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

BASELINE ASSESSMENT REPORT

AA. Mathiveri, AA. Himandhoo, ADh. Kunburudhoo, Dh. Bandidhoo, Dh. Hulhudheli, M. Veyvah and M. Naalaafushi

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ASSIGNMENT DETAILS

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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 01. The project client is Ministry of Environment and is funded by the Green Climate Fund (GCF). This report will present the main findings from the baseline groundwater assessment for 07 islands.

This project is with the distinct objectives to 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 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
- Geophysical Survey
- Pumping Test
- Permeability Test
- Soil Profile 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 effort was 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 1 islands are relatively low-lying islands, with average elevation roughly 1 m above mean sea level. With the exception of M. Naalaafushi, all islands in this list have experienced moderate to severe shore erosion on their windward faces, where eroded shorelines are either eroded to the point where vegetation roots are exposed, or sediments accumulate to form ridges. M. Naalaafushi has not experienced any erosion on its windward face due to the presence of a revetment going along the entire eastern shoreline.

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

Table 1 Lot I island topography summary

Island	Average Elevation (m)	Atoll Location	Highest Windward Ridge Elevation	Mean DTM Error (cm)	Shoreline Length (m)
AA. Mathiveri	0.799	North	1.60	-1.07	3120
AA. Himandhoo	1.130	West	1.65	+1.40	2880
ADh. Kunburudhoo	1.058	East	1.25	+4.90	1428
Dh. Hulhudheli	1.100	West	1.50	+4.46	3313
Dh. Bandidhoo	1.396	Northeast	1.80	-0.84	2278
M. Naalaafushi	0.733	East	1.50	+3.29	2225
M. Veyvah	1.160	East	1.85	-0.84	3938

The Topographical Survey detailed methodology is presented in Section 4.2 and the results are presented in Sections 5.2, 6.2, ..., 12.2 for the seven 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

Island	Population		Total island wide daily water consumption (m^3)				
	Number	Density	Household	Commercial	Institutional	Industrial	Total
AA. Mathiveri	1006	47.7	175	11.9	6.15	0.370	193
AA. Himandhoo	848	40.8	138	3.22	5.04	-	146
ADh. Kunburudhoo	624	110	97	1.03	1.52	0.020	99.9
Dh. Hulhudheli	958	44.8	183	0.56	4.99	-	189
Dh. Bandidhoo	997	41	209	-	10.3	0.286	220
M. Naalaafushi	535	42.8	93	0.26	2.10	0.199	95.1
M. Veyvah	339	7.92	62	0.70	1.15	18.3	82.2

In M. Veyvah, industrial usage is high because of large scale fish processing work. Likewise, in AA. Mathiveri, commercial usage is high due to an upsurge of guesthouses with the development of guesthouse tourism. As evident in the table above, ADh. Kunburudhoo has the third lowest consumption due to high salinity in groundwater. Approximately 91% of the surveyed households in ADh. Kunburudhoo reported salt concentration in their groundwater. Contrarily, Dh. Bandidhoo has the highest usage due to lower contamination in groundwater. Generally, domestic water consumption ranges from 156 to 210 LPCD with an average of 178 LPCD.

The Social Survey detailed methodology is presented in Section 4.3 and results are presented in Sections 5.3, 6.3, ..., 12.3 for the seven 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 in all islands:

Table 3: Water Quality (Physiochemical) Summary Table

	EC (µS/cm)	Turbidity (FNU)	DO (mg/L)	pH	Temp (°C)	Sal (ppt)	NH_3 (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)
AA. Mathiveri	1416	2.91	3.36	7.45	30.48	0.64	1.03	6.61	0.24
AA. Himandhoo	3696	2.30	3.19	7.25	29.95	1.83	7.98	28.7	0.34
ADh. Kunburudhoo	20910	1.88	3.91	7.27	30.60	11.30	56.47	100	0.32
Dh. Hulhudheli	1349	1.20	3.67	7.42	29.33	0.61	4.96	19.4	0.44
Dh. Bandidhoo	619	0.18	5.25	7.47	29.28	0.27	1.44	12.0	0.22
M. Naalaafushi	3608	3.32	3.80	7.54	29.45	1.82	5.90	16.7	0.30
M. Veyvah	2329	3.43	3.12	7.49	27.71	1.16	8.04	21.0	0.26

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH_3= Ammonia, NO_3^-= Nitrate, PO_4^{3-}=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 indicate 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 based on physiochemical parameters for all sampling locations and classified into categories. Dh. Bandidhoo was classified as "Very Good", AA. Mathiveri, Dh. Hulhudheli, AA. Himandhoo, M. Veyvah and M. Naalaafushi was classified as "Good", and ADh. Kunburudhoo was classified as "Very Poor" based on calculated WQI.

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.

Table 4: Water Quality (Microbiological) Summary Table

	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
AA. Mathiveri	1416	2.91
AA. Himandhoo	3696	2.30
ADh. Kunburudhoo	20910	1.88
Dh. Hulhudheli	1349	1.20
Dh. Bandidhoo	619	0.18
M. Naalaafushi	3608	3.32
M. Veyvah	2329	3.43

The construction of gravity sewerage systems is either under construction or have been planned for all islands which upon commissioning are 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, ..., 12.4 for the seven 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 7 islands except AA. Himandhoo. A well practical for pumping was not available in AA. Himandhoo. The average value of Aquifer Transmissivity is 56.00 m^2/day, with values ranging from 18.07 m^2/day to 92.00 m^2/day. The average value of Aquifer Storativity is 0.17, with values ranging from 0.122 to 0.210.

The Pumping Test detailed methodology is presented in Section 4.5 and results are presented in Sections 5.5, 6.5, ..., 12.5 for the seven 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 7 islands. The average Permeability value for Lot 01 islands is 15.18 m/day, with values ranging from 0.41 m/day to 41.59 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.

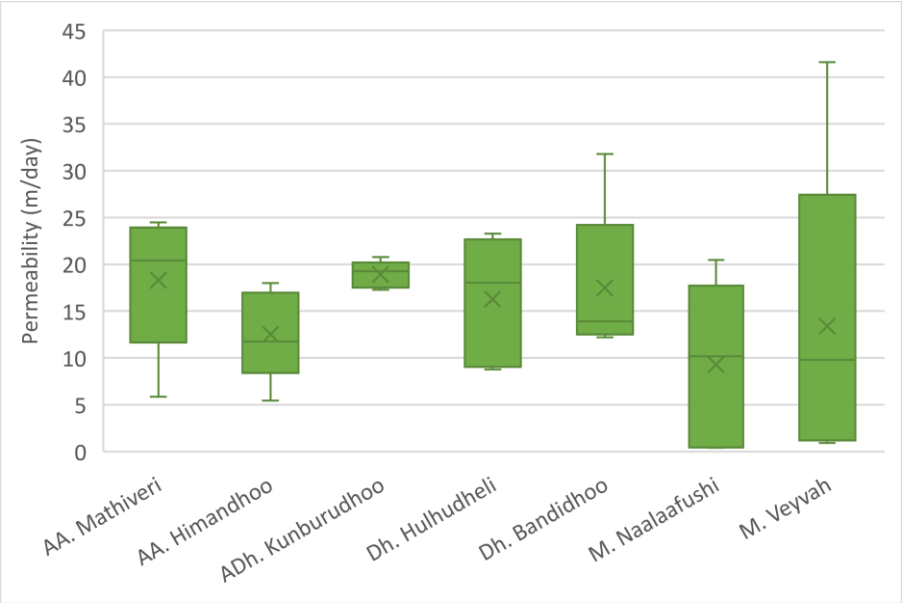

Figure 1: Permeability values across seven islands

The Permeability Test detailed methodology is presented in Section 4.6 and results are presented in Sections 5.6, 6.6, ..., 12.6 for the seven islands.

The soil profiles of the islands help broaden 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 detailed methodology is presented in Section 4.7 and results are presented in Sections 5.7, 6.7, ..., 12.7 for the seven 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. 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. The data sets available in this survey is a combination of local information collected through social survey and secondary rainfall data from Hulhule and Kahdhoo 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. Flooding Area (ha)	Avg. Duration (hr)
AA. Mathiveri	89	0.389	0.703	0.5 hr
AA. Himandhoo	78	0.438	0.435	0.5 hr
ADh. Kunburudhoo	67	0.372	0.103	0.5 hr
Dh. Hulhudheli	43	0.330	0.585	2-4 hr
Dh. Bandidhoo	34	0.356	0.489	0.5 hr
M. Naalaafushi	64	0.286	0.19	2-4 hr
M. Veyvah	83	0.414	0.37	0.5 hr

A common feature in all seven project islands is the 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 on roads and low-lying areas. This stagnated water is later released to the atmosphere or sea by infiltration into ground and sub-surface flow during low tide.

Use of stormwater to recharge freshwater aquifer has been considered via MAR designs such as infiltration pit, infiltration trench and infiltration basin and they are to be studied further 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, ..., 12.8 for the seven 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). The comparison of these contours with EC (Electric 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 time of taking ER, a set of tools in ArcGIS was used. 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	Area (ha)	Avg. thickness of FWL (m)	Max thickness of FWL (m)	FWL volume (m^3)	Aquifer stress level
AA. Mathiveri	21.1	2.85	4.37	260,964	Not Stressed
AA. Himandhoo	20.8	1.48	2.67	113,917	Not stressed
ADh. Kunburudhoo	5.69	1.05	1.40	39,788	Highly Stressed
Dh. Hulhudheli	21.4	1.72	4.99	371,691	Not stressed
Dh. Bandidhoo	24.3	4.16	7.29	436,921	Not stressed
M. Naalaafushi	12.5	0.95	1.90	100,468	Not Stressed
M. Veyvah	42.8	0.56	1.29	275,827	Not Stressed

A relationship was built between freshwater lens volume and ground water withdrawal amount and realized that freshwater aquifer is already highly stressed in some islands whereas some are not stressed at the existing condition. Aquifer stress level 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, ..., 12.9 for the seven islands.

Soil Water Balance (SWB) Modelling

- Soil Water Balance (SWB) modelling was carried out by defining the project islands using 10m x 10m grids and assigning climate data, flow direction, land use data soil type, and soil water storage capacities. SWB model was run on daily time steps 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 39,769 m^3/yr to 284,334 m^3/yr and they are summarized below.

Table 7: Annual recharge for project islands

Island Name	Annual Rainfall (m^3)	Annual Recharge (m^3)	Recharge/Rainfall (%)
AA. Mathiveri	421,217	140,265	33
AA. Himandhoo	393,897	120,336	30.6
ADh. Kunburudhoo	126,250	39,769	31.5
Dh. Hulhudheli	456,380	148,323	32.5
Dh. Bandidhoo	541,281	128,987	24
M. Naalaafushi	284,334	284,334	18.4
M. Veyvah	456,380	116,377	20.3

- 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.
- Comparison of estimated monthly recharge and monthly pumping quantity over 20 years period reveals that percentage of months where pumping exceeds recharge rate is 17.5% in M. Veyvah (lowest) and 82.1% in ADh. Kunburudhoo (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 (%)
AA. Mathiveri	54.6%
AA. Himandhoo	46.3%
ADh. Kunburudhoo	82.1%
Dh. Hulhudheli	49.6%
Dh. Bandidhoo	54.6%
M. Naalaafushi	47.1%
M. Veyvah	17.5%

- Annual safe yields were computed and compared with annual ground abstraction amount and found that withdrawal amount exceeds safe yield in three 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
AA. Mathiveri	69,656	70,608	1.37%	Slightly High
AA. Himandhoo	66,864	53,470	-20%	No impact
ADh. Kunburudhoo	3300	36,469	1005%	Extremely High
Dh. Hulhudheli	79,515	68,813	-13.4%	No Impact
Dh. Bandidhoo	48,702	80,266	64.8%	Very high
M. Naalaafushi	52,403	34,718	-33.75%	No Impact
M. Veyvah	92,655	23,721	-74.4	No Impact

The SWB Modelling detailed methodology is presented in Section 4.10 and results are presented in Sections 5.10, 6.10, ..., 12.10 for the seven 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.
- Saltwater intrusion pattern and concentration contours were predicted for all seven project islands by simulating the model for 20 years period on monthly time step in the existing condition.

The SUTRA Modelling detailed methodology is presented in Section 4.11 and results are presented in Sections 5.11, 6.11, ..., 12.11 for the seven islands.

Executive Summary Table is given on the following page.

Island	Mathiveri	Himandhoo	Kunburudhoo	Hulhudheli	Bandidhoo	Naalaafushi	Veyvah
Atoll	**Alifu Alifu**	**Alifu Alifu**	**Alifu Dhaalu**	**Dhaalu**	**Dhaalu**	**Meemu**	**Meemu**
Shape of the island							
General Overview of Island and Demography							
Area (Ha)	21.1	20.8	5.69	21.4	24.3	12.5	42.8
Length (m) & Width (m)	669 & 604	790 & 290	880 & 160	970 & 290	620 & 530	920 & 210	1540 & 350
Population	1006	848	624	958	997	535	339
Pop. density (per /hectar)	47.7	40.8	110	44.8	41	42.8	7.92
Land Cover- and Built-up Area (As a percentage of total land area)							
Roof area (%)	16%	17%	25%	15%	13%	13%	3.9%
Thick Vegetation (%)	31%	29%	12%	28%	33%	29%	64%
Thin Vegetation (%)	17%	19%	25%	19%	18%	17%	8.5%
Bare lands (%)	35%	36%	39%	38%	36%	40%	23%
Farmlands (%)	1%	-	-	-	-	0.2%	0.053%
Socio-economic Condition							
Overview	Island with established and growing local tourism industry	Island with fast growing local tourism industry	Island with severe salinization attributed to narrow shape of the island	Island with ongoing harbour construction	Island with good water quality	Island with tsunami damage	Large island with commercial fish processing facilities
Number of restaurants	4	2	1	2	-	2	2
No. of Guesthouses	6	3	1	-	-	-	1
Present Sanitation and Water-use Characteristics							
Presence of Sewer Network	None	None	None	Present	None	None	None
Presence of Water Supply	None	None	None	None	None	None	None
Households with RW tanks	81%	80%	95%	100%	100%	94%	93%
Rainwater use for drinking	100%	84%	91%	100%	100%	100%	88%
Groundwater non-potable use	100%	100%	100%	100%	100%	100%	100%
RW Storage Capacity (m^3)	349	380	284	325	376	295	152
Water Quality Aspects (Selected Parameters; please refer to respective chapters for other details and data)							
Water Quality Index (WQI)	11.68 ± 5.91	29.5 ±33.8	155 ± 73.3	12.5 ± 8.62	5.77 ± 2.29	27.8 ± 36.7	20.8 ± 19.6
Elect. Conductivity (µS/cm)	1,416 ± 731	3,696 ± 4,765	20,910 ± 9,674	1,349 ± 1,105	619 ± 180	3,608 ± 5,031	2,329 ± 2,705
Ammonia (mg/L)	1.03 ± 0.95	7.98 ± 11.97	56.47 ± 44.42	4.96 ± 7.73	1.44 ± 2.79	5.90 ± 8.28	7.80 ± 12.18
Faecal Cont	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Groundwater Availability, Usage, Water Balance and Recharge Potential							
Freshwater Lens Volume (m^3) & Thickness (m)	260,964 m^3 & 2.85 m	113,917 m^3 & 1.48 m	39,788 m^3 & 1.05 m	371,691 m^3 & 1.72 m	436,921 m^3 & 4.16 m	100,468 m^3 & 0.95 m	275,827 m^3 & 0.56 m
Rainwater Harvesting (m^3/yr)	7,074	5,724	4,409	6,878	6,310	3,858	**6,878**
Groundwater Extraction (m^3/yr)	70,608	53,470	36,469	68,813	80,266	34,718	23,721
Safe Yield (m^3/year)	69,656	66,864	3300	79,515	48,702	52,403	92,655
Usage / Safe Yield (%)	1.37%	-20%	1005%	-13.4%	64.8%	-33.8%	-74.4%
Present Aquifer Condition	**Minorly Stressed**	**Stressed**	**Highly Stressed**	**Not Stressed**	**Not Stressed**	**Stressed**	**Minorly Stressed**
Priority order for MAR	(4)	(2)	(1)	(7)	(6)	(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 01. The project client is Ministry of Environment and is funded by the Green Climate Fund (GCF). This report will present the main findings from the baseline groundwater assessment for 07 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 km^2 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. 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 management can help the government to deliver safe and secure freshwater to the people in the island.

In line with these objectives, the Ministry of Environment has contracted Epoch Associates for the assignment "Assessing groundwater resources and design of aquifer recharge systems in selected islands of Maldives".

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.

These MAR systems will be socially, economically, and technically feasible and sustainable in its design, construction, operation and maintenance.

A map showing all the islands is attached in the following page.

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 2 below shows the yearly average of daily maximum and minimum temperature for the year 2019 across various regions of the Maldives

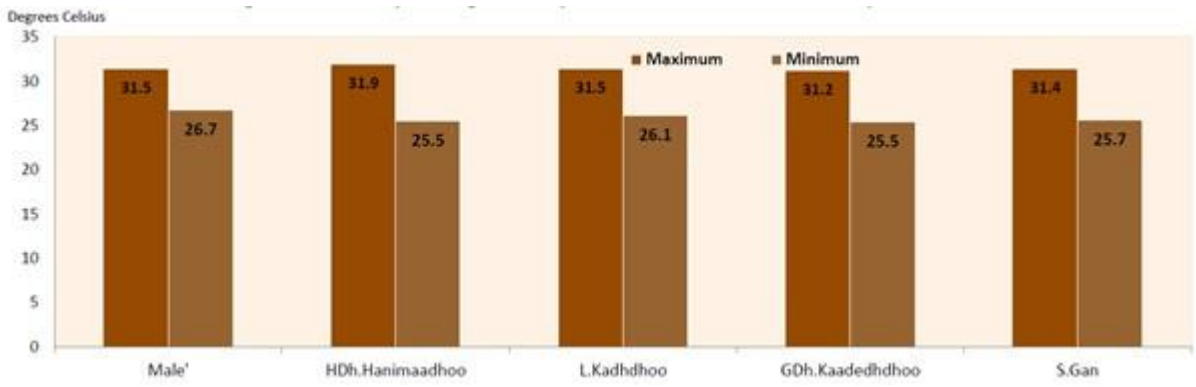


Figure 2: Yearly average of daily maximum and minimum temperature, 2019 (Source: NBS, 2020)

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 3. There is a very small fluctuation in the maximum and minimum temperatures throughout the year.

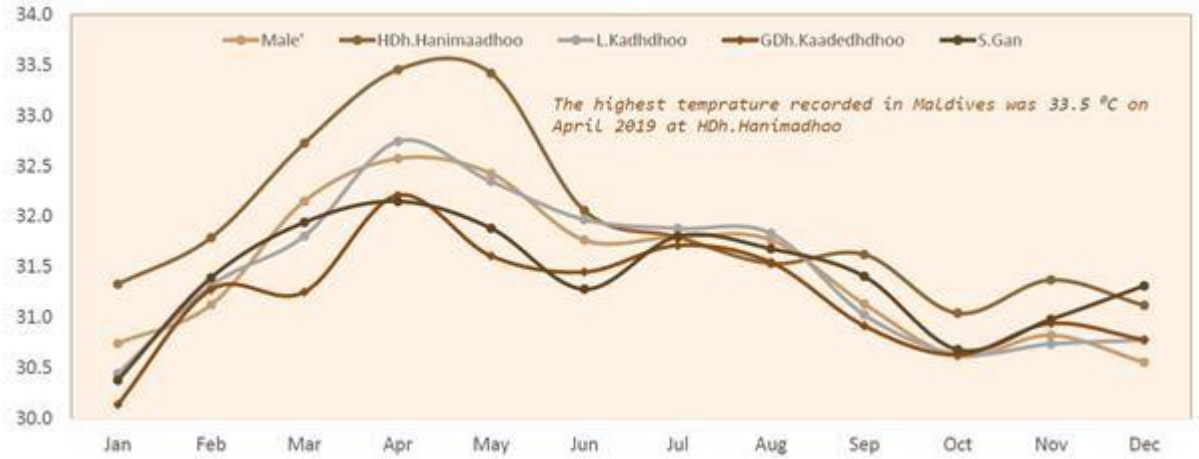


Figure 3: Monthly maximum daily temperature by locality (Source: NBS 2020)

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 occurs in May and October for the region. During these months on approximately an average of 260mm of rainfall is recorded. Rainfall is lowest towards the end and beginning of the year that recedes with the NE monsoon.

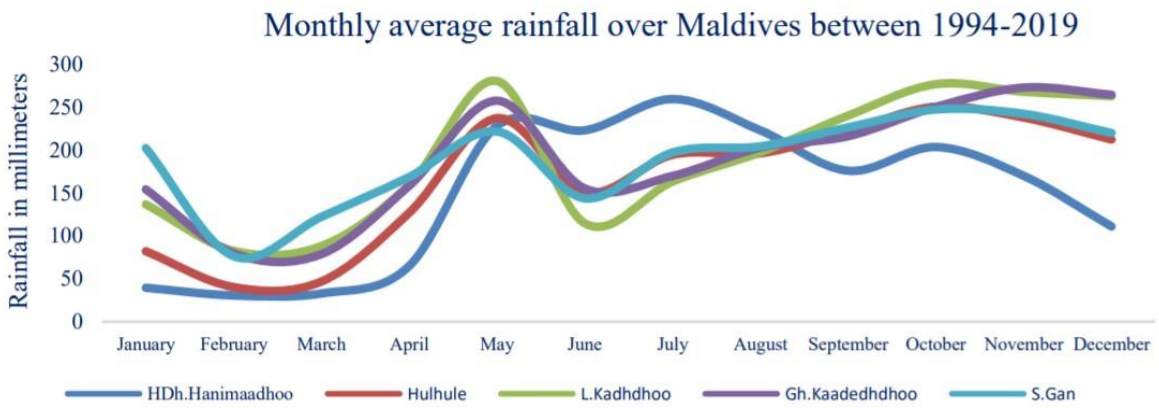


Figure 4: Monthly average rainfall over Maldives between 1994-2019 (Source: MMS, 2020)

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).

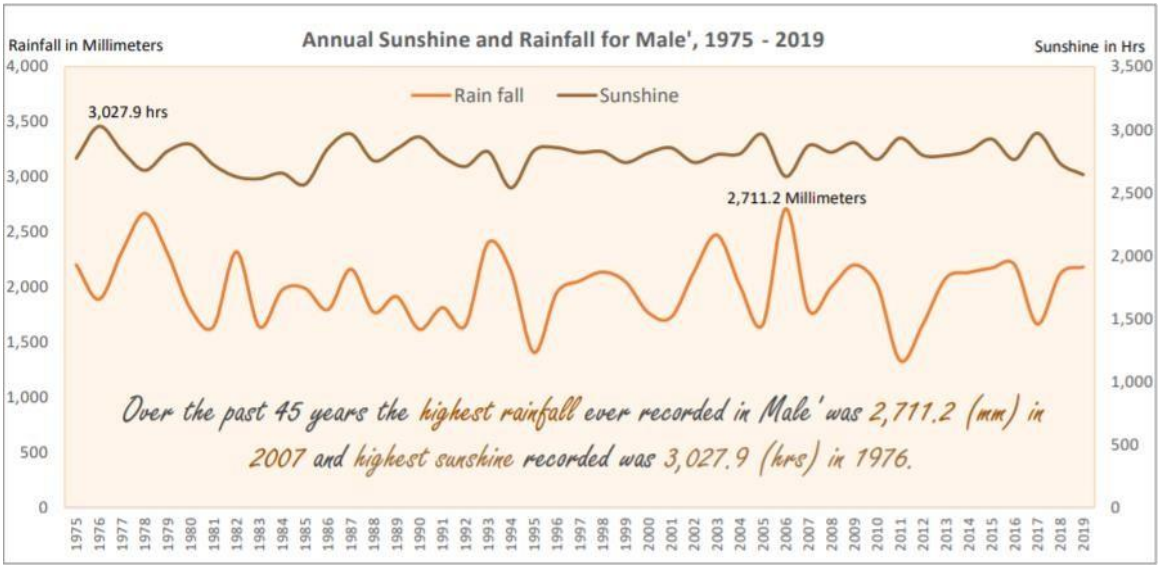


Figure 5: Annual sunshine and Rainfall for Male'. 1975 - 2019 (Source: NBS, 2020)

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 medium for AA. Himandhoo and low for the other 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
AA. Mathiveri	Low	Low	Low	Low	Very Low	Moderate
AA. Himandhoo	Medium	Low	Low	Moderate	Very Low	Moderate
ADh. Kunburudhoo	Low	Low	Low	Moderate	Low	High
Dh. Bandidhoo	Low	Low	High	High	Low	Moderate
Dh. Hulhudheli	Low	Low	Medium	Medium	Very Low	Moderate
M. Veyvah	Low	Low	Low	Medium	Low	Very High
M. Naalaafushi	Low	Low	Medium	High	Low	Very High

*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 6 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 6. M. Veyvah and M. Naalaafushi are in moderate surge hazard zones while the rest of the islands are in low surge hazard zones.

Figure 6: Storm surge Hazard zones (UNDP, 2006)

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

Name of Island	Surge Hazard Zone
AA. Mathiveri	Low
AA. Himandhoo	Low
ADh. Kunburudhoo	Low
Dh. Bandidhoo	Low
Dh. Hulhudheli	Low
M. Veyvah	Moderate
M. Naalaafushi	Moderate

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 07 islands in the scope of this assignment were included in the 45 islands. Figure 7 extracted from this document shows the perceived varying salinity odor, color and debris levels in the islands. AA. Himandhoo and ADh. Kunburudhoo recorded high percentages of salinity perception at 65% and 81% respectively. It was observed that salinity increased with population density and decreased with the area of the island as well as the latitude.

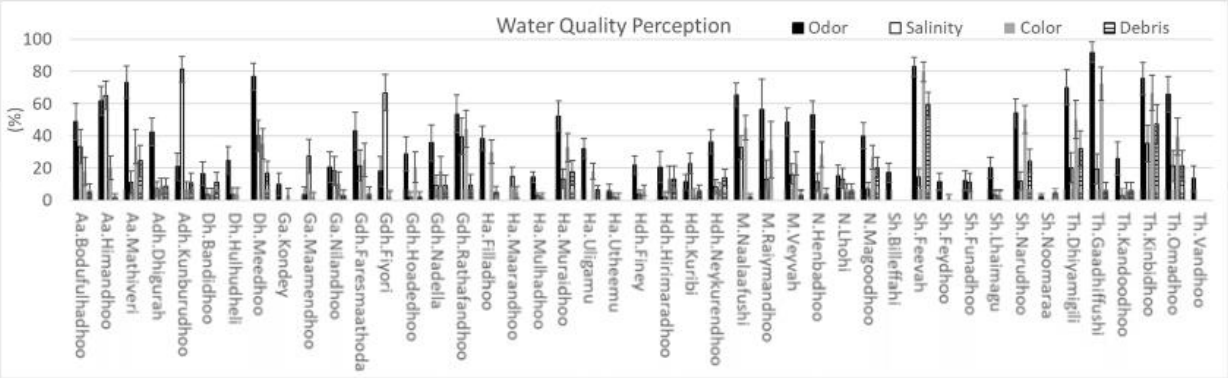


Figure 7: Groundwater quality perception of the respondents (Jaleel et. al., 2020)

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 the 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.

- Introduction
- Literature Review
- Methodology
- Baseline Assessment of 7 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 (µS/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 ± 2,683	250,231	5.90	112	572 & 234	644	684
HDh. Nolhivaranfaru	2,240 ± 3,522	335,176	4.52	305	1196 & 830	1828	1501
Sh. Funadhoo	7,547 ± 9,712	5,473	2.70	488	1694 & 594	1701	2182
N, Henbadhoo	4,239 ± 1,631	21,989	2.87	90	129 & 66	253	218
R. Maduvvari	3,689 ± 4,155	40,316	4.96	284	169 & 114	518	453
B. Dharavandhoo	1,008 ± 399	285,925	4.86	256	1455 & 340	1052	1712
AA. Bodufulhadhoo	6,182 ± 3,748	10,298	1.51	239	54 & 68	271	293
ADh. Dhigurah	2,725 ± 4,347	145,149	5.34	199	824 & 314	765	1022
M. Raimandhoo	5,039 ± 8,474	45,368	3.41	53	403 & 159	331	456
Th. Kinbidhoo	939 ± 271	113,029	8.46	316	535 & 241	660	851
Dh. Meedhoo	952 ± 498	117,827	4.11	324	798 & 189	700	1122
GA. Kon'dey	636 ± 119	601,600	4.18	132	1495 & 720	1073	1998
GDh. Fiyoari	997 ± 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. Nolhivaranfaru	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 µS/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 µS/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 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 guildelines 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 07 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 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 is 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 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)**

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 km^2 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 20 yr period (1996 to 2005). Soil data for grids had been collected from the U.S. Department of Agriculture, National Resource Conservation Service. Model had been simulated for 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 found results were consistent.

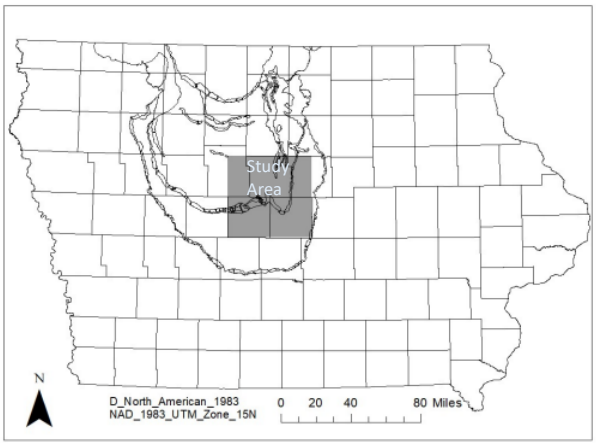


Figure 8: Location Map (Day, 2019)

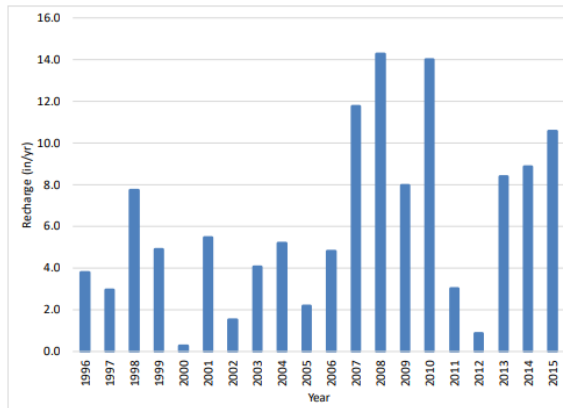


Figure 9: Estimated Annual Recharge by SWB Model (Day, 2019)

- **Numerical Simulation of Groundwater Availability in Central Moloka'i, Hawai'I (Oki, D.S., Engott, J.A., and Rotzoll, K., 2020)**

A groundwater study carried out using SUTRA model (3 dimensional) for central Moloka'i, Hawai'i. 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 Kualapuʻu 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 30 years was 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 AA. Mathiveri, AA. Himandhoo and Dh. Hulhudheli
- 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.

Meetings were held with Ministry of National Planning, Housing and Infrastructure to obtain details of any planned significant infrastructure projects in the 07 islands to ensure that any proposed MAR design aligns with future road development and drainage plans.

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 controls 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

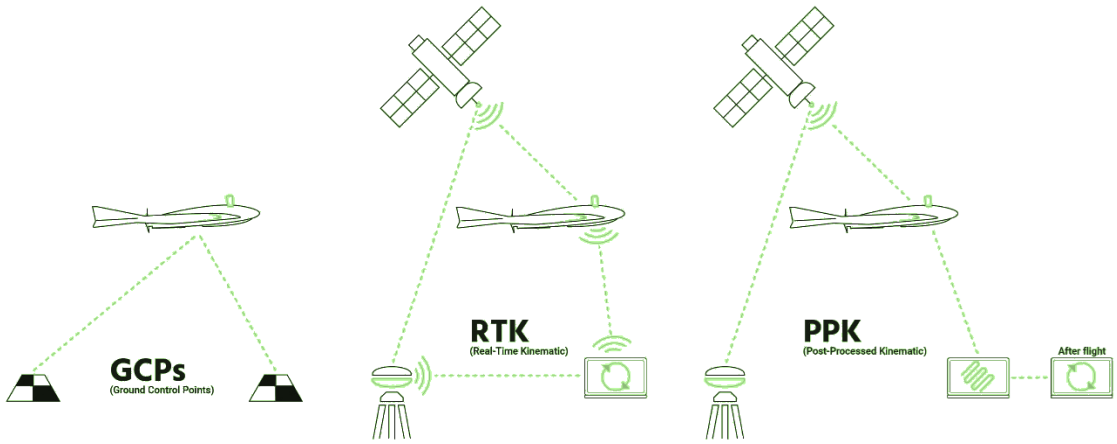


Figure 10: Different methods to carry out accurate UAV mapping

Drone based UAV surveying was used in this project to produce Digital Surface Models (DSM) of the surface, Digitized layers for use 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.

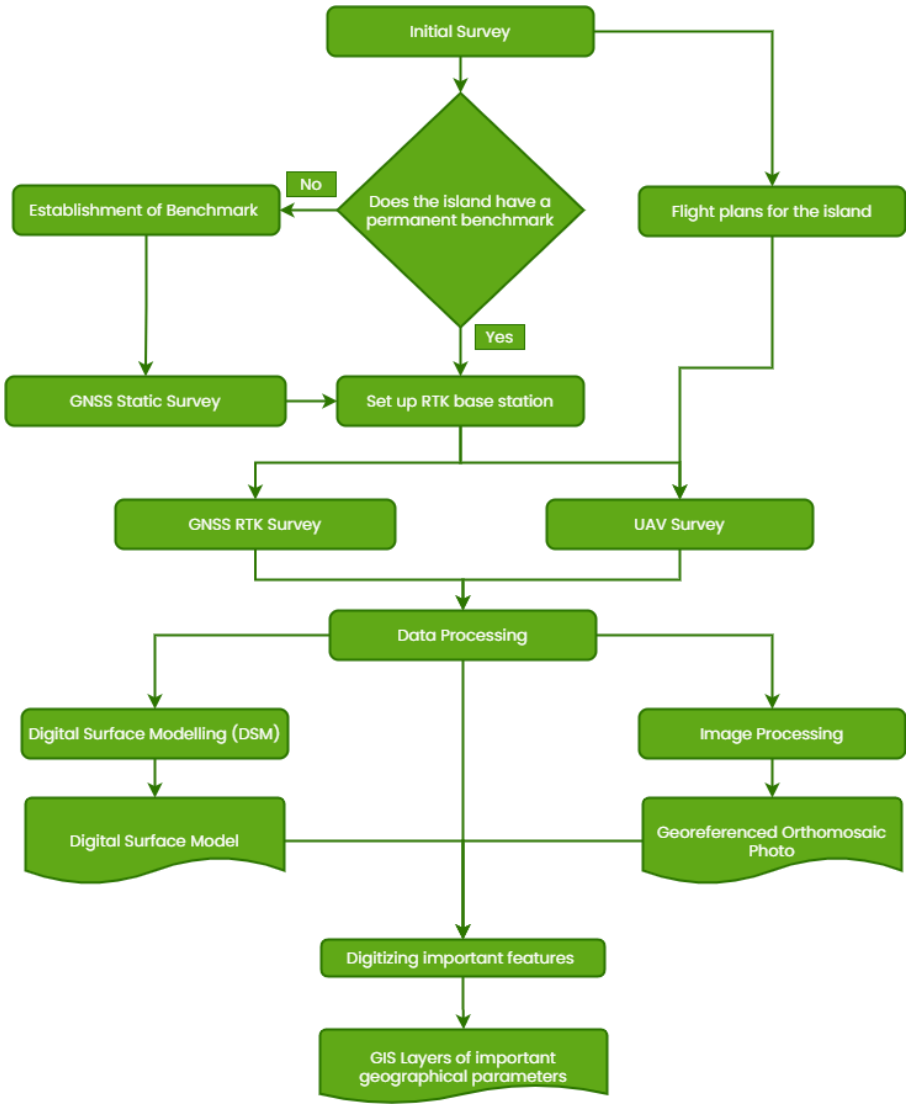


Figure 11: Flowchart for proposed methodology

4.2.1.1.1 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.

4.2.1.1.2 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.

4.2.1.1.3 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 fight 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.

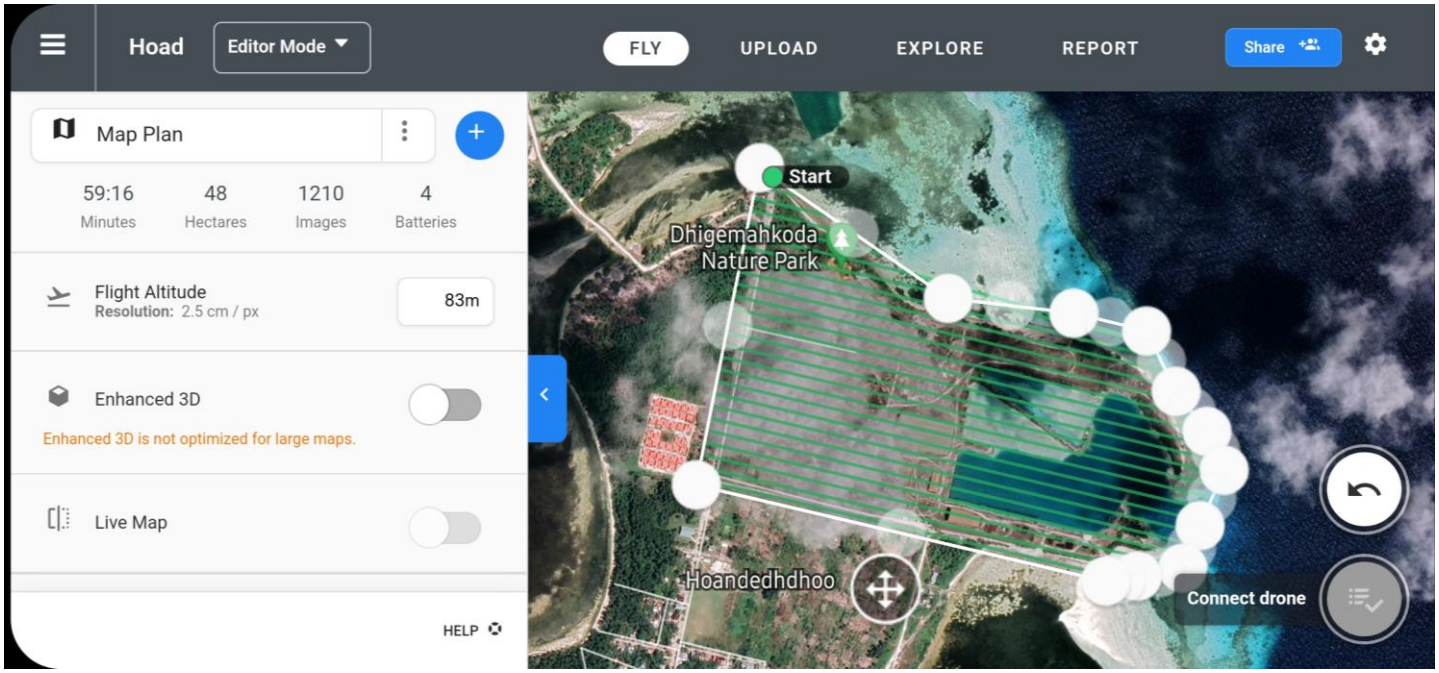


Figure 12: An example of the flight plan produced for a drone that allows the altitude and flight direction to be determined and gives estimates of the flight duration and resolution

4.2.1.1.4 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).

4.2.1.1.5 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

4.2.1.1.6 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.

4.2.1.1.7 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 seven 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 particular 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.

4.3.2.1 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 = 0.1

Assumptions made: Household numbers for each island were retrieved from census 2014 data, which may be subject to change to more current numbers once the survey is underway.

Table 18: Percentage of households sampled per island

Island	No. of Households (Island Council, 2021)	Minimum Sample Percentage (MOE 5%)
AA. Mathiveri	100	79
AA. Himandhoo	96	77
ADh. Kunburudhoo	58	50
Dh. Bandidhoo	84	69
Dh. Hulhudheli	108	96
M. Veyvah	47	42
M. Naalaafushi	81	67

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

4.3.2.2 Sampling methodology

A quantitative, structured questionnaire was administered face to face for 5 islands and via phone on 2 islands due to the Covid-19 guidelines present at the time of surveying. 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.

4.3.2.3 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

The average discharge rates of shower taps, garden hose, bathroom faucets and kitchen sink faucets were obtained from field investigations on the island itself in Liters per minute. The average duration of time spent on each activity is multiplied by the discharge rate to obtain the total volume of groundwater

used for each activity. For WC flushing, the total number of times toilet is flushed daily is multiplied by the total volume of water used by the flush tank for one flush. For laundry category, the number of times laundry is done daily is multiplied by the total volume of water used by the machine for one wash. The total groundwater consumption per capita per day was calculated as the sum of all activities. This value is multiplied by the total population of the island to obtain the total domestic water consumption.

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 farmers that was used to calculate the total water consumption.

For the first three islands (AA. Mathiveri, ADh. Kunburudhoo and Dh. Hulhudheli) where social survey was conducted, the questionnaire did not include questions regarding dishwashing and bathroom faucet usage in the domestic water usage questionnaire. An average daily value of 18L and 4L was calculated for bathroom faucet usage and dishwash usage respectively from the other islands where questions regarding bathroom faucet usage and dishwash usage were asked. Therefore, for AA. Mathiveri, ADh. Kunburudhoo and Dh. Hulhudheli, these average values were assumed in final calculations.

4.3.4 Limitations

All the surveys undertaken in the islands maintained 95% confidence interval with an error margin of 5% except M. Veyvah. In M. Veyvah, the error margin is 6% and this is mainly because of the following reasons.

- Incorrect numbers
- Households not having any occupants
- Not wanting 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 five attempts were made on different occasions to determine unavailability of the participant.

On the same note, only 25% of the industrial farms in each island were surveyed. In future research, it is recommended to achieve 100% in this sector to have a significant and a more precise estimation of the industrial water consumption.

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 by only considering the domestic water demand using the present domestic water demand (LPCD) 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 seven 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 Survey

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 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 measurements 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 were 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 ± 10% for pH, conductivity, or dissolved oxygen or less than ± 0.2 ˚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 Water quality standards

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

4.4.1.2 Correlation Matrix

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.

4.4.1.3 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 (Wi) 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)	NH_3 (mg/L)	NO_3^- (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 ith 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 Survey

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, 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 prevent touching the inside or lip of the sampling bags.
- 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.

The results of the Water Quality Survey are presented in Sections 5.4, 6.4, …, 11.4 for the seven 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 where it does not impact the groundwater use in the island. The test was carried out in accordance with the dewatering regulation 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 was carried out.
- The raw data from the test was analysed 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.

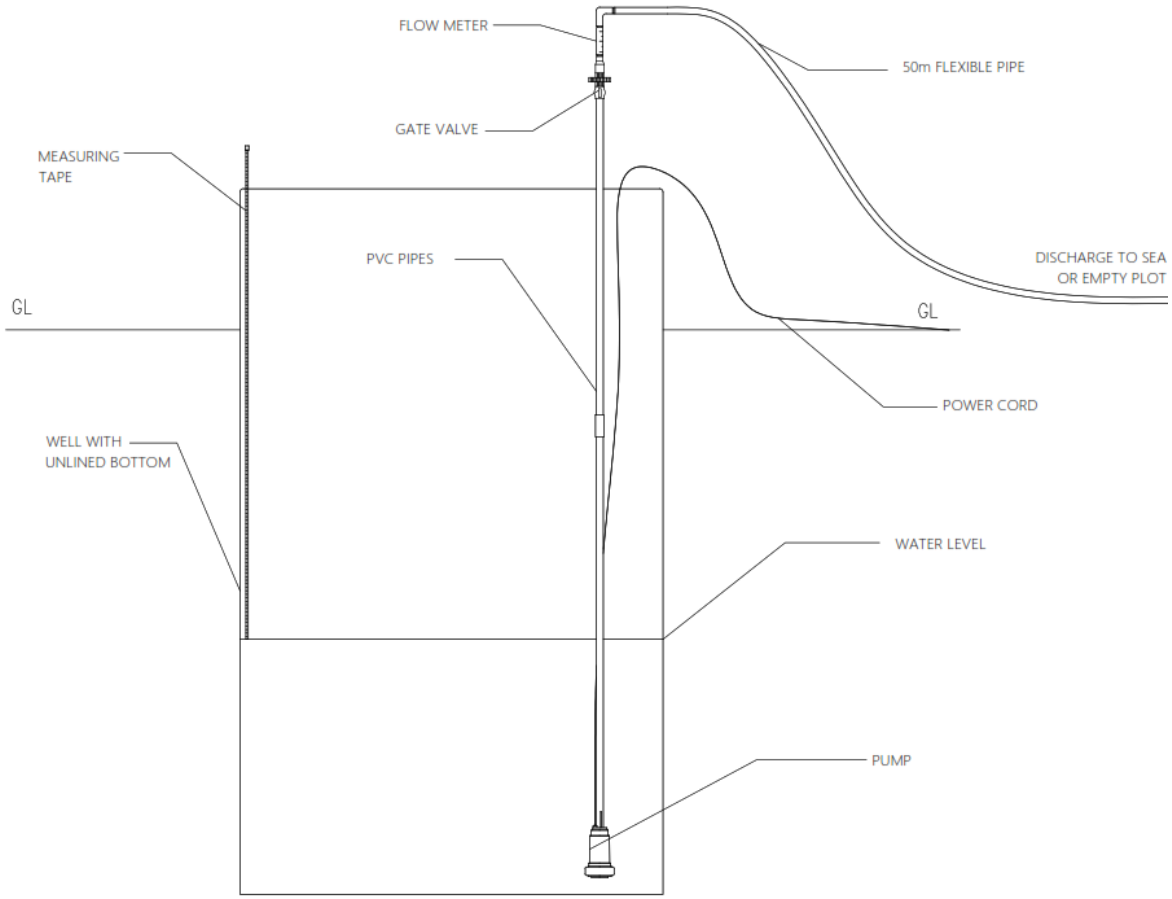


Figure 13: Pumping Test Setup

The results of the Pumping Test are presented in Sections 5.6, 6.6, …, 11.6 for the seven 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

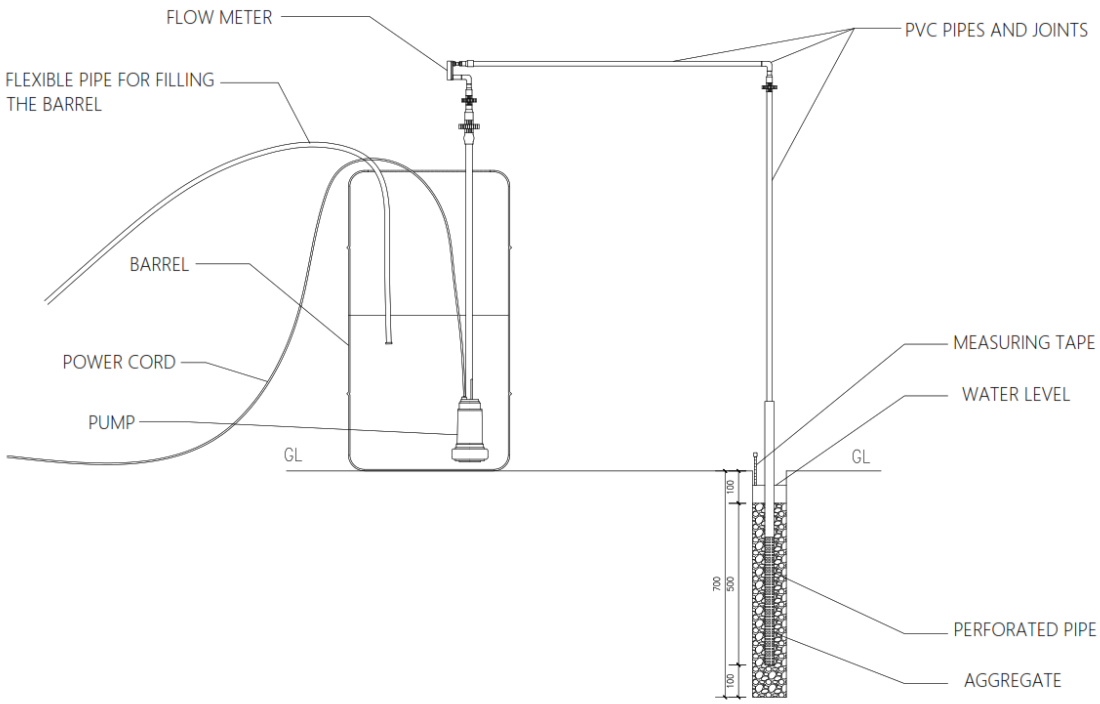


Figure 14: Set up of a typical constant head permeability test

Constant Head Gravity Permeability Tests were carried out to obtain permeability by measuring water absorbance of unconsolidated materials. Permeability tests were carried out by 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.
- 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 15) 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:

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

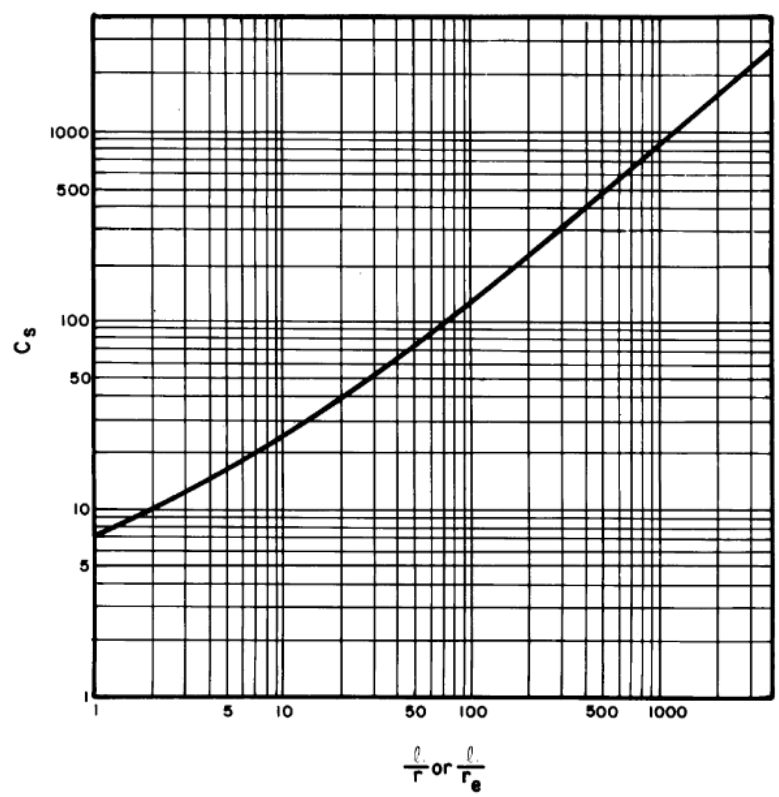


Figure 15: Conductivity coefficients for semispherical flow in saturated materials through partially penetrating cylindrical test wells (Engineering Geology Field Manual, vol. II, 2001)

The results of the Permeability Testing are presented in Sections 5.7, 6.7, …, 11.7 for the seven 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.

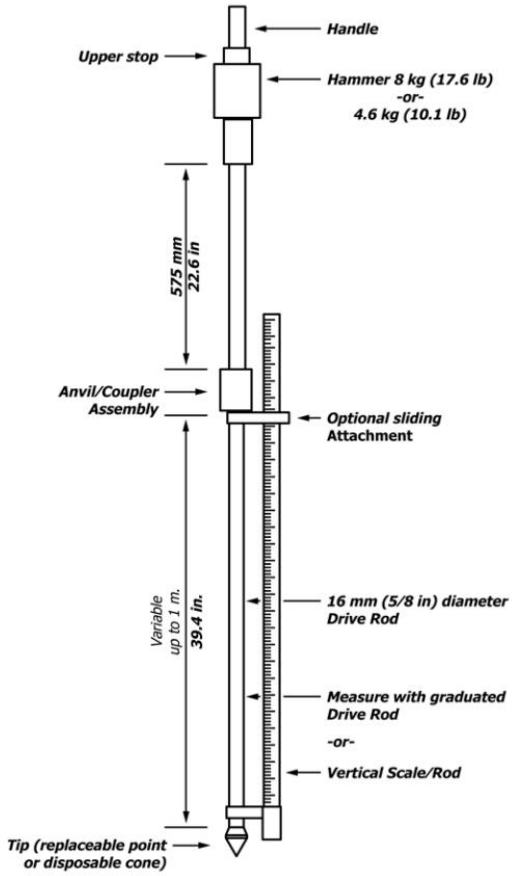


Figure 16. Schematic of Dynamic Cone Penetrometer apparatus (ASTM D 6951 – 03)

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 millimetres, 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 17: 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 16) 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 18: Dynamic Cone Penetrometer Testing on-site

The results of the Soil Profile Survey are presented in Sections 5.8, 6.8, …, 11.8 for the seven islands.

4.8 Flood Assessment and Inundation Survey

4.8.1 General/objective

Catchment of the flood water are 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 of 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 whether station was utilized. Based on the information collected that 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 for design & management purposes. 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, literatures, and other existing project reports.

4.8.2 Approach/methodology

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.

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 crucial in determining 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.

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 examined 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 conceptualizing 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 5.9, 6.9, …, 11.9 for the seven 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 19: 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 20 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.

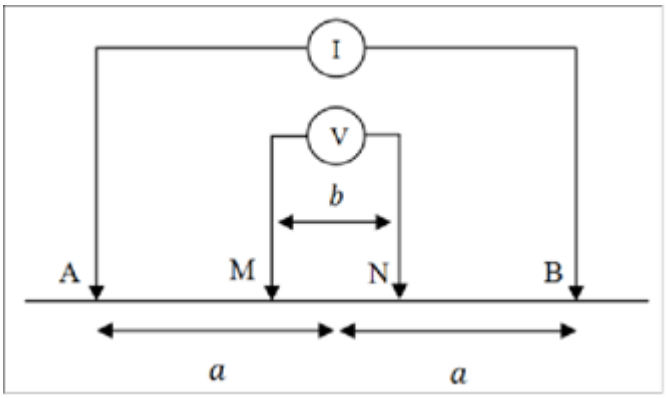


Figure 20: Diagram for the Schlumberger Array

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

Procedures 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 also 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 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).

Figure 21 shows the photographs taken during ER survey together with equipment used for the same.

Figure 21: 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 layer 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. The table below 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 from start to 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 3D view of freshwater layer underneath of the island and the same data was used for volumetric calculation as described below.

IV. The other alternative method used for freshwater volume estimation is transferring freshwater levels and saline water levels from ER measured locations to 10m x 10m 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.

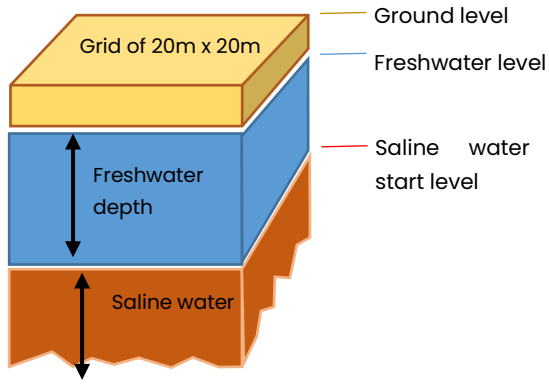


Figure 22: Grids for freshwater volume estimation

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

Freshwater lens Thickness (m) = (6.94*LOG (width of the island)-14.38) *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 should have resulted from empirical formula since only two factors are included in this formula but in reality, 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 formula for the given project scope.

The results of the Geophysical Survey are presented in Sections 5.5, 6.5, ..., 11.5 for the seven 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 23 shows the flow-chart that shows the relationship between SWB modelling and freshwater lens profile estimation.

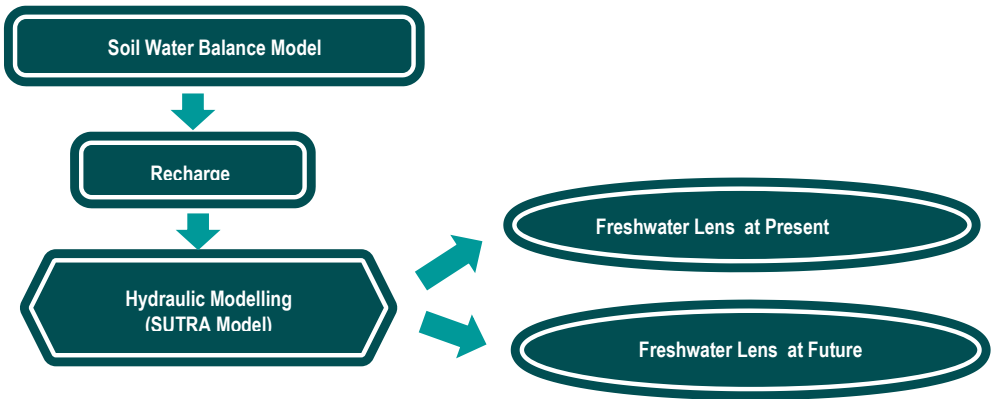


Figure 23: Flow-chart showing relationship between SWB model and freshwater lens estimation

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, 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.

