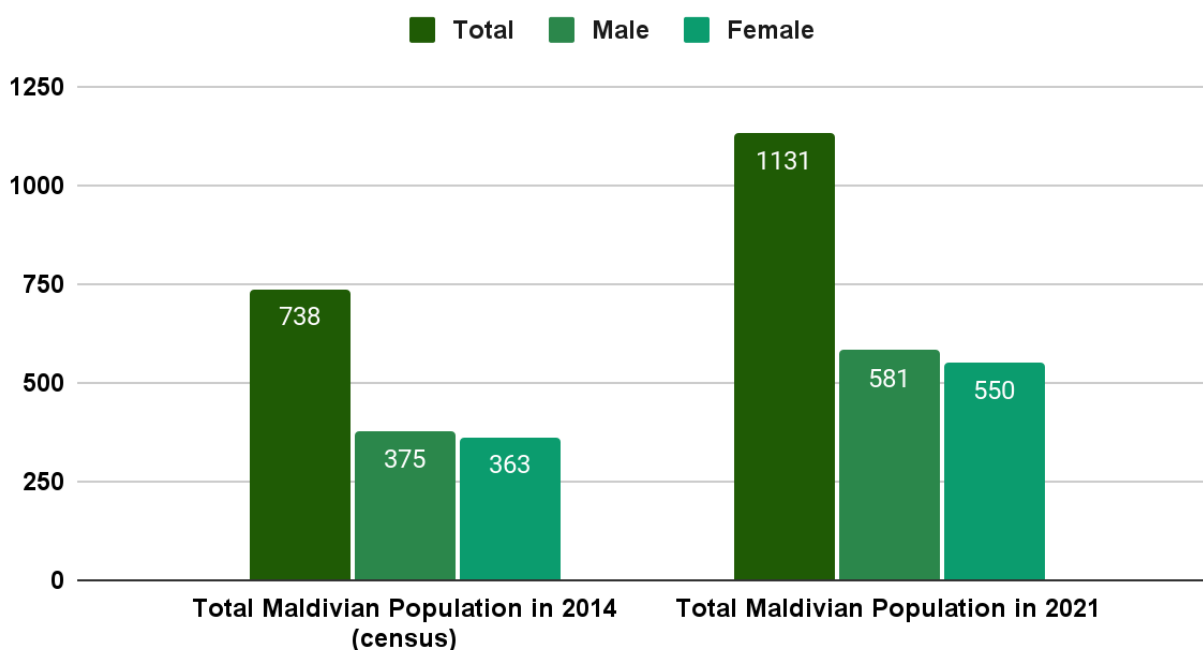


Figure 142: GDh. Nadella Population

Table 119: GDh. Nadella Population (Census, 2014)

Resident Population according to Census 2014										
Atoll	Locality	Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
GDh	Nadella	776	401	375	738	375	363	38	26	12

8.3.2 Socio-Economic Activities

GDh. Nadella is an inhabited island in Gaafu Dhaalu Atoll's administrative unit and physically part of Huvadhoo Atholhu Dhekunuburi Atoll in the Maldives'. This island is well-known for its sea cucumber fishery activities. The island also has 1 cafe/restaurant and 7 shops.

8.3.3 Facilities available

8.3.3.1 Health Care

GDh. Nadella Health Center currently has one doctor, 2 nurses and 4 beds. The health facilities in the island are bare minimum and many island residents find that the health center needs to be upgraded and service hours need to be extended.

8.3.3.2 Education

GDh. Nadella school has 168 students, 27 teachers and 11 administrative staff. The island school offers education upto grade 10 standard.

8.3.3.3 Utilities

Electricity on the island is provided by state owned utility company FENAKA. The island currently does not have a sewerage and sanitation system.

8.3.3.4 Transportation

The island has a harbour which was developed in 2007. The transportation between GDh. Nadella island and other islands is by sea.

8.3.4 Water resources, water usage and water consumption

In GDh. Nadella there are a total of 152 households. 112 out of 152 households were surveyed, while maintaining a 95% confidence interval and geo-coordinated sampling points. A map of households surveyed is attached in Annex V.

Table 120: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	112/152households = 74%
Percentage of well fitted with pumps	94%
Ground water	Usage in percentage
Source of drinking	0%
Source of cooking	2%

8.3.4.1 Existing water and sanitation

The main form of sanitation is via the use of septic tanks. Each household has one or two septic tanks, and the septic tanks are cleaned periodically by disposing the septic waste into the sea. According to the Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22), annex 4 states that the households should keep a 15 meters (49.2126 ft) distance between septic tank and nearest well. The main reason for this standard is to negate any possible causes of contamination in the groundwater. This being the recommended standard, majority of the surveyed households were reported with less than 49 feet distance between septic tank and water well. In GDh. Nadella 88 percent reported to have less than 49ft distance between septic tanks and water well while, 10% reported to have more than 49 feet distance.

Rainwater is primarily used for cooking. Many homes use rainwater from neighbouring houses or bottled water when rainwater is not readily available during the dry season. Rainwater collected from rooftops is stored mostly in water tanks, whether at home or communal rainwater tanks. In GDh. Nadella, 4 houses have connected rainwater to the well and have reported improvement in groundwater. On the same note, 94% of the households have rainwater drained to the ground.

8.3.4.2 Water usage and resources

Based on the survey conducted in GDh. Nadella, 101 houses have HDPE rainwater tanks for rainwater storage. 96% of the households use rainwater for cooking and 76% use rainwater for drinking. While groundwater is mainly used for gardening, household cleaning with all the houses fitted with water pumps. The following sections regard further details about various groundwater usage and consumption scenarios in the island.

8.3.4.3 Domestic water usage

Based on household water usage surveys in GDh. Nadella, **304,239** Liters of groundwater is used daily in the households. A total of **269** Liters of groundwater are consumed per capita per day. In GDh. Nadella, 72% of the surveyed households shower more than 3 times daily and take 15 minutes to shower on an average. This is a factor for high groundwater usage.

Table 121: Domestic groundwater use data for GDh. Nadella

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
171.78	27.91	16.16	30.79	3.31	13.26	5.78	269

*All units are in Liters per capita per day

8.3.4.4 Commercial water usage

Based on the survey conducted in GDh. Nadella, there is currently one operational café on this island. A total of **46** Liters of groundwater are used by the commercial sector.

Table 122: Commercial groundwater use data for GDh. Nadella

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Full Night Cafe	7.5	33.3	-	5	46
					46

*All units are in Liters per day

8.3.4.5 Institutional water usage

Based on the survey conducted in GDh. Nadella there are currently five institutions that have groundwater well facilities and that use groundwater. A total of **3,999** Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 123: Institutional groundwater use data for GDh. Nadella

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Health Center	109.6	360	–	94.6	564
GDh. Nadella School	1236	365	5	–	1,606
Powerhouse	218	720	–	–	938
Council	218	540	1.4	–	760
GDh. Nadella Court	60.6	60	10	–	131
					3,999

*All units are in Liters per day

8.3.5 Present & Future water demand

In GDh. Nadella the present water demand is at **308,284** Liters per day and it is expected to decrease groundwater usage with the establishment of water supply services in the island. The year 2021 figures are as per the latest island council data. For the figures in year 2036 and 2054, it is as per Maldives Populations Projections Report published by the National Bureau of Statistics.

Population Projection - GDH.Nadella

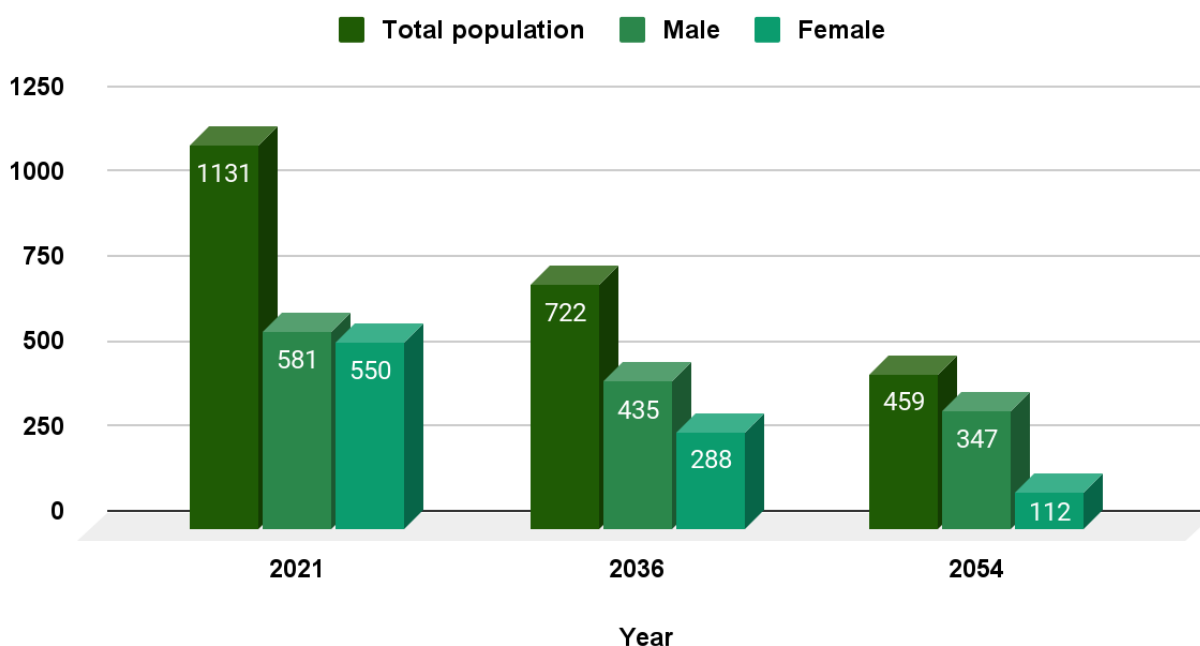


Figure 143: Population Projection – GDh. Nadella

Table 124: Present groundwater demand – GDh. Nadella

Year	Total Population	Domestic water demand	Commercial water demand	Institutional water demand	Groundwater usage
2021	1,131	304,239	46	3,999	308,284

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 269 Liters per day. For the year 2036, water supply usage is expected to be 50 Liters per capita per day. After deducting 50 Liters from 269 Liters, the groundwater demand is expected to be 219 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 722 is expected to be **158,118** Liters per day.

For the year 2054, water supply usage is expected to be 75 Liters per capita per day. After deducting 75 Liters from 269 Liters, the groundwater demand is expected to be 194 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 459 is expected to be **89,046** Liters per day.

Table 125: Future domestic water demand – GDh. Nadella

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	722	269	50	219	158,118
2054	459	269	75	194	89,046

8.3.6 Water related issues

From 112 households surveyed in GDh. Nadella, most houses reported smell (35%) and milky texture (23%) in their respective wells. As per the social survey, saline intrusion has been observed after the Tsunami. The households also report foul taste and color changes in groundwater. Only 14% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gases such as Hydrogen Sulfide which causes unpleasant smells.

Table 126: Signs of contamination reported by households

Types of contamination	Data in % out of 96 households surveyed
Smell	35%
Milky	23%
Foul taste	6%
Salty	6%
Color change	2%
None	53%

The following table details out the changes in groundwater quality reported by the households during tidal or seasonal changes.

Table 127: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 96 households surveyed
Changes with tidal variations	38%
Groundwater quality is better in rainy months (Hulhangu season)	14%
Long periods without rain causes bad smell	13%
Long periods without rain causes bad taste	3%
Rain makes it worse	2%
No change	45%

8.4 Groundwater Quality

8.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the map of locations where groundwater quality points were taken is attached to Annex VI. The full list of measured parameters is attached to Annex VII. Table 128 summarizes the water quality results.

Table 128: Statistical summary of groundwater physiochemical parameters in GDh. Nadella

	EC ($\mu\text{S/cm}$)	Turbidity (FNU)	DO (mg/L)	pH	Temp ($^{\circ}\text{C}$)	Sal (ppt)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
Standards	<1500 Potable purposes <2500 Non- potable purposes Source ¹	<5 Source ²		6.5-8.5 Source ²			<1.5 Odour threshold <35 Taste threshold Source ¹	<50 Source ¹	
Mean	1349	1.20	3.67	7.42	29.33	0.61	4.96	19.44	0.44
Median	1015	0.34	3.43	7.34	29.20	0.46	1.93	12.26	0.34
SD	1105	2.05	1.40	0.23	2.02	0.47	7.73	21.12	0.36
Min	502	0.00	1.53	7.12	26.80	0.22	0.13	3.89	0.10
Max	7297	10.64	7.45	8.05	39.70	3.01	35.51	114.96	1.84
CV	0.82	1.71	0.38	0.03	0.07	0.77	1.56	1.09	0.80

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH₃= Ammonia, NO₃= Nitrate, PO₄³⁻=Phosphate,
SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source¹ = WHO Drinking Water Guidelines, 2017. Source² = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 825 $\mu\text{S/cm}$ fall below the WHO Standard for potable water (1500 $\mu\text{S/cm}$).
- Zero samples had higher EC than 2500 $\mu\text{S/cm}$. Two samples had EC between 1500 $\mu\text{S/cm}$ and 2500 $\mu\text{S/cm}$ while 38 samples had EC lower than 1500 $\mu\text{S/cm}$. The EC distribution of samples is shown in Figure 145.
- The mean Turbidity level at 0.98 NTU falls below the URA Guidelines for drinking water (5 NTU). Only two samples had a higher Turbidity level than 5 NTU.
- Dissolved Oxygen ranged from 1.51 mg/L to 11.06 mg/L with a mean of 4.23 mg/L.
- All samples fell within the pH range of 6.5–8.5 as per URA Guidelines for drinking water with a mean pH of 7.45.
- Temperature ranges from 26.28 $^{\circ}\text{C}$ to 30.39 $^{\circ}\text{C}$ depending on the well characteristics and time of day reading was taken. Mean temperature was 28.15 $^{\circ}\text{C}$.
- Salinity ranged from 0.14ppt to 0.83ppt with a mean of 0.38ppt.
- The mean Ammonia concentration was 3.50 mg/L which is higher than the WHO threshold for odour and well below the threshold for taste. 62.5% of samples had concentration below 1.5 mg/L and 37.5% of samples had concentration between 1.5 mg/L and 35 mg/L. The Ammonia concentration distribution is shown in Figure 144.

- The mean Nitrate concentration was 6.61 mg/L which falls below the WHO Standard for Nitrate concentration (50 mg/L). One sample had Nitrate concentration higher than the standard.
- Phosphate concentration ranges from 0.06 to 0.49 mg/L with a mean concentration of 0.24 mg/L. There is no WHO guideline value for phosphate concentration. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater. 2 samples (5% of all tested samples) had phosphate concentration below 0.1 mg/L. Phosphate concentrations are generally higher in densely populated areas.

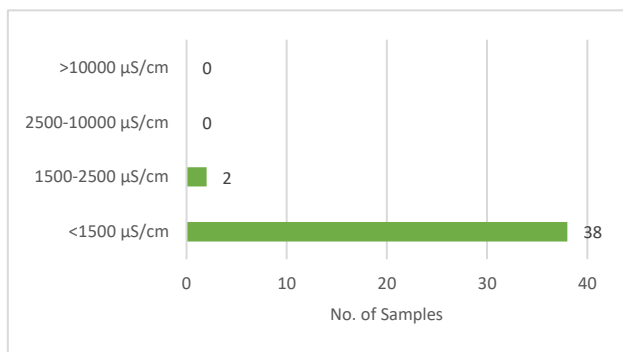


Figure 145: EC Distribution in GDh. Nadella

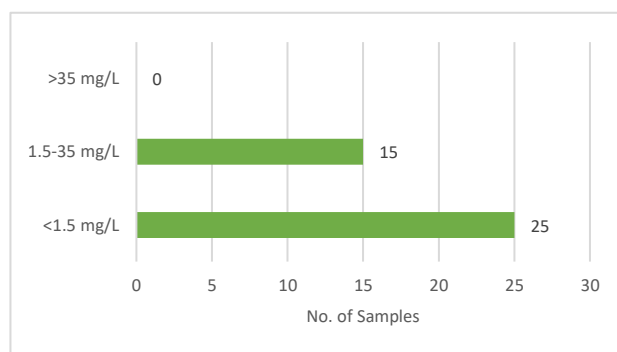


Figure 144: Ammonia Concentration Distribution in GDh. Nadella

The spatial distribution of all the parameters measured are shown in Figure 146 (a-i).

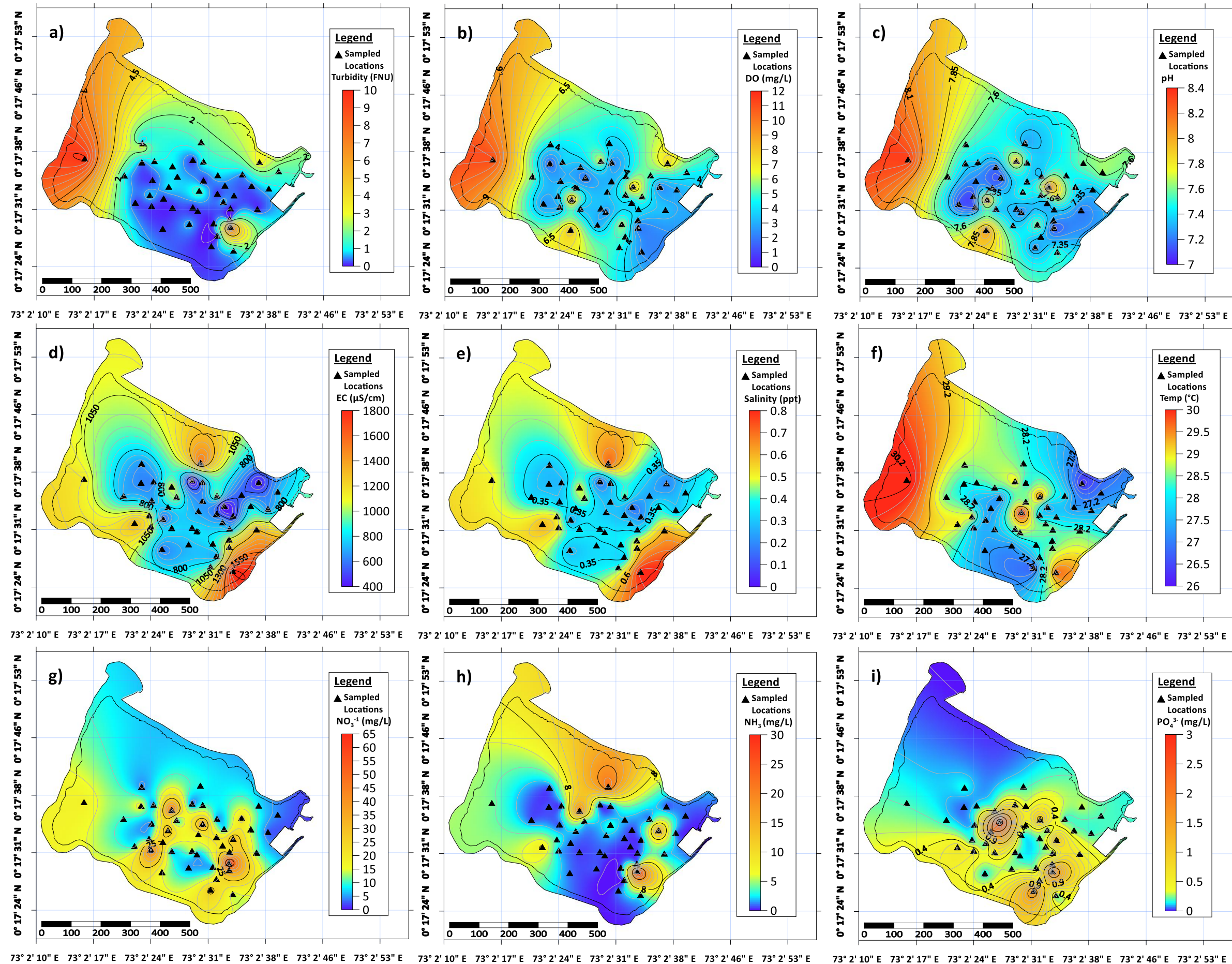


Figure 146: Spatial variation of physiochemical parameters in GDh. Nadella

Over-extraction of groundwater is known to lead to salinization of the freshwater lens at the point. Therefore, the common areas where social survey was conducted, and water quality was checked were compared to see if areas with high water usage had high Electrical Conductivity as well. 26 common areas were identified, and a graph of EC was plotted against Daily Household Water Usage. The correlation coefficient of EC to Water usage is 0.286 and the R-squared of the plot is 0.0819 as indicated from the Figure 147. Therefore, there is no significant relation between EC and Water Usage as per the findings from the Social Survey and Water Quality Survey. The Spatial distribution of EC and water usage is shown in Annex VIII.

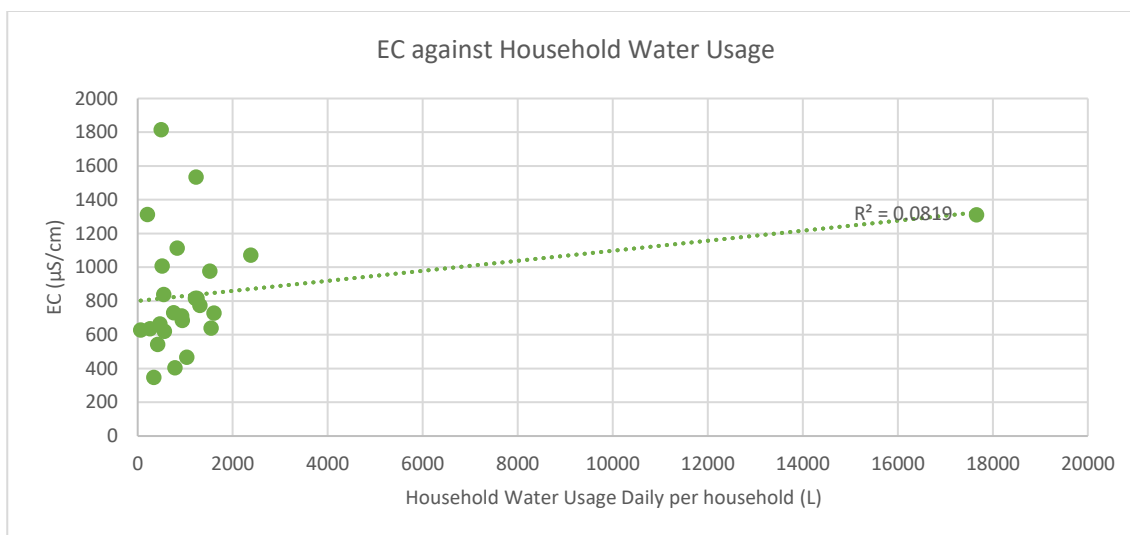


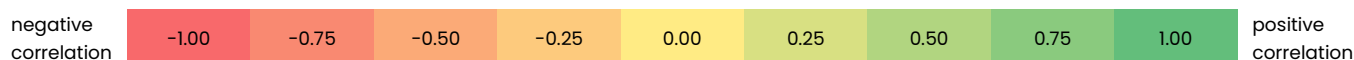
Figure 147: EC against Water Usage in GDh. Nadella

8.4.1.1 Correlation Matrix

The correlation matrix for GDh. Nadella along with the colour bar is given below. Red colour indicates negative correlation while green colour indicates positive correlation.

Table 129: Correlation matrix analysis result of the groundwater quality parameters in GDh. Nadella

Variables	Turbidity (FNU)	DO (mg/L)	pH	EC (µS/cm)	Sal (ppt)	Temp (°C)	NO ₃ (mg/L)	NH ₃ (mg/L)
DO (mg/L)	0.31							
pH	0.27	0.86						
EC (µS/cm)	0.23	-0.35	-0.40					
Sal (ppt)	0.22	-0.36	-0.41	1.00				
Temp (°C)	0.30	-0.01	0.07	0.40	0.36			
NO ₃ ⁻ (mg/L)	0.08	-0.09	-0.19	0.18	0.18	-0.02		
NH ₃ (mg/L)	0.47	-0.27	-0.28	0.49	0.50	0.12	0.27	
PO ₄ ³⁻ (mg/L)	0.18	-0.25	-0.38	0.22	0.23	-0.23	0.28	0.23



The correlation matrix for GDh. Nadella along with the colour bar is given below. Red colour indicates negative correlation while green colour indicates positive correlation.

Table 129 shows a strong positive correlation coefficient between pH/DO ($r=0.86$) and EC/Sal ($r=1.00$). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlations between salinity and conductivity are as expected. There are no strong negative correlations between parameters observed.

8.4.1.2 Water Quality Index

The WQI for 40 samples range from 1.87 to 19.99, with a mean of 7.12. The WQI was divided into four categories and Table 130 shows the categorization of samples. 82.5% of samples were classified as "Very Good", 17.5% of samples were classified as "Good", 0% of samples were classified as "Poor" and 0% of samples were classified as "Very Poor". The high value of WQI at some locations relative to others were found to be mainly from the high turbidity at two locations and high Nitrate concentration at one location. The spatial distribution of WQI is shown in Figure 148.

Table 130: WQI Categorization for GDh. Nadella

WQI	Category	No. of samples	Percentage
0 to 10	Very Good	33	82.5%
10 to 20	Good	7	17.5%
20 to 50	Poor	0	0%
>50	Very Poor	0	0%

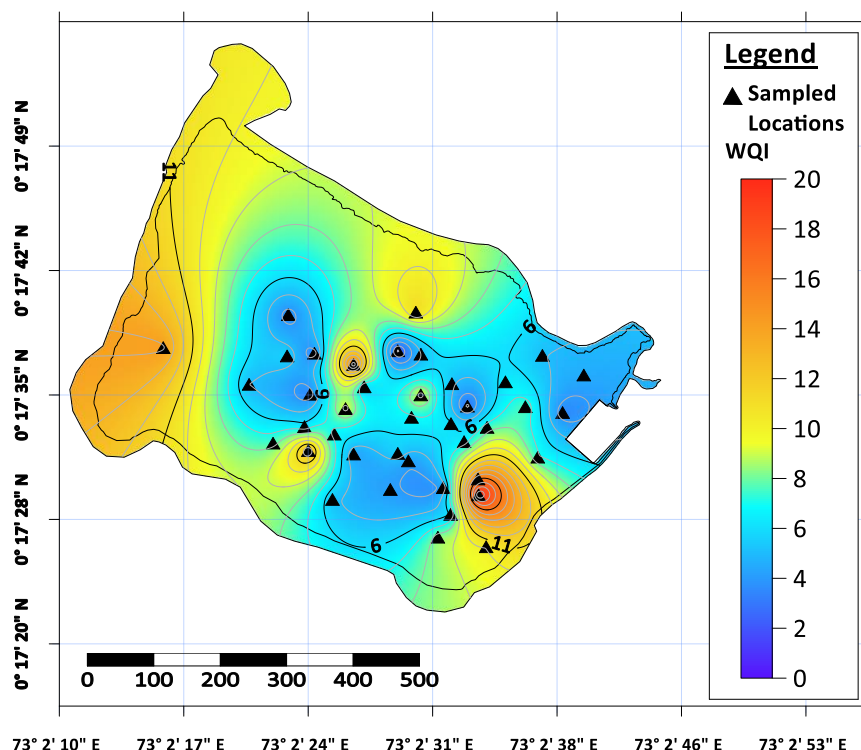


Figure 148: Spatial Distribtuion of WQI in GDh. Nadella

8.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 131 summarizes the results.

Table 131: Microbiological Parameters of GDh. Nadella Groundwater

DATA ID	Total (MPN/100ml)	Coliform (MPN/100ml)	Faecal (MPN/100ml)	Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq01	16		6			Location does not fall within the coverage of social survey
wq03	13		Not Detected		50 to 60	Septic Tank.
wq05	1		Not Detected		30	Septic Tank. Septic Waste cleaned once every 5 years and buried in household
wq07	1120		23			Location does not fall within the coverage of social survey
wq09	31		Not Detected			Location does not fall within the coverage of social survey
wq11	8		Not Detected			Previous Council Office
wq14	7		Not Detected			Location does not fall within the coverage of social survey
wq17	233		11			Location does not fall within the coverage of social survey
wq19	770		1		10	Septic Tank.
wq22	Not Detected		Not Detected		8 to 10	Septic Tank. Septic Waste cleaned once every 2 years and buried in household
wq27	816		28		50	Septic Tank. Not cleaned yet.
wq33	68		Not Detected		10	Septic Tank. Not cleaned yet.
wq37	6		Not Detected		10	Septic Tank. Septic Waste cleaned once every 5 years and buried in household
wq38	62		2			Location does not fall within the coverage of social survey
wq40	1		Not Detected		30 to 40	Septic Tank. Not cleaned yet.

*Distance between water well and nearest septic tank (feet)

Faecal Coliform was detected in 6 samples and Total Coliform was detected in 14 samples.

The effects of effluent leakage from septic tanks and local outfall pipes are evident in the microbiological survey results. On average, there is an approximate distance of 24.5 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Faecal Coliform and Total Coliform is given in Figure 149. On average, Faecal Coliform detected is low or none on the centre of the island adjacent to the harbour. Moderately even spatial distribution of Total Coliform was observed with lower count detected near the harbour.

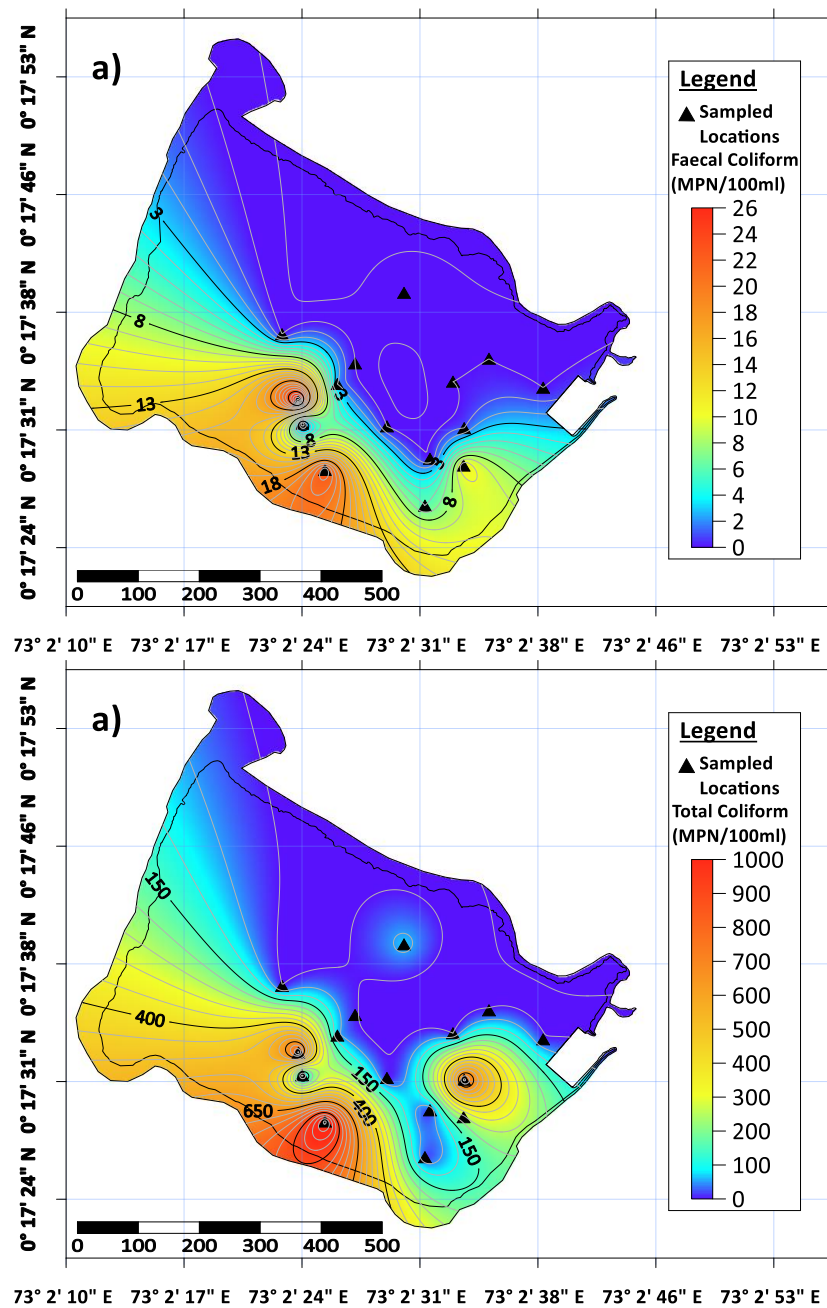


Figure 149: Total (a) and Faecal (b) Contamination Distribution in GDh. Nadella

The Total Coliform and Faecal Coliform Contamination was plotted against the distance between septic tank and well, to identify the correlation between these two variables. The graphs are given below.

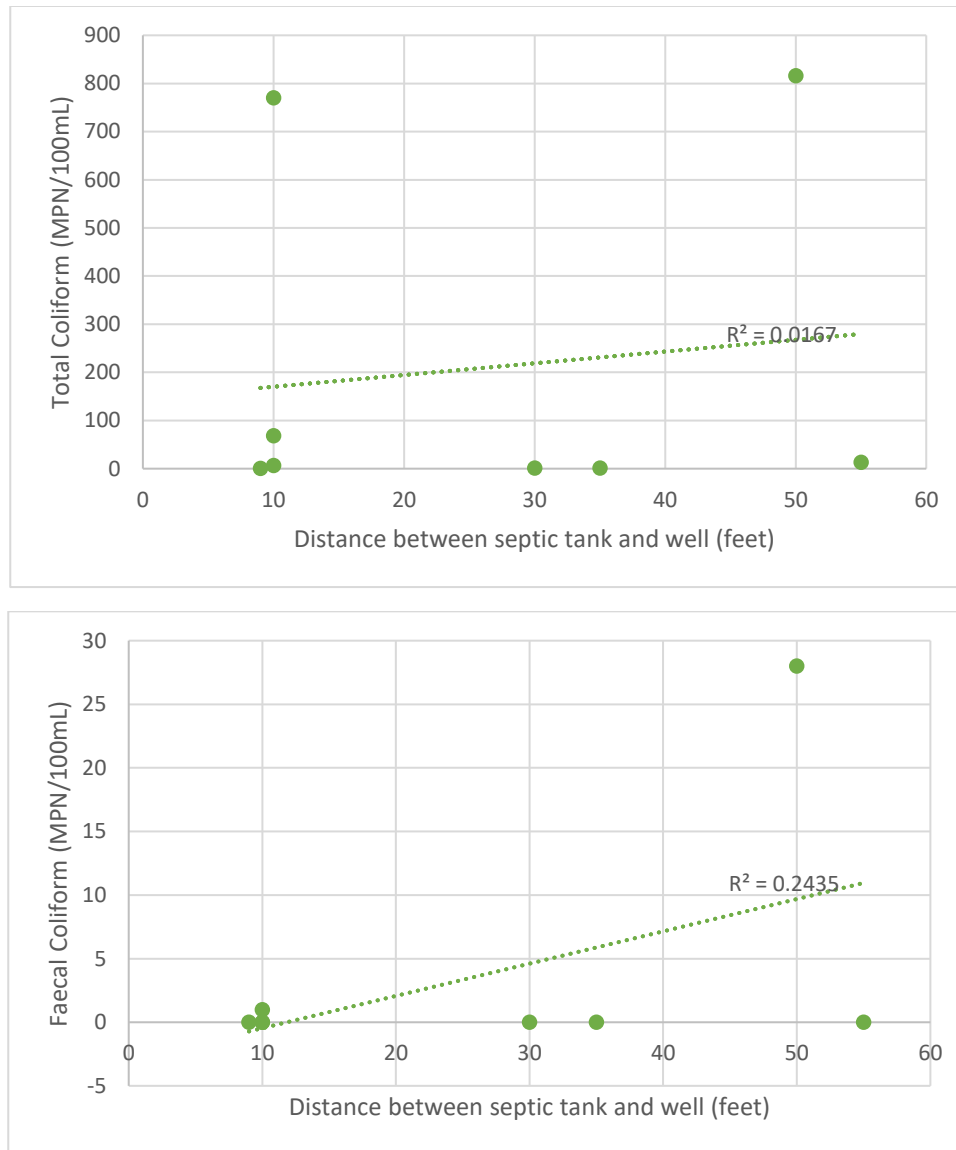


Figure 150: Microbiological Contamination against Septic Tank distancing - Hoandehdhoo

The correlation coefficient of Total Coliform to distance between septic tank and well is 0.129 and the R-squared of the plot is 0.0167. The correlation coefficient of Faecal Coliform to distance between septic tank and well is 0.493 and the R-squared of the plot is 0.244. Therefore, there is no significant relationship observed between the parameters.

8.5 Pumping Test

8.5.1 Test location

A suitable well without a base was not available from GDh. Nadella. The cemetery well had a placed flat coral stone bed and was not fully enclosed, hence it was selected to be used for the pumping test. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 151 below shows the location for the pumping test at GDh. Nadella.



Figure 151: Pumping test location – GDh. Nadella

8.5.2 Pumping rate, pumping hours and collected data

A constant rate pumping test was carried out at GDh. Nadella. The test began at 1030 hours on 25 November 2021 and lasted for 135 minutes. A flowrate of 25 LPM was maintained for the pumping phase which lasted from the 0–35th minute. The recovery phase of the test lasted from 36th–135th minute for more than a 90% recovery.

8.5.3 Hydrogeological parameter estimation

The Cooper-Jacob Solution for Unconfined Aquifer Models was used to process the data from the pumping test using the software, AQTESOLV. The Aquifer Transmissivity (T) value was estimated to be $1.85 \times 10^{-4} \text{ m}^2/\text{s}$ (15.95 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.1079 for GDh. Nadella. The full data set of the pumping test at GDh. Nadella has been annexed at Annex XII.

8.6 Permeability Test

8.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 152 below. The originally proposed locations were changed as necessary due to unavailability of water and electricity for testing, inaccessibility of proposed locations, as well as the prioritizing of public lands that can be used for potential design solutions over private lands.



Figure 152: Permeability Test Locations – GDh. Nadella

8.6.2 Measured data

Table 132: Permeability Test Measured Data - GDh. Nadella

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m ³ /s)	K (m/s)	K (m/day)
NDL-PMB1	0.600	0.860	27	7.5	7.50	0.000125	1.16E-04	10.050
NDL-PMB2	0.600	0.540	35	12.0	0.35	0.000006	1.10E-05	0.952
NDL-PMB3	0.600	0.850	27	7.5	40.00	0.000667	6.28E-04	54.240
NDL-PMB4	0.600	0.880	27	7.5	27.50	0.000458	4.17E-04	36.020
NDL-PMB5	0.600	1.400	27	7.5	42.50	0.000708	4.05E-04	34.990

Note: H = Height of water in well (m), Tu = distance from water level in casing to water table (m),
Cu = Conductivity Coefficient, r = borehole radius, Q = Steady flow into well, K = Coefficient of permeability.

8.6.3 Permeability estimation and identified features

The average permeability value for the GDh. Nadella is 27.250 m/day, with permeability values ranging from 0.952 m/day to 54.240 m/day. As highlighted in Section Soil Profile Survey, the island soil profile is predominantly Sands, and the K values above are consistent with the range of K values obtained for Sands (Robertson (2010)).

8.7 Soil Profile Survey

8.7.1 Test locations

Soil Profile surveys were carried in 7 locations across the island, as outlined in Figure 153 below. Out of the 7 locations, 5 points were permeability test locations, and the remaining 2 points were chosen in a way that ensured a uniform coverage of the entire island.



Figure 153: Soil Profile Survey Locations – GDh. Nadella

8.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 154 below. Even though there are variances in the colour due to environmental factors, the island soil profile is made up of Uniformly Graded Sand for the observed depth.

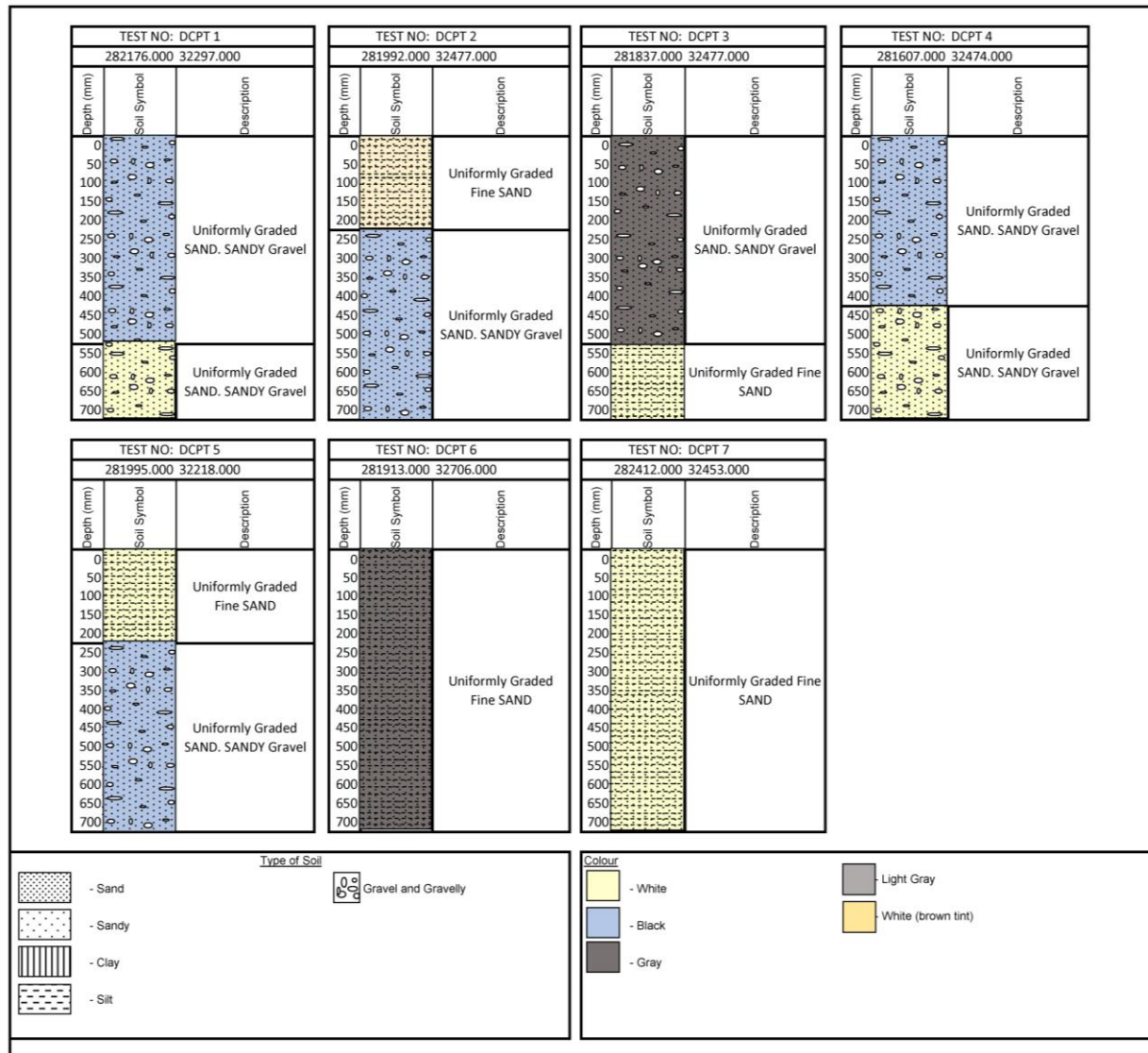


Figure 154: Soil Profile - GDh. Nadella

8.8 Flood Assessment and Inundation Survey

8.8.1 Flood occurrence and flood impact

GDh. Nadella has coastal erosion problems from the south side of the island which has an impact on flooding patterns of the island. The island has also observed recurrent flooding episodes associated with swells and rainwater flooding. The first one was due to tidal swelling on 10 July 2020 in which houses on the south side of the island were moderately affected. The residents reported stormwater induced flooding events in the past 4 years with minor and moderate damages. As per the social survey, 23 households reported rain induced flood incidents in the year 2021 and 5 households reported flooding incidents in 2017. In the two incidents, 26 houses reported partial damages of furniture and household appliances along with broken fences and trees.

As evident by the flooding events, 59% households report flooding as a severe problem. (Refer to flood severity component of Annex XIII: Flood Maps).

The flooding originates mostly from roof runoff (70%) as per the Social Survey. Most responses state multiple sources for the flooding within their properties such as from neighbours' roof, off the road, and general run off in the area. Perceived causes of flooding as per social survey are given in table below.

Table 133: Perceived causes of flooding – GDh. Nadella

Perceived causes of flooding				
Roof run off	Neighbours' roof	Off the road	General run off in the area	No flooding within the plot
70%	4%	29%	41%	18%

From the social survey, 94% of households report that they drain rainwater overflow from storage and roofs to the ground. Most responses state multiple ways for the discharge of rainwater overflow to the roads, open areas within the plot and to the well. Details of discharge of rainwater overflow are given in the table below.

Table 134: Discharge of rainwater overflow – GDh. Nadella

Discharge of rainwater overflow			
Ground	Roads	Open area within the plot	Drained to well
94%	2%	0%	4%

8.8.2 Flood Depth and Inundation area identification

In GDh. Nadella, significant flooding areas are the cemetery road and in front of the island council (refer to Annex XIII: Flood Maps). Many households reported that it takes 2 to 4 hours to inundate the area once heavy rain starts and an average of 1.03 ft is estimated to be the flooding depth when there is rainfall.

8.8.3 Draining flood water

There is no established drainage system within the island. However, due to recent flooding events, emergency drainage channels were established behind council office to divert flood water into the sea and alleviate the flooded areas. As per the social survey, 37.5% observe that the water drains during the rainfall itself, 22.7% observe that the water drains in less than 4 hours, 9.1% observe that the water drains within 4-24 hours and 30.7% observe that it takes more than 24 hours for water to drain.

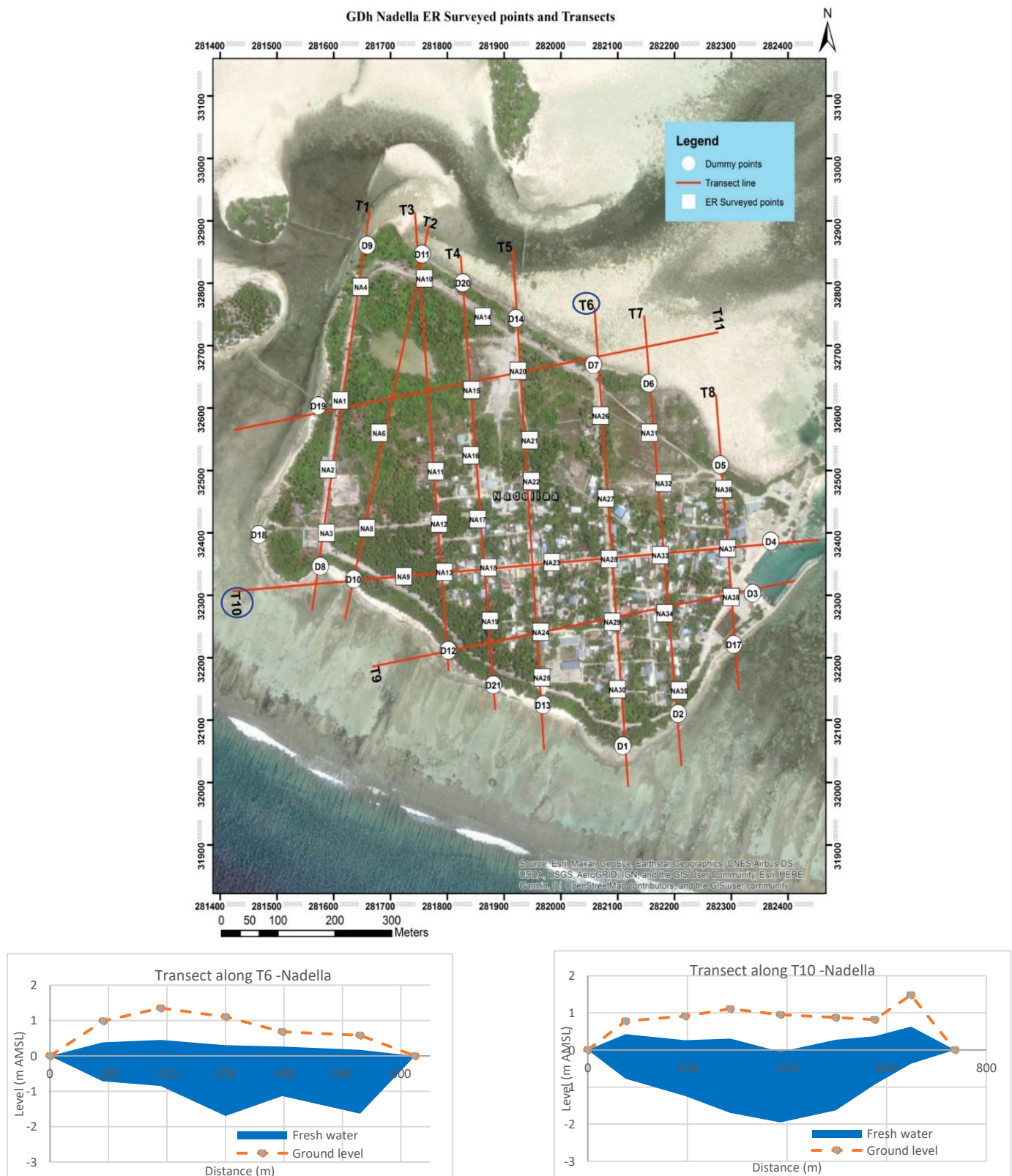
Table 135: Draining period - GDh. Nadella

Draining period			
only while raining	drains less than 4hrs	takes 4-24 hrs	more than 24hrs
37.5%	22.7%	9.1%	30.7%

8.9 Geophysical Survey

8.9.1 Surveyed Locations

Locations where ER sounding measurement taken at GDh. Nadella Island are shown in Figure 155 together with transect lines. There are 36 ER measurement locations and the number of transects in this island is 10.



8.9.2 Freshwater levels and saline water levels

From processed ER data using GeoVES 1.5 – GeoElectrical Model depth to freshwater starting level and depth to freshwater lens bottom level (saline water start level) were determined and they were converted to elevation with respect to mean sea level using ground collected through drone survey. Table 136 below shows the estimated levels at ER surveyed locations of GDh. Nadella Island and freshwater lens thickness.

Table 136: Freshwater lens levels and thickness – GDh. Nadella island

No	Map ID	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	Na01	0.72	0.32	0.07	0.25
2	Na02	1.24	0.89	0.19	0.70
3	Na03	1.50	1.10	0.10	1.00
4	Na04	0.66	0.16	-0.64	0.80
5	Na06	0.80	0.43	-0.57	1.00
6	Na08	0.72	0.32	-0.88	1.20
7	Na09	1.48	0.63	-0.37	1.00
8	Na10	0.51	0.21	-0.59	0.80
9	Na11	1.13	0.78	-0.82	1.60
10	Na12	1.43	0.43	-1.07	1.50
11	Na13	0.82	0.37	-0.93	1.30
12	Na14	0.60	0.30	-1.20	1.50
13	Na15	0.55	0.25	-1.65	1.90
14	Na16	1.31	0.56	-1.24	1.80
15	Na17	0.76	0.31	-1.39	1.70
16	Na18	0.87	0.27	-1.63	1.90
17	Na19	0.90	0.63	-0.57	1.20
18	Na20	0.62	0.27	-1.38	1.65
19	Na21	0.67	0.27	-1.23	1.50
20	Na22	0.59	0.29	-1.31	1.60
21	Na23	0.95	-0.05	-1.95	1.90
22	Na24	1.44	0.94	-0.66	1.60
23	Na25	1.81	1.63	0.23	1.40
24	Na26	0.58	0.17	-1.63	1.80
25	Na27	0.68	0.26	-1.14	1.40
26	Na28	1.11	0.31	-1.69	2.00
27	Na29	1.35	0.45	-0.85	1.30
28	Na30	0.98	0.38	-0.72	1.10
29	Na31	0.61	-0.09	-0.59	0.50
30	Na32	0.73	0.31	-0.99	1.30
31	Na33	0.91	0.26	-1.24	1.50
32	Na34	0.68	0.33	-1.07	1.40
33	Na35	0.95	0.65	0.20	0.45
34	Na36	0.85	0.45	-0.65	1.10
35	Na37	0.78	0.43	-0.77	1.20
36	Na38	1.07	0.37	-0.83	1.20

Average freshwater thickness of GDh. Nadella Island is 1.31m.

Data in Table 136 were used to plot freshwater lens cross sections along 10 transects and they are given in Annex IX. Of these sectional plots 2 were given in Figure 155 and they represent the transect plot along the longitudinal section and cross section of the island that passes through island middle. Dotted lines in these plots indicate ground level variation with respect to mean sea level along the transect lines.

8.9.3 Freshwater lens spatial extent

For the purpose of identifying spatial distribution of upper and lower level of freshwater lens the computed freshwater levels and saline water levels at ER points were exported to ArcGIS and used to generate contours with help of interpolation tools available in the same software. The generated contours are shown in Figure 156 and the processed ER data were used to develop a 3D view of the freshwater lens and it is also shown in Figure 156.

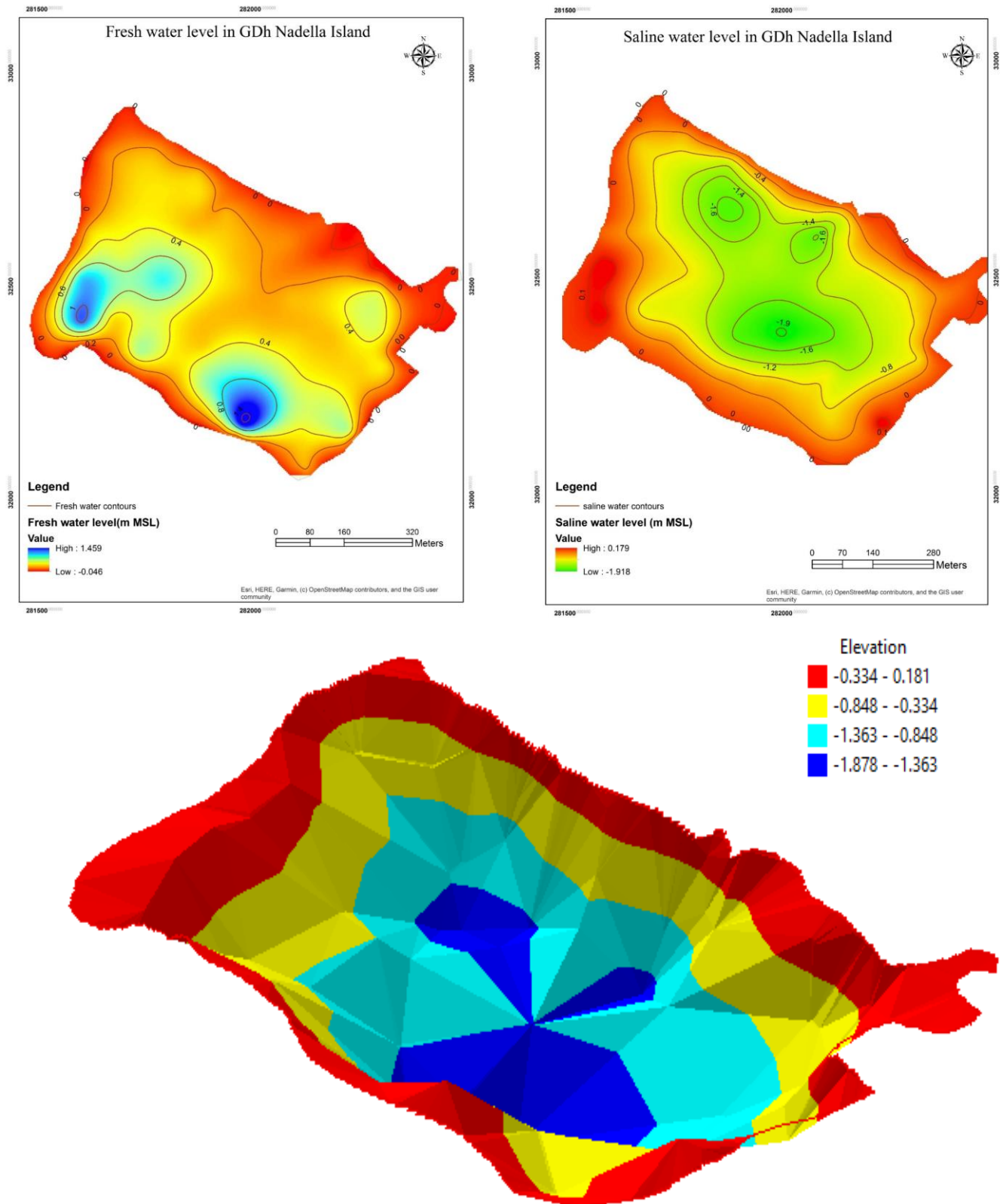


Figure 156: Top Left: Contours of Freshwater lens upper level, Top Right: Contours of Freshwater lens lower level, Bottom: 3D view of Freshwater lens bottom level - GDh. Nadella island

8.9.4 Freshwater lens storage volume and stress level

For the estimation of freshwater volume, the depth difference between freshwater-saline water interface and freshwater upper level was computed at each ER measurement points and they were then used to determine freshwater volume stored in the ground at time of taking ER measurements. Both “Triangle method” and Tools in ArcGIS software were used to perform this computation. Figure 157 shows triangles considered for the above said computation and refer Annex X for detail calculation.

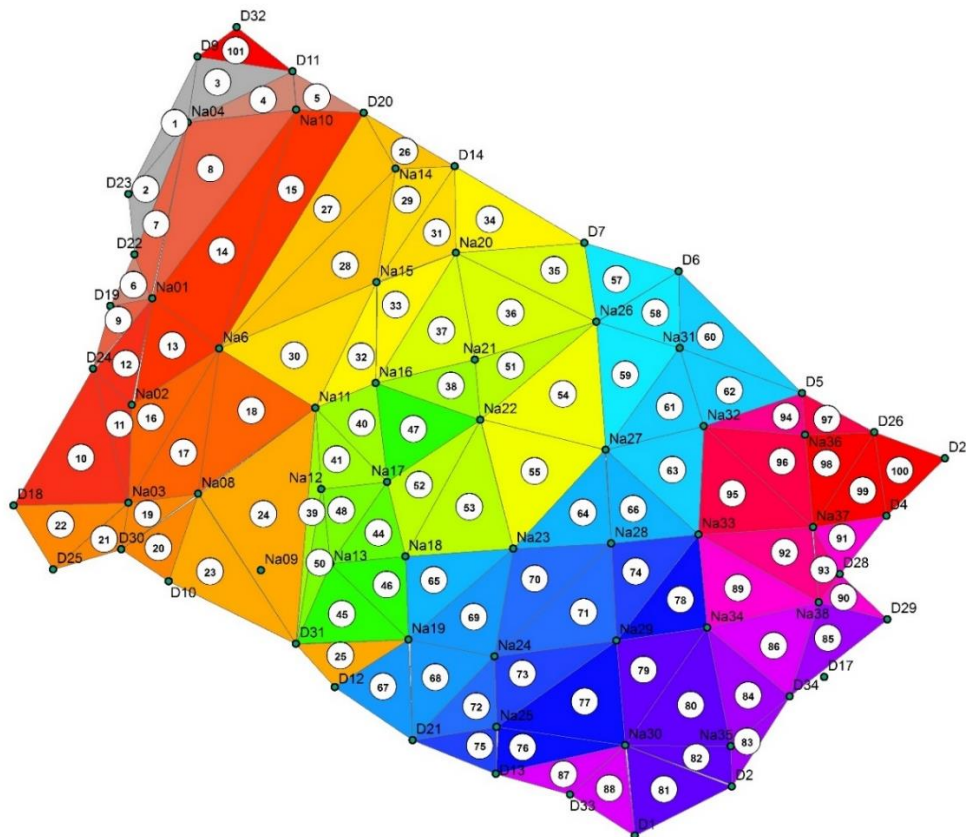


Figure 157: Triangles for freshwater volume computation – GDh. Nadella island

Stress level on freshwater aquifer of GDh. Nadella island was determined by computing ratio between freshwater lens volume and annual groundwater abstraction for non-potable water usage at present. When this ratio was more than 1.5, the island was treated as “not stressed” and if it was between 1.5 and 1 the aquifer was assumed to be “stressed” and any other lower ratio was taken as “highly stressed” aquifer. This criterion was developed based on saline water issues collected from the project islands during field work. The computed freshwater volume, water abstraction and aquifer stress level are given in Table 137.

Table 137: Freshwater lens volume and aquifer stress level – GDh. Nadella island

Item	Value	Unit
Freshwater lens volume – Triangle method	89,483	m ³
Freshwater lens volume – ArcGIS	94,109	m ³
Groundwater abstraction	111,047	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	0.8	-
Aquifer stress level	Highly stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 10.1m. This deviates by 405% from the maximum measured value of 2m, which is more reliable as it results from a more comprehensive, site-specific methodology.

8.10 SWB Modelling

8.10.1 Topography for flow direction

Topographical data assigned to model grids for computation of D8 flow directions is shown in Figure 158 according to this figure elevation of the island is changing from -0.119 mAMS L to 2.440 mAMS L and average elevation is 1.254 mAMS L



Figure 158: Elevation data assigned for SWB modelling - Nadella Island

8.10.2 Land use categorization and area estimation

Land use map prepared for SWB modelling of GDh. Nadella island is shown in together with table a showing land classification and their respective areas. It could be noted from the Figure 180 that 20m x 20m grids are adequate to represent the island land use for SWB modelling purpose.



Land use	Symbol	Area (m ²)	Area (%)
Residential		210800	46.4%
Forest		105600	23.3%
Commercial		20800	4.6%
Ground		2400	0.5%
Bare land		107200	23.6%
Wetland		7200	1.6%
Agriculture		0	0

Figure 159: Land use for SWB model - GDh. Nadella Island

8.10.3 Recharge estimation and distribution

Monthly recharge values estimated at grid cells of the SWB model were extracted and used to identify its variation over years and months (refer Figure 160 and Table 138). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 146.4, 351.6 and 523.6 respectively over a 20 year period.
- There is a good relationship between annual rainfall and annual recharge, but it is not linear but inverse exponential.
- Annual average rainfall is around 2270 mm but for 5 consecutive years (from 2008 to 2012) annual rainfall was below average. It indicates that there would be serious issue of saline water intrusion into the freshwater lens during such period as the recharge value would be considerably lower than annual average recharge value (inverse exponential relationship).
- Variation among the monthly average recharge value is very high. It is lowest on month of March and highest in November.
- Water consumption (pumping) for non-potable use on 6-month period is less than the recharge value on the respective months. It indicates that GDh. Nadella island is heavily depending on groundwater storage and there would be serious issues of saline water intrusion into this island.

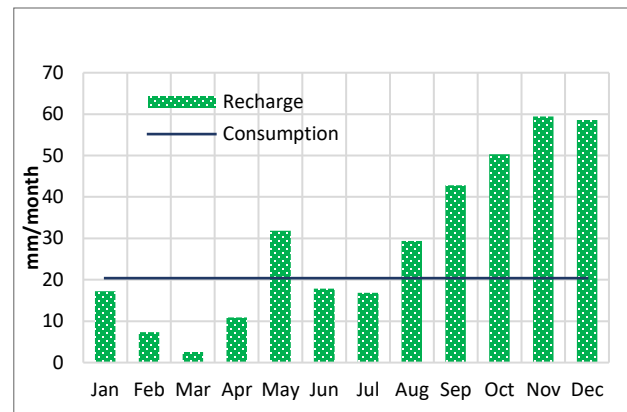
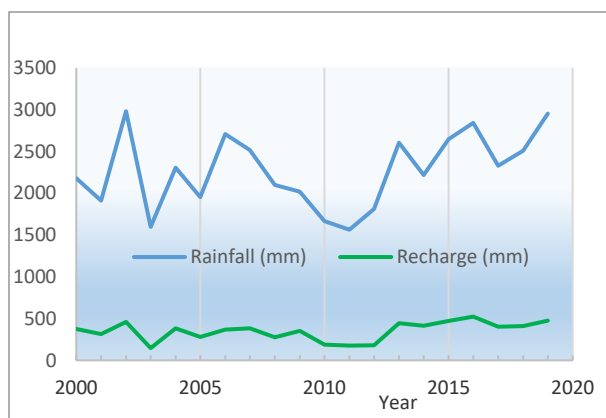


Figure 160: Monthly and annual recharge distribution – GDh. Nadella island

Table 138: Monthly recharge estimated by SWB model – GDh. Nadella Island

Year	Monthly Recharge (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.7	0.0	0.0	6.0	4.6	42.5	26.0	32.2	119.7	35.4	71.6	36.1
2001	0.0	0.0	0.0	21.2	7.0	0.0	6.3	37.2	74.5	58.4	69.9	41.2
2002	2.7	11.9	10.5	22.7	39.0	51.0	31.5	8.6	29.0	92.0	65.0	97.2
2003	0.4	0.0	0.0	4.3	29.8	20.6	29.6	15.1	0.0	0.7	28.2	17.8
2004	35.7	0.0	0.0	9.6	0.0	0.0	22.8	39.5	56.8	57.3	103.0	57.8
2005	23.6	13.1	0.0	0.0	20.6	47.7	32.3	20.0	13.5	106.4	2.9	0.0
2006	33.7	53.0	0.0	0.1	0.0	2.0	4.4	3.5	49.2	5.1	137.7	81.0
2007	60.8	0.0	0.0	0.0	8.1	37.0	22.6	0.8	30.9	97.9	6.9	119.2
2008	24.6	0.0	0.0	22.6	24.3	13.2	21.7	2.0	0.0	54.6	63.6	48.6
2009	33.1	19.9	0.0	0.0	49.1	0.0	0.9	84.9	23.0	41.1	53.4	48.1
2010	10.8	0.0	0.0	19.3	11.3	0.0	31.6	58.8	40.3	17.6	0.0	0.0
2011	0.0	0.0	0.0	0.2	13.6	0.0	0.0	5.5	0.0	50.9	17.3	87.9
2012	0.0	9.1	0.0	0.0	11.3	4.3	7.2	5.7	6.8	92.3	33.0	9.7
2013	0.0	0.0	5.1	15.4	70.1	9.5	23.0	36.1	12.2	25.9	128.5	120.3
2014	0.0	0.0	4.2	9.5	112.3	0.0	2.8	9.1	135.1	30.2	68.7	43.1
2015	3.1	11.2	0.0	0.0	12.8	22.3	13.1	98.5	29.5	80.8	96.3	105.0
2016	59.8	0.6	20.2	45.8	60.8	2.3	16.4	120.5	21.1	47.8	72.7	55.5
2017	2.6	0.0	9.5	0.0	88.9	0.0	18.6	12.4	85.2	0.0	58.4	125.3
2018	0.0	1.2	0.0	32.7	51.5	48.5	29.1	0.0	53.3	99.9	53.7	40.9
2019	65.4	19.0	3.8	8.6	43.5	56.2	8.1	16.8	76.6	46.0	57.4	75.3

8.10.4 Water Balance

As per estimation, annual recharge estimated by the SWB model is 159,539 m³ and it is 15.5% of annual average rainfall (refer Figure 161).

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	1,030,212	2,719	7,637	527,434	159,539	332,882	111,047
%	100.0%	0.3%	0.7%	51.2%	15.5%	32.3%	10.8%

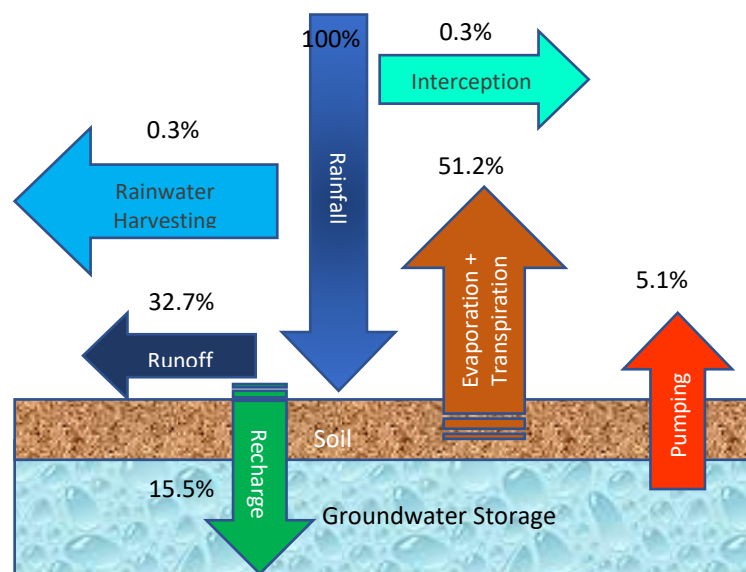


Figure 161: Annual water balance – GDh. Nadella Island

8.10.5 Deficit estimation, dry month identification and safe yield

Deficit calculation was carried out to identify whether recharge over a month period is smaller than or larger than the pumping quantity in the island. Monthly recharge time series estimated by the SWB model was compared with total pumping quantity of the island (9,254 m³/month) and if recharge exceeds the pumping quantity it was taken as “no deficit” and on other hand if pumping quantity exceeds the recharging value it was taken as “deficit”.

Table 139: Deficit percentage - GDh. Nadella

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	127	52.98%

It is to be noted that “deficit” doesn’t mean failure or inadequate freshwater for pumping, but it is to be interpreted that the number of months when pumping is to be supported by groundwater storage in addition to recharging quantity. As per estimation, pumping at GDh. Nadella island has a 52.9% dependency on the groundwater storage.

Determining safe yield which is defined as the attainment and maintenance of a long-term balance between the annual amount of groundwater withdrawn by pumping and the annual amount of recharge is important for small islands and there are various methods to estimate this amount. One simple method is checking whether ground water abstraction is less than or equal to 10% of average annual rainfall (MoEnv. 2020). The comparison of the estimated ground water withdrawal (111,047 m³/yr) with safe abstraction volume (57,658 m³/yr) shows that present withdrawal is 93 % higher than the safe yield.

8.11 SUTRA Modelling

8.11.1 Model representation and topographical features

SUTRA modeling requires model domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island (refer Figure 162). The other boundary defined in the model was island outline which can be taken as the shoreline for most of the cases except at harbor area and the inner part of the island was subdivided into several polygons representing different land use areas and it was accomplished by importing GIS shape files of island land use and then drawing polygons on them. Some other boundaries were also defined to represent island features such as lake and elevation change in the middle of the reef. Mesh with irregular quadrilateral elements were produced for all closed boundaries. Mesh size defined for outer boundaries (area between shoreline and model domain) were 3 to 4 times larger than the same size defined for the inner part of the island. Elevation at shoreline was defined as zero whereas elevations for inner part of the island was assigned from topographical data used for SWB modelling. Figure 162 shows model domain and SUTRA model mesh with topographical changes.

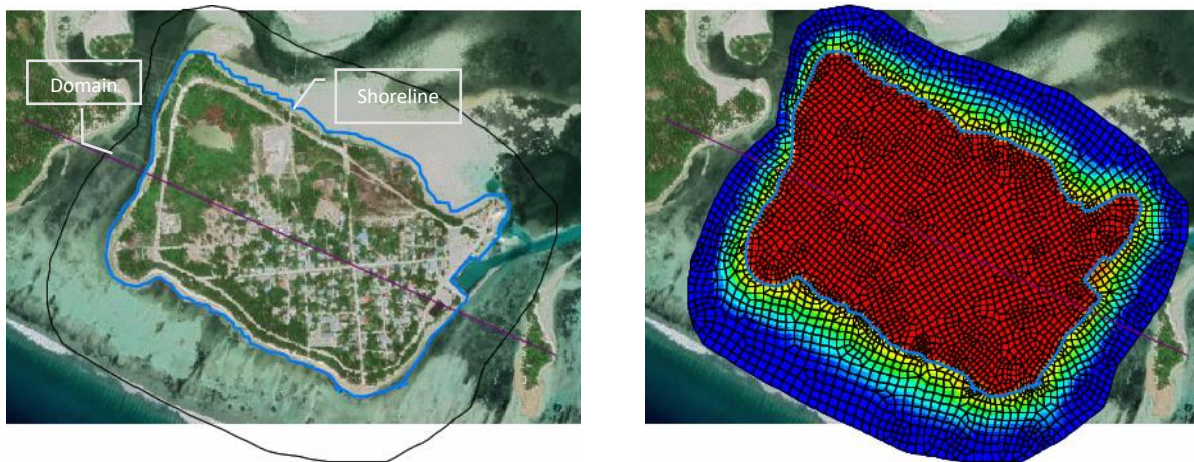


Figure 162: Model boundaries and model mesh - GDh. Nadella island

8.11.2 Pressure boundaries

Specified pressure boundary was defined along the model domain so that it would cause saline water intruding into the island when pressure along the outer boundary of freshwater lens is less due to lower recharge and/or groundwater abstraction is high. Figure 163 shows the pressure boundary defined for GDh. Nadella island.

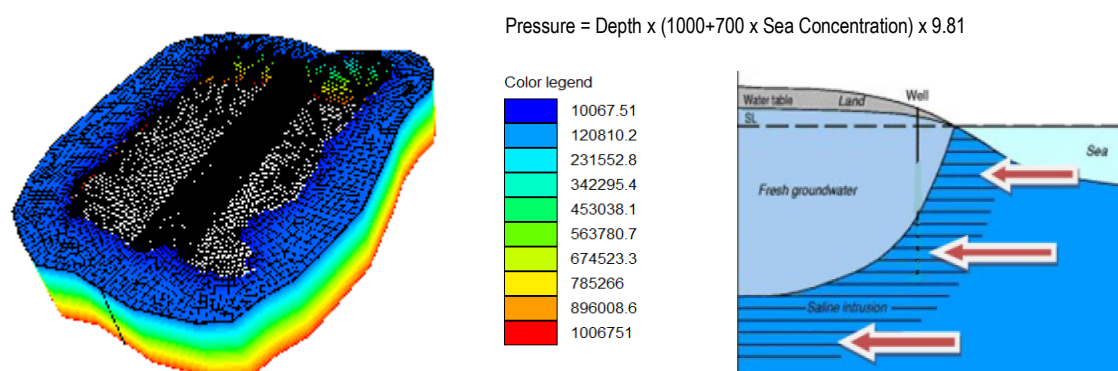


Figure 163: Pressure boundary at SUTRA model - GDh. Nadella island

8.11.3 Assigning recharge on land use basis

Recharge rates estimated by the SWB model for each grid cells were lumped on land use basis using VB program and ArcGIS tool and they were then used to estimate the monthly average recharge rate on residential area, commercial area, and other land use. Table 140 shows monthly recharge rate estimate for GDh. Nadella island.

Table 140: Recharge for SUTRA model - GDh. Nadella island

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	41.0	33.9	8.5	32.1	37.4	5.4	0

8.11.4 Groundwater abstraction

Groundwater pumping takes place at individual houses, restaurants, and institutes. Since all well locations are not available and abstraction rate would also change place to place a simplified approach was adopted by defining a polygon around the residential area (area highlighted in blue in the below map) and assigning average pumping rate of 9,254 m³/month.

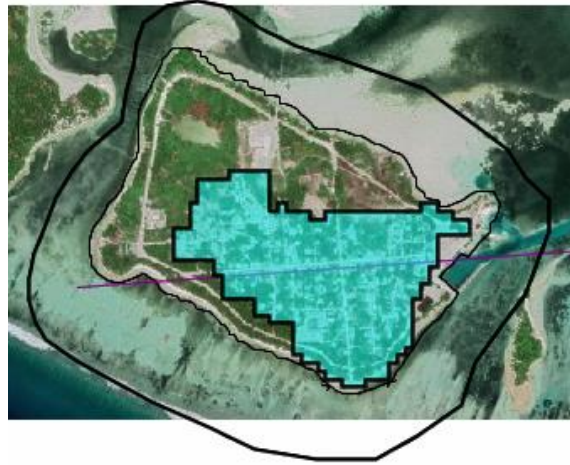


Figure 164: Pumping region at SUTRA model - GDh. Nadella island

8.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20 yr period is shown in Figure 165. The orange-coloured component in the 3D view represents sea water concentration around the island and the section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0375 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top and at the central portion. Freshwater lens predicted for GDh. Nadella island is very shallow as shown in Figure 165.

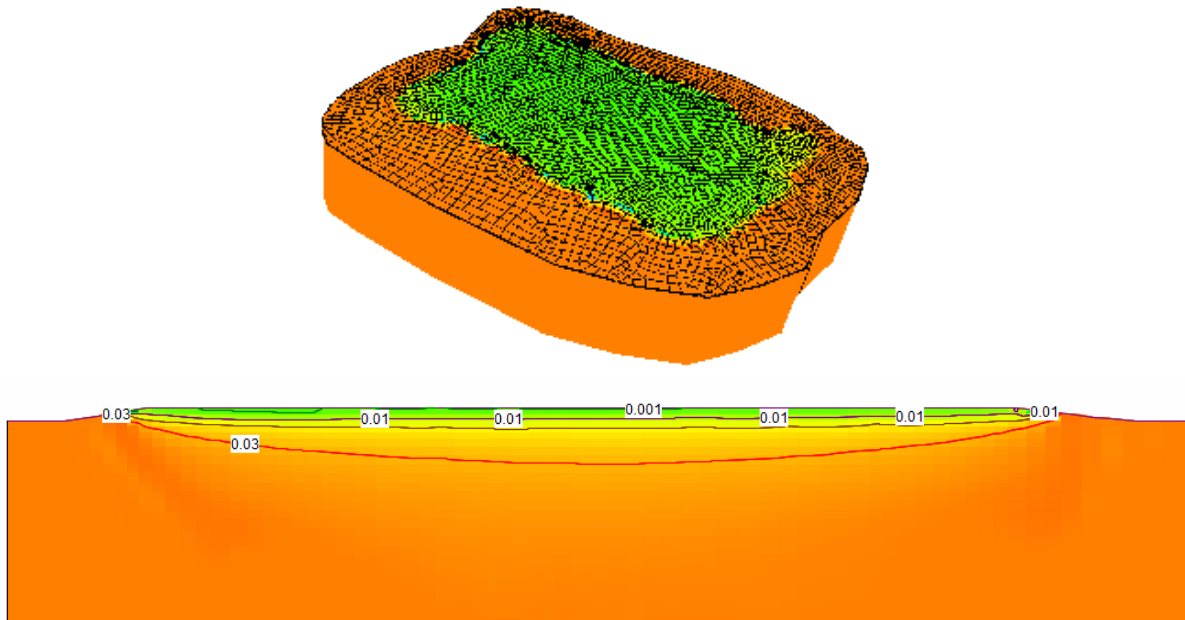


Figure 165: Saltwater distribution - GDh. Nadella island

8.12 Summary of Baseline Assessment

Summary of findings extracted from field works, laboratory test, modelling and analysis are presented below.