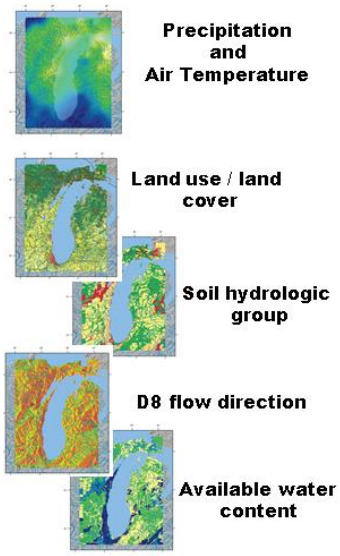


Figure 24: Data Requirements for SWB Model (Westenbroek et al, 2010)

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.

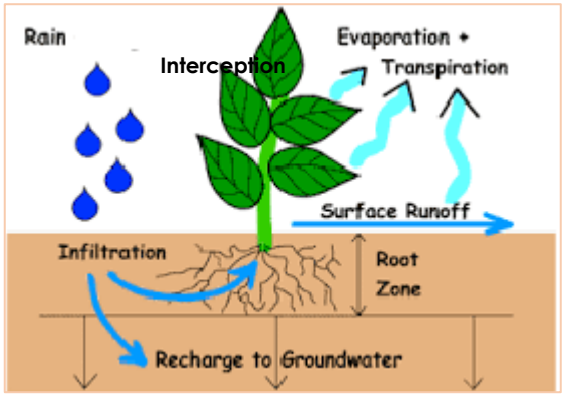


Figure 25: Components for estimation of recharge (Westenbroek et al, 2010)

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

Recharge = (Precipitation + Snowmelt + Inflow) – (Interception + outflow + Evapotranspiration) - ΔSoil 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 10m x 10m was selected to define the model domain of all seven 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)
AA. Mathiveri	117	155	21.2
AA. Himandhoo	94	158	19.9
ADh. Kunburudhoo	50	137	6.4
Dh. Hulhudheli	93	203	20.4
Dh. Bandidhoo	117	146	24.1
M. Naalaafushi	214	64	12.7
M. Veyvah	388	226	41.3

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 fall 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_{AVG} (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 AA. Mathiveri, AA. Himandhoo and ADh. Kunburudhoo were collected from Hulhule weather station and climate data for Dh. Hulhudheli, Dh. Bandidhoo, M. Naalaafushi and M. Veyvah were collected from Kahdhoo weather station for 20yr period.

Climate data recorded at 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 26 shows average monthly variation of rainfall (a) and annual rainfall variation over 30 years period (from 1991 to 2020) for Hulhule weather station. Figure 27 shows average monthly variation of rainfall (a) and annual rainfall variation over 30 years period (from 1991 to 2020) for Kahdhoo weather station.

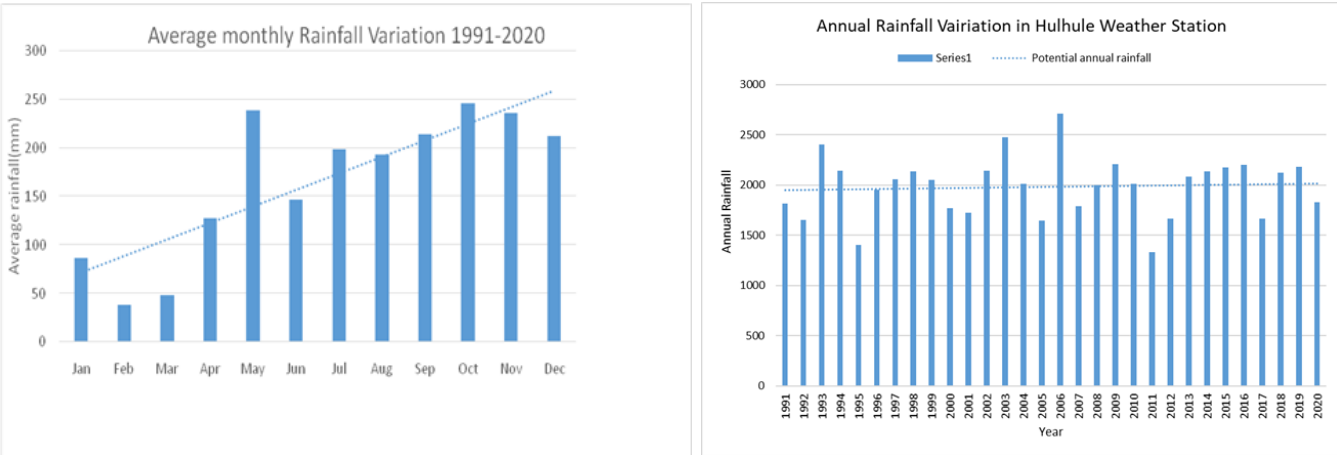


Figure 26: Average monthly (a) and Annual (b) Rainfall Variation at Hulhule Weather Station

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 study island falls into 7 categories and they are summarized in Table 27.

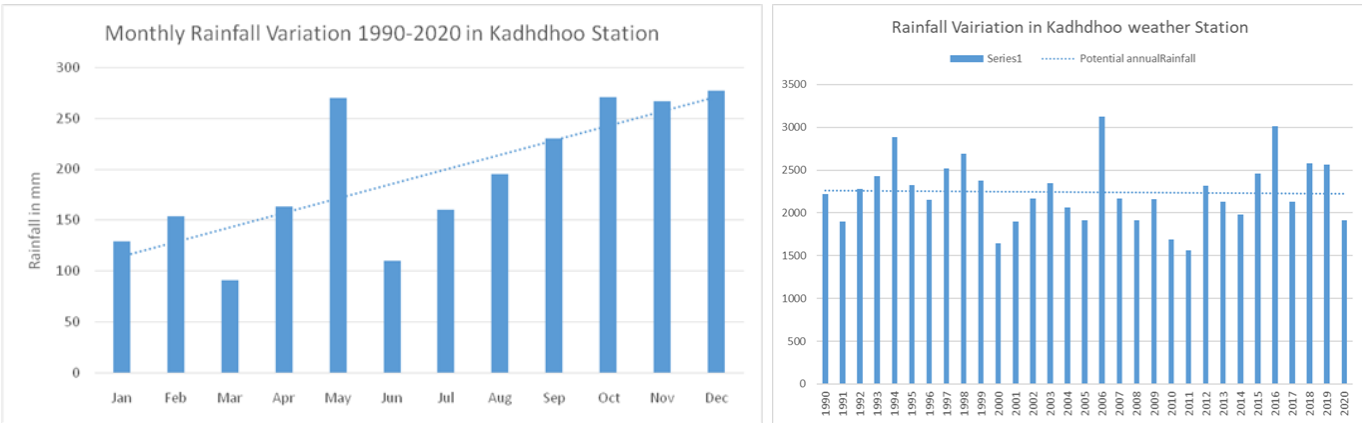


Figure 27: Average monthly (a) and Annual (b) Rainfall Variation at Kahdhoo Weather Station

Table 27: Land use category for Project 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

	Curve Number		
Hydrologic soil group	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 the most fitting representative soil group for Lot 1 islands. It is important to note that, there are few patches in the island that represent Class A soil groups.

<u>Flow Direction</u>

Flow direction is basically generated from the topographical data and it decides flow direction from each cell to its downslope neighbour, or neighbours. 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.

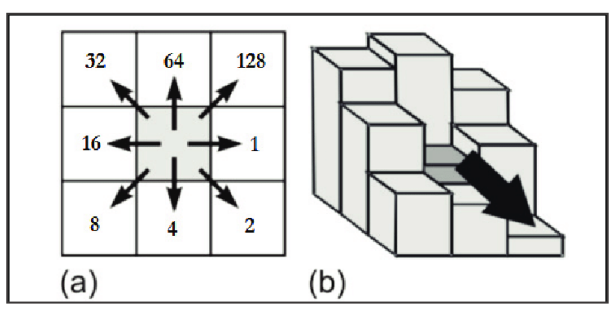


Figure 28: Cell flow direction in ArcGIS

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 project 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 a daily time step 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 has to be converted into required units (millimeter or cubic meter) before using them 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.

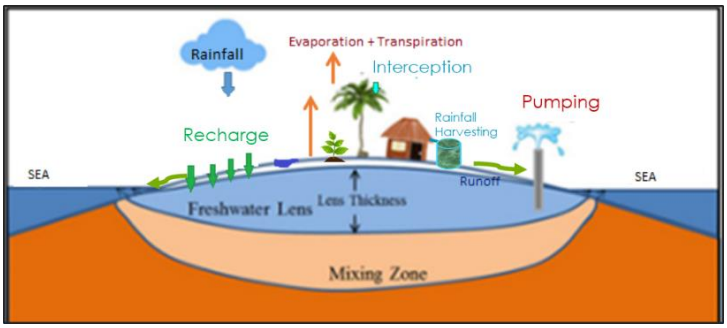


Figure 29: Components of water balance

- Precipitation: rainfall from Hulhule and Kahdhoo station
- Rainfall 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 seven 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. 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 dispersity. 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.

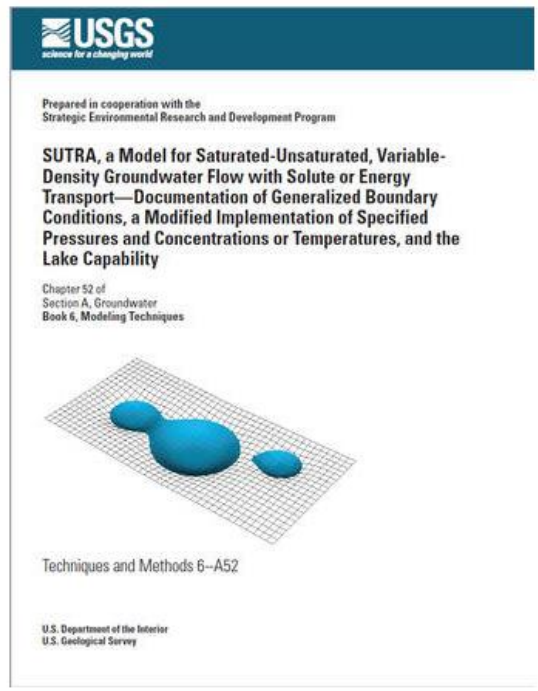


Figure 30: Cover image from the SUTRA 3.0 manual

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

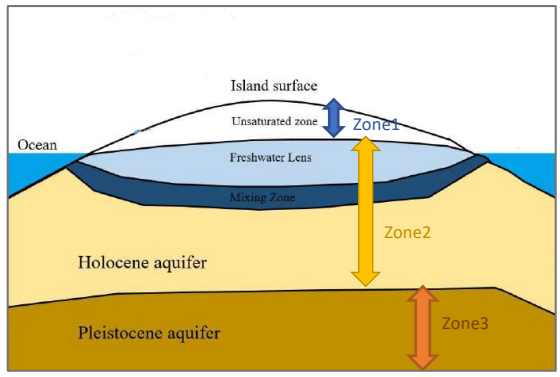


Figure 31: Layer definition for SUTRA modelling purposes

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 categories. 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 one of PhD dissertations.

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: 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 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 the project 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, …, 11.11 for the project islands.

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

5 AA. Mathiveri

5.1 Island Overview and Location

The island of AA. Mathiveri, belonging to Ari Atholhu Uthuruburi Atoll, is in the central region of Maldives at 04°11'30"N and 72°44'47"E. It is approximately 84.9 km West of the capital Male'.

Table 31: Island Geographical Data

Island	AA. Mathiveri
Atoll	Ari Atholhu Uthuruburi Atoll
Location	04°11'30"N and 72°44'47"E

Figure 32: Island Location – AA. Mathiveri

5.1.1 Island features

The island is located in the northern side of Alifu Alifu atoll. The island has vast sandy beaches and has a historically significant banyan tree which is protected. The island extends up to 0.669 km in length from toe to toe and a width of 0.604 km from toe to toe. The island has a harbour at its Northeast side of the island. In the southern tip of the island, a designated waste centre is established for dumping waste.

About one-third of the island's surface is vegetation. Thick vegetation is mostly located at the outer edges around the island. The west side of the island is also covered mostly by thick vegetation. The island is mostly populated in the centre of the island. The Land Use Characterization map is attached to Annex II.

Table 32: Area Distribution in AA. Mathiveri

Area	21.1 ha	
Length	0.669 km	
Width	0.604 km	
	Area (m²)	**% of total area**
Roof cover	32,767	16%
Vegetation (Thick)	66,385	31%
Vegetation (Thin)	36,240	17%
Bare Lands	74,505	35%
Farmlands	1,364	1%
Wetlands	-	0%
Total	211,392	100%

Figure 33: Land Use Characterization – AA. Mathiveri

5.2 Topographical Features

Permanent Survey Marks PSM 0304, PSM 0305 and PSM 0306 were used as benchmarks for AA. Mathiveri topographical survey and drone survey. These details are currently not available via the Maldives Land Survey Authority Website https://www.mlsa.gov.mv/psm as the report for the issued benchmarks have not been submitted according to MLSA.

Discrepancies are noted between a previous survey carried out in 2020 for a water and sanitation project and the most recent survey during the field visit. There remains some uncertainty about the benchmark levels which are at an average of 0.7m for the whole island which would imply there would be a lot more wave-driven flooding during low tide and difficulties accessing the harbour without temporary stairs during high tide. Therefore, 0.12 m was added so that AA. Mathiveri DSM could be bias corrected. This value was based on the initial survey carried out in 2020.

Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 1129 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.23 cm per pixel. 9 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 33: GCP Statistics for AA. Mathiveri

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	-0.000307	-0.000126	0.000496
Sigma [m]	0.0221	0.0329	0.0439
RMS Error [m]	0.0221	0.0329	0.0439

AA. Mathiveri is a relatively low-lying island, with most of its ground surface below elevation of 1 m. The road surfaces do not appear to have its elevation raised, with most falling in between 0.6 m and 0.8 m. However, there are some exceptions, which are:

- Harbour area: Ground surface here was likely raised during the harbour project to match the newly reclaimed area within the project, which was carried out in the early 2010s.
- Ridge formation: This is formed on the southern shoreline, which is also the windward side that is exposed to Southwestern swells. The direct wave impact has accumulated sediment which formed ridges as seen in profile 1 and 4.

The ground surface elevations excluding for the western side of the island is the lowest, ranging between 0.6 m to 0.3 m. The remaining island area has ground surface elevations which are relatively similar, ranging between 0.7 m to 1 m. The island has undergone moderate deforestation around the early 2010s, making way for more residential areas and roads.

The Digital terrain model (DTM) was produced at a resolution of 0.1 m spatial resolution for the purposes of analysis. The figure below shows the plot of GPS spot heights vs Sampled DTM elevations for the island of AA. Mathiveri. The DTM slightly underestimates the elevations with a mean of -1.07 cm.

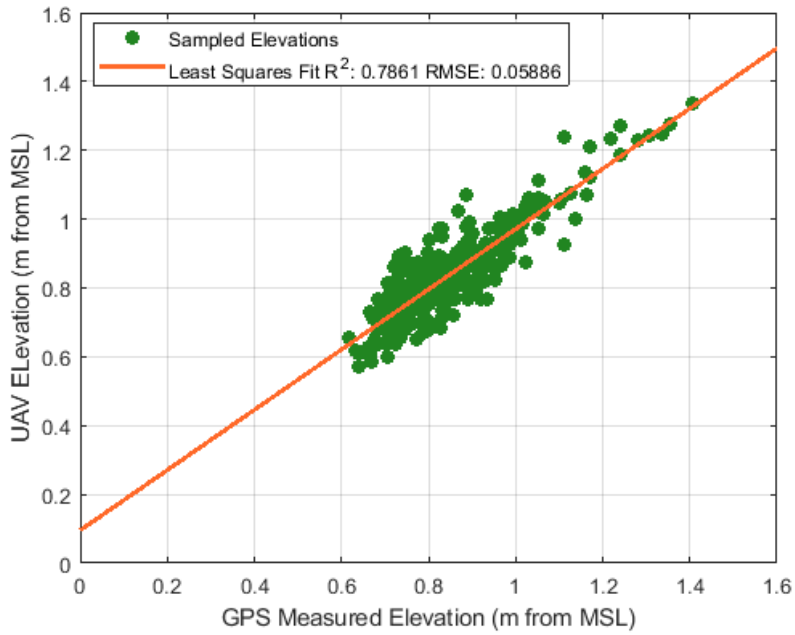


Figure 34: Linear Regression Plot for AA. Mathiveri Sample Unmanned Aerial Vehicle (UAV) elevations

Table 34: Error Statistics for AA. Mathiveri DTM

Parameter	*Value (cm)*
Mean	-1.07
Standard Error	0.34
Median	-1.13
Mode	#N/A
Standard Deviation	6.09
Sample Variance	37.09
Kurtosis	0.67
Skewness	0.26
Range	36.95
Minimum	-18.63
Maximum	18.32
Sum	-350.82
Count	327.00

5.2.1 Level changes

AA. Mathiveri has an average elevation of 0.7986 m with a standard deviation of 0.376. Digital Terrain Model elevations range from -0.6 to 1.7 m from MSL. The distribution of elevations has a positively skewed distribution with 0.8 m being the highest frequency for elevations.

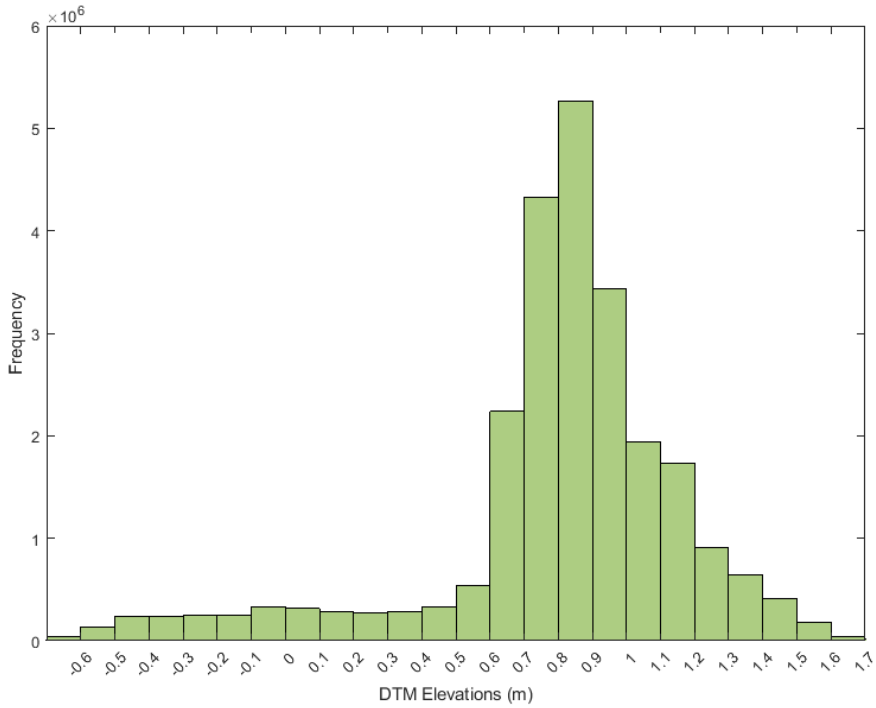


Figure 35: Raster Histogram created for AA. Mathiveri DTM

Figure 36 shows the Digital Terrain Model Elevations and Profiles for AA. Mathiveri Island.

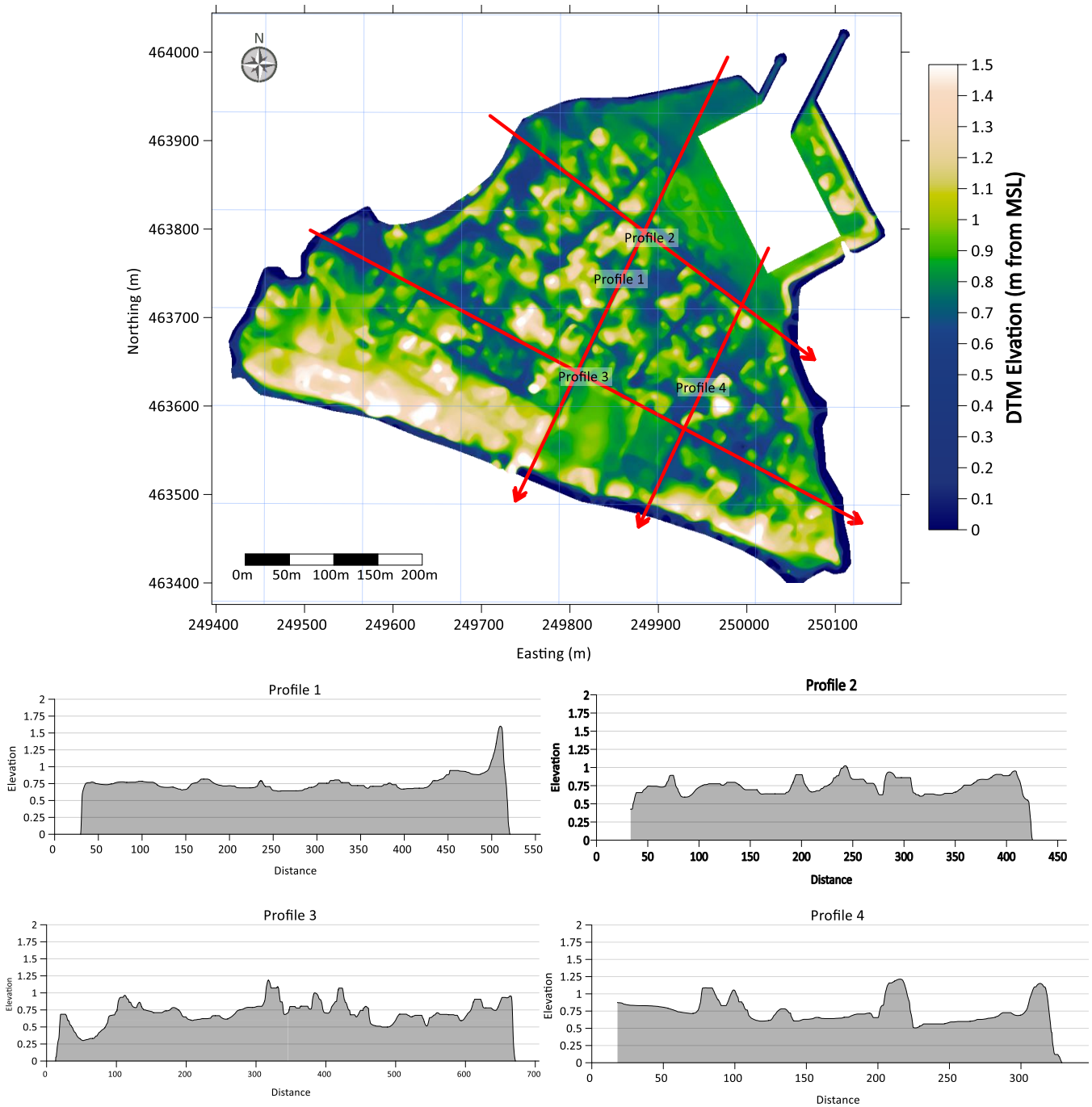


Figure 36: Digital Terrain Model Elevations and Profiles for AA. Mathiveri

Profile 1, which goes from north to south, has an extremely level surface, with ground elevation at a near constant 0.75 m throughout the profile. The exception is at the end, where there is a ridge formation with elevation of 1.5 m., which would be located at the southern shoreline. The ridge is a result of strong wave impact on this shoreline, leading to accumulating sediments higher up.

Profile 2 also has a near constant elevation of 0.75 similar to Profile 1, and spans from west to east. The lack of a ridge at the end of the island was a notable observation. This is likely due to less severe wave impact on this part of the shoreline as there is a greater buffer zone for wave dissipation before reaching the shore.

Profile 3 spans from west to east, starting with a ridge on the western shoreline, with an elevation of 0.7m. This ridge is most likely formed due to the short buffer zone between this shoreline and the reef line, which limits wave energy dissipation, leading to stronger wave impact on this shoreline. A point of interest is the low beach elevation behind the ridge, which only comes up to about 0.3 m. The ground level starts to incline and reach a near constant level of about 0.75 m at 100 m in, which continues throughout the remaining part of the profile.

Profile 4, which also spans from north to south, starts with a constant elevation of 0.8 m up to 50m, which corresponds to the harbor section. The profile shows a general depression at the middle, with both ends sloping down towards the center. However, there is a ridge formation at the end of Profile 4, which is due to the strong wave impact on the southern shoreline, similar to processes described for the ridge in Profile 1.

5.2.2 Shoreline

AA. Mathiveri has a shoreline length of 3120 m. The coastal protection features around the island are as follows.

- Breakwater: The island has two breakwaters, which are as follows.
    - Rubble mound breakwater: The rubble mound breakwater is found on the northeast side of the island, lining up the access channel to the harbor. Northeasterly swell waves approaching from the windward side is absorbed and dissipated by this breakwater to offer protection to berthed vessels within the harbor. However, it should be noted that the orientation of these breakwaters is not optimal as it allows some of these swell waves to propagate into the harbor. The breakwater is connected to the island with direct access. Crest height for the breakwater varies between +0.8 m and 1 m above mean sea level. The breakwater is highlighted in orange.
    - Sand filled breakwater: The sand filled breakwater is found on the northeast side of the island. Northeasterly swell waves approaching from the windward side is absorbed and dissipated by this breakwater to offer protection to berthed vessels within the harbor. The breakwater is detached from the island itself and has an access platform connecting it to the island. Crest height for the breakwater varies between +1 m and 1.3 m above mean sea level. The breakwater is highlighted in orange.
- Revetment: The revetment is found on the southeastern corner of the harbor. The revetment serves as shore protection and prevents erosion at these locations by dissipating wave energy from easterly wind waves generated within the atoll basin. Crest height of the revetment is around +1.5 m above mean sea level. The revetment is highlighted in green.
- Quay wall: These structures are found within the harbor and are highlighted in yellow. Crest height of quay walls is around +1 m above mean sea level.
- Retaining wall: This structure is found on the north corner of the harbor, highlighted in blue. Crest height of the retaining walls is around +0.9 m above mean sea level.
- Concrete blocks: This structure is found northwest of the harbor lining up the shoreline, highlighted in purple. Crest height of these concrete blocks varies between +0.6 m and +0.8 m above mean sea level.
- Revetment like structure on southwestern shoreline: This structure was built by island residents by dumping quarry rock along the original shoreline to prevent further erosion and has been highlighted in red. Crest height of this structure varies between 0 m and +0.6 m above mean sea level.
- Breakwater like structure on southern shoreline: Significant erosion has been observed on the southern shoreline, which is reinforced by the visible beach rock (aanugandu) on this shoreline. The quarry rocks dumped here by the islanders were likely purposed to prevent beach erosion any further from this point, which has clearly not been achieved as seen in the overhead drone image. This structure has been highlighted in navy and has crest height varying between +0.3 m and +0.6 m above mean sea level.

- Revetment/Groyne like structure on the south-eastern shoreline. The structure is highlighted in brown.

The southeastern shoreline has undergone severe beach erosion, where the shoreline has regressed to expose vegetation roots and beach rock (aanugandu).

Figure 37: Orthomosaic of AA. Mathiveri

5.2.3 Reef

AA. Mathiveri is located on the northern edge of the Alif Alif Atoll. It is the only major island on the south of this particular reef, with a stretch on land to the south of AA. Mathiveri called Mathiveri Finolhu. The shape and orientation of Mathiveri Finolhu gives the impression that it was once a part of the main island but got disconnected due to the strong south-westerly swell waves that approach the windward side of this island to make way for a tidal pass. The reef spans roughly around 4.3 km along its longest section. For the main wave direction (southwest), a buffer zone can be about 400 m on the shortest section, going up to 900 m for the same wave direction.

Figure 38: Sentinel 2 imagery of AA. Mathiveri reef taken in February 2022

5.3 Socio Economic Status

5.3.1 Demography

The island has a registered population of 623 as per the 2014 census, with a total of 308 males and 315 females. The island population density is 47 people per hectare. The population figures have drastically increased over the past years where the total registered local population climbed up to 1006. The following table and graph illustrate the demographic breakdown of AA. Mathiveri.

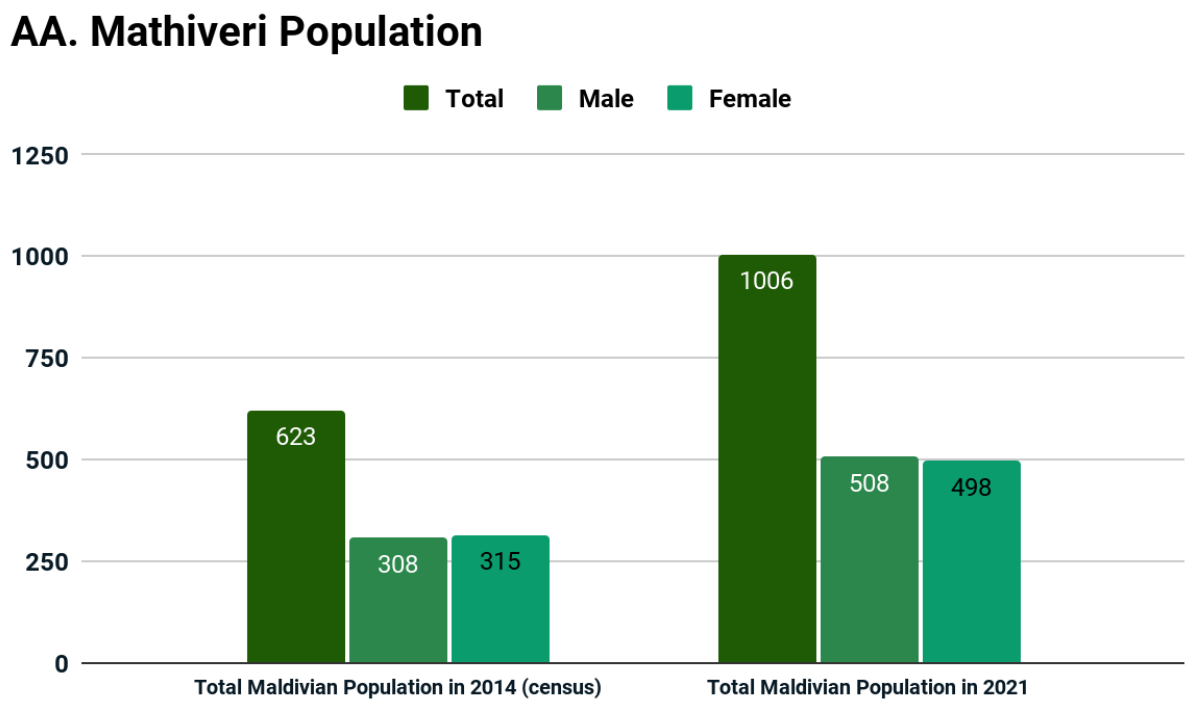


Figure 39: AA. Mathiveri Population

Table 35: AA. Mathiveri Population (Census, 2014)

Atoll	Locality	Resident Population according to Census 2014								
		Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
AA	Mathiveri	662	338	324	623	308	315	39	30	9

5.3.2 Socio-Economic Activities

AA. Mathiveri is an inhabited island in Alif Alif Atoll's administrative unit and physically part of Ari Atholhu Uthuruburi Atoll in the Maldives. This island is well-known for tourism and yellowfin tuna fishing. The people in the island work in the fishing industry and the majority of the fishing boats are registered and licensed for fish processing and fish exporting. There are currently 9 guest houses registered with the Ministry of Tourism for this island. The island also has dive schools, cafes and restaurants that provide for the tourism industry. As per island council, AA. Mathiveri has 3 designated lands for farming amounting to 20,000 square feet.

5.3.3 Facilities available

5.3.3.1 Health Care

AA. Mathiveri island health post was built in 1997, which later became the island Health Center in 2004. Currently, the hospital has one doctor, 4 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.

5.3.3.2 Education

AA. Mathiveri has Husnaa pre-school and Mathiveri school. Mathiveri school has a total of 220 students enrolled and the pre-school has 40 students. The island school offers education up to grade 10 standard.

5.3.3.3 Utilities

Electricity in the island is provided by State Electric Company Limited (STELCO) with four (4) generators with a total capacity of 920KW in the power station.

5.3.3.4 Transportation

The island has a harbor which was reconstructed in 2010. The transportation between AA. Mathiveri island and other islands is by sea. The island has Maldives Transport and Contracting Company (MTCC) ferry services and other private speed launches. The speed boats often travel 3-4 times a week.

5.3.4 Water resources, water usage and water consumption survey

In AA. Mathiveri there are a total of 100 households inhabited currently. 87 out of 100 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	**87/100 households = 87%**
Percentage of well fitted with pumps	99%
Ground water	**Usage in percentage**
Source of drinking	0%
Source of cooking	0%

5.3.4.1 Existing water and sanitation

The main form of sanitation is via the use of local outfall pipe and 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 groundwater well. In AA. Mathiveri, 48 percent reported to have less than 49ft distance between septic tanks and water well while, 32% reported that they do not know an exact distance between them

Rainwater is also the primary supply of water for cooking. Many homes utilize rainwater from neighboring houses or bottled water when rainwater is scarce during the dry season. Rainwater collected from rooftops is stored in water tanks, whether communal or home tanks. Rainwater is the primary source of drinking water in AA. Mathiveri.

5.3.4.2 Water usage and resources

Based on the survey conducted in AA. Mathiveri, 81 houses have HDPE rainwater tanks for rainwater storage. Also, 100% of the households use rainwater for cooking and 79% 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 water usage and consumption scenarios in the island.

5.3.4.3 Domestic water usage

Based on household water usage surveys in AA. Mathiveri, **175,044** liters of water is used daily in households. A total of **174** liters of groundwater are consumed per capita per day.

Table 37: Domestic groundwater use data for AA. Mathiveri

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
75.2	26	11	37.9	1.36	18	4	**174**

*All units are in Liters per capita per day

5.3.4.4 Commercial water usage

In AA. Mathiveri, there are currently four operational café'/restaurants and 6 guesthouses on this island. A total of 11,884 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 AA. Mathiveri

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Sky View	-	-	120	1.43	121
Palato	90	12.11	120	5	227
Second Home	7.5	-	180	1.43	189
Cool Choice	7.5	-	-	10	17.5
					555

*All units are in Liters per day

Table 39: Guesthouse groundwater use data for AA. Mathiveri

Guesthouse	Average Occupancy	Total (L/day)
Ari Villa	75%	1050
Riveli Retreat	50%	1373
Milano Guesthouse	90%	3015
Holiday Mathiveri Inn	50%	1934
Veli Beach Inn	75%	2198
Royal Reef	50%	1759
		11,329

5.3.4.5 Industrial water usage

Based on the survey conducted in AA. Mathiveri, there is currently one farming plot and a total of 370 Liters of groundwater are used daily

Table 40: Industrial groundwater use data for AA. Mathiveri

No.of farms	Type of plantation	Farming period	Plantation size (sqft)	Total (Liters)
1	Fruit & Vegetable	Throughout the year	20,000	370
				370

5.3.4.6 Institutional water usage

Based on the survey conducted in AA. Mathiveri, there are currently seven institutions that have groundwater well facilities and use groundwater. A total of 6149 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 AA. Mathiveri

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Mathiveri School	1233	1440	0	-	2673
Health Center	230	450	9	35.5	725
Council/WDC	40	720	10	-	770
Police Station	47	120	2	92.7	262
Court	61	360	30	-	451
Husna Pre-School	243	360	45	-	648
STELCO	70	540	5	6.2	622
					6149

*All units are in Liters per day

5.3.5 Present & Future water demand

In AA. Mathiveri, the present water demand is at 193,447 Liters per day inclusive of domestic, commercial, institutional and industrial water demand. Groundwater usage is expected to decrease with the establishment of water supply services in the island. The year 2021 population figures are as per the latest island council data. For the population figures in years 2036 and 2054, it is as per Maldives Populations Projections Report published by the National Bureau of Statistics. These population figures were used to calculate the present and future water demand. Future water demand was calculated only considering the domestic water demand using the present domestic water demand (LPCD).

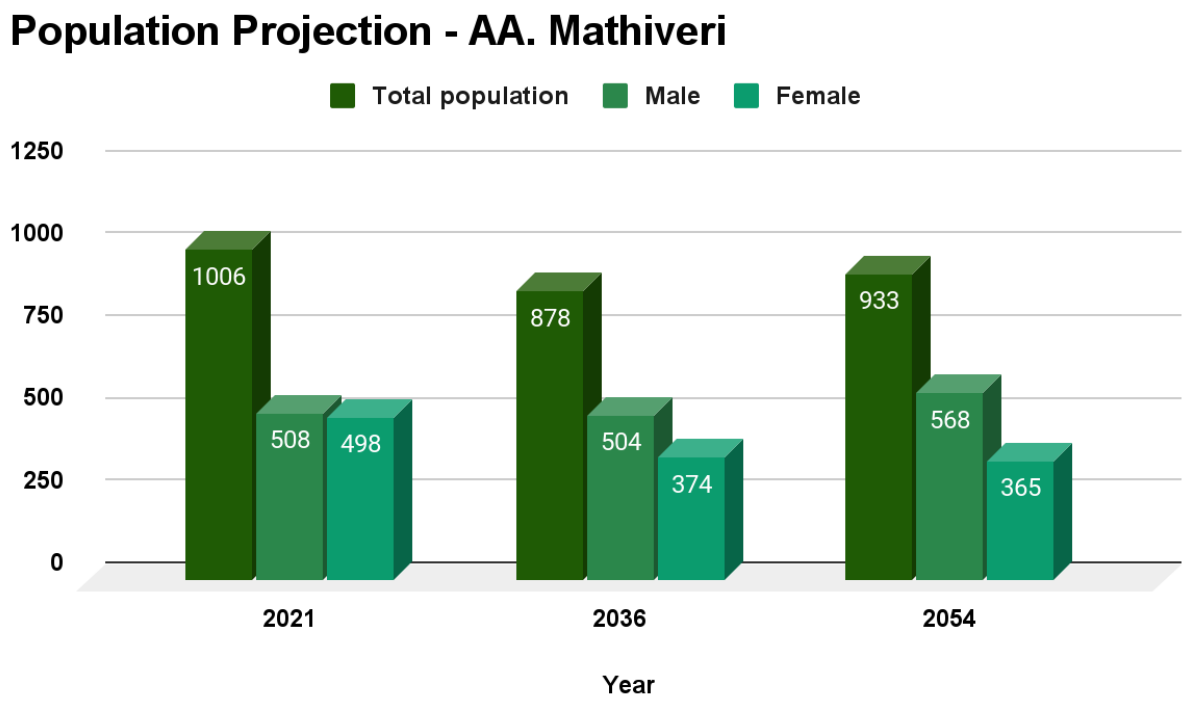


Figure 40: Population Projection - AA. Mathiveri

Table 42: Present groundwater demand - AA. Mathiveri

Year	Total Population	Domestic water demand	Commercial water demand	Institutional water demand	Industrial water demand	Groundwater usage
2021	1006	175,044	11,884	6149	370	**193,447**

*All units are in Liters per day

For the years 2036 and 2054, the total domestic water usage is expected to stay consistent at 174 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 174 Liters, the groundwater demand is expected to be 124 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 878 is expected to be 108,172 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 174 Liters, the groundwater demand is expected to be 99 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 933 is expected to be 92,367 Liters per day.

Table 43: Future domestic water demand - AA. Mathiveri

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	878	174	50	124	**108,872**
2054	933	174	75	99	**92,367**

5.3.6 Water related issues

From 87 households surveyed in AA. Mathiveri, most houses reported smell (77%) and foul taste (31%) in their respective wells. According to the social survey, 51% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gasses such as hydrogen sulphide which cause unpleasant smells. From the interview with Mathiveri Health Center, they highlighted that there are some cases of skin irritation, hair fall, and dandruff issues reported due to groundwater. Some residents also believe groundwater has become worse after the Tsunami. However, the exact number of health issues pertinent to ground water was not identified or recorded. From the social survey, there was also an indication of oil contamination from the houses near the old power station during the 2004 Tsunami.

Table 44: Signs of contamination reported by households

Types of contamination	Data in % out of 87 households surveyed
Smell	77%
Milky	17%
Foul taste	31%
Salty	13%
None	16%

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 87 households surveyed
Changes with tidal variations	16.1
Groundwater quality is better in rainy months	48.3
Long periods without rain causes bad smell	58
Long periods without rain causes bad taste	22
Rain makes it worse	0
No change	20

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 AA. Mathiveri

	EC (µS/cm)	Turbidity (FNU)	DO (mg/L)	pH	Temp (°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 threshhold <35 Taste threshhold Source[1]	<50 Source[1]	
Mean	1416	2.91	3.36	7.45	30.48	0.64	1.03	6.61	0.24
Median	1128	1.47	3.05	7.43	30.10	0.50	0.76	6.31	0.23
SD	731	3.87	1.45	0.22	1.15	0.35	0.95	4.20	0.12
Min	559	0.11	1.33	6.95	28.70	0.22	0.05	1.37	0.06
Max	3862	20.2	8.07	8.22	34.80	1.83	4.18	19.03	0.49
CV	0.52	1.33	0.43	0.03	0.04	0.54	0.92	0.63	0.51

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH_3= Ammonia, NO_3^- = Nitrate, PO_4^{3-}=Phosphate,
SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source[1] = WHO Drinking Water Guidelines, 2017. Source[2] = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 1416 µS/cm fall within the WHO Standard for potable water (<1500 µS/cm). The maximum value for EC (3862 µS/cm) was observed at a guesthouse which was currently occupied and had an average occupancy rate of 50%.
- As expected, the EC of the groundwater in the center of the island and adjacent to the harbor is lower than the coastal areas of the island which indicate saltwater intrusion at the periphery of the island.
- Four samples had higher EC than 2500 µS/cm and their locations were evenly spread throughout the island with one of them being a guesthouse and the three others being inhabited households. Nine samples had EC between 1500 µS/cm and 2500 µS/cm while 27 samples had EC lower than 1500 µS/cm. The EC distribution of samples is shown in Figure 41.

- The mean Turbidity level at 2.91 NTU fall within the URA Guidelines for drinking water (<5 NTU). Only six samples had higher Turbidity level than 5 NTU, with one sample having higher turbidity than 10 NTU at 20.2 NTU.
- Dissolved Oxygen ranged from 1.33 mg/L to 8.07 mg/L with a mean of 3.36 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 28.70°C to 34.8°C depending on the well characteristics and time of day reading was taken. Mean temperature was 30.48°C.
- Salinity ranged from 0.22ppt to 1.83ppt with a mean of 0.64ppt.
- The mean Ammonia concentration was 1.03 mg/L which is lower than the WHO threshold for odor and well below the threshold for taste. 70% of samples had concentration below 1.5 mg/L and 30% of samples had concentration between 1.5 mg/L and 35 mg/L.
- The mean Nitrate concentration was 6.61 mg/L which falls within the WHO Standard for Nitrate concentration (<50 mg/L). No samples had Nitrate concentration higher than the standard.
- Phosphate concentration ranges from 0.06 to 1.49 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. 7 samples (18% of all tested samples) had concentration lower than 0.1 mg/L.

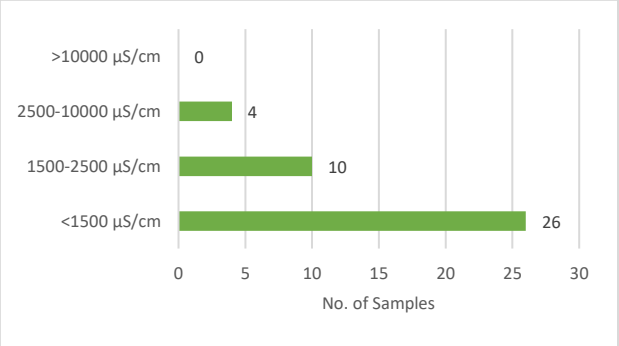


Figure 41: EC Distribution in AA. Mathiveri

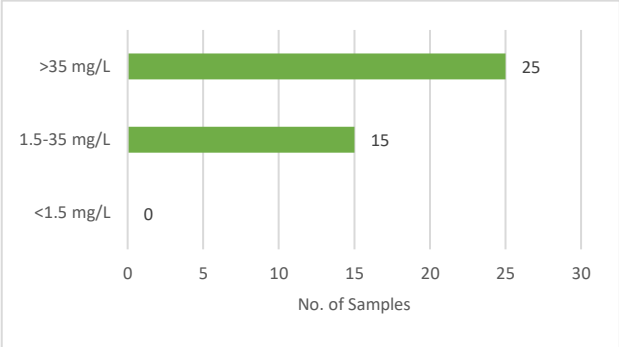


Figure 42: Ammonia Concentration Distribution in AA. Mathiveri

The spatial distribution of all the parameters measured are shown in Figure 43 (a-i).

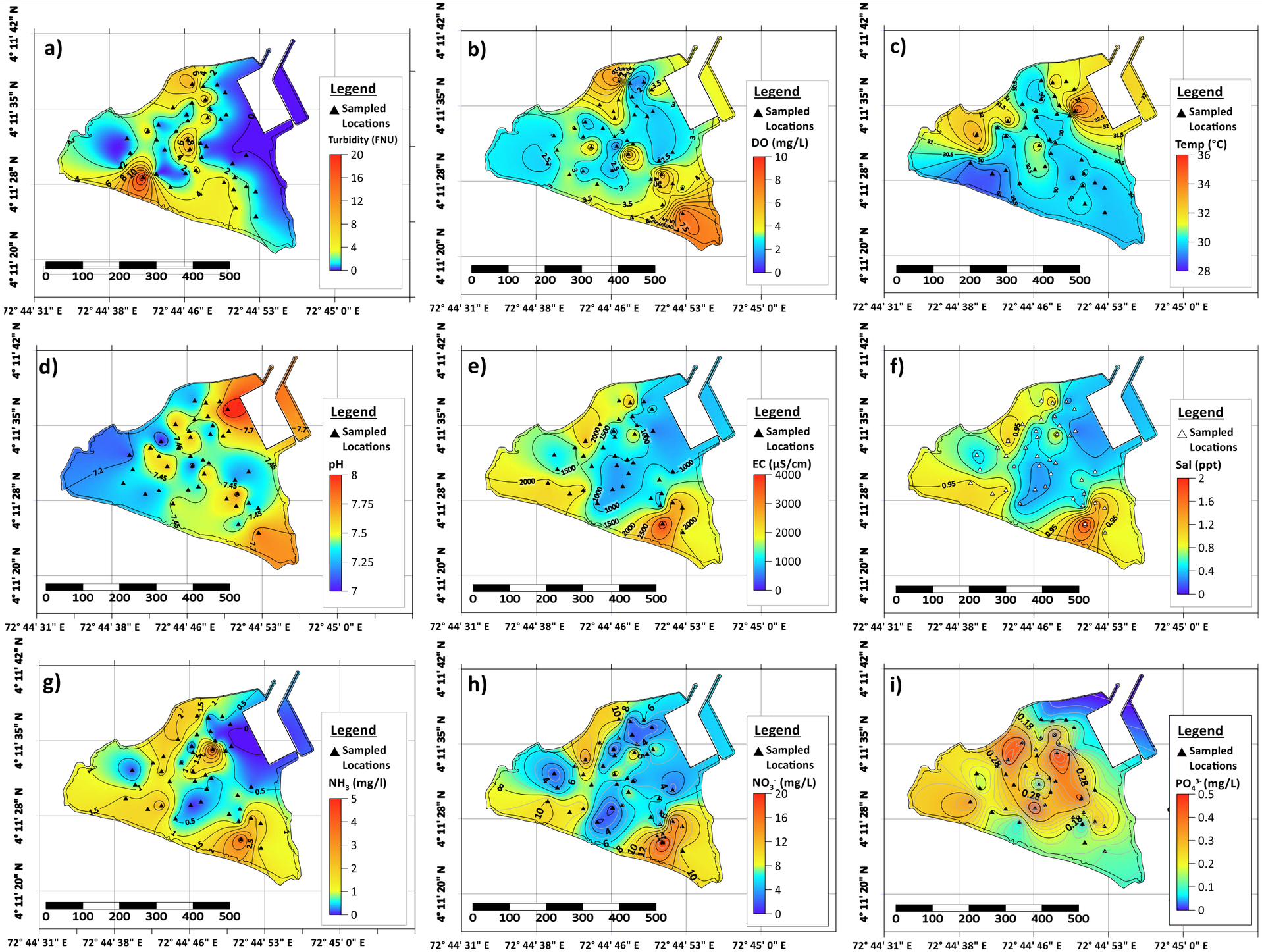


Figure 43: Spatial variation of physiochemical parameters in AA. Mathiveri

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 0.197 and the R-squared of the plot is 0.0389 as indicated from the Figure 44. 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.

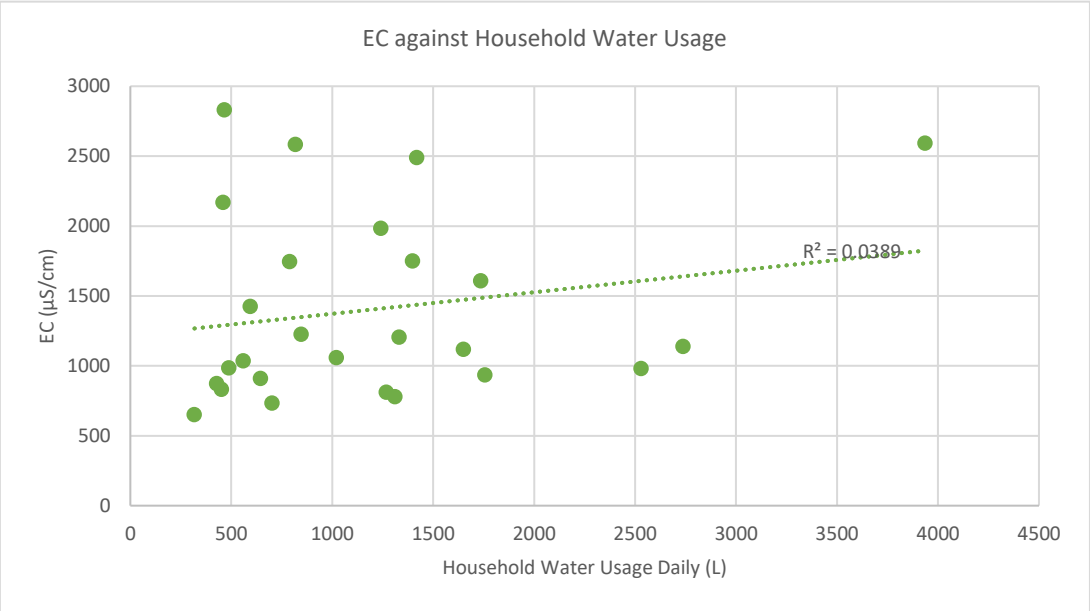


Figure 44: EC against Water Usage in AA. Mathiveri

5.4.1.1 Correlation Matrix

The correlation matrix for AA. Mathiveri 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 AA. Mathiveri

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)	0.08							
pH	-0.18	0.42						
EC (µS/cm)	0.10	0.07	-0.23					
Sal (ppt)	0.11	0.07	-0.22	***1.00				
Temp (°C)	-0.22	-0.36	-0.11	-0.24	-0.27			
NO_3^- (mg/L)	0.18	0.17	0.17	0.78	0.79	-0.25		
NH_3 (mg/L)	0.30	0.08	0.08	0.75	0.76	-0.34	0.83	
PO_4^{3-} (mg/L)	-0.13	-0.24	-0.15	0.08	0.08	-0.20	0.13	0.23

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 EC/Sal (r=1.00), EC/NO_3^- (r=0.78), EC/NH_3 (r=0.75), Sal/NO_3^- (r=0.79), Sal/NH_3 (r=0.76) and NO_3/NH_3 (r=0.83). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlations between salinity and conductivity and temperature are as expected. There are no strong negative correlations between parameters observed.

5.4.1.2 Water Quality Index

The WQI for 40 samples range from 4.74 to 29.62 with a mean WQI of 11.68. The WQI was divided into four categories and Table 129 shows the categorization of samples. 50% of samples were classified as "Very Good", 42.5% of samples were classified as "Good", 7.5% of samples were classified as "Poor" and 0% of samples were classified as "Very Poor". The high value of WQI at some locations were found due to high EC and high turbidity. The spatial distribution of WQI is shown in Figure 45.

Table 48: WQI Categorization for AA. Mathiveri

WQI	Category	No. of samples	Percentage
0 to 10	Very Good	20	50.0%
10 to 20	Good	17	42.5%
20 to 50	Poor	3	7.5%
>50	Very Poor	0	0.0%

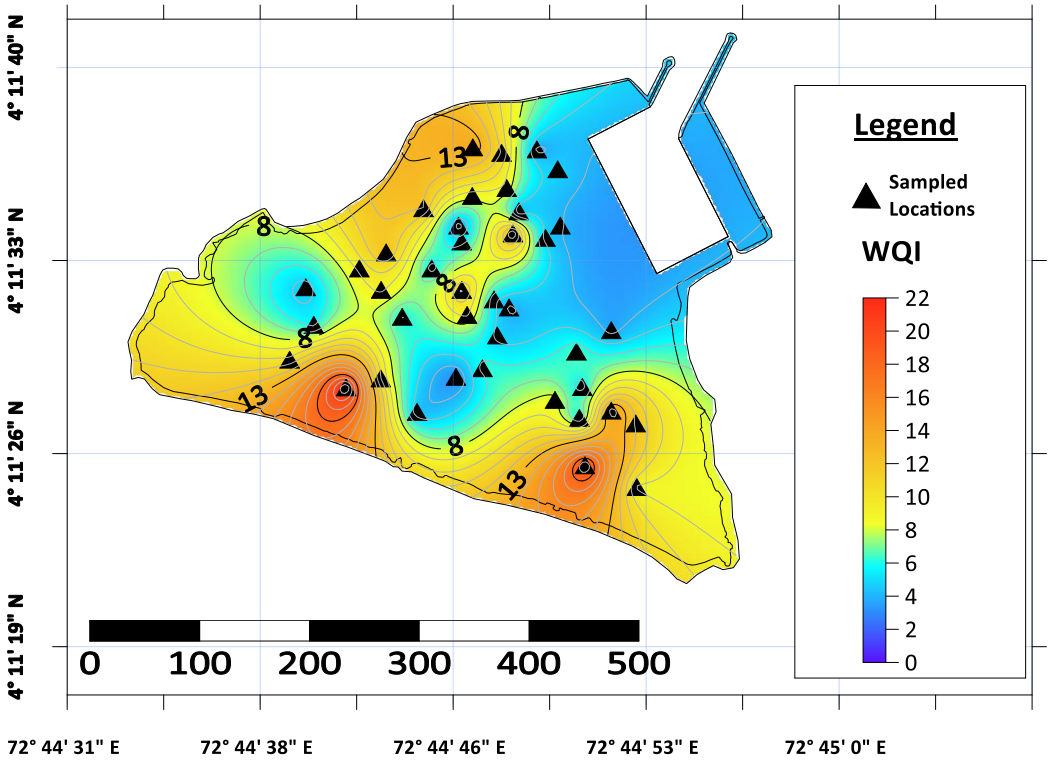


Figure 45: Spatial Distribution of WQI in AA. Mathiveri

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 AA. Mathiveri

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq02	28	2		Connected to a local outfall pipe
wq06	142	Not detected		Connected to a local outfall pipe
wq08	261	54	3	Connected to a local outfall pipe
wq10	75	1	50	Connected to a local outfall pipe
wq15	>2420	435		Well in abandoned plot
wq18	>2420	162		Powerhouse
wq20	461	12		Social Survey not carried out
wq21	1203	1203	50	Connected to a local outfall pipe
wq22	326	18		Mosque
wq27	1300	15	50	Connected to a local outfall pipe
wq30	199	Not detected	25	Septic Tank. Pumped out to sea. Cleaned every 6 months
wq32	291	15		Fini Maizaan - Community Space
wq34	435	96		Connected to a local outfall pipe
wq37	1414	17	40	Connected to a local outfall pipe
wq39	>2420	461	40	Connected to a local outfall pipe

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

Faecal Coliform was detected in 13 samples and Total Coliform was detected in all 15 samples with 3 samples containing Total Coliform count higher than 2400 MPN/100ml.