- General overview, demography, and climatology

Item	Details
Atoll	Huvadhu Atholhu Uthuruburi Atoll
Length	0.88 km
Width	0.56 km
Area	43.7 ha
Population	1,131
Population/area	25.88 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use



Topographical map



Average elevation = 1.13 m above MSL

Shoreline length = 3369 m

	% of total area
Roof cover	8%
Vegetation (Thick)	22%
Vegetation (Thin)	33%
Bare Lands	34%
Farmlands	0%
Wetlands	2%

• Water consumption

Category	Domestic	Commercial	Institutional	Industrial	Total
Rate (m ³ /d)	304	0.046	4.00	-	308

- Water quality parameters – Physiochemical

Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC ($\mu\text{S}/\text{cm}$)	1,349 $\pm$ 1,105	1500
Turbidity (FNU)	1.20 $\pm$ 2.05	5
DO (mg/L)	3.67 $\pm$ 1.40	
pH	7.42 $\pm$ 0.23	6.5-8.5
Temp ($^{\circ}\text{C}$)	29.33 $\pm$ 2.02	
Sal (ppt)	0.61 $\pm$ 0.47	
NH₃ (mg/L)	4.96 $\pm$ 7.73	1.5 (Odour Threshold)
NO₃⁻ (mg/L)	19.44 $\pm$ 21.12	50
PO₄³⁻ (mg/L)	0.44 $\pm$ 0.36	

- Water quality parameters – Microbiological

Number of samples tested = 15

Parameter	Value range	Average value	Remarks (on permit limit)
Total Coliform (MPN/100ml)	Not detected - >1120	210.13	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not detected - 28	4.73	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	15.95	m ² /day
Storativity	1	0.1079	-
Permeability	7	0.952 – 54.240 Average – 27.250	m/day
Soil profile	5	Mostly uniformly graded sand and well graded sand and gravel on the South Western ridge of the island	

- Flooding

Flooding days per year	Inundation area (m ²)	Inundation depth (m)
63	11,000	0.314

- Electric Resistivity survey

- Measurement taken at 36 locations and number of transect is 10.
- Average freshwater thickness in the island is 1.31 m.
- Freshwater lens volume and aquifer stress level

Item	Value	Unit
Freshwater lens volume – Triangle method	89,483	m ³
Freshwater lens volume – ArcGIS	94,109	m ³
Groundwater abstraction	111,047	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	0.8	-
Aquifer stress level	Highly stressed	-

- SWB modelling
 - Annual recharge is 159,539 m³ and it is 15.5% of annual rainfall (2270 mm)
 - Annual water balance

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	1,030,212	2,719	7,637	527,434	159,539	332,882	111,047
%	100.0%	0.3%	0.7%	51.2%	15.5%	32.3%	10.8%

- Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 52.98% in an average year and it is compensated by ground water storage.
 - Ground water withdrawal (111,047m³/yr) is 93% higher than the safe abstraction (57,658m³/yr).
- SUTRA modelling
 - Average monthly recharge assigned to SUTRA model

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	41.0	33.9	8.5	32.1	37.4	5.4	0

- Freshwater lens prediction (allowable concentration for potable use is 0.001)

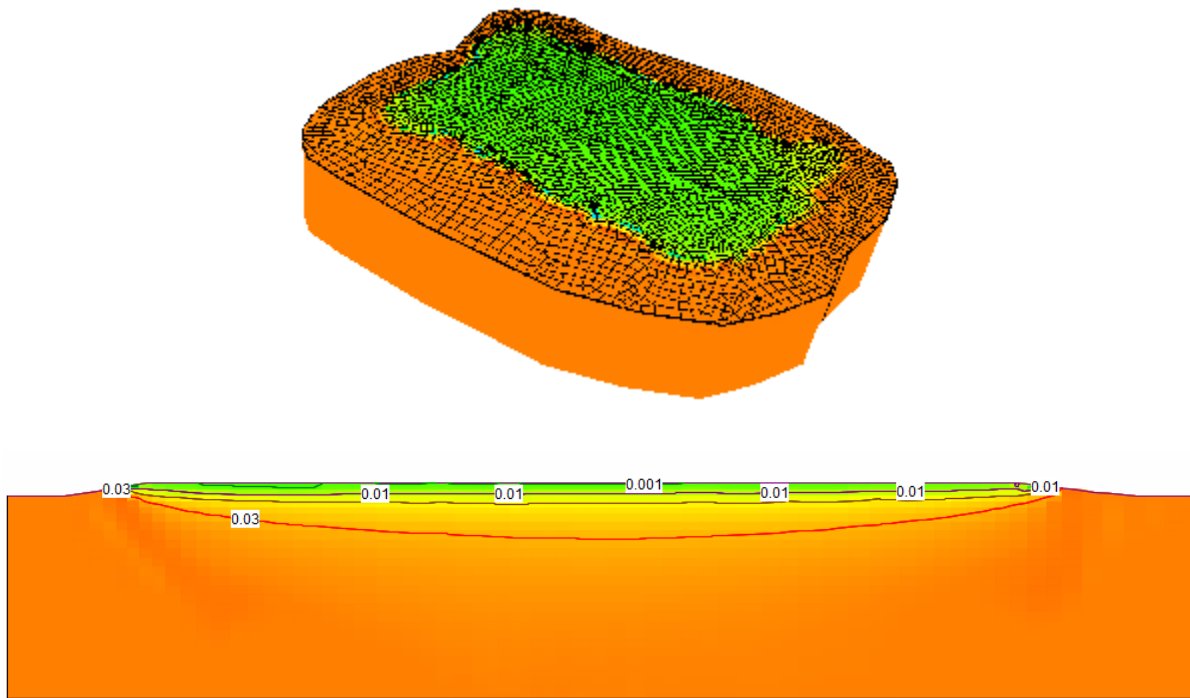


Figure 166: Saltwater distribution - GDh. Nadella island

9 GDh. Rathafandhoo

9.1 Island Overview and Location

The Island of GDh. Rathafandhoo, belonging to Huvadhoo Atholhu Dhekunuburi Atoll, is in the Southern region of Maldives at 0°15'09.9"N and 73°06'17.1"E. It is approximately 437.6 km South-West of the capital Male'.

Table 141: Island Geographical Data

Island	GDh. Rathafandhoo
Atoll	Huvadhoo Atholhu Dhekunuburi Atoll
Location	0°15'09.9"N and 73°06'17.1"E

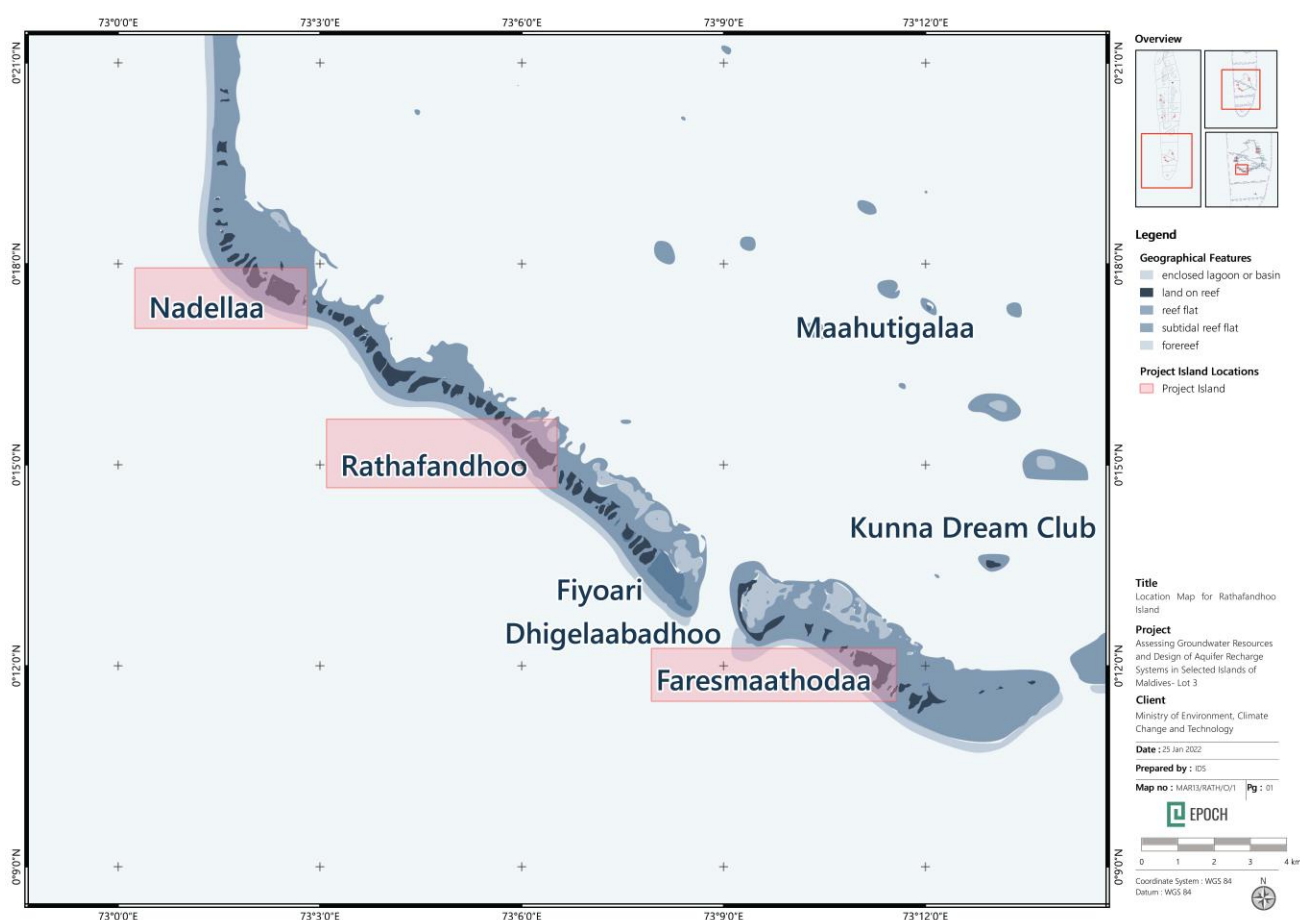


Figure 167: Location map - GDh. Rathafandhoo

9.1.1 Island features

The island is in the southwestern rim of Gaafu Dhaalu Atoll. The island extends up to 0.87 km in length and has a width of 0.56 km. The total area of the island is 38.2 hectares. The island has a harbour at its northern east side. Around two-third of the island is covered in thin vegetation. The west part of the island

is somewhat concentrated with thick vegetation. Some of the vegetation is also concentrated at the north edge of the island. Only about two-third of the island is populated, which is mostly the southern part of the island. This part of the island has also observed severe erosion which has affected livelihood of the residents. The island also has one wetland on the Southern side of the island.

Table 142: Area Distribution in GDh. Rathafandhoo

Area	38.3 ha	
Length	0.87 km	
Width	0.56 km	
	Area (m²)	% of total area
Roof cover	40,667	11%
Vegetation (Thick)	85,734	22%
Vegetation (Thin)	196,439	52%
Bare Lands	57,728	15%
Farmlands	-	0%
Wetlands	2,778	1%
Total	382,846	100%



Figure 168: Land Use Characterization – GDh. Rathafandhoo

9.2 Topographical Features

Permanent Survey Marks PSM 0414 and PSM 0413 were used as benchmarks for GDh. Rathafandhoo topographical survey and drone survey with benchmark details available at <https://www.mlsa.gov.mv/psm>. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 2760 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.30 cm per pixel. 12 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 143 GCP Statistics for GDh. Rathafandhoo

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	-0.000033	0.000141	0.000214
Sigma [m]	0.0205	0.0159	0.0111
RMS Error [m]	0.0205	0.0159	0.0111

The Digital Surface Model in Annex III indicates that the windward region of the island (Average Elevation 2.5 m) is higher than the leeward region (Average elevation of 0.5 m). This trend is particularly visible along the long main road that goes from the harbour to the ridge in GDh. Rathafandhoo. The Harbour was rehabilitated in the last 10 years but the regions near the quay wall remain higher than the island average. In contrast, for the wetland in the Southeast, the elevations are much lower than the island average.

Roof elevations generally do not exceed 5–7 m and very few houses have multistorey buildings in GDh. Rathafandhoo. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Thick vegetation with heights greater than 10 m are primarily seen on the eastern periphery of the island. It is also noteworthy that the entire island has dense thick and thin vegetation with elevations that are generally higher than 10m.

The Digital terrain model was produced at a resolution of 0.1 m spatial resolution for the purposes of analysis. The scatter plot for sampled UAV Elevations vs GPS Spot heights is presented below along with statistics for the regression line. The error statistics for sampled elevations are given in the table below and indicate that the drone survey slightly overestimates the elevation with a mean of 4.37 cm

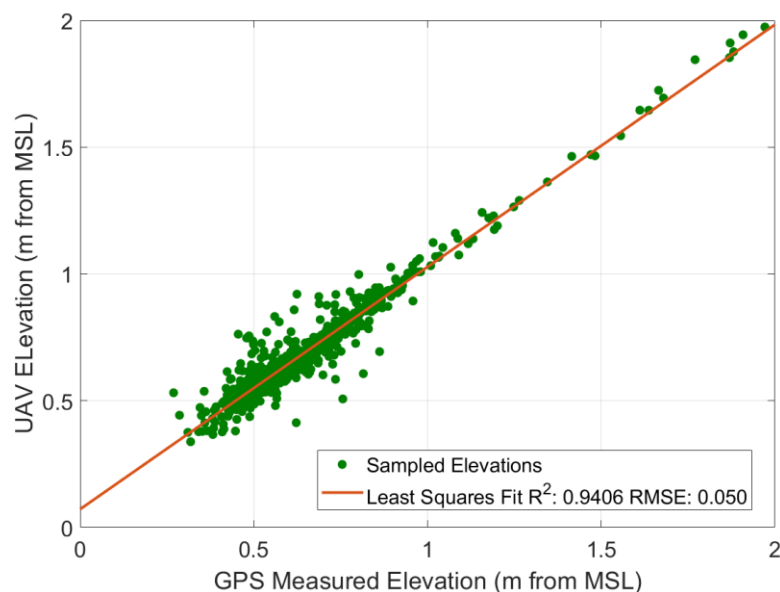


Figure 169 Linear Regression Plot for GDh. Rathafandhoo Sample UAV elevations

Table 144 Error Statistics for DTM sampled elevations for GDh. Rathafandhoo

Parameter	Value (cm)
Mean	4.37
Standard Error	0.18
Median	4.00
Mode	3.60
Standard Deviation	5.10
Sample Variance	26.05
Kurtosis	7.30
Skewness	0.70
Range	55.60
Minimum	-24.90
Maximum	30.70
Sum	3563.80
Count	816.00

9.2.1 Level changes

GDh. Rathafandhoo has an average elevation of 0.899 m with a standard deviation of 1.00. Digital Terrain Model elevations range from -0.6 to 3.6 m from MSL. The distribution of elevations is positively skewed with 0.7 m being the highest frequency for elevations.

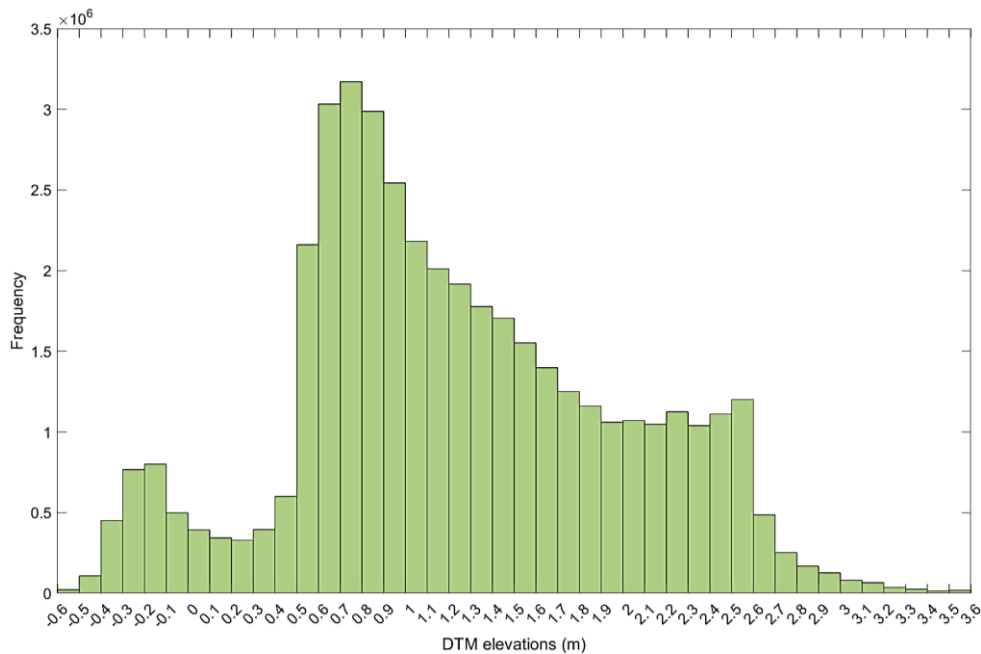


Figure 170 Histogram of Elevations in GDh. Rathafandhoo

GDh. Rathafandhoo island has distinctive features that are found in the southern islands of Maldives whereby a high ridge exists on the windward side due to continuous wave action and overtopping. The ridge can be as high as 2.5 m but decreases considerably near the wetland area which has an elevation of around 0.7 m.

Elevation profiles processed through Golden Software Surfer is shown below. Profile 1 indicates the elevation of the main road that stretches from the north east to the south east. The elevation remains around 0.75m and is generally flat and constant.

However, profile 2 shows the extent of change from the leeward to windward side. Besides peaks at the ridge at the shoreline and other vegetated areas around 100 and 200 m in the profile, elevation of the island changes by a large extent from 325 m onwards to form a ridge that is 2.6 m high with a steep gradient on the shoreward side.

Profile 3 along a main road also shows a very clear change starting from the harbour region which is higher with a ridge elevation around 1m from MSL to a large change beyond 425 m to form a high and steep ridge 2.7 m high. The average elevation of the island in the center remains around 0.75m.

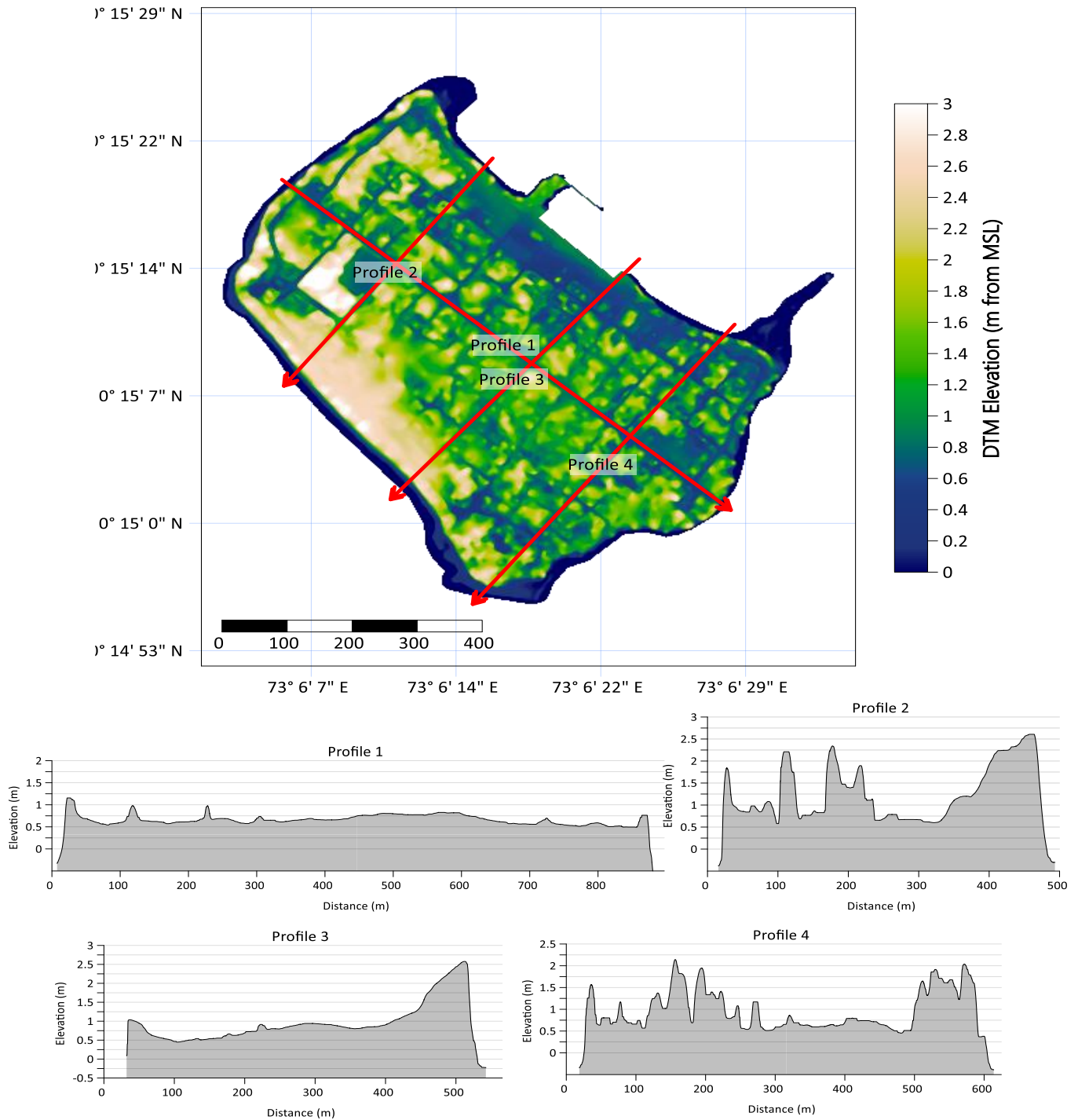


Figure 171 Digital Terrain Model Elevations and Profiles for GDh. Rathafandhoo Island

9.2.2 Shoreline

GDh. Rathafandhoo shoreline is 3134 m long. The island follows the typical shape of an island on the western ridge of Huvadhoo Atoll with features such as the fanned out sediment regions (yellow) that are exposed during low tide and elevated ridges on the windward shoreline that serves as a natural flood defense.



Figure 172 Orthomosaic generated for GDh. Rathafandhoo. Windward region with large gravel sized sediment (orange) and fanned out sediment that are exposed during low tide (yellow)

9.2.3 Reef

GDh. Rathafandhoo is found on the same reef as GDh. Hoandehdhoo and GDh. Nadella along with dozens of uninhabited islands strewn across this reef. The two islands immediately north east of GDh. Rathafandhoo are Kurehdhoo and Dhiyanigillaa respectively. The three islands immediately southeast of GDh. Rathafandhoo are Dherukerehaa, Faahuttaa and Meyragillaa. All 5 islands have recently been assigned as part of GDh. Rathafandhoo council's expanse.



Figure 173 Sentinel 2 imagery taken of GDh. Rathafandhoo Reef in January 2022

9.3 Socio Economic Status

9.3.1 Demography

The Island of GDh. Rathafandhoo has a registered population of 514 as per the 2014 census, with a total of 273 males and 241 females. The island population density is 38.3 people per hectare as per the 2021 figures. The population figures have drastically increased over the past years where the total registered local population climbed up to 1382. The following table and graph illustrate the demographic breakdown of GDh. Rathafandhoo.

GDH.Rathafandhoo

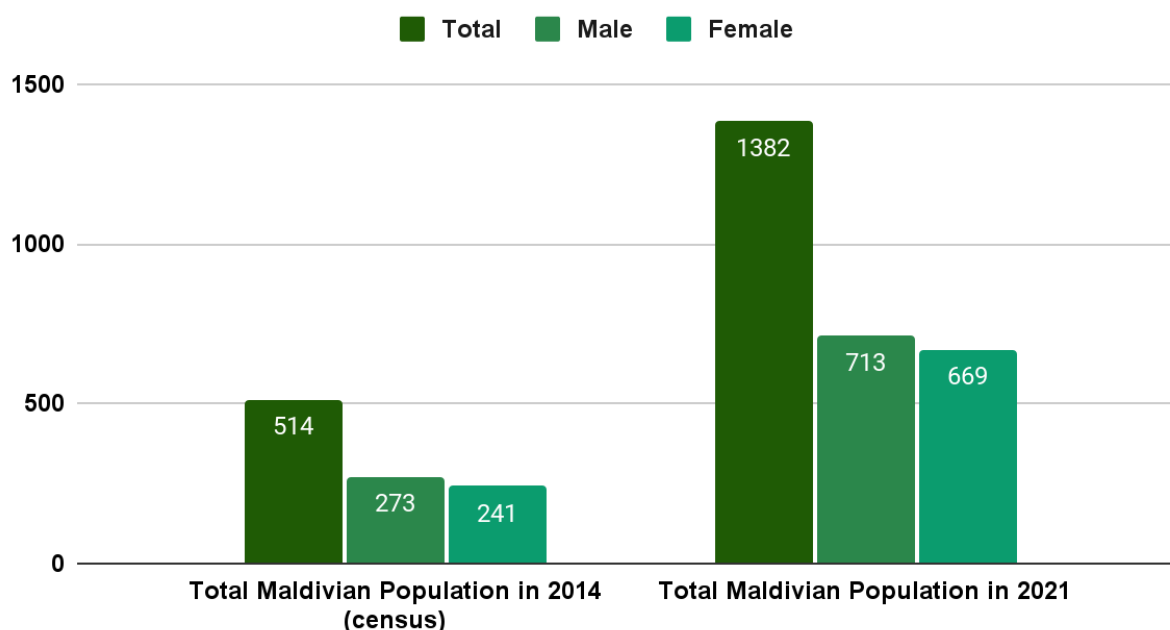


Figure 174: GDh. Rathafandhoo Population

Table 145: GDh. Rathafandhoo Population (Census, 2014)

Resident Population according to Census 2014										
Atoll	Locality	Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
GDh	Rathafandhoo	550	302	248	514	273	363	36	29	7

9.3.2 Socio-Economic Activities

GDh. Rathafandhoo is an inhabited island in Gaafu Dhaalu Atoll's administrative unit and physically part of Huvadhu Atholhu Dhekunuburi Atoll in the Maldives'. This island is well-known for its fishery and agricultural activities. The island also has 2 cafes/restaurants and 10 shops.

9.3.3 Facilities available

9.3.3.1 Health Care

GDh. Rathafandhoo Health Center currently has 1 doctor, 3 nurses and 5 beds. The health facilities in the island are bare minimum and many island residents find that the health center needs to be upgraded and service hours need to be extended.

9.3.3.2 Education

GDh. Rathafandhoo school has 97 students, 25 teachers and 11 administrative staff. The island school offers education upto grade 10 standard.

9.3.3.3 Utilities

Electricity on the island is provided by state owned utility company FENAKA. The island currently does not have a sewerage and sanitation system.

9.3.3.4 Transportation

The island has a harbor which was developed by MTCC in 2006. The transportation between GDh. Rathafandhoo island and other islands is by sea.

9.3.4 Water resources, water usage and water consumption

In GDh. Rathafandhoo there are a total of 150 households. 69 out of 150 households were surveyed with geo-coordinated sampling points. Additionally, the 95% confidence interval was maintained with an error margin of 9%. Many households were also unresponsive and not willing to take part in the survey because of unavailability. A maximum of three attempts were made on different occasions to determine unavailability of the participant. A map of households surveyed is attached in Annex V.

Table 146: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	69/150 households = 46%
Percentage of well fitted with pumps	96%
Ground water	Usage in percentage
Source of drinking	0
Source of cooking	0

9.3.4.1 Existing water and sanitation

The main form of sanitation is via the use of septic tanks. Each household has one or two septic tanks, and the septic tanks are cleaned periodically by disposing the septic waste into the sea. According to the Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22), annex 4 states that the households should keep a 15 meters (49.2126 ft) distance between septic tank and nearest well. The main reason for the adoption of this standard is to negate any possible causes of contamination in the groundwater. This being the recommended standard, majority of the surveyed households were reported with less than 49ft distance between septic tank and water well. In GDh. Rathafandhoo 84 percent reported to have less than 49ft distance between septic tanks and water well while, 7% reported that they do not know an exact distance between them.

Rainwater is also the primarily used for cooking. Many homes use rainwater from neighbouring houses or bottled water when rainwater is not readily available during the dry season. Rainwater collected from rooftops is stored mostly in water tanks, whether at home or communal rainwater tanks.

In GDh. Rathafandhoo, 6 houses have connected rainwater to the well and have reported improvement in groundwater. On the same note, 84% of the households have rainwater drained to the ground.

9.3.4.2 Water usage and resources

Based on the survey conducted in GDh. Rathafandhoo, 93% of the houses have HDPE rainwater tanks for rainwater storage. Also, 97% of the households use rainwater for cooking and 84% use rainwater for drinking. While groundwater is mainly used for gardening, household cleaning with 96% of the houses fitted with water pumps. The following sections regard further details about various water usage and consumption scenarios in the island.

9.3.4.3 Domestic water usage

Based on household water usage surveys in GDh. Rathafandhoo, **406,308** Liters of water is used daily in the households. A total of **294** Liters of groundwater are consumed per capita per day. In GDh. Rathafandhoo, 48% of the surveyed households shower more than 3 times daily and take 19 minutes to shower on an average. This is a factor for high groundwater usage.

Table 147: Domestic groundwater use data for GDh. Rathafandhoo

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
166	25.37	12.57	46.86	3.21	30.12	9.62	294

*All units are in Liters per capita per day

9.3.4.4 Commercial water usage

Based on the survey conducted in GDh. Rathafandhoo, there are currently two operational café'/restaurants. A total of **899** Liters of groundwater are used by commercial entities and their detailed breakdown is given in the table below.

Table 148: Commercial groundwater use data for GDh. Rathafandhoo

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Coffeeology	168.8	121.14	-	180	15
Zaithooni cafe	101.3	-	302.8	-	10
					899

*All units are in Liters per day

9.3.4.5 Industrial water usage

GDh. Rathafandhoo has one industrial farm, and the total groundwater usage is **430** Liters daily.

Table 149: Groundwater use for Farming in for GDh. Rathafandhoo

Total farms	Type of plantation	Farming period	Plantation size (sqft)	Total
1	Fruit Vegetable	Throughout the year	4000	430

9.3.4.6 Institutional water usage

Based on the survey conducted in GDh. Rathafandhoo, there are currently six institutions that have groundwater well facilities and use groundwater on this island. A total of **3,190** Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 150: Institutional groundwater use data for GDh. Rathafandhoo

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Hospital	254.39	120	60	331.2	765.6
Police Station	36.3	-	-	1059.8	1096.1
GDh. Rathafandhoo School	1011.5	-	4.3	-	1015.8
Powerhouse	117.4	-	2.9	-	120.2
Council Office	94	-	2.9	-	96.8
Magistrate Court	85	-	10.7	-	95.5
					3,190

*All units are in Liters per day

9.3.5 Present & Future water demand

In GDh. Rathafandhoo the present water demand is at **410,797** Liters per day and it is expected to decrease groundwater usage with the establishment of water supply services in the island. The year 2021 figures are as per the latest island council data. For the figures in year 2036 and 2054, it is as per Maldives Populations Projections Report published by the National Bureau of Statistics.

Population Projection - GDH.Rathafandhoo

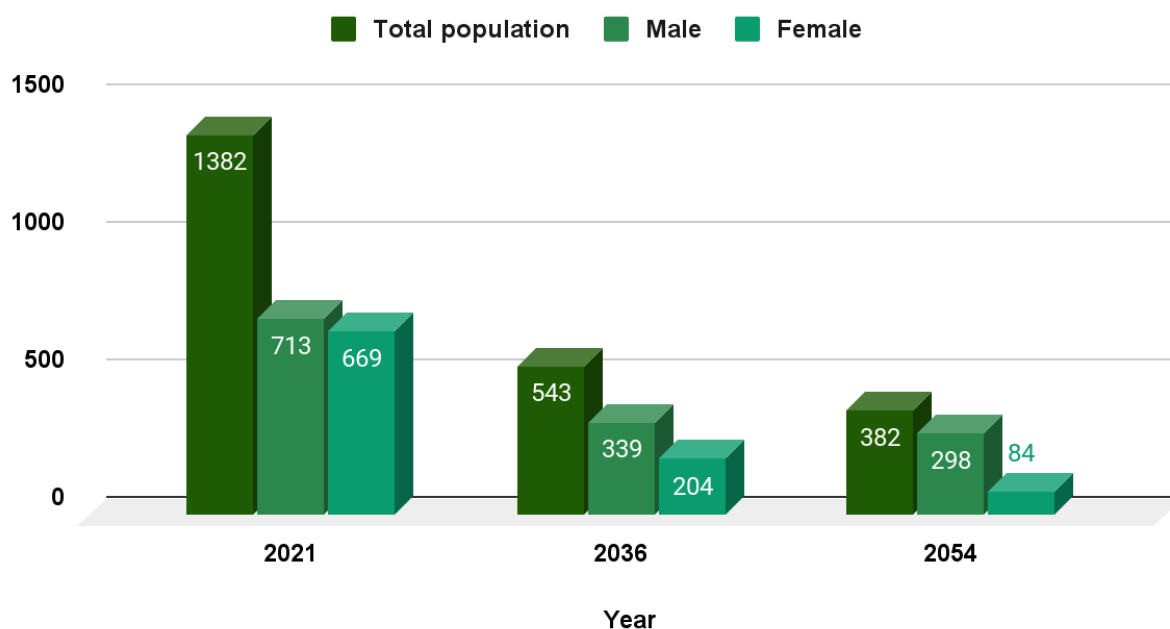


Figure 175: Population Projection -GDh. Rathafandhoo

Table 151: Present groundwater demand – GDh. Rathafandhoo

Year	Total Population	Domestic water demand	Industrial water demand	Institutional water demand	Industrial water demand	Groundwater usage
2021	1382	406,308	899	3,190	400	410,797

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 239 Liters per day. For the year 2036, water supply usage is expected to be 50 Liters per capita per day. After deducting 50 Liters from 294 Liters, the groundwater demand is expected to be 244 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 543 is expected to be **132,492** Liters per day.

For the year 2054, water supply usage is expected to be 75 Liters per capita per day. After deducting 75 Liters from 294 Liters, the groundwater demand is expected to be 219 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 382 is expected to be **83,658** Liters per day.

Table 152: Future domestic water demand – GDh. Rathafandhoo

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	543	294	50	244	132,492
2054	382	294	75	219	83,658

9.3.6 Water related issues

From 69 households surveyed in GDh. Rathafandhoo, most houses reported smell (49%) and Milky/cloudy texture (16%) in their respective wells. Only 22% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gases such as Hydrogen Sulfide which causes unpleasant smells.

Table 153: Signs of contamination reported by households

Types of contamination	Data in % out of 69 households surveyed
Smell	49%
Milky	16%
Foul taste	6%
Salty	13%
None	43%

The following table details out the changes in groundwater quality reported by the households during tidal or seasonal changes.

Table 154: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 69 households surveyed
Changes with tidal variations	39%
Groundwater quality is better in rainy months (Hulhangu season)	55%
Long periods without rain causes bad smell	25%
Long periods without rain causes bad taste	6%
Rain makes it worse	0%
No change	20%

9.4 Groundwater Quality

9.4.1 Physiochemical survey results

Groundwater quality measurements were taken at 40 selected locations and the following Table 155 summarizes the water quality results. Map of locations where groundwater quality points were taken for physiochemical analysis is attached to Annex VI. The full list of measured parameters is attached to Annex VII.

Table 155: Statistical summary of groundwater physiochemical parameters in GDh. Rathafandhoo

	EC ($\mu\text{S}/\text{cm}$)	Turbidity (FNU)	DO (mg/L)	pH	Temp ($^{\circ}\text{C}$)	Sal (ppt)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
Standards	<1500 Potable purposes <2500 Non-potable purposes Source ¹	<5 Source ²		6.5-8.5 Source ²			<1.5 Odour threshold <35 Taste threshold Source ¹	<50 Source ¹	
Mean	1376	1.38	4.50	7.47	28.41	0.66	2.65	6.88	0.40
Median	874	0.47	4.26	7.44	28.31	0.41	0.95	4.56	0.25
SD	1816	2.37	2.36	0.34	1.53	0.94	4.90	7.11	0.42
Min	313	-0.02	0.81	6.90	26.56	0.14	0.10	1.37	0.05
Max	11154	11.70	11.14	8.64	35.39	5.77	28.16	39.03	2.08
CV	1.32	1.71	0.52	0.05	0.05	1.43	1.85	1.03	1.07

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH₃= Ammonia, NO₃⁻= Nitrate, PO₄³⁻=Phosphate, SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source¹ = WHO Drinking Water Guidelines, 2017. Source² = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 1376 $\mu\text{S}/\text{cm}$ is lower than both the WHO Standard for potable water (1500 $\mu\text{S}/\text{cm}$) and the WHO Standard for non-potable water (2500 $\mu\text{S}/\text{cm}$). The maximum value for EC (11,154 $\mu\text{S}/\text{cm}$) was observed at an uninhabited household near the mangrove area.
- 1 sample had higher EC than 2500 $\mu\text{S}/\text{cm}$. 8 samples had EC between 1500 $\mu\text{S}/\text{cm}$ and 2500 $\mu\text{S}/\text{cm}$ while 30 samples had EC lower than 1500 $\mu\text{S}/\text{cm}$. The EC distribution is shown in Figure 177.
- EC of groundwater is higher near the coast of the island and lower in the centre of the island.
- The mean Turbidity level at 1.38 NTU fall below the URA Guidelines for drinking water (5 NTU). Three samples had higher Turbidity level than 5 NTU.
- Dissolved Oxygen ranged from 0.81 mg/L to 11.41 mg/L with a mean of 4.50 mg/L.
- All samples fell within the pH range of 6.5-8.5 as per URA Guidelines for drinking water with a mean pH of 7.47.
- Temperature ranges from 26.56 $^{\circ}\text{C}$ to 35.39 $^{\circ}\text{C}$ depending on the well characteristics and time of day reading was taken. Mean temperature was 28.41 $^{\circ}\text{C}$.

- Salinity ranged from 0.14ppt to 5.77ppt with a mean of 0.66ppt.
- The mean Ammonia concentration was 2.65 mg/L which is higher than the WHO threshold for odour but well below the threshold for taste. 65% of samples had concentration below 1.5 mg/L, 35% of samples had concentration between 1.5 mg/L and 35 mg/L and 0% of samples had concentration higher than 35 mg/L. The Ammonia concentration distribution is shown in Figure 176.
- The mean Nitrate concentration was 6.88 mg/L which falls below the WHO Standard for Nitrate concentration (50 mg/L). No sample had Nitrate concentration higher than the WHO standard.
- Phosphate concentration ranges from 0.05 to 2.08 mg/L with a mean concentration of 0.25 mg/L. There is no WHO guideline value for phosphate concentration. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater. Four samples tested had phosphate concentration below 0.1 mg/L. Phosphate concentrations are generally higher in densely populated areas.

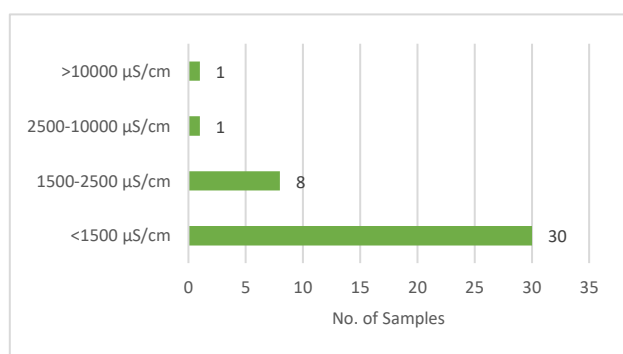


Figure 176: EC Distribution in GDh. Rathafandhoo

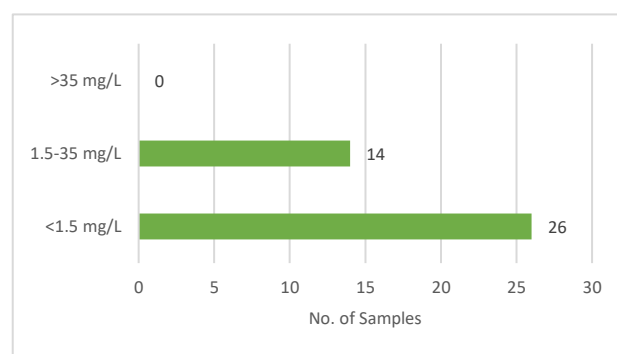


Figure 177: Ammonia Concentration Distribution in GDh. Rathafandhoo

The spatial distribution of all the parameters measured are shown in Figure 178(a-i).