The effects of effluent leakage from septic tanks and local outfall pipes are evident in the microbiological survey results. Their effect on groundwater is concerning. On average, there is an approximate distance of 30 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Total Coliform and Faecal Coliform is given in Figure 46. Moderately even spatial distribution of Total Coliform was observed with lower count detected near the harbor. Faecal Coliform detected is low or none in the center of the island adjacent to the harbor.

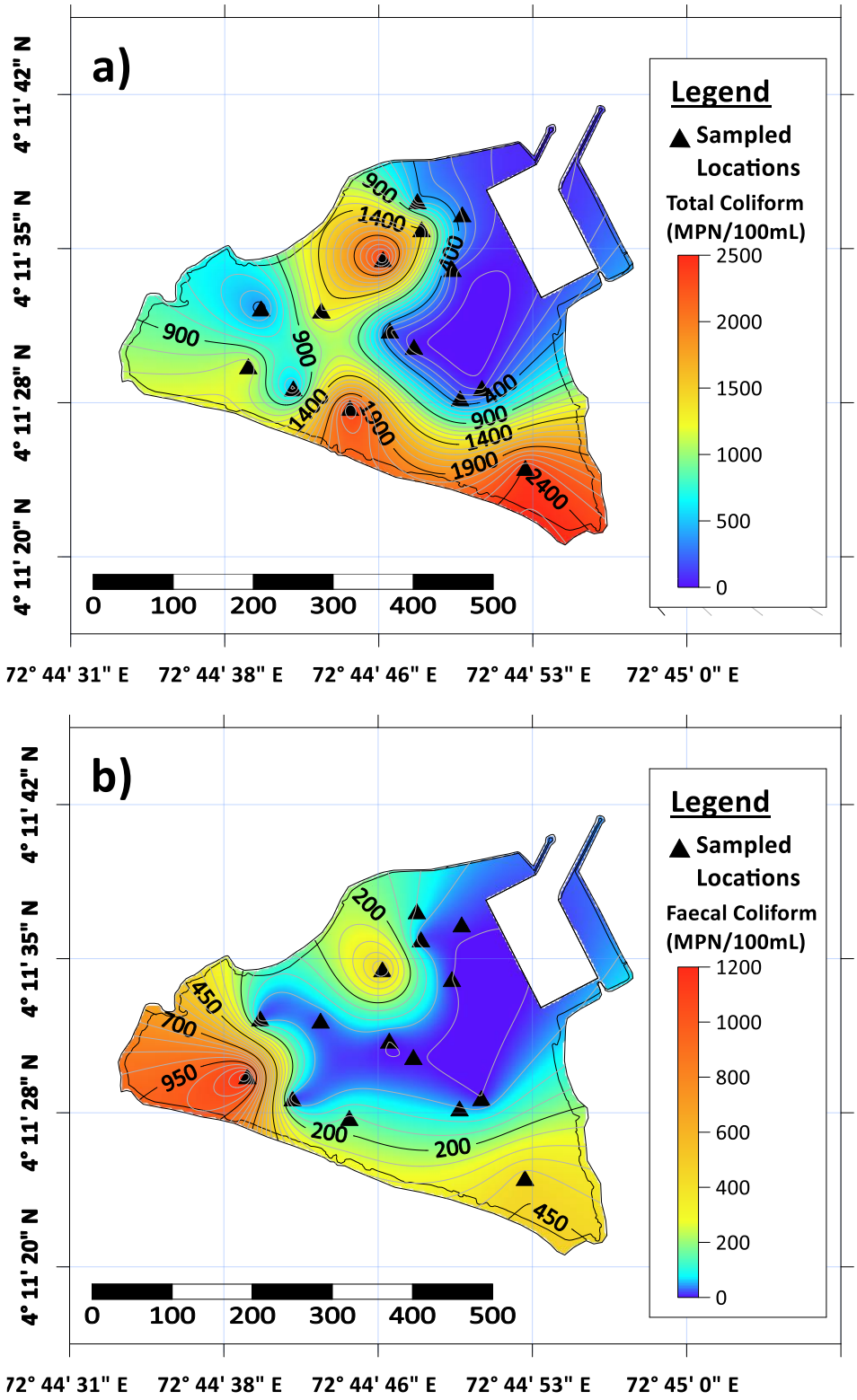


Figure 46: Total (a) and Faecal (b) Contamination Distribution in AA. Mathiveri

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.

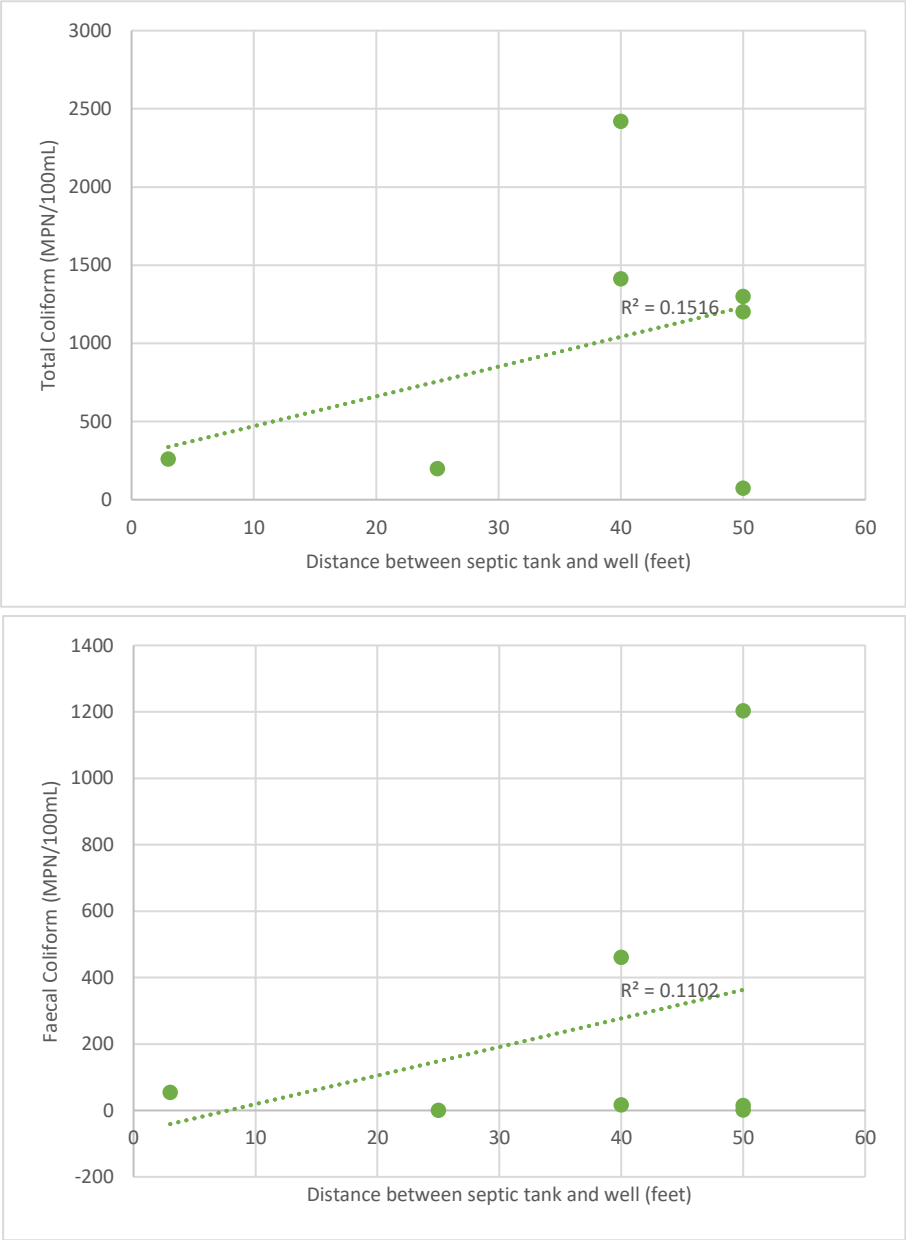


Figure 47: Microbiological Contamination against Septic Tank distancing - Mathiveri

The correlation coefficient of Total Coliform to distance between septic tank and well is 0.389 and the R-squared of the plot is 0.1516 as indicated from the Figure 47. The correlation coefficient of Faecal Coliform to distance between septic tank and well is 0.332 and the R-squared of the plot is 0.11 as indicated from the Figure 47. Therefore, there is a positive relationship observed between the parameters.

5.5 Pumping Test

5.5.1 Test location

A well in construction, with base yet to be placed was available from a private land in AA. Mathiveri 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 48 below shows the location for the pumping test at AA. Mathiveri.

Figure 48: Pumping test location – AA. Mathiveri

5.5.2 Pumping rate, pumping hours, and collected data

A step-drawdown pumping test was carried out at AA. Mathiveri. The test began at 1057 hours on 19 August 2021 and lasted for 483 minutes. A flowrate of 40 LPM was maintained for 0-125th minute of the test. The well was then allowed to recover for 126th-186th minute. Pumping was resumed again at 70 LPM for 187th-360th minute. The final recovery phase of the test lasted from 361st-483rd minute for more than a 100% 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 5.65x10-4 m^2/s (48.80 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.124 for AA. Mathiveri. The processed data of the pumping test at AA. Mathiveri has been annexed at Annex XI.

5.6 Permeability Test

5.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 49 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 49: Permeability Test Locations – AA. Mathiveri

5.6.2 Measured data

Table 50: Permeability Test Measured Data - AA. Mathiveri

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m^3/s)	K (m/s)	K (m/day)
MTV- PMB1	0.6	0.69	35	12	11.00	0.000183	2.71E-04	23.41
MTV- PMB2	0.6	0.80	35	12	9.50	0.000158	2.02E-04	17.44
MTV- PMB3	0.6	0.75	35	12	3.00	0.000050	6.80E-05	5.87
MTV- PMB4	0.6	0.51	35	12	8.50	0.000142	2.83E-04	24.48
MTV- PMB5	0.6	0.72	35	12	10.00	0.000167	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.

5.6.3 Permeability estimation and identified features

The average permeability value for AA. Mathiveri is 18.32 m/day, with permeability values ranging from 5.87 m/day to 24.48 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 50 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 50: Soil Profile Survey Locations – AA. Mathiveri

5.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 51 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.

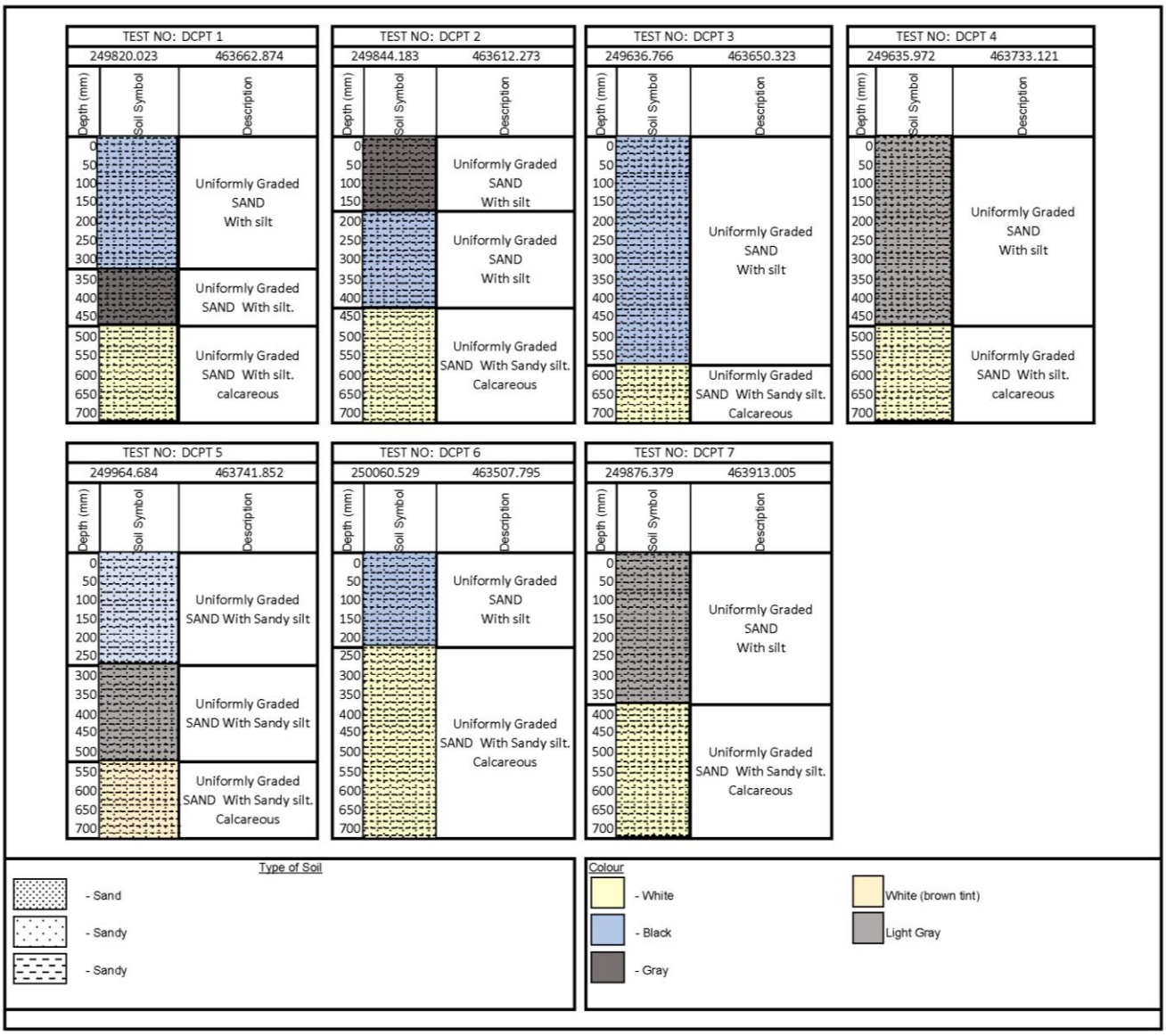


Figure 51: Soil Profile - AA. Mathiveri

5.8 Flood Assessment and Inundation Survey

5.8.1 Flood occurrence and flood impact

For the island AA. Mathiveri, around 52% of the houses reported that flooding occurs mostly when it rains heavily. There is significant flooding observed near the Health Centre which is near the harbour. The higher elevation of reclaimed areas around the harbour causes flooding in the adjacent areas with lower elevation such as the Health Centre. According to the survey, 20% of the houses reported that the harbour project had a major impact on the flooding pattern of the island.

AA. Mathiveri has also observed recurrent flooding episodes associated with swells and rainwater flooding. Most significant flooding incident was on 17th September 2004, whereas the island harbor was collapsed. Recent flooding cases have been reported twice in the year 2020. The first one was due to tidal swelling on 28 May 2020 in which several houses were moderately affected, and one house was badly damaged (refer to photos in Figure 52).

Figure 52: Tidal Swelling in AA. Mathiveri - May 2020 (AA. Mathiveri Council, 2021)

The second instance was on 17 November 2020, which was due to heavy rainfall (refer to photos in Figure 53).

Figure 53: Rain induced flooding in AA. Mathiveri - November 2020 (AA. Mathiveri Council, 2021)

During these two incidents, the flooded water was pumped out and sandbags were used to mitigate further damages.

In AA. Mathiveri, flooding originates mostly from roof runoff (68%) 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 the table below.

Table 51: Perceived causes of flooding – AA. Mathiveri

Perceived causes of flooding				
Roof run off	**Neighbours' roof**	**Off the road**	**General run off in the area**	**No flooding within the plot**
68%	21%	17%	12%	12%

Despite the flooding incidents in AA. Mathiveri, 62% of the households report flooding as an acceptable problem (refer to flood severity component of Flood Maps in Annex XII). This can be due to continuous flood mitigation efforts by the island council and police station as reported by households.

From the social survey, 43% 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 ground which are roads, open areas within the plot and drains to the well. Details of discharge of rainwater overflow are given in the table below.

Table 52: Discharge of rainwater overflow – AA. Mathiveri

Discharge of rainwater overflow			
Ground	**Roads**	**Open area within the plot**	**Drained to well**
43%	0%	31%	26%

5.8.2 Inundation area identification

The common flooding areas are the harbour area, school, and Health Centre (refer to Annex XII: Flood Maps). Based on the social survey responses, an average of 1.28ft is estimated as the flooding depth when there is heavy rainfall. Also, 59% reported that it takes 30 minutes to inundate the area once the heavy rain starts.

5.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 66% observe that the water drains during the rainfall itself, 25% observe that the water drains in less than 4 hours, 9% observe that the water drains in less than 4-24 hours and 0% observe that it takes more than 24 hours for water to drain.

Table 53: Draining period – AA. Mathiveri

Draining period			
only while raining	**drains less than 4hrs**	**takes 4-24 hrs**	**more than 24hrs**
66%	25%	9%	0%

5.9 Geophysical Survey

5.9.1 Surveyed locations, freshwater levels and saline water levels

Locations where ER sounding measurements were taken at AA. Mathiveri island are shown in Figure 54 together with transect lines and cross section. Electrical Resistivity location maps are given in Annex IX. There are 24 ER measurement locations and the number of transects in this island is 13.

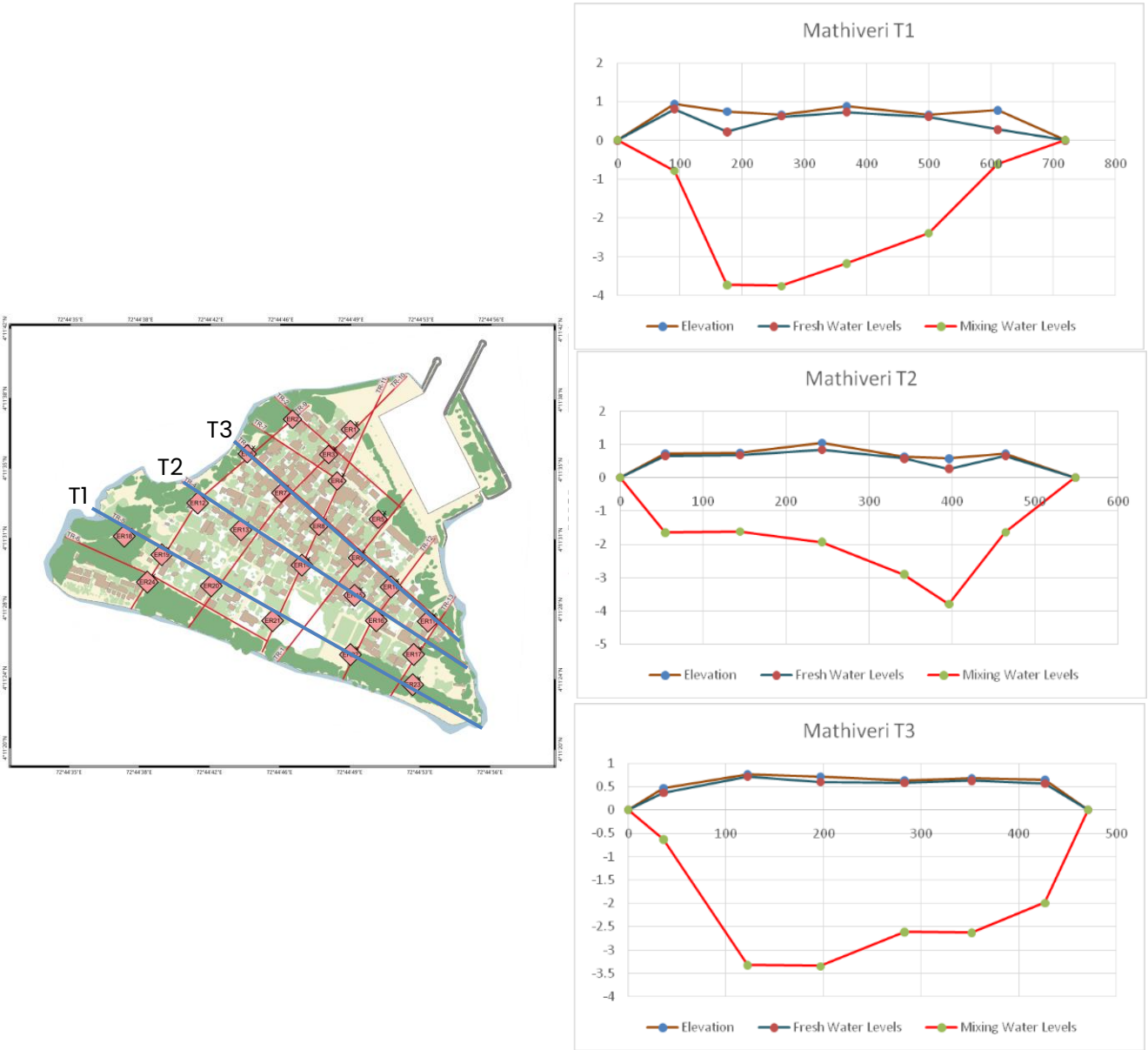


Figure 54: ER surveyed locations and transect lines – AA. Mathiveri Island

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 109 below shows the estimated levels at ER surveyed locations of AA. Mathiveri Island and freshwater lens thickness.

Table 54: Freshwater lens levels and thickness – AA. Mathiveri island

No	Location	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	23	0.72	0.67	-2.15	2.82
2	22	0.84	0.34	-0.56	0.9
3	21	0.69	0.64	-2.83	3.47
4	20	0.83	0.78	-2.45	3.23
5	19	0.73	0.68	-3.61	4.29
6	24	0.47	0.37	-0.63	1
7	18	0.76	0.71	-3.32	4.03
8	12	0.71	0.59	-3.35	3.94
9	13	0.63	0.58	-2.61	3.19
10	14	0.67	0.62	-2.63	3.25
11	15	0.64	0.57	-1.99	2.56
12	16	0.71	0.65	-1.65	2.3
13	17	0.73	0.68	-1.62	2.3
14	11	1.03	0.83	-1.94	2.77
15	10	0.62	0.57	-2.91	3.48
16	9	0.56	0.26	-3.80	4.06
17	8	0.72	0.66	-1.64	2.3
18	7	0.94	0.81	-0.79	1.6
19	6	0.74	0.21	-3.73	3.94
20	1	0.67	0.62	-3.75	4.37
21	3	0.89	0.73	-3.17	3.9
22	2	0.66	0.61	-2.39	3
23	4	0.78	0.28	-0.62	0.9
24	5	0.96	0.67	-0.24	0.91

Average freshwater thickness of AA. Mathiveri island is 2.85m. Maximum recorded thickness of freshwater lens of the Island by ER survey is 4.37 m & minimum is 0.9 m

Data in Table 109 was used to plot freshwater lens cross sections along 13 transects. Of these sectional plots, 3 were given in Figure 54 and they represent the transect plots along the longitudinal section of the island

5.9.2 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 55.

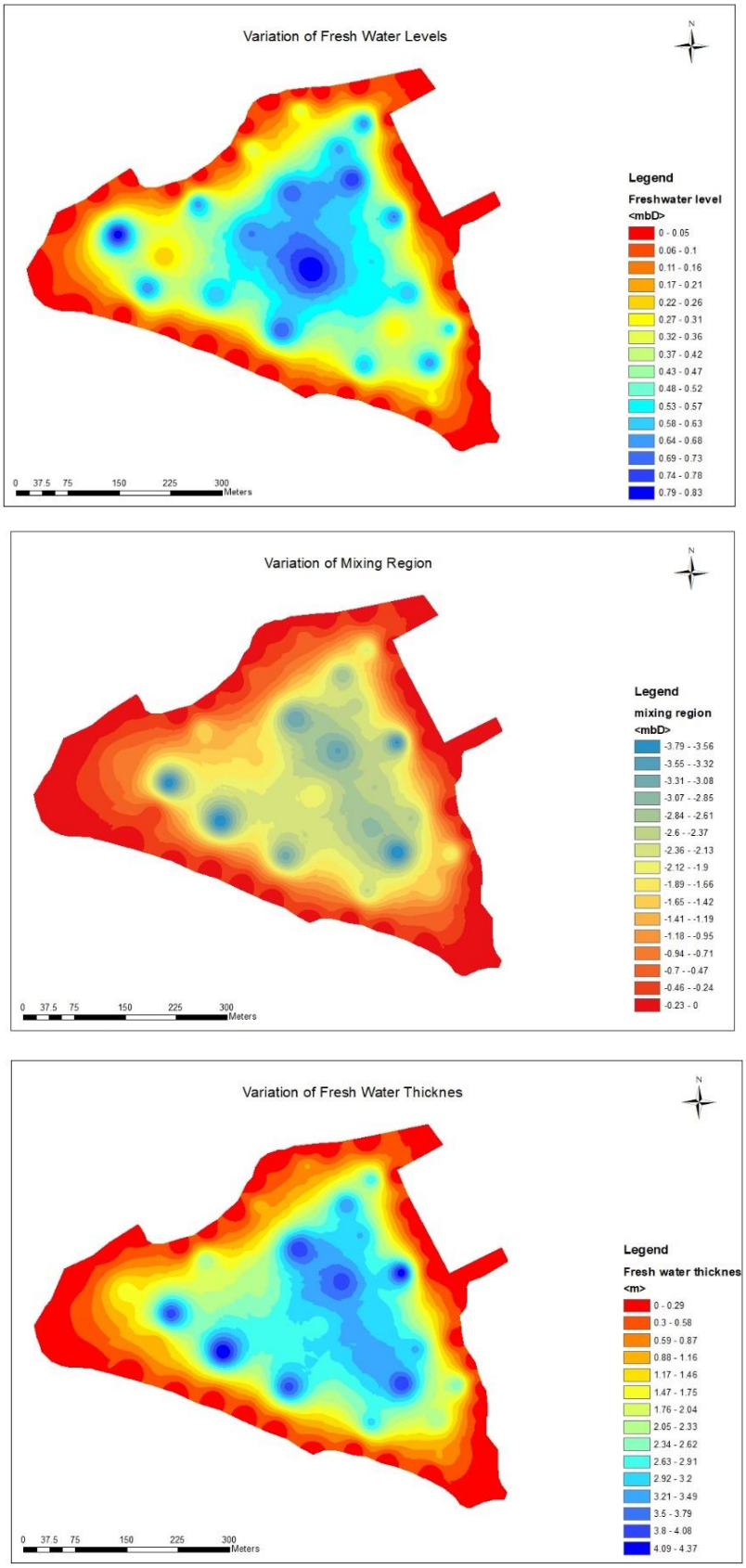


Figure 55: Top: Contours of Freshwater lens upper level, Middle: Contours of Freshwater lens lower level, Bottom: Spatial distribution of thickness of freshwater lens – AA. Mathiveri Island

5.9.3 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 the time of taking ER measurements. Tools in ArcGIS software were used to perform this computation.

Stress level on freshwater aquifer of AA. Mathiveri 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 – AA. Mathiveri island

Item	Value	Unit
Freshwater lens volume - ArcGIS	260,964	m^3
Groundwater abstraction	70,608	m^3/yr
Freshwater lens volume/ Groundwater abstraction	3.70	-
Aquifer stress level	Not Stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 9.16m. This deviates by 110% from the maximum measured value of 4.37m, which is more reliable as it results from a more comprehensive, site-specific methodology.

5.10 SWB Modelling

5.10.1 Land use categorization and area estimation

Table showing land classification and their respective areas are shown in Table 56.

Table 56: Land Use Classification – AA. Mathiveri

	Area (m^2)	% of total area
Roof cover	32,767	16%
Vegetation (Thick)	66,385	31%
Vegetation (Thin)	36,240	17%
Bare Lands	74,505	35%
Farmlands	1,364	1%
Total	211,392	100%

5.10.2 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 56 Table 57). The following observations were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 5367 m^3, 116,360 m^3 and 73,886 m^3 respectively over a 20 year period.
- There is a good relationship between annual rainfall and annual recharge, but it is not linear instead an inverse exponential.
- Annual average rainfall is around 1983 mm
- Variation among the monthly average recharge value is very high. It is lowest on month of March and highest in November.

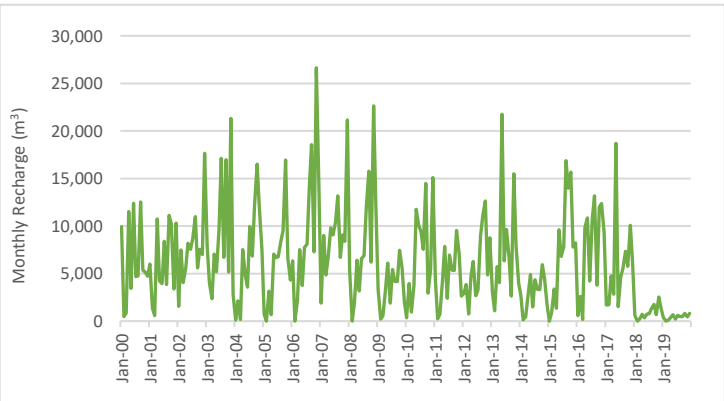


Figure 56: Monthly and annual recharge distribution in AA. Mathiveri

Table 57: Monthly recharge estimated by SWB model – AA. Mathiveri Island

Year	Monthly Recharge (m^3)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2000	9,949	467	866	11,519	3,448	12,385	4,683	4,769	12,518	5,348	5,138	4,726
2001	6,009	1,348	575	10,760	4,210	3,961	8,386	3,837	11,133	10,232	3,373	10,318
2002	1,571	7,498	4,034	5,579	8,176	7,562	8,682	10,974	5,596	7,558	7,004	17,631
2003	7,901	4,017	2,360	7,034	5,180	9,622	17,103	6,695	16,983	5,146	21,305	2,807
2004	116	2,120	193	7,511	4,854	3,588	9,923	6,850	12,163	16,515	11,897	7,562
2005	717	-	3,133	674	7,060	6,665	6,781	8,369	9,494	16,940	6,618	4,330
2006	6,335	-	2,210	7,519	3,751	7,751	8,103	14,004	18,554	7,288	26,631	14,215
2007	1,885	8,997	4,841	6,695	9,811	9,075	10,419	13,169	6,716	9,069	8,405	21,157
2008	5,385	-	1,879	6,391	3,188	6,588	6,888	11,904	15,771	6,194	22,636	12,082
2009	3,350	199	553	3,261	6,113	1,882	5,421	4,182	4,152	7,436	5,577	2,054
2010	340	3,942	952	3,751	11,763	10,030	9,435	7,545	14,482	2,944	5,446	15,094
2011	4,295	255	709	4,180	7,838	2,413	6,950	5,361	5,323	9,533	7,149	2,634
2012	2,889	3,857	760	4,686	6,270	2,664	3,284	8,955	11,092	12,617	4,864	8,756
2013	3,067	1,100	5,744	4,057	21,738	6,355	9,635	6,742	2,634	15,480	7,876	4,010
2014	2,680	159	443	2,608	4,891	1,506	4,337	3,345	3,321	5,949	4,461	1,644
2015	-	896	3,377	1,342	9,614	6,806	7,813	16,887	13,968	15,646	7,783	8,208
2016	599	2,591	183	9,852	10,850	4,232	10,723	13,182	3,777	11,989	12,354	9,342
2017	1,708	1,729	4,754	2,838	18,692	1,521	4,639	5,561	7,341	5,752	10,077	6,096
2018	602	-	210	714	356	736	770	1,330	1,763	692	2,530	1,350
2019	376	22	62	366	686	211	608	469	466	834	452	814

5.10.3 Water Balance

As per estimation, annual recharge estimated by the SWB model is 140,265 m^3 and it is 33.3% of annual average rainfall (refer Figure 57).

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	421,217	7074	176,911	140,265	96,880	70,608
%	100%	1.68%	42%	33.3%	23%	16.8%

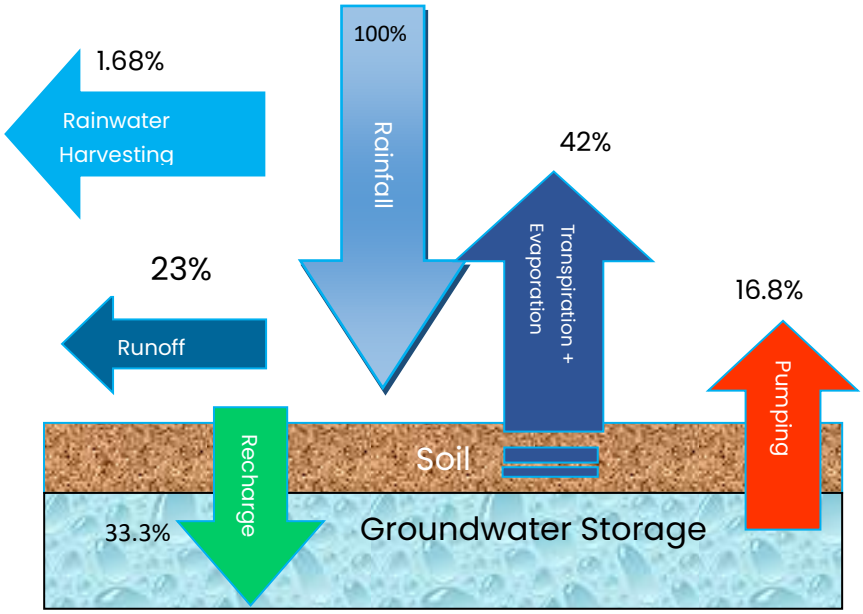


Figure 57: Annual water balance – AA. Mathiveri Island

5.10.4 Deficit estimation, dry month identification and safe yield

Deficit calculation was carried out to identify whether recharge over a monthly 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 (5884 m^3/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 58: Deficit percentage – AA. Mathiveri

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	131	54.6

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 AA. Mathiveri island has a 54.6% dependency on 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 (70,608 m^3/yr) with safe abstraction volume (69,656 m^3/yr) shows that present withdrawal is 1.37% higher than the safe yield. Therefore, it could be inferred that present groundwater abstraction is slightly high and it could lead to up-coning freshwater-saline water interface in future.

5.11 SUTRA Modelling

5.11.1 Model representation and mesh production

SUTRA modeling requires mode domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island. The other boundary defined in the model was island outline which can be referred as shoreline for most of the cases except at harbor area and the inner part of the island which was subdivided into several polygons representing different land use and it was accomplished by importing GIS shape files of island land use and then drawing polygon on these layers. 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.

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 58 shows the pressure boundary defined for AA. Mathiveri island.

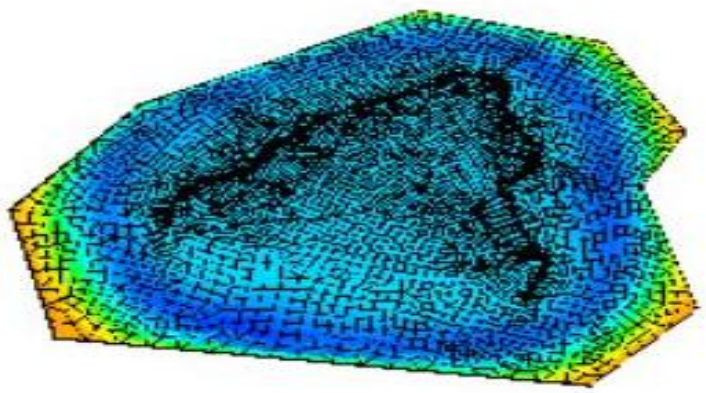


Figure 58: Pressure boundary at SUTRA model - Mathiveri island

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 they were then used to estimate the monthly average recharge rate on residential area, commercial area, and other land use.

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 vary spatially a simplified approach was adopted by defining a polygon around the residential area.

5.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20 yr period is shown in Figure 59. The section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0357 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top.

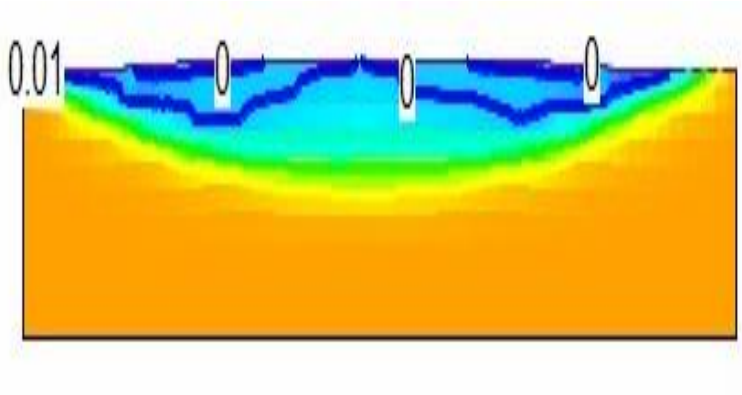


Figure 59: Saltwater distribution – AA. Mathiveri island

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	Ari Atholhu Uthuruburi Atoll
Length	0.669 km
Width	0.604 km
Area	21.1 ha
Population	1,006
Population/area	47.68 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use

Land use map

Topographical map

Average elevation = 0.799 m above MSL

Shoreline length = 3,120 m

	% of total area
Roof cover	16%
Vegetation (Thick)	31%
Vegetation (Thin)	17%
Bare Lands	35%
Farmlands	1%
Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Industrial	Institutional	Total
Rate (m^3/d)	175	11.88	0.37	6.15	193

- Water quality parameters – Physiochemical
  Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	1416 ± 731	1500
Turbidity (FNU)	2.91 ± 3.87	5
DO (mg/L)	3.36 ± 1.45	
pH	7.45 ± 0.22	6.5-8.5
Temp (°C)	30.48 ± 1.15	
Sal (ppt)	0.64 ± 0.35	
NH_3 (mg/L)	1.03 ± 0.95	1.5 (Odour Threshhold)
NO_3^- (mg/L)	6.61 ± 4.20	50
PO_4^{3-} (mg/L)	0.24 ± 0.12	

- Water quality parameters – Microbiological
  Number of samples tested = 15

Parameter	Value range	Average value	Remarks *(on permit limit)*
Total Coliform (MPN/100ml)	28 - >2420	893	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not Detected - 1203	166.07	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	23.41	m^2/day
Storativity	1	1.499	-
Permeability	7	5.87 – 24.48 Average – 18.32	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

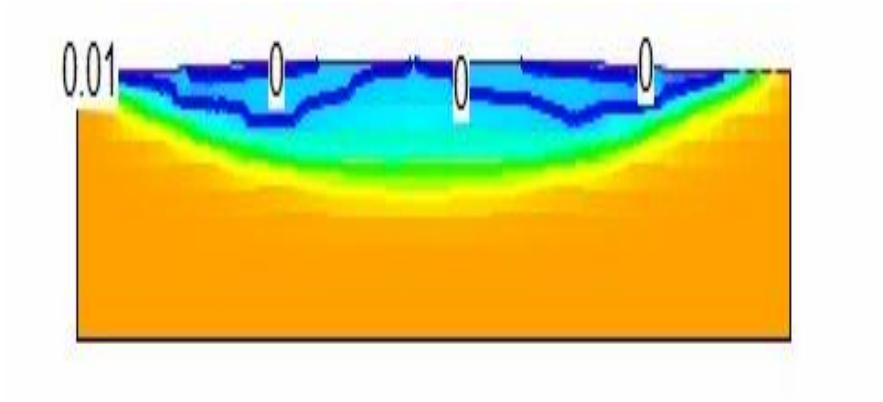
Flooding days per year	Inundation area (m^2)	Inundation depth (m)
89	7030	0.389

- Electric Resistivity survey
  - Measurement taken at 24 locations
  - Average freshwater thickness in the island is 2.85 m.
  - Freshwater lens volume and aquifer stress level

Item	Value	Unit
Freshwater lens volume - ArcGIS	260,964	m^3
Groundwater abstraction	70,608	m^3/yr
Freshwater lens volume/ Groundwater abstraction	3.70	-
Aquifer stress level	Not Stressed	-

- SWB modelling
  - Annual recharge is 140,265 $m^3$and it is 33.3% of annual rainfall (1983 mm)
  - Annual water balance

Unit	Component					
	Rainfall	Rainfall Harvesting	Evapotranspiration	Recharge	Runoff	Pumping
m^3	421,217	7074	176,911	140,265	96,880	70,608
%	100%	1.68%	42%	33.3%	23%	16.8%



  - Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 54.6% in an average year, and it is compensated by ground water storage.
  - Ground water withdrawal (70,608 m^3/yr) is 1.37% higher than the safe abstraction (69,656 m^3/yr).

- SUTRA modelling
  - Average monthly recharge assigned to SUTRA model
  - Freshwater lens prediction (allowable concentration for potable use is 0.001)

6 AA. Himandhoo

6.1 Island Overview and Location

The Island of AA. Himandhoo, belonging to Ari Atholhu Uthuruburi Atoll, is in the central region of Maldives at 03°55′16″N and 72°44′40″E. It is approximately 88.8 km South-West of the capital Male'.

Table 59: Island Geographical Data

Island	AA. Himandhoo
Atoll	Ari Atholhu Uthuruburi Atoll
Location	03°55′16″N and 72°44′40″E

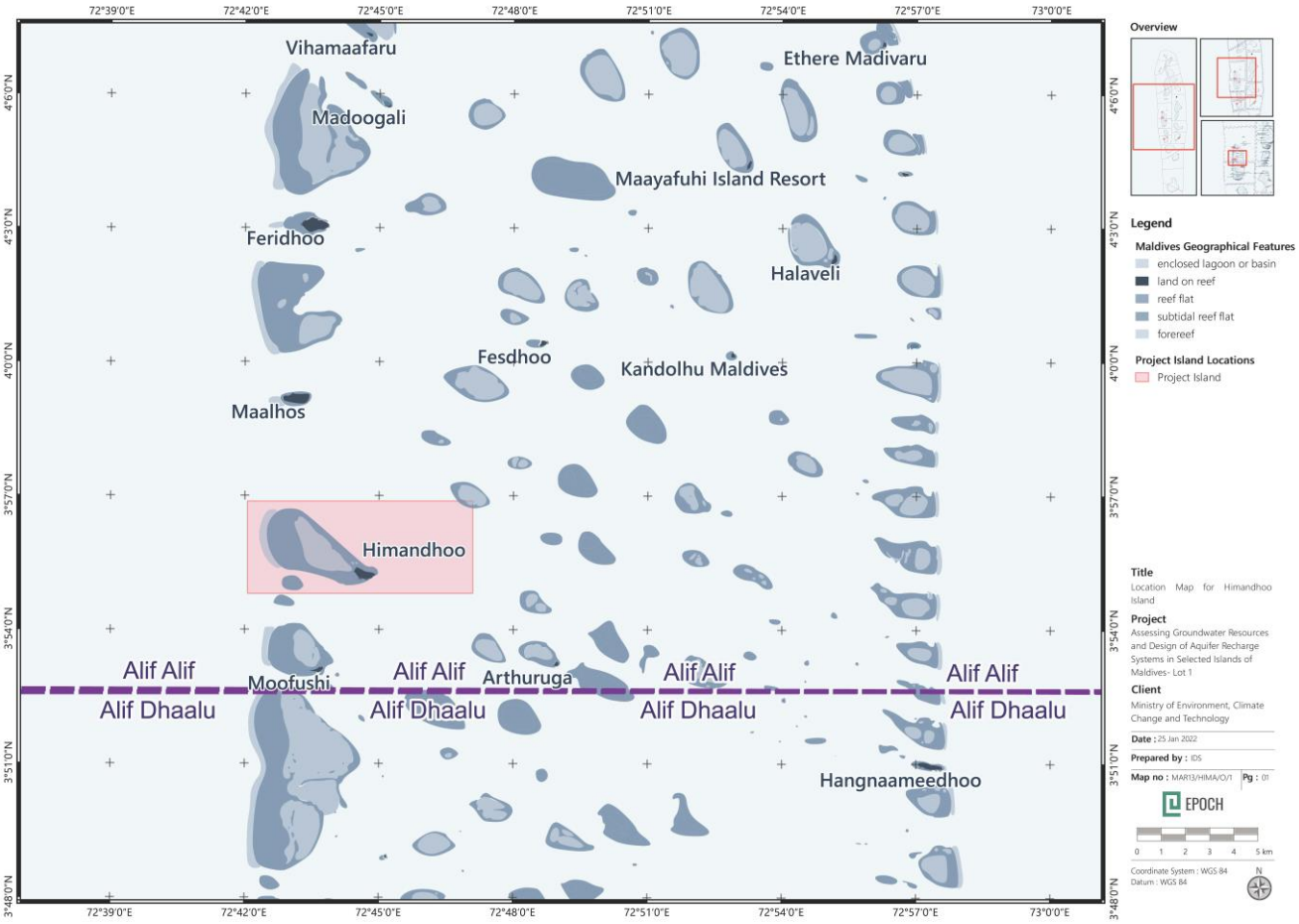


Figure 60: Location Map – AA. Himandhoo

6.1.1 Island features

AA. Himandhoo is located on an isolated reef on the western rim of the North Ari Atoll. AA. Himandhoo has the most mobile beach among the western rim islands (Shaig, A., 2020). The island extends up to 0.79 km in length from toe to toe and a width of 0.29 km from toe to toe. The island experiences severe erosion on the eastern end and in the south side beach.

AA. Himandhoo has a harbour at its Southern side of the island. The island also has a waste centre in the east side of the island. About two-third of the island's surface is vegetation. Thick vegetation is mostly located in the west side of the island. The eastern part of the island has some concentrated thick vegetation. About one-third of the island is populated, which is mostly the centre and east side of the island. The Land Use Characterization map is attached to Annex II.

Table 60: Area Distribution in AA. Himandhoo

Area	20.8 ha	
Length	0.79 km	
Width	0.29 km	
	Area (m^2)	% of total area
Roof cover	34,327	17%
Vegetation (Thick)	59,766	29%
Vegetation (Thin)	39,538	19%
Bare Lands	74,129	36%
Farmlands	-	0%
Wetlands	-	0%
Total	207,759	100%

Figure 61: Land Use Characterization

6.2 Topographical Features

Permanent Survey Marks PSM 5747, PSM 5748 and PSM 5749 were used as benchmarks for AA. Himandhoo topographical survey and drone survey. These details are currently not available via the Maldives Land Survey Authority Website https://www.mlsa.gov.mv/psm and MLSA has indicated that despite the Permanent survey marks being issued, the report has not been submitted. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 1353 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 3.72 cm per pixel. 13 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 61 GCP Statistics for AA. Himandhoo

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	8.455063	1.807485	0.038638
Sigma [m]	35.315	19.119	0.1602
RMS Error [m]	36.313	19.205	01648

AA. Himandhoo is a relatively low-lying island, with elevations around the island remaining at or lower than 1 m above mean sea level. The island does not show a definitive peak elevation, however there are a few depressions, one found on the north-western corner of the island (0.6 m to 0.75 m) and the other on the football pitch found near the harbour (0.7 m to 0.8 m). The newly built harbour and its surrounding area also does not go above 1 m. AA. Himandhoo has a ridge on its north-eastern shoreline, where wind waves from the atoll basin have the greatest impact. With the exception of the harbour, the island does not have any coastal protection structures built.

Roof elevations generally do not exceed 5-7 m and very few houses have multi-storey buildings in AA. Himandhoo. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Thick vegetation with heights greater than 10 m are found on a patch on the north-western corner of the island, as well as peripheries on the southwestern and eastern side of the island. Vegetation found throughout the island generally all exceed 10 m.

The Digital terrain model (DTM) 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 AA. Himandhoo. The DTM slightly overestimates the elevations with a mean of 1.40 cm.

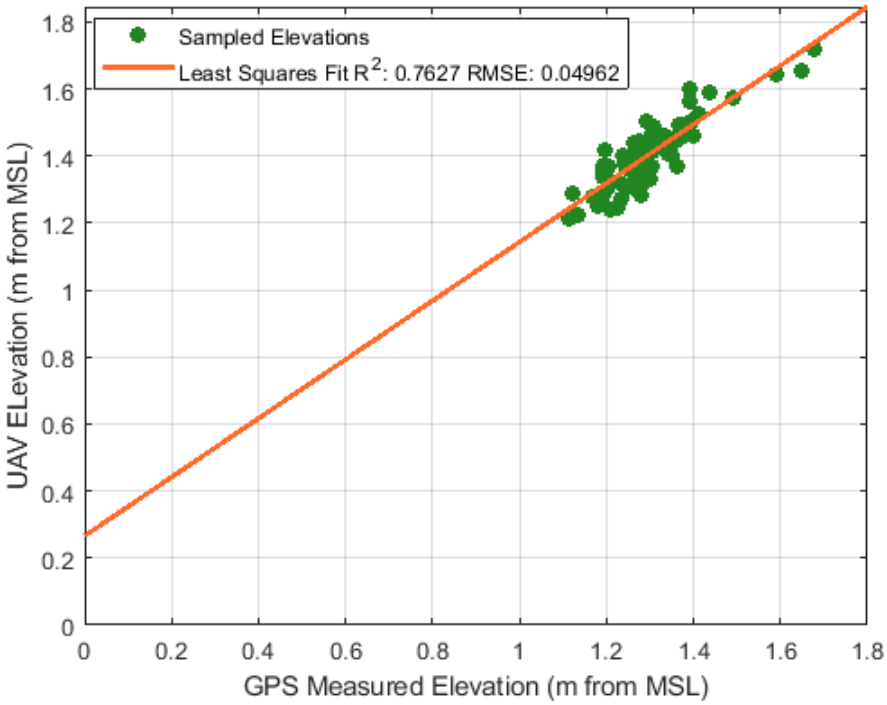


Figure 62: Linear Regression Plot for AA. Himandhoo Sample UAV elevations

Table 62: Error Statistics for AA. Himandhoo DTM

Parameter	*Value (cm)*
Mean	1.40
Standard Error	0.01
Median	1.39
Mode	#N/A
Standard Deviation	0.10
Sample Variance	0.01
Kurtosis	0.75
Skewness	0.66
Range	0.51
Minimum	1.21
Maximum	1.72
Sum	113.34
Count	81.00

6.2.1 Level changes

AA. Himandhoo has an average elevation of 1.13 m with a standard deviation of 0.391. Digital Terrain Model elevations range from -0.6 to 2.1 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 -0.3 m from MSL.

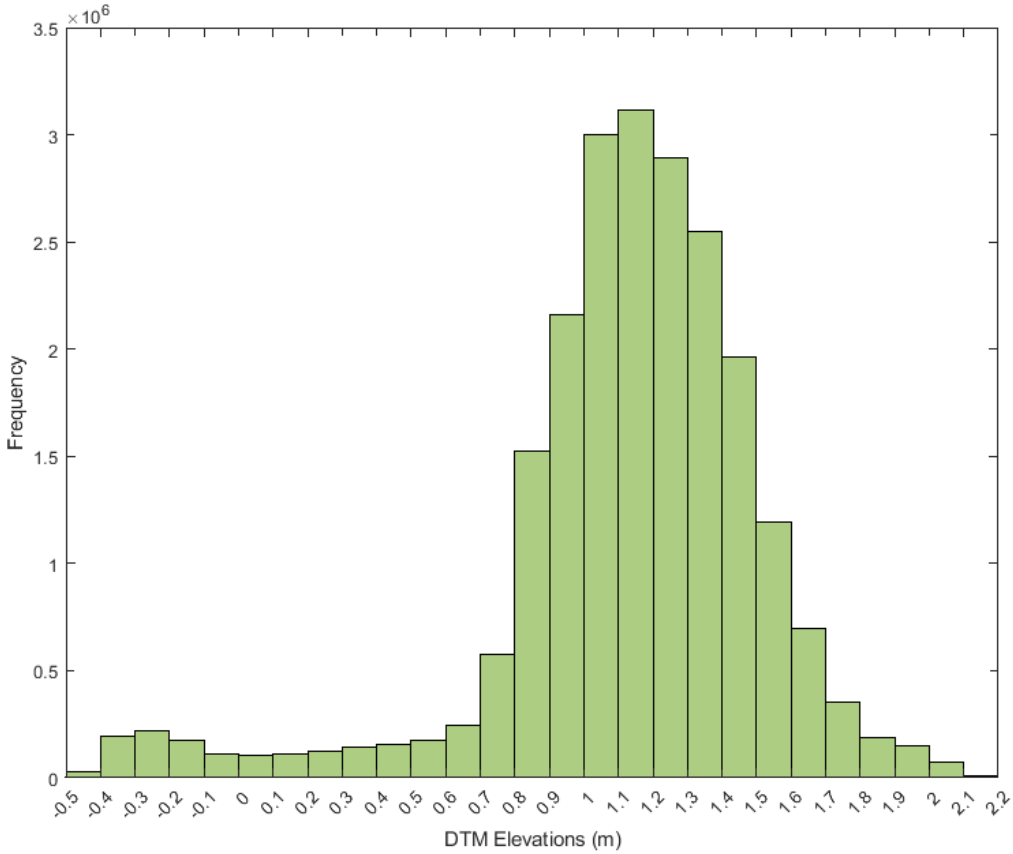


Figure 63: Raster Histogram created for AA. Himandhoo DTM

The island terrain shows that the residential areas are mostly at higher elevations compared to the island peripheries, which is generally lower. However, there is a stretch of properties built behind the harbor which falls into a depressed zone, as shown by profiles 1 and 3. Profile 1 shows a general elevation of 1.25 m within the island, with the exceptions being the depression at the 150 m mark and the elevated ridge as shown by the peak at the end of the profile (500 m), presumably due to strong wave impact on the beach at this location. Profile 3 is slightly different, as shown by the initial depression from start to 100 m in the profile, which is the harbor and its surrounding area. The remaining length of the profile shows a relatively level surface, averaging 1.6 m. This profile however does not show a ridge at the beach at end of profile, indicating that wave impact on this section of beach is calmer compared to southern areas along the beach.

Both profiles 2 and 4 show similar patterns, with the start of each profile (northern beach) showing lower elevations (1.00 m and 1.35 m respectively), followed by inclines climbing up till 1.75 m in both profiles. After the peak, both profiles start declining up to the end, which shows prominent ridges built up to roughly 1.5 m, most likely due to strong wave activity at the southern beach.

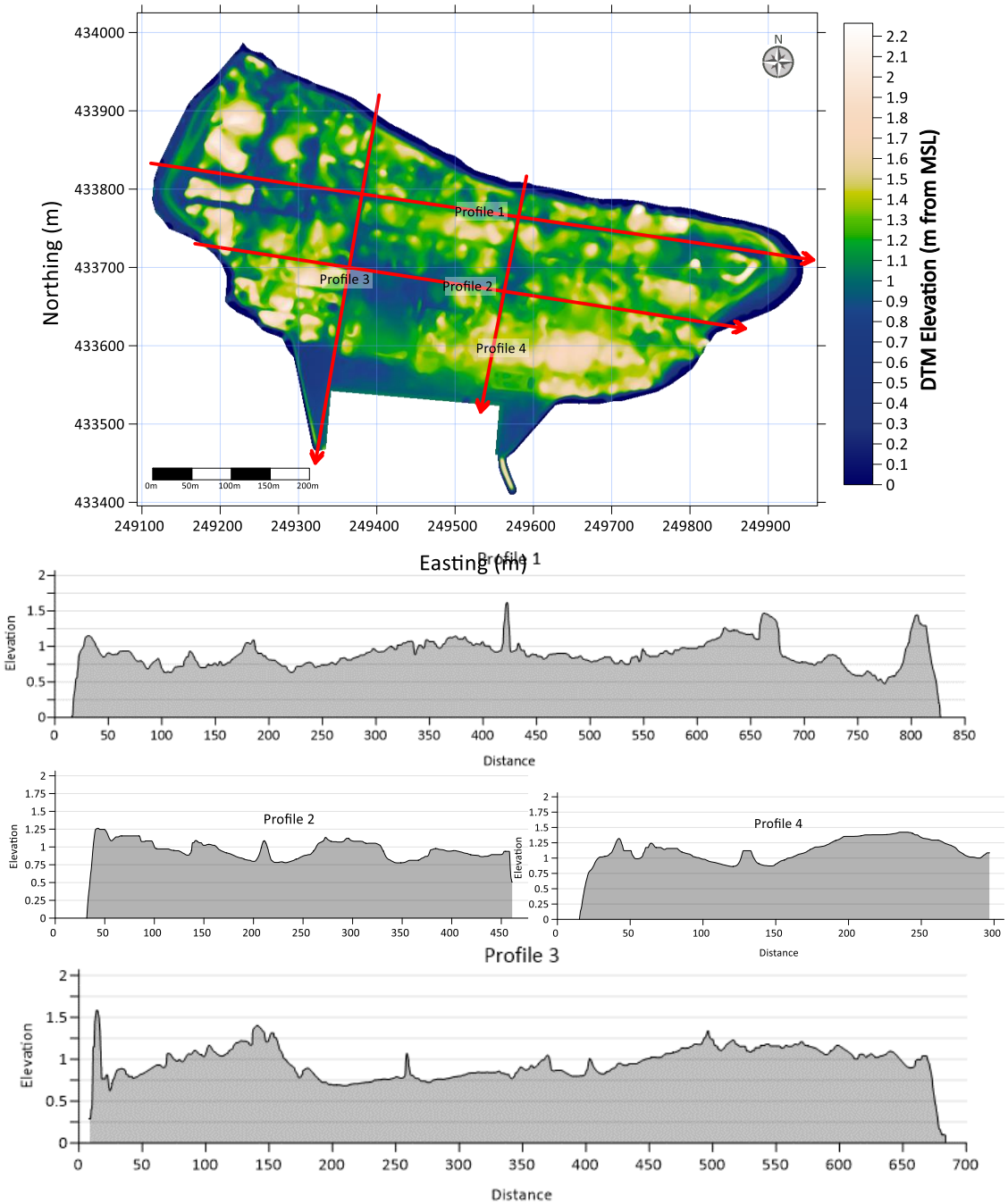


Figure 64: Digital Terrain Model Elevations and Profiles for AA. Himandhoo Island

6.2.2 Shoreline

AA. Himandhoo has a shoreline length of 2880 m. The island has all of its coastal protection on its harbor as follows.

- Breakwater: The sand filled breakwater is found on the south side of the island. Southwestern swell waves approaching from the windward direction is absorbed and dissipated by this breakwater to offer protection to berthed vessels within the harbor. The breakwater is detached from the island itself and has an access platform connecting it to the island. Crest height for the breakwater varies between +1.5 and +1.7 m above mean sea level. The breakwater is highlighted in orange.
- Revetment: The island has two revetments, one on the western side of the harbor and the other on the eastern side of the harbor. The revetment serves as shore protection and prevents erosion at these locations by dissipating wave energy from westerly wind waves generated within the atoll basin and southwestern swells from the windward direction. Crest height of western and eastern revetment vary, with the western revetment being around +1 m to +1.4 m and eastern revetment at+1 m above mean sea level. The revetments are highlighted in green.
- Quay wall: These structures are found within the harbor and are highlighted in yellow. Crest height of quay walls is around +1.3 m above mean sea level.

The southeastern and northeastern shoreline has undergone severe beach erosion, where the shoreline has regressed to expose vegetation roots and specifically beach rock (aanugandu) on the southeastern shoreline.

Figure 65: Orthomosaic of AA. Himandhoo

6.2.3 Reef

AA. Himandhoo is located on the western periphery of the Alif Alif Atoll, being the only island to be located at the south-eastern end on this particular reef. The nearest inhabited islands are Maalhos to the north and Moofushi to the south, which is a resort. The reef measures roughly 5 km along its longest section. For the major wave direction, which is the southwestern swell waves approaching from the windward side, the shortest buffer zone measures about 250 m.

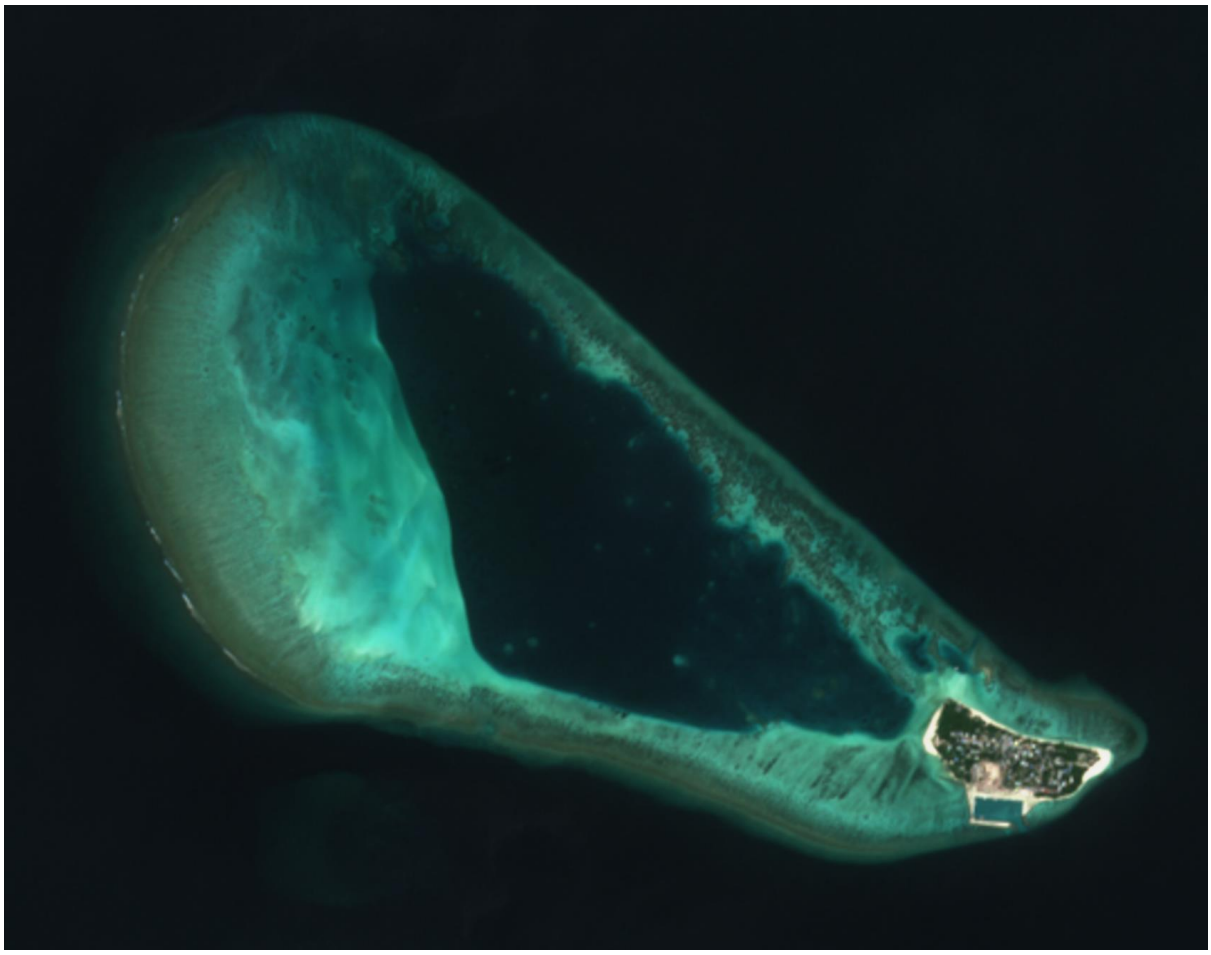


Figure 66: Sentinel 2 imagery of AA. Himandhoo reef taken in February 2022

6.3 Socio Economic Status

6.3.1 Demography

The island has a registered population of 666 as per the 2014 census, with a total of 342 males and 324 females. The island population density is 40.8 people per hectare. The population figures have drastically increased over the past years where the total registered local population climbed up to 848. The following table and graph illustrate the demographic breakdown of AA. Himandhoo.

Figure 67: AA. Himandhoo Population

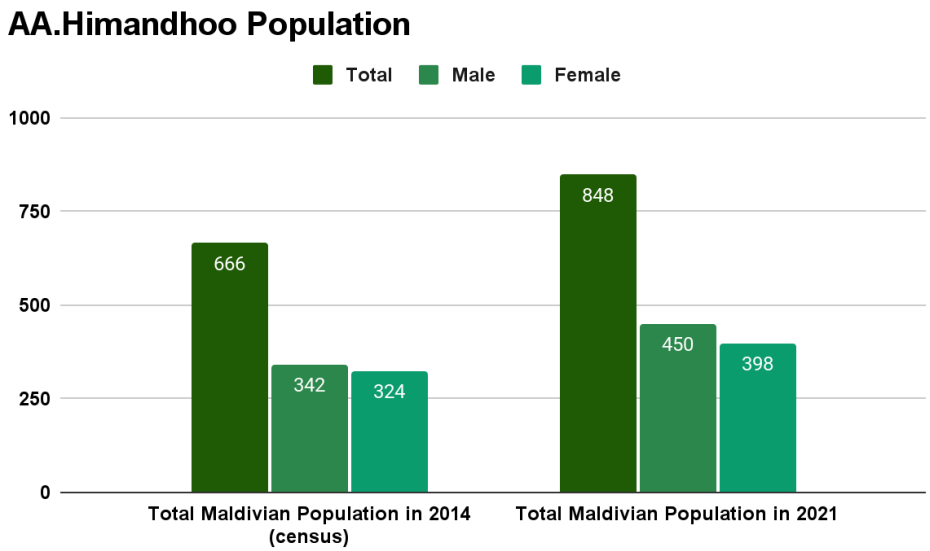


Table 63: AA. Himandhoo Population (Census, 2014)

Resident Population according to Census 2014										
Atoll	Locality	Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
AA	Himandhoo	724	389	335	666	342	324	58	47	11

6.3.2 Socio-Economic Activities

AA. Himandhoo is an inhabited island in Alif Alif Atoll's administrative unit and physically part of Ari Atholhu Uthuruburi Atoll in the Maldives'. This island is well-known for its fishing activities. With the enhancement of tourism activities, many people are now working in tourist resorts and the guesthouse industry. The atoll is famous among tourists for its unique diving spots.

6.3.3 Facilities available

6.3.3.1 Health Care

AA. Himandhoo island Health Center has one doctor, 3 nurses and 7 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

AA. Himandhoo has community pre-school and Himandhoo school. The community pre-school has 30 students and Himandhoo school has a total of 248 students enrolled. The island school offers education up to grade 10th standard.

6.3.3.3 Utilities

Currently, a water and sewerage project are ongoing in the island and is expected to finish in June 2022.

6.3.3.4 Transportation

The island has a harbor which was reconstructed in April 2019. The transportation between AA. Himandhoo island and other islands is by sea. The island has Maldives Transport and Contracting Company (MTCC) ferry services and other private speed launches. The speed boats often travel 3-4 times a week.

6.3.4 Water resources, water usage and water consumption survey

In AA. Himandhoo, there are a total of 96 households inhabited currently. 79 out of 96 households were surveyed via phone call, while maintaining a 95% confidence interval and geo-coordinated sampling points. A map of households surveyed is attached in Annex V. A map of households surveyed is attached in Annex H.

Table 64: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	**79/96 households = 82%**
Percentage of well fitted with pumps	97%
Ground water	**Usage in percentage**
Source of drinking	0%
Source of cooking	3.80%

6.3.4.1 Existing water and sanitation

The main form of sanitation is via the use of local outfall pipe and septic tanks. AA. Himandhoo island reported local outfall in the middle of the road. In AA. Himandhoo 30 percent reported to have less than 49ft distance between septic tanks and water well. The majority of the surveyed households (59%) reported they do not know the exact distance between them. While remaining 9% reported to have more than 49ft distance between septic tanks and water well. 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.

6.3.4.2 Water usage and resources

Based on the survey conducted in AA. Himandhoo, 77 houses have HDPE rainwater tanks for rainwater storage. 77% of the households use rainwater for cooking and 84% use rainwater for drinking. Rainwater collected from rooftops is stored in water tanks, whether communal or home tanks. Many homes utilize rainwater from neighboring houses or bottled water when rainwater is scarce during the dry season. While groundwater is mainly used for gardening and household cleaning with 97% of the houses fitted with water pumps.

The following sections regard 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 AA. Himandhoo, **138,224** liters of water is used daily in the households. A total of **163** liters of groundwater are consumed per capita per day.

Table 65: Domestic groundwater use data for AA. Himandhoo

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
73.8	30.8	8.62	25.9	1.23	19	4	**163**

*All units are in Liters per capita per day

6.3.4.4 Commercial water usage

Based on the survey conducted in AA. Himandhoo, there are currently two operational café'/restaurants and three guesthouses on this island. Many guest houses were commercially active before covid but only three are operational now. Two out of three guesthouses include food outlets and the guesthouses with food outlets reported high groundwater usage. All guest houses are reported to have pumps and oxygen pumps connected to their wells. A total of **3224** Liters of groundwater are used by commercial entities and their detailed breakdown is given in the table below.

Table 66: Café'/ Restaurant groundwater use data for AA. Himandhoo

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Irumaa Cafe	2.3	6.06	240	5	253
Corner hut	22.5	90.9	120	5	238
					492

*All units are in Liters per day

Table 67: Guesthouse groundwater use data for AA. Himandhoo

Guesthouse	Average Occupancy	Total (L/day)
Origami inn guest house	25%	1096
Kuri Himandhoo Inn	25%	434
Marina bay villa guest house	100%	1202
		2732

6.3.4.5 Institutional water usage

Based on the survey conducted in AA. Himandhoo, there are currently eight institutions that has groundwater well facilities and use groundwater on this island. A total of **5044** Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 68: Institutional groundwater use data for AA. Himandhoo

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Himandhoo School	1338	726	5	0	2069
Himandhoo Pre School	39.1	0	5	0	44
Health Center	218	120	10	331	679
Council	157	720	5	0	882
Police Station	60.6	120	2	297	479
Court	39.1	0	5	0	44
Community Pre-School	218	360	7	0	585
Powerhouse	109	0	5	148	262
					5044

*All units are in Liters per day

6.3.5 Present & Future water demand

In AA. Himandhoo, the present water demand is at **146,492** liters inclusive of domestic, commercial and institutional water demand. 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.

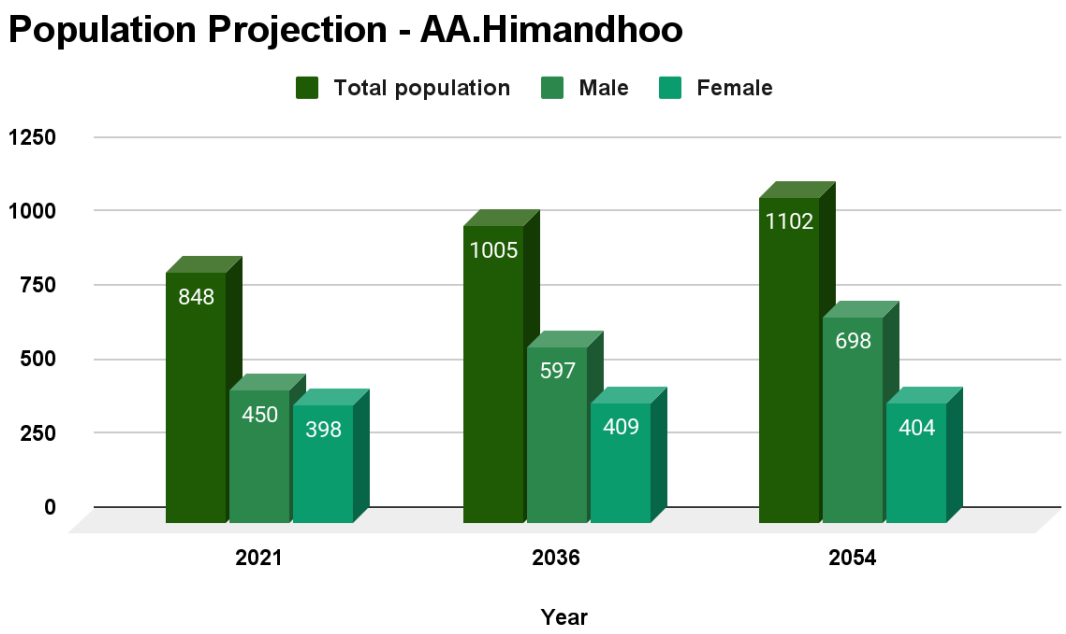


Figure 68: Population Projection - AA. Himandhoo

Table 69: Present groundwater demand - AA. Himandhoo

Year	Total Population	Domestic water demand	Commercial water demand	Institutional water demand	Groundwater usage
2021	848	138,224	3224	5044	**146,492**

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 163 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 163 Liters, the groundwater demand is expected to be 113 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 1005 is expected to be 113,565 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 196 Liters, the groundwater demand is expected to be 88 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 1102 is expected to be 96,976 Liters per day.

Table 70: Future domestic water demand - AA. Himandhoo

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	1005	163	50	113	113,565
2054	1102	163	75	88	96,976

6.3.6 Water related issues

From 79 households surveyed in AA. Himandhoo, most houses reported smell (62%) and salty taste (33%) in their respective wells. According to the social survey, 38% 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 71: Signs of contamination reported by households

Types of contamination	Data in % out of 79 households surveyed
Smell	62%
Milky	18%
Foul taste	25%
Salty	33%
None	28%

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

Table 72: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 79 households surveyed
Changes with tidal variations	11%
Groundwater quality is better in rainy months	56%
Long periods without rain causes bad smell	37%
Long periods without rain causes bad taste	28%
Rain makes it worse	0%
No change	16%

6.4 Groundwater Quality

6.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 73 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 73: Statistical summary of groundwater physiochemical parameters in AA. Himandhoo

	EC (µS/cm)	Turbidity (FNU)	DO (mg/L)	pH	Temp (°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 threshhold <35 Taste threshold Source[1]	<50 Source[1]	
Mean	3696	2.30	3.19	7.25	29.95	1.83	7.98	28.65	0.34
Median	2029	0.43	2.97	7.26	29.70	0.91	2.63	17.54	0.22
SD	4765	5.29	1.23	0.23	1.14	2.64	11.97	29.00	0.30
Min	481	0.00	1.58	6.81	28.20	0.21	0.10	1.24	0.06
Max	26,428	29.35	7.41	7.91	32.50	14.96	54.99	127.35	1.30
CV	1.29	2.31	0.39	0.03	0.04	1.44	1.50	1.01	0.89

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH_3= Ammonia, NO_3^-= Nitrate, PO_4^{3-}=Phosphate,
SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source[1] = WHO Drinking Water Guidelines, 2017. Source[2] = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 3696 µS/cm is higher than the WHO Standard for potable water (<1500 µS/cm) and non-potable water (<2500 µS/cm).
- Twelve samples had EC lower than 1500, 12 samples had EC between 1500-2500, 12 samples had EC between 2500-10000 and 4 samples had EC greater than 10000. The Electrical Conductivity distribution of tested samples is presented in Figure 69.
- The mean Turbidity level at 2.3 NTU fall within the URA Guidelines for drinking water (<5 NTU). Only four samples had higher Turbidity level than 5 NTU.
- Dissolved Oxygen ranged from 1.58 mg/L to 7.41 mg/L with a mean of 3.19 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 7.25.
- Temperature ranges from 28.2°C to 32.5°C depending on the well characteristics and time of day reading was taken. Mean temperature was 29.95°C.
- Salinity ranged from 0.21ppt to 14.96ppt with a mean of 1.83ppt.

- The mean Ammonia concentration was 7.98 mg/L which is higher than the WHO threshold for odour but well below the WHO threshold for taste. 38% of samples had concentration below 1.5 mg/L, 58% of samples had concentration between 1.5 mg/L and 35 mg/L and 5% of samples had concentration higher than 35 mg/L. The ammonia concentration distribution is shown in Figure 70.
- The mean Nitrate concentration was 28.65 mg/L which falls within the WHO Standard for Nitrate concentration (<50 mg/L). Only 4 samples had Nitrate concentration higher than the standard.
- Phosphate concentration ranges from 0.06 to 1.30 mg/L with a mean concentration of 0.34 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.

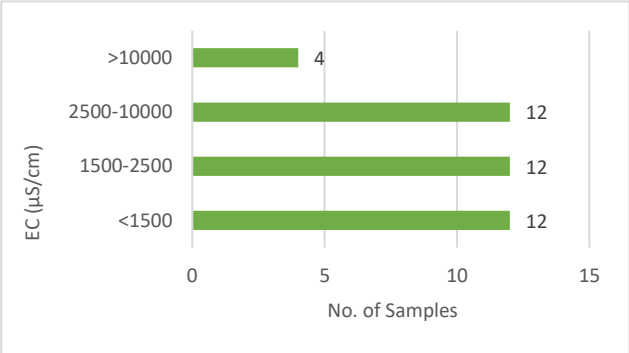


Figure 69: EC Distribution in AA. Himandhoo

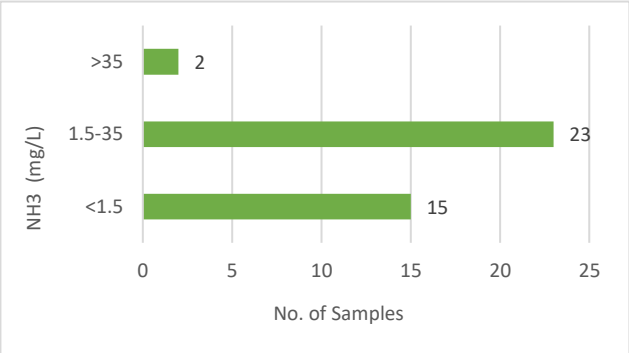


Figure 70: Ammonia Distribution in AA. Himandhoo

The spatial distribution of all the parameters measured are shown in Figure 71 (a-i).

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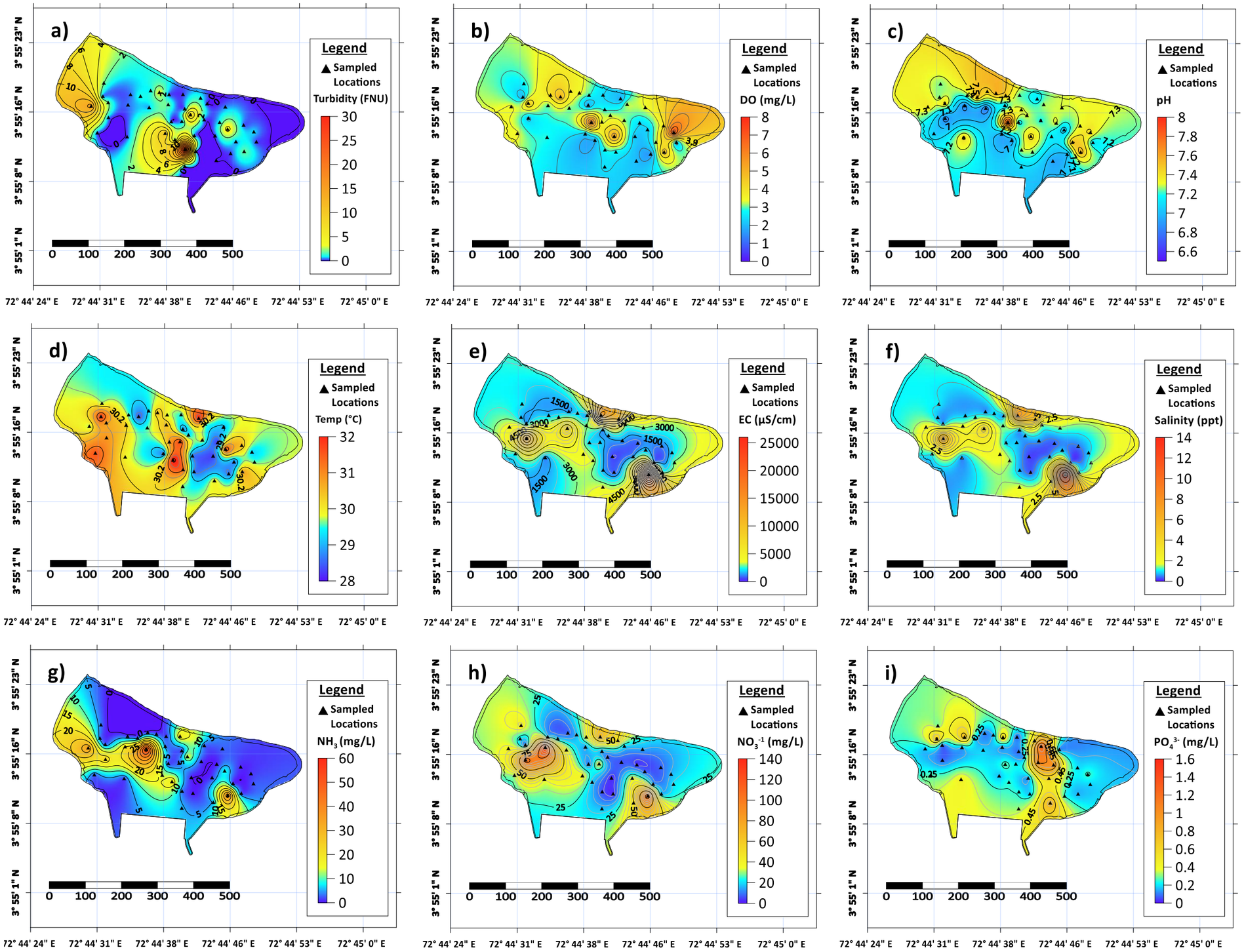


Figure 71: Spatial variation of physiochemical parameters in AA. Himandhoo

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 -0.115 and the R-squared of the plot is 0.0113 as indicated from the Figure 72. 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.

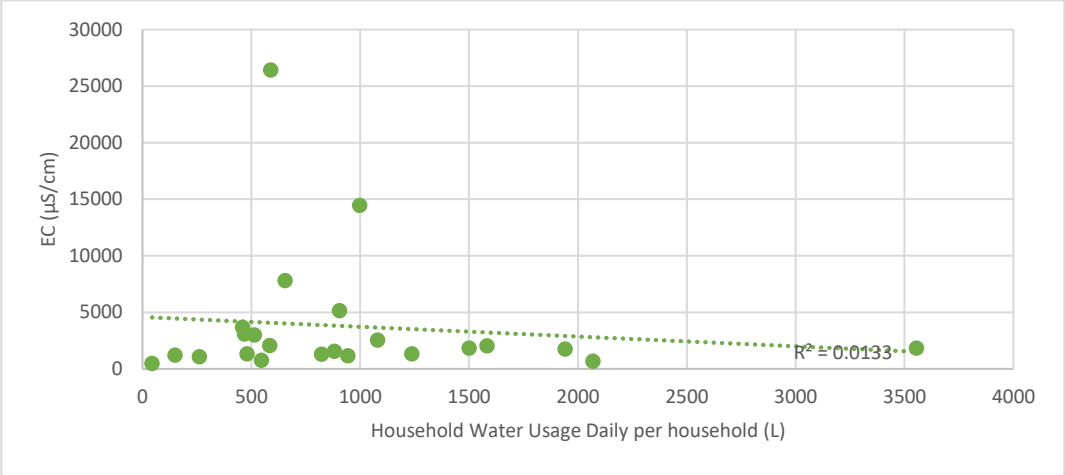


Figure 72: EC against Water Usage in AA. Himandhoo

6.4.1.1 Correlation Matrix

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

Table 74: Correlation matrix of the groundwater quality parameters in AA. Himandhoo

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)	-0.06							
pH	0.03	0.67						
EC (µS/cm)	-0.10	-0.35	-0.42					
Sal (ppt)	-0.10	-0.34	-0.40	***1.00				
Temp (°C)	0.13	-0.13	-0.17	-0.01	-0.04			
NO_3 (mg/L)	-0.13	-0.35	-0.54	0.72	0.71	0.05		
NH_3 (mg/L)	0.13	-0.29	-0.54	0.67	0.66	0.03	0.57	
PO_4^{3-} (mg/L)	-0.16	-0.16	-0.16	-0.13	-0.13	0.01	-0.14	-0.23

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation

Table 74 shows a strong positive correlation coefficient between EC/Sal (r=1.00), EC/NO_3 (r=0.72), EC/NH_3 (r=0.67), Sal/NO_3 (r=0.71) and Sal/NH_3 (r=0.66). 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 negative correlations observed between pH and EC, Sal, NO_3 and NH_3.

6.4.1.2 Water Quality Index

In this study, the computed WQI ranges from 2.25 to 120.13, with a mean of 20.30. The WQI was divided into four categories and Table 75 shows the categorization of samples. 35% of samples were classified as "Very Good", 40% of samples were classified as "Good", 17.5% of samples were classified as "Poor" and 7.5% of samples were classified as "Very Poor". The high value of WQI at some locations have been found to be mainly from the high EC, high Ammonia concentration and high Nitrate concentrations. The spatial distribution of WQI is as per Figure 73.

Table 75: Water Quality Classification based on WQI – AA. Himandhoo

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	14	35%
10 to 20	Good	16	40%
20 to 50	Poor	7	17.5%
>50	Very Poor	3	7.5%

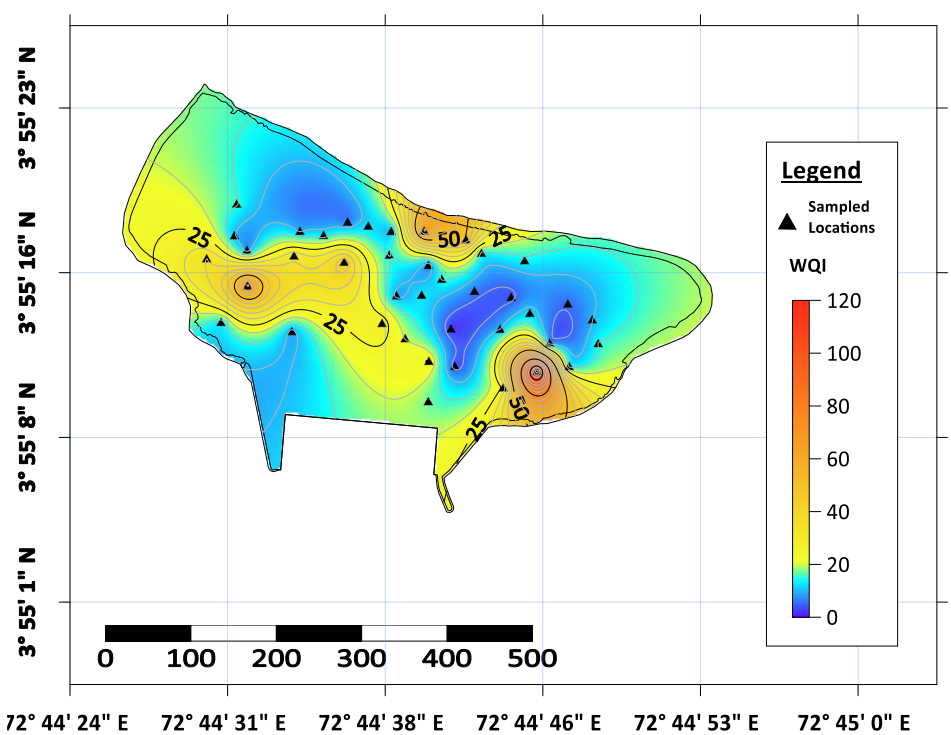


Figure 73: Spatial Distribution of WQI in AA. Himandhoo

6.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 76 summarizes the results.

Table 76: Microbiological Parameters of groundwater in AA. Himandhoo

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq03	579	Not detected		Preschool
wq04	>2420	2		Magistrate Court
wq06	33	Not detected		Island Council Office
wq09	308	31		Social Survey not carried out
wq11	387	Not detected	20	Connected to a local outfall pipe
wq14	2420	4		Connected to a local outfall pipe
wq16	12	Not detected		Connected to a local outfall pipe
wq18	>2420	Not detected		Social Survey not carried out
wq20	25	Not detected	10	Septic Tank. Septic Waste pumped out to sea once every 2-3 years or once it is filled
wq24	>2420	15		Social Survey not carried out
wq26	1046	11	45	Septic Tank. Septic Waste buried inside household once every 5 years
wq30	>2420	41	20	Septic Tank. Not Cleaned yet.
wq31	>2420	Not detected		Septic Tank. Septic Waste pumped out to sea once every 2 years.
wq37	649	23		Connected to a local outfall pipe
wq39	140	Not detected	50	Connected to a local outfall pipe

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

Faecal Coliform was detected in 7 samples and Total Coliform was detected in all 15 samples with 5 samples detecting Total Coliform count higher than 2400 MPN/100ml.

As per the Social Survey, 41.5% of all households use Septic Tanks for sewage disposal and 58.5% of houses are connected to a local outfall pipe.

From the 15 samples tested, 60% of households that are connected to local outfall pipe does not have any faecal coliform contamination in their groundwater while 50% of households that use septic tanks does not have any faecal coliform contamination in their groundwater. There is no correlation observed between faecal and total coliform contamination, and the distance between water well and septic tank. The sample size is too small to draw any significant conclusions about the effect of different sewerage disposal methods on faecal and total coliform contamination of groundwater. The sewage disposal information was collected only for households as part of the social survey and therefore this information

is not available for institutions. On average, there is an approximate distance of 32 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Total Coliform and Faecal Coliform is given in Figure 74. 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. 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.

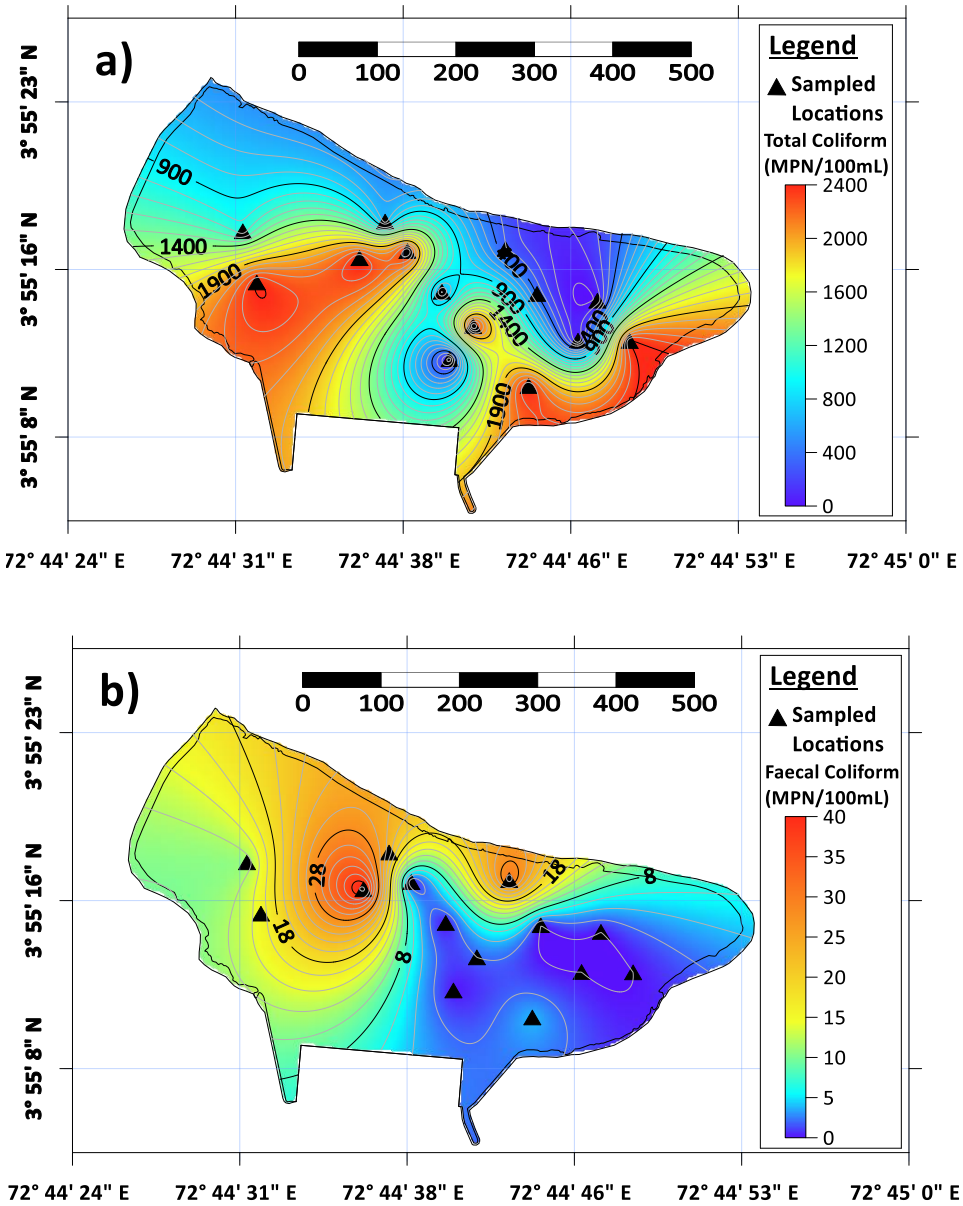
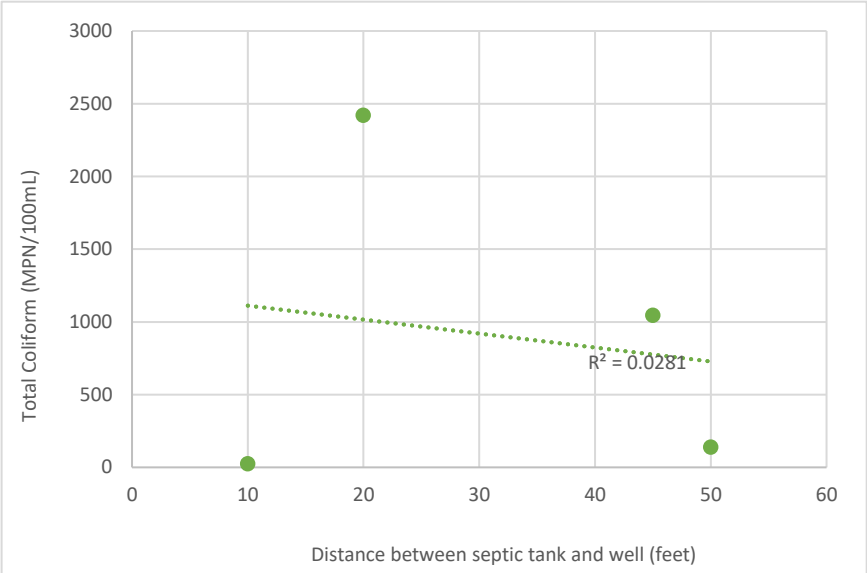


Figure 74: Total (a) and Faecal (b) Contamination Distribution in AA. Himandhoo

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.



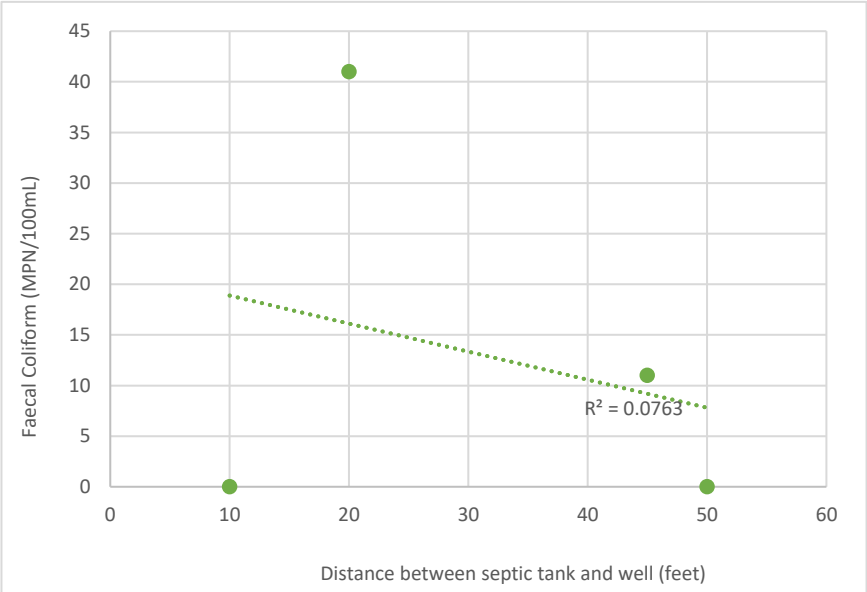


Figure 75: Microbiological Contamination against Septic Tank distancing - Himandhoo

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.168 and the R-squared of the plot is 0.0281 as indicated from the Figure 75. The correlation coefficient of Faecal Coliform to distance between septic tank and well is -0.276 and the R-squared of the plot is 0.0763 as indicated from the Figure 75. Therefore, there isn't a significant relationship observed between the parameters.

6.5 Pumping Test

Pumping Test was not carried out at AA. Himandhoo since a well practically suitable for pumping was not available from the public areas of the island and as the island was placed under monitoring for Covid-19 by the Health Protection Agency, it was not possible to access private properties.

6.6 Permeability Test

6.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 76 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 76: Permeability Test Locations – AA. Himandhoo

6.6.2 Measured data

Table 77: Permeability Test Measured Data - AA. Himandhoo

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m^3/s)	K (m/s)	K (m/day)
HMD-PMB1	0.6	1.00	35	12	8.00	0.000133	1.36E-04	11.75
HMD-PMB2	0.6	0.64	35	12	2.38	0.000040	6.32E-05	5.46
HMD-PMB3	0.6	1.38	35	12	15.00	0.000250	1.85E-04	15.96
HMD-PMB4	0.6	1.04	35	12	8.00	0.000133	1.31E-04	11.30
HMD-PMB5	0.6	1.06	35	12	13.00	0.000217	2.08E-04	18.01

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 AA. Himandhoo is 12.5 m/day, with permeability values ranging from 5.46 m/day to 18 m/day. As highlighted in Section **Soil Profile Survey**, the island soil profile is predominantly Sand, and the K values above are consistent with the range of K values obtained for Sand (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 77 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 77: Soil Profile Survey Locations – AA. Himandhoo

6.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 78 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.

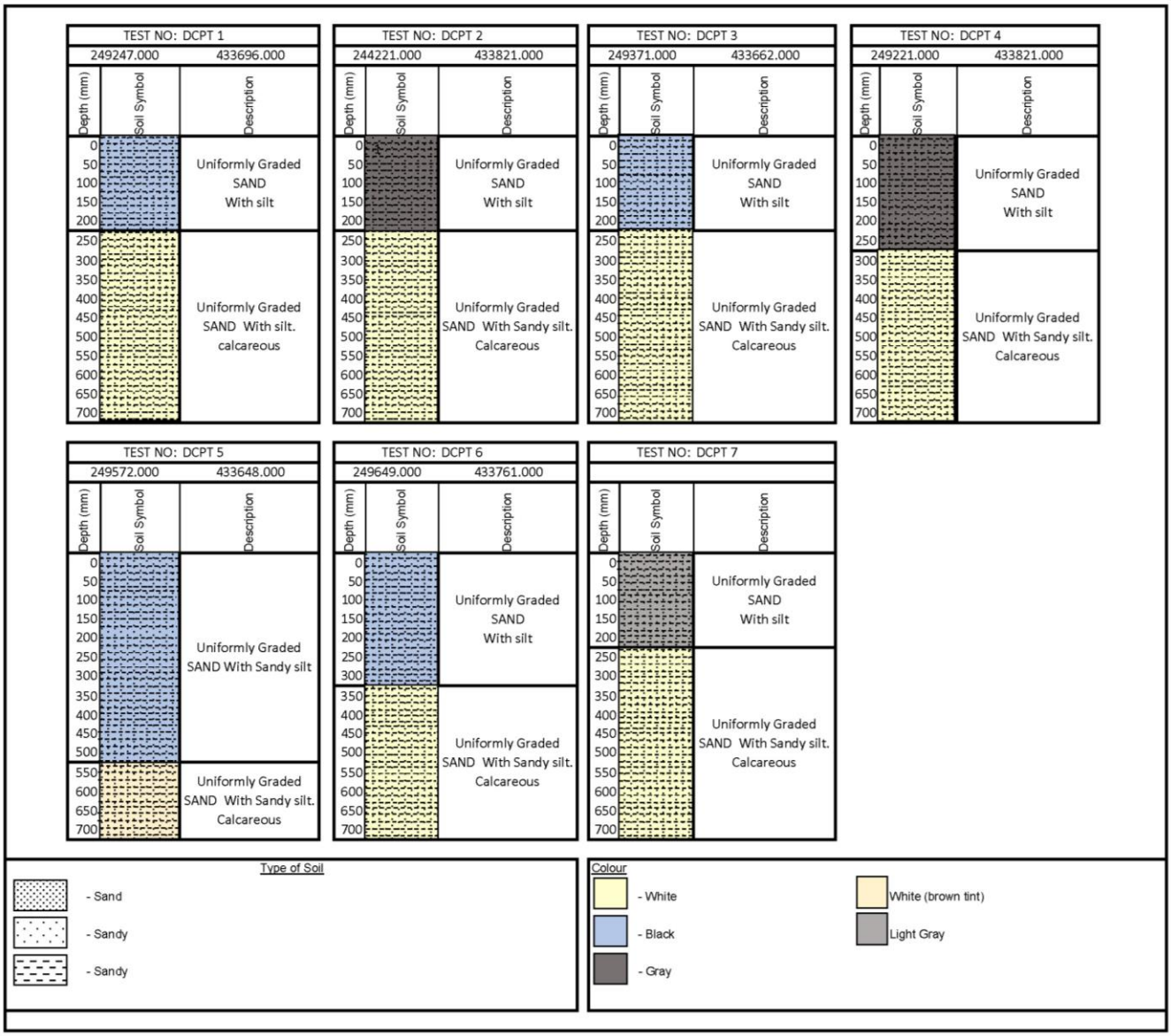


Figure 78: Soil Profile - AA. Himandhoo

6.8 Flood Assessment and Inundation Survey

6.8.1 Flood occurrence and flood impact

Flooding is mainly not an issue for the households in AA. Himandhoo but there are certain roads which have significant flooding issues. In AA. Himandhoo, 46% of the respondents reported that flooding occurs every time it rains heavily. As per the social survey, 11 households reported rain induced flood incidents in the year 2019 and 8 households reported flooding incidents in 2020. In the two incidents, 25 houses reported minor damages along with broken fences and trees. On the same note, 68% of the households reported that they experienced no damages and only minor inconveniences by recent flooding events.

Many respondents reported that harbour construction and soil erosion have induced a major impact on the flooding pattern of the island. In AA. Himandhoo, 53% of the household's report flooding as an acceptable problem (refer to flood severity component of Flood Maps in Annex XII).

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 78: Perceived causes of flooding – AA. Himandhoo

Perceived causes of flooding				
Roof run off	**Neighbours' roof**	**Off the road**	**General run off in the area**	**No flooding within the plot**
44%	16%	10%	10%	52%

From the social survey, 39% of households report that they drain rainwater overflow from storage and roofs to the well. Most responses state multiple ways for the discharge of rainwater overflow to the ground, roads, and open areas within the plot. Details of discharge of rainwater overflow are given in the table below.

Table 79: Discharge of rainwater overflow – AA. Himandhoo

Discharge of rainwater overflow			
Ground	**Roads**	**Open area within the plot**	**Drained to well**
39%	9%	22%	39%

6.8.2 Inundation area identification

Common flooding areas are the mosque, school road and police station roads which are all reported as significant flooding (refer to Annex XII: Flood Maps). Many households reported that it takes 30 minutes or less to inundate the area once heavy rain starts and an average of 1.44ft is estimated to be the flooding depth when there is heavy rainfall.

6.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 29% observe that the water drains during the rainfall itself, 20% observe that the water drains in less than 4 hours, 15% observe that the water drains in less than 4-24 hours and 36% observe that it takes more than 24 hours for water to drain.

Table 80: Draining period – AA. Himandhoo

Draining period			
only while raining	**drains less than 4hrs**	**takes 4-24 hrs**	**more than 24hrs**
29%	20%	15%	36%

According to the latest Multi-hazard Risk Atlas of Maldives published by Asian Development Bank, AA. Himandhoo has been categorized to medium level risk for rain induced flood. In AA. Himandhoo, 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.

6.9 Geophysical Survey

6.9.1 Surveyed locations

Locations where ER sounding measurements were taken at AA. Himandhoo island are shown in Figure 79 together with transect lines. There are 21 ER measurement locations and the number of transects in this island is 10.

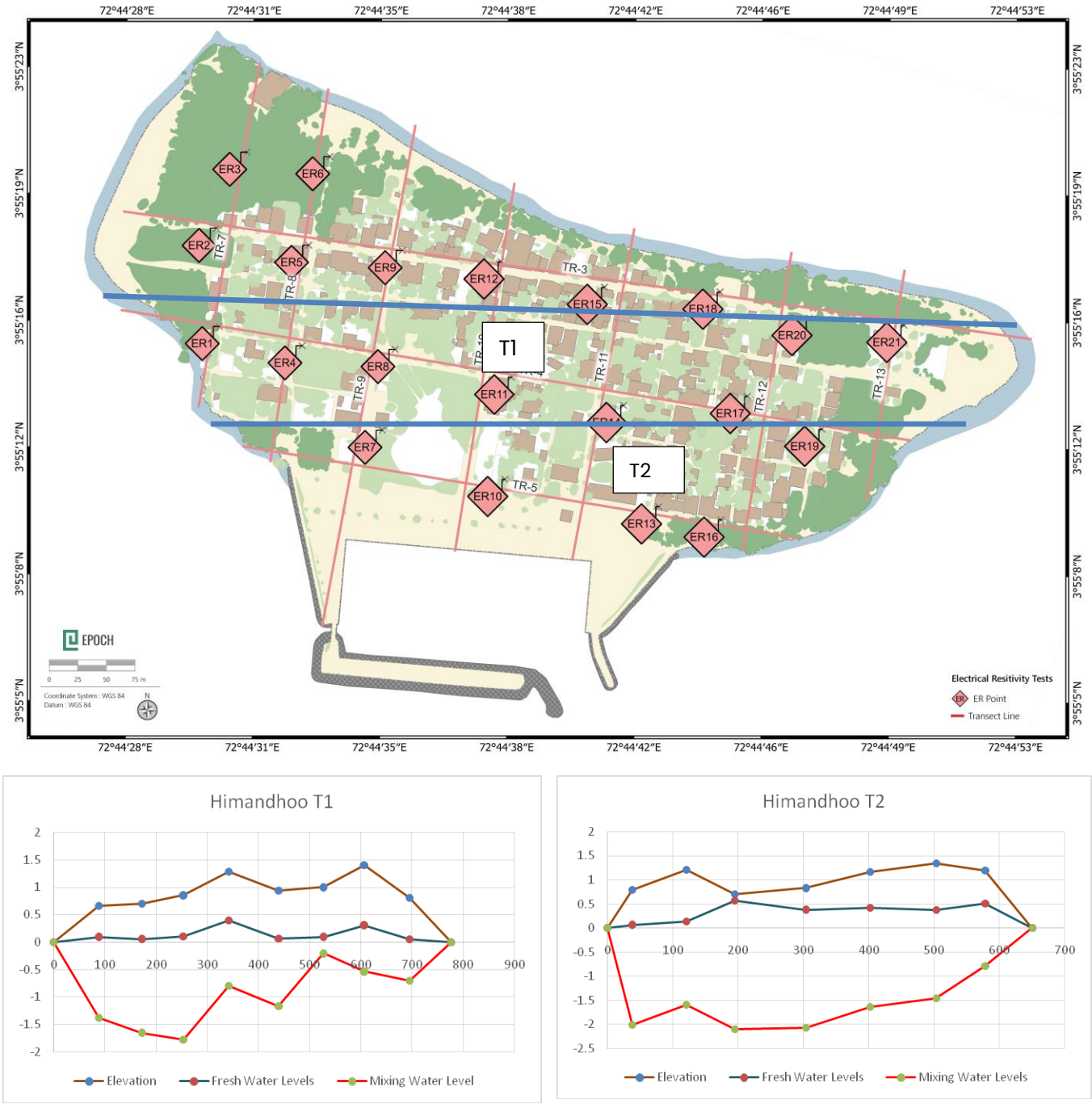


Figure 79: ER surveyed locations and transect lines – AA. Himandhoo Island

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 109 below shows the estimated levels at ER surveyed locations of AA. Himandhoo Island and freshwater lens thickness.

Table 81: Freshwater lens levels and thickness – AA. Himandhoo island

No	Level (m AMSL)			Freshwater lens thickness (m)
	Ground	Freshwater	Saline water	
1	0.79	0.06	-2.01	2.08
2	0.65	0.10	-1.39	1.48
3	0.81	0.06	-1.27	1.33
4	1.21	0.14	-1.59	1.73
5	0.70	0.05	-1.65	1.71
6	0.90	0.15	-1.94	2.09
7	1.01	0.26	-1.07	1.33
8	0.70	0.57	-2.10	2.67
9	0.85	0.10	-1.78	1.88
10	1.25	0.46	-0.47	0.93
11	0.83	0.38	-2.07	2.45
12	1.28	0.39	-0.80	1.19
13	1.29	0.41	-0.61	1.02
14	1.17	0.42	-1.64	2.06
15	0.93	0.06	-1.17	1.23
16	1.30	0.41	-0.50	0.92
17	1.34	0.37	-1.46	1.83
18	0.99	0.09	-0.21	0.30
19	1.20	0.51	-0.79	1.31
20	1.39	0.30	-0.54	0.84
21	0.80	0.05	-0.70	0.75

Average freshwater thickness of AA. Himandhoo island is 1.48m. Maximum recorded thickness of freshwater lens of the Island by ER survey is 2.67 m & minimum is 0.30 m

Data in Table 81 were used to plot freshwater lens cross sections along 10 transects. Of these sectional plots 2 were given in Figure 79 and they represent the transect plots along the longitudinal section of the island.

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 80.

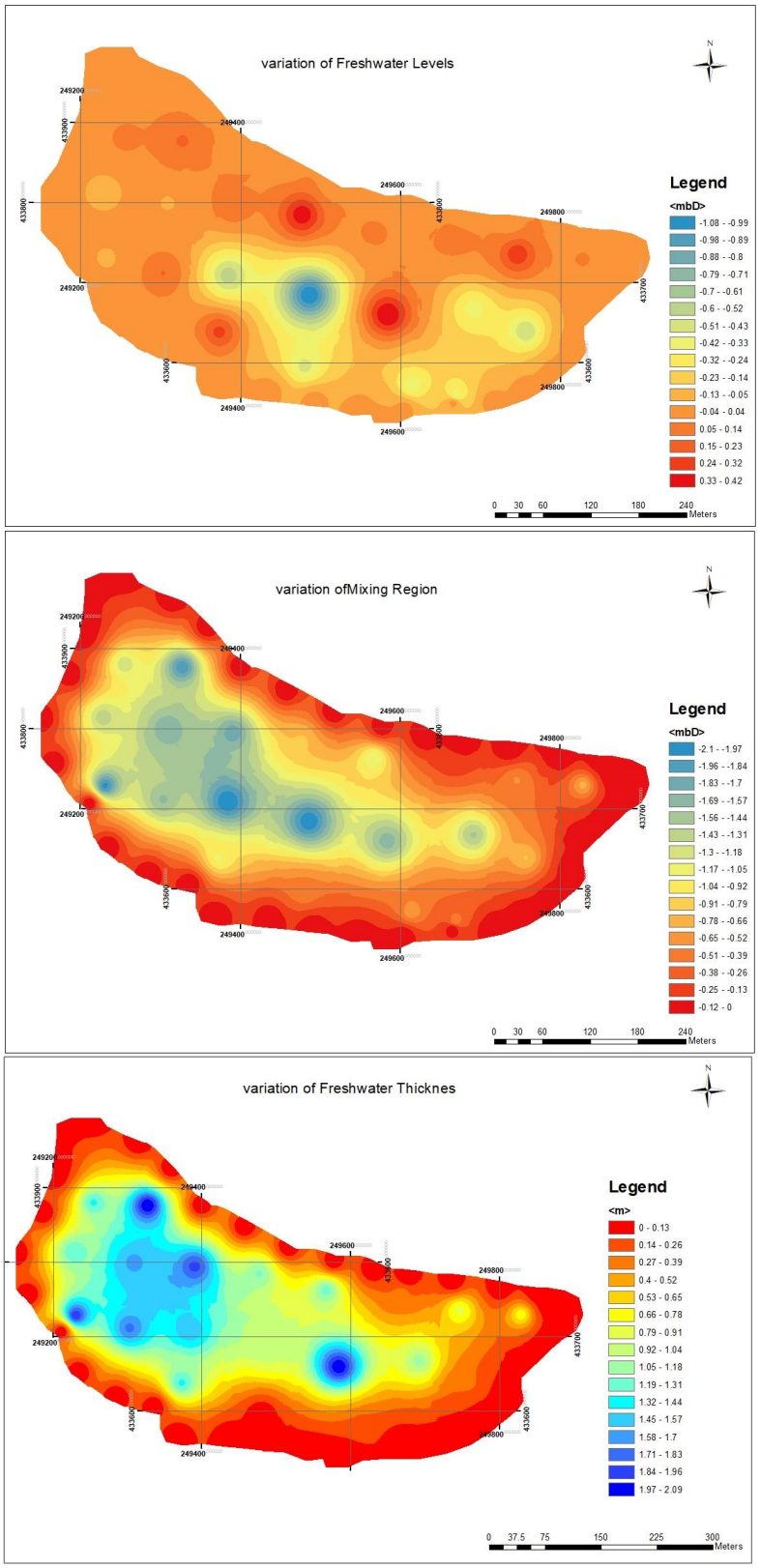


Figure 80: Spatial distribution of thickness of freshwater lens

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. Tools in ArcGIS software were used to perform this computation.

Stress level on freshwater aquifer of AA. Himandhoo 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 82.

Table 82: Freshwater lens volume and aquifer stress level – AA. Himandhoo island

Item	Value	Unit
Freshwater lens volume - ArcGIS	113,917	m^3
Groundwater abstraction	53,470	m^3/yr
Freshwater lens volume/ Groundwater abstraction	2.13	-
Aquifer stress level	Not Stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 4.78m. This deviates by 78.4% from the maximum measured value of 2.68m, which is more reliable as it results from a more comprehensive, site-specific methodology.