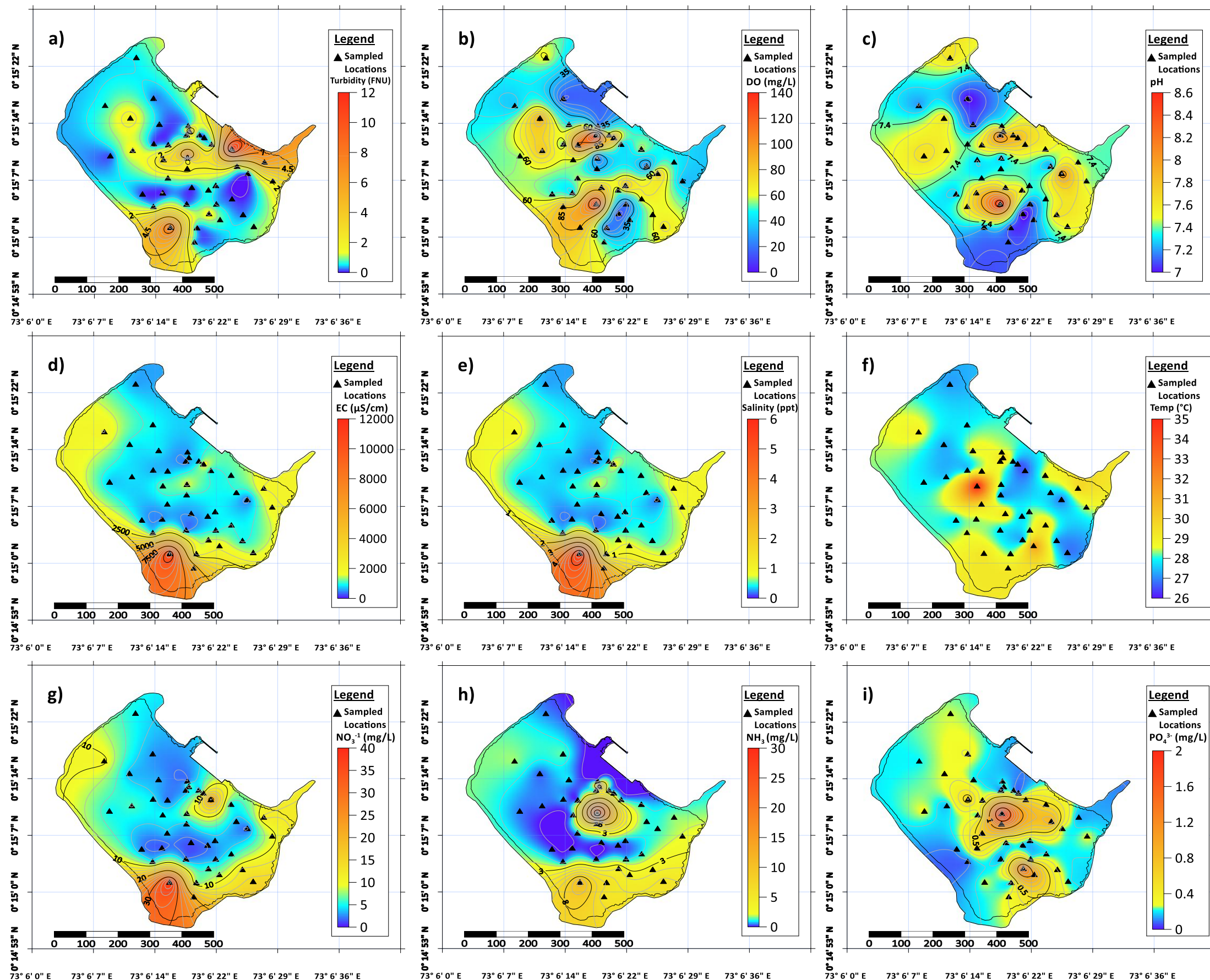


Figure 178: Spatial variation of physiochemical parameters in GDh. Rathafandhoo

As a principle, excessive groundwater usage leads to overextraction causing salinization of the freshwater lens. The Social Survey findings were used to calculate the daily water consumption at each household, institution, and other commercial entities. The EC values at these locations were plotted against water consumption to check if increasing water usage leads to salinization. The correlation coefficient of EC to Water usage is -0.172 and the R-squared of the plot is 0.0296 as indicated from the Figure 179. Therefore, there is no significant relationship observed between EC and Water Usage for the island as per the findings from the Social Survey and Water Quality Survey. The Spatial distribution of EC and water usage is shown in Annex VIII.

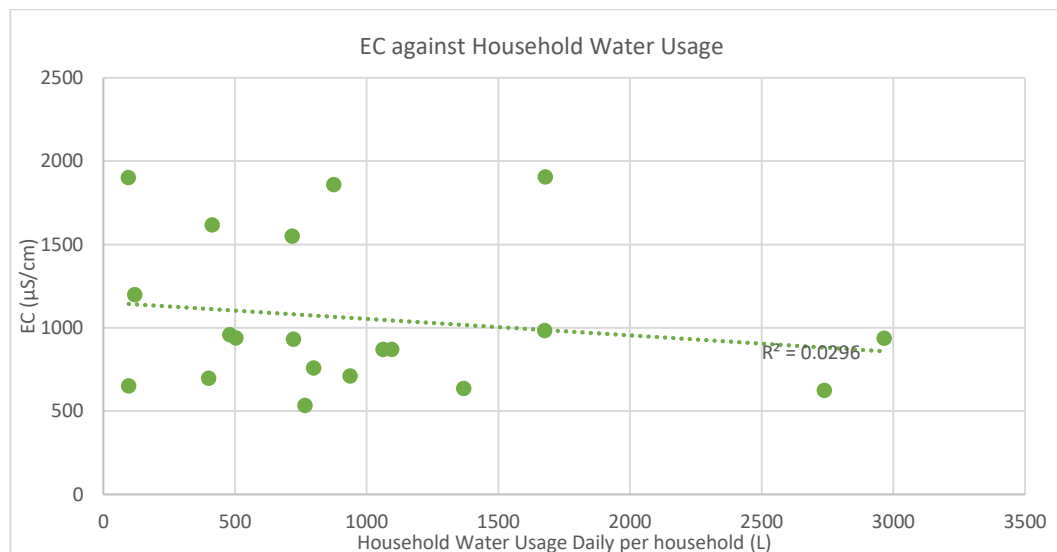


Figure 179: EC against Water Usage in GDh. Rathafandhoo

9.4.1.1 Correlation Matrix

The correlation matrix for GDh. Rathafandhoo along with the colour bar is given below. Red colour indicates negative correlation while green colour indicates positive correlation.

Table 156: Correlation matrix of the groundwater quality parameters in GDh. Rathafandhoo

Variables	Turbidity (FNU)	DO (mg/L)	pH	EC ($\mu\text{S/cm}$)	Sal (ppt)	Temp ($^{\circ}\text{C}$)	NO_3^- (mg/L)	NH_3 (mg/L)
DO (mg/L)	-0.01							
pH	-0.12	0.78						
EC ($\mu\text{S/cm}$)	0.45	-0.01	-0.30					
Sal (ppt)	0.45	0.00	-0.29	1.00				
Temp ($^{\circ}\text{C}$)	0.25	-0.04	-0.23	0.17	0.15			
NO_3^- (mg/L)	0.39	-0.02	-0.19	0.86	0.86	0.02		
NH_3 (mg/L)	0.20	-0.22	-0.22	0.36	0.35	0.02	0.36	
PO_4^{3-} (mg/L)	0.09	-0.46	-0.33	0.01	0.00	-0.08	0.01	0.65

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation
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Table 156 shows a strong positive correlation coefficient between DO/pH ($r=0.78$), EC/Sal ($r=1.00$), EC/ NO_3^- ($r=0.86$) and Sal/ NO_3^- ($r=0.86$). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlations between salinity and conductivity are as expected. There are no strong negative correlations between parameters observed.

9.4.1.2 Water Quality Index

In this study, the computed WQI ranges from 1.79 to 55.34, with a mean of 7.58. The WQI was divided into four categories and Table 157 shows the categorization of samples. 82.5% of samples were classified as "Very Good", 12.5% of samples were classified as "Good", 2.5% of samples were classified as "Poor" and 2.5% of samples were classified as "Very Poor". The high value of WQI at two locations were found to be mainly from the high EC. The spatial distribution of WQI is as per Figure 180.

Table 157: Water Quality Classification based on WQI – GDh. Rathafandhoo

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	33	82.5%
10 to 20	Good	5	12.5%
20 to 50	Poor	1	2.5%
>50	Very Poor	1	2.5%

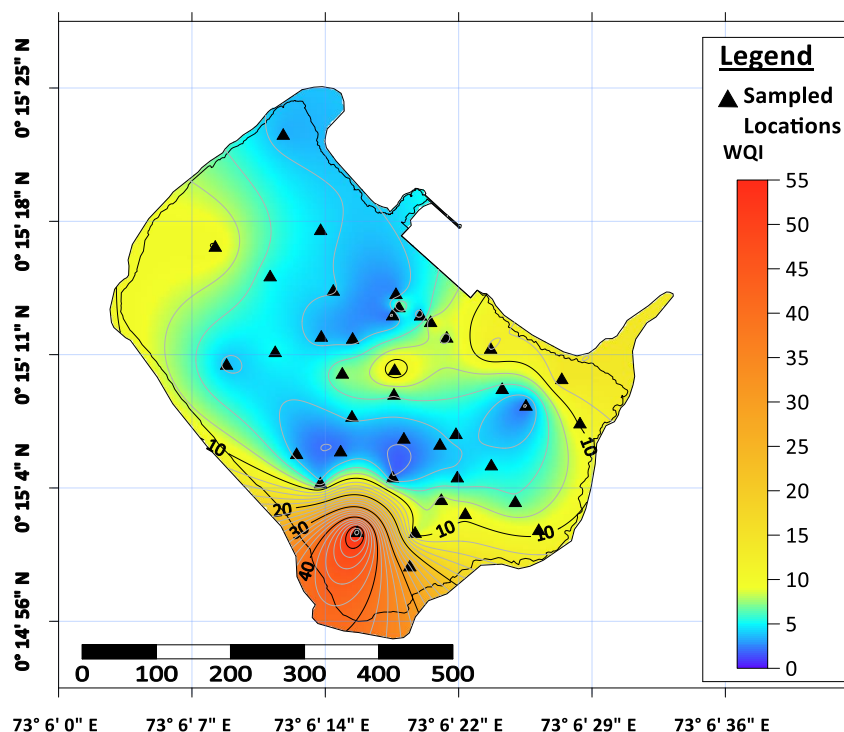


Figure 180: Spatial Distribution of WQI in GDh. Rathafandhoo

9.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 158 summarizes the results.

Table 158: Microbiological Parameters of groundwater in GDh. Rathafandhoo

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq02	38	38		Location does not fall within the coverage of social survey
wq04	17	Not Detected		Health Center
wq06	66	Not Detected		Court
wq11	56	Not Detected	75	Septic Tank. Not cleaned yet.
wq12	34	4		Location does not fall within the coverage of social survey
wq17	2420	30		Location does not fall within the coverage of social survey
wq20	>2420	47	N/A	Septic Tank. Not cleaned yet.
wq23	1120	1120		Location does not fall within the coverage of social survey
wq28	1203	1046	25	Septic Tank. Not cleaned yet.
wq30	1046	146		Location does not fall within the coverage of social survey
wq32	225	38		Location does not fall within the coverage of social survey
wq33	345	40	20	Septic Tank.
wq36	980	63	16	Septic Tank. Septic Tank cleaned once a year and waste buried elsewhere in island.
wq38	345	8		Location does not fall within the coverage of social survey
wq40	461	3		Location does not fall within the coverage of social survey

*Distance between water well and nearest septic tank (feet)

Faecal Coliform was detected in 12 samples and Total Coliform was detected in all 15 samples. 1 sample containing Total Coliform count higher than 2400 MPN/100mL was detected.

The effects of effluent leakage from septic tanks are evident in the microbiological survey results. On average, there is an approximate distance of 22 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Faecal Coliform and Total Coliform is given in Figure 181(a and b). Moderately even spatial distribution of both Faecal and Total Coliform were observed.

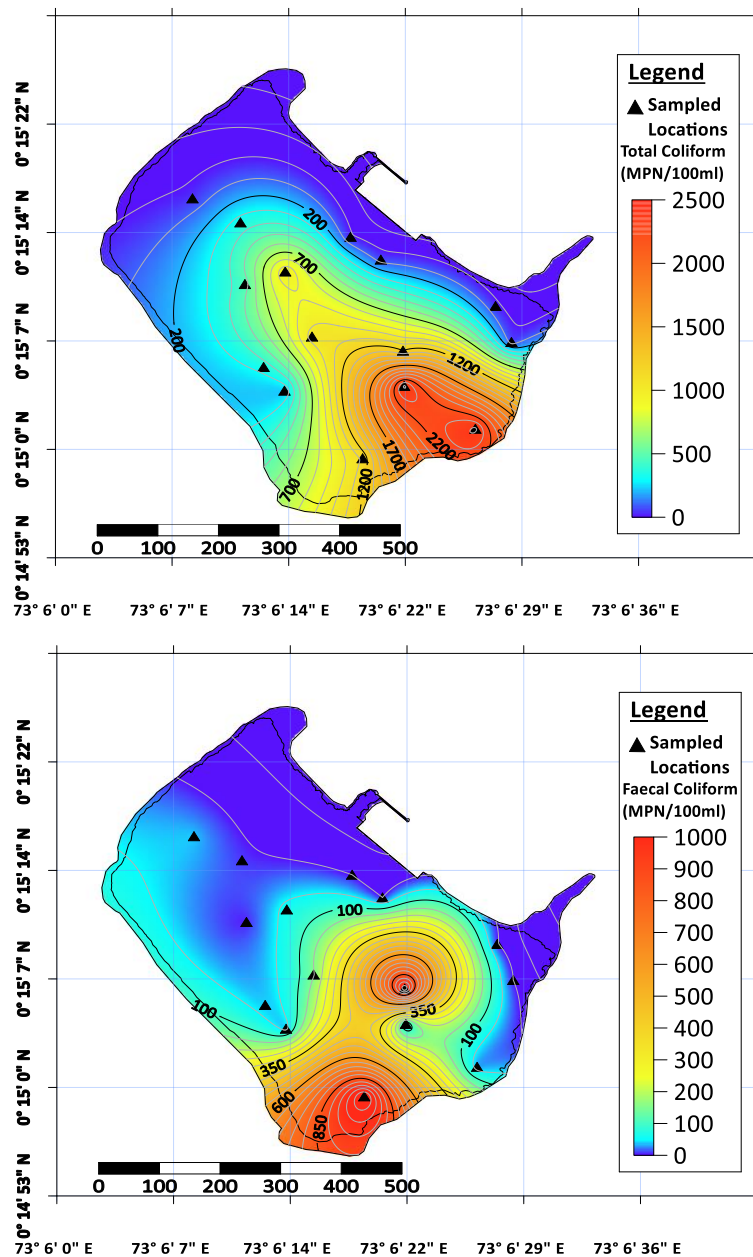


Figure 181: Total (a) and Faecal (b) Contamination Distribution in GDh. Rathafandhoo

The Total Coliform and Faecal Coliform Contamination was plotted against the distance between septic tank and well, to identify the correlation between these two variables. The graphs are given below.

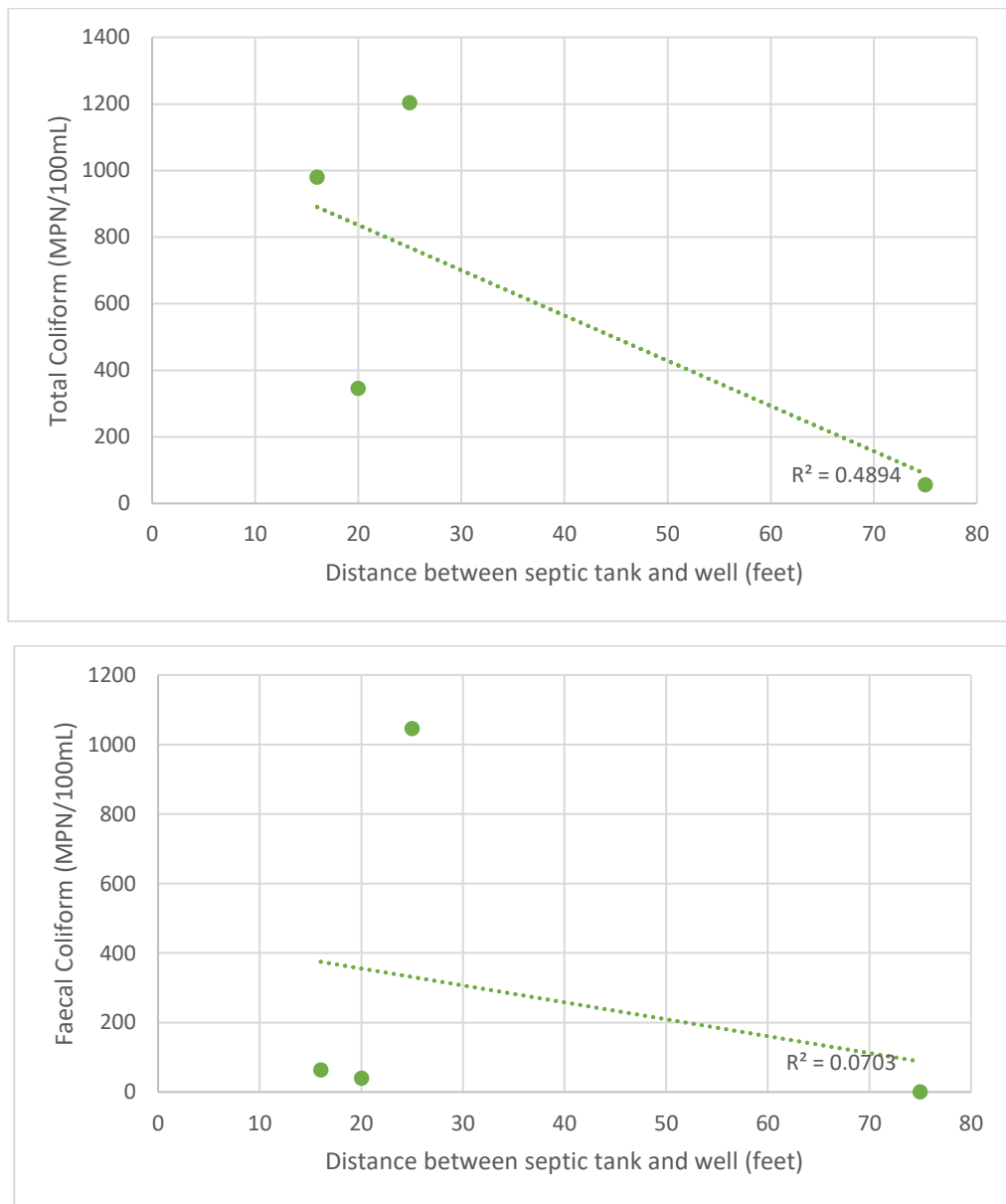


Figure 182: Microbiological Contamination against Septic Tank distancing - Rathafandhoo

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.7 and the R-squared of the plot is 0.489. The correlation coefficient of Faecal Coliform to distance between septic tank and well is -0.235 and the R-squared of the plot is 0.0703. Therefore, there is no significant relationship observed between the parameters.

9.5 Pumping Test

9.5.1 Test location

A well with a Sandy Gravel bed base was available from an uninhabited house in GDh. Rathafandhoo and hence, it was selected to be used for the pumping test. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 183 below shows the location for the pumping test at GDh. Rathafandhoo.



Figure 183: Pumping test location - GDh. Rathafandhoo

9.5.2 Pumping rate, pumping hours and collected data

A constant rate pumping test was carried out at GDh. Rathafandhoo. The test began at 1642 hours on 27 November 2021 and lasted for 120 minutes. A flowrate of 20 LPM was maintained for the pumping phase which lasted from the 0–30th minute. The recovery phase of the test lasted from 31st–120th minute for more than a 90% recovery.

9.5.3 Hydrogeological parameter estimation

The Cooper-Jacob Solution for Unconfined Aquifer Models was used to process the data from the pumping test. The analysis was carried out using the software, AQTESOLV. The Aquifer Transmissivity (T) value was estimated to be $1.60 \times 10^{-4} \text{ m}^2/\text{s}$ (13.86 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.1387 for GDh. Rathafandhoo. The full data set of the pumping test at GDh. Rathafandhoo has been annexed at Annex XII.

9.6 Permeability Test

9.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 184 below. The originally proposed locations were changed as necessary due to unavailability of water and electricity for testing, inaccessibility of proposed locations, as well as the prioritizing of public lands that can be used for potential design solutions over private lands.

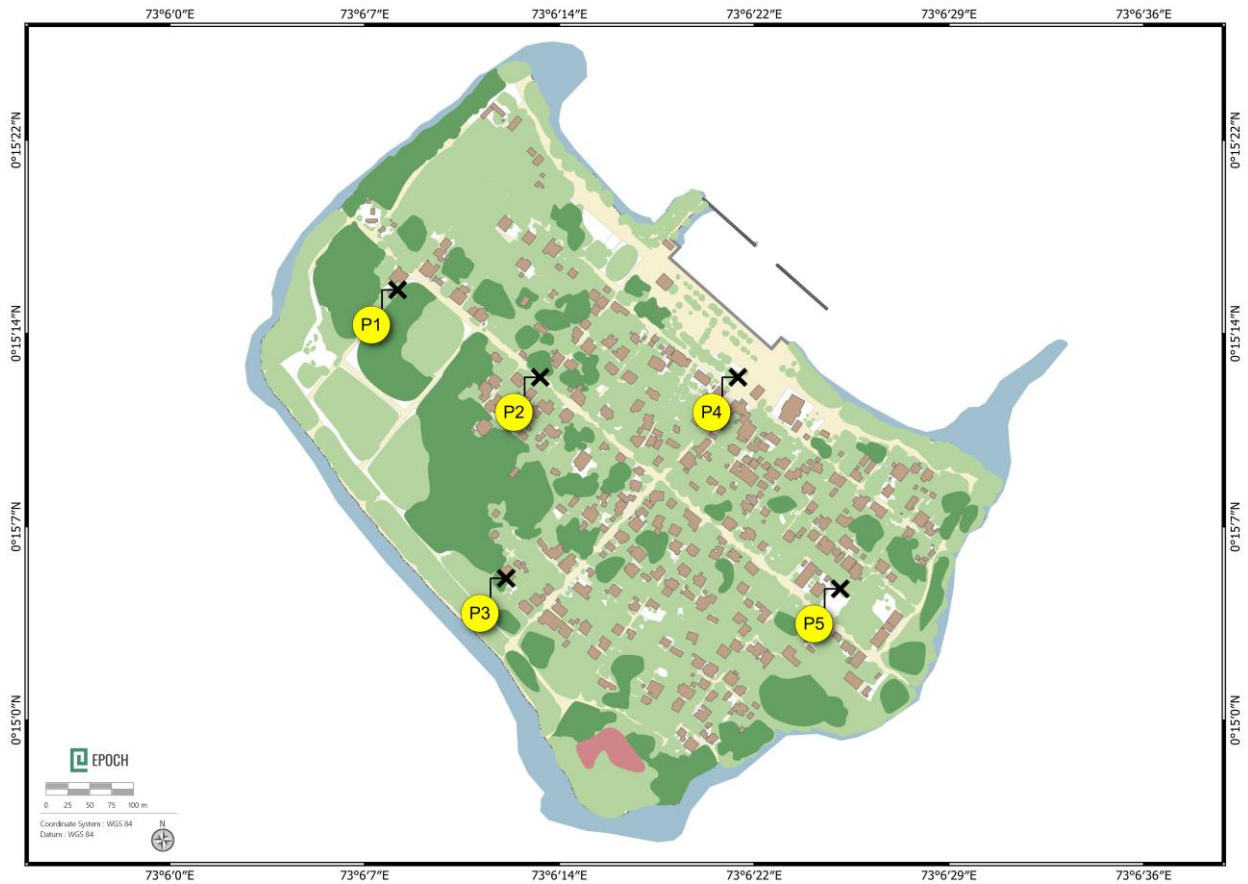


Figure 184: Permeability Test Locations - GDh. Rathafandhoo

9.6.2 Measured data

Table 159: Permeability Test Measured Data - GDh. Rathafandhoo

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m ³ /s)	K (m/s)	K (m/day)
RTF-PMB1	0.600	0.450	35	12.0	0.90	0.000015	3.40E-05	2.937
RTF-PMB2	0.600	0.300	35	12.0	0.75	0.000013	4.25E-05	3.671
RTF-PMB3	0.600	1.425	27	7.5	40.00	0.000667	3.74E-04	32.350
RTF-PMB4	0.600	0.400	35	12.0	31.00	0.000517	1.32E-03	113.800
RTF-PMB5	0.600	0.400	35	12.0	0.75	0.000013	3.19E-05	2.754

Note: H = Height of water in well (m), Tu = distance from water level in casing to water table (m),
Cu = Conductivity Coefficient, r = borehole radius, Q = Steady flow into well,
K = Coefficient of permeability.

9.6.3 Permeability estimation and identified features

The average permeability value for the GDh. Rathafandhoo is 31.102 m/day, with permeability values ranging from 2.754 m/day to 113.800 m/day. As highlighted in Section 9.7 – **Soil Profile Survey**, the island soil profile is predominantly Sands, and the K values above are consistent with the range of K values obtained for Sands (Robertson (2010)).

9.7 Soil Profile Survey

9.7.1 Test locations

Soil Profile surveys were carried in 7 locations across the island, as outlined in Figure 185 below. Out of the 7 locations, 5 points were permeability test locations, and the remaining 2 points were chosen in a way that ensured a uniform coverage of the entire island.

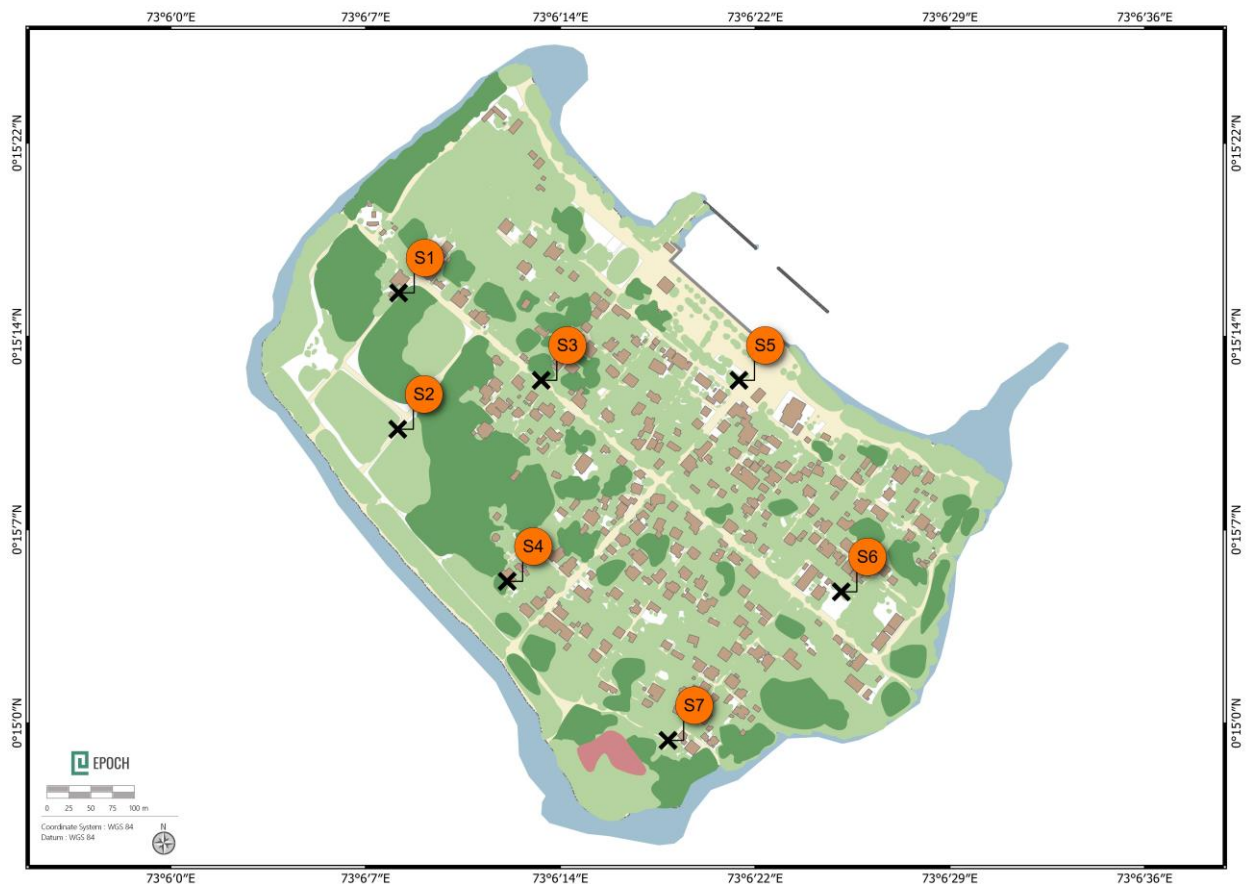


Figure 185: Soil Profile Survey Locations - GDh. Rathafandhoo

9.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 186 below. Even though there are variances in the colour due to environmental factors, the island soil profile is made up of Uniformly Graded Sand for the observed depth.

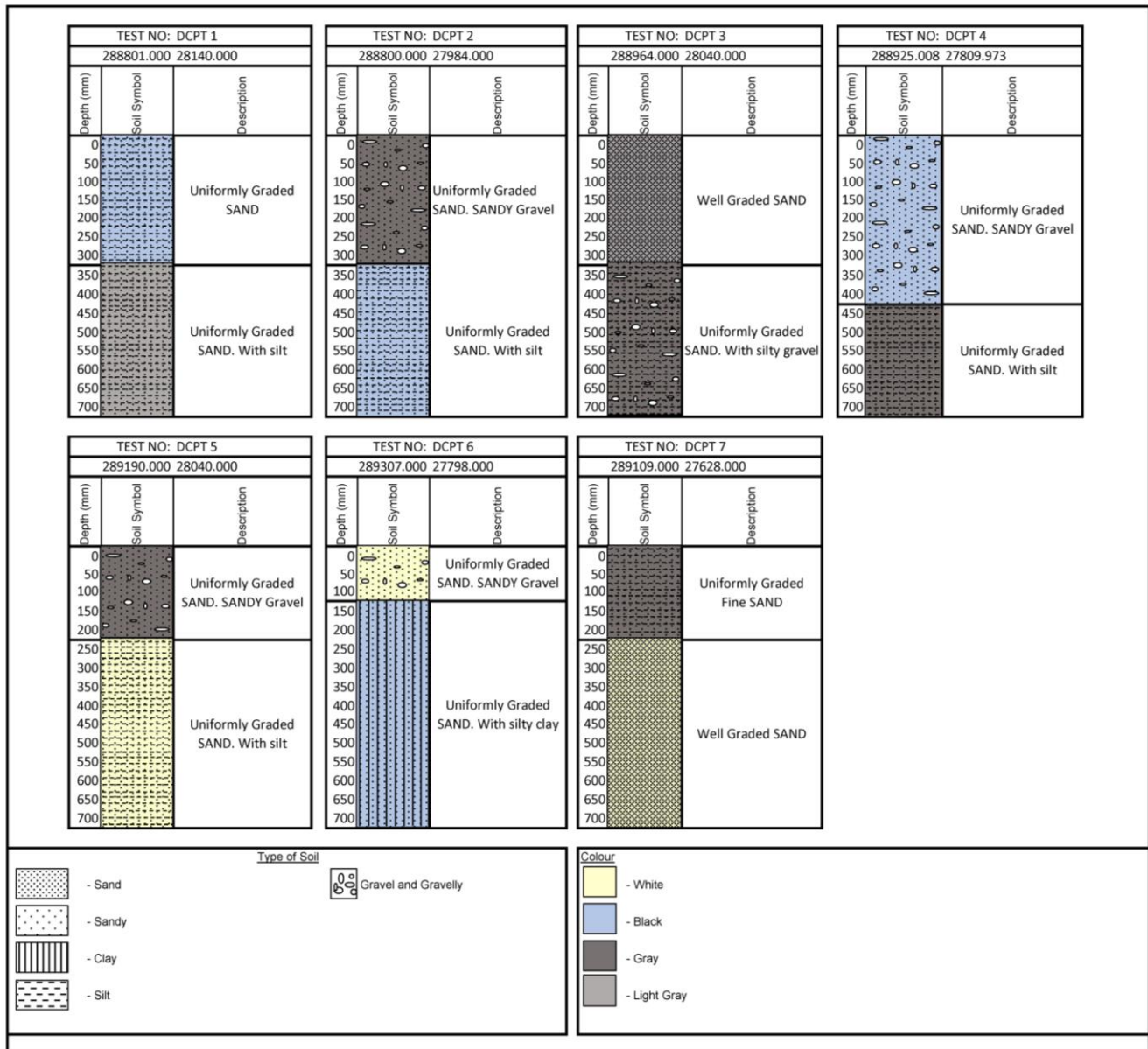


Figure 186: Soil Profile – GDh. Rathafandhoo

9.8 Flood Assessment and Inundation Survey

9.8.1 Flood occurrence and flood impact

GDh. Rathafandhoo has coastal erosion problems on the Southeast side of the island which has an impact on flooding patterns of the island. In GDh. Rathafandhoo, around 72% of the houses reported that flooding occurs mostly when it rains heavily. According to the survey, the majority of the houses reported that island reclamation work and harbour construction had a major impact on the flooding pattern of the island. The island council also reports flooding has increased in front of the council office after the harbour project.

The flooding originates mostly from roof runoff (52%) as per the Social Survey. Most responses state multiple sources for the flooding within their properties such as from neighbours' roof, off the road, and general run off in the area. Perceived causes of flooding as per social survey are given in table below.

Table 160: Perceived causes of flooding – GDh. Rathafandhoo

Perceived causes of flooding				
Roof run off	Neighbours' roof	Off the road	General run off in the area	No flooding within the plot
52%	7%	26%	17%	28%

From the social survey, 86.6% of households report that they drain rainwater overflow from storage and roofs to the ground. Most responses state multiple ways for the discharge of rainwater overflow to the roads, open areas within the plot and to the well. Details of discharge of rainwater overflow are given in the table below.

Table 161: Discharge of rainwater overflow – GDh. Rathafandhoo

Discharge of rainwater overflow			
Ground	Roads	Open area within the plot	Drained to well
86.6%	4.48%	0%	8.96%

In GDh. Rathafandhoo, 56% households report flooding as an acceptable problem (Refer to flood severity component of Flood Maps in Annex XIV). This can be due to continuous flood mitigation efforts by the island council and residents.

9.8.2 Flood Depth and Inundation area identification

The common flooding areas are the mangrove area, main road and Veylihankoda area (refer to Annex XIII: Flood Maps). Based on the social survey responses, an average of 0.8ft is estimated as the flooding depth when there is a heavy rainfall. Also, 52% reported that it takes 2-4 hours to inundate the area once the heavy rain starts.

9.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 64% observe that the water drains during the rainfall itself, 25% observe that the water drains in less than 4 hours, 2.5% observe that the water drains in less than 4-24 hours and 8% observe that it takes more than 24 hours for water to drain.

Table 162: Draining period - GDh. Rathafandhoo

Draining period			
only while raining	drains less than 4hrs	takes 4-24 hrs	more than 24hrs
64.2%	25%	2.5%	8.3%

9.9 Geophysical Survey

9.9.1 Surveyed Locations

Locations where ER sounding measurement taken at GDh. Rathafandhoo island are shown in Figure 187 together with transect lines. There are 29 ER measurement locations and the number of transects in this island is 9.

GDh Rathafandhoo ER Surveyed points and Transects

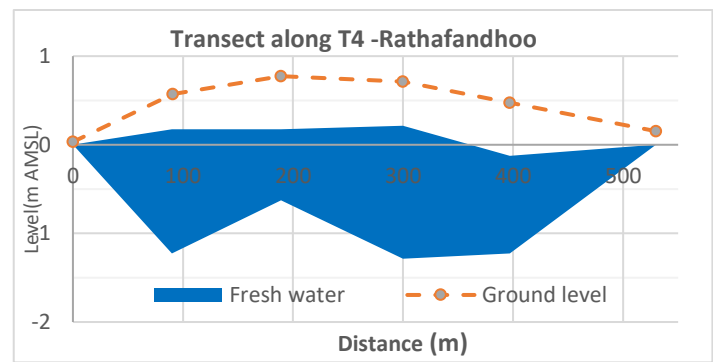
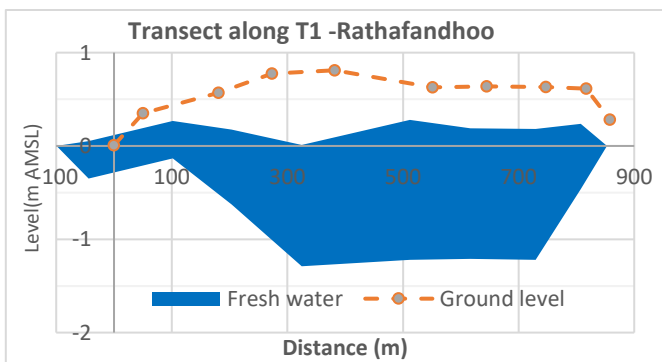


Figure 187: ER surveyed locations and transect lines – GDh. Rathafandhoo Island

9.9.2 Freshwater levels and saline water levels

From processed ER data using GeoVES 1.5 – GeoElectrical Model depth to freshwater starting level and depth to freshwater lens bottom level (saline water start level) were determined and they were converted to elevation with respect to mean sea level using ground collected through drone survey. Table 163 below shows the estimated levels at ER surveyed locations of GDh. Rathafandhoo Island and freshwater lens thickness.

Table 163: Freshwater lens levels and thickness – GDh. Rathafandhoo island

No	Map ID	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	Ra1	0.616	0.236	-0.464	0.70
2	Ra2	0.644	0.044	-0.756	0.80
3	Ra3	0.838	0.338	-0.262	0.60
4	Ra4	1.423	1.073	0.523	0.55
5	Ra5	0.568	0.118	-1.282	1.40
6	Ra6	0.631	0.181	-1.219	1.40
7	Ra7	1.533	0.933	0.133	0.80
8	Ra8	0.570	0.070	-1.430	1.50
9	Ra9	0.639	0.189	-1.211	1.40
10	Ra10	0.874	0.524	-1.076	1.60
11	Ra11	2.485	1.485	0.285	1.20
12	Ra12	2.751	2.301	1.201	1.10
13	Ra13	0.629	0.279	-1.221	1.50
14	Ra14	0.606	0.106	-1.394	1.50
15	Ra16	0.656	0.056	-0.744	0.80
16	Ra17	0.352	0.052	-0.348	0.40
17	Ra18	0.482	0.132	-0.468	0.60
18	Ra19	1.900	1.450	0.200	1.25
19	Ra20	0.861	0.441	-0.909	1.35
20	Ra21	0.811	0.011	-1.289	1.30
21	Ra22	0.472	-0.028	-1.528	1.50
22	Ra23	0.476	-0.125	-1.225	1.10
23	Ra24	0.714	0.214	-1.286	1.50
24	Ra25	0.774	0.174	-0.626	0.80
25	Ra26	0.573	0.173	-1.227	1.40
26	Ra27	0.507	0.157	-0.243	0.40
27	Ra28	0.630	0.280	-1.720	2.00
28	Ra29	0.568	0.268	-0.132	0.40
29	Ra30	0.497	0.147	-0.553	0.70

Average freshwater thickness of GDh. Rathafandhoo island is 1.09m.

Data in Table 163 was used to plot freshwater lens cross sections along 9 transects and they are given in Annex IX. Of these sectional plots 2 were given in Figure 187 and they represent the transect plot along the longitudinal section and cross section of the island that passes through island middle. Dotted lines in these plots indicate ground level variation with respect to mean sea level along the transect lines.

9.9.3 Freshwater lens spatial extent

For the purpose of identifying spatial distribution of upper and lower level of freshwater lens the computed freshwater levels and saline water levels at ER points were exported to ArcGIS and used to generate contours with help of interpolation tools available in the same software. The generated contours are shown in Figure 188 and the processed ER data were used to develop a 3D view of the freshwater lens and it is also shown in Figure 188.

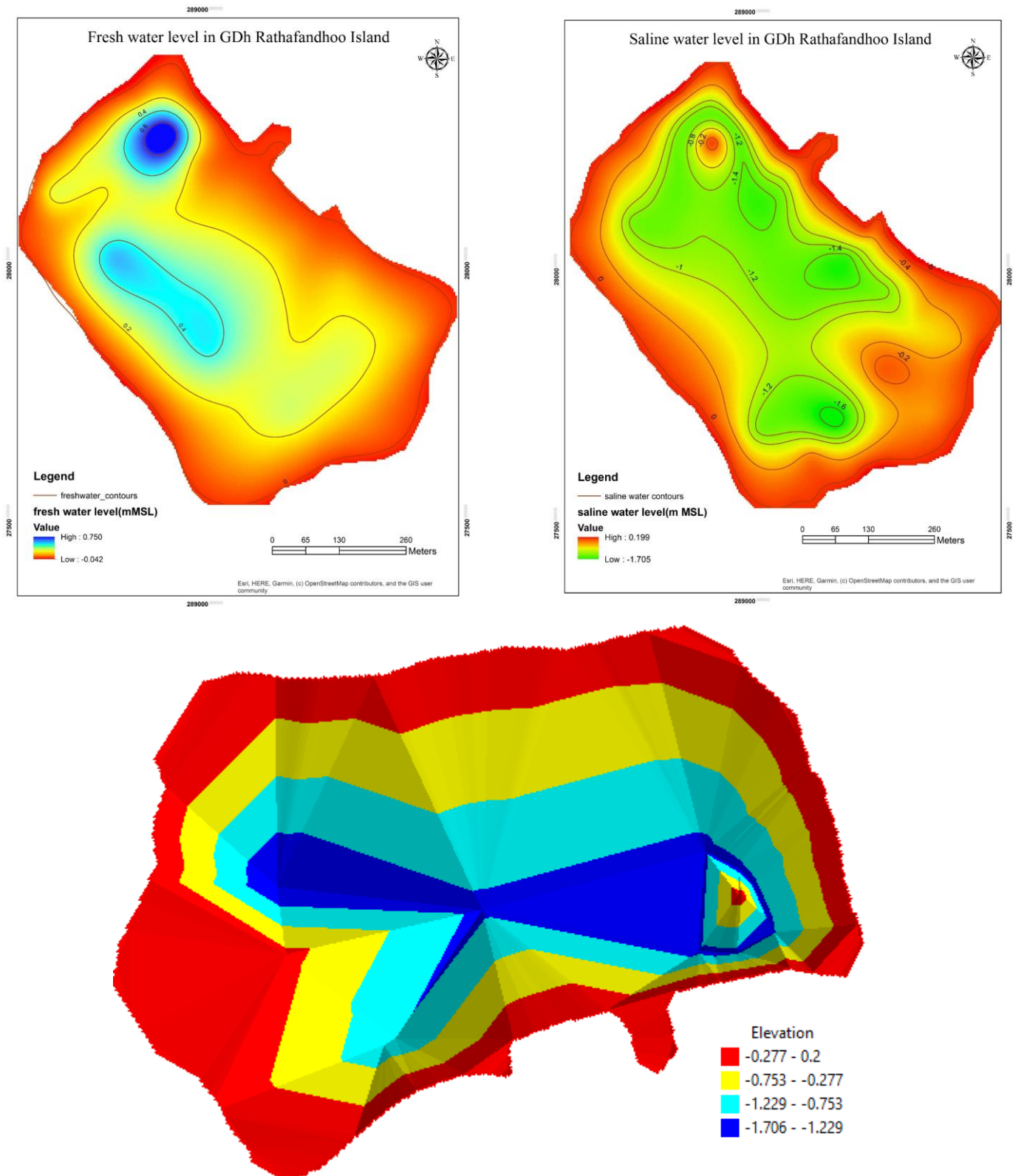


Figure 188: Top Left: Contours of Freshwater lens upper level, Top Right: Contours of Freshwater lens lower level, Bottom: 3D view of Freshwater lens bottom level - GDh. Rathafandhoo island

9.9.4 Freshwater lens storage volume and stress level

For the estimation of freshwater volume, the depth difference between freshwater-saline water interface and freshwater upper level was computed at each ER measurement points and they were then used to determine freshwater volume stored in the ground at time of taking ER measurements. Both “Triangle method” and Tools in ArcGIS software were used to perform this computation. Figure 189 shows triangles considered for the aforementioned computation. Detailed calculations can be found in Annex X: Freshwater Lens volume calculations

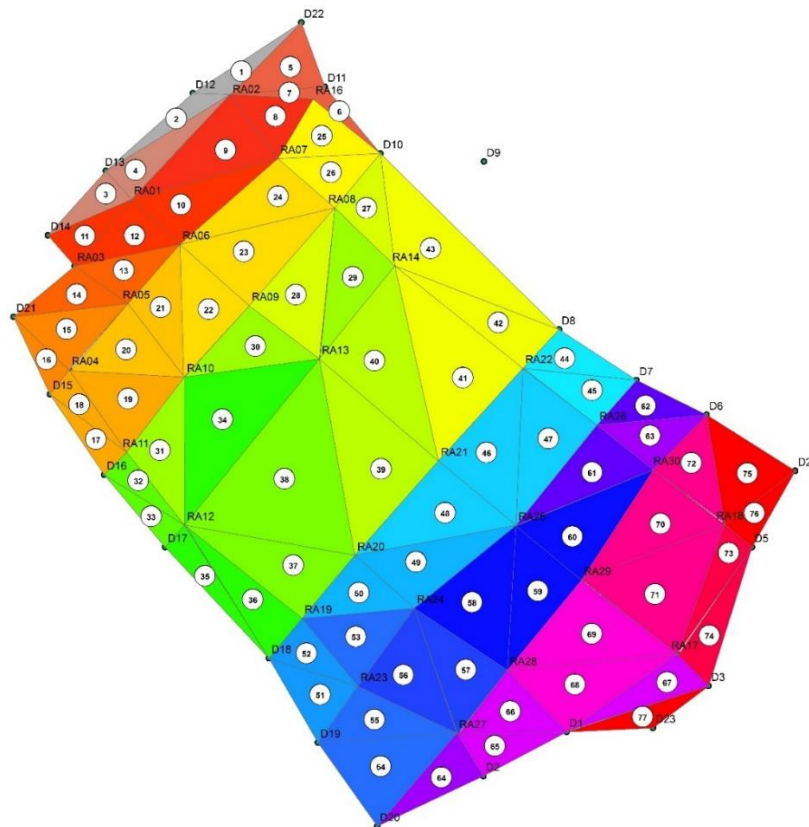


Figure 189: Triangles for freshwater volume computation – GDh. Rathafandhoo island

Stress level on freshwater aquifer of GDh. Rathafandhoo island was determined by computing ratio between freshwater lens volume and annual groundwater abstraction for non-potable water usage at present. When this ratio was more than 1.5, the island was treated as “not stressed” and if it was between 1.5 and 1 the aquifer was assumed to be “stressed” and any other lower ratio was taken as “highly stressed” aquifer. This criterion was developed based on saline water issues collected from the project islands during field work. The computed freshwater volume, water abstraction and aquifer stress level are given in Table 164.

Table 164: Freshwater lens volume and aquifer stress level – GDh. Rathafandhoo island

Item	Value	Unit
Freshwater lens volume – Triangle method	71,541	m ³
Freshwater lens volume – ArcGIS	70,419	m ³
Groundwater abstraction	148,302	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	0.5	-
Aquifer stress level	Highly stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation equates to 9.3m. This deviates by 365% from the maximum measured value of 2m, which is more reliable as it results from a more comprehensive, site-specific methodology.

9.10 SWB Modelling

9.10.1 Topography for flow direction

Topographical data assigned to model grids for computation of D8 flow directions is shown in Figure 190 and according to this figure elevation of the island is changing from 0.057 mAMSL to 2.951 mAMSL and average elevation is 1.342 mAMSL.



Figure 190: Elevation data assigned for SWB modelling - GDh. Rathafandhoo Island

9.10.2 Land use categorization and area estimation

Land use map prepared for SWB modelling of GDh. Rathafandhoo island is shown in Figure 191 together with table a showing land classification and their respective areas. It could be noted from the Figure 2 that 20m x 20m grids are adequate to represent the island land use for SWB modelling purpose.

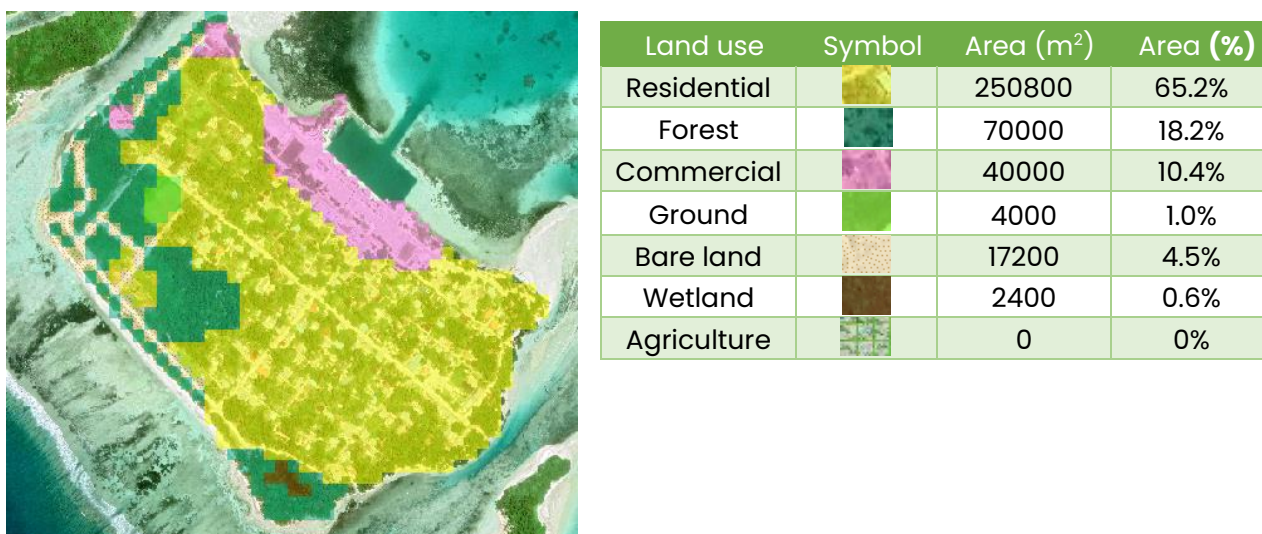


Figure 191: Land use for SWB model - GDh. Rathafandhoo Island

9.10.3 Recharge estimation and distribution

Monthly recharge values estimated at grid cells of the SWB model were extracted and used to identify its variation over years and months (refer Figure 192 and Table 165). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 94.4, 272.0 and 394.3 respectively over a 20 years period.
- There is a good relationship between annual rainfall and annual recharge, it is not linear but inverse exponential.
- Annual average rainfall is around 2270 mm but for 5 consecutive years (from 2008 to 2012) annual rainfall was below average. It indicates that there would be a serious issue of saline water intrusion into the freshwater lens during such period as the recharge value would be considerably lower than annual average recharge value (inverse exponential relationship).
- Variation among the monthly average recharge value is very high. It is lowest on month of March and highest in November.
- Water consumption (pumping) for non-potable use on 8-month period is less than the recharge value on the respective months. It indicates that GDh. Rathafandhoo island heavily depends on groundwater storage and there would be serious issues of saline water intrusion into this island.

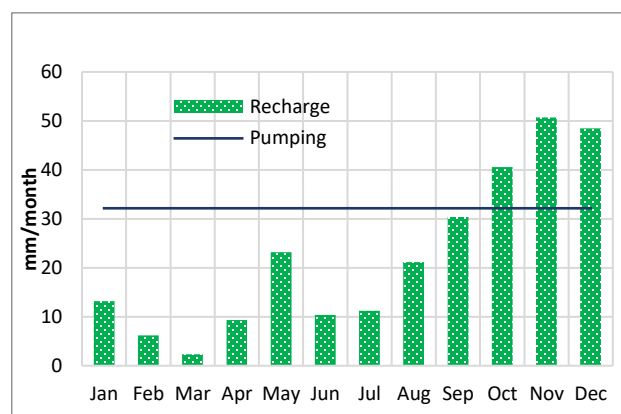
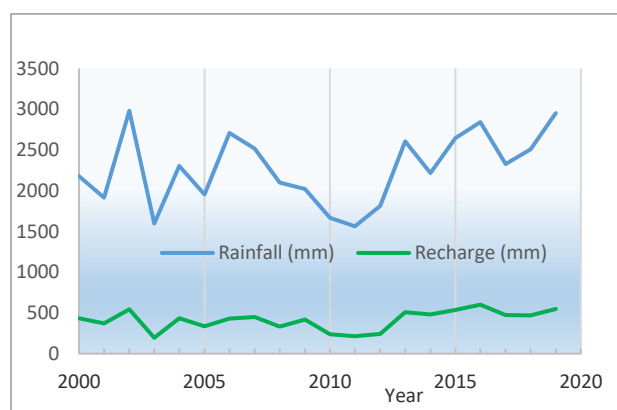


Figure 192: Monthly and annual recharge distribution – GDh. Rathafandhoo island

Table 165: Monthly recharge estimated by SWB model – GDh. Rathafandhoo Island

Year	Monthly Recharge (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	4.4	0.0	0.0	7.8	10.7	54.5	30.8	36.2	132.2	37.3	79.2	40.0
2001	0.0	0.0	0.0	34.8	10.4	0.0	10.9	52.5	80.8	62.3	75.6	45.8
2002	5.9	18.9	15.2	26.1	42.3	71.0	36.5	13.1	38.0	99.9	69.1	108.1
2003	2.2	0.0	0.0	7.5	39.2	29.6	33.1	18.6	0.0	7.8	37.3	20.1
2004	42.2	0.0	0.0	12.2	0.1	0.1	29.9	45.4	65.5	66.4	110.2	61.9
2005	31.1	14.0	0.0	0.0	35.5	56.0	40.3	23.4	18.7	115.0	3.7	0.0
2006	44.3	59.0	0.0	3.7	0.0	5.5	9.9	9.5	53.3	7.9	149.4	88.9
2007	69.5	0.0	0.0	2.7	18.0	42.9	29.4	4.4	38.9	105.4	10.9	128.4
2008	32.6	0.0	0.0	32.8	27.6	17.5	29.7	5.5	0.0	61.1	73.6	54.1
2009	38.5	21.4	0.0	0.0	59.8	0.0	5.7	100.7	25.4	49.9	57.2	59.2
2010	13.6	0.0	0.0	31.6	15.9	0.0	44.0	66.9	47.6	18.5	0.1	0.0
2011	0.0	0.0	0.0	5.3	23.0	0.0	0.0	8.8	0.0	64.9	17.9	93.5
2012	0.0	15.0	0.0	0.0	21.4	8.1	14.8	12.0	14.7	102.1	35.7	16.6
2013	0.0	0.0	10.1	17.8	79.5	12.4	30.3	48.3	13.8	30.7	139.1	129.0
2014	0.0	0.0	8.3	14.5	125.1	0.0	5.5	17.2	152.1	33.9	77.4	46.5
2015	8.4	14.1	0.0	0.0	24.2	26.7	14.0	113.0	33.3	86.4	103.2	113.3
2016	64.5	4.4	24.6	54.1	66.3	5.7	25.4	130.1	24.0	59.6	82.2	60.4
2017	2.6	0.0	13.6	0.0	103.9	0.0	28.6	22.9	97.9	0.0	67.4	137.2
2018	0.0	5.4	0.1	38.3	57.8	55.7	34.7	0.0	67.1	111.2	57.2	42.5
2019	71.3	29.0	6.8	15.2	52.1	65.2	13.0	20.5	84.2	49.3	61.2	80.8

9.10.4 Water Balance

As per estimation, annual recharge estimated by the SWB model is 104,485 m³ and it is 12.0% of annual average rainfall (refer Figure 193).

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	872,276	1,517	9,534	448,799	104,485	307,941	148,302
%	100.0%	0.2%	1.1%	51.5%	12.0%	35.3%	17.0%

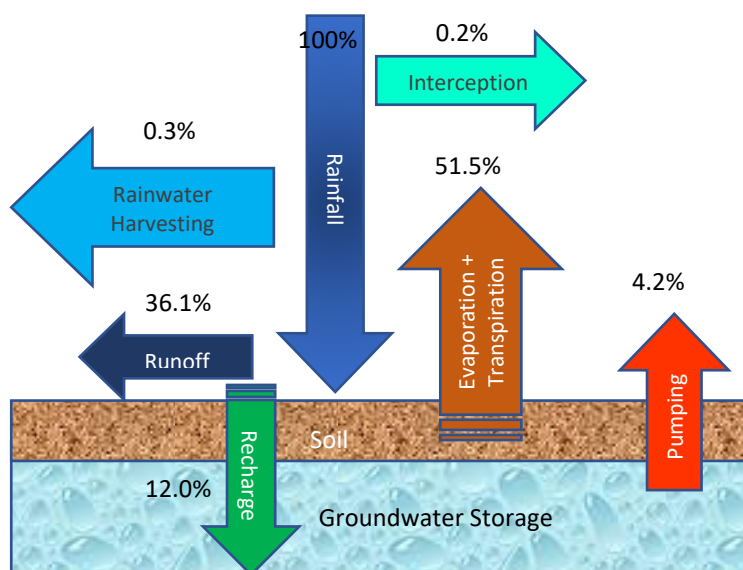


Figure 193: Annual water balance - GDh. Rathafandhoo Island

9.10.5 Deficit estimation, dry month identification and safe yield

Deficit calculation was carried out to identify whether recharge over a month period is smaller than or larger than the pumping quantity in the island. Monthly recharge time series estimated by the SWB model was compared with total pumping quantity of the island (12,359 m³/month) and if recharge exceeds the pumping quantity it was taken as “no deficit” and on other hand if pumping quantity exceeds the recharging value it was taken as “deficit”.

Table 166: Deficit percentage - GDh. Rathafandhoo

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	174	72.5%

It is to be noted that “deficit” doesn’t mean failure or inadequate freshwater for pumping, but it is to be interpreted that the number of months when pumping is to be supported by groundwater storage in addition to recharging quantity. As per estimation, pumping at GDh. Rathafandhoo is 72.5% dependent on the groundwater storage.

Determining safe yield which is defined as the attainment and maintenance of a long-term balance between the annual amount of groundwater withdrawn by pumping and the annual amount of recharge is important for small islands and there are various methods to estimate this amount. One simple method is checking whether ground water abstraction is less than or equal to 10% of average annual rainfall (MoEnv. 2020). The comparison of the estimated ground water withdrawal (148,302 m³/yr) with safe abstraction volume (48,768 m³/yr) shows that present withdrawal is 204 % higher than the safe yield.

9.11 SUTRA Modelling

9.11.1 Model representation and topographical features

SUTRA modelling requires model domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island (refer Figure 194). The other boundary defined in the model was island outline which can be taken as the shoreline for most of the cases except at harbour area and the inner part of the island which was subdivided into several polygons representing different land use areas and it was accomplished by importing GIS shape files of island land use areas and then drawing polygons on shape files. Some other boundaries were also defined to represent island features such as lake and elevation change in the middle of the reef. Mesh with irregular quadrilateral elements were produced for all closed boundaries. Mesh size defined for outer boundaries (area between shoreline and model domain) were 3 to 4 times larger than the same size defined for the inner part of the island. Elevation at shoreline was defined as zero whereas elevations for inner part of the island was assigned from topographical data used for SWB modelling. Figure 194 shows model domain and SUTRA model mesh with topographical changes.

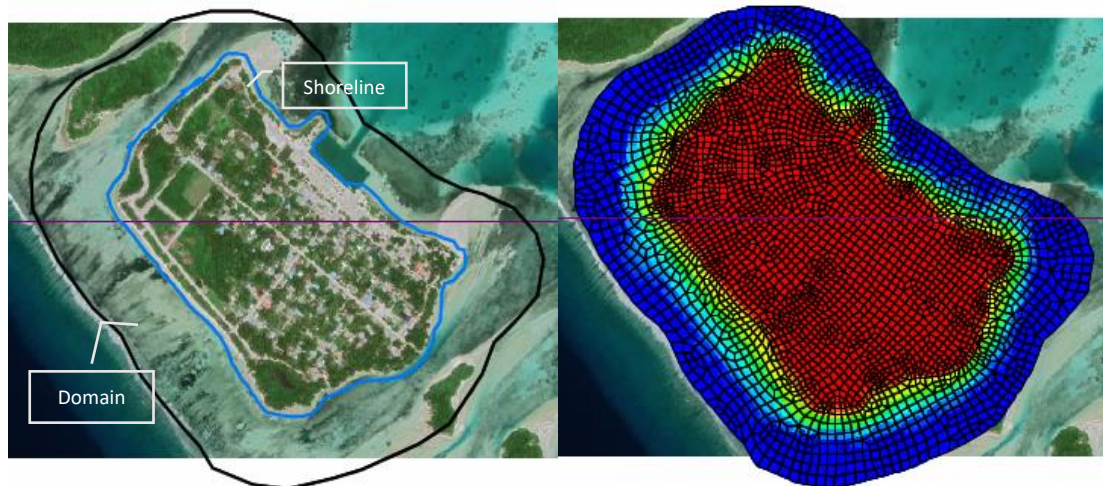


Figure 194: Model boundaries and model mesh - GDh. Rathafandhoo island

9.11.2 Pressure boundaries

Specified pressure boundary was defined along the model domain so that it would cause saline water intruding into the island when pressure along the outer boundary of freshwater lens is less due to lower recharge and/or groundwater abstraction is high. Figure 195 shows the pressure boundary defined for GDh. Rathafandhoo island.

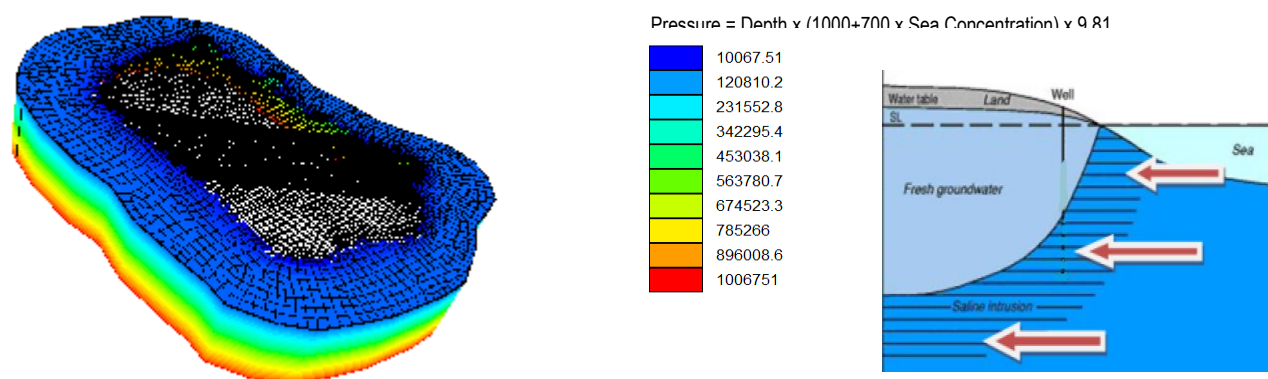


Figure 195: Pressure boundary at SUTRA model - GDh. Rathafandhoo island

9.11.3 Assigning recharge on land use basis

Recharge rates estimated by the SWB model for each grid cells were lumped on land use basis using VB program and ArcGIS tool and they were then used to estimate the monthly average recharge rate on residential area, commercial area, and other land use. Table 1 shows monthly recharge rate estimate for GDh. Rathafandhoo island.

Table 167: Recharge for SUTRA model - GDh. Rathafandhoo island

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	43.9	7.1	35.9	19.5	45.9	38.5	0

9.11.4 Groundwater abstraction

Groundwater pumping takes place at individual houses, restaurants, and institutes. Since all well locations are not available and abstraction rate would also change place to place a simplified approach was adopted by defining a polygon around the residential area (area highlighted in blue in the below map) and assigning average pumping rate of 12,359 m³/month.



Figure 196: Pumping region at SUTRA model – GDh. Rathafandhoo island

9.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20 year period is shown in Figure 197. The orange-coloured component in the 3D view represents sea water concentration around the island and the section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0375 (= 37.5 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top and at very shallow water depth.

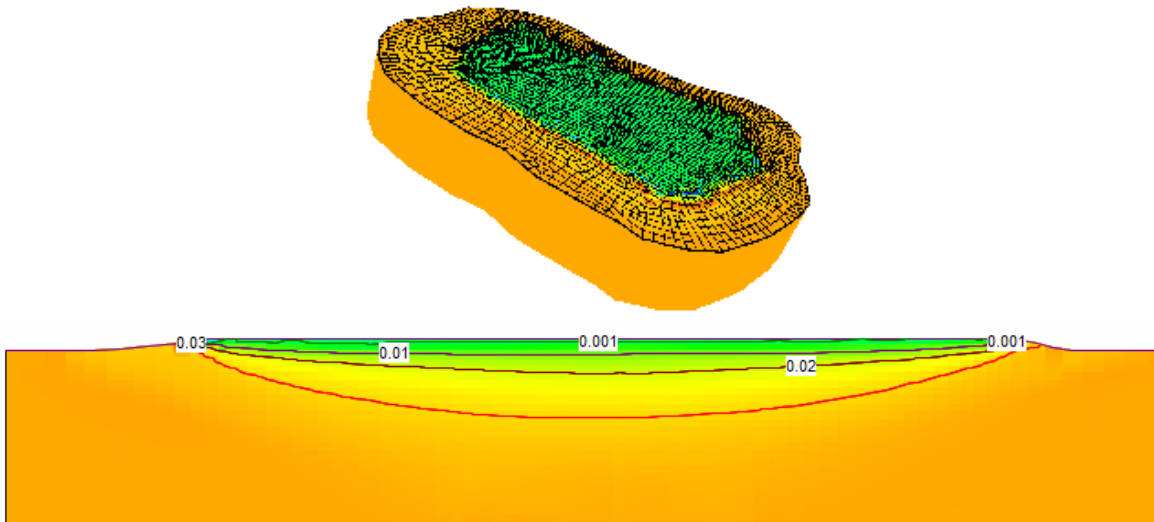


Figure 197: Saltwater distribution – GDh. Rathafandhoo island

9.12 Summary of Baseline Assessment

Summary of findings extracted from field works, laboratory test, modelling and analysis are presented below.

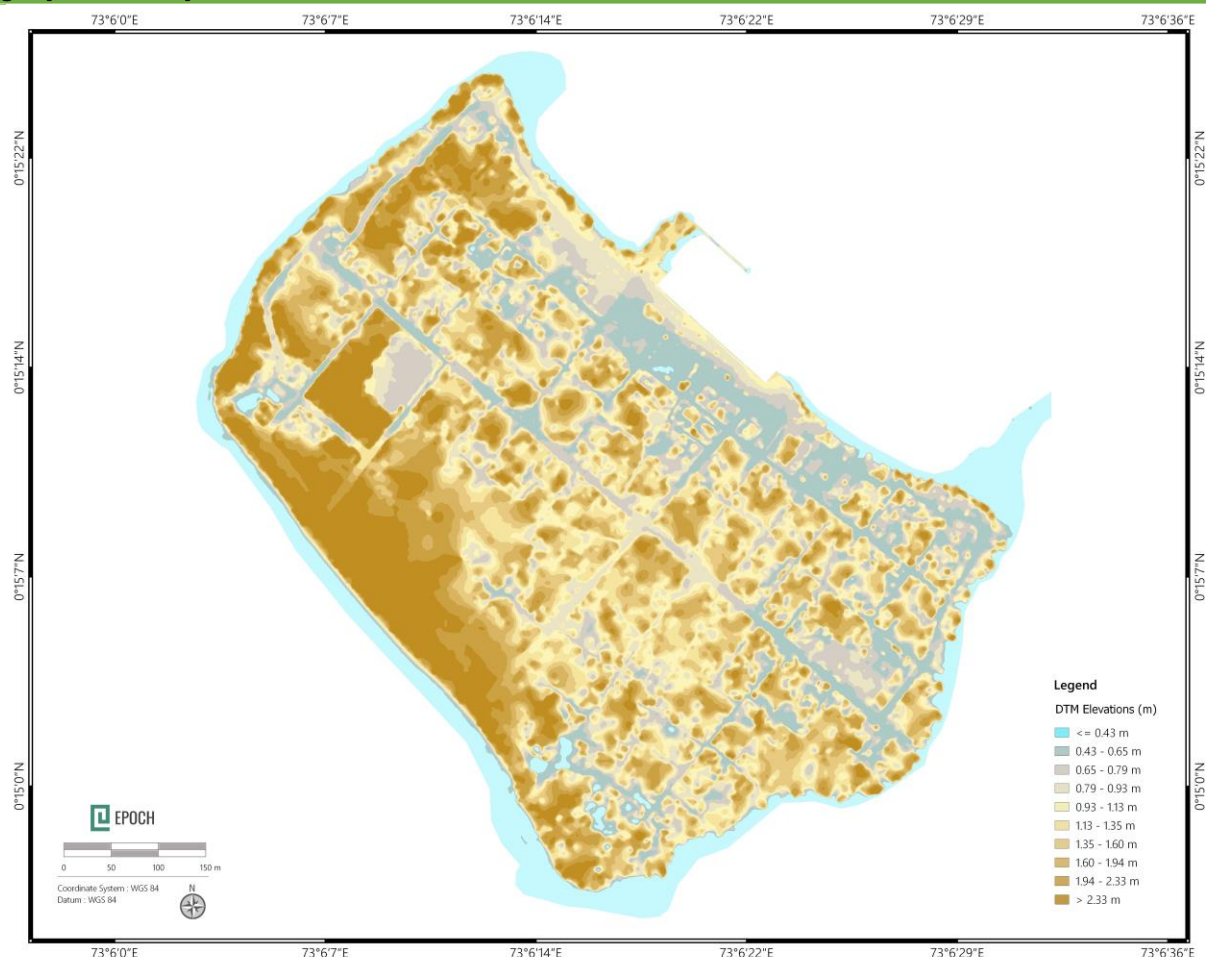
- General overview, demography, and climatology

Item	Details
Atoll	Huvadhoo Atholhu Uthuruburi Atoll
Length	0.87 km
Width	0.56 km
Area	38.3 ha
Population	1,382
Population/area	36.08 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use



Topographical map



Average elevation = 0.90 m above MSL

Shoreline length = 3134 m

	% of total area
Roof cover	11%
Vegetation (Thick)	22%
Vegetation (Thin)	52%
Bare Lands	15%
Farmlands	0%
Wetlands	1%

• Water consumption

Category	Domestic	Commercial	Institutional	Industrial	Total
Rate (m³/d)	406	0.90	3.19	0.43	411

- Water quality parameters – Physiochemical

Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC ($\mu\text{S/cm}$)	1,376 $\pm$ 1,816	1500
Turbidity (FNU)	1.38 $\pm$ 2.37	5
DO (mg/L)	4.50 $\pm$ 2.36	
pH	7.47 $\pm$ 0.34	6.5–8.5
Temp ($^{\circ}\text{C}$)	28.41 $\pm$ 1.53	
Sal (ppt)	0.66 $\pm$ 0.94	
NH₃ (mg/L)	2.65 $\pm$ 4.90	1.5 (Odour Threshold)
NO₃⁻ (mg/L)	6.88 $\pm$ 7.11	50
PO₄³⁻ (mg/L)	0.40 $\pm$ 0.42	

- Water quality parameters – Microbiological

Number of samples tested = 15

Parameter	Value range	Average value	Remarks (<i>on permit limit</i>)
Total Coliform (MPN/100ml)	17 – >2420	718.4	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not detected – 1,120	172.2	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	13.86	m ² /day
Storativity	1	0.1387	–
Permeability	7	2.754 – 113.800 Average – 31.102	m/day
Soil profile	5	Mostly uniformly graded sand and well graded sand and gravel on the South Western ridge of the island	

- Flooding

Flooding days per year	Inundation area (m ²)	Inundation depth (m)
50	11,000	0.229

- Electric Resistivity survey

- Measurement taken at 29 locations and number of transect is 9.
- Average freshwater thickness in the island is 1.09 m.
- Freshwater lens volume and aquifer stress level

Item	Value	Unit
Freshwater lens volume - Triangle method	71,541	m ³
Freshwater lens volume - ArcGIS	70,419	m ³
Groundwater abstraction	148,302	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	0.5	-
Aquifer stress level	highly stressed	-

- SWB modelling
 - Annual recharge is 104,485 m³ and it is 12.0% of annual rainfall (2270 mm)
 - Annual water balance

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	872,276	1,517	9,534	448,799	104,485	307,941	148,302
%	100.0%	0.2%	1.1%	51.5%	12.0%	35.3%	17.0%

- Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 72.5% in an average year, and it is compensated by ground water storage.
- Ground water withdrawal (148,302m³/yr) is 204% higher than the safe abstraction (48,768m³/yr).

- SUTRA modelling
 - Average monthly recharge assigned to SUTRA model

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	43.9	7.1	35.9	19.5	45.9	38.5	0

- Freshwater lens prediction (allowable concentration for potable use is 0.001)

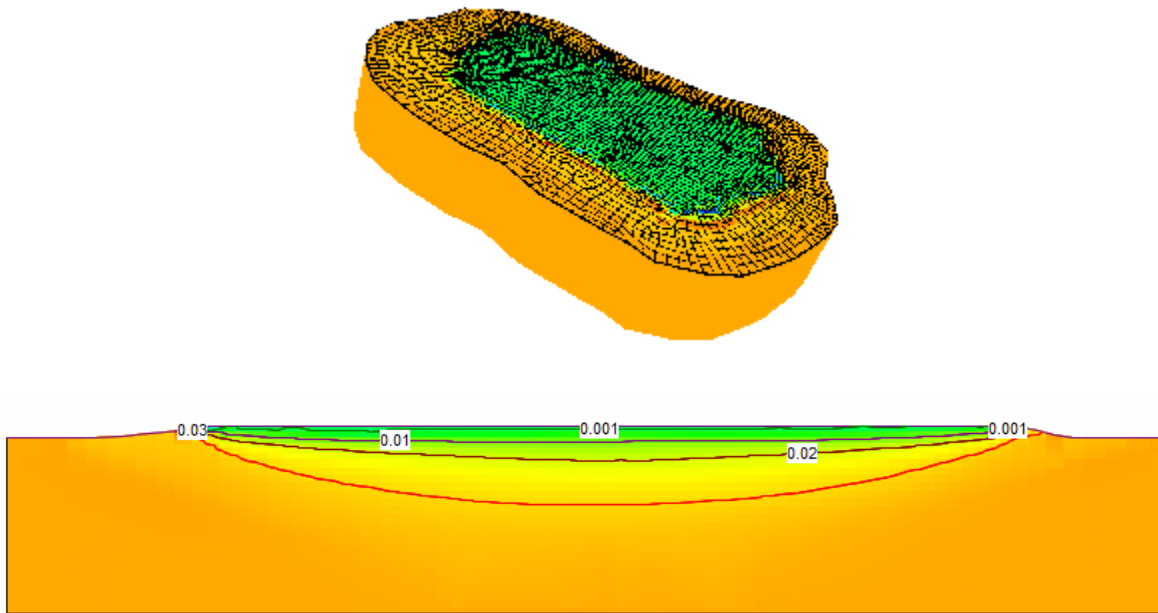


Figure 198: Saltwater distribution - GDh. Rathafandhoo island

10 GDh. Faresmaathoda

10.1 Island Overview and Location

The Island of GDh. Faresmaathoda, belonging to Huvadhu Atholhu Dhekunuburi Atoll, is in the Southern region of Maldives at 0°12'03.6"N and 73°11'11.9"E. It is approximately 443 km South-West of the capital Male'.