6.10 SWB Modelling

6.10.1 Land use categorization and area estimation

Table with land classification and their respective areas are shown below.

Table 83: Land Use Classification – AA. Himandhoo

	Area (m^2)	% of total area
Roof cover	34,327	17%
Vegetation (Thick)	59,766	29%
Vegetation (Thin)	39,538	19%
Bare Lands	74,129	36%
Total	207,759	100%

6.10.2 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 81 and Table 84). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 5019 m^3, 108,813 m^3 and 69,093 m^3 respectively over a 20 year period.
- There is a good relationship between annual rainfall and annual recharge, but it is not linear instead an inverse exponential.
- Annual average rainfall is around 1983 mm
- Variation among the monthly average recharge value is very high. It is lowest in month of March and highest in November.

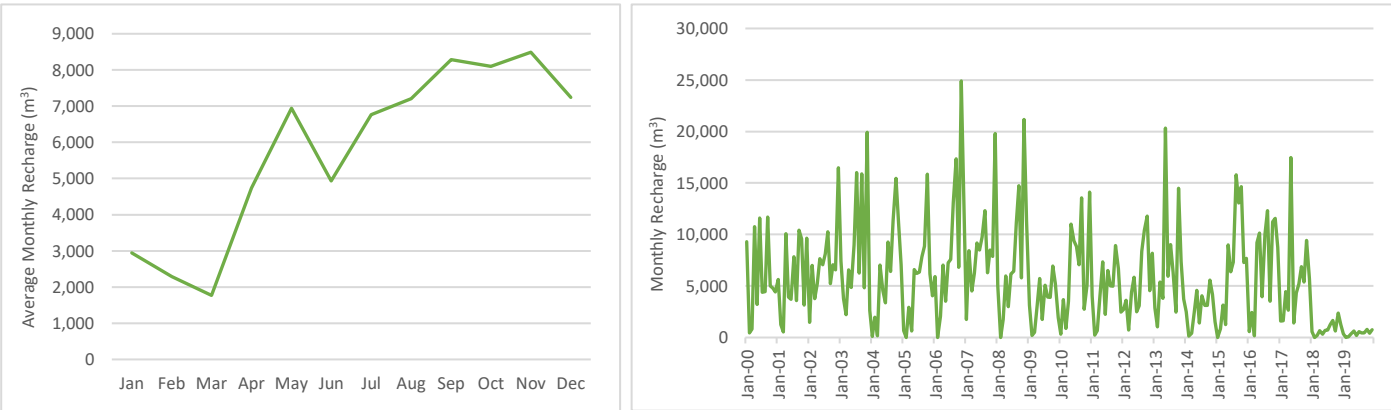


Figure 81: Monthly and annual recharge distribution in AA. Himandhoo

Table 84: Monthly recharge estimated by SWB model – AA. Himandhoo Island

Year	Monthly Recharge (m^3)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2000	9,304	437	810	10,772	3,224	11,582	4,379	4,460	11,706	5,001	4,804	4,419
2001	5,619	1,260	538	10,062	3,937	3,704	7,842	3,588	10,411	9,568	3,155	9,648
2002	1,469	7,012	3,773	5,217	7,646	7,072	8,119	10,262	5,233	7,068	6,550	16,487
2003	7,389	3,757	2,207	6,578	4,844	8,998	15,994	6,261	15,881	4,812	19,923	2,625
2004	108	1,983	181	7,024	4,539	3,355	9,279	6,405	11,374	15,444	11,125	7,072
2005	670	-	2,930	630	6,602	6,233	6,341	7,826	8,878	15,841	6,188	4,050
2006	5,924	-	2,067	7,032	3,507	7,248	7,577	13,096	17,350	6,815	24,904	13,293
2007	1,763	8,414	4,527	6,261	9,175	8,486	9,743	12,315	6,280	8,481	7,860	19,785
2008	5,035	-	1,757	5,977	2,981	6,161	6,441	11,132	14,748	5,793	21,168	11,299
2009	3,133	186	517	3,049	5,717	1,760	5,070	3,911	3,883	6,953	5,215	1,921
2010	318	3,687	890	3,508	11,000	9,380	8,823	7,056	13,543	2,753	5,093	14,115
2011	4,016	238	663	3,909	7,329	2,256	6,499	5,013	4,978	8,915	6,686	2,463
2012	2,701	3,607	711	4,382	5,864	2,491	3,071	8,374	10,373	11,799	4,549	8,188
2013	2,868	1,029	5,371	3,794	20,328	5,943	9,010	6,305	2,463	14,476	7,365	3,750
2014	2,506	149	414	2,439	4,574	1,408	4,056	3,128	3,106	5,563	4,172	1,537
2015	-	838	3,158	1,255	8,990	6,364	7,306	15,792	13,062	14,632	7,278	7,675
2016	560	2,423	171	9,213	10,146	3,957	10,027	12,327	3,532	11,211	11,553	8,736
2017	1,597	1,617	4,445	2,654	17,480	1,422	4,338	5,200	6,865	5,379	9,423	5,701
2018	563	-	196	668	333	689	720	1,244	1,648	647	2,366	1,263
2019	351	21	58	342	641	197	569	439	436	780	423	761

6.10.3 Water Balance

As per estimation, annual recharge estimated by the SWB model is 120,336 m^3 and it is 30.6% of annual average rainfall (refer Figure 82).

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	393,897	5,724.3	181,193	120,336	86,657	53,470
%	100%	1.45%	46.0%	30.6%	22%	13.6%

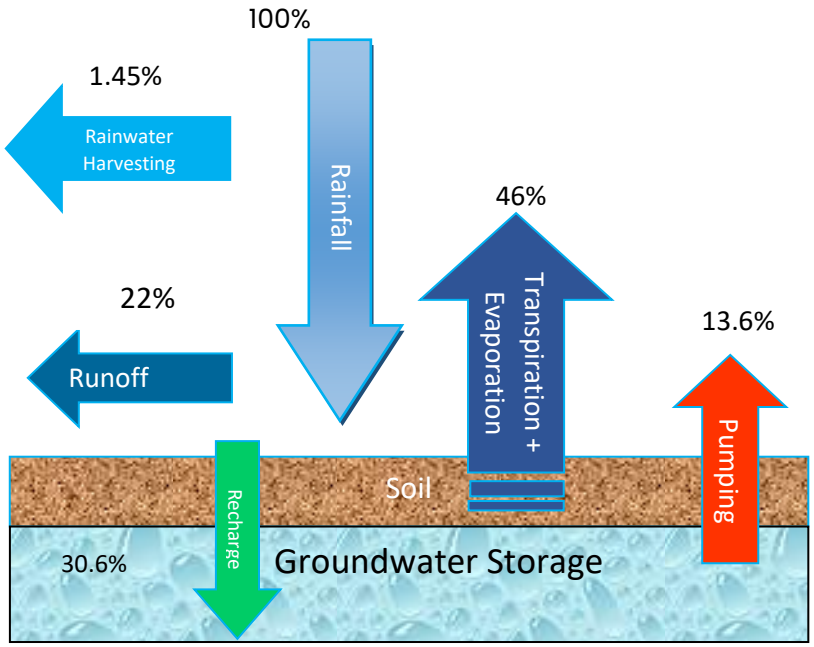


Figure 82: Annual water balance – AA. Himandhoo Island

6.10.4 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 (4456 m^3/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 85: Deficit percentage – AA. Himandhoo

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	111	46.3

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 AA. Himandhoo island was 46.3% dependent on 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 (53,470 m^3/yr) with safe abstraction volume (66,864 m^3/yr) shows that present withdrawal is 20% less than the safe yield. Therefore, it could be inferred that present groundwater abstraction is within the allowable limit and it has insignificant influence in up-coning freshwater-saline water interface in the existing condition.

6.11 SUTRA Modelling

6.11.1 Model representation and mesh production

SUTRA modelling requires mode domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island. The other boundary defined in the model was island outline which can be referred as shoreline most of the cases except at harbour area and the inner part of the island was subdivided to several polygons representing different land use and it was accomplished by importing GIS shape files of island land use and then drawing polygon 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.

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 83 shows the pressure boundary defined for AA. Himandhoo island.

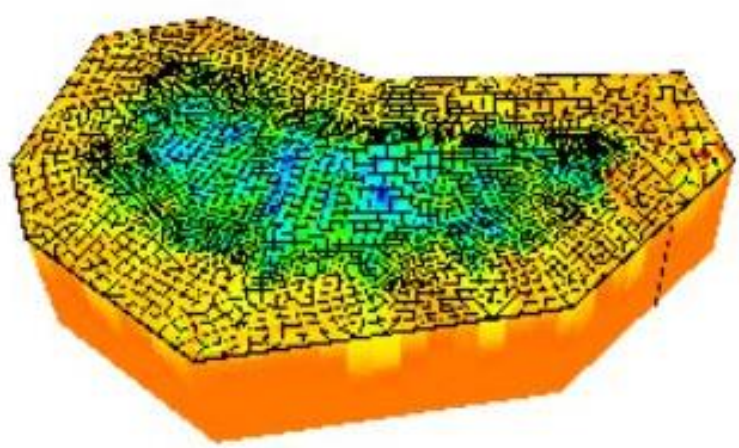


Figure 83: Pressure boundary at SUTRA model – AA. Himandhoo island

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.

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 change place to place a simplified approach was adopted by defining a polygon around the residential area.

6.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20 yr period is shown in Figure 84. The section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0357 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top.

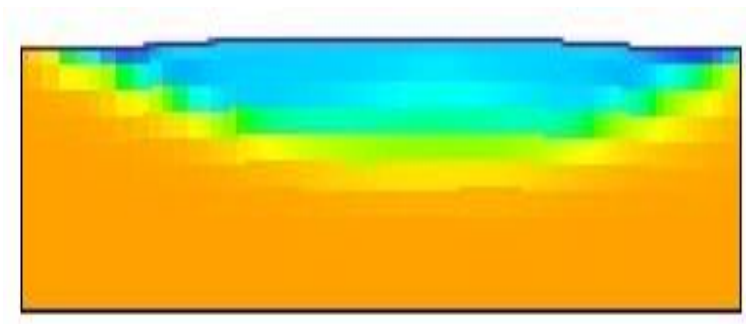


Figure 84: Saltwater distribution – AA. Himandhoo island

6.12 Summary of Baseline Assessment

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

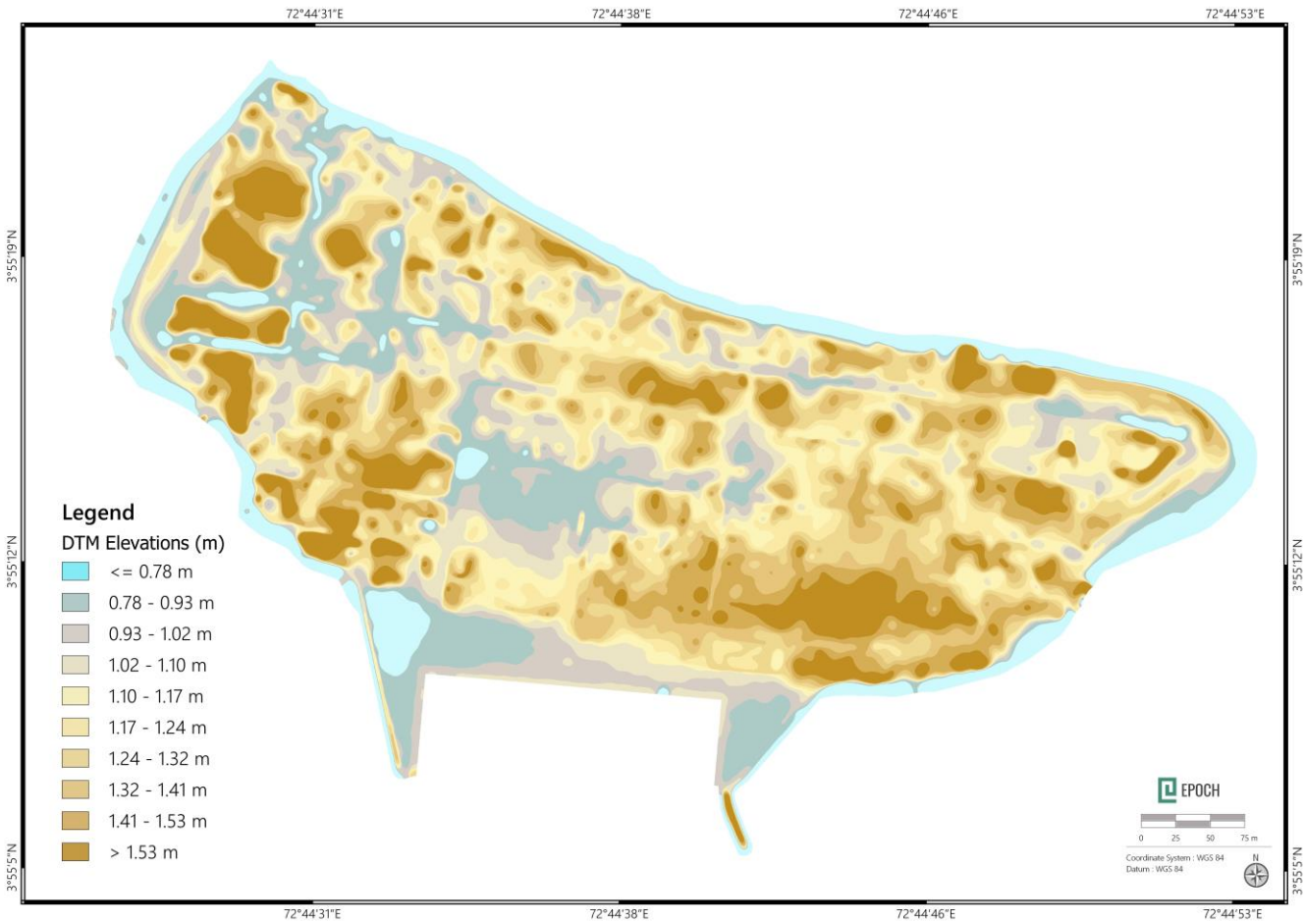
- General overview, demography, and climatology

Item	Details
Atoll	Ari Atholhu Uthuruburi Atoll
Length	0.79 km
Width	0.29 km
Area	20.7 ha
Population	848
Population/area	40.97 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use

Land use map

Topographical map



Average elevation = 1.130 m above MSL

Shoreline length = 2880 m

	% of total area
Roof cover	17%
Vegetation (Thick)	29%
Vegetation (Thin)	19%
Bare Lands	36%
Farmlands	0%
Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Industrial	Institutional	Total
Rate (m^3/d)	138	3.22	-	5.04	146

- Water quality parameters – Physiochemical
  Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	3696 ± 4765	1500
Turbidity (FNU)	2.30 ± 5.29	5
DO (mg/L)	3.19 ± 1.23	
pH	7.25 ± 0.23	6.5-8.5
Temp (°C)	29.95 ± 1.14	
Sal (ppt)	1.83 ± 2.64	
NH_3 (mg/L)	7.98 ± 11.97	1.5 (Odour Threshhold)
NO_3^- (mg/L)	28.65 ± 29.00	50
PO_4^{3-} (mg/L)	0.34 ± 0.30	

- Water quality parameters – Microbiological
  Number of samples tested = 15

Parameter	Value range	Average value	Remarks *(on permit limit)*
Total Coliform (MPN/100ml)	12 - >2420	1,179.93	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not detected - 41	8.47	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1		m^2/day
Storativity	1		-
Permeability	7	5.46– 18 Average – 12.5	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m^2)	Inundation depth (m)
78	4350	0.438

- Electric Resistivity survey
  - Measurement taken at 21 locations
  - Average freshwater thickness in the island is 1.48 m.
  - Freshwater lens volume and aquifer stress level

Item	Value	Unit
Freshwater lens volume - ArcGIS	113,917	m^3
Groundwater abstraction	53,470	m^3/yr
Freshwater lens volume/ Groundwater abstraction	2.13	-
Aquifer stress level	Not Stressed	-

- SWB modelling
  - Annual recharge is 120,336 m^3 and it is 30.6% of annual rainfall (1983mm)
  - Annual water balance

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	393,897	5,724.3	181,193	120,336	86,657	53,470
%	100%	1.45%	46.0%	30.6%	22%	13.6%

  - Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 46.3% in an average year, and it is compensated by ground water storage.
  - Ground water withdrawal (53,470 m^3/yr) is 20% less than the safe abstraction (66,864 m^3/yr).

- SUTRA modelling
  - Average monthly recharge assigned to SUTRA model
  - Freshwater lens prediction (allowable concentration for potable use is 0.001)

7 ADh. Kunburudhoo

7.1 Island Overview and Location

The Island of ADh. Kunburudhoo, belonging to Ari Atholhu Dhekunuburi Atoll, is in the central region of Maldives at 03°46′33″N and 72°55′28″E.

Table 86: Island Geographical Data

Island	ADh. Kunburudhoo
Atoll	Ari Atholhu Dhekunuburi Atoll
Location	03°46′33″N and 72°55′28″E

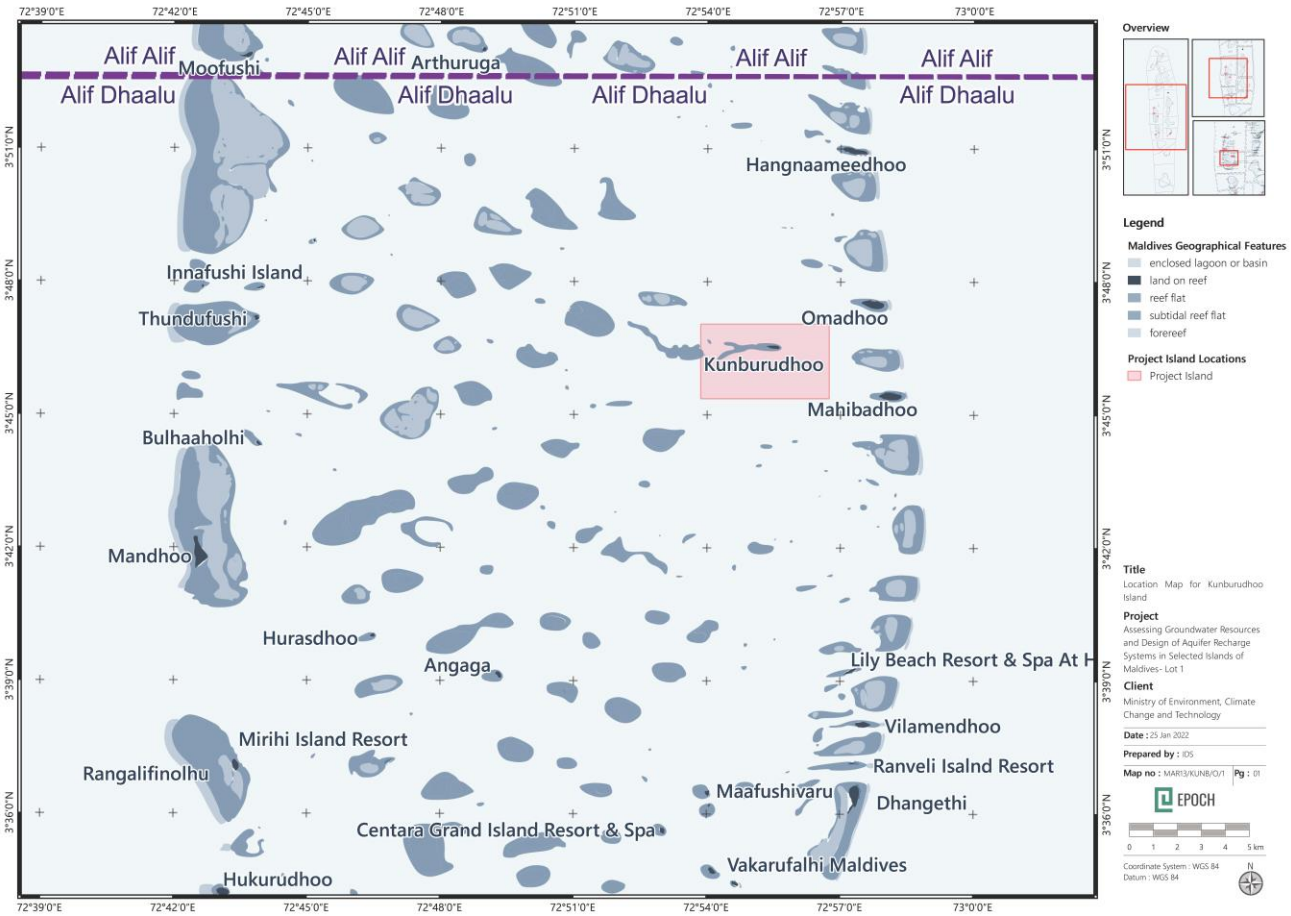


Figure 85: Location Map – ADh. Kunburudhoo

7.1.1 Island features

ADh. Kunburudhoo is known as one of the Northern most inhabited islands in the atoll. The island has a vast white beach on the west side of the island. The island extends up to 0.88 km in length from toe to toe and a width of 0.16 km from toe to toe.

ADh. Kunburudhoo has a harbour at its Southern side of the island. About one-third of the island's surface is thick vegetation. Thin vegetation is mostly located at the outer edges of the southern and east parts of 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. About two-third of the island is populated, which is mostly in the centre and eastern side of the island. The Land Use Characterization map is attached to Annex II.

Table 87: Area Distribution in ADh. Kunburudhoo

Area	5.69 ha	
Length	0.88 km	
Width	0.16 km	
	Area (m²)	**% of total area**
Roof cover	14,024	25%
Vegetation (Thick)	6,801	12%
Vegetation (Thin)	13,974	25%
Bare Lands	22,043	39%
Farmlands	-	0%
Wetlands	-	0%
Total	56,891	100%

Figure 86: Land Use Characterization - Kunburudhoo

7.2 Topographical Features

Permanent Survey Marks PSM 0283, PSM 0284 and PSM 0285 were used as benchmarks for ADh. Kunburudhoo topographical survey and drone survey. These details are currently not available via the Maldives Land Survey Authority Website https://www.mlsa.gov.mv/psm and MLSA noted that corrected reports have not been submitted for issued benchmark plates. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 1297 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.27 cm per pixel. 16 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 88: GCP Statistics for ADh. Kunburudhoo

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	0.000447	-0.000531	-0.002735
Sigma [m]	0.0150	0.0218	0.0542
RMS Error [m]	0.0150	0.0218	0.0542

ADh. Kunburudhoo is a relatively low-lying island, with surface elevations at or below 1 m above mean sea level throughout the island. The most interesting feature of the island is the highly dynamic stretch of beach (thundi) on its eastern side, whose profile varies according to the monsoons. This thundi is most prominent during the Northeast monsoon, and almost disappears during the Southwest monsoon, leading to expansion of beaches on the northern shoreline. Roads throughout the island are slightly lower than the average island elevation, with most elevations falling in between 0.6 m to 0.9 m. Also of note is the deforestation carried out around the late 2000s on the eastern shoreline to make way for shore protection structures, namely a stepped revetment along this shoreline. The stepped revetment has been dismantled and fallen apart considerably along its length as of writing this report, indicating that the design was not adequate to cater for the wave conditions experienced at this face.

Roof elevations generally do not exceed 5-7 m and very few houses have multistorey buildings in ADh. Kunburudhoo. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Vegetation is sparse on ADh. Kunburudhoo, limited to a vegetation line along the periphery of the island. Vegetation with heights greater than 10 m is limited, with a considerable amount falling under this height.

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 ADh. Kunburudhoo. The DTM slightly overestimates the elevations with a mean of 4.90 cm.

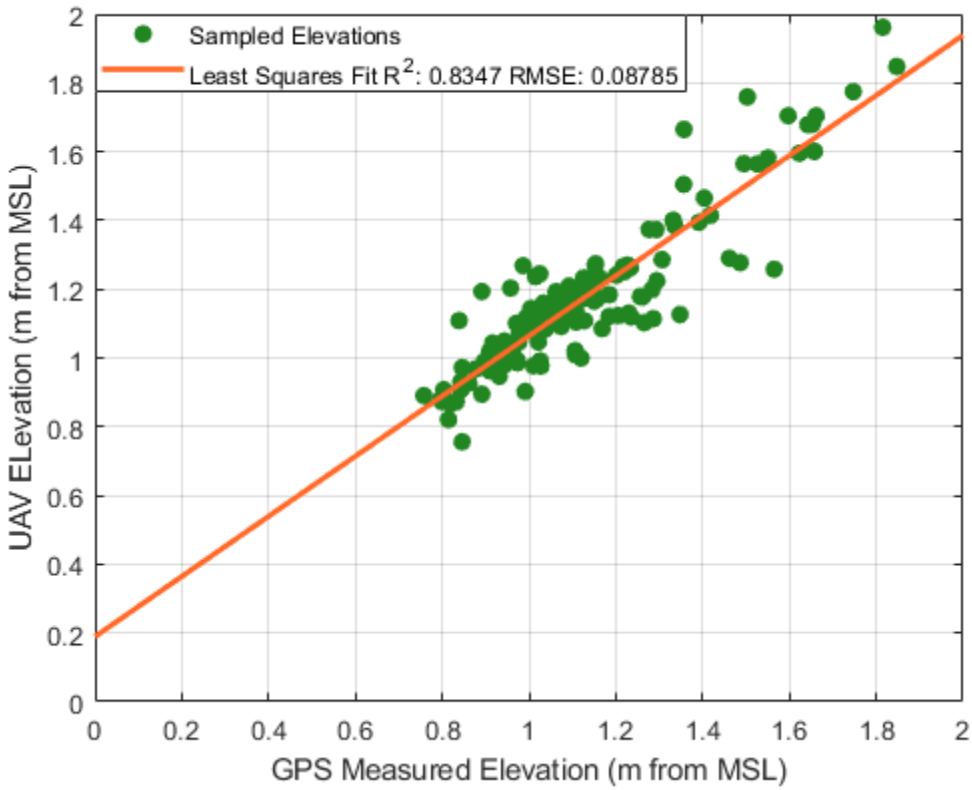


Figure 87: Linear Regression Plot for ADh. Kunburudhoo Sample UAV elevations

Table 89: Error Statistics for ADh. Kunburudhoo DTM

Parameter	*Value (cm)*
Mean	4.90
Standard Error	0.74
Median	6.12
Mode	#N/A
Standard Deviation	9.20
Sample Variance	84.65
Kurtosis	2.43
Skewness	-0.53
Range	61.44
Minimum	-30.67
Maximum	30.77
Sum	760.06
Count	155.00

7.2.1 Level changes

ADh. Kunburudhoo has an average elevation of 1.058 m with a standard deviation of 0.476. Digital Terrain Model elevations range from -0.6 to 1.7 m from MSL. The distribution of elevations has a skewed distribution with 1.1 m being the highest frequency for elevations.

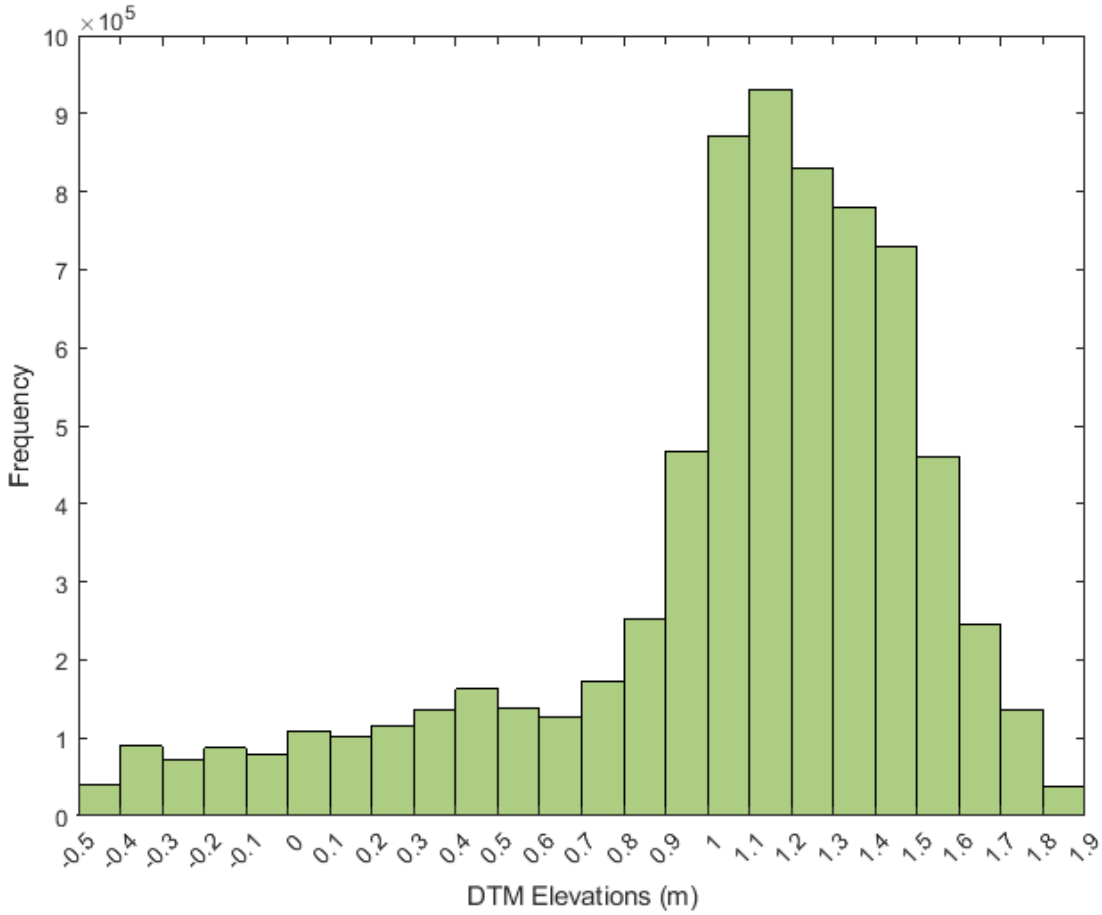


Figure 88: Raster Histogram created for ADh. Kunburudhoo DTM

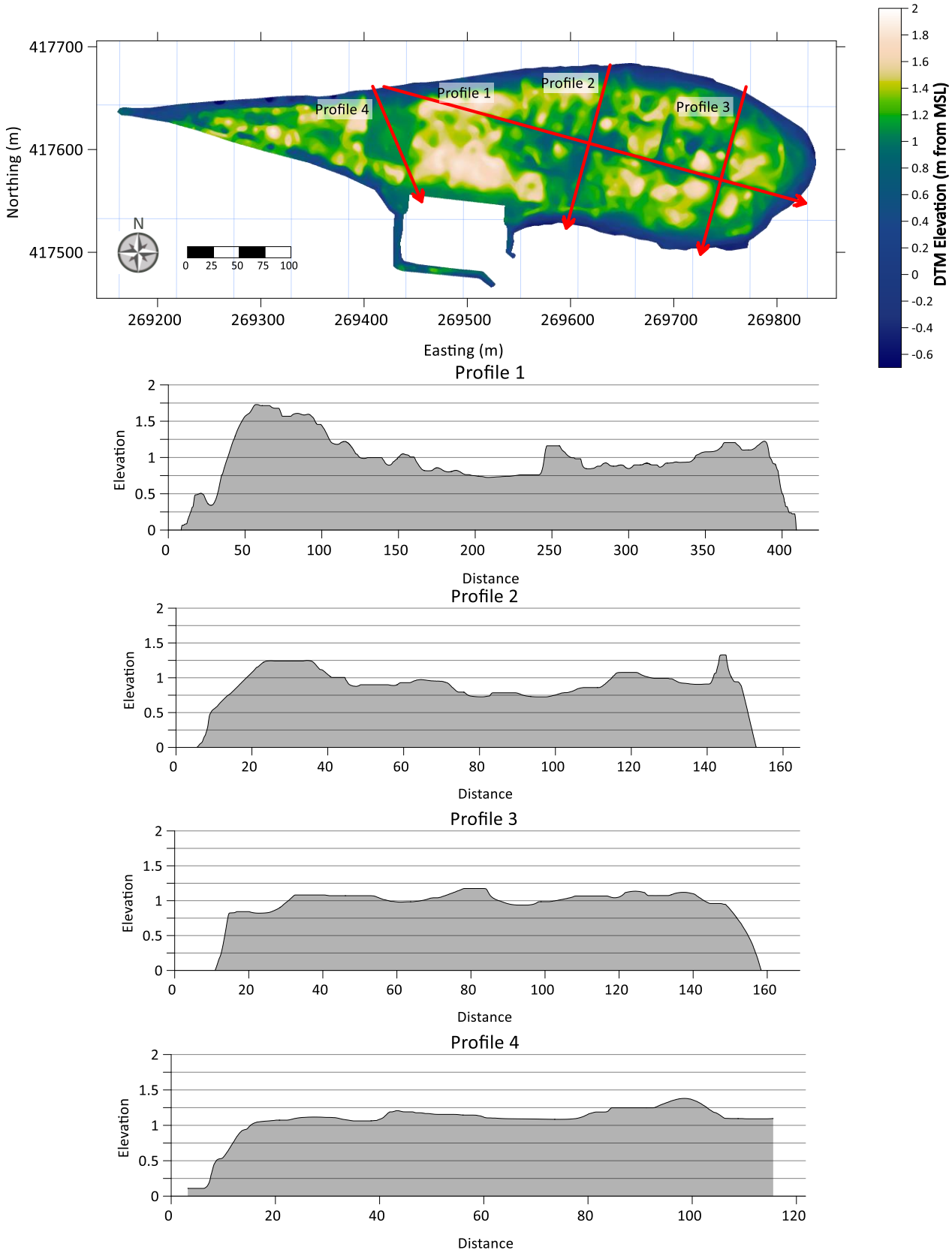


Figure 89: Digital Terrain Model Elevations and Profiles for ADh. Kunburudhoo Island

Profile 1, which goes from west to east, starts with a peak of 1.75 m which corresponds to the dynamic beach where sediment is deposited during the Southwestern monsoon. The high elevation here is likely to be linked to this process and it would be expected to decrease in height during the Northeastern monsoon when the sediment is stripped away. Following the peak, the elevation starts to decline and forms a depression in the middle of the profile of elevation 0.75 m. The profile ends on a slight ridge of elevation 1.25 m, which corresponds to the eastern shoreline.

Profile 2, which spans north to south, starts with a ridge of elevation 1.25 m, which would correspond to the northern shoreline. Similar to the ridge in Profile 1, this ridge is likely the result of the longshore sediment transport during the Southwestern monsoon, piling up sediments to form this ridge. The profile then starts to decline to a depression, ending off with a peak elevation of about 1.3 m, which would be due to the quarry rocks dumped on the southern shoreline near the harbor.

Profile 3, which spans north to south as well, remains at an almost constant elevation throughout of roughly 1 m, with no notable features present. Similarly, profile 4, which spans northwest to southeast, has a very constant elevation throughout. It starts with an incline, which shows the natural beach slope, after which the profile flattens out at around 1.2 m elevation for the remainder of the profile. The sharp fall at the end is due to the quay wall in the harbor, which is where this profile terminates.

7.2.2 Shoreline

ADh. Kunburudhoo has a shoreline length of 1428 m. The coastal protection features around the island are as follows.

- Breakwater: Two rubble mound breakwaters are found on the south side of the island. Southwesterly swells approaching from the windward side is absorbed and dissipated by these breakwaters to offer protection to berthed vessels within the harbor. The breakwaters are connected directly to the island with direct access. Point of note is the poor condition of the breakwater as of writing this report, where sections of the main breakwater have collapsed into the water, along with the non-standard slopes on the leeward side of the breakwater. Excluding the collapsed sections, crest height of both breakwaters ranges between +1.1 to +1.2 m above mean sea level. The breakwater is highlighted in orange.
- Revetment: The island has two revetments, one west of the harbor and the other on the eastern side of the harbor. The revetment serves as shore protection and prevents erosion at these locations by dissipating wave energy from southwesterly swell waves approaching from the windward side. Crest height of both revetments are around +0.7 m and +0.9 m above mean sea level respectively. The revetments are highlighted in green.
- Quay wall: These structures are found within the harbor and are highlighted in yellow. Crest height of quay walls is between +0.9 m and +1 m above mean sea level.
- Stepped revetment: The stepped revetment is found on the eastern side of the island, protecting the shoreline. This revetment was constructed around the late 2000s to address the issue of severe erosion experienced on this shoreline during the 2004 Indian Ocean tsunami. Given the state of the shoreline today, the revetment can be marked as successful. However, the revetment has started to deteriorate, with step blocks getting dislodged and causing nearby sections to start falling apart as well. This will only get worse as time passes, so action needs to be taken to stop the revetment from falling apart as it has been integral to the protection of this shoreline. The stepped revetment is highlighted in purple.

The shoreline around the island appears to be in good condition, with no severe erosion observed at any location. The most interesting coastal mechanism on the island is the thundi, whose profile is reactive to seasonal patterns. Due to the unique way waves interact with this island, where waves converge at the western end of the island, sediments accumulate in a way that elongates the western end of the island to form the thundi, which has been the main selling point for tourism on the island.

Figure 90: Orthomosaic of ADh. Kunburudhoo

7.2.3 Reef

ADh. Kunburudhoo is the only island on its reef, present on the eastern edge. The island is located near the western periphery of the Alif Dhaalu Atoll, and measures about 2.8 km on its longest section. Buffer zones on the eastern edges of the island are about 50 m, with lengths getting progressively longer moving towards the western edges. Point of interest is how the thundi formation follows a similar shape to the underlying reef structure.

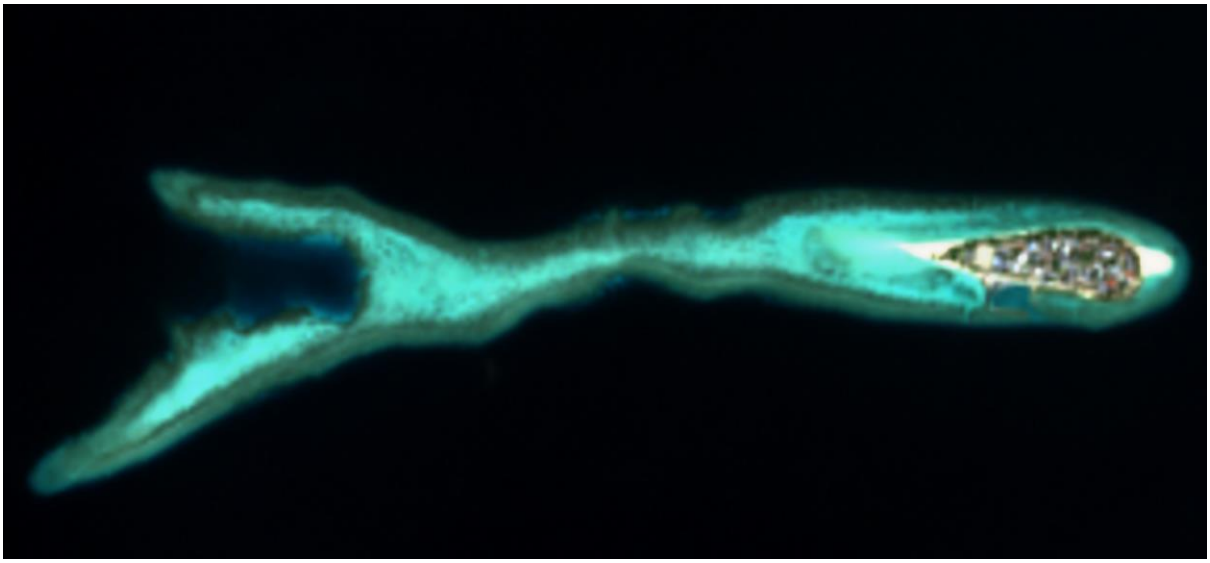


Figure 91: Sentinel 2 imagery of ADh. Kunburudhoo reef taken in February 2022

7.3 Socio Economic Status

7.3.1 Demography

The island has a registered population of 437 as per the 2014 census, with a total of 209 males and 228 females. The island population density is 110 people per hectare. The population figures have drastically increased over the past years where the total registered local population climbed up to 624 as per the island council (2021). The total number of households is 58. The following table and graph illustrate the demographic breakdown of ADh. Kunburudhoo.

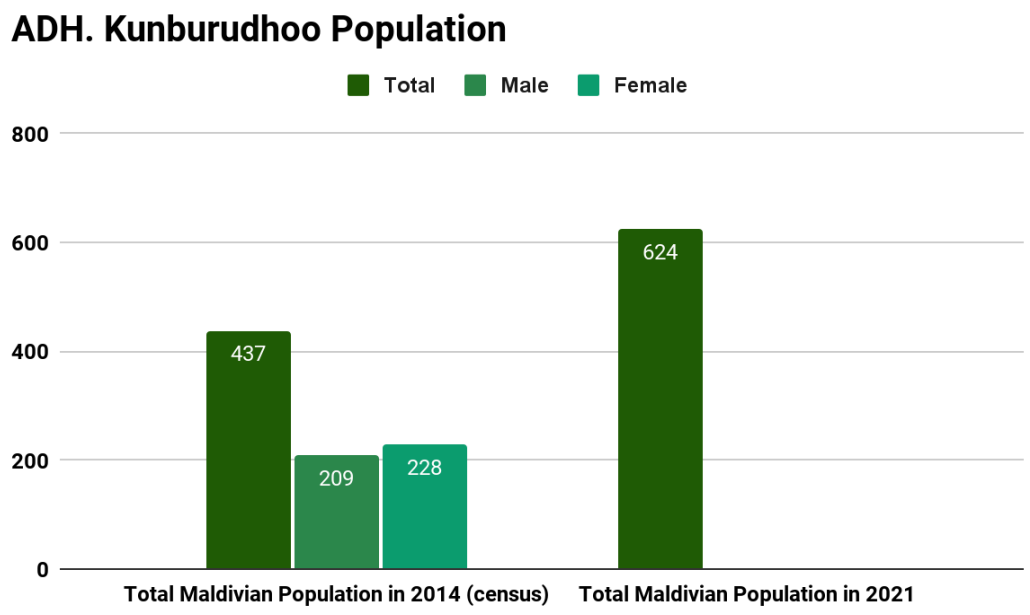


Figure 92: ADh. Kunburudhoo Population

Table 90: ADh. Kunburudhoo Population (Census, 2014)

		Resident Population according to Census 2014								
		Total			Maldivians			Foreigners		
Atoll	Locality	Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
ADh	Kunburudhoo	462	22	233	437	209	228	25	20	5

7.3.2 Socio-Economic Activities

ADh. Kunburudhoo is an inhabited island in Alif Dhaalu Atoll's administrative unit and physically part of Ari Atholhu Dhekunuburi Atoll in the Maldives'. The people in ADh. Kunburudhoo work mostly in government jobs and the fishing industry. With the development of guesthouse and homestay tourism, it is expected that more people will be working in the tourism industry. The island is also famously known as pioneers in designing sailing boat roofs that are used commonly in tourist resorts.

7.3.3 Facilities available

7.3.3.1 Health Care

ADh. Kunburudhoo Health Center provides basic health care facilities and is currently graded as grade 1 health care facility. There are 10 staff working in the Health Center ensuring essential health care in the island. ADh. Kunburudhoo Health Center is still in need of essential services such as laboratory services.

7.3.3.2 Education

ADh. Kunburudhoo has one school, and 38 staff are working in the school currently. A total of 138 students are enrolled in pre-primary, primary and lower secondary schools.

7.3.3.3 Utilities

Currently, a water and sewerage project are ongoing in the island and is expected to finish in June 2022.

7.3.3.4 Transportation

ADh. Kunburudhoo has a 3000 ft x 200 ft small harbor and currently speed boats travel 3-4 times a week from Male' to the island.

7.3.4 Water resources, water usage and water consumption survey

In ADh. Kunburudhoo, there are a total of 58 inhabited households. 57 out of 58 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 91: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	**57/58 households = 98%**
Percentage of well fitted with pumps	96%
Ground water	**Usage in percentage**
Source of drinking	0%
Source of cooking	0%

7.3.4.1 Existing water and sanitation

The main form of sanitation facility is via the use of local outfall pipes and septic tanks. Based on the survey, 65 percent of the survey households have connected their sanitation to a local outfall pipe. While the remaining 35 percent uses septic tanks as sanitation facilities. In ADh. Kunburudhoo 89 percent reported to have less than 49ft distance between septic tanks and groundwater well. While the remaining 7% reported having more than 49ft distance and 4% reported that they do not know an exact distance between them. 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.

7.3.4.2 Water usage and resources

Based on the survey conducted in ADh. Kunburudhoo, 54 houses have HDPE rainwater tanks for rainwater storage. 98% of the households use rainwater for cooking and 91% use rainwater for drinking. Rainwater collected from rooftops is stored in water tanks, whether communal or home tanks. Many homes utilize rainwater from neighboring houses or bottled water when rainwater is scarce during the dry season. While most houses reported groundwater is mainly used for gardening, household cleaning, toilet flushing and showering with 96% of the houses fitted with water pumps. The following sections outline further details about various water usage and consumption scenarios in the island.

7.3.4.3 Domestic water usage

Based on household water usage surveys in ADh. Kunburudhoo, **97,344** liters of groundwater is used daily in the households. A total of **151** liters of groundwater are consumed per capita per day.

Table 92: Domestic groundwater use data for ADh. Kunburudhoo

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
84.6	25.4	12.1	11	0.89	18	3.99	**156**

*All units are in Liters per capita per day

7.3.4.4 Commercial water usage

Based on the survey conducted in ADh. Kunburudhoo, there is currently one operational café'/restaurant and one guesthouse on this island. A total of **1033** Liters of groundwater are used by commercial entities and their detailed breakdown is given in the table below.

Table 93: Café'/ Restaurant groundwater use data for ADh. Kunburudhoo

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Udhares Cafe	101	0	20	7.50	**129**

*All units are in Liters per day

Table 94: Guesthouse groundwater use data for ADh. Kunburudhoo

Guesthouse	Average Occupancy	Total (L/day)
Suvasa Inn	30%	**904**

7.3.4.5 Industrial water usage

In ADh. Kunburudhoo, out of the 4 fish processing units surveyed, only one fish processing unit uses groundwater for cutting and cleaning, while rainwater is used for rest of the activities such as cooking, smoking and rihaakuru production.

Table 95: Institutional groundwater use data for ADh. Kunburudhoo

Number of fish processing unit	Fish processing activities	Number of days in a week	Total water usage for fish processing unit daily (Liters)
1	Cutting and Cleaning, Cooking and Smoking, Rihaakuru Production	5	20
Total Industrial water usage per day			**20**

7.3.4.6 Institutional water usage

Based on the survey conducted in ADh. Kunburudhoo, there are currently four institutions that has groundwater well facilities and use groundwater on this island. A total of 1518 Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 96: Institutional groundwater use data for ADh. Kunburudhoo

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Kunburudhoo School	837	-	40	-	877
Health Centre	78.3	320	14	-	412
Council	125	10	0	-	135
STELCO	78.3	10	5	-	93.3
					1518

*All units are in Liters per day

7.3.5 Present & Future water demand

In ADh. Kunburudhoo, the present water demand is at **99,909** liters per day inclusive of domestic, commercial, institutional, and industrial water demand. 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.

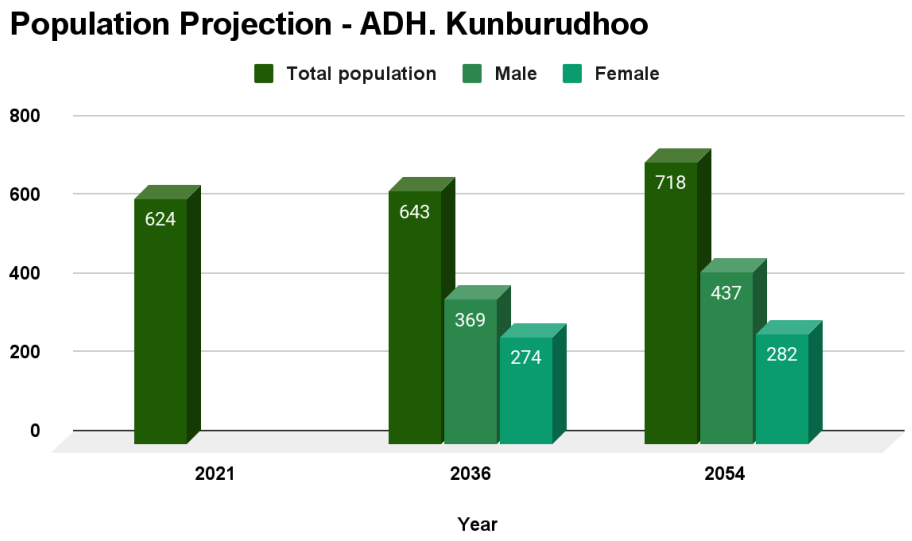


Figure 93: Population Projection - ADh. Kunburudhoo

Table 97: Present groundwater demand - ADh. Kunburudhoo

Year	Total Population	Domestic water demand	Commercial water demand	Institutional water demand	Industrial water demand	Groundwater usage
2021	624	97,344	1033	14.3	14.3	**99,909**

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 156 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 156 Liters, the groundwater demand is expected to be 106 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 643 is expected to be 68,158 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 156 Liters, the groundwater demand is expected to be 81 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 718 is expected to be 58,158 Liters per day.

Table 98: Future domestic water demand - ADh. Kunburudhoo

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	643	156	50	106	68,158
2054	718	156	75	81	58,158

7.3.6 Water related issues

From 57 households surveyed in ADh. Kunburudhoo, most houses reported salty taste and smell in their respective wells. As per social survey, 91 percent reported having salty taste and 47 percent reported having a smell in their groundwater. Despite having reported several groundwater related contamination, only 23% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gasses such as hydrogen sulphide which cause unpleasant smells. It was also noted from the social survey that the residents of the island also have a general distrust of desalinated plant water sent from the resorts and MWSC in Male'. Hence, the residents are heavily relying on groundwater and rainwater for domestic purposes.

Table 99: Signs of contamination reported by households

Types of contamination	Data in % out of 57 households surveyed
Smell	47%
Milky	7%
Foul taste	9%
Salty	91%
None	0%

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

Table 100: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 57 households surveyed
Changes with tidal variations	19%
Groundwater quality is better in rainy months	89%
Long periods without rain causes bad smell	33%
Long periods without rain causes bad taste	14%
Rain makes it worse	0%
No change	5%

7.4 Groundwater Quality

7.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 101 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 101: Groundwater physiochemical parameters statistical summary - ADh. Kunburudhoo

	EC (µS/cm)	Turbidity (FNU)	DO (mg/L)	pH	Temp (°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 threshhold <35 Taste threshhold Source[1]	<50 Source[1]	
Mean	20,910	1.88	3.91	7.27	30.60	11.30	56.47	100.4	0.32
Median	21,435	0.31	3.62	7.19	30.25	11.07	44.92	103.5	0.29
SD	9674	4.13	1.42	0.29	1.61	5.64	44.22	41.4	0.15
Min	3427	0.04	1.51	6.96	28.30	1.59	2.71	19.9	0.12
Max	39,103	19.66	7.65	8.60	38.30	22.20	162.97	166.8	0.80
CV	0.46	2.20	0.36	0.04	0.05	0.50	0.78	0.41	0.47

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH_3= Ammonia, NO_3^-= Nitrate, PO_4^{3-}=Phosphate,
SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source[1] = WHO Drinking Water Guidelines, 2017. Source[2] = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 20,910 µS/cm is significantly higher than the WHO Standard for potable water (<1500 µS/cm) and non-potable water (<2500 µS/cm). All of the samples tested had higher EC than the WHO Standard for potable and non-potable purposes. The mosque sample tested had lowest EC of 3427 µS/cm.
- Since the island is very narrow and densely populated, saline intrusion is dominant in all of the samples tested. Only five samples tested had EC below 10000 µS/cm, four of them being households in the center of the island and the fifth sample being the mosque well. The EC distribution is shown in Figure 94.
- The mean Turbidity level at 1.88 NTU fall within the URA Guidelines for drinking water (<5 NTU). Only three samples had higher Turbidity level than 5 NTU.
- Dissolved Oxygen ranged from 1.51 mg/L to 7.65 mg/L with a mean of 3.91 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 7.27. Only the mosque well sample had pH of 8.6.

- Temperature ranges from 28.30°C to 38.3°C depending on the well characteristics and time of day reading was taken. Mean temperature was 30.60°C.
- Salinity ranged from 1.59ppt to 22.2ppt with a mean of 11.3ppt.
- The mean Ammonia concentration was 56.47 mg/L which is significantly higher than the WHO threshold for odour and the threshold for taste. 0% of samples had concentration below 1.5 mg/L, 38% of samples had concentration between 1.5 mg/L and 35 mg/L and 63% of samples had concentration higher than 35 mg/L. The presence of ammonia having a higher concentration than 35 mg/L indicates odour is present which correlates to the social survey results where 47% of households surveyed answered that smell was present in the groundwater. The Ammonia concentration distribution is shown in Figure 95.
- The mean Nitrate concentration was 100.4 mg/L which is more than double the WHO Standard for Nitrate concentration (50 mg/L). Only four samples had Nitrate concentration lower than the standard.
- Phosphate concentration ranges from 0.12 to 0.80 mg/L with a mean concentration of 0.32 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. No samples tested had concentration lower 0.1 mg/L.
- Similar to EC, the concentration of Ammonia, Nitrate and Phosphate are generally lower in the center of the island.
- The spatial distribution of all the parameters measured are shown in Figure 96 (a-i).

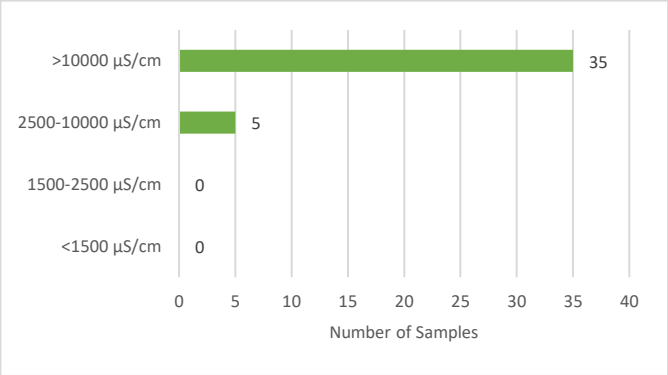


Figure 94: EC Distribution in ADh. Kunburudhoo

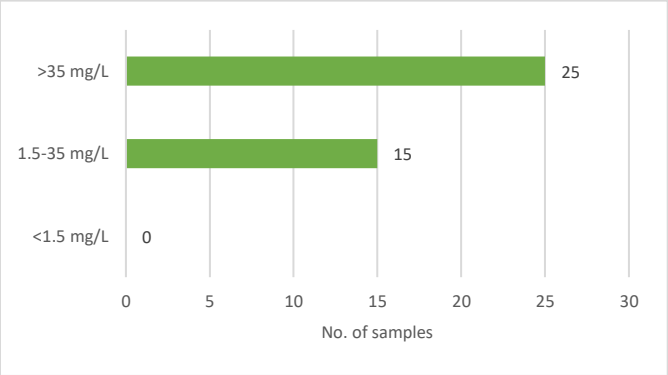


Figure 95: Ammonia Distribution in ADh. Kunburudhoo

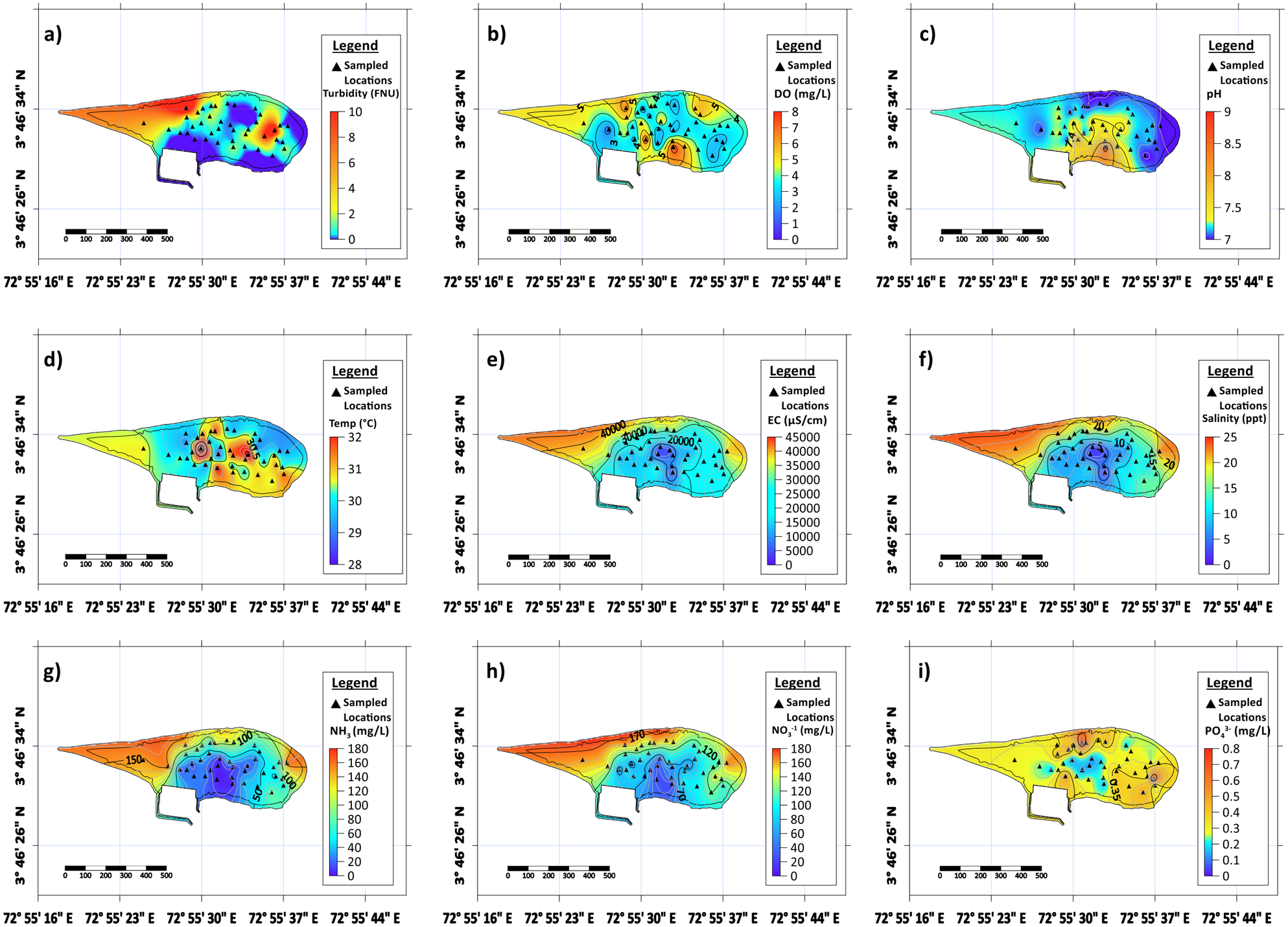


Figure 96: Spatial variation of physiochemical parameters in ADh. Kunburudhoo

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 0.181 and the R-squared of the plot is 0.0328 as indicated from the Figure 97. 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.