Table 168: Island Geographical Data

Island	GDh. Faresmaathoda
Atoll	Huvadhu Atholhu Dhekunuburi Atoll
Location	0°12'03.6"N and 73°11'11.9"E

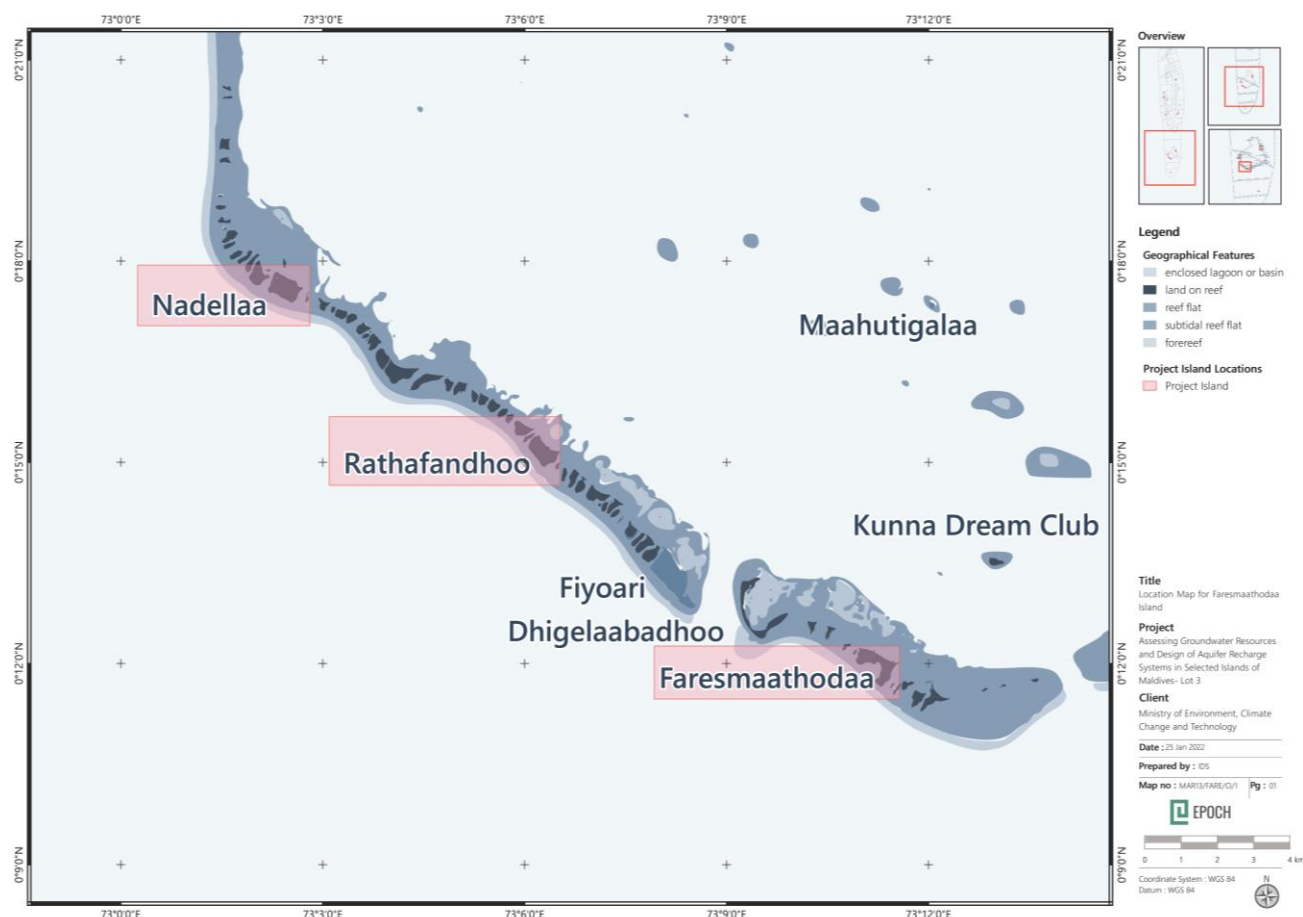


Figure 199: Location map - GDh. Faresmaathoda

10.1.1 Island features

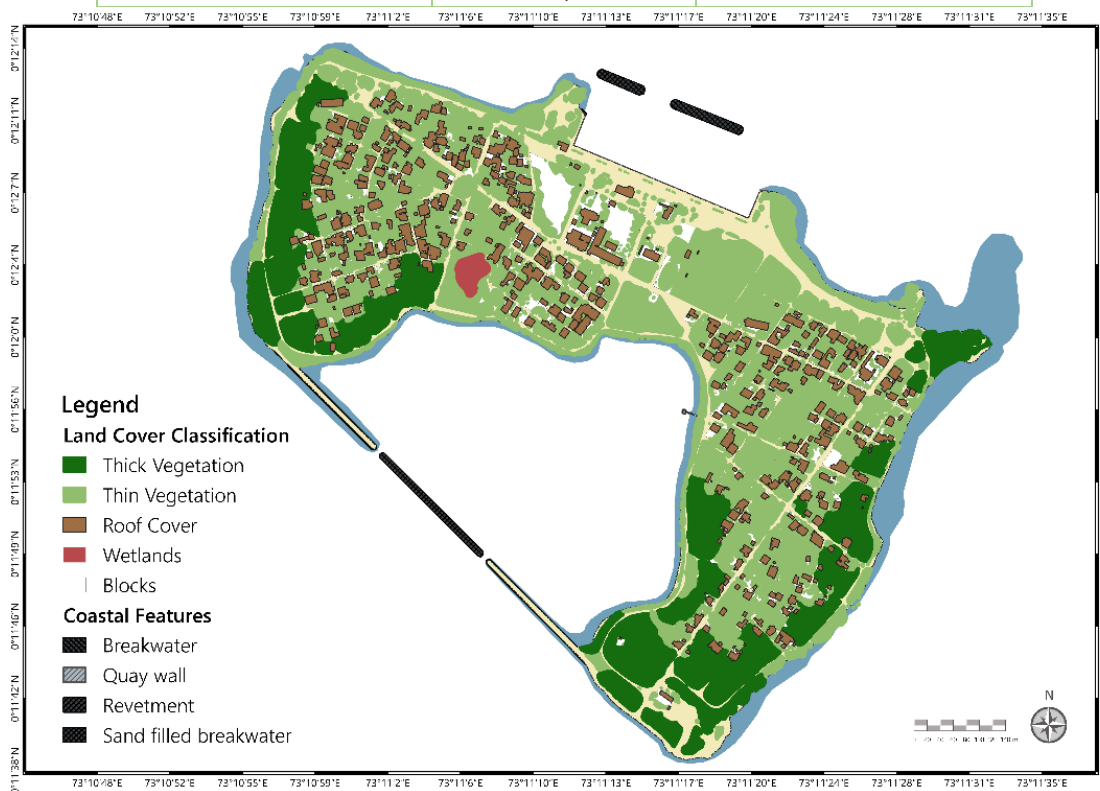
The island is located on the southern peripheral reef of Gaafu Dhaalu Atoll. The island was originally two separate islands (Fares and Maathoda) until they were joined by the reclamation of the shallow water passage between them during the 1990s. GDh. Faresmaathoda have swampy land and traditionally the

locals depended largely on agriculture. The total area of land of GDh. Faresmaathoda is 474,275m² out of which 11% is reclaimed land. The island extends up to 1.07 km in length from toe to toe and a width of 0.79 km from toe to toe.

The island has a harbor at its northern side. Around one-third of the island is covered in vegetation. The southern part of the island is covered entirely by said vegetation. Some of the vegetation is also concentrated at the northwest edge of Maathoda side. The island has one wetland on the west side of Maathoda island. Only about two-third of the island is populated, which is the northern part in Maathoda island and eastern side of Fares island.

Table 169: Area Distribution in GDh. Faresmaathoda

Area	47.4ha	
Length	1.07 km	
Width	0.79 km	
	Area (m²)	% of total area
Roof cover	60,750	13%
Vegetation (Thick)	90,953	19%
Vegetation (Thin)	197,933	42%
Bare Lands	122,188	26%
Farmlands	-	0%
Wetlands	2,451	1%
Total	474,275	100%



10.2 Topographical Features

Permanent Survey Marks PSM 0476, PSM 0477 and PSM 0478 were used as benchmarks for GDh. Faresmaathoda topographical survey and drone survey. These details are currently not available via the Maldives Land Survey Authority Website <https://www.mlsa.gov.mv/psm>. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 3189 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.25 cm per pixel. 15 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 170 GCP Statistics for GDh. Faresmaathoda

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	0.00134	-0.000867	-0.00280
Sigma [m]	0.0317	0.0373	0.166
RMS Error [m]	0.0317	0.0373	0.166

GDh. Faresmaathoda was originally two Islands Fares and Maathodaa before the land between the islands were reclaimed in 1998. These two islands have distinctive topographies. Maathodaa Island on the west has a wetland which has been gradually transformed over the last years into the children's park area. This area has a much lower elevation due to the existence of the wetland as well as alterations by the island council. Fares on the other hand is a far more elongated island on the eastern side with higher elevations. The reclaimed area in between Fares and Maathodaa is generally flat except for the football grounds which have a slightly lower elevation of 0.6m. As GDh. Faresmaathoda does not have an elevated ridge similar to other islands on the western ridge it has been protected

Roof elevations generally do not exceed 5–7 m and very few houses have multistorey buildings in GDh. Faresmaathoda. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Thick vegetation with heights greater than 10 m are primarily seen on the windward rims of Fares and Maathodaa. It is also noteworthy that despite the Southern region having dense thick and thin vegetation the elevations are generally lower than 10m.

The Digital terrain model was produced at a resolution of 0.1 m spatial resolution for the purposes of analysis. The figure below the plot of GPS spot heights vs Sampled DTM elevations for the island of GDh. Faresmaathoda. The DTM slightly overestimates the elevations with a mean of 2.11 cm. The DTM does not contain any elevation information related to the detached breakwaters of GDh. Faresmaathoda.

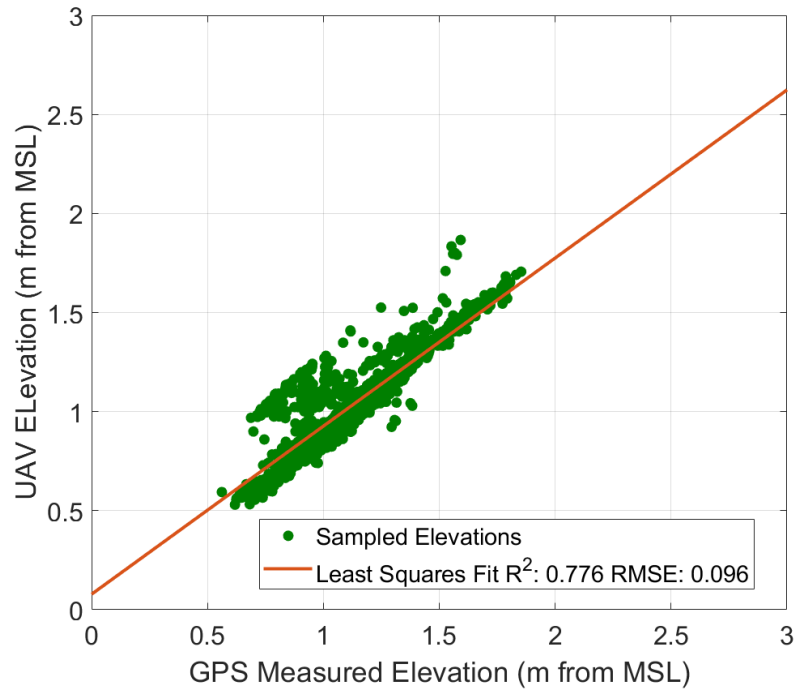


Figure 200 Linear Regression Plot for GDh. Faresmaathoda Sample UAV elevations

Table 171 Error Statistics for GDh. Faresmaathoda DTM

Parameter	Value (cm)
Mean	2.11
Standard Error	0.23
Median	-0.98
Mode	-2.42
Standard Deviation	10.13
Sample Variance	102.68
Kurtosis	5.09
Skewness	2.25
Range	66.82
Minimum	-25.65
Maximum	41.17
Sum	4002.31
Count	1899.00

10.2.1 Level changes

GDh. Faresmaathoda has an average elevation of 1.16 m with a standard deviation of 0.502. Digital Terrain Model elevations range from -0.6 to 2.9 m from MSL. The distribution of elevations has a symmetrical bimodal distribution with 1.1 m being the highest frequency for elevations. A second peak is observed near 0.2 m from MSL.

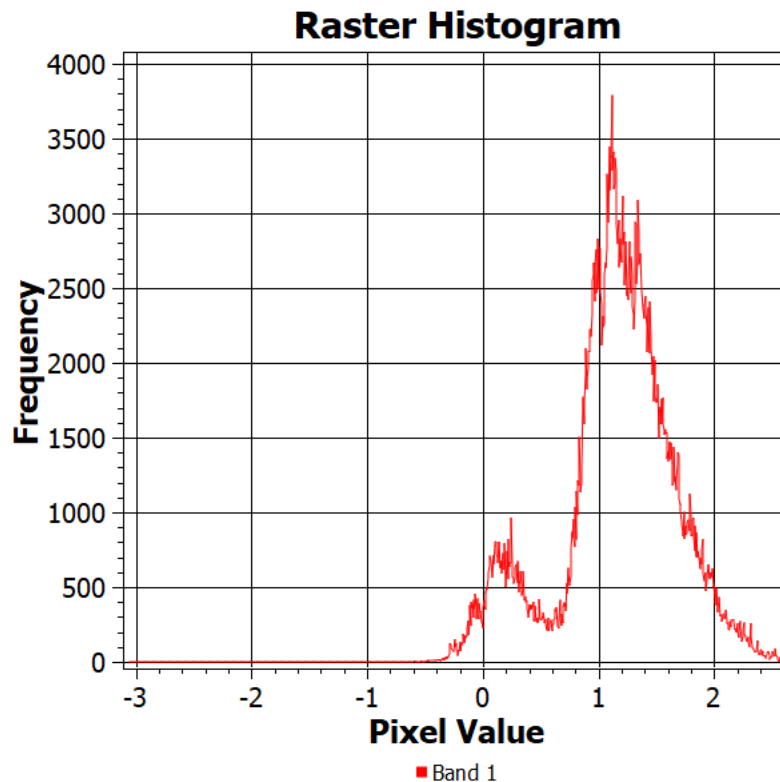


Figure 201 Raster Histogram created for GDh. Faresmaathoda DTM through QGIS for the Elevation Band 1

Analysis of the GDh. Faresmaathoda terrain reveals stark differences in the different island regions. Profile 1 in the original Fares islands shows two ridges with a well-developed 2.25 m steep ridge towards the windward side and a smaller ridge next to the low tide area that has developed presumably due to wave action inside the atoll.

Profile 2 in the original Maathodaa island has several peaks and troughs as there were not clear long roads and the vegetated areas were captured in the profile as peaks and some roads as troughs. Despite this a clear 2m ridge can be seen on the windward side. The low region on this ridge is the ring road that runs through the windward periphery of the islands.

Profile 3 which shows the main long road also does not go along only roads, so several peaks and troughs were observed. The center of the island (reclaimed area is pretty flat due to lack of vegetation in general.

Profile 4 and 5 go from the leeward side to the windward side. Profile 4 which passes through the wetland clearly shows a very low region around 325 m which corresponds to the wetland.

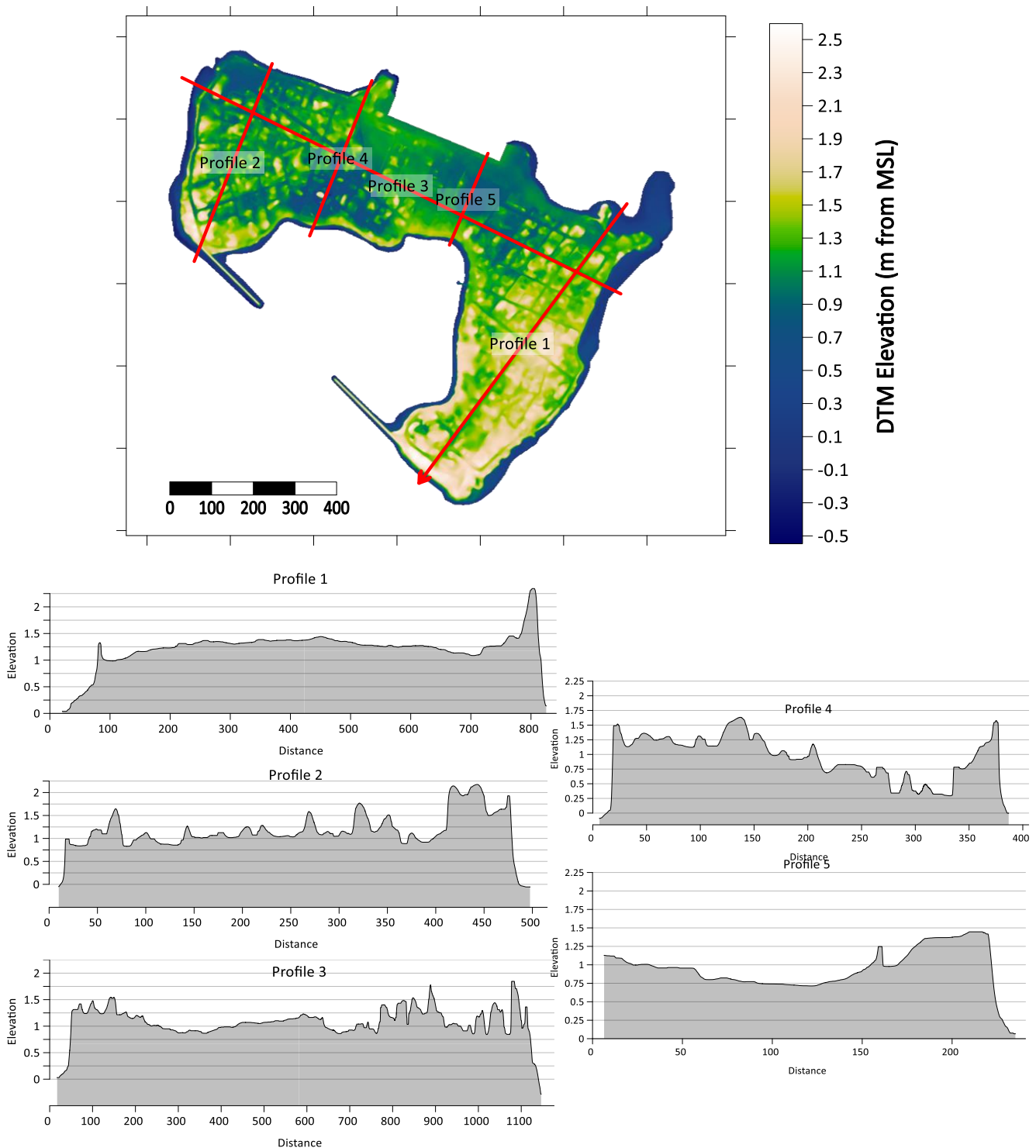


Figure 202 Digital Terrain Model Elevations and Profiles for GDh. Faresmaathoda Island

10.2.2 Shoreline

GDh. Faresmaathoda has a shoreline length of 5180 m. The island has a relatively wide harbour that serves the fishing population of the GDh. Faresmaathoda. Three breakwaters at around 1.6-1.8m protect the GDh. Faresmaathoda shorelines from wave driven flooding from westerly swell waves from the windward direction.



Figure 203 Orthomosaic of GDh. Faresmaathoda. Original Maathodaa Island is shown in blue, Original Fares Island is shown in red and reclaimed area is shown in purple

10.2.3 Reef

GDh. Faresmaathoda, similar to three other islands in this Project is found on a reef with several islands. The island within the confines of the breakwater and shoreline of GDh. Faresmaathoda is unnamed and given the code LD0063 by MLSA. The islands to the northwest of GDh. Faresmaathoda are Kelaihuttaa and Hoothodeyaa. The five islands to the southeast of GDh. Faresmaathoda have been combined through reclamation for an airport that is underway. A causeway is expected to connect the airport and GDh. Faresmaathoda and faint region is already observed in the image below.



Figure 204 Sentinel 2 imagery of GDh. Faresmaathoda reef taken in January 2022

10.3 Socio Economic Status

10.3.1 Demography

GDh. Faresmaathoda is an inhabited island in Gaafu Dhaalu Atoll's administrative unit which has been reclaimed in 1998 to join two separate islands, Fares and Maathoda. The island is physically part of Huvadhu Atholhu Dhekunuburi Atoll in the Maldives'. However, the people started living in the reclaimed areas in 2008. The Island has a registered population of 1024 as per the 2014 census, with a total of 527 males and 497 females. The island population density is 39 people per hectare as per the 2014 figures. The population figures have drastically increased over the past years where the total registered local population climbed up to 1849. The following table and graph illustrates the demographic breakdown of GDh. Faresmaathoda.

GDH.Faresmaathoda Population

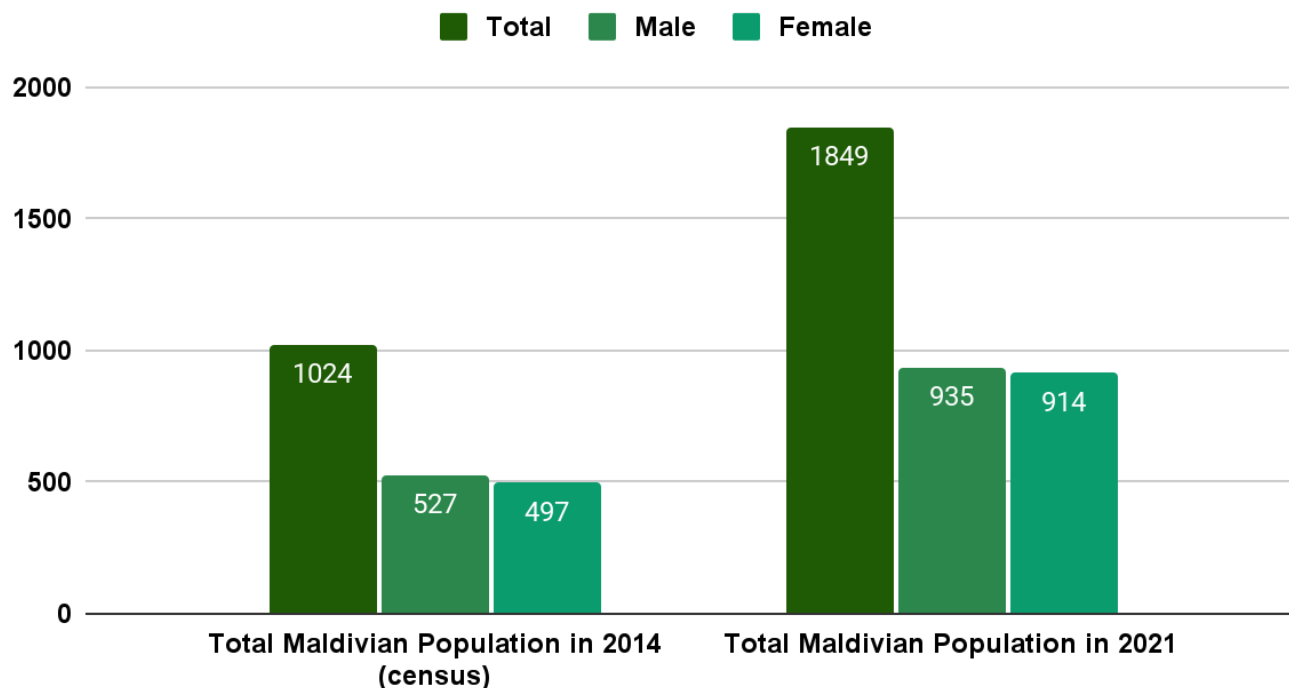


Figure 205: GDh. Faresmaathoda Population

Table 172: GDh. Faresmaathoda Population (Census, 2014)

Resident Population according to Census 2014										
Atoll	Locality	Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female

GDh	Faresmaathoda	1,104	600	504	1,024	527	497	80	73	7
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10.3.2 Socio-Economic Activities

The people in the island are well known for fishing which is their main source of income. The island also has 2 cafes/restaurants and 7 guesthouse beds that provide for the tourism industry.

10.3.3 Facilities available

10.3.3.1 Health Care

GDh. Faresmaathoda Health Center was built on 10th January 2004. Currently, the hospital has one doctor, 8 nurses and 11 beds. The health facilities in the island are bare minimum and many island residents find that the Health Center needs to be upgraded and service hours need to be extended.

10.3.3.2 Education

GDh. Faresmaathoda has Huvadho school. The school has 212 students, 36 teachers and 4 administrative staff. The island school offers education upto grade 10 standard.

10.3.3.3 Utilities

Electricity on the island is provided by state owned utility company FENAKA. The island currently does not have a sewerage and sanitation system.

10.3.3.4 Transportation

The island has a harbour which was developed in January 2018. The transportation between GDh. Faresmaathoda and other islands is by sea. The island has Southern Transport Link (STL) ferry services between Fuvamulah and GDh. Faresmaathoda, the island also has other private speed launches. Currently, GDh. Faresmaathoda Airport is being developed upon reclamation of several small islands in the lagoon to create a sufficient land area for the project. The project includes a construction of a 1200-meter runway, taxiway, apron and service roads.

10.3.4 Water resources, water usage and water consumption

In GDh. Faresmaathoda there are a total of 235 households. 120 out of 235 households were surveyed with geo-coordinated sampling points. Additionally, the 95% confidence interval was maintained with an error margin of 6.5%. Many households were also unresponsive and not willing to take part in the survey because of unavailability. A maximum of three attempts were made on different occasions to determine unavailability of the participant. A map of households surveyed is attached in Annex V.

Table 173: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	120/235 households = 51%
Percentage of well fitted with pumps	99%
Ground water	Usage in percentage
Source of drinking	0
Source of cooking	0

10.3.4.1 Existing water and sanitation

The main form of sanitation facility is via the use of septic tanks and local outfall pipes. Based on the survey, 98 percent of the surveyed households have connected their sanitation to septic tanks with each household having 3 septic tanks on an average. While the remaining 2 percent has connected to local outfall pipes.

In GDh. Faresmaathoda, 87 percent of the population reported to have less than 49ft distance between septic tanks and groundwater well. While the remaining 13% reported to have more than 49ft distance.

According to the Regulation regarding Conservation and Protection of Water Resources (Regulation number: 2021/R-22), annex 4 states that the households should keep a 15-meter (49.2126 ft) distance between septic tank and nearest well. The main reason for the adoption of this standard is to negate any possible causes of contamination in the groundwater.

Rainwater is also the primarily used for cooking. Many homes use rainwater from neighbouring houses or bottled water when rainwater is not readily available during the dry season. Rainwater collected from rooftops is stored mostly in water tanks, whether at home or communal rainwater tanks.

In GDh. Faresmaathoda, 12 houses have connected rainwater to the well and have reported improvement in groundwater. On the same note, 87% of the households have rainwater drained to the ground.

10.3.4.2 Water usage and resources

Based on the survey conducted, out of 120 houses surveyed in GDh. Faresmaathoda, 113 of the houses have HDPE rainwater tanks for rainwater storage. 99% of the households use rainwater for cooking and 65% use rainwater for drinking. Rainwater collected from rooftops is stored in water tanks, whether communal or home tanks. Many homes utilize rainwater from neighbouring houses or bottled water when rainwater is scarce during the dry season. While groundwater is mainly used for gardening, household cleaning with all the houses fitted with water pumps. The following sections regard further details about various water usage and consumption scenarios in the island.

10.3.4.3 Domestic water usage

Based on household water usage surveys in GDh. Faresmaathoda, **456,703** Liters of groundwater is used daily in the households. A total of **247** Liters of groundwater are consumed per capita per day.

Table 174: Domestic groundwater use data for GDh. Faresmaathoda

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
133	42	12	33	1.34	22	4	247

*All units are in Liters per capita per day

10.3.4.4 Commercial water usage

Based on the survey conducted in GDh. Faresmaathoda, there is currently one operational café and 1 guesthouse on this island. A total of **1,224** Liters of groundwater are used by commercial entities and their detailed breakdown is given in the tables below.

Table 175: Groundwater use data for a Café in GDh. Faresmaathoda

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Break Point	158	-	-	-	158
					158

*All units are in Liters per day

Table 111: Groundwater use for a guesthouse in for GDh. Faresmaathoda

Guesthouse	Average Occupancy	Total (L/day)
Small Island Lodge	25%	1,066
		1,066

10.3.4.5 Industrial water usage

Currently, there is no industrial work being carried out within the island. Fish processing activities are also carried out in Keliiahutta, which is an uninhabited island near GDh. Faresmaathoda. Also, large fishing vessels visit the island to obtain groundwater and it is estimated that **714 Liters** of groundwater is used by the vessels every day.

10.3.4.6 Institutional water usage

Based on the survey conducted in GDh. Faresmaathoda there are currently six institutions that have groundwater well facilities and that use groundwater. A total of **4,827** Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 112: Institutional groundwater use data for GDh. Faresmaathoda

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Ice Plant Building	46.96	-	0.7	-	47.66
Fenaka	125.2	180	20	-	325.2
Police Station	62.6	60	10	1059.8	1192.4
Council office	218	240	10	-	468
Huvadhoo School	1166	360	160	151.4	1837.4
Health Center	299	120	18	519.3	956.3
					4,827

*All units are in Liters per day

10.3.5 Present & Future water demand

In GDh. Faresmaathoda, the present water demand is at **463,468** Liters per day and groundwater usage is expected to decrease with the establishment of water supply services in the island. The year 2021 figures are as per the latest island council data. For the figures in year 2036 and 2054, it is as per Maldives Populations Projections Report published by the National Bureau of Statistics.

Population Projection - GDH.Faresmaathodaa

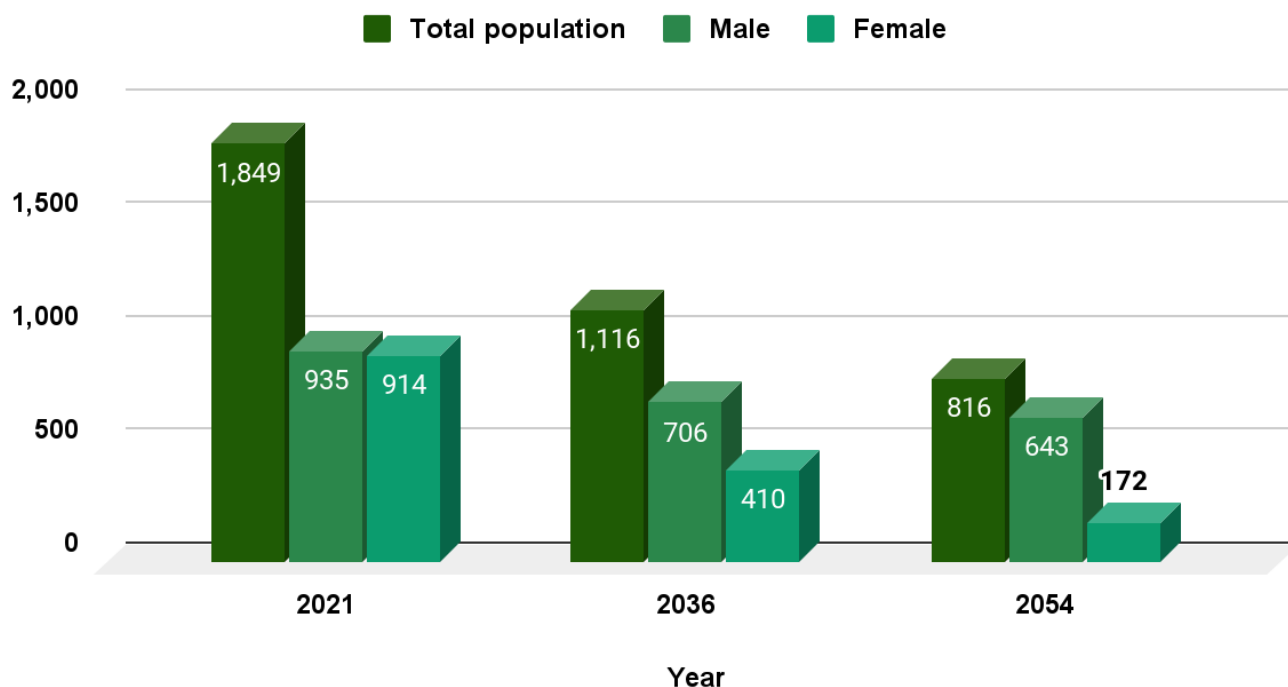


Figure 206: Population Projection – GDh. Faresmaathoda

Table 176: Present groundwater demand – GDh. Faresmaathoda

Year	Total Population	Domestic water demand	Commercial water demand	Industrial water demand	Industrial water demand	Groundwater usage
2021	1,849	456,703	1,224	4827	714	463,468

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 247 Liters per day. For the year 2036, water supply usage is expected to be 50 Liters per capita per day. After deducting 50 Liters from 247 Liters, the groundwater demand is expected to be 197 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 1,116 is expected to be **219,852** Liters per day.

For the year 2054, water supply usage is expected to be 75 Liters per capita per day. After deducting 75 Liters from 247 Liters, the groundwater demand is expected to be 172 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 816 is expected to be **140,352** Liters per day.

Table 177: Future domestic water demand – GDh. Faresmaathoda

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	1,116	247	50	197	219,852
2054	816	247	75	172	140,352

10.3.6 Water related issues

From 120 households surveyed in GDh. Faresmaathoda, most houses reported unpleasant smells (58%) and milky and cloudy texture (30%) in their respective wells. Only 25% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gases such as Hydrogen Sulfide which causes unpleasant smells. Groundwater is observed to be worse in Fares since there is significant swell wave intrusion.

Table 178: Signs of contamination reported by households

Types of contamination	Data in % out of 120 households surveyed
Smell	58%
Milky	30%
Foul taste	12%
Changes in color	0%
Salty	20%
None	36%

The following table details out the changes in groundwater quality reported by the households during tidal or seasonal changes.

Table 179: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 120 households surveyed
Changes with tidal variations	16%
Groundwater quality is better in rainy months (Hulhangu season)	51%
Long periods without rain causes bad smell	33%
Long periods without rain causes bad taste	12%
Rain makes it worse	0%
No change	31%

10.4 Groundwater Quality

10.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 180 summarizes the water quality results. Map of locations where groundwater quality points were taken for physiochemical analysis is attached to Annex VI. The full list of measured parameters is attached to Annex VII.

Table 180: Groundwater physiochemical parameters statistical summary – GDh. Faresmaathoda

	EC ($\mu\text{S}/\text{cm}$)	Turbidity (FNU)	DO (mg/L)	pH	Temp ($^{\circ}\text{C}$)	Sal (ppt)	NH ₃ (mg/L)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
Standards	<1500 Potable purposes <2500 Non-potable purposes Source ¹	<5 Source ²		6.5-8.5 Source ²			<1.5 Odour threshold <35 Taste threshold Source ¹	<50 Source ¹	
Mean	1381	1.46	3.62	7.53	28.75	0.65	2.80	9.96	0.30
Median	805	0.53	3.37	7.45	28.78	0.37	1.80	7.83	0.22
SD	1283	2.39	1.93	0.40	1.38	0.65	3.45	8.59	0.26
Min	108	0.00	1.25	6.97	25.94	0.05	0.16	1.02	0.05
Max	6249	12.13	8.07	9.25	34.00	3.19	15.28	40.66	1.26
CV	0.93	1.64	0.53	0.05	0.05	1.00	1.23	0.86	0.87

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH₃= Ammonia, NO₃⁻= Nitrate, PO₄³⁻=Phosphate, SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source¹ = WHO Drinking Water Guidelines, 2017. Source² = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 1381 $\mu\text{S}/\text{cm}$ is lower than the WHO Standard for potable water (1500 $\mu\text{S}/\text{cm}$) and the WHO Standard for non-potable water (2500 $\mu\text{S}/\text{cm}$).
- 29 samples had EC lower than 1500 $\mu\text{S}/\text{cm}$, 5 had EC between 1500 and 2500 $\mu\text{S}/\text{cm}$, 6 between 2500 and 10,000 $\mu\text{S}/\text{cm}$. None of the samples were above 10,000 $\mu\text{S}/\text{cm}$. EC distribution is shown in Figure 208.
- As expected, the EC of the groundwater in the centre of the island GDh. Faresmaathoda in the reclaimed areas is higher than the other areas of the island. However, the EC in the centre of the two provinces (which were previously two separate islands Fares and Maathodaa) is lower.
- The mean Turbidity level at 1.46 NTU falls below the URA Guidelines for drinking water (5 NTU). 3 of the samples had higher Turbidity than 5 NTU with the maximum turbidity at 12.13 NTU.
- Dissolved Oxygen ranged from 1.25 mg/L to 8.07 mg/L with a mean of 3.62 mg/L.
- All samples except one fell within the pH range of 6.5–8.5 as per URA Guidelines for drinking water with a mean pH of 7.53.

- WQ22 had a pH of 9.25 and an extremely low EC (108.3 $\mu\text{S}/\text{cm}$). Since this sample was taken from an open well and it had rained before water sample collection, the sample was most likely saturated with rainwater thus giving the higher pH and lower EC.
- Temperature ranges from 25.9°C to 34.0°C depending on the well characteristics and time of day reading was taken. Mean temperature was 28.8°C.
- Salinity ranged from 0.05ppt to 3.19ppt with a mean of 0.65ppt.
- The mean Ammonia concentration was 2.80 mg/L which is higher than the WHO threshold for odor but well below the threshold for taste. 50% of samples had concentration below 1.5 mg/L, 50% of samples had concentration between 1.5 mg/L and 35 mg/L and none of the samples had concentration higher than 35 mg/L. The Ammonia concentration distribution is shown in Figure 207.
- The mean Nitrate concentration was 9.96 mg/L which falls below the WHO Standard for Nitrate concentration (50 mg/L). None of the samples had Nitrate concentration higher than the WHO standard.
- Phosphate concentration ranges from 0.05 to 1.26 mg/L with a mean concentration of 0.29 mg/L. There is no WHO guideline value for phosphate concentration. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater. 4 samples tested were below 0.1 mg/L. Phosphate concentrations are generally higher in densely populated areas.

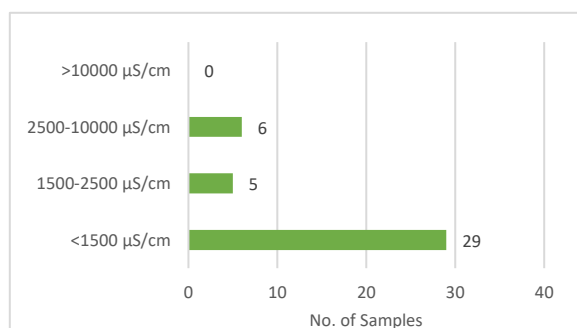


Figure 208: EC Distribution in GDh. Faresmaathoda

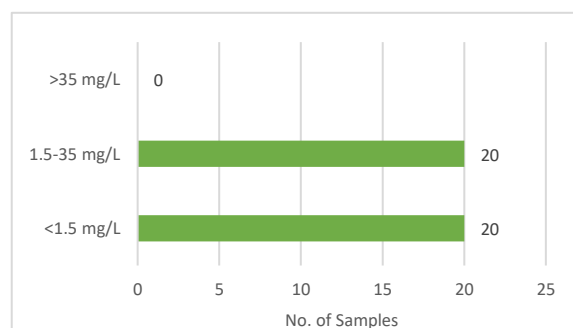


Figure 207: Ammonia concentration distribution in GDh. Faresmaathoda

The spatial distribution of all the parameters measured are shown in Figure 209 (a-i).

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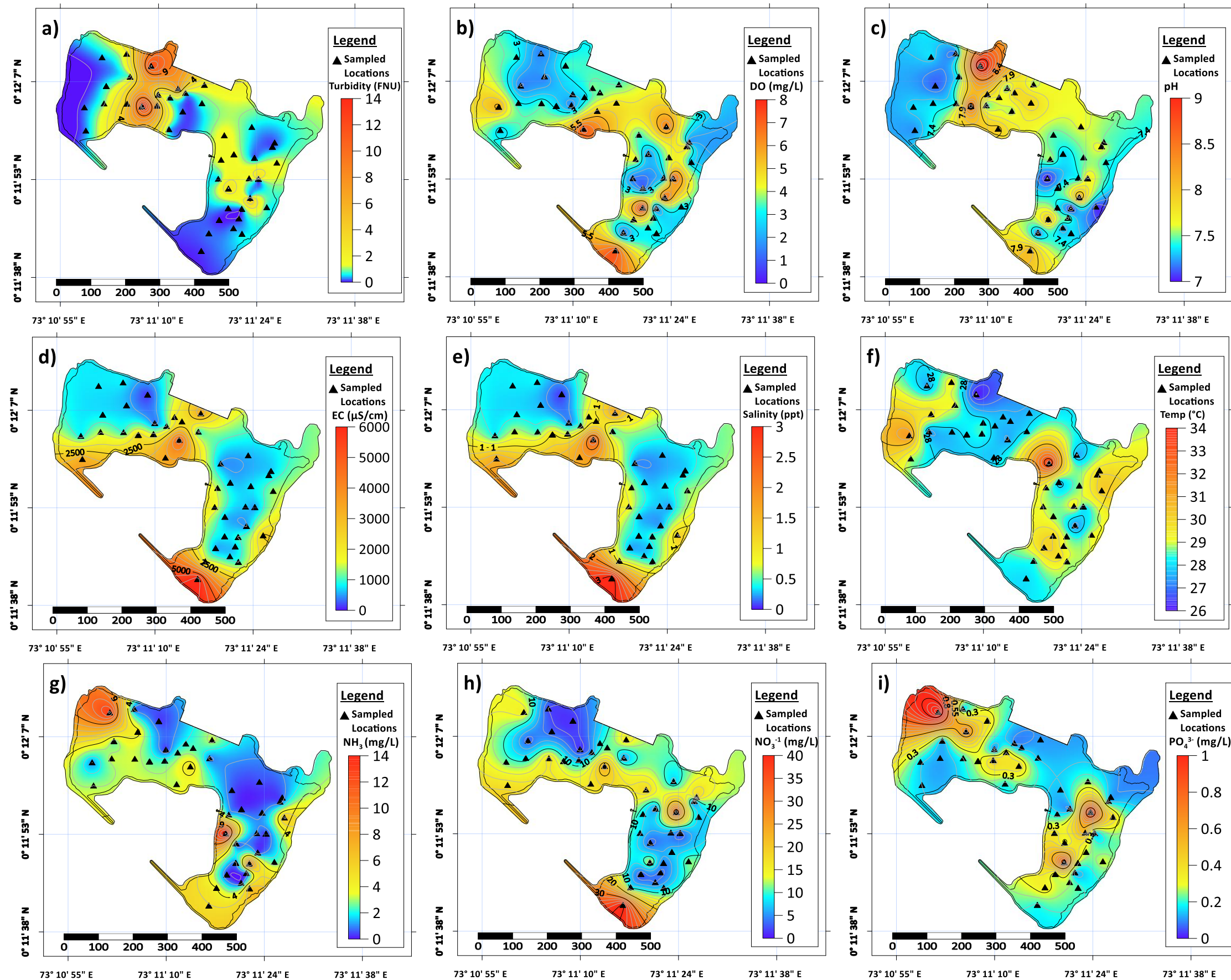


Figure 209: Spatial variation of physiochemical parameters in GDh. Faresmaathoda

As a principle, excessive groundwater usage leads to overextraction causing salinization of the freshwater lens. The Social Survey findings were used to calculate the daily water consumption at each household, institution and other commercial entities. The EC values at these locations were plotted against water consumption to check if increasing water usage leads to salinization. The correlation coefficient of EC to Water usage is -0.0243 and the R-squared of the plot is 0.0006 as indicated from the Figure 210. Therefore, there is no significant relationship observed between EC and Water Usage for the island as per the findings from the Social Survey and Water Quality Survey. The Spatial distribution of EC and water usage is shown in Annex VIII.

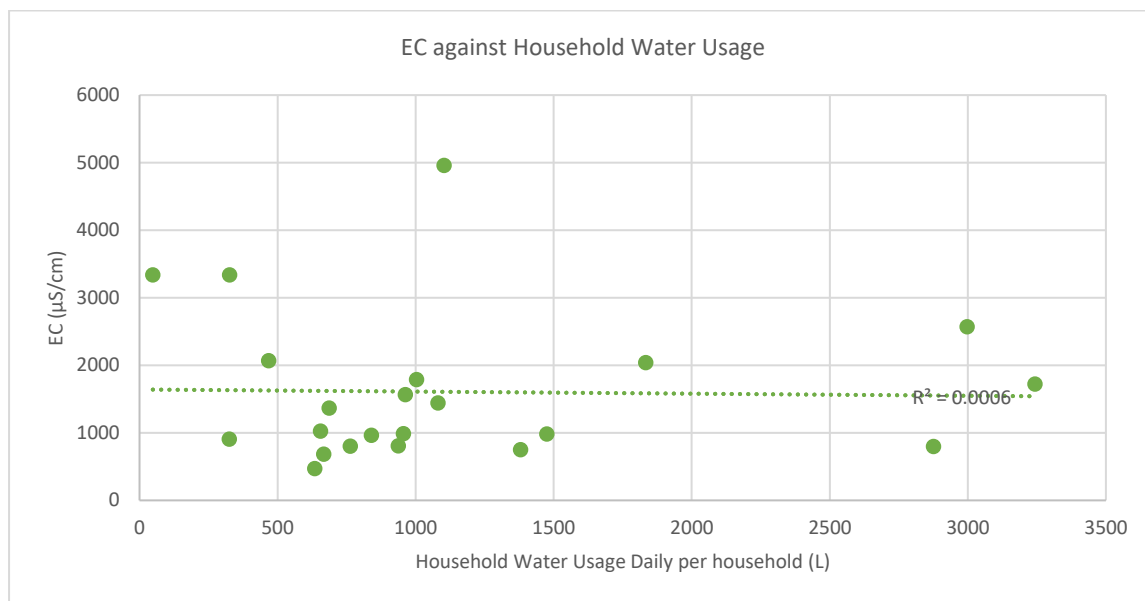


Figure 210: EC against Water Usage in GDh. Faresmaathodaa

10.4.1.1 Correlation Matrix

The correlation matrix for GDh. Faresmaathoda along with the colour bar is given below. Red colour indicates negative correlation while green colour indicates positive correlation.

Table 181: Correlation matrix of the groundwater quality parameters in GDh. Faresmaathoda

Variables	Turbidity (FNU)	DO (mg/L)	pH	EC (µS/cm)	Sal (ppt)	Temp (°C)	NO ₃ ⁻ (mg/L)	NH ₃ (mg/L)
DO (mg/L)	-0.11							
pH	0.48	0.44						
EC (µS/cm)	-0.15	0.25	-0.01					
Sal (ppt)	-0.15	0.26	0.01	***1.00				
Temp (°C)	-0.33	-0.11	-0.41	-0.24	-0.25			
NO ₃ ⁻ (mg/L)	-0.22	0.35	0.00	0.66	0.66	-0.01		
NH ₃ (mg/L)	-0.17	-0.25	-0.36	0.27	0.26	-0.14	0.17	
PO ₄ ³⁻ (mg/L)	-0.06	0.04	-0.08	-0.14	-0.13	-0.06	0.24	0.37

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation
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Table 181 shows a strong positive correlation coefficient between EC/Sal ($r=1.00$). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlations between salinity and conductivity are as expected. There are no strong negative correlations between parameters observed.

10.4.1.2 Water Quality Index

In this study, the computed WQI ranges 2.45 to 31.38, with a mean of 8.22. The WQI was divided into four categories and Table 182 shows the categorization of samples. 75% of samples were classified as "Very Good", 20% of samples were classified as "Good", 5% of samples were classified as "Poor" and 0% of samples were classified as "Very Poor". The high value of WQI at two locations were found to be mainly from the high EC. The spatial distribution of WQI is as per Figure 211.

Table 182: Water Quality Classification based on WQI – GDh. Faresmaathoda

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	30	75%
10 to 20	Good	8	20%
20 to 50	Poor	2	5%
>50	Very Poor	0	0%

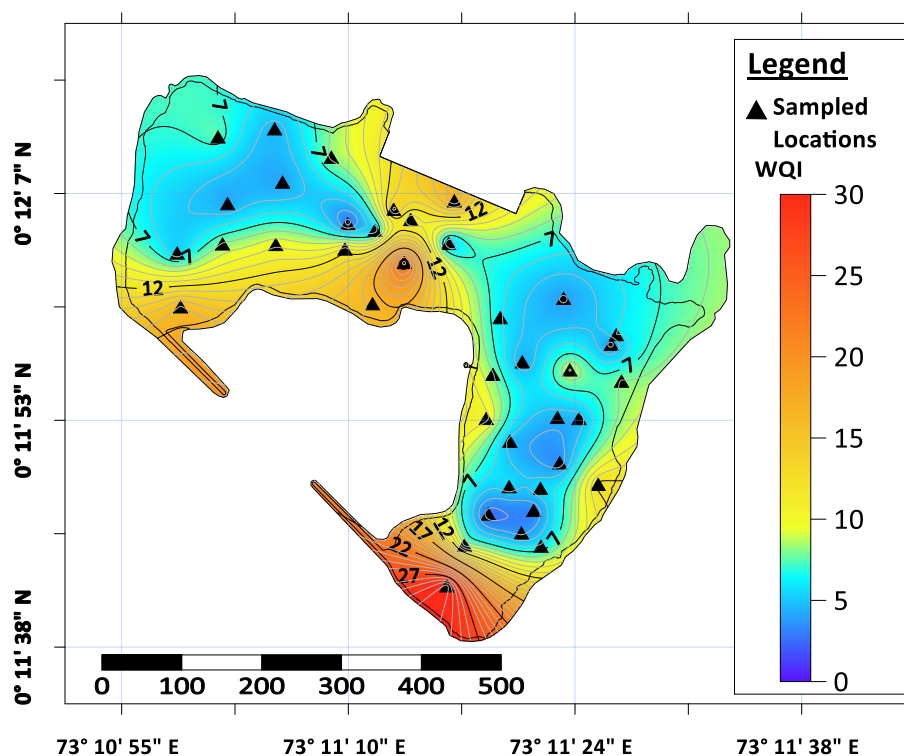


Figure 211: Spatial Distribution of WQI in GDh. Faresmaathoda

10.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following table summarizes the results.

Table 183: Microbiological Parameters of groundwater in GDh. Faresmaathoda

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq02	>2420	Not Detected	35	Septic Tank. Not cleaned yet.
wq05	116	Not Detected	25	Septic Tank. Septic Tank cleaned every 5 years and waste pumped out to sea
wq07	325	1	10	Septic Tank. Septic Tank cleaned once every 2 years and waste buried in household
wq09	>2420	187	12.5	Septic Tank. Septic Tank cleaned every 2 years and waste pumped out to sea
wq14	1550	Not Detected	55	Septic Tank. Septic Tank cleaned once every 5 years and waste buried in household
wq17	2420	Not Detected		Location does not fall within the coverage of social survey
wq21	12	Not Detected		Location does not fall within the coverage of social survey
wq22	>2420	>2420		Location does not fall within the coverage of social survey
wq24	>2420	Not Detected		School
wq30	>2420	Not Detected	17.5	Septic Tank. Septic Tank cleaned once a year and waste buried in household
wq32	>2420	Not Detected	85	Septic Tank. Septic Tank cleaned every 5 years and waste pumped out to sea
wq33	>2420	Not Detected		Location does not fall within the coverage of social survey
wq35	135	4	30	Septic Tank. Not cleaned yet.
wq37	261	Not Detected		Location does not fall within the coverage of social survey
wq40	2	Not Detected		Location does not fall within the coverage of social survey

*Distance between water well and nearest septic tank (feet)

Faecal Coliform was detected in 4 samples with 1 sample detecting more than 2420 MPN/100mL. Total Coliform was detected in all 15 samples, with 7 samples detecting more than 2420 MPN/100mL.

The effects of effluent leakage from septic tanks and local outfall pipes are evident in the microbiological survey results. On average, there is an approximate distance of 26 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Faecal Coliform and Total Coliform is given in Figure 212 (a and b).

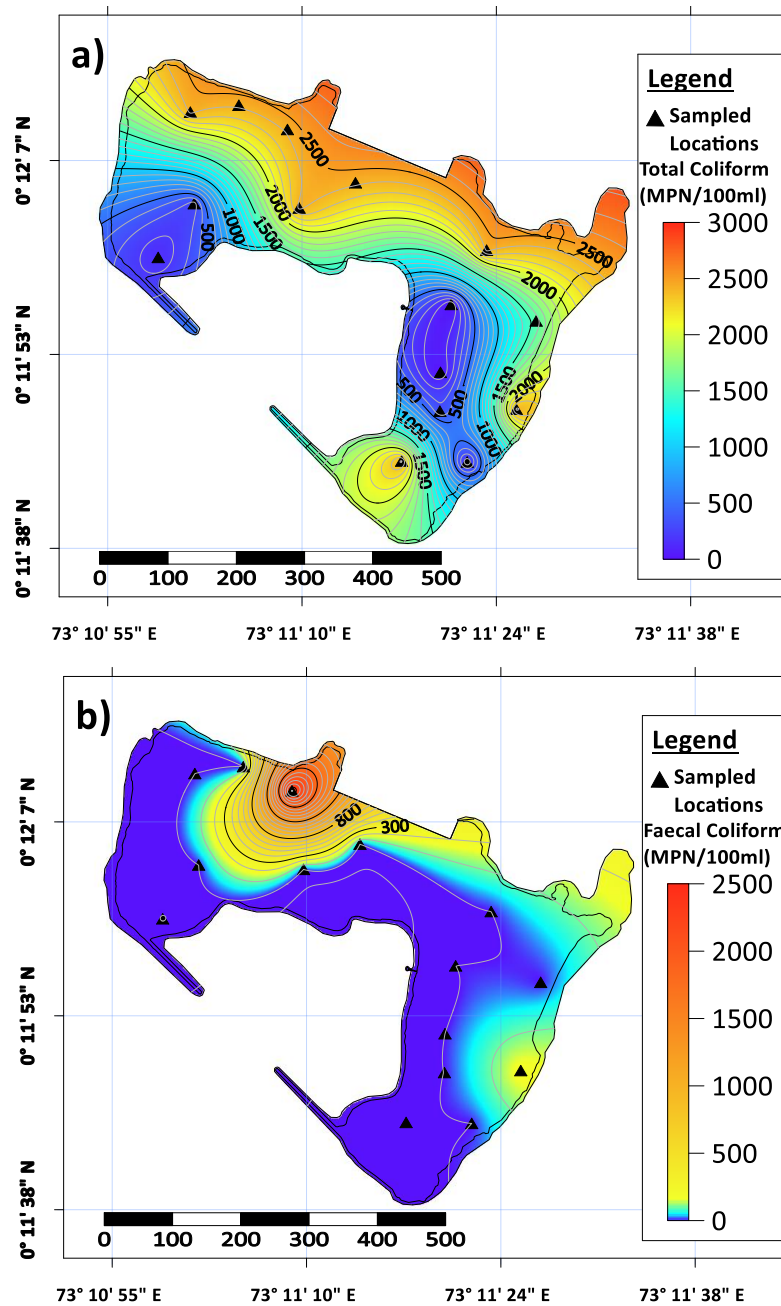


Figure 212: Total (a) and Faecal (b) Contamination Distribution in GDh. Faresmaathoda

The Total Coliform and Faecal Coliform Contamination was plotted against the distance between septic tank and well, to identify the correlation between these two variables. The graphs are given below.

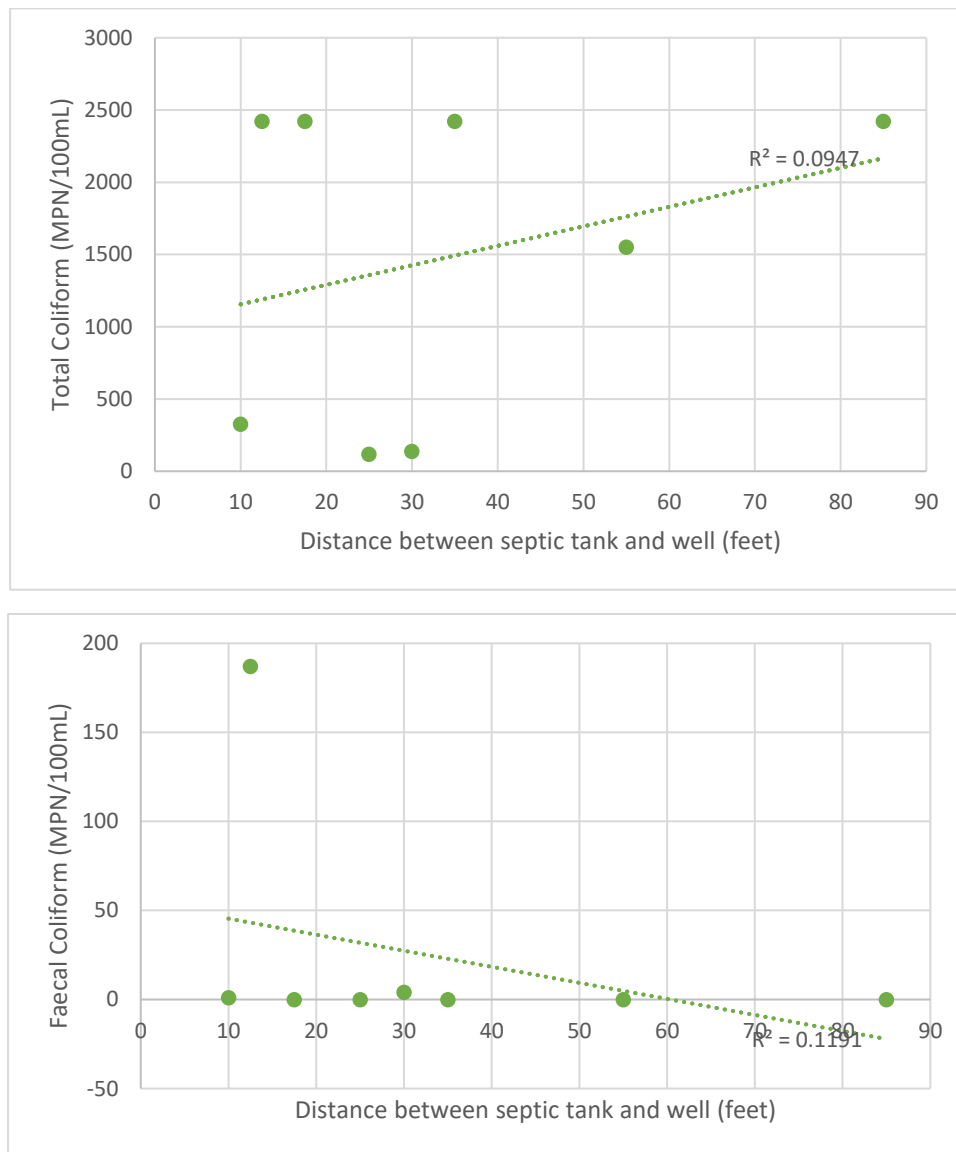


Figure 213: Microbiological Contamination against Septic Tank distancing - Faresmaathoda

The correlation coefficient of Total Coliform to distance between septic tank and well is 0.308 and the R-squared of the plot is 0.0947. The correlation coefficient of Faecal Coliform to distance between septic tank and well is -0.345 and the R-squared of the plot is 0.119. Therefore, there is no significant relationship observed between the parameters.

10.5 Pumping Test

10.5.1 Test location

A well in construction, with a Sandy Gravel bed base was available from a private land in GDh. Faresmaathoda and hence, it was selected to be used for the pumping test. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 214 below shows the location for the pumping test at GDh. Faresmaathoda.



Figure 214: Pumping test location – GDh. Faresmaathoda

10.5.2 Pumping rate, pumping hours and collected data

A constant rate pumping test was carried out at GDh. Faresmaathoda. The test began at 1950 hours on 30 November 2021 and lasted for 180 minutes. A flowrate of 20 LPM was maintained for the pumping phase which lasted from the 0–110th minute. The recovery phase of the test lasted from 111th–180st minute for more than a 100% recovery, due to incremental tide.

10.5.3 Hydrogeological parameter estimation

The Cooper-Jacob Solution for Unconfined Aquifer Models was used to process the data from the pumping test. The analysis was carried out using the software, AQTESOLV. The Aquifer Transmissivity (T) value was estimated to be $4.69 \times 10^{-3} \text{ m}^2/\text{s}$ (405.5 m^2/day) and the Aquifer Storativity (S) was

estimated to be 0.008487 for GDh. Faresmaathoda. The full data set of the pumping test at GDh. Faresmaathoda has been annexed at Annex XII.

10.6 Permeability Test

10.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 215 below. The originally proposed locations were changed as necessary due to unavailability of water and electricity for testing, inaccessibility of proposed locations, as well as the prioritizing of public lands that can be used for potential design solutions over private lands over private lands.



Figure 215: Permeability Test Locations – GDh. Faresmaathoda

10.6.2 Measured data

Table 184: Permeability Test Measured Data - GDh. Faresmaathoda

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m ³ /s)	K (m/s)	K (m/day)
MTD-PMB1	0.600	0.750	27	7.5	40.00	0.000667	7.11E-04	61.470
MTD-PMB2	0.600	0.825	35	12.0	15.00	0.000250	3.09E-04	26.700
MTD-PMB3	0.600	0.640	35	12.0	7.40	0.000123	1.97E-04	16.980
MTD-PMB4	0.600	0.400	35	12.0	2.00	0.000033	8.50E-05	7.343
MTD-PMB5	0.600	0.885	27	7.5	4.50	0.000075	6.78E-05	5.861

Note: H = Height of water in well (m),
 Tu = distance from water level in casing to water table (m),
 Cu = Conductivity Coefficient,
 r = borehole radius,
 Q = Steady flow into well,
 K = Coefficient of permeability.

10.6.3 Permeability estimation and identified features

The average permeability value for the GDh. Faresmaathoda is 23.671 m/day, with permeability values ranging from 5.861 m/day to 61.470 m/day. As highlighted in Soil Profile Survey, the island soil profile is predominantly Sands, and the K values above are consistent with the range of K values obtained for Sands (Robertson (2010)).

10.7 Soil Profile Survey

10.7.1 Test locations

Soil Profile surveys were carried in 7 locations across the island, as outlined in Figure 216 below. Out of the 7 locations, 5 points were permeability test locations, and the remaining 2 points were chosen in a way that ensured a uniform coverage of the entire island.

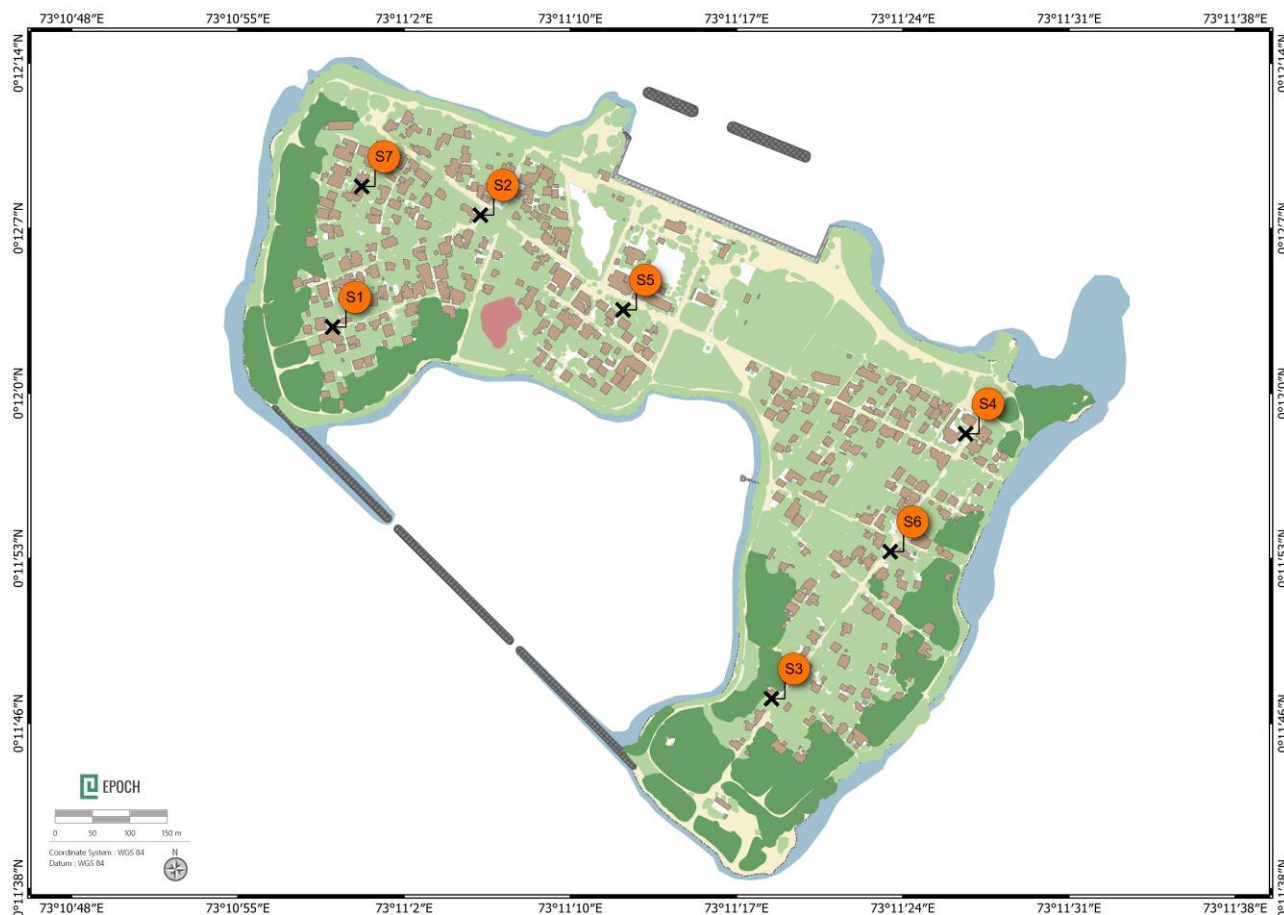


Figure 216: Soil Profile Survey Locations – GDh. Faresmaathoda

10.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 217 below. Even though there are variances in the colour due to environmental factors, the island soil profile is made up of Uniformly Graded Sand for the observed depth.

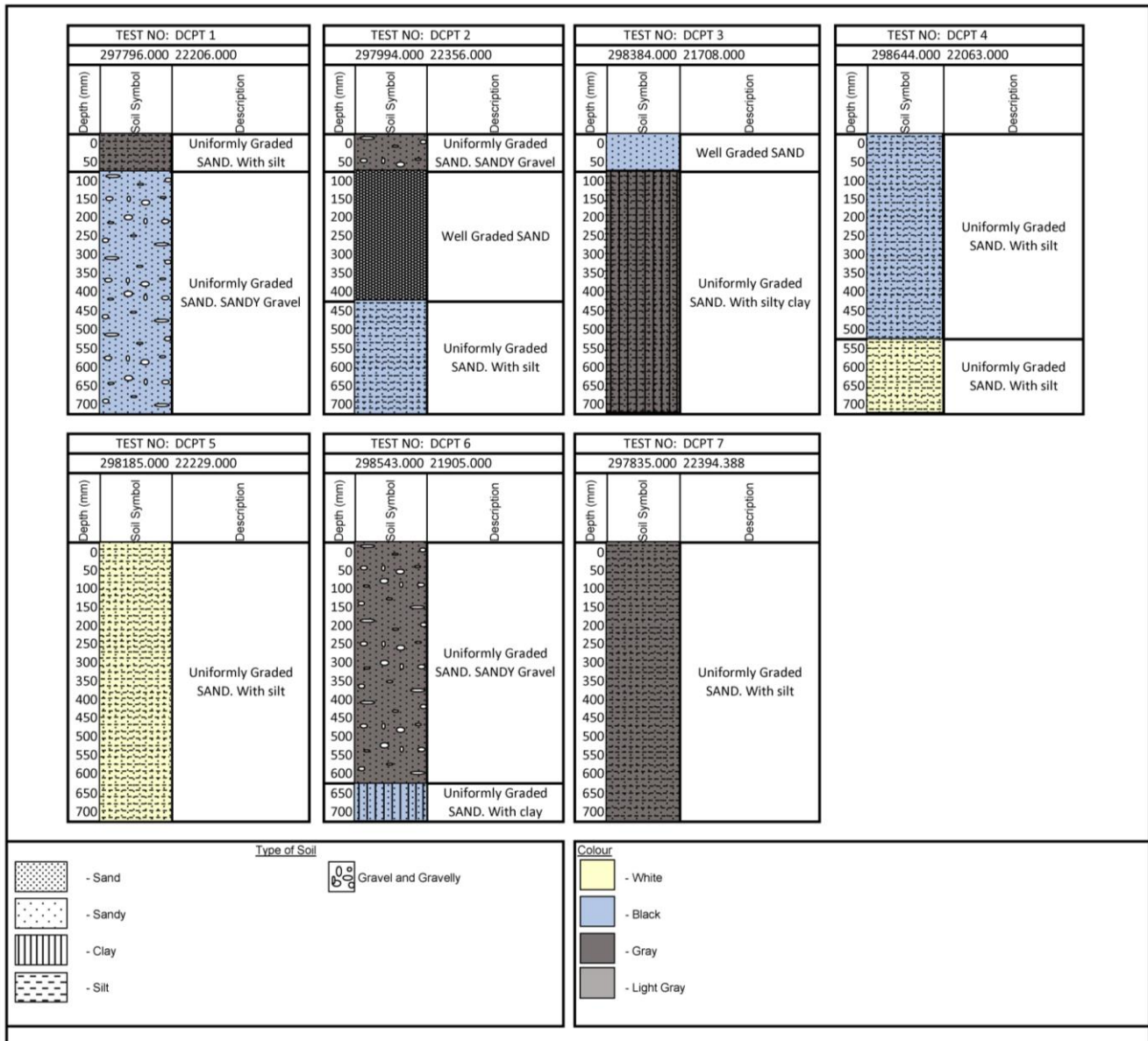


Figure 217: Soil Profile - GDh. Faresmaathoda

10.8 Flood Assessment and Inundation Survey

10.8.1 Flood occurrence and flood impact

In GDh. Faresmaathoda, around 66% of the houses reported that flooding occurs mostly when it rains heavily. According to the survey, 48% of the houses reported that the road development work had a major impact on the flooding pattern of the island.

The island is also at high risk of surge during extreme weather conditions, which causes powerful swell waves (UNDP report on Disaster risk profile for Maldives November 2006). This was also evident from the social survey where the majority of residents reported extreme swell waves in the year 2007 as the significant historical flooding in the island. It was also reported that the entire island of Fares and one third of Maathoda was flooded with maximum inundation measured in excess of 1.5m (Land and Marine Environmental Resources Group, 2013).

From the Social Survey, it was also observed that the ring road around the island has been filled by sediment which makes the level higher than the rest of the island thereby rainwater flows into the island.

The flooding originates mostly from roof runoff (35%) as per the Social Survey. Most responses state multiple sources for causes of flooding within their properties such as from neighbours' roof, off the road, and general run off in the area. Perceived causes of flooding as per social survey are given in table below.

Table 185: Perceived causes of flooding – GDh. Faresmaathoda

Perceived causes of flooding				
Roof run off	Neighbours' roof	Off the road	General run off in the area	No flooding within the plot
35%	5%	26%	2%	54%

From the social survey, 87% of households report that they drain rainwater overflow from storage and roofs to the ground. Most responses state multiple ways for the discharge of rainwater overflow such as to the ground, roads, open areas within the plot and to the well. Details of discharge of rainwater overflow are given in the table below.

Table 186: Discharge of rainwater overflow – GDh. Faresmaathoda

Discharge of rainwater overflow			
Ground	Roads	Open area within the plot	Drained to well
88.9%	0.8%	0%	10.3%

Despite the flooding incidents in GDh. Faresmaathoda, 79% of the households report flooding as an acceptable problem. (Refer to flood severity component of Annex XIII: Flood Maps) This can be due to continuous flood mitigation efforts by the island council and residents.

10.8.2 Flood Depth and Inundation area identification

The common flooding areas are the mangrove area, main road and Veylihankoda area. (refer to Annex XIII: Flood Maps) Based on the social survey responses, an average of 0.8ft is estimated as the flooding depth when there is a heavy rainfall. Also, 52% reported that it takes 2-4 hours to inundate the area once the heavy rain starts.

10.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 64% observe that the water drains during the rainfall itself, 25% observe that the water drains in less than 4 hours, 2.5% observe that the water drains in less than 4-24 hours and 8% observe that it takes more than 24 hours for water to drain.

Table 187: Draining period - GDh. Faresmaathoda

Draining period			
only while raining	drains less than 4hrs	takes 4-24 hrs	more than 24hrs
64.2%	25%	2.5%	8.3%

10.9 Geophysical Survey

10.9.1 Surveyed Locations

Locations where ER sounding measurement taken at GDh. Faresmaathoda island are shown in Figure 89 together with transect lines. There are 31 ER measurement locations and the number of transects in this island is 10.



Figure 218: ER surveyed locations and transect lines – GDh. Faresmaathoda Island

10.9.2 Freshwater levels and saline water levels

From processed ER data using GeoVES 1.5 – GeoElectrical Model depth to freshwater starting level and depth to freshwater lens bottom level (saline water start level) were determined and they were converted to elevation with respect to mean sea level using ground collected through drone survey. Table 188 below shows the estimated levels at ER surveyed locations of GDh. Faresmaathoda Island and freshwater lens thickness.

Table 188: Freshwater lens levels and thickness – GDh. Faresmaathoda island

No	Map ID	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	F2	1.440	0.740	-0.560	1.30
2	F3	1.435	1.135	0.585	0.55
3	F4	1.250	0.900	-0.150	1.05
4	F5	0.940	0.590	-0.660	1.25
5	F6	1.363	0.863	-0.487	1.35
6	F8	1.237	0.587	-0.413	1.00
7	F9	1.090	0.490	-0.510	1.00
8	F10	1.309	0.509	-0.341	0.85
9	F11	1.341	0.891	-0.309	1.20
10	F12	0.879	0.379	-0.721	1.10
11	F13	0.904	0.104	-1.096	1.20
12	F14	0.795	0.295	-0.805	1.10
13	F15	1.075	0.275	-0.925	1.20
14	F16	0.991	0.541	-0.309	0.85
15	F17	1.249	0.649	-0.601	1.25
16	F19	0.990	0.390	-0.510	0.90
17	F20	0.637	0.187	-1.613	1.80
18	F21	1.090	0.290	-1.310	1.60
19	F22	1.163	0.563	-0.337	0.90
20	F23	1.368	0.968	0.168	0.80
21	F24	0.634	0.234	-0.066	0.30
22	F25	1.317	0.967	0.367	0.60
23	F26	0.948	0.378	-1.022	1.40
24	F27	1.022	0.722	-0.528	1.25
25	F28	1.189	0.439	-0.761	1.20
26	F30	1.133	0.133	-1.867	2.00
27	F32	0.956	0.456	-0.744	1.20
28	F33	1.182	0.832	-0.068	0.90
29	F34	1.043	0.543	-0.457	1.00
30	F35	0.900	0.400	-0.600	1.00
31	F36	0.789	0.389	-0.811	1.20

Average freshwater thickness of GDh. Faresmaathoda island is 1.11 m.

Data in Table 188 were used to plot freshwater lens cross sections along 10 transects and they are given in Annex IX. Of these sectional plots 2 were given in Figure 218 and they represent the transect plot along T1 and T5. Dotted lines in these plots indicate ground level variation with respect to mean sea level along the transect lines.

10.9.3 Freshwater lens spatial extent

For the purpose of identifying spatial distribution of upper and lower level of freshwater lens the computed freshwater levels and saline water levels at ER points were exported to ArcGIS and used to generate contours with help of interpolation tools available in the same software. The generated contours are shown in Figure 219 and the processed ER data were used to develop a 3D view of the freshwater lens and it is also shown in Figure 219.

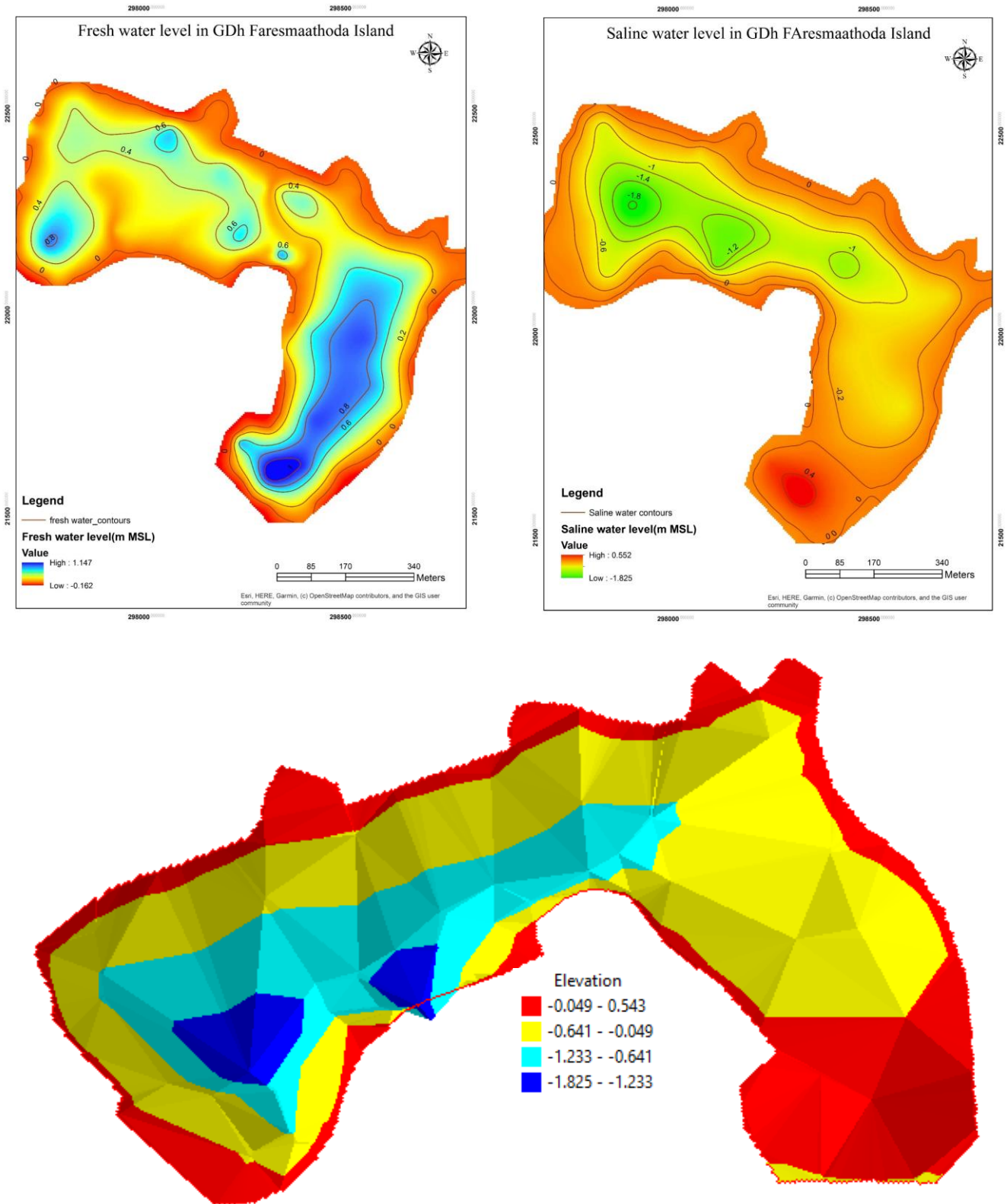


Figure 219: Contours of Freshwater lens upper level – GDh. Faresmaathoda island

10.9.4 Freshwater lens storage volume and stress level

For the estimation of freshwater volume, the depth difference between freshwater-saline water interface and freshwater upper level was computed at each ER measurement points and they were then used to determine freshwater volume stored in the ground at time of taking ER measurements. Both “Triangle method” and Tools in ArcGIS software were used to perform this computation. Figure 220 shows triangles considered for the aforementioned computation. Detailed calculations can be found in Annex X: Freshwater Lens volume calculations

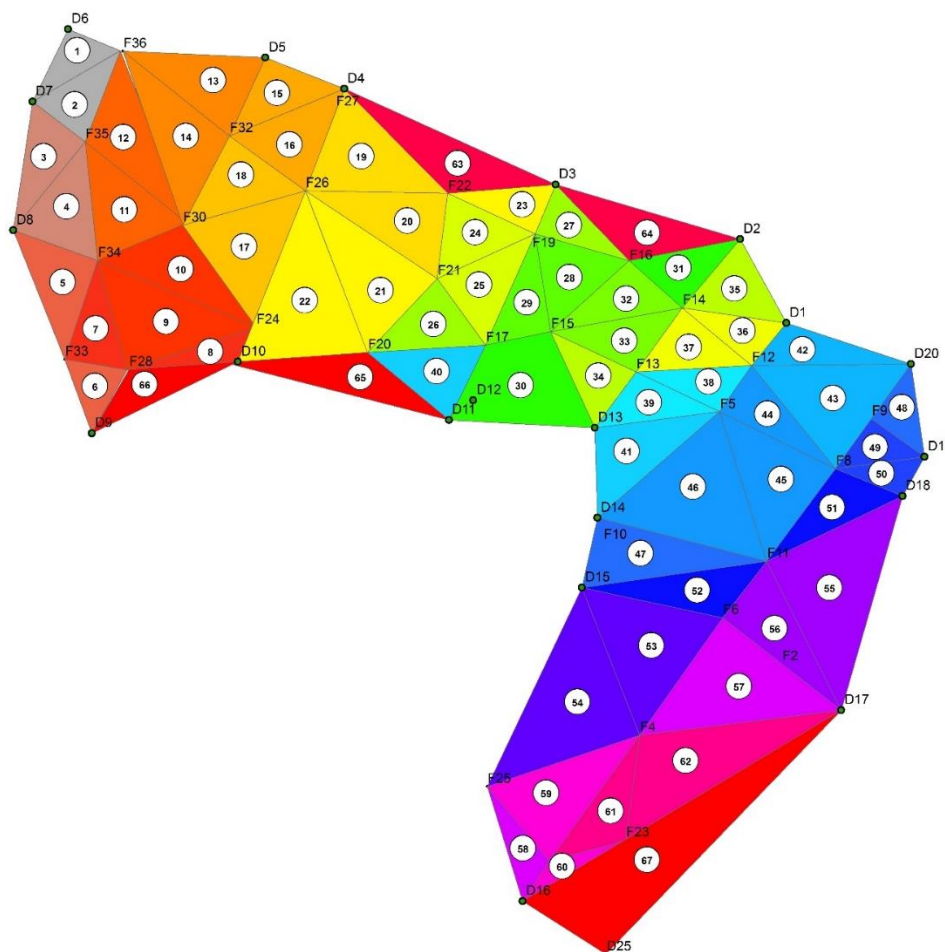


Figure 220: Triangles for freshwater volume computation – GDh. Faresmaathoda island

Stress level on freshwater aquifer of GDh. Faresmaathoda island was determined by computing ratio between freshwater lens volume and annual groundwater abstraction for non-potable water usage at present. When this ratio was more than 1.5, the island was treated as “not stressed” and if it was between 1.5 and 1 the aquifer was assumed to be “stressed” and any other lower ratio was taken as “highly stressed” aquifer. This criterion was developed based on saline water issues collected from the project islands during field work. The computed freshwater volume, water abstraction and aquifer stress level are given in Table 189.