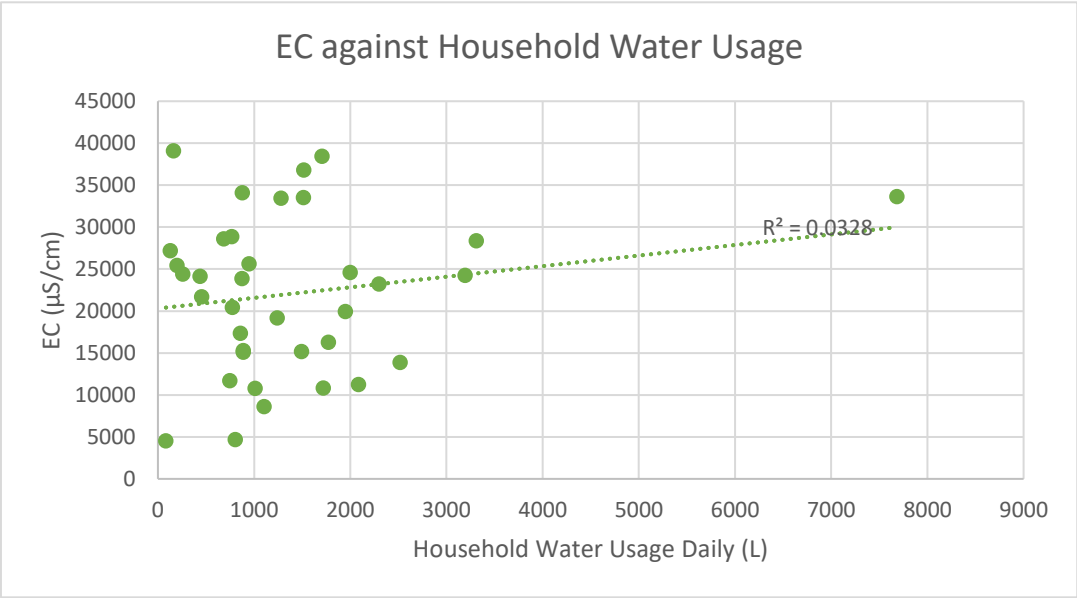


Figure 97: EC against Water Usage in ADh. Kunburudhoo

7.4.1.1 Correlation Matrix

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

Table 102: Correlation matrix of the groundwater quality parameters in ADh. Kunburudhoo

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)	0.19							
pH	-0.09	0.62						
EC (µS/cm)	0.31	-0.12	-0.59					
Sal (ppt)	0.31	-0.11	-0.59	***1.00				
Temp (°C)	-0.05	0.02	0.16	-0.07	-0.13			
NO_3 (mg/L)	0.27	-0.13	-0.13	0.89	0.89	-0.13		
NH_3 (mg/L)	0.30	-0.11	-0.11	0.92	0.94	-0.16	0.90	
PO_4^{3-} (mg/L)	0.02	-0.22	-0.43	0.44	0.43	-0.16	0.49	0.32

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation

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

Table 102 shows a strong positive correlation coefficient between EC/Sal (r=1.00), EC/NO_3 (r=0.89), EC/NH_3 (r=0.92), Sal/NO_3 (r=0.89), Sal/NH_3 (r=0.94) and NH_3/NO_3 (r=0.90). 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.

7.4.1.2 Water Quality Index

In this study, the computed WQI ranges from 17.2 to 197, with a mean of 102. The WQI was divided into four categories and Table 103 shows the categorization of samples. 0% of samples were classified as "Very Good", 2.5% of samples were classified as "Good", 12.5% of samples were classified as "Poor" and 85% of samples were classified as "Very Poor". The high value of WQI at majority of the locations have been found to be mainly from the high EC, high Nitrate concentration and high Ammonia concentration at most locations. The spatial distribution of WQI is as per Figure 98.

Table 103: Water Quality Classification based on WQI – ADh. Kunburudhoo

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	0	0%
10 to 20	Good	1	3%
20 to 50	Poor	5	13%
>50	Very Poor	34	85%

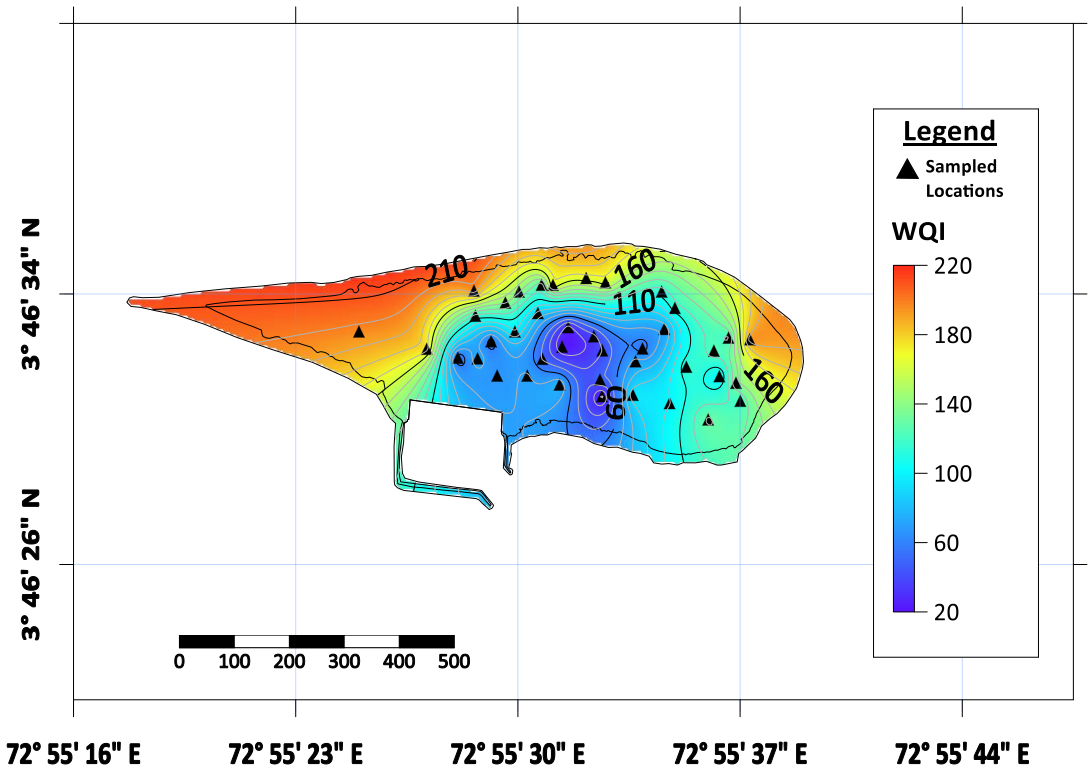


Figure 98: Spatial Distribution of WQI in ADh. Kunburudhoo

7.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 104 summarizes the results.

Table 104: Microbiological Parameters of groundwater in ADh. Kunburudhoo

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq01	>2420	>2420	-	School
wq02	>2420	4	10	Connected to a local outfall pipe
wq03	>2420	60	10	Septic Tanks
wq04	>2420	Not detected	30	Connected to a local outfall pipe
wq05	>2420	Not detected	10	Connected to a local outfall pipe
wq06	Not detected	Not detected	-	Connected to a local outfall pipe. Bathroom currently not being used.
wq07	3	Not detected	-	Health Center
wq08	>2420	8	-	Udhares Café
wq09	>2420	29	10	Connected to a local outfall pipe
wq10	>2420	Not detected	15	Connected to a local outfall pipe
wq11	>2420	>2420	10	Connected to a local outfall pipe
wq12	>2420	55	10	Connected to a local outfall pipe
wq13	>2420	2420	20	Septic Tanks
wq14	>2420	Not detected	40	Septic Tanks
wq15	166	1	20	Connected to a local outfall pipe

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

Faecal Coliform was detected in 9 samples with 2 samples containing Faecal Coliform count greater than 2420 MPN/100ml. Total Coliform was detected in 14 samples with 12 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. Their effect in the groundwater is concerning. On average, there is an approximate distance of 24 feet between septic tanks and the nearest well as observed from social survey.

It should be noted that for sample wq06 which detected zero faecal and total coliform count, the Social Survey indicated that the bathroom was currently not being used and the residents of the household used a bathroom in a different house for toilet use and showering purposes.

The spatial distribution of Total Coliform and Faecal Coliform is given in Figure 99. Lower count of Total Coliform was observed near the center of the island adjacent to the harbour, while extremely high levels of total coliform count was observed on the rest of the island. Faecal Coliform is not detected on the Center and East side of the island while it was detected on the West and North-East side of the island.

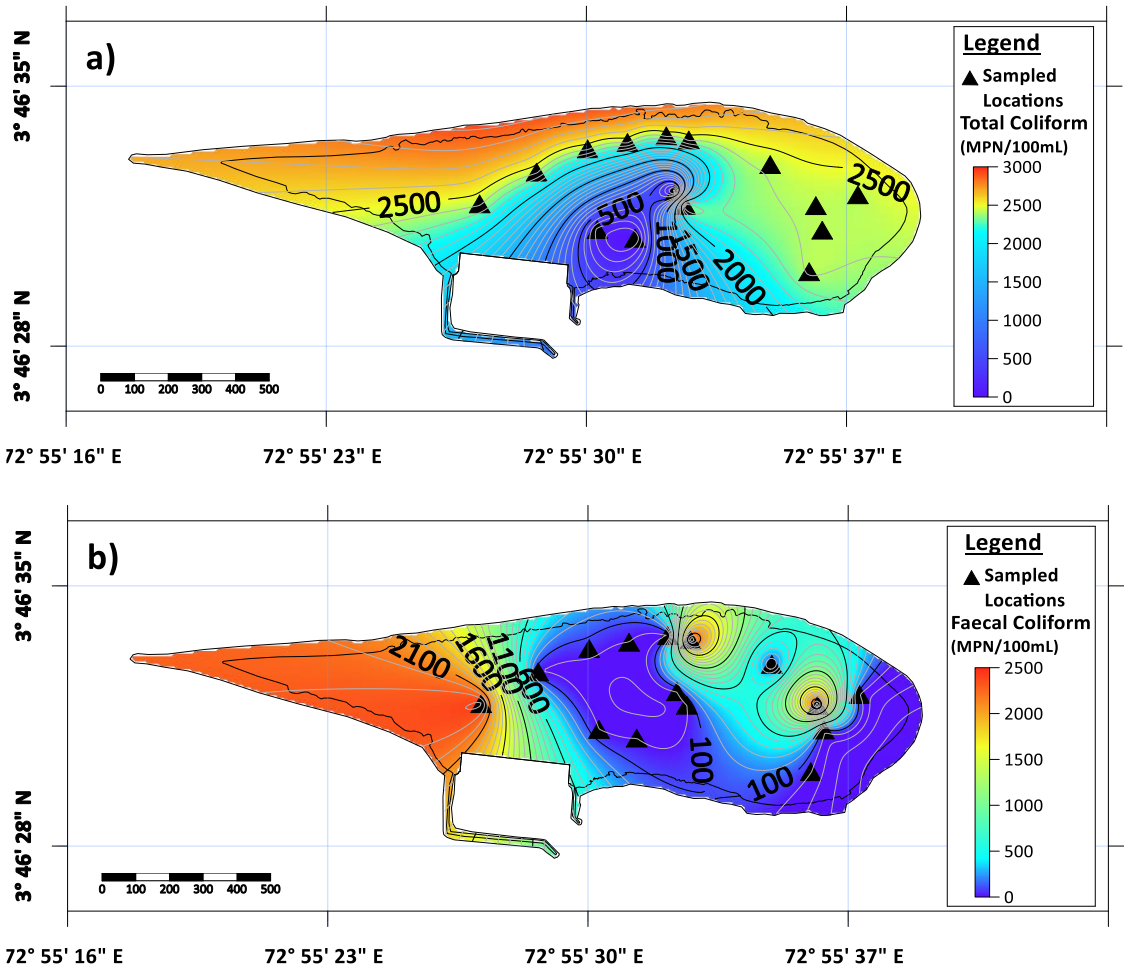
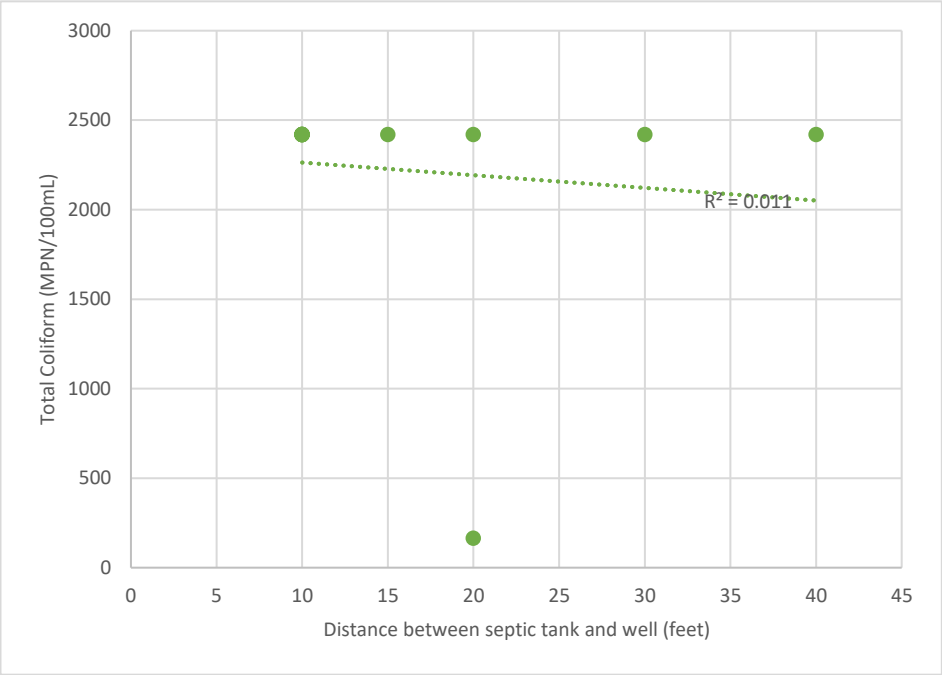


Figure 99: Total (a) and Faecal (b) Contamination Distribution in ADh. Kunburudhoo

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.



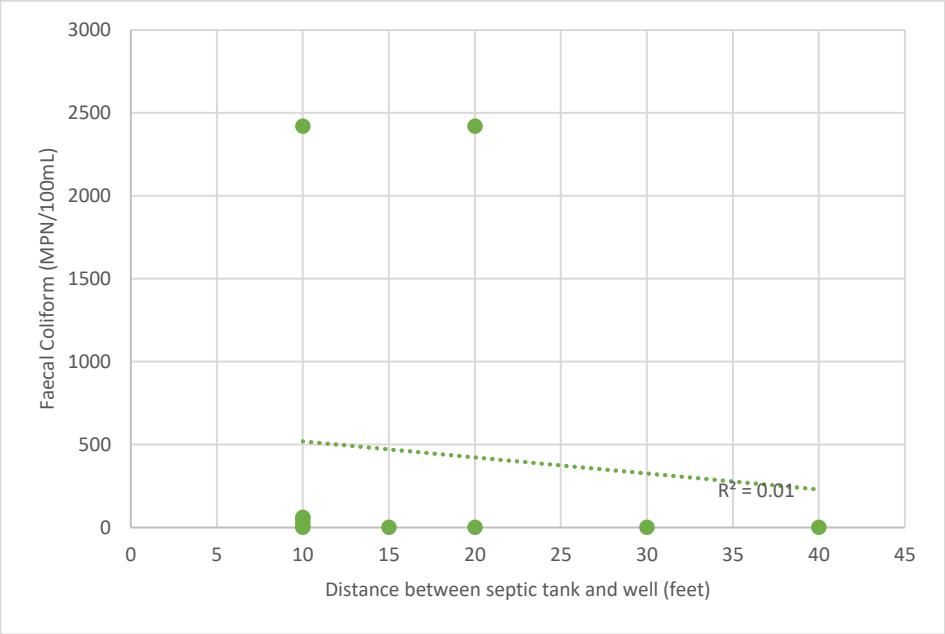


Figure 100: Microbiological Contamination against Septic Tank distancing - Kunburudhoo

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.105 and the R-squared of the plot is 0.011 as indicated from the Figure 100. The correlation coefficient of Faecal Coliform to distance between septic tank and well is -0.100 and the R-squared of the plot is 0.01 as indicated from the Figure 100. Therefore, there isn't a significant relationship observed between the parameters.

7.5 Pumping Test

7.5.1 Test location

A well without a base was not available in ADh. Kunburudhoo. Therefore, it was decided to carry out the test at the new mosque as the mosque well would be unused for most parts of the day. The chosen well had an inlet of approximately 2 inches' diameter at the concrete base plate. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 101 below shows the location for the pumping test at ADh. Kunburudhoo.

Figure 101: Pumping test location - ADh. Kunburudhoo

7.5.2 Pumping rate, pumping hours, and collected data

A constant rate pumping test was carried out at ADh. Kunburudhoo. The test began at 1150 hours on 24 August 2021 and lasted for 68 minutes. A constant flowrate of 50 LPM was maintained for the pumping phase which lasted from 0-48th minute of the test. The recovery phase of the test lasted from 49th-68thth 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 8.56x10-4 m2/s (73.99 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.1994 for ADh. Kunburudhoo. The full data set of the pumping test at ADh. Kunburudhoo has been annexed at Annex XI.

7.6 Permeability Test

7.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 102 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 102: Permeability Test Locations - ADh. Kunburudhoo

7.6.2 Measured data

Table 105: Permeability Test Measured Data - ADh. Kunburudhoo

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m^3/s)	K (m/s)	K (m/day)
KBD-PMB1	0.6	1.06	35	12	15.00	0.000250	2.41E-04	20.78
KBD-PMB2	0.6	1.22	35	12	16.00	0.000267	2.23E-04	19.26
KBD-PMB3	0.6	0.61	35	12	8.14	0.000136	2.27E-04	19.60
KBD-PMB4	0.6	0.85	35	12	10.00	0.000167	2.00E-04	17.28
KBD-PMB5	0.6	1.24	35	12	15.00	0.000250	2.06E-04	17.76

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 ADh. Kunburudhoo is 18.94 m/day, with permeability values ranging from 17.28 m/day to 20.78 m/day. As highlighted in Section 7.7, 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 7 locations across the island, as outlined in Figure 103 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 103: Soil Profile Survey Locations - ADh. Kunburudhoo

7.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 104 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.

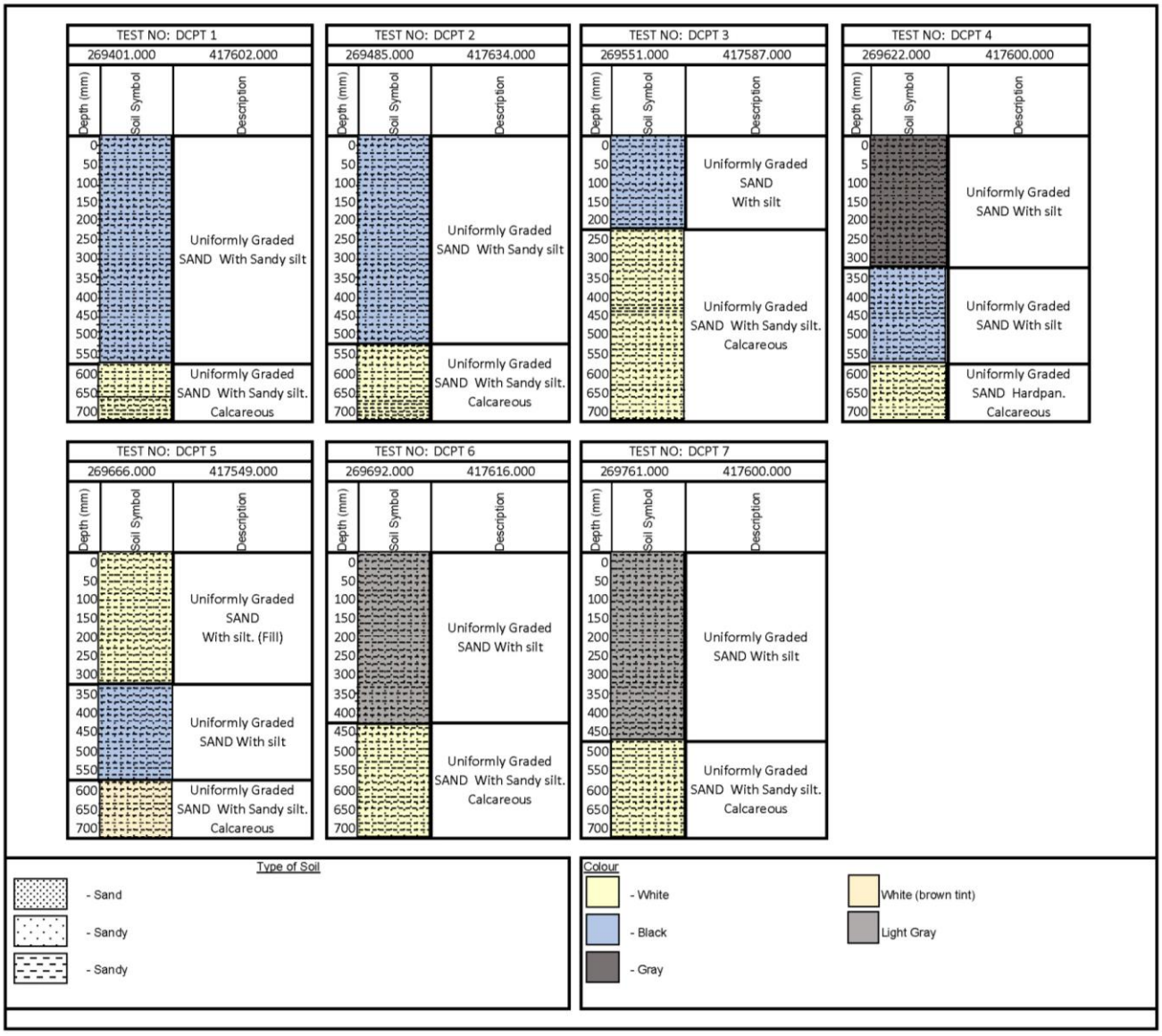


Figure 104: Soil Profile - ADh. Kunburudhoo

7.8 Flood Assessment and Inundation Survey

7.8.1 Flood occurrence and flood impact

The island has severe erosion problems and houses located in the middle of the island experience flooding issues. However, the houses on the sides reported that they do not experience major flooding issues but have saline intrusion. Around 54% of the houses reported that flooding occurs mostly when it rains heavily. Also, 14% of the household's report that they have noticed changes in flooding patterns after roads were filled with sand. As per the social survey, 18 households reported rain induced flood incidents in the year 2021 and 11 households reported flooding incidents in 2020. In the two incidents, 25 houses reported minor damages, mostly broken fences and trees. There were also 2 houses reporting flood incidents in 2019 where one house reported damages to household appliances along with broken fences and trees. The other household reported partial damages to appliances along with broken fences and trees. On the same note, 54% of the households reported that they experienced no damages and only minor inconveniences by recent flooding events.

ADh. Kunburudhoo is also one of the 51 inhabited islands listed with coastal protection by the government. Coastal protection is critical for islands like ADh. Kunburudhoo as it helps to conserve the abundant aquatic resources and serve as a protection against floods, storm surge and coastal erosion.

In the social survey, 21% of the respondents rated flooding as a severe problem due to frequent flooding events and prolonged draining periods caused by heavy rainfall (refer to flood severity component of Flood Maps in Annex XII).

The flooding originates mostly from roof runoff (60%) as per the Social Survey. Most responses state multiple sources for the flooding within their properties such as from neighbors' 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 106: Perceived causes of flooding – ADh. Kunburudhoo

Perceived causes of flooding				
Roof run off	**Neighbours' roof**	**Off the road**	**General run off in the area**	**No flooding within the plot**
60%	23%	9%	16%	26%

From the social survey, 53% 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 which include overflow 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 107: Discharge of rainwater overflow – ADh. Kunburudhoo

Discharge of rainwater overflow			
Ground	**Roads**	**Open area within the plot**	**Drained to well**
53%	2%	32%	19%

7.8.2 Inundation area identification

Based on the social survey responses, an average of 1.22ft is estimated as the flooding depth when there is a heavy rainfall. Also, 53% reported that it takes 30 minutes to inundate the area once the heavy rain starts. The common flooding areas are in the center of the island (refer to Annex XII: Flood Maps).

7.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 50% observe that the water drains during the rainfall itself, 17% observe that the water drains in less than 4 hours, 31% observe that the water drains in less than 4-24 hours and 2% observe that it takes more than 24 hours for water to drain.

Table 108: Draining period – ADh. Kunburudhoo

Draining period			
only while raining	**drains less than 4hrs**	**takes 4-24 hrs**	**more than 24hrs**
50%	17%	31%	2%

Some institutions also reported that it takes 2-3 days or even up to 1 week for water to drain after a heavy rainfall and flooding event. There were also flooding incidents reported in early 2021, where emergency drainage channels were used to alleviate the flooded areas.

7.9 Geophysical Survey

7.9.1 Surveyed locations

Locations where ER sounding measurement taken at ADh. Kunburudhoo island are shown in Figure 105 together with transect lines. There are 21 ER measurement locations and the number of transects in this island is 12.

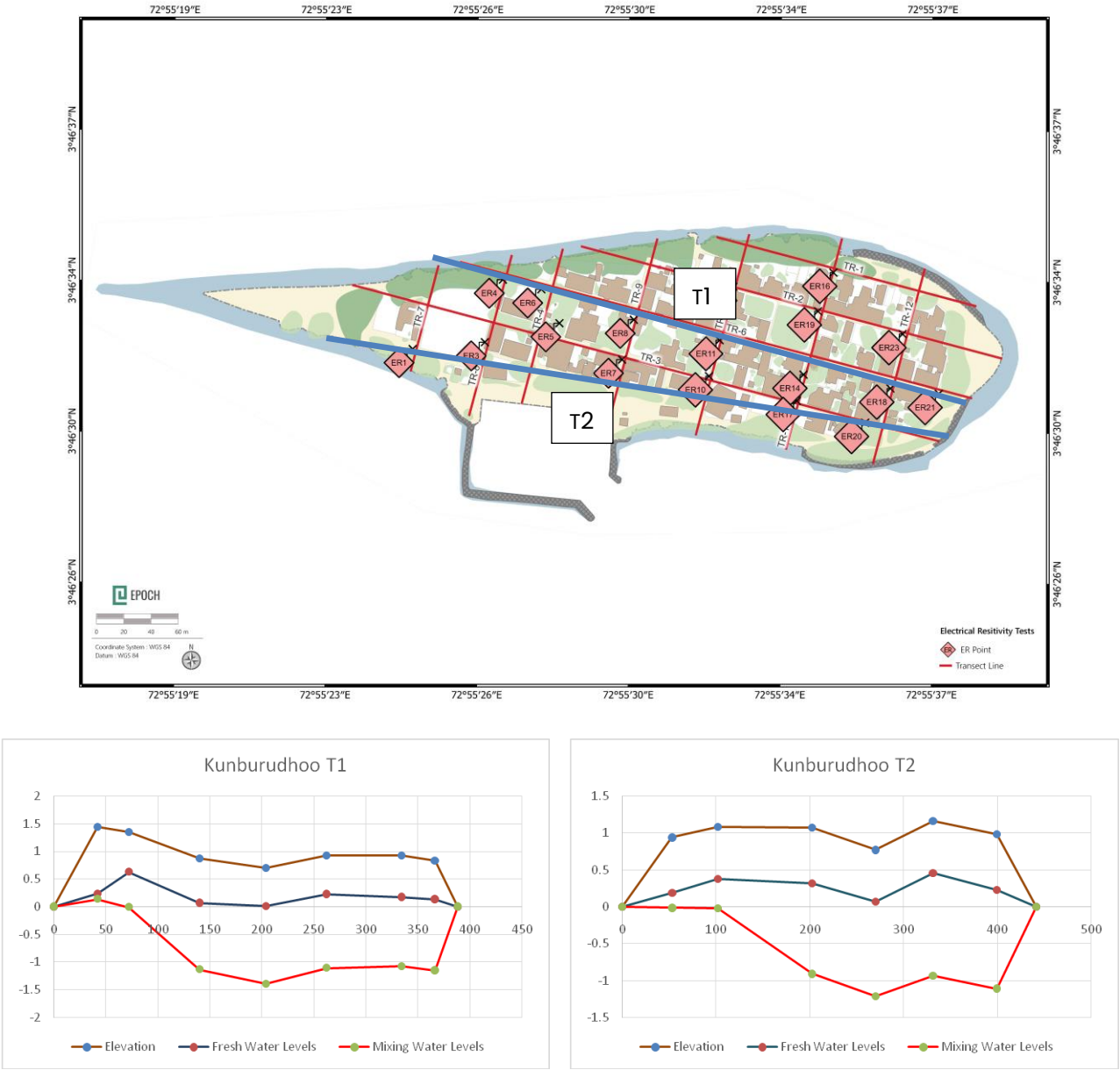


Figure 105: ER surveyed locations and transect lines – ADh. Kunburudhoo Island

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 109 below shows the estimated levels at ER surveyed locations of ADh. Kunburudhoo Island and freshwater lens thickness.

Table 109: Freshwater lens levels and thickness – ADh. Kunburudhoo island

No	Level (m AMSL)			Freshwater lens thickness (m)
	Ground	Freshwater	Saline water	
1	0.94	0.19	-0.01	0.20
2	1.08	0.38	-0.02	0.40
3	1.44	0.24	0.14	0.10
4	1.30	0.10	-0.65	0.75
5	1.34	0.62	-0.01	0.63
6	1.07	0.32	-0.91	1.23
7	0.87	0.07	-1.13	1.20
8	0.77	0.07	-1.21	1.28
9	0.70	0.01	-1.39	1.40
10	0.83	0.13	-1.19	1.32
11	0.93	0.23	-1.10	1.33
12	0.98	0.23	-0.92	1.15
13	1.16	0.46	-0.93	1.39
14	0.92	0.17	-1.08	1.25
15	0.83	0.13	-1.15	1.28
16	0.98	0.23	-1.11	1.34
17	1.03	0.28	-1.06	1.34
18	0.92	0.17	-1.17	1.34

Average freshwater thickness of ADh. Kunburudhoo island is 1.05m. Maximum recorded thickness of freshwater lens of the Island by ER survey is 1.40 m & minimum is 0.05 m

Data in Table 109 were used to plot freshwater lens cross sections along 12 transects. Of these sectional plots 2 were given in Figure 105 and they represent the transect plots along the longitudinal section of the island.

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 106.

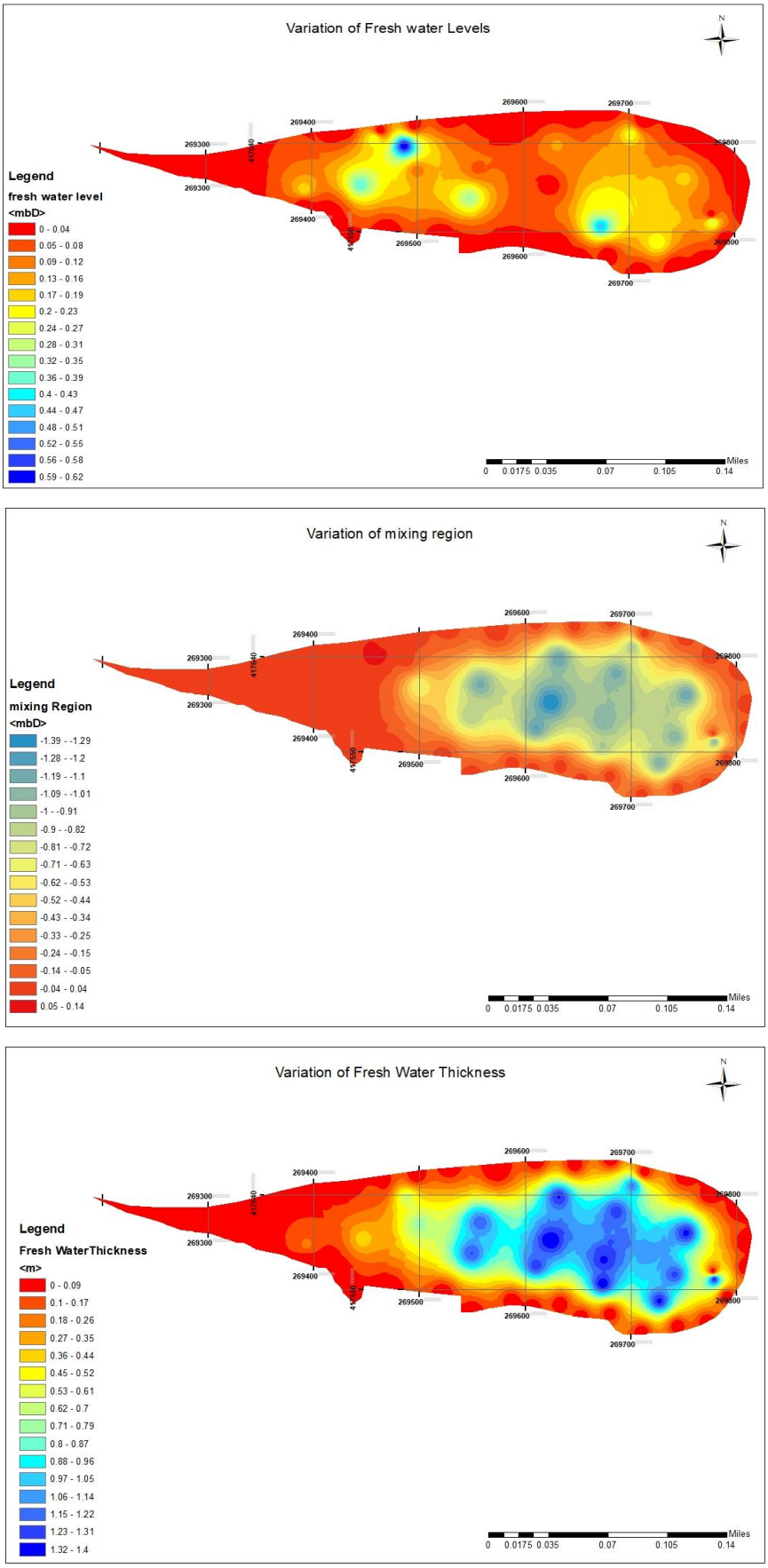


Figure 106: Spatial distribution of thickness of freshwater lens

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. Tools in ArcGIS software were used to perform this computation.

Stress level on freshwater aquifer of ADh. Kunburudhoo 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 110.

Table 110: Freshwater lens volume and aquifer stress level – ADh. Kunburudhoo island

Item	Value	Unit
Freshwater lens volume - ArcGIS	39,788	m^3
Groundwater abstraction	36,469	m^3/yr
Freshwater lens volume/ Groundwater abstraction	1.09	-
Aquifer stress level	Stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 1.59m. This deviates by 13.6% from the maximum measured value of 1.40m, which is more reliable as it results from a more comprehensive, site-specific methodology.

7.10 SWB Modelling

7.10.1 Land use categorization and area estimation

Table showing land classification and their respective areas are shown in Table 111.

Table 111: Land Use Classification – ADh. Kunburudhoo

	Area (m^2)	% of total area
Roof cover	14,024	25%
Vegetation (Thick)	6,801	12%
Vegetation (Thin)	13,974	25%
Bare Lands	22,043	39%
Total	56,891	100%

7.10.2 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 107 and Table 112). The following was noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 10,593, 58,447 and 276,768 m^3 respectively over a 20 year period.
- There is a good relationship between annual rainfall and annual recharge, but it is not linear instead an inverse exponential.
- Annual average rainfall is around 1983 mm
- Variation among the monthly average recharge value is very high. It is lowest during the month of January and highest in May.

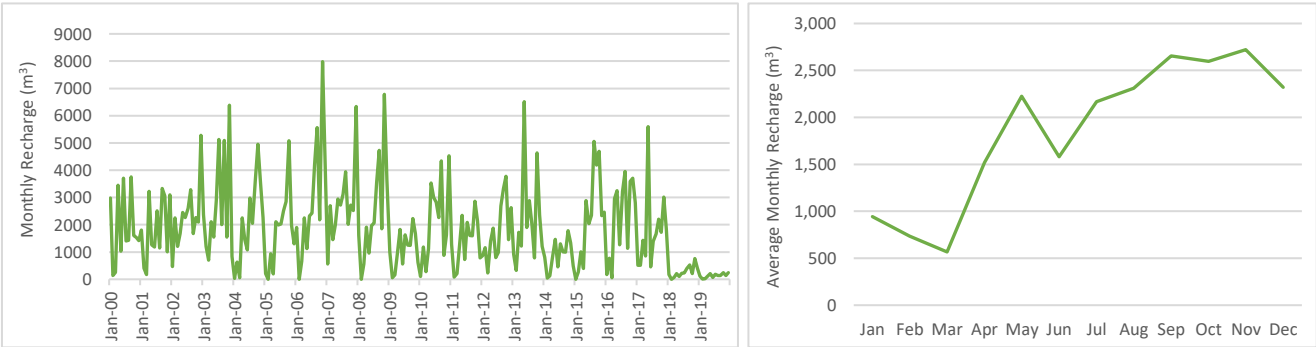


Figure 107: Monthly and annual recharge distribution in ADh. Kunburudhoo

Table 112: Monthly recharge estimated by SWB model – ADh. Kunburudhoo Island

Year	Monthly Recharge (m^3)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2000	2,982	140	260	3,453	1,033	3,712	1,404	1,429	3,752	1,603	1,540	1,417
2001	1,801	404	172	3,225	1,262	1,187	2,514	1,150	3,337	3,067	1,011	3,092
2002	471	2,247	1,209	1,672	2,451	2,267	2,602	3,289	1,677	2,265	2,099	5,284
2003	2,368	1,204	708	2,108	1,553	2,884	5,126	2,007	5,090	1,542	6,386	841
2004	35	635	58	2,251	1,455	1,075	2,974	2,053	3,646	4,950	3,566	2,267
2005	215	-	939	202	2,116	1,998	2,032	2,508	2,845	5,077	1,984	1,298
2006	1,899	-	662	2,254	1,124	2,323	2,429	4,197	5,561	2,184	7,982	4,260
2007	565	2,697	1,451	2,007	2,941	2,720	3,123	3,947	2,013	2,718	2,519	6,341
2008	1,614	-	563	1,916	956	1,975	2,064	3,568	4,727	1,857	6,785	3,621
2009	1,004	60	166	977	1,832	564	1,625	1,253	1,244	2,229	1,671	616
2010	102	1,182	285	1,124	3,526	3,006	2,828	2,261	4,341	882	1,632	4,524
2011	1,287	76	213	1,253	2,349	723	2,083	1,607	1,595	2,857	2,143	789
2012	866	1,156	228	1,404	1,879	798	984	2,684	3,325	3,782	1,458	2,624
2013	919	330	1,722	1,216	6,516	1,905	2,888	2,021	789	4,640	2,361	1,202
2014	803	48	133	782	1,466	451	1,300	1,003	996	1,783	1,337	493
2015	-	269	1,012	402	2,882	2,040	2,342	5,061	4,187	4,690	2,333	2,460
2016	180	777	55	2,953	3,252	1,268	3,214	3,951	1,132	3,593	3,703	2,800
2017	512	518	1,425	851	5,603	456	1,390	1,667	2,200	1,724	3,020	1,827
2018	180	-	63	214	107	221	231	399	528	208	758	405
2019	113	7	19	110	206	63	182	141	140	250	136	244

7.10.3 Water Balance

As per estimation, annual recharge estimated by the SWB model is 39,769 m^3 and it is 31.5% of annual average rainfall (refer to Figure 108).

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	126,250	4,409	59,338	39,769	15,150	36,469
%	100%	3.5%	49%	31.5%	16%	28.9%

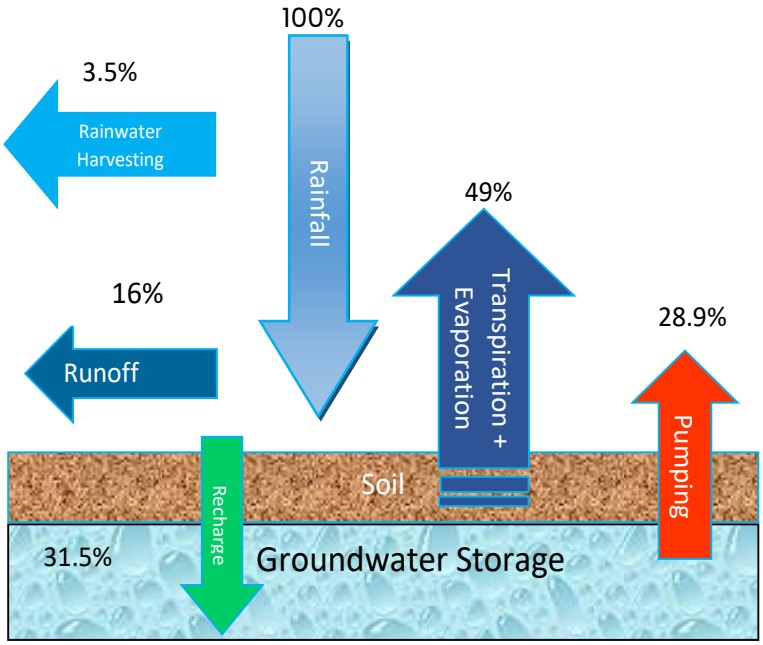


Figure 108: Annual water balance – ADh. Kunburudhoo Island

7.10.4 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 (3039 m^3/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 113: Deficit percentage – ADh. Kunburudhoo

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	197	82.1

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 ADh. Kunburudhoo island depend 82.1% 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 (36,469 m^3/yr) with safe abstraction volume (3300 m^3/yr) shows that present withdrawal is 1005% higher than the safe yield. Therefore, it could be inferred that present groundwater abstraction is high and it would lead to up-coning freshwater-saline water interface in future.

7.11 SUTRA Modelling

7.11.1 Model representation and mesh production

SUTRA modelling requires mode domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island. The other boundary defined in the model was island outline which can be referred as shoreline most of the cases except at harbour area and the inner part of the island was subdivided to several polygons representing different land use and it was accomplished by importing GIS shape files of island land use and then drawing polygon 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.

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 109 shows the pressure boundary defined for ADh. Kunburudhoo island.

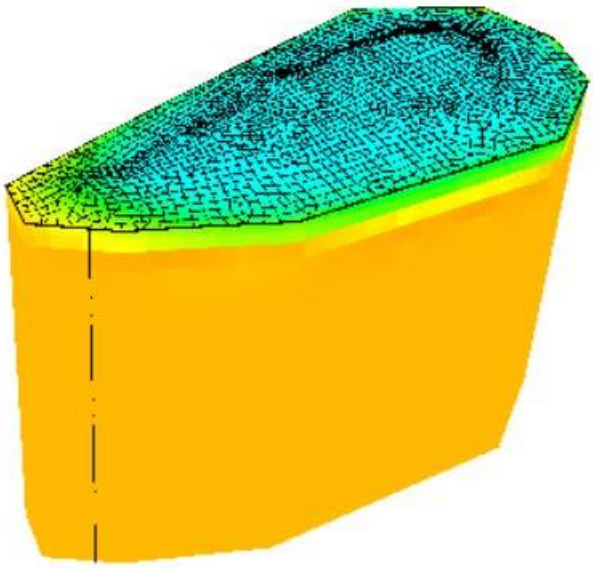


Figure 109: Pressure boundary at SUTRA model – ADh. Kunburudhoo island

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.

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.

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 110. The section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0357 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top.

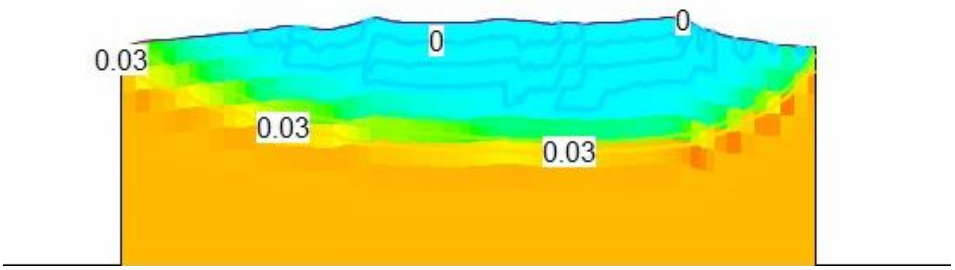


Figure 110: Saltwater distribution – ADh. Kunburudhoo island

7.12 Summary of Baseline Assessment

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

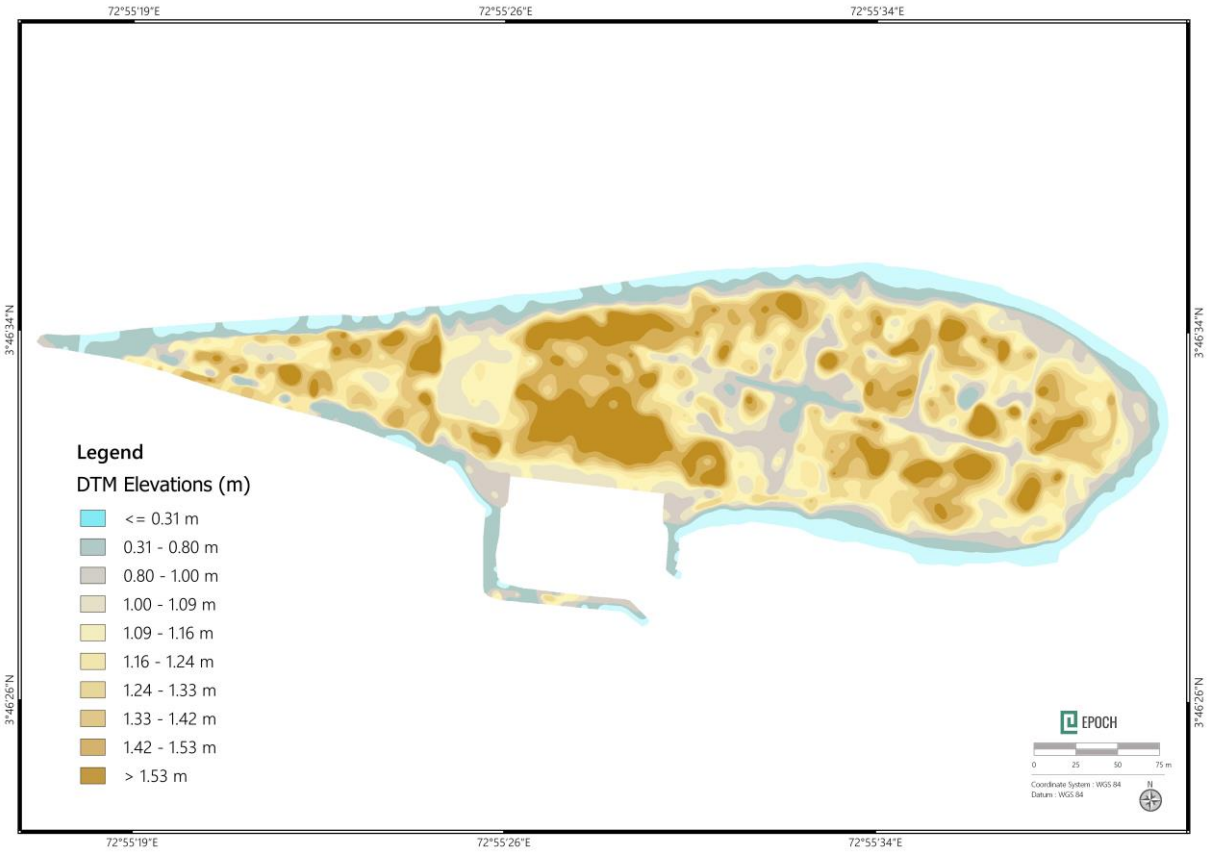
- General overview, demography, and climatology

Item	Details
Atoll	Ari Atholhu Dhekunuburi Atoll
Length	0.88 km
Width	0.16 km
Area	5.69 ha
Population	624
Population/area	110 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use
  Data from level survey, drone survey and photometric survey

Land use map

Topographical map



		% of total area
Average elevation = 1.058 m above MSL	Roof cover	25%
	Vegetation (Thick)	12%
Shoreline length =1428 m	Vegetation (Thin)	25%
	Bare Lands	39%
	Farmlands	0%
	Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Industrial	Institutional	Total
Rate (m^3/d)	97	1.03	0.02	1.52	99.9

- Water quality parameters – Physiochemical
  Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	20,910 ± 9,674	1500
Turbidity (FNU)	1.88 ± 4.13	5
DO (mg/L)	3.91 ± 1.42	
pH	7.27 ± 0.29	6.5-8.5
Temp (°C)	30.60 ± 1.61	
Sal (ppt)	11.30 ± 5.64	
NH_3 (mg/L)	56.47 ± 44.22	1.5 (Odour Threshhold)
NO_3^- (mg/L)	100.4 ± 41.4	50
PO_4^{3-} (mg/L)	0.32 ± 0.15	

- Water quality parameters – Microbiological
  Number of samples tested = 15

Parameter	Value range	Average value	Remarks *(on permit limit)*
Total Coliform (MPN/100ml)	Not detected - >2420	1,947.27	Should not be detected
Faecal Coliform (MPN/100ml)	Not detected - >2420	494.47	Should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	73.99	m^2/day
Storativity	1	0.1994	-
Permeability	7	17.28 – 20.78 Average – 18.94	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m^2)	Inundation depth (m)
67	1030	0.372

- Electric Resistivity survey
  - Measurement taken at 18 locations.
  - Average freshwater thickness in the island is 1.05 m.
  - Freshwater lens volume and aquifer stress level

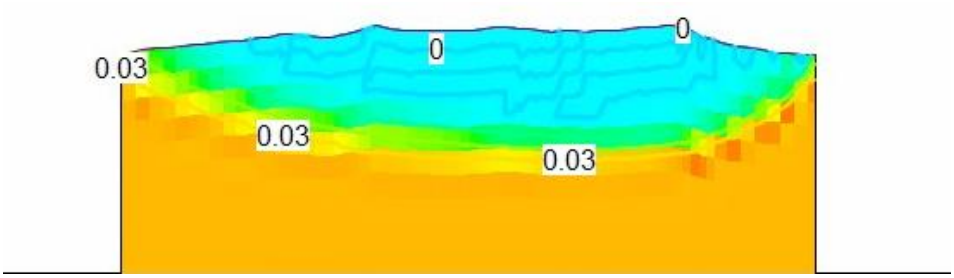
Item	Value	Unit
Freshwater lens volume - ArcGIS	39,788	m^3
Groundwater abstraction	36,469	m^3/yr
Freshwater lens volume/ Groundwater abstraction	1.09	-
Aquifer stress level	Stressed	-

- SWB modelling
  - Annual recharge is 39,769 m^3 and it is 31.5% of annual rainfall (1983 mm)
  - Annual water balance

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	126,250	4,409	59,338	39,769	15,150	36,469
%	100%	3.5%	47%	31.5%	12%	28.9%

  - Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 82.1% in an average year, and it is compensated by ground water storage.
  - Ground water withdrawal (36,469m^3/yr) is 1,05% higher than the safe abstraction (3300m^3/yr).

- SUTRA modelling
  - Average monthly recharge assigned to SUTRA model



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

8 Dh. Hulhudheli

8.1 Island Overview and Location

The Island of Dh. Hulhudheli, belonging to Nilandhe Atholhu Dhekunuburi, is in the Southern Central region of Maldives at 2°51'31.6"N and 72°50'47.6"E.

Table 114: Island Geographical Data

Island	Dh. Hulhudheli
Atoll	Nilandhe Atholhu Dhekunuburi
Location	2°51'31.6"N and 72°50'47.6"E

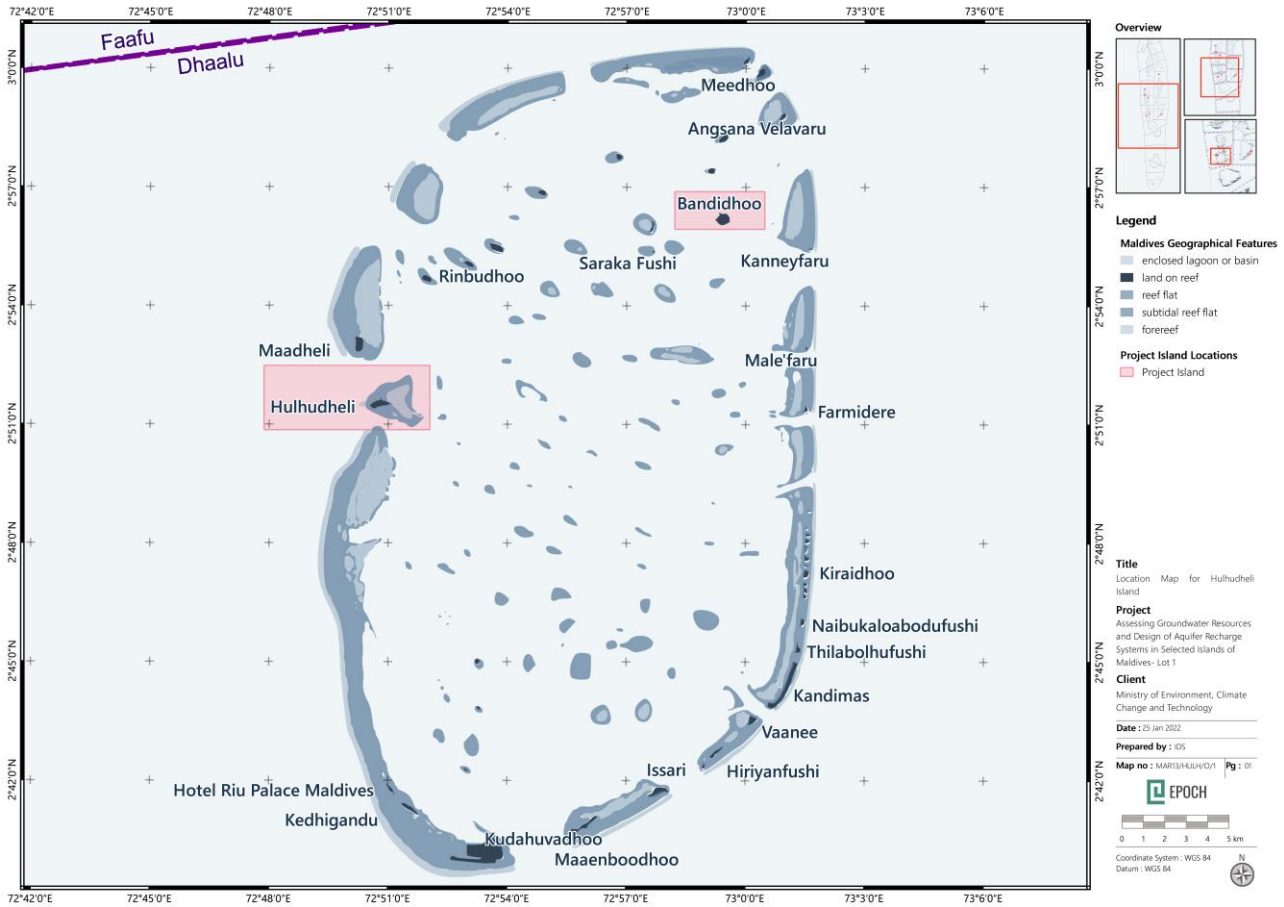


Figure 111: Location map – Dh. Hulhudheli

8.1.1 Island features

The island is formed within its own coral reef system about 4.7 km from the rim of Dhaalu atoll. Dh. Hulhudheli extends up to 0.97 km in length and a has width of 0.29 km from toe to toe. The island lies south-west, about 8.6km from Dh. Rinbudhoo which is the closest inhabited island.