Table 189: Freshwater lens volume and aquifer stress level – GDh. Faresmaathoda island

Item	Value	Unit
Freshwater lens volume – Triangle method	75,539	m ³
Freshwater lens volume – ArcGIS	75,625	m ³
Groundwater abstraction	166,697	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	0.5	-
Aquifer stress level	Highly stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation equates to 6.4m. This deviates by 220% from the maximum measured value of 2m, which is more reliable as it results from a more comprehensive, site-specific methodology.

10.10 SWB Modelling

10.10.1 Topography for flow direction

Topographical data assigned to model grids for computation of D8 flow directions is shown in Figure 221 and according to this figure elevation of the island is changing from -0.036 mAMSL to 2.475 mAMSL and average elevation is 1.289 mAMSL.



Figure 221: Elevation data assigned for SWB modelling - GDh. Faresmaathoda Island

10.10.2 Land use categorization and area estimation

Land use map prepared for SWB modelling of GDh. Faresmaathoda island is shown in Figure 222 together with table a showing land classification and their respective areas. It could be noted from the Figure 222 that 20m x 20m grids are adequate to represent the island land use for SWB modelling purpose.

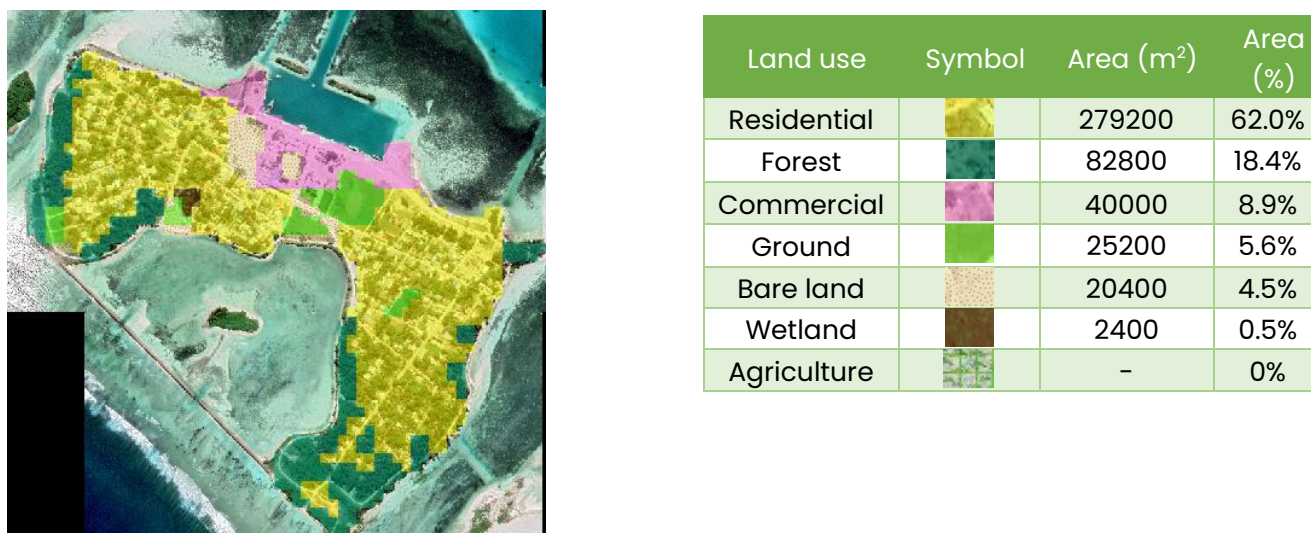


Figure 222: Land use for SWB model - GDh. Faresmaathoda Island

10.10.3 Recharge estimation and distribution

Monthly recharge values estimated at grid cells of the SWB model were extracted and used to identify its variation over years and months (refer Figure 223 and Table 190). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 120.0, 311.7 and 443.4 respectively over a 20-year period.
- There is a good relationship between annual rainfall and annual recharge, it is not linear but inverse exponential.
- Annual average rainfall is around 2270 mm but for 5 consecutive years (from 2008 to 2012) annual rainfall was below average. It indicates that there would be serious issue of saline water intrusion into the freshwater lens during such period as the recharge value would be considerably lower than annual average recharge value (inverse exponential relationship)
- Variation among the monthly average recharge value is very high. It is lowest on month of March and highest in November
- Water consumption (pumping) for non-potable use on 6-month period is less than the recharge value on the respective months. It indicates that GDh. Faresmaathoda island is heavily depending on groundwater storage and there would be serious issues of saline water intrusion into this island.

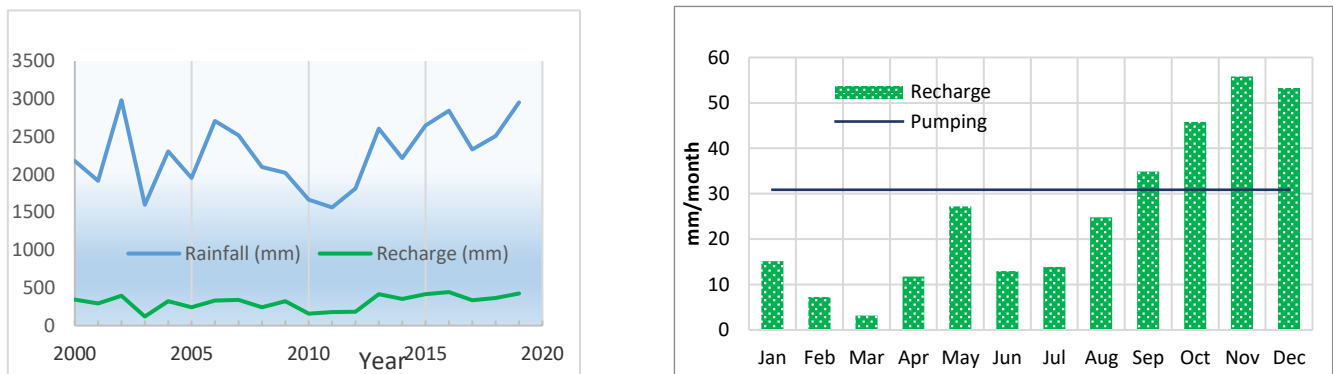


Figure 223: Monthly and annual recharge distribution – GDh. Faresmaathoda island

Table 190: Monthly recharge estimated by SWB model - GDh. Faresmaathoda Island

Year	Monthly Recharge (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	3.9	0.0	0.4	7.9	6.9	35.3	21.8	26.4	101.4	38.1	63.2	37.8
2001	0.0	0.0	0.0	21.2	7.2	0.2	8.4	29.9	64.2	55.4	69.1	39.1
2002	4.8	9.0	11.9	18.3	32.4	40.0	24.2	10.5	21.1	79.6	63.4	80.0
2003	3.6	0.0	0.1	5.5	22.3	13.5	21.5	7.6	1.1	7.9	25.7	11.2
2004	28.3	0.0	0.0	11.1	1.6	1.6	17.4	34.3	41.0	44.2	93.5	51.1
2005	25.2	12.8	0.0	0.6	22.7	29.9	23.7	17.9	11.1	95.0	3.7	1.0
2006	24.2	46.9	0.3	4.1	1.3	3.4	6.3	5.8	41.5	5.2	125.1	69.0
2007	46.3	0.0	0.0	3.3	12.2	27.8	17.2	2.4	26.7	89.0	8.2	105.4
2008	13.5	0.0	0.4	20.6	16.4	8.8	14.3	8.0	0.7	49.1	58.4	50.9
2009	32.1	20.7	0.4	2.0	45.3	0.1	3.6	67.7	26.4	34.5	51.7	38.6
2010	6.0	0.2	0.5	17.9	9.5	0.7	27.6	45.9	31.1	16.9	1.8	0.1
2011	0.0	0.0	0.4	4.7	14.7	0.0	0.1	7.7	0.9	44.6	20.3	87.2
2012	0.0	12.9	0.4	0.2	12.6	3.9	9.8	7.2	10.0	83.5	32.9	10.1
2013	0.2	0.8	10.8	18.0	67.5	5.6	21.4	25.2	11.1	31.7	114.9	108.8
2014	0.4	0.6	8.2	10.7	91.8	0.1	4.7	9.1	99.4	28.1	64.1	35.5
2015	8.8	9.8	0.3	0.4	14.2	11.8	8.8	74.8	24.5	80.6	87.3	93.8
2016	54.0	3.1	16.3	38.0	48.6	4.9	17.5	99.7	17.6	28.9	64.5	50.4
2017	2.9	0.0	7.6	0.2	65.8	0.0	13.2	14.3	60.7	2.0	53.8	116.7
2018	0.0	4.3	1.1	37.7	45.8	33.6	19.7	0.0	43.3	84.9	53.3	41.0
2019	59.3	15.5	6.5	12.9	23.3	38.7	6.5	17.7	63.4	47.1	60.7	73.1

10.10.4 Water Balance

As per estimation, annual recharge estimated by the SWB model is 140,149 m³ and it is 13.7% of annual average rainfall (refer from Figure 224).

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m ³	1,021,136	2,071	12,553	539,432	140,149	326,931	166,697
%	100.0%	0.2%	1.2%	52.8%	13.7%	32.0%	16.3%

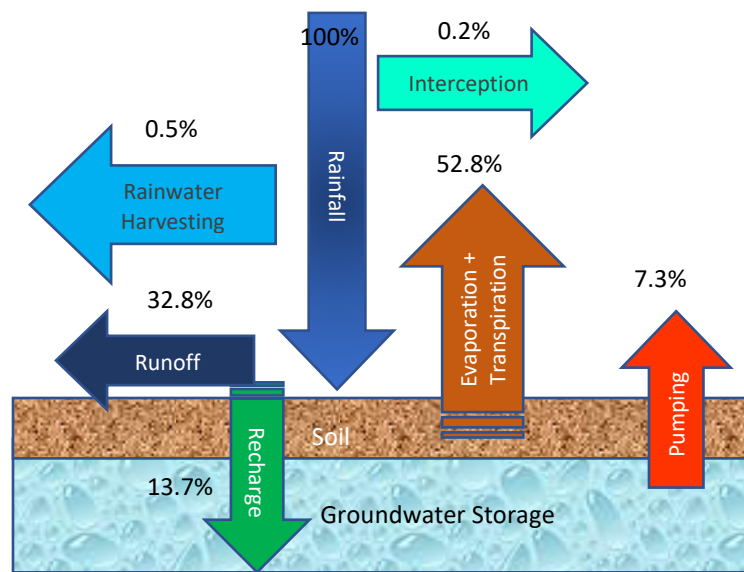


Figure 224: Annual water balance - GDh. Faresmaathoda Island

10.10.5 Deficit estimation, dry month identification and safe yield

Deficit calculation was carried out to identify whether recharge over a month period is smaller than or larger than the pumping quantity in the island. Monthly recharge time series estimated by the SWB model was compared with total pumping quantity of the island (13,891 m³/month) and if recharge exceeds the pumping quantity it was taken as “no deficit” and on other hand if pumping quantity exceeds the recharging value it was taken as “deficit”.

Table 191: Deficit percentage - GDh. Faresmaathoda

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	163	67.9

It is to be noted that “deficit” doesn’t mean failure or inadequate freshwater for pumping, but it is to be interpreted that the number of months when pumping is to be supported by groundwater storage in addition to recharging quantity. As per estimation, pumping at GDh. Faresmaathoda island is 67.9% dependent on the groundwater storage.

Determining safe yield which is defined as the attainment and maintenance of a long-term balance between the annual amount of groundwater withdrawn by pumping and the annual amount of recharge is important for small islands and there are various methods to estimate this amount. One simple method is checking whether ground water abstraction is less than or equal to 10% of average annual rainfall (MoEnv. 2020). The comparison of the estimated ground water withdrawal (13,891 m³/yr) with safe abstraction volume (57,150 m³/yr) shows that present withdrawal is 192 % higher than the safe yield.

10.11 SUTRA Modelling

10.11.1 Model representation and topographical features

SUTRA modelling requires model domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island (refer Figure 225). The other boundary defined in the model was island outline which can be taken as the shoreline for most of the cases except at harbour area and the inner part of the island was subdivided into several polygons representing different land use areas and it was accomplished by importing GIS shape files of island land use and then drawing polygons on shape files. Some other boundaries were also defined to represent island features such as lake and elevation change in the middle of the reef. Mesh with irregular quadrilateral elements were produced for all closed boundaries. Mesh size defined for outer boundaries (area between shoreline and model domain) were 3 to 4 times larger than the size defined for the inner part of the island. Elevation at shoreline was defined as zero whereas elevations for inner part of the island was assigned from topographical data used for SWB modelling. Figure 225 shows model domain and SUTRA model mesh with topographical changes.



Figure 225: Model boundaries and model mesh - GDh. Faresmaathoda island

10.11.2 Pressure boundaries

Specified pressure boundary was defined along the model domain so that it would cause saline water intruding into the island when pressure along the outer boundary of freshwater lens is less due to lower recharge and/or groundwater abstraction is high. Figure 226 shows the pressure boundary defined for GDh. Faresmaathoda island.

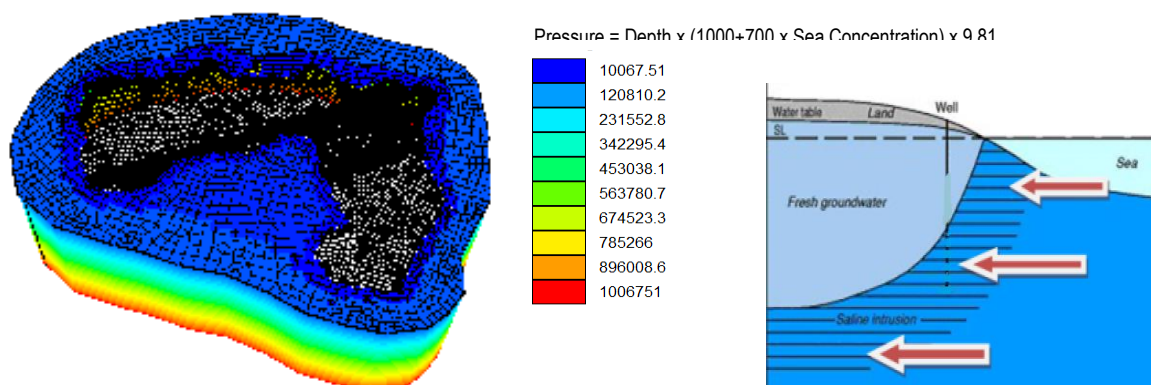


Figure 226: Pressure boundary at SUTRA model - GDh. Faresmaathoda island

10.11.3 Assigning recharge on land use basis

Recharge rates estimated by the SWB model for each grid cells were lumped on land use basis using VB program and ArcGIS tool and they were then used to estimate the monthly average recharge rate on residential area, commercial area, and other land use. Table 192 shows monthly recharge rate estimate for GDh. Faresmaathoda island.

Table 192: Recharge for SUTRA model - GDh. Faresmaathoda island

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	35.3	5.9	6.9	27.0	32.4	6.9	27.8

10.11.4 Groundwater abstraction

Groundwater pumping takes place at individual houses, restaurants, and institutes. Since all well locations are not available and abstraction rate would also change place to place a simplified approach was adopted by defining a polygon around the residential area (area highlighted in blue in the below map) and assigning average pumping rate of 13,891 m³/month.



Figure 227: Pumping region at SUTRA model - GDh. Faresmaathoda island

10.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20 yr period is shown in Figure 228. The orange-coloured component in the 3D view represents sea water concentration around the island and the section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0375 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top and at the central portion where there is relatively low abstraction of ground water.

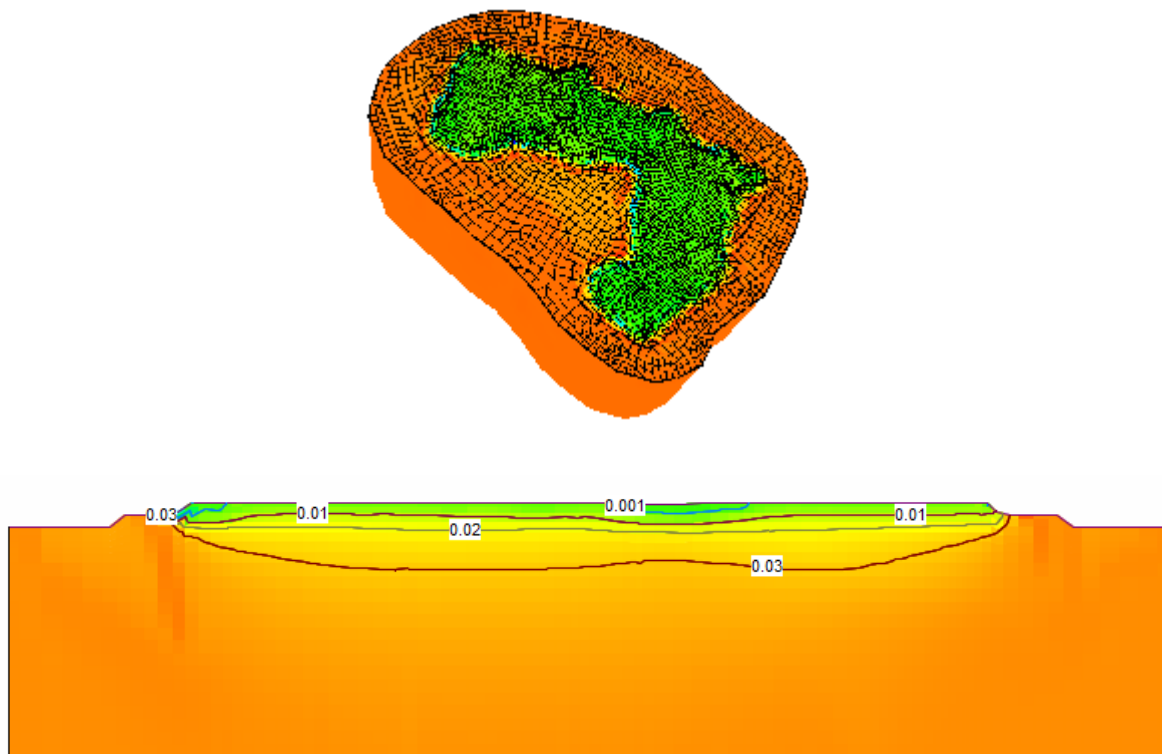


Figure 228: Saltwater distribution - GDh. Faresmaathoda island

10.12 Summary of Baseline Assessment

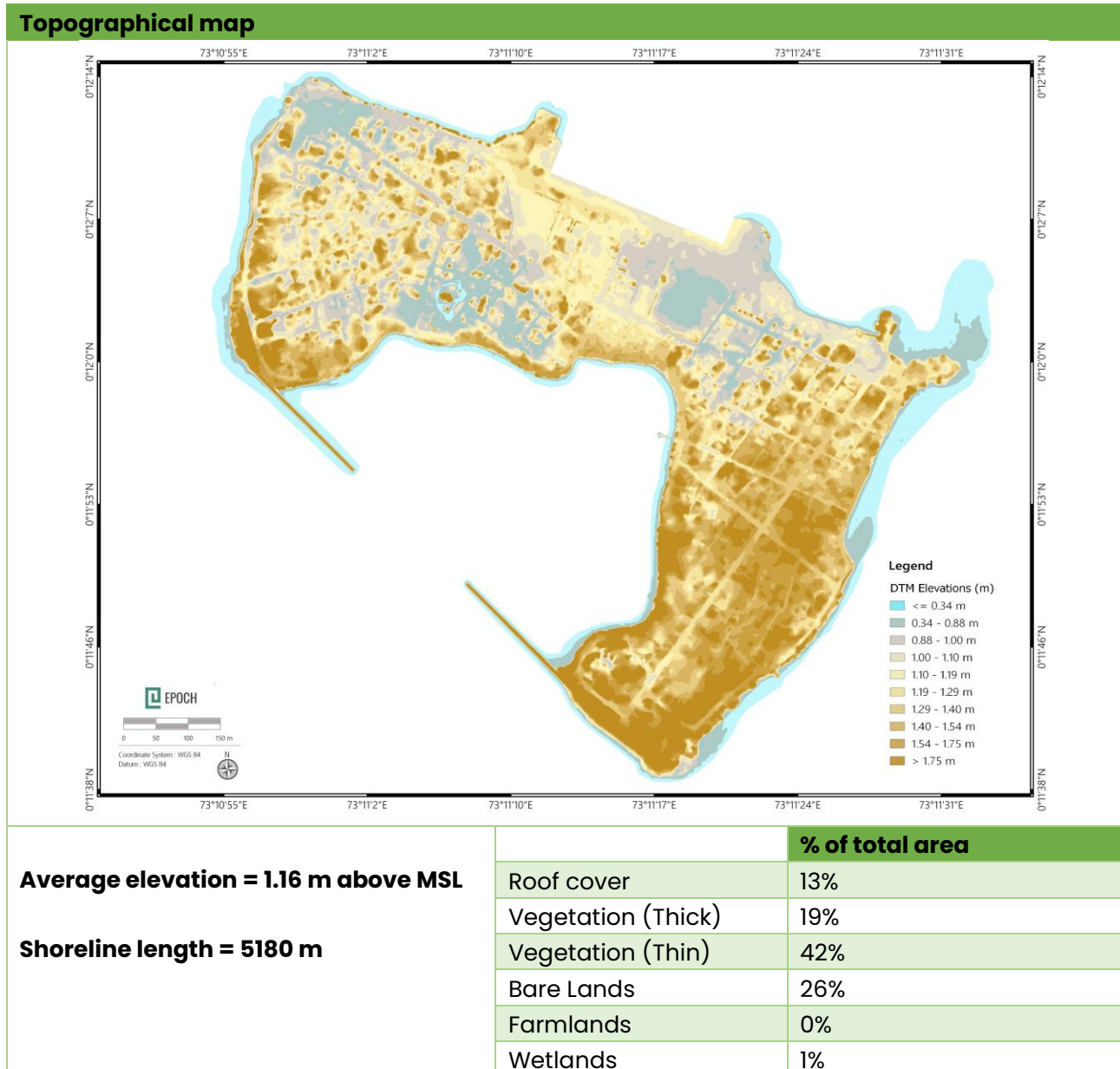
Summary of findings extracted from field works, laboratory test, modelling and analysis are presented below.

- General overview, demography, and climatology

Item	Details
Atoll	Huvadhoo Atholhu Uthuruburi Atoll
Length	1.07 km
Width	0.79 km
Area	47.4 ha
Population	1,849
Population/area	39.00 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use





• Water consumption

Category	Domestic	Commercial	Institutional	Industrial	Total
Rate (m ³ /d)	457	1.22	4.83	0.714	463

- Water quality parameters – Physiochemical

Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC ($\mu\text{S}/\text{cm}$)	1,381 $\pm$ 1,283	1500
Turbidity (FNU)	1.46 $\pm$ 2.39	5
DO (mg/L)	3.62 $\pm$ 1.93	
pH	7.53 $\pm$ 0.40	6.5–8.5
Temp ($^{\circ}\text{C}$)	28.75 $\pm$ 1.38	
Sal (ppt)	0.65 $\pm$ 0.65	
NH ₃ (mg/L)	2.80 $\pm$ 3.45	1.5 (Odour Threshold)
NO ₃ ⁻ (mg/L)	9.96 $\pm$ 8.59	50
PO ₄ ³⁻ (mg/L)	0.30 $\pm$ 0.26	

- Water quality parameters – Microbiological

Number of samples tested = 15

Parameter	Value range	Average value	Remarks (<i>on permit limit</i>)
Total Coliform (MPN/100ml)	2 – >2420	1450.73	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not detected – >2420	174.13	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	405.5	m ² /day
Storativity	1	0.008487	-
Permeability	7	5.861 – 61.470 Average – 23.671	m/day
Soil profile	5	Mostly uniformly graded sand and well graded sand and gravel on the South Western ridge of the island	

- Flooding

Flooding days per year	Inundation area (m ²)	Inundation depth (m)
34	14,000	0.238

- Electric Resistivity survey

- Measurement taken at 31 locations and number of transect is 10.
- Average freshwater thickness in the island is 1.11 m.
- Freshwater lens volume and aquifer stress level

Item	Value	Unit
Freshwater lens volume - Triangle method	75,539	m ³
Freshwater lens volume - ArcGIS	75,625	m ³
Groundwater abstraction	166,697	m ³ /yr
Freshwater lens volume/ Groundwater abstraction	0.5	-
Aquifer stress level	highly stressed	-

- SWB modelling
 - Annual recharge is 140,149 m³ and it is 13.7% of annual rainfall (2270 mm)
 - Annual water balance

Unit	Component						
	Rainfall	Interception	Rainwater Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m³	1,021,136	2,071	12,553	539,432	140,149	326,931	166,697
%	100.0%	0.2%	1.2%	52.8%	13.7%	32.0%	16.3%

- Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 67.9% in an average year, and it is compensated by ground water storage.
- Ground water withdrawal (13,891m³/yr) is 192% higher than the safe abstraction (57,150 m³/yr).

- SUTRA modelling
 - Average monthly recharge assigned to SUTRA model

Land use	Forest	Commercial	Bare land	Residential	Ground	Wetland	Agriculture
Recharge (mm/month)	35.3	5.9	6.9	27.0	32.4	6.9	27.8

- Freshwater lens prediction (allowable concentration for potable use is 0.001)

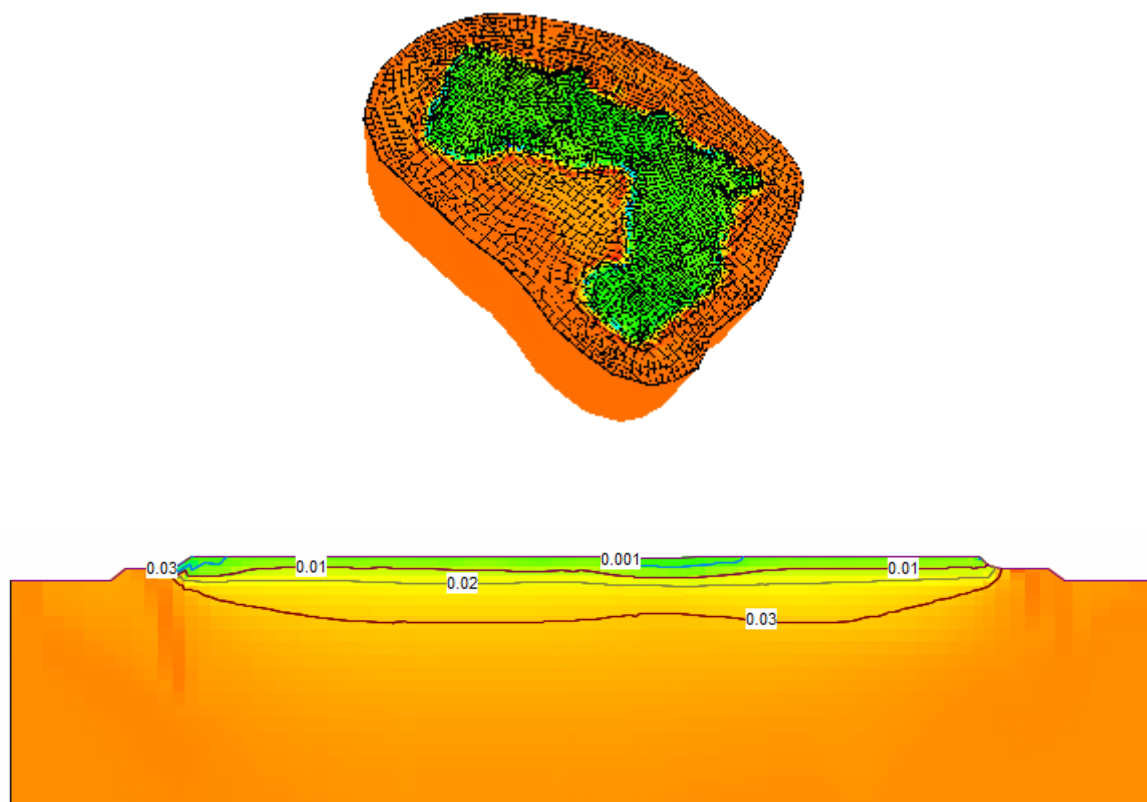


Figure 229: Saltwater distribution - GDh. Faresmaathoda island

11 Conclusion and Recommendations

The field surveys and investigations together with the groundwater modelling carried for the baseline assessment of the islands reveals an urgent need for recharge and replenishment of the freshwater lens.

The social surveys carried throughout the islands indicates that domestic groundwater usage is considerably higher in all of the islands. The domestic water consumption ranges from 239 to 294 LPCD. it is recommended to conduct awareness programs to encourage and educate people about the role of the freshwater lens and to reduce their water consumption.

Based on the water quality testing carried for the physiochemical parameters, the water quality is found to be very good across all the islands. However, the microbiological testing carried on samples indicates widespread contamination across all islands. This could possibly be attributed to the leakages from septic tanks and local outfall lines. Though the construction of gravity sewerage systems is planned to be completed within the next few years, it is vital to ensure proper decommissioning of the existing sewerage infrastructures in order to avoid continued leakages in the future. The Electrical conductivity results from the groundwater samples collected indicate that the groundwater quality is well within the range for non-potable uses. However, there are some islands where groundwater is being used for cooking and the current groundwater quality is not preferable for such usage.

The Electrical Conductivity values at measured locations were plotted against water consumption to check if increasing water usage leads to salinization as indicated from the Figure 230. There is no significant relationship observed between Electrical Conductivity and Water Usage for the islands as per the findings from the Social Survey and Water Quality Survey.

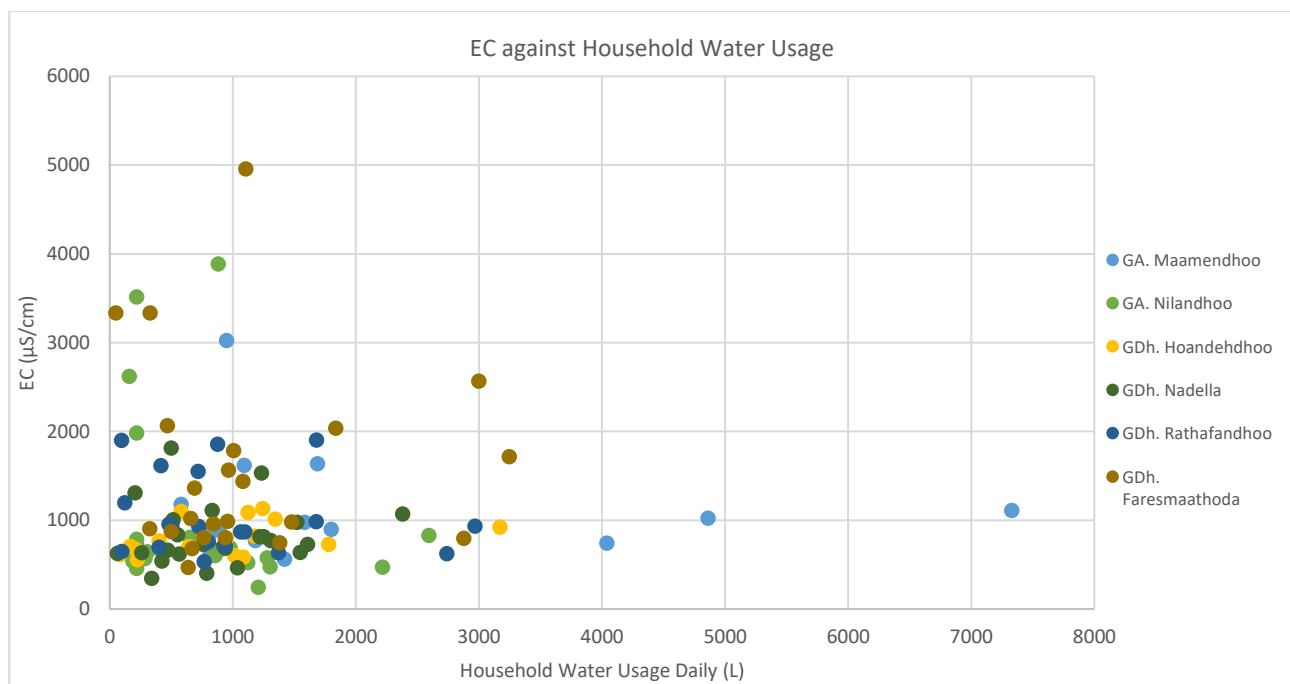


Figure 230: Electrical Conductivity against Household Water Usage for all islands

The microbiological testing carried on samples indicates widespread contamination across all islands. This could possibly be attributed to the leakages from septic tanks and local outfall lines. Though the construction of gravity sewerage systems is planned to be completed within the next few years, it is vital to ensure proper decommissioning of the existing sewerage infrastructures in order to avoid continued leakages in the future.

The Total Coliform and Faecal Coliform Contamination was plotted against the distance between septic tank and well for all islands, to identify the correlation between these two variables. The graphs are given below (Figure 231). There is no significant relationship observed between Total Coliform, Faecal Coliform and distance between septic tank and nearest well.

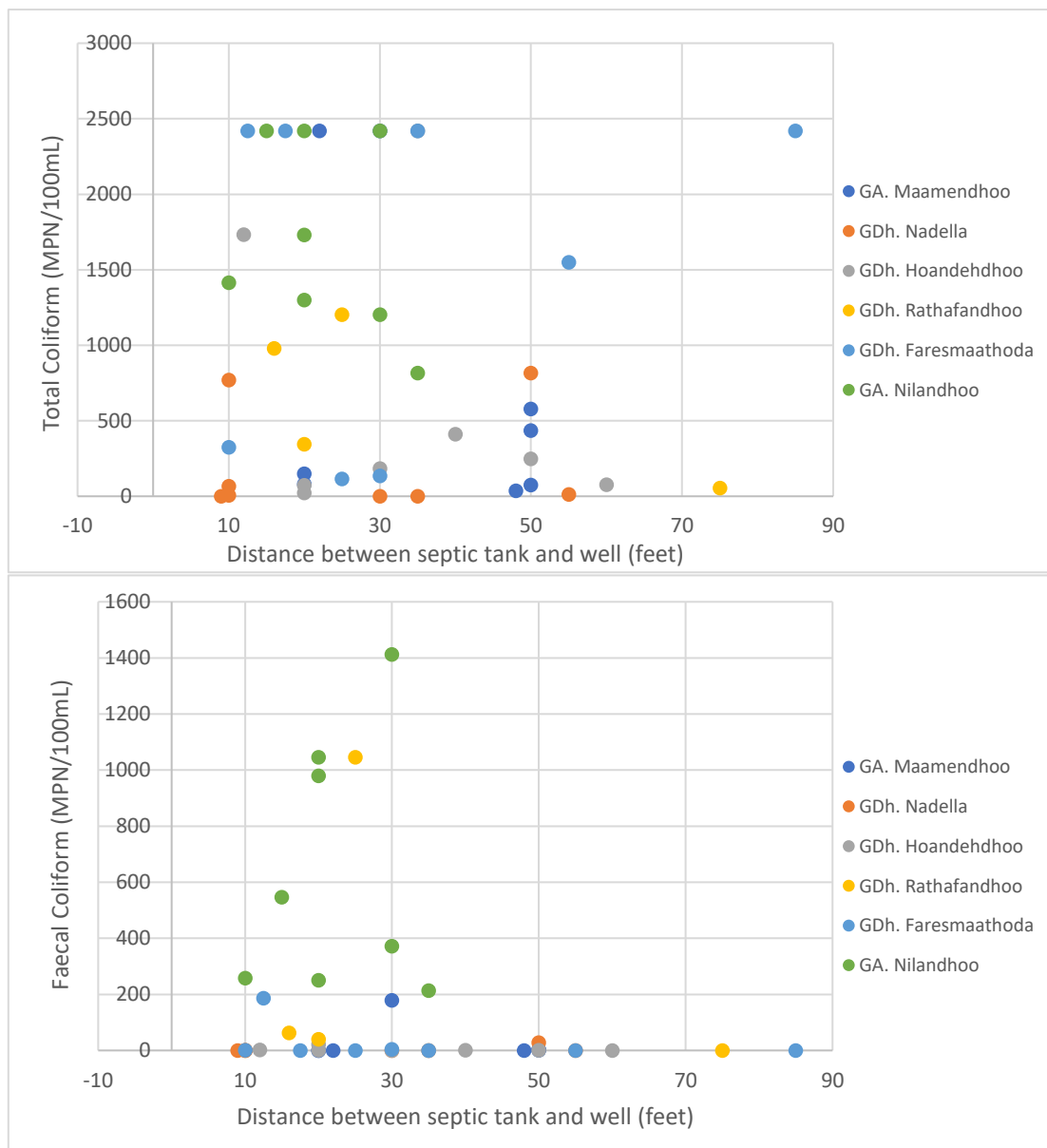


Figure 231: Correlation between microbiological contamination and distance between septic tank and well

The geophysical surveys carried out indicates that there are some islands with highly stressed aquifers (GDh. Faresmaathoda, GDh. Nadella and GDh. Rathafandhoo) while two islands (GA. Maamendhoo and GDh. Hoandehdhoo) have slightly stressed aquifers. GA. Nilandhoo aquifer is not stressed.

The SWB modelling carried indicates that recharge percentages for the islands ranges from 12% to 16.1% of the rainfall value. It is also noted that a significant amount of rainfall is lost as runoff into the sea. Additionally, the modelling indicates that the current pumping rates exceeds the safe yields of the aquifer in all islands except GDh. Hoandehdhoo. The SUTRA modelling carried indicates Saltwater intrusion pattern and concentration contours that match the site observations from the geophysical and water quality survey.

While some aquifers are not stressed, all the islands except GDh. Hoandehdhoo exceed the safe yield and therefore is susceptible to saltwater intrusion there by rendering the aquifer unusable for human consumption. As such the need for Managed aquifer recharge systems are clearly evident from this baseline assessment. One of the most significant streams of water cycle that can be diverted into ground aquifer through recharge is the surface water runoffs.

Spaces are available for the construction of MAR design such as infiltration pit, infiltration trench and infiltration basin and soil permeability and soil profile are in favour of MAR design. However, depth between ground level and groundwater table is an important item to decide on type and sizing of MAR design and they will be considered together other social, environmental, and economic factors during feasibility study.

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13 Annex I: Stakeholder consultation and meeting

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