The island has a harbour at its Northern-east side of the island. About two-third of the island's surface is vegetation. Thin vegetation is mostly located in the west side and center of the island. The west side of the island is covered mostly by thick vegetation. About two-third of the island is populated,

which is mostly in north and east side of the island. The Land Use Characterization map is attached to Annex II.

Table 115: Area Distribution in Dh. Hulhudheli

Area	21.4 ha	
Length	0.97 km	
Width	0.29 km	
	Area (m^2)	% of total area
Roof cover	32,314	15%
Vegetation (Thick)	59,797	28%
Vegetation (Thin)	40,209	19%
Bare Lands	80,956	38%
Farmlands	-	0%
Total	213,960	100%

Figure 112: Land Use Characterization – Dh. Hulhudheli

8.2 Topographical Features

Permanent Survey Marks PSM 0387, PSM 0477 and PSM 0388 were used as benchmarks for Dh. Hulhudheli topographical survey and drone survey. These details are currently not available via the Maldives Land Survey Authority Website https://www.mlsa.gov.mv/psm as MLSA has reported that corrected reports have not been submitted for the issued benchmarks. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 1306 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.26 cm per pixel. 11 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 116: GCP Statistics for Dh. Hulhudheli

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	0.000032	0.000204	-0.000363
Sigma [m]	0.0108	0.0123	0.0195
RMS Error [m]	0.0108	0.0123	0.0195

Dh. Hulhudheli has a peak elevation at the centre of the island, declining outwards towards the shore for naturally formed parts of the island. In contrast, the newly built harbour and its vicinity has a slightly higher elevation with respect to similar areas. The island also has naturally formed ridges on both eastern and western shorelines due to high wave activity at these locations. Point of interest is the football pitch, which shows great variation, with elevations ranging from 0.8 m to 1.4 m. With the exception of the harbour, the island does not have any coastal protection structures built. Also of interest is the deforestation that has been carried out in the mid-2010s to make way for new residential plots and roads on the south side of the island.

Roof elevations generally do not exceed 5-7 m and very few houses have multistorey buildings in Dh. Hulhudheli. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Think vegetation can be found on the western and north-western peripheries of the island, with lower elevated vegetation found along the southern periphery. Areas with thick vegetation all exceed 10 m in height, while the vegetation of the southern periphery range from 5 m to 9 m.

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 Dh. Hulhudheli. The DTM slightly overestimates the elevations with a mean of 4.46 cm.

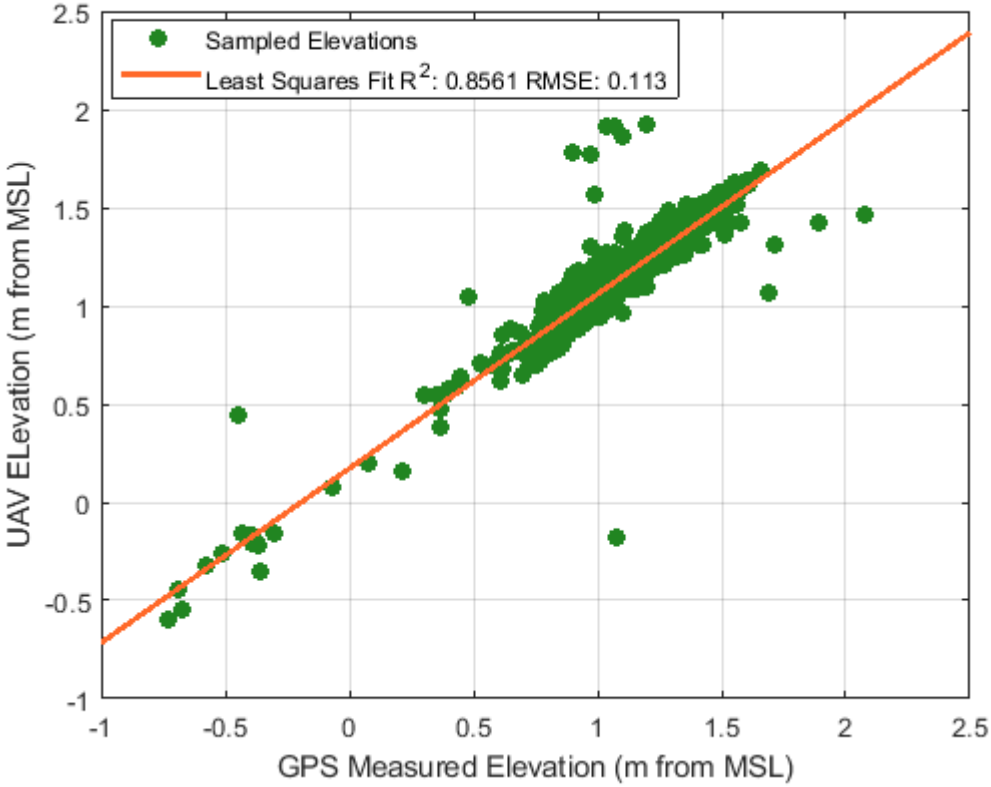


Figure 113: Linear Regression Plot for Dh. Hulhudheli Sample UAV elevations

Table 117: Error Statistics for Dh. Hulhudheli DTM

Parameter	*Value (cm)*
Mean	4.46
Standard Error	0.80
Median	3.61
Mode	#N/A
Standard Deviation	23.03
Sample Variance	530.34
Kurtosis	453.43
Skewness	-18.16
Range	654.63
Minimum	-565.34
Maximum	89.29
Sum	3716.94
Count	833.00

8.2.1 Level changes

Dh. Hulhudheli has an average elevation of 1.10 m with a standard deviation of 0.457. Digital Terrain Model elevations range from -0.6 to 2.1 m from MSL. The distribution of elevations has a symmetrical bimodal distribution with 1.3 m being the highest frequency for elevations. A second peak is observed near -0.1 m from MSL.

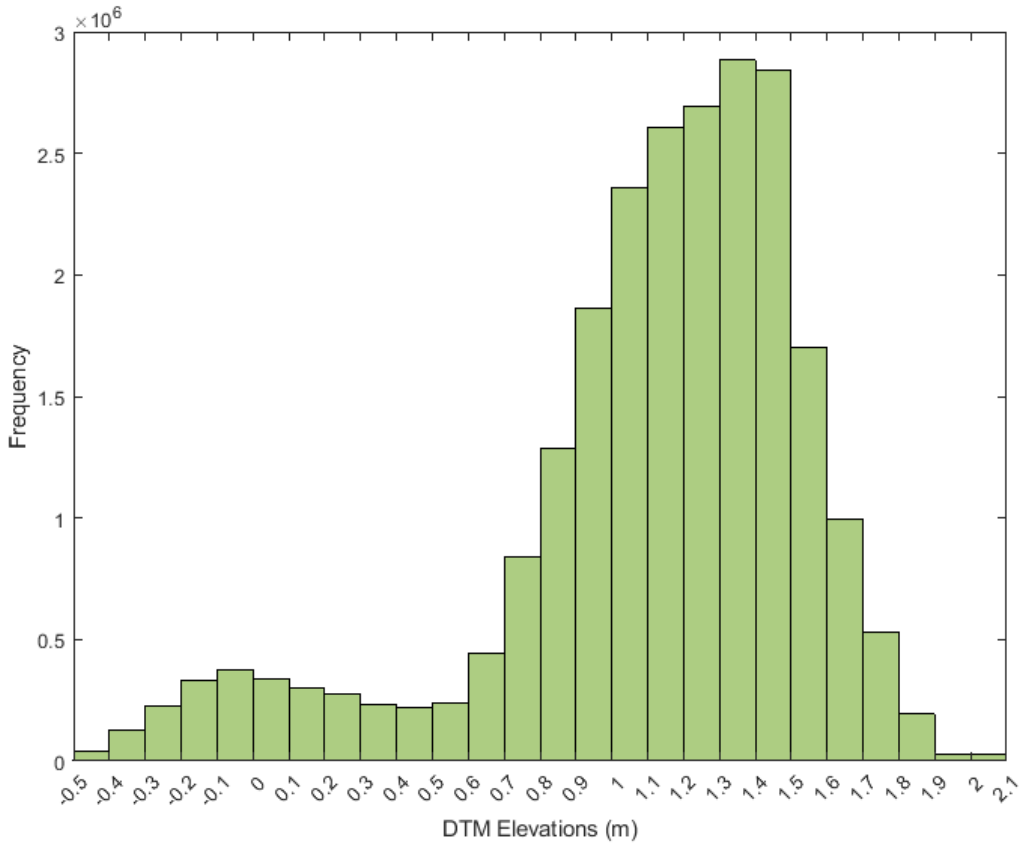


Figure 114: Raster Histogram created for Dh. Hulhudheli DTM

Profiles 1 and 2 both go from west to east, with both showing similar patterns. There is an initial incline in elevation going till 450 m, which is then followed by a depression up to the shoreline. The eastern shoreline, which is at the end of these profiles, both show ridges formed due to wave impact, more so in profile 1. Interestingly, there does not appear to be a ridge formed on the western shoreline, where wave impact is expected to be stronger due to the island orientation and location with respect to the atoll, being exposed to the Southwestern swells. The absence of a ridge on the western shoreline could be due to the intense wave impact stripping away the beach here to the extent where vegetation line roots are exposed, as shown by the drone images taken. The elevations shown for these profiles indicate that the eastern shoreline faces stronger waves, which could be due to two reasons:

- SW swells are undergoing diffraction and refraction to bend waves to reach this shoreline. This is unlikely to be the primary reason for the ridge formation as the same waves should

have direct impact on the western shoreline, which shows no ridge formation on profiles 1 and 2.

- Wind waves generated within the atoll basin having a direct impact on the eastern shoreline during the Northeastern monsoon. This is supported by the location at which ridges are formed.

Profile 3 shows little variation between the start to 175m, which is followed by a decline further along the profile. However, the end of the profile shows a ridge formed at the southwestern shoreline. This ridge is the result of the direct wave impact, supplemented by the short buffer zone, which ultimately leads to unbroken waves reaching this shoreline directly.

The newly constructed harbor extension has a relatively lower elevation compared to the island, which could be attributed to the harbor project not being completed as of writing this report. This lower elevated area is shown in Profile 4 from start to 150 m, which then starts to incline towards the island center (250 m). The remaining profile then starts to decline gradually towards the shoreline.

Profile 5, which starts from the harbor, has a constant elevation of 1.5 m up to 50 m. followed by a decline till the end of the profile, where a small ridge has formed, presumably due to broken waves from the Southwestern swells.

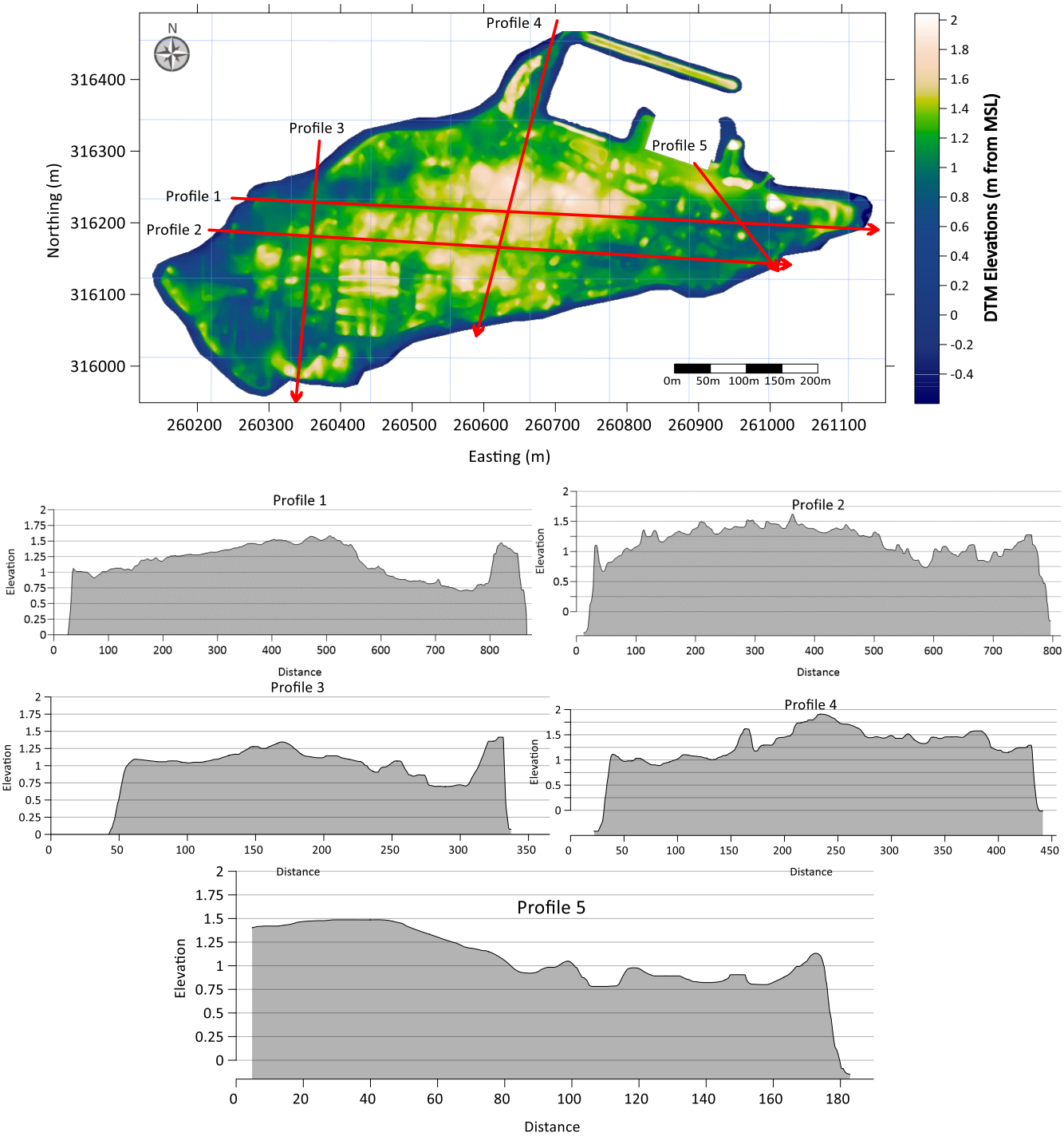


Figure 115: Digital Terrain Model Elevations and Profiles for Dh. Hulhudheli Island

8.2.2 Shoreline

Dh. Hulhudheli has a shoreline length of 3313 m. The island has all of its coastal protection on its harbor as follows (note that the harbor construction is not complete, is subject to change).

- Breakwater: The sand filled breakwater is found on the northeast side of the island. Southwestern swell waves approaching from the windward direction is absorbed and dissipated by this breakwater to offer protection to berthed vessels within the harbor. The breakwater is directly connected to the harbor with direct access. Crest height for the breakwater is around +1.8 m above mean sea level. The breakwater is highlighted in orange.
- Revetment: The revetment is found on the northwestern corner of the harbor. The revetment serves as shore protection and prevents erosion behind it by dissipating wave energy from southwestern swells from the windward direction. Crest height of is around +1.1 m above mean sea level. The revetments are highlighted in green.
- Quay wall: These structures are found within the harbor and are highlighted in yellow. Crest height of quay walls is around +1.4 m above mean sea level.

The western and southwestern shoreline has undergone severe beach erosion, where the shoreline has regressed to expose vegetation roots and specifically beach rock (aanugandu) on the southeastern shoreline.

Figure 116: Orthomosaic of Dh. Hulhudheli

8.2.3 Reef

Dh. Hulhudheli is located on the western periphery of the Dhaalu Atoll, being the only island to be located on the western end of this particular reef. There are no nearby inhabited islands, with the nearest uninhabited island being Maadheli to the north on a different reef. The reef measures roughly 3.1 km along its longest section. For the major wave direction, which is the southwestern swell waves approaching from the windward side, the shortest buffer zone measures about 250m.

Figure 117: Sentinel 2 imagery of Dh. Hulhudheli reef taken in February 2022

8.3 Socio Economic Status

8.3.1 Demography

The island has a registered population of 681 as per the 2014 census, with a total of 328 males and 353 females. The island population density per hectare is at 41. The population figures have drastically increased over the past years where the total registered local population climbed up to 958. In 2014, there were 25 more females than males (52:48 percent) while in 2021, the island had an equal number of male and female population. The following table and graph illustrates the demographic breakdown of Dh. Hulhudheli.

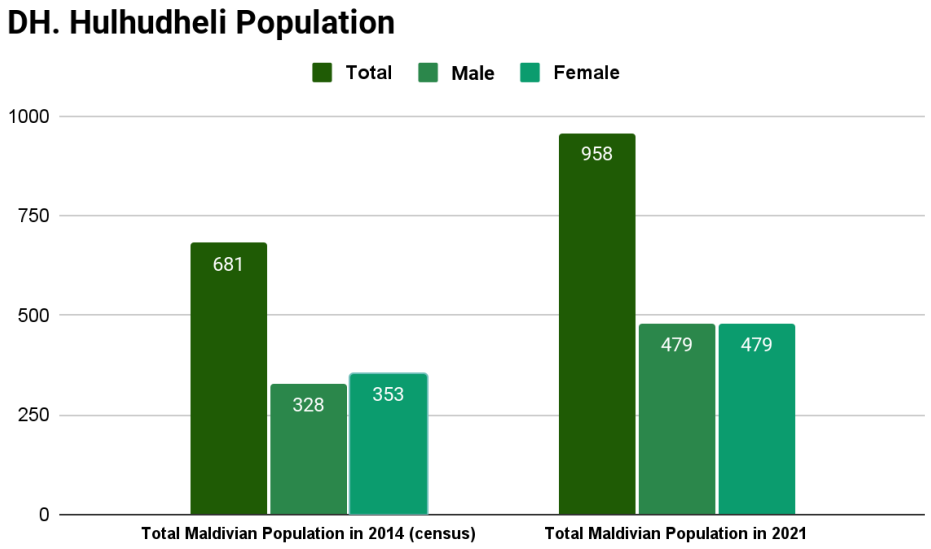


Figure 118: Dh. Hulhudheli Population

Table 118: Dh. Hulhudheli 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
Dh	Hulhudheli	719	364	355	681	328	353	38	36	2

8.3.2 Socio-Economic Activities

Dh. Hulhudheli is an inhabited island in Dhaalu Atoll's administrative unit and physically part of Nilandhe Atoll in the Maldives' southernmost region. It is an administrative constituency on an island in central province, governed by the Hulhudheli Island Council. This island is well-known for its excellent craftsmanship, particularly silversmith work. The people in the island are also involved in fisheries, construction, and tourism activities. In the past two years, the government has invested in Fish Aggregating Devices (FAD) and also deployed fish weighing boats. Due to this, fishing activities

in Dh. Hulhudheli have been further amplified while making it less labour intensive for the fishermen. Currently, the island has 6 commercial fishing boats and 2 cafes.

8.3.3 Facilities available

8.3.3.1 Health Care

Dh. Hulhudheli Island has a modest level of healthcare infrastructure that is staffed by Family Health Workers. At the moment, one doctor works at the Hulhudheli Health Center, ensuring basic injury care and illness prevention services.

8.3.3.2 Education

Dh. Hulhudheli has pre-school, primary and secondary education. The secondary school offers subjects in business, science, and B-tech. According to School Statistics issued by Ministry of Education (2017), the total number of students enrolled in the schools total up to 197.

8.3.3.3 Utilities

Electricity in the island is provided by state-owned utility company FENAKA Corporation with two (2) generators (600KW and 300KW) with a total capacity of 900KW in the power station. According to the Ministry of National Planning, Housing and Infrastructure, an ongoing project of water and sanitation system is currently being implemented in Dh. Hulhudheli. The work is expected to finish by the end of 2022.

8.3.3.4 Transportation

The island has island pick up services and has weekly and daily speedboat ferries to Male'. As per council, there are three speed boats operating on the island. Currently, Dh. Hulhudheli harbor upgrading work is being carried out by Maldives Transport and Contracting Company (MTCC) company. The work is expected to finish by the end of 2022.

8.3.4 Water resources, water usage and water consumption survey

Currently, there are a total of 125 inhabited households in the island. 96 out of 125 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 119: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	**96/125 households = 75.2%**
Percentage of well fitted with pumps	100%
Ground water	**Usage in percentage**
Source of drinking	0%
Source of cooking	0%

8.3.4.1 Existing water and sanitation

The island has a sewage disposal network installed in 2018 that is being utilized currently. The main form of sanitation is via the use of island sewerage network connection and septic tanks. A piped water supply system is currently under construction and is expected to finish by 2022. Rainwater

collected from rooftops is stored in water tanks, whether communal or home tanks. Rainwater is the primary source of drinking water. Rainwater is also the primary supply of water for cooking. Many homes utilize rainwater from neighboring houses or bottled water when rainwater is scarce during the dry season. The households are recommended to keep a 15 meters (49.2 ft) distance between septic tank and the 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 Dh. Hulhudheli 33% reported to have less than 49ft distance between septic tanks and water well. Meanwhile, 63% reported that they do not know the exact distance between both well and septic tank.

8.3.4.2 Water usage and resources

Based on the survey conducted in Dh. Hulhudheli, all the houses have HDPE rainwater tanks for rainwater storage. 100% of the households use rainwater for drinking and 98% use rainwater for cooking. While groundwater is mainly used for gardening, household cleaning with all the houses fitted with water pumps. The following sections outlinefurther details about various water usage and consumption scenarios in the island.

8.3.4.3 Domestic water usage

Based on household water usage surveys in Dh. Hulhudheli, **182,978** liters of water is used daily in the households. A total of **191** liters of groundwater are consumed per capita per day.

Table 120: Domestic groundwater use data for Dh. Hulhudheli

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
90.6	32.8	10.9	32.8	1.63	18	4	**191**

*All units are in Liters per capita per day

8.3.4.4 Commercial water usage

Based on the survey conducted in Dh. Hulhudheli, there are currently two operational café'/restaurant and no guesthouses on this island. A total of 561 Liters of groundwater are used by commercial entities and their detailed breakdown is given in the table below.

Table 121: Commercial groundwater use data for Dh. Hulhudheli

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Green DIamond Cafe	90	61	180	5.71	336
Endheri Coffee house	45	30	125	25	225
					561

*All units are in Liters per day

8.3.4.5 Institutional water usage

Based on the survey conducted in Dh. Hulhudheli, there are currently five institutions that has groundwater well facilities and use groundwater on this island. A total of 4991 Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 122: Institutional groundwater use data for Dh. Hulhudheli

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Health Centre	141	720	30	151	1042
Hulhudheli Council	157	360	5	-	522
Hulhudheli School	1684	200	26	-	1910
FENAKA	117	720	2	-	839
Hulhudheli Pre School	133	540	5	-	678
					4991

*All units are in Liters per day

8.3.5 Present & Future water demand

In Dh. Hulhudheli, the present water demand is at **188,530** liters per day inclusive of domestic, commercial, institutional, and industrial water demand. 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.

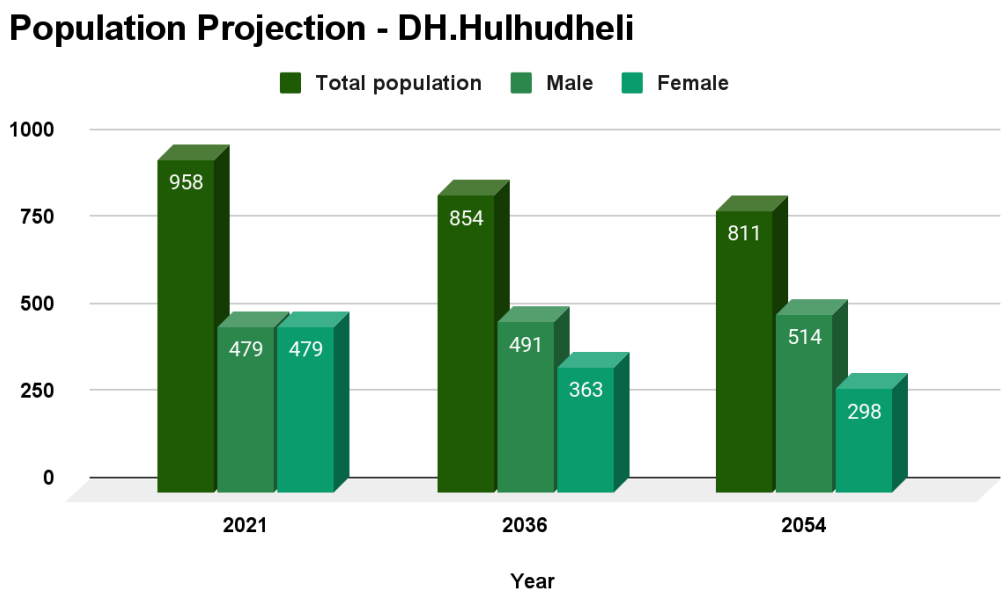


Figure 119: Population Projection - Dh. Hulhudheli

Table 123: Present groundwater demand - Dh. Hulhudheli

Year	Total Population	Domestic water demand	Commercial water demand	Institutional water demand	Groundwater usage
2021	958	182,978	561	4,991	**188,530**

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 191 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 191 Liters, the groundwater demand is expected to be 141 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 854 is expected to be 120,414 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 191 Liters, the groundwater demand is expected to be 116 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 811 is expected to be 94,076 Liters per day.

Table 124: Future domestic water demand - Dh. Hulhudheli

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	854	191	50	141	120,414
2054	811	191	75	116	94,076

8.3.6 Water related issues

From 96 households surveyed in Dh. Hulhudheli, most houses reported smell and foul taste in their wells. However, majority of the surveyed households also reported having no contamination in their groundwater. Only 9% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gasses such as hydrogen sulphide which causes unpleasant smells. In Dh. Hulhudheli the usage of oxygen pumps is not as much due to less contamination in groundwater.

Table 125: Signs of contamination reported by households

Types of contamination	Data in % out of 96 households surveyed
Smell	39.6%
Milky	12.5%
Foul taste	20.8%
Salty	7.29%
None	55.2%

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

Table 126: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 96 households surveyed
Changes with tidal variations	20.8%
Groundwater quality is better in rainy months	50%
Long periods without rain causes bad smell	29.2%
Long periods without rain causes bad taste	19.8%
Rain makes it worse	2.08%
No change	41.7%

8.4 Groundwater Quality

8.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 127 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 127: Physiochemical Parameters of Dh. Hulhudheli Groundwater

	EC (µS/cm)	Turbidity (FNU)	DO (mg/L)	pH	Temp (°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 threshhold <35 Taste threshhold 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 NH_3= Ammonia, NO_3= Nitrate, PO_4^{3-}=Phosphate,
SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source[1] = WHO Drinking Water Guidelines, 2017. Source[2] = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 1349 µS/cm fall below the WHO Standard for potable water (<1500 µS/cm). The maximum value for EC (7297 µS/cm) was observed at the new Powerhouse which is located away from the inhabited areas near the shoreline of the island.
- Only two samples had higher EC than 2500 µS/cm and both of them were located significantly close to the shoreline. Six samples had EC between 1500 µS/cm and 2500 µS/cm while 31 samples had EC lower than 1500 µS/cm. The EC distribution is shown in Figure 121.
- The mean Turbidity level at 1.2 NTU fall within the URA Guidelines for drinking water (<5 NTU). Only two samples had higher Turbidity level than 5 NTU.
- All samples fell within the pH range of 6.5-8.5 as per URA Guidelines for drinking water with a mean pH of 7.42.
- Temperature ranges from 26.80°C to 39.7°C depending on the well characteristics and time of day reading was taken. Mean temperature was 29.33°C.
- Salinity ranged from 0.22ppt to 3.01ppt with a mean of 0.61ppt.
- The mean Ammonia concentration was 4.96 mg/L which is higher than the WHO threshold for odour but well below the threshold for taste. 23% of samples had concentration below 1.5 mg/L, 75% of samples had concentration between 1.5 mg/L and 35 mg/L and 3% of samples

had concentration higher than 35 mg/L. The Ammonia concentration distribution is shown in Figure 120.

- The mean Nitrate concentration was 19.44 mg/L which falls within the WHO Standard for Nitrate concentration (<50 mg/L). Only 3 samples had Nitrate concentration higher than the standard.
- Phosphate concentration ranges from 0.1 to 1.84 mg/L with a mean concentration of 0.44 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. None of the samples tested were below 0.1 mg/L.
- Phosphate concentration is generally higher in densely populated residential area.

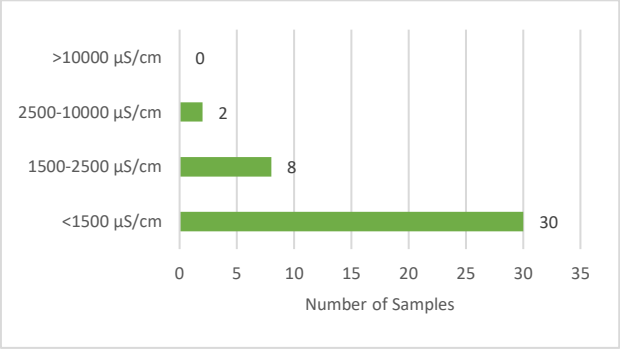


Figure 121: EC Distribution in Dh. Hulhudheli

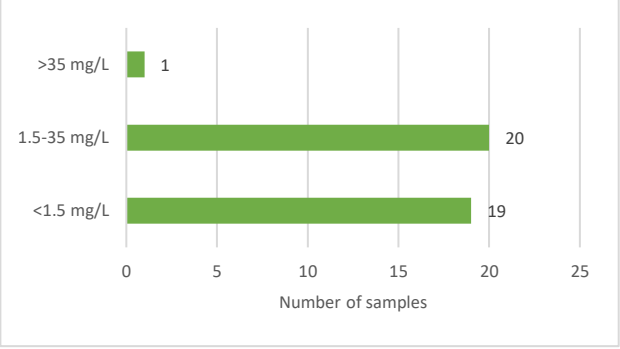


Figure 120: Ammonia Concentration Distribution in Dh. Hulhudheli

The spatial distribution of all the parameters measured are shown in Figure 122 (a-i).

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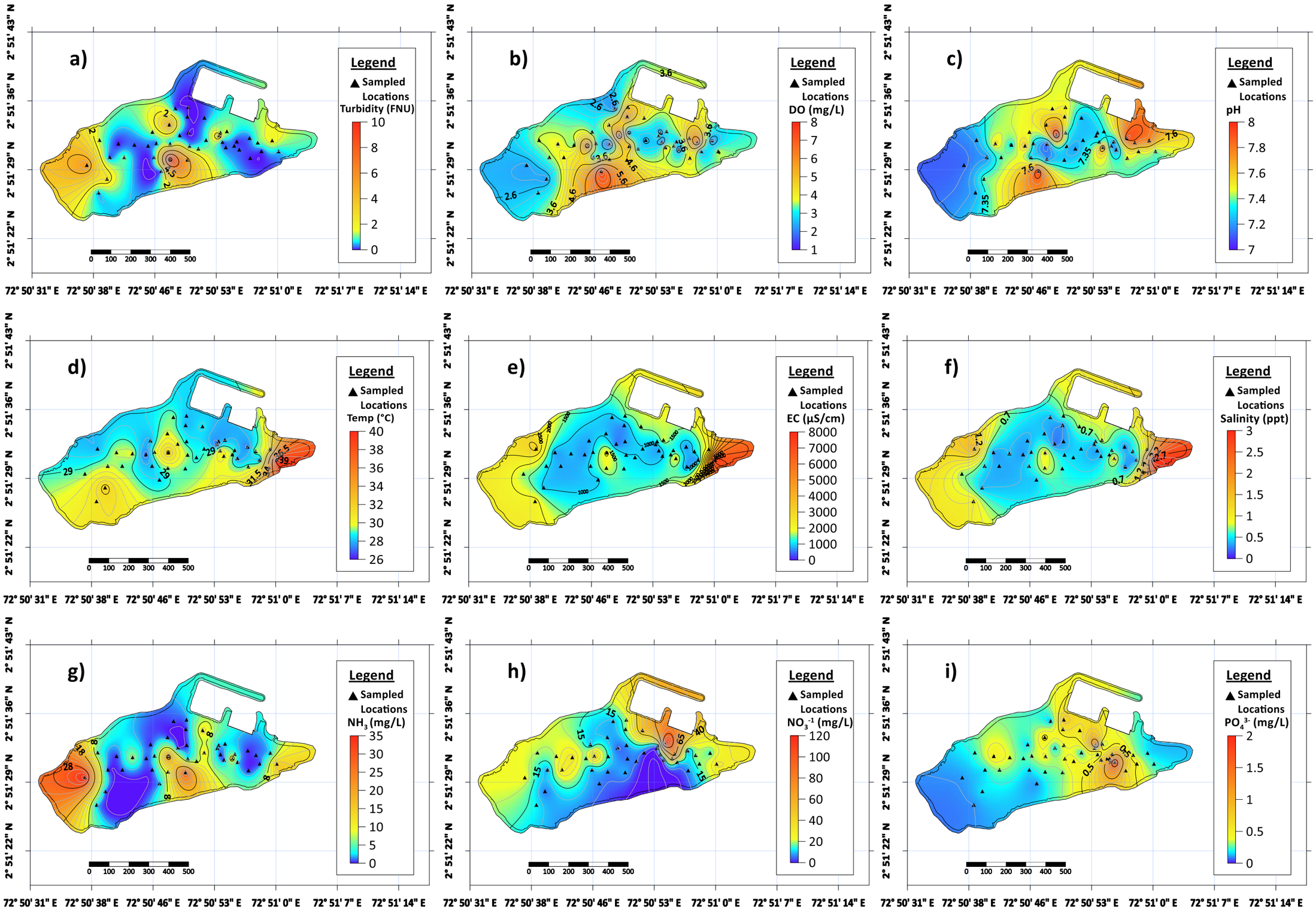


Figure 122: Spatial variation of physiochemical parameters in Dh. Hulhudheli

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 0.025 and the R-squared of the plot is 0.0006 as indicated from the Figure 123. 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.

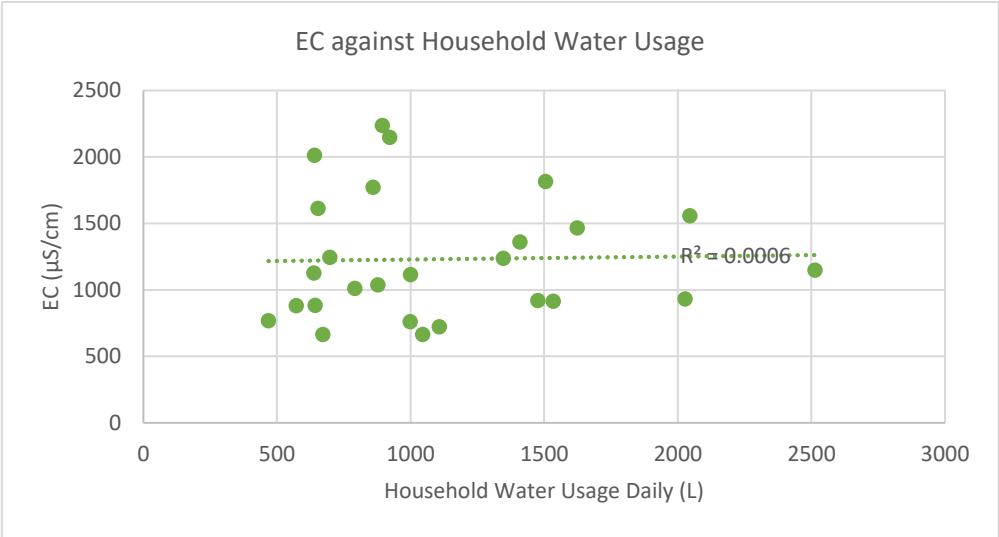


Figure 123: EC against Water Usage in Dh. Hulhudheli

8.4.1.1 Correlation Matrix

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

Table 128: Correlation matrix analysis result of the groundwater quality parameters in Dh. Hulhudheli

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)	0.02							
pH	-0.21	0.64						
EC (µS/cm)	0.07	-0.15	-0.21					
Sal (ppt)	0.08	-0.16	-0.24	***1.00				
Temp (°F)	-0.01	-0.15	-0.03	0.75	0.70			
NO_3 (mg/L)	-0.13	-0.09	-0.09	0.19	0.21	0.00		
NH_3 (mg/L)	0.44	-0.19	-0.19	0.34	0.34	0.27	0.10	
PO_4^{3-} (mg/L)	-0.16	-0.17	-0.17	-0.07	-0.05	-0.27	0.09	-0.13

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation

Table 128 shows a strong positive correlation coefficient between EC/Sal (r=1.00), EC/Temp (r=0.75) and Sal/Temp (r=0.70). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlations between salinity and conductivity and temperature 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 2.59 to 34.3 with a mean WQI of 9.12. The WQI was divided into four categories and Table 129 shows the categorization of samples. 70% of samples were classified as "Very Good", 25% 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 from the high EC at one location close to the shoreline and high Nitrate concentration at the other. The spatial distribution of WQI is shown in Figure 124.

Table 129: WQI Categorization for Dh. Hulhudheli

WQI	Category	No. of samples	Percentage
0 to 10	Very Good	28	70%
10 to 20	Good	10	25%
20 to 50	Poor	2	5%
>50	Very Poor	0	0%

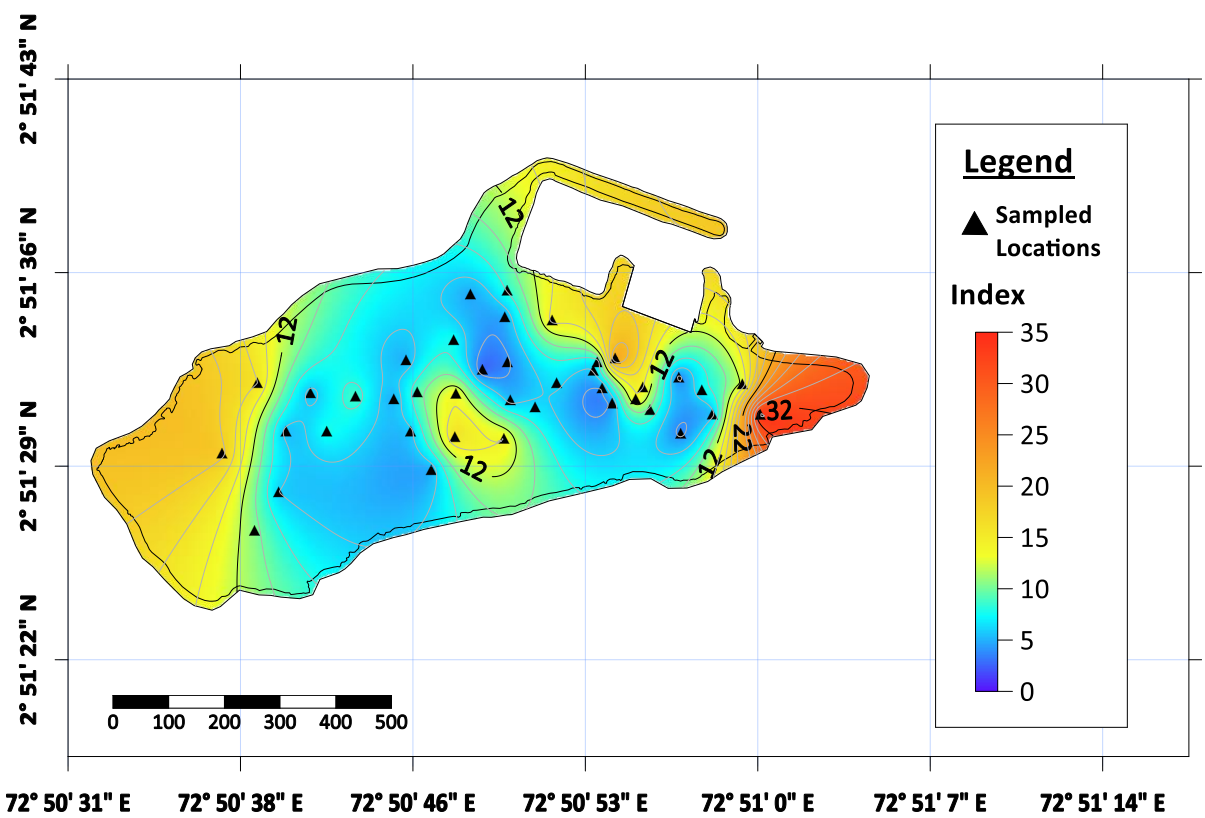


Figure 124: Spatial Distribution of WQI in Dh. Hulhudheli

8.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 130 summarizes the results.

Table 130: Microbiological Parameters of Dh. Hulhudheli Groundwater

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq01	>2420	3		Connected to island sewerage network. No Septic Tanks used.
wq02	>2420	208		Connected to island sewerage network. No Septic Tanks used.
wq03	17	2		Connected to island sewerage network. No Septic Tanks used.
wq04	>2420	91		Connected to island sewerage network. No Septic Tanks used.
wq05	>2420	291	12	Connected to island sewerage network. No Septic Tanks used but they gave information about previously used septic tanks.
wq06	>2420	113	20	Connected to island sewerage network. No Septic Tanks used but they gave information about previously used septic tanks which have never been cleaned
wq07	1986	20	30	Connected to island sewerage network. No Septic Tanks used but they gave information about previously used septic tanks which have never been cleaned
wq08	186	23		Connected to island sewerage network. No Septic Tanks used.
wq09	>2420	1986		Empty Household
wq10	74	4		Health Centre
wq11	46	Not Detected		School
wq12	>2420	23		Rental House
wq13	>2420	Not Detected		Preschool
wq14	>2420	3		Connected to island sewerage network. No Septic Tanks used.
wq15	160	Not Detected		Connected to island sewerage network. No Septic Tanks used.

*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 with 9 samples containing Total Coliform count higher than 2400 MPN/100ml.

Since this island has a sewerage network commissioned in 2018 that is being utilized currently, it was expected for the faecal and total coliform count to be lower than other islands. However, since most

households have not fully decommissioned their previously used septic tanks, the effects of effluent from these tanks are still evident in the groundwater. On average, there is an approximate distance of 29 feet between septic tanks and the nearest well as observed from social survey. The spatial distribution of Total Coliform and Faecal Coliform is given in Figure 125. Total Coliform was detected in all samples with an even distribution across the island. High count of Faecal Coliform is detected on the South side of the island.

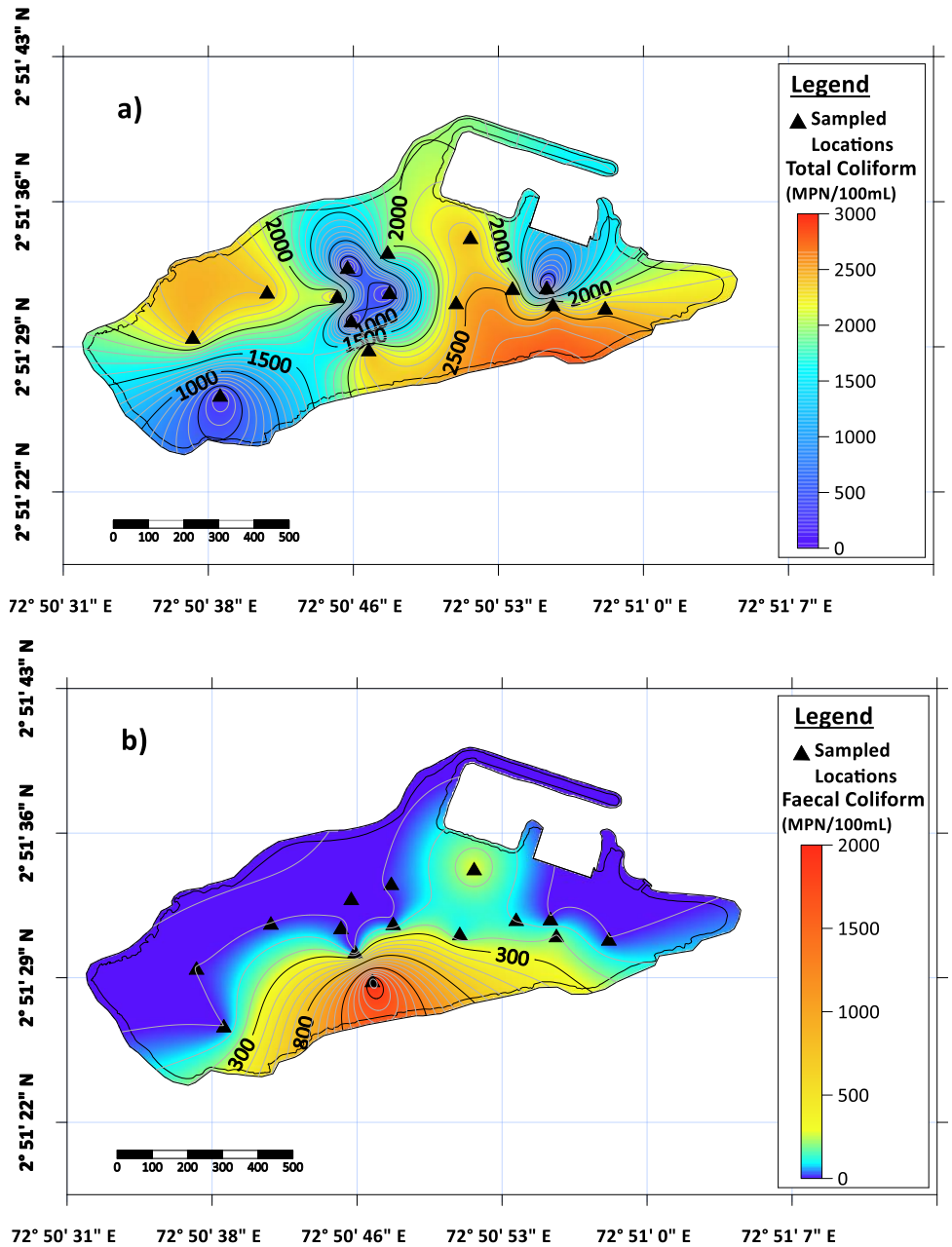
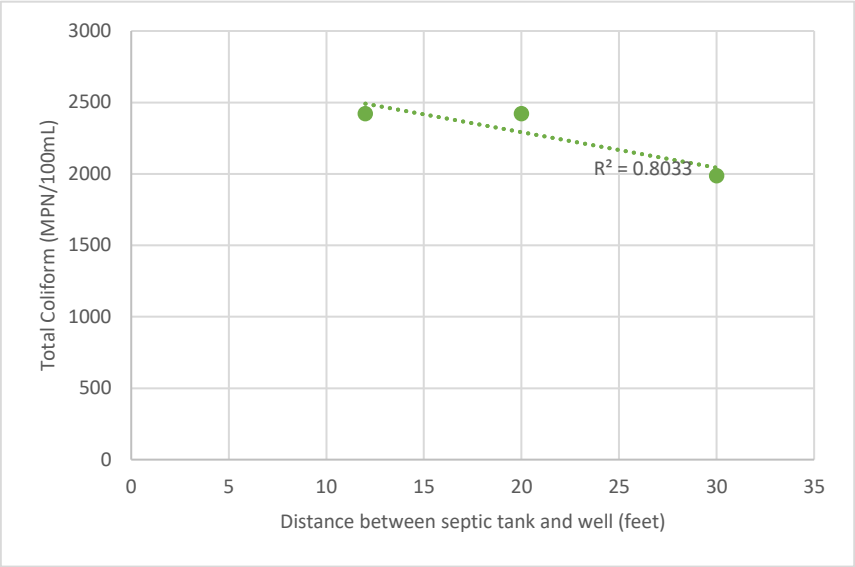


Figure 125: Total (a) and Faecal (b) Contamination Distribution in Dh. Hulhudheli

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.



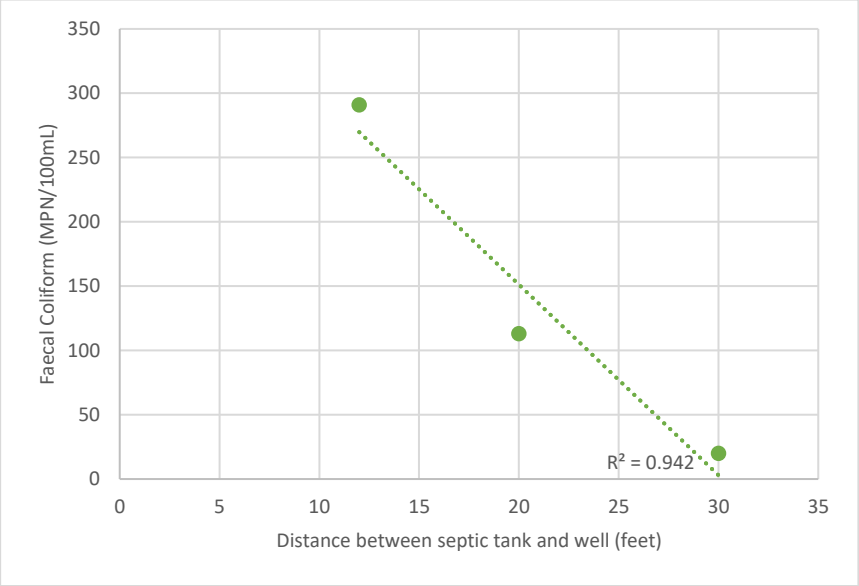


Figure 126: Microbiological Contamination against Septic Tank distancing - Hulhudheli

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.896 and the R-squared of the plot is 0.803 as indicated from the Figure 126. The correlation coefficient of Faecal Coliform to distance between septic tank and well is -0.971 and the R-squared of the plot is 0.942 as indicated from the Figure 126. Therefore, there is a significant negative relationship observed between the parameters.

8.5 Pumping Test

8.5.1 Test location

A well without a base was not available in Dh. Hulhudheli. Therefore, it was decided to carry out the test at the new mosque as the mosque well would be unused for most parts of the day. The chosen well had an inlet of approximately 2 inches' diameter at the concrete base plate. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 127 below shows the location for the pumping test at Dh. Hulhudheli.

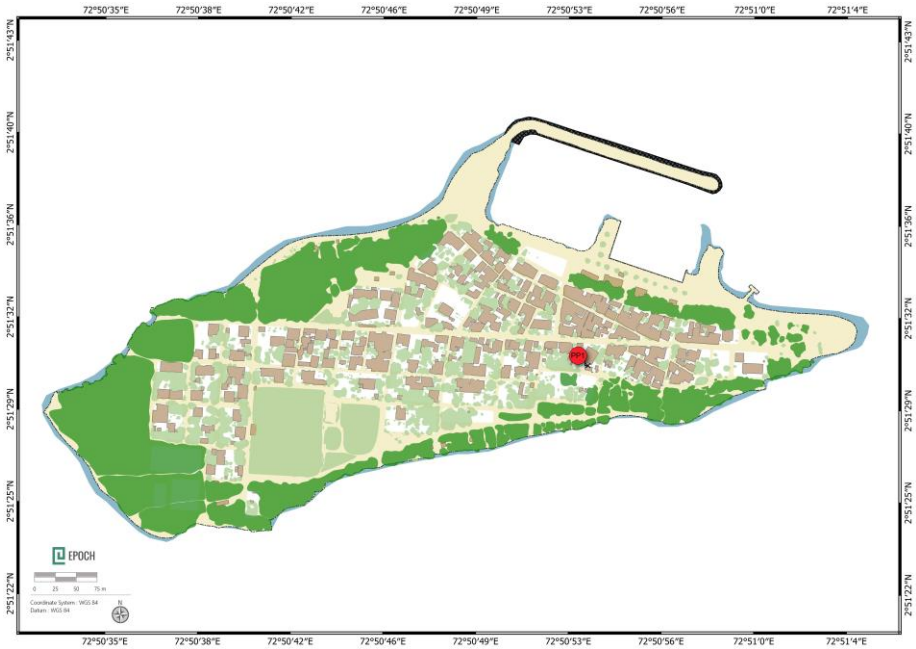


Figure 127: Pumping test location - Dh. Hulhudheli

8.5.2 Pumping rate, pumping hours, and collected data

A step-drawdown pumping test was carried out at Dh. Hulhudheli. The test began at 1602 hours on 27 August 2021 and lasted for 125 minutes. A flowrate of 30 LPM was maintained for 0-60th minute of the test. The flow was then gradually increased to 40 LPM for 60th-62nd minute, 50 LPM for 63rd-67th minute, 60 LPM for 68th-70th minute, 70 LPM for 71st-83rd minute, and 80 LPM for 84th-90th minute. The recovery phase of the test lasted from 91st-125th minute for more than a 93% 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. The analysis was carried out using the software, AQTESOLV. The Aquifer Transmissivity (T) value was estimated to be 8.77x10^{-4} m2/s (75.75 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.1906 for Dh. Hulhudheli. The full data set of the pumping test at Dh. Hulhudheli has been annexed at Annex XI.

8.6 Permeability Test

8.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 128 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.

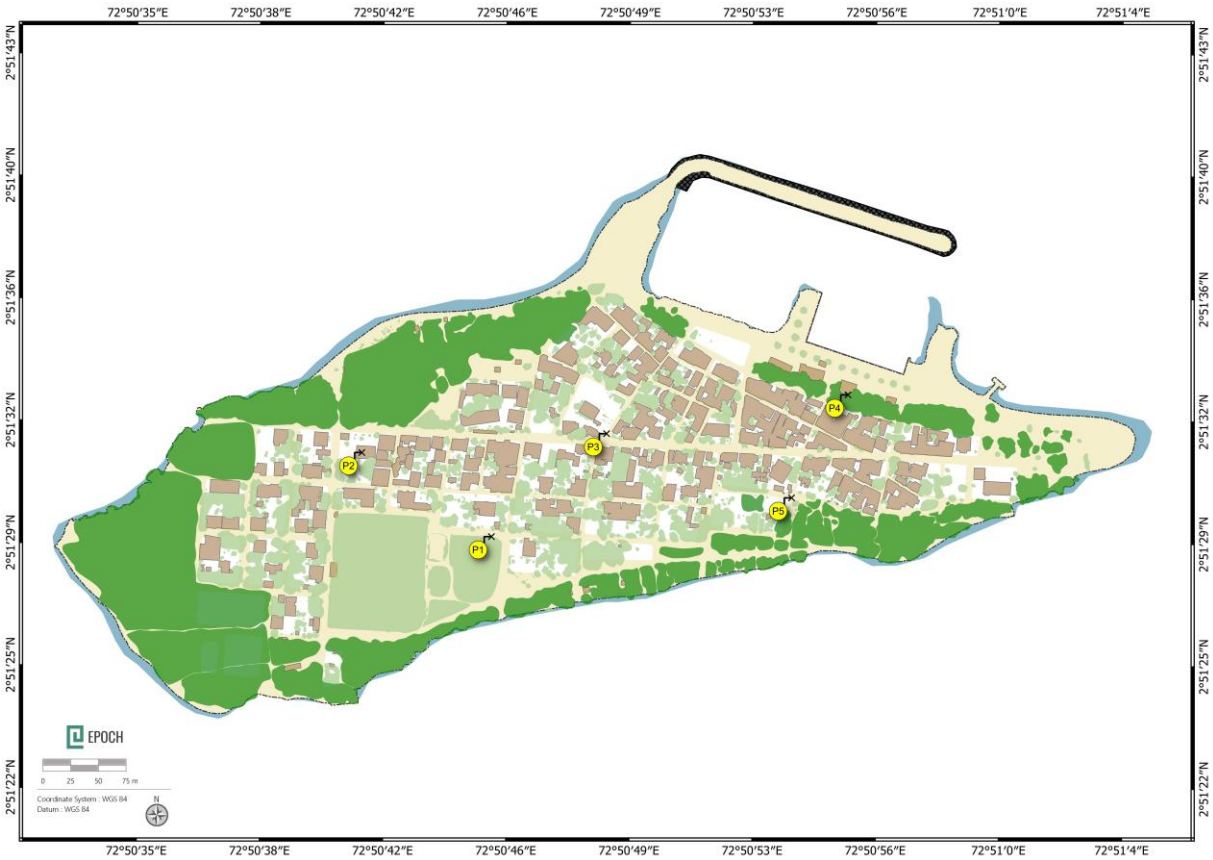


Figure 128: Permeability Test Locations - Dh. Hulhudheli

8.6.2 Measured data

Table 131: Permeability Test Measured Data - Dh. Hulhudheli

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m3/s)	K (m/s)	K (m/day)
HDL-PMB1	0.640	1.145	35	12.8	7.24	0.000121	1.08E-04	9.32
HDL-PMB2	0.600	1.140	35	12.0	14.00	0.000233	2.09E-04	18.04
HDL-PMB3	0.600	1.400	35	12.0	21.00	0.000350	2.55E-04	22.03
HDL-PMB4	0.600	0.820	35	12.0	13.00	0.000217	2.69E-04	23.28
HDL-PMB5	0.675	0.600	34	13.5	3.50	0.000058	1.02E-04	8.78

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 Dh. Hulhudheli is 16.29 m/day, with permeability values ranging from 8.78 m/day to 23.28 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 129 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.

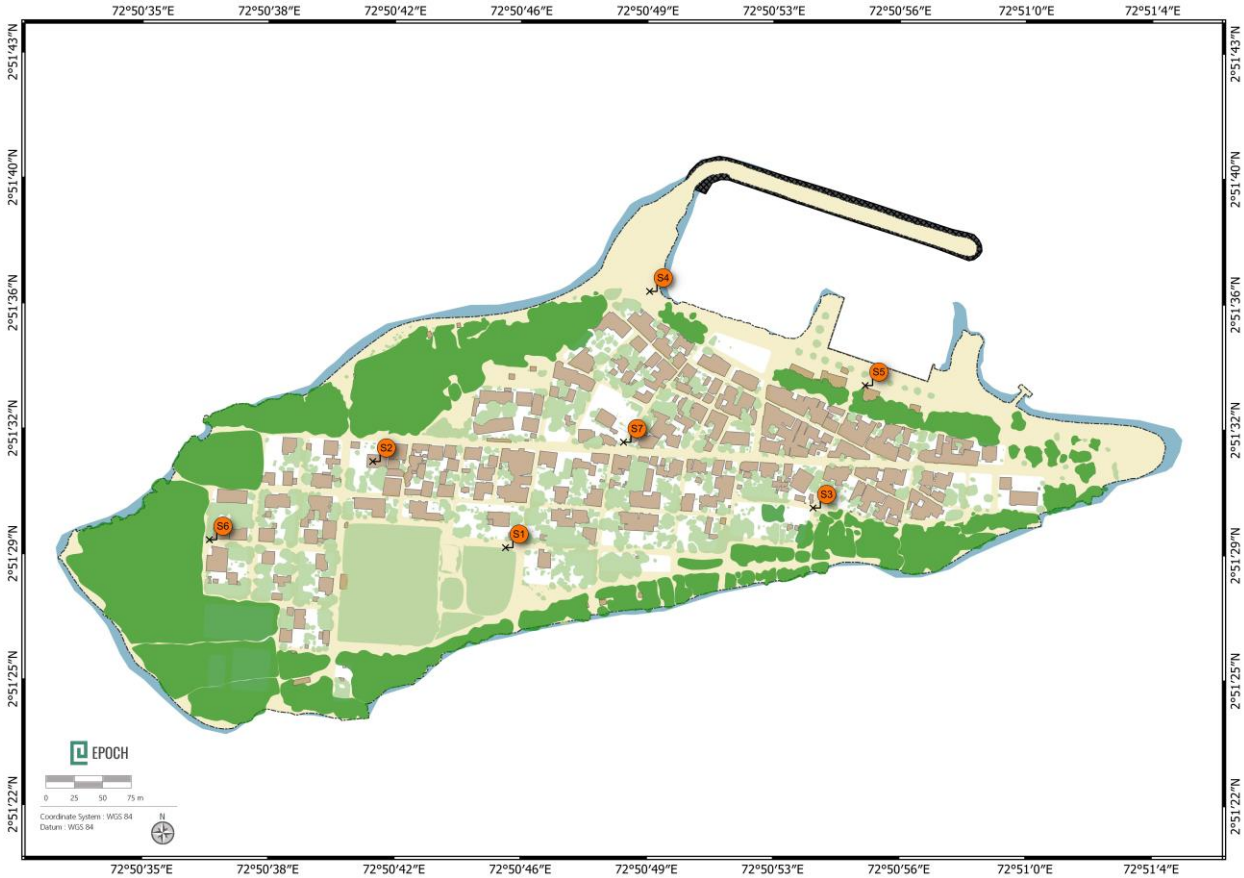


Figure 129: Soil Profile Survey Locations - Dh. Hulhudheli

8.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 130 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.

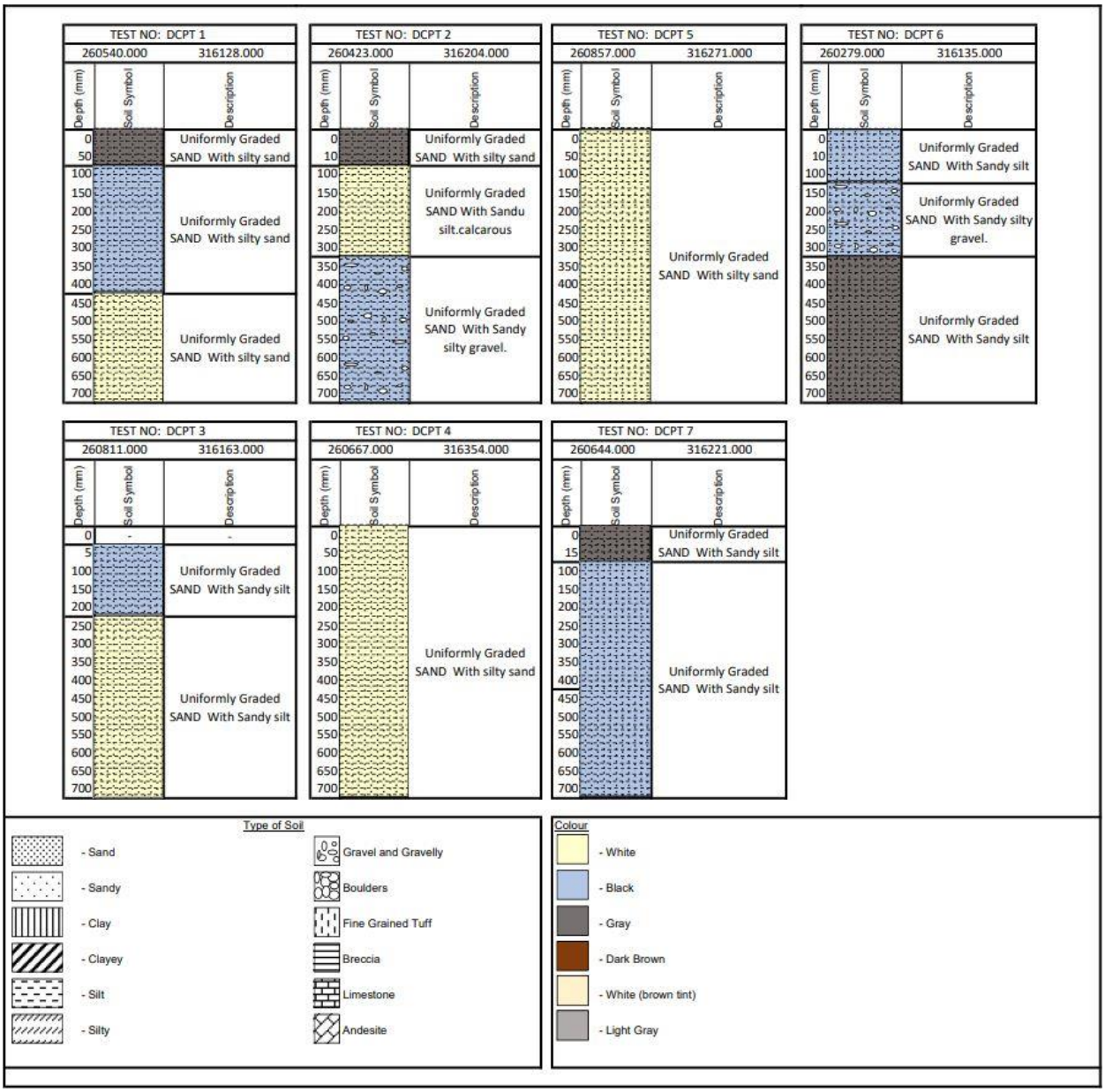


Figure 130: Soil Profile - Dh. Hulhudheli

8.8 Flood Assessment and Inundation Survey

8.8.1 Flood occurrence and flood impact

The island has not reported any severe seasonal flooding incidents. Only 25% of the respondents reported that ponding occurs every time it rains heavily. Island residents also stated that because of the island topography, the water flows out from two sides of the island.

Ponding usually 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 neighbors' 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 132: Perceived causes of flooding – Dh. Hulhudheli

Perceived causes of flooding				
Roof run off	**Neighbours' roof**	**Off the road**	**General run off in the area**	**No flooding within the plot**
44%	21%	4%	8%	51%

As per social survey, 43% of the households also report flooding as an acceptable problem (refer to flood severity component of Flood Maps in Annex XII). This can be due to continuous flood mitigation efforts by the island council and residents as reported by households.

From the social survey, 50% 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 which include overflow to the ground, roads, open areas within the plot, to the well and to the sewerage network. Details of discharge of rainwater overflow are given in the table below.

Table 133: Discharge of rainwater overflow – Dh. Hulhudheli

Discharge of rainwater overflow				
Ground	**Roads**	**Open area within the plot**	**Drained to well**	**Sewerage network**
51%	16%	17%	15%	1%

8.8.2 Inundation area identification

Based on the social survey responses, an average of 1.08ft is estimated as the flooding depth when there is heavy rainfall. Majority of the respondent's indicated flooding does not happen often in the island. Therefore, the flood depth accumulated was reported by only 6% of the surveyed respondents. Also, 37% reported that it takes 2-4 hours to inundate the area once the heavy rain starts. Common ponding areas reported in Dh. Hulhudheli are near the mosque, school, football field, main road, harbor and beach (thundi area) (refer to Annex XII: Flood Maps).

8.8.3 Draining flood water

The island has a gravity sewer system within the island but there is no established storm water drainage system in the island. As per the social survey, 86% observe that the water drains during the rainfall itself, 7% observe that the water drains in less than 4 hours, 7% observe that the water drains in less than 4-24 hours and 0% observe that it takes more than 24 hours for water to drain.

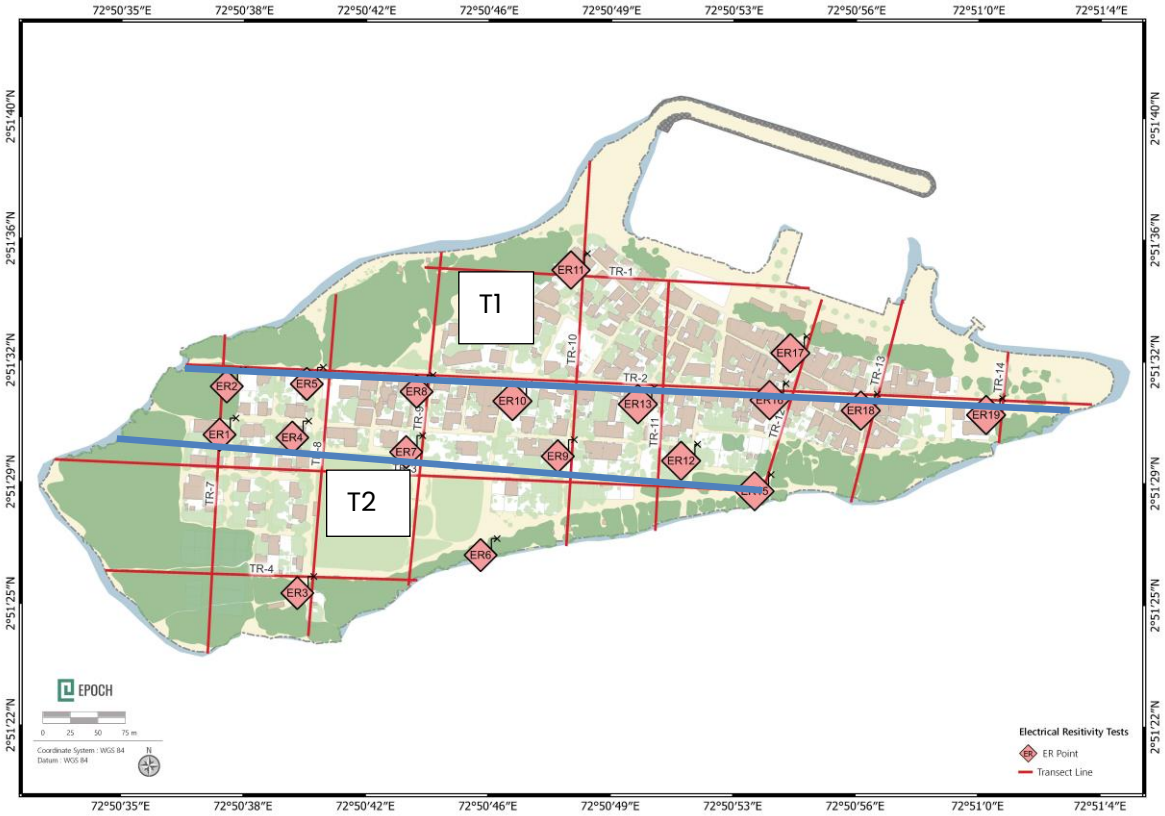
Table 134: Draining period – Dh. Hulhudheli

Draining period			
only while raining	**drains less than 4hrs**	**takes 4-24 hrs**	**more than 24hrs**
86%	7%	7%	0%

8.9 Geophysical Survey

8.9.1 Surveyed locations

Locations where ER sounding measurements were taken at Dh. Hulhudheli island are shown in Figure 131 together with transect lines. There are 18 ER measurement locations and the number of transects in this island is 12.



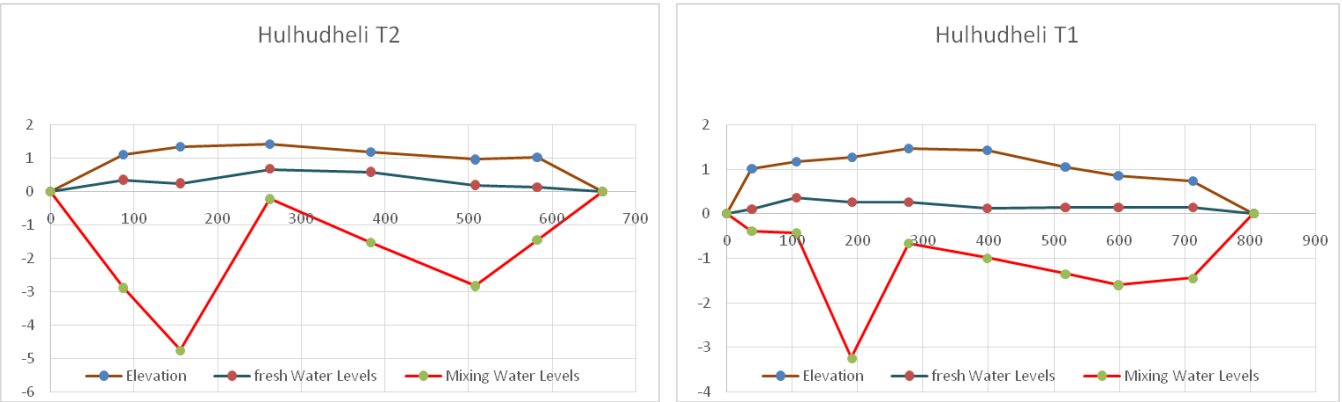


Figure 131: ER surveyed locations and transect lines – Dh. Hulhudheli Island

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 135 below shows the estimated levels at ER surveyed locations of Dh. Hulhudheli Island and freshwater lens thickness.

Table 135: Freshwater lens levels and thickness – Dh. Hulhudheli island

No	Location	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	2	1.01	0.11	-0.39	0.50
2	5	1.16	0.36	-0.44	0.80
3	8	1.26	0.26	-3.24	3.50
4	10	1.46	0.26	-0.66	0.92
5	13	1.42	0.12	-0.99	1.11
6	16	1.04	0.14	-1.35	1.49
7	18	0.84	0.14	-1.60	1.74
8	19	0.73	0.13	-1.45	1.58
9	15	1.03	0.13	0.35	-0.22
10	12	0.96	0.19	-2.82	3.01
11	9	1.18	0.58	-1.52	2.10
12	7	1.42	0.67	-0.21	0.88
13	4	1.34	0.24	-4.75	4.99
14	1	1.10	0.35	-2.87	3.22
15	3	0.91	0.16	-2.02	2.18
16	6	1.11	0.11	-0.04	0.15
17	11	1.05	0.07	-0.40	0.47
18	17	1.16	0.31	-2.14	2.45

Average freshwater thickness of Dh. Hulhudheli island is 1.72m. Maximum recorded thickness of freshwater lens of the Island by ER survey is 4.99 m & minimum is -0.22 m

Data in Table 135 were used to plot freshwater lens cross sections along 10 transects. Of these sectional plots 2 were given in Figure 131 and they represent the transect plots along the longitudinal section of the island.

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 132.

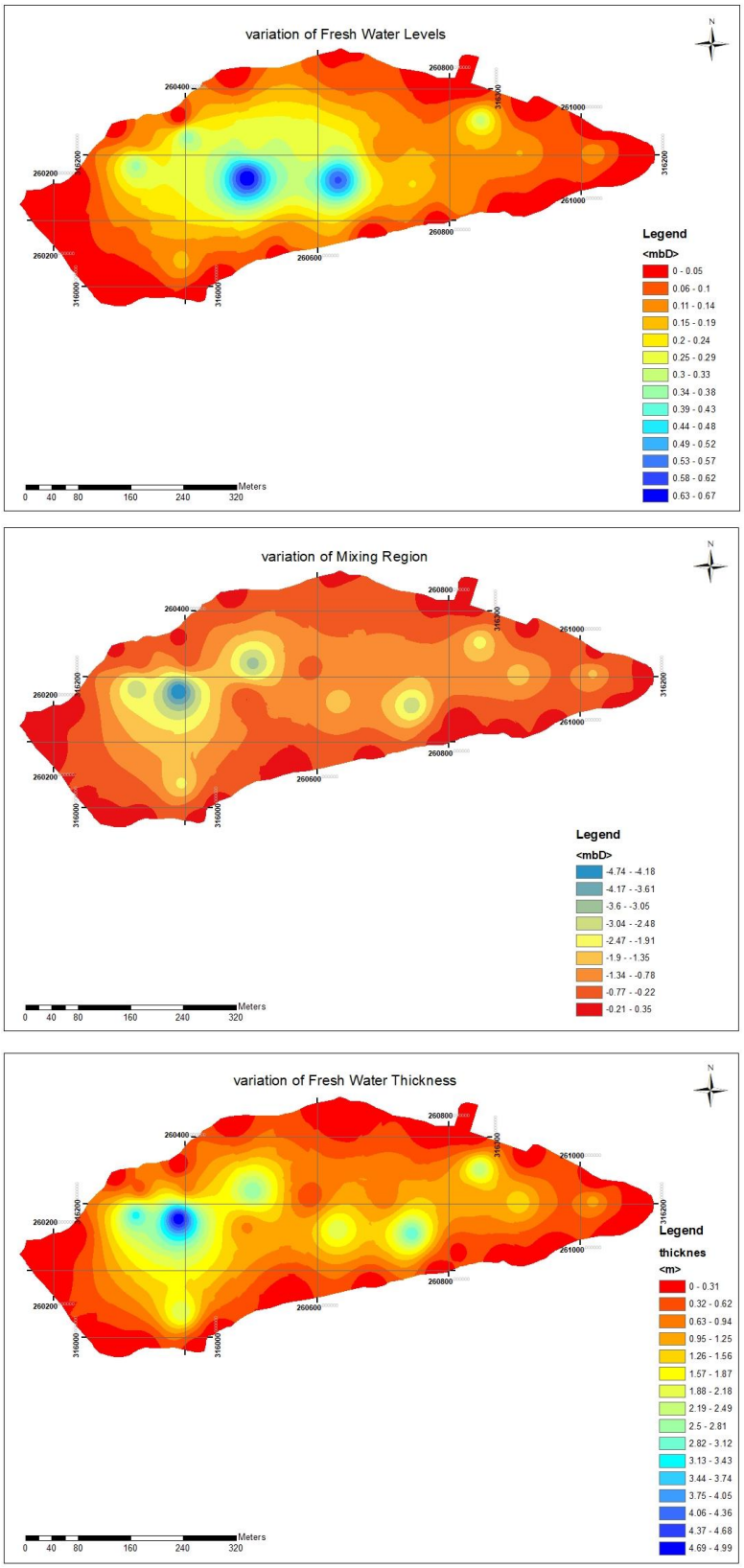


Figure 132: Top: Contours of Freshwater lens upper level, Middle: Contours of Freshwater lens lower level, Bottom: Spatial distribution of thickness of freshwater lens in Dh. Hulhudheli

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. Tools in ArcGIS software were used to perform this computation.

Stress level on freshwater aquifer of Dh. Hulhudheli 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 136.

Table 136: Freshwater lens volume and aquifer stress level – Dh. Hulhudheli island

Item	Value	Unit
Freshwater lens volume - ArcGIS	371,691	m^3
Groundwater abstraction	68,813	m^3/yr
Freshwater lens volume/ Groundwater abstraction	5.4	-
Aquifer stress level	Not Stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 5.40m. This deviates by 20.3% from the maximum measured value of 4.49m, which is more reliable as it results from a more comprehensive, site-specific methodology.

8.10 SWB Modelling

8.10.1 Land use categorization and area estimation

Table showing land classification and their respective areas are shown in Table 137.

Table 137: Land Use Classification – Dh. Hulhudheli

	Area (m^2)	% of total area
Roof cover	32,314	15%
Vegetation (Thick)	59,797	28%
Vegetation (Thin)	40,209	19%
Bare Lands	80,956	38%
Total	213,960	100%

8.10.2 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 Table 138). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 33,863 m^3, 111,482 m^3 and 77,870 m^3 respectively over a 20 year period.
- There is a good relationship between annual rainfall and annual recharge, but it is not linear instead an inverse exponential.
- Annual average rainfall is around 2243 mm
- Variation among the monthly average recharge value is very high. It is lowest on month of February and highest in November.

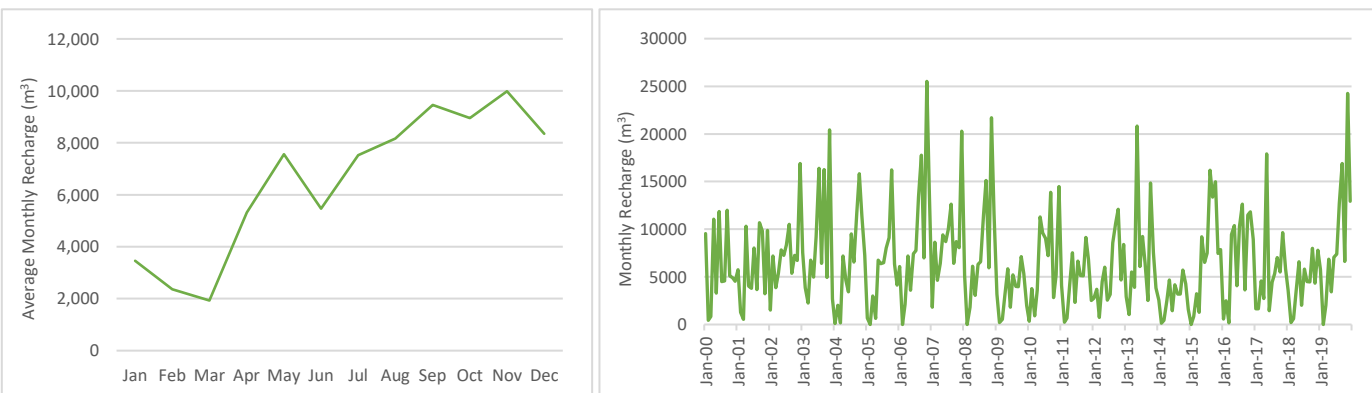


Figure 133: Monthly and annual recharge distribution in Dh. Hulhudheli

Table 138: Monthly recharge estimated by SWB model – Dh. Hulhudheli Island

Year	Monthly Recharge (m^3)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2000	9,533	448	830	11,036	3,304	11,866	4,487	4,569	11,994	5,124	4,922	4,528
2001	5,757	1,291	551	10,309	4,034	3,795	8,035	3,676	10,666	9,803	3,232	9,885
2002	1,505	7,184	3,865	5,345	7,833	7,245	8,319	10,514	5,362	7,241	6,711	16,892
2003	7,570	3,849	2,262	6,740	4,963	9,219	16,386	6,415	16,271	4,930	20,412	2,689
2004	111	2,031	185	7,196	4,651	3,438	9,507	6,563	11,654	15,823	11,399	7,245
2005	687	-	3,002	646	6,764	6,386	6,497	8,018	9,096	16,230	6,340	4,149
2006	6,069	-	2,118	7,204	3,594	7,426	7,764	13,418	17,776	6,982	25,515	13,619
2007	1,806	8,620	4,638	6,414	9,400	8,695	9,982	12,617	6,434	8,690	8,053	20,271
2008	5,159	-	1,800	6,124	3,055	6,312	6,599	11,405	15,110	5,935	21,688	11,576
2009	3,210	190	530	3,124	5,857	1,803	5,194	4,007	3,978	7,124	5,343	1,968
2010	325	3,777	912	3,594	11,271	9,610	9,040	7,229	13,876	2,821	5,218	14,462
2011	4,115	244	680	4,005	7,509	2,312	6,659	5,137	5,100	9,134	6,850	2,524
2012	2,768	3,696	729	4,489	6,008	2,552	3,146	8,580	10,627	12,089	4,660	8,389
2013	2,939	1,054	5,503	3,887	20,827	6,089	9,231	6,460	2,524	14,832	7,546	3,842
2014	2,568	152	424	2,499	4,686	1,443	4,155	3,205	3,182	5,699	4,274	1,575
2015	-	859	3,236	1,286	9,211	6,521	7,485	16,179	13,383	14,991	7,457	7,864
2016	574	2,483	175	9,439	10,396	4,054	10,273	12,630	3,618	11,486	11,836	8,951
2017	1,636	1,657	4,555	2,719	17,909	1,457	4,445	5,328	7,033	5,511	9,655	5,841
2018	3,601	213	595	3,505	6,571	2,023	5,827	4,495	4,462	7,992	4,334	7,802
2019	5,766	-	2,012	6,844	3,414	7,055	7,375	12,747	16,888	6,633	24,239	12,938

8.10.3 Water Balance

- As per estimation, annual recharge estimated by the SWB model is 148,323 m^3 and it is 32.5% of annual average rainfall (refer Figure 134).

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	456,380	6,878	214,499	148,323	86,412	68,813
%	100.0%	1.5%	47%	32.5%	19%	15.1%

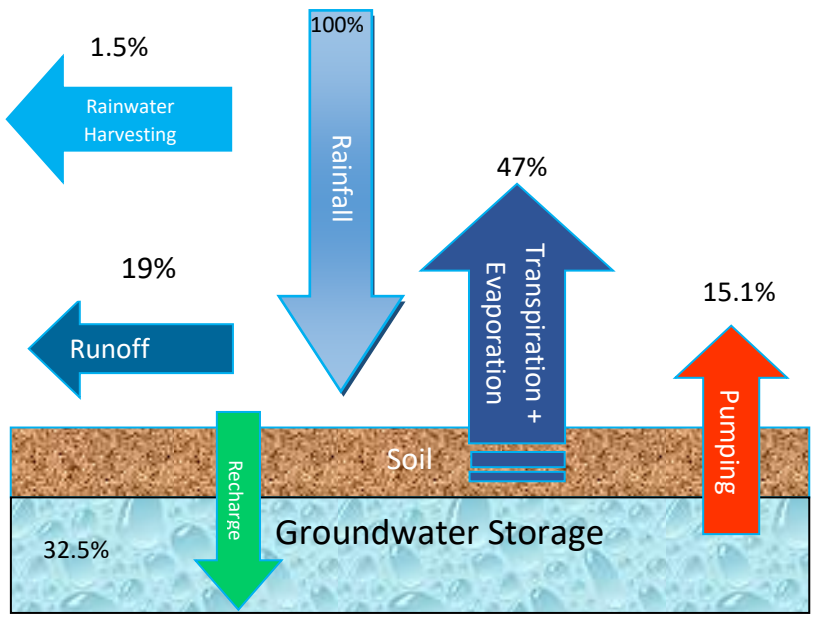


Figure 134: Annual water balance – Dh. Hulhudheli Island

8.10.4 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 (5734 m^3/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 – Dh. Hulhudheli

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	119	49.6

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 Dh. Hulhudheli island has a 49.6% 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 (68,813 m^3/yr) with safe abstraction volume (79,515 m^3/yr) shows that present withdrawal is 13.5% less than the safe yield.

8.11 SUTRA Modelling

8.11.1 Model representation and mesh production

SUTRA modelling requires mode domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island. The other boundary defined in the model was island outline which can be referred as shoreline most of the cases except at harbour area and the inner part of the island was subdivided to several polygons representing different land use and it was accomplished by importing GIS shape files of island land use and then drawing polygon 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.

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 135 shows the pressure boundary defined for Dh. Hulhudheli island.

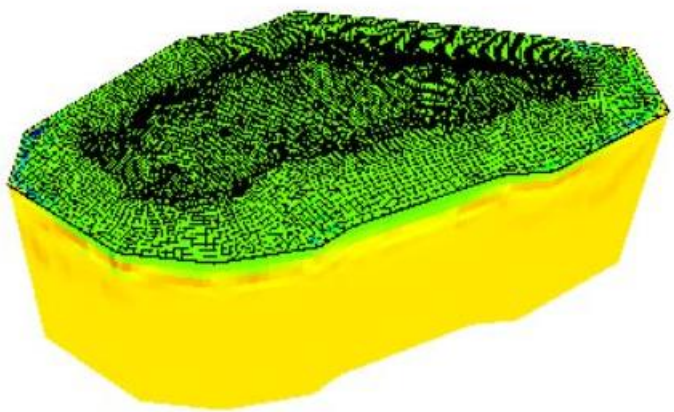


Figure 135: Pressure boundary at SUTRA model - Hulhudheli island

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.

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.

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 136. The section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0357 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top.

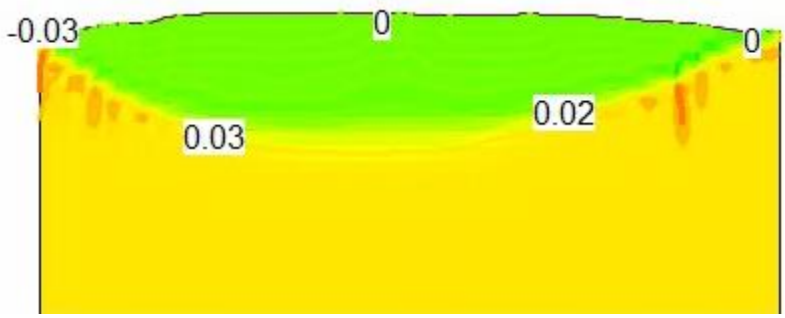


Figure 136: Saltwater distribution – Dh. Hulhudheli island

8.12 Summary of Baseline Assessment

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

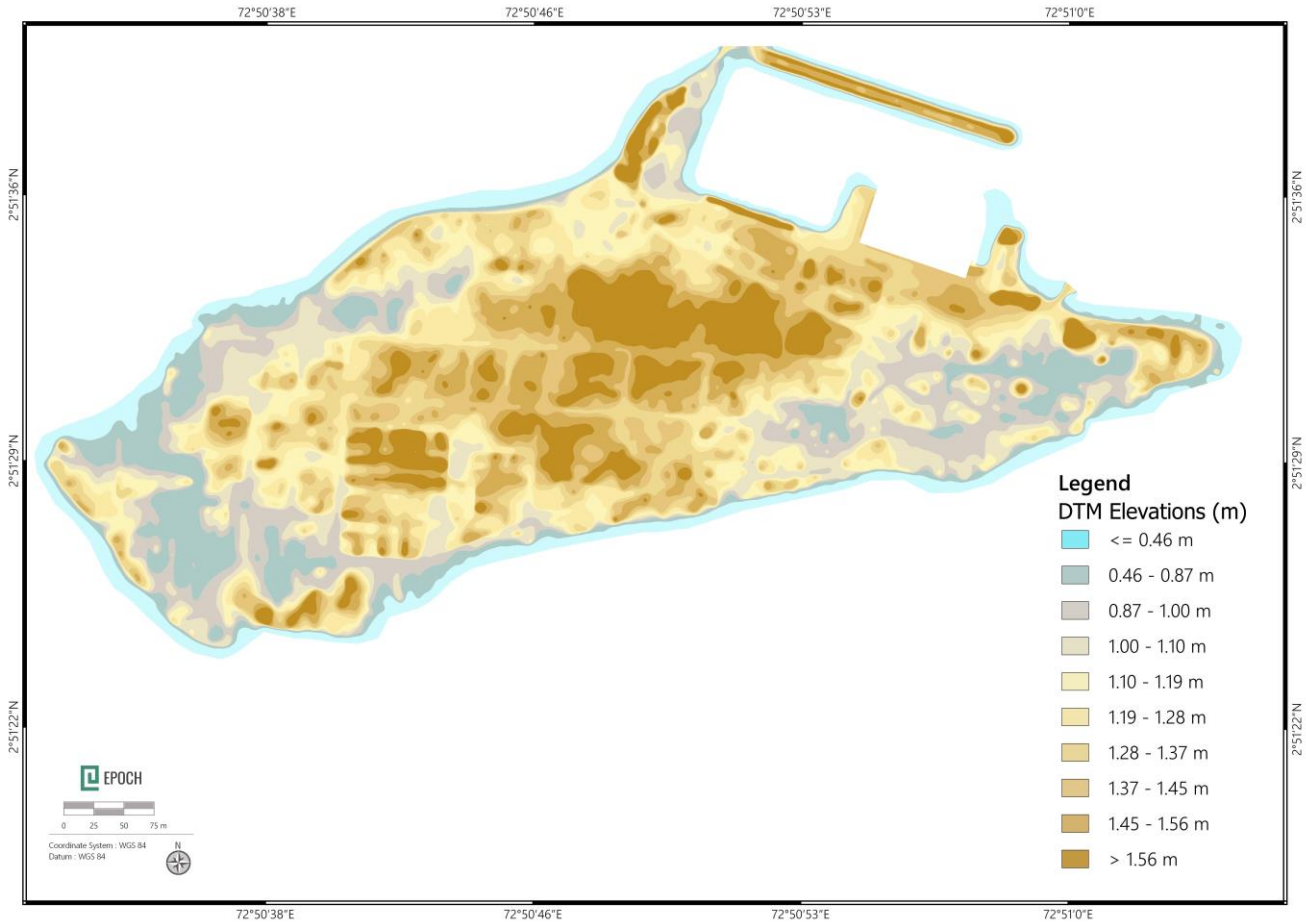
- General overview, demography, and climatology

Item	Details
Atoll	Nilandhe Atholhu Dhekunuburi
Length	0.97 km
Width	0.29 km
Area	21.3 ha
Population	958
Population/area	44.98 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use

Land use map

Topographical map



Average elevation = 1.100 m above MSL

Shoreline length = 3,313 m

	% of total area
Roof cover	15%
Vegetation (Thick)	28%
Vegetation (Thin)	19%
Bare Lands	38%
Farmlands	0%
Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Industrial	Institutional	Total
Rate (m^3/d)	183	0.56	-	4.99	189

- Water quality parameters – Physiochemical
  Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	1,349 ± 1,105	1500
Turbidity (FNU)	1.20 ± 2.05	5
DO (mg/L)	3.67 ± 1.40	
pH	7.42 ± 0.23	6.5-8.5
Temp (°C)	29.33 ± 2.02	
Sal (ppt)	0.61 ± 0.47	
NH_3 (mg/L)	4.96 ± 7.73	1.5 (Odour Threshhold)
NO_3^- (mg/L)	19.44 ± 21.12	50
PO_4^{3-} (mg/L)	0.44 ± 0.36	

- Water quality parameters – Microbiological
  Number of samples tested = 15

Parameter	Value range	Average value	Remarks *(on permit limit)*
Total Coliform (MPN/100ml)	17 - >2420	1616.6	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not detected - 1986	184.47	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	75.75	m^2/day
Storativity	1	0.1906	-
Permeability	7	8.78 – 23.28 Average – 16.29	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m^2)	Inundation depth (m)
43	5,850	0.330

- Electric Resistivity survey
  - Measurement taken at 18 locations.
  - Average freshwater thickness in the island is 1.56 m.
  - Freshwater lens volume and aquifer stress level

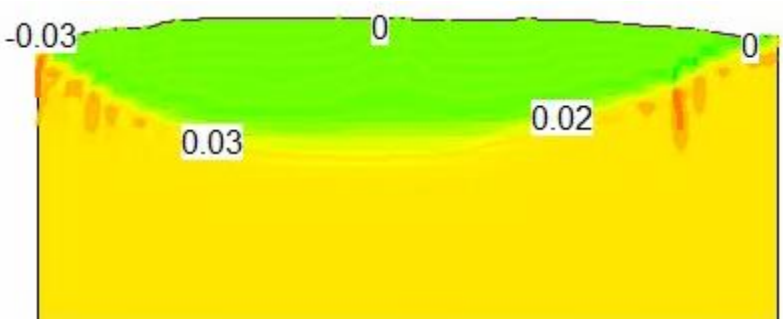
Item	Value	Unit
Freshwater lens volume - ArcGIS	371,691	m^3
Groundwater abstraction	68,813	m^3/yr
Freshwater lens volume/ Groundwater abstraction	5.4	-
Aquifer stress level	Not Stressed	-

- SWB modelling
  - Annual recharge is 148,323m^3 and it is 32.5% of annual rainfall (2242 mm)
  - Annual water balance

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	456,380	6,878	214,499	148,323	86,412	68,813
%	100.0%	1.5%	47%	32.5%	19%	15.1%

  - Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 49.6% in an average year, and it is compensated by ground water storage.
  - Ground water withdrawal (68,813m^3/yr) is 13.5% lower than the safe abstraction (79,515m^3/yr).

- SUTRA modelling
  - Average monthly recharge assigned to SUTRA model
  - Freshwater lens prediction (allowable concentration for potable use is 0.001)



9 Dh. Bandidhoo

9.1 Island Overview and Location

The Island of Dh. Bandidhoo, belonging to Nilandhe Atholhu Dhekunuburi Atoll, is in the Southern Central region of Maldives at 2°56'12.3"N and 72°59'25.5"E. It is approximately 149 km South-West of the capital Male'.

Table 140: Island Geographical Data

Island	Dh. Bandidhoo
Atoll	Nilandhe Atholhu Dhekunuburi Atoll
Location	2°56'12.3"N and 72°59'25.5"E

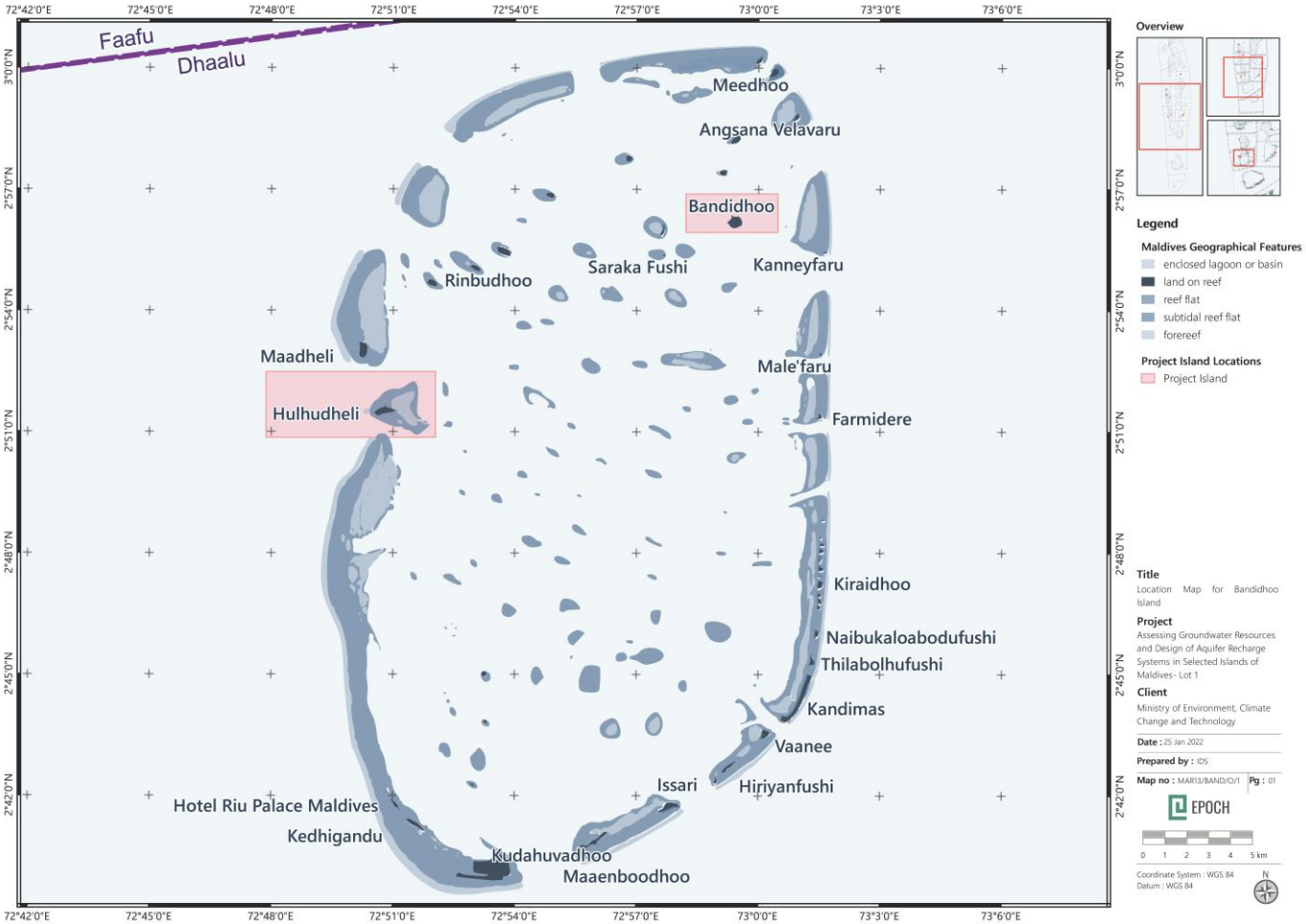


Figure 137: Location map – Dh. Bandidhoo

9.1.1 Island features

The island geographically has a circular shape and island extends up to 0.62 km in length from toe to toe and a width of 0.53 km from toe to toe. Dh. Bandidhoo has an old Friday Mosque which is made from coral rocks and is considered as a heritage site. The resident livelihood largely depend on agriculture as water surrounds the island from both sides.

The island has a harbour at its Northern-west side of the island. About two-third of the island's surface is vegetation. Thin vegetation is mostly located in the east side and center of the island. The west side and outer edge of the island is covered mostly by thick vegetation. About two-third of the island is populated, which is mostly in the north and east side of the island. The Land Use Characterization map is attached to Annex II.

Table 141: Area Distribution in Dh. Bandidhoo

Area	24.3 ha	
Length	0.62 km	
Width	0.53 km	
	Area (m^2)	**% of total area**
Roof cover	32,767	13%
Vegetation (Thick)	79,673	33%
Vegetation (Thin)	43,442	18%
Bare Lands	86,482	36%
Total	242,862	100%

Figure 138: Land Use Characterization – Dh. Bandidhoo

9.2 Topographical Features

Permanent Survey Marks PSM 0431, PSM 0432 and PSM 0433 were used as benchmarks for Dh. Bandidhoo topographical survey and drone survey. These details are currently not available via the Maldives Land Survey Authority Website https://www.mlsa.gov.mv/psm. MLSA has reported that a PSM Mark has been issued for Dh. Bandidhoo, but the CSS Report has not been submitted by the party that applied for the PSM. Digital Surface Models (DSM) and Orthomosaic were derived in Pix4D Mapper using 1310 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.23 cm per pixel. 20 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 142: GCP Statistics for Dh. Bandidhoo

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	-0.000367	-0.000153	0.00130
Sigma [m]	0.0229	0.0267	0.0909

Dh. Bandidhoo has a peak elevation on a strip starting at the periphery road on its eastern side (about 1.7 m) further inland along a main road (1.8 m). The roads within the island have greater elevations (1.5 m) than what appears to be the natural island level (1.3 m) as indicated by some yards in houses and the football pitch on the island, indicating that some road levelling or raising works has been carried out at some point. The greatest depression is found on the periphery road on the western and southern side of the island, which ranges from 1.2 m to 0.8 m. There is a ridge found on the south-eastern shoreline of the island, where most wave exposure is observed. The absence of a ridge on the eastern shoreline is likely due to extreme erosion which has stripped away the beach to the point where the vegetation line roots have been exposed, indicating greatest wave impact and erosion rate. With the exception of the harbour, the island does not have any coastal protection structures built.

Roof elevations generally do not exceed 5-7 m and very few houses have multi-storey buildings in Dh. Bandidhoo. 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 periphery of the island, with another patch found behind the harbour and the southwestern corner of the island. The periphery regions all have vegetation with elevations greater than 10 m, with the remaining regions showing greater variation with elevations of 1.5 m to 18 m.

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 Dh. Bandidhoo. The DTM slightly underestimates the elevations with a mean of -0.84 cm. The DTM does not contain any elevation information related to the detached breakwater of Dh. Bandidhoo.

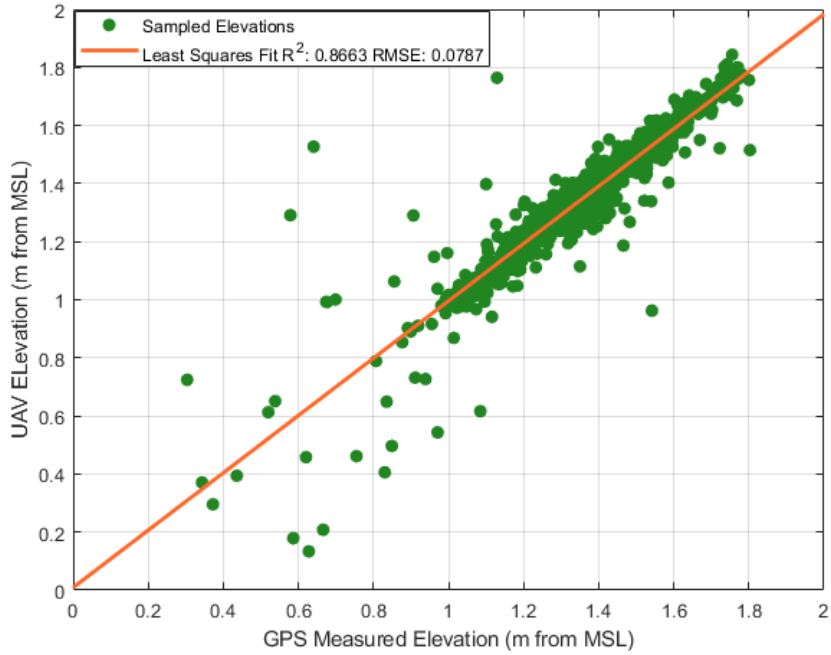


Figure 139: Linear Regression Plot for Dh. Bandidhoo Sample UAV elevations

Table 143: Error Statistics for Dh. Bandidhoo DTM

Parameter	Value (cm)
Mean	-0.84
Standard Error	0.24
Median	-0.41
Mode	#N/A
Standard Deviation	7.87
Sample Variance	61.95
Kurtosis	36.57
Skewness	1.50
Range	146.59
Minimum	-57.95
Maximum	88.64
Sum	-874.82
Count	1045.00

9.2.1 Level changes

Dh. Bandidhoo has an average elevation of 1.396 m with a standard deviation of 0.394. Digital Terrain Model elevations range from -0.5 to 2.1 m from MSL. The distribution of elevations has a symmetrical bimodal distribution with 1.5 m being the highest frequency for elevations. A second peak is observed near -0.1 m from MSL.

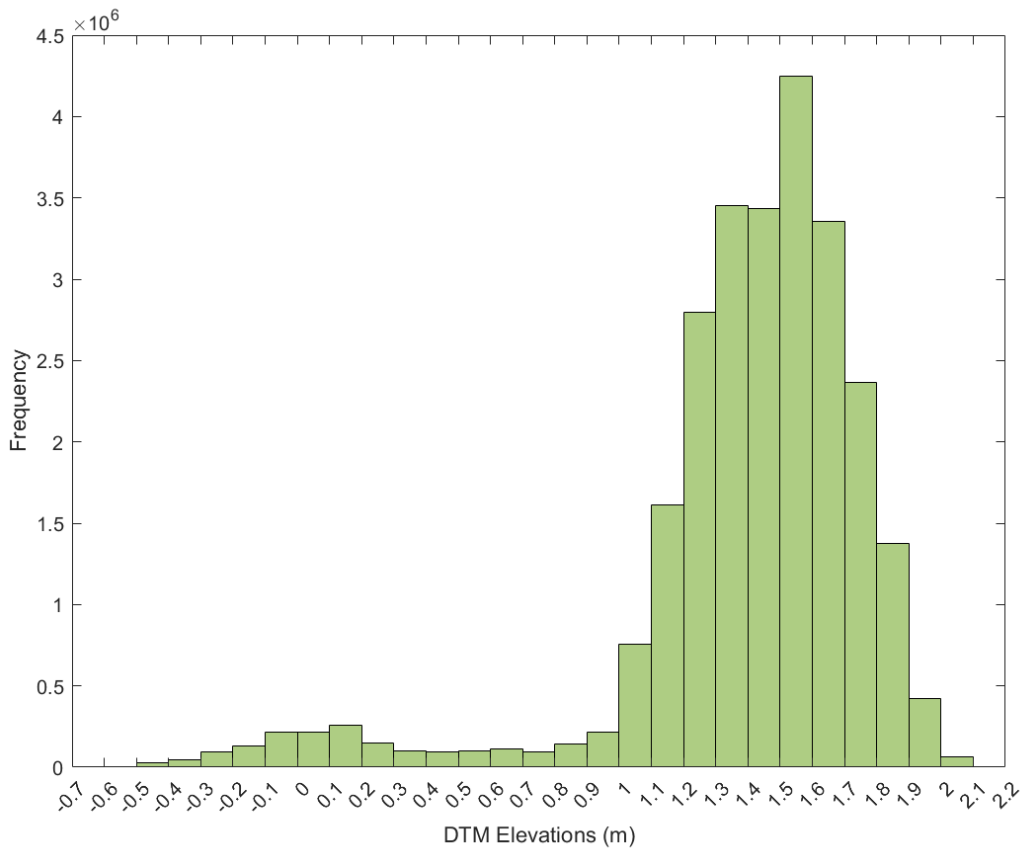


Figure 140: Raster Histogram created for Dh. Bandidhoo DTM

The island terrain shows that the residential areas are mostly at higher elevations compared to the island peripheries, which is generally lower. However, there is a stretch of properties built behind the harbor which falls into a depressed zone, as shown by profiles 1 and 3. Profile 1 shows a general elevation of 1.25 m within the island, with the exceptions being the depression at the 150 m mark and the elevated ridge as shown by the peak at the end of the profile (500 m), presumably due to strong wave impact on the beach at this location. Profile 3 is slightly different, as shown by the initial depression from start to 100 m in the profile, which is the harbor and its surrounding area. The remaining length of the profile shows a relatively level surface, averaging 1.6 m. This profile however does not show a ridge at the beach at end of profile, indicating that wave impact on this section of beach is calmer compared to further south along the beach.

Both profiles 2 and 4 show similar patterns, with the start of each profile (northern beach) showing lower elevations (1.00 m and 1.35 m respectively), followed by inclines climbing up till 1.75 m in both profiles. After the peak, both profiles start declining up to the end, which shows prominent ridges built up to roughly 1.5 m, most likely due to strong wave activity at the southern beach.

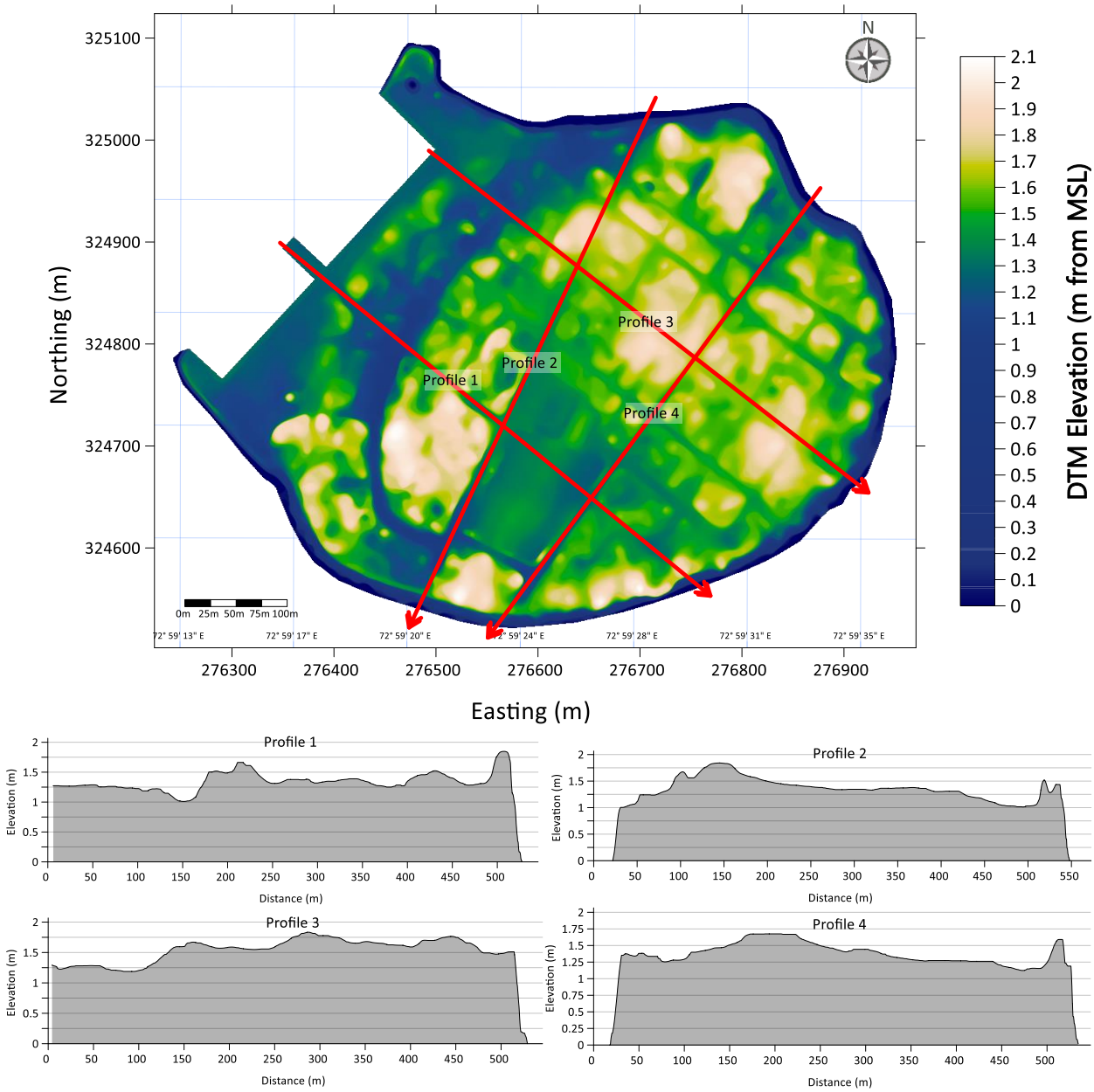


Figure 141: Digital Terrain Model Elevations and Profiles for Dh. Bandidhoo Island

9.2.2 Shoreline

Dh. Bandidhoo has a shoreline length of 2278 m. The island has all its coastal protection on its harbor as follows.

- Breakwater: The rubble mound breakwater is found on the northwest side of the island. Westerly wind waves generated within the atoll basin is absorbed and dissipated by this breakwater to offer protection to berthed vessels within the harbor. The breakwater is detached from the island itself and does not have any access platforms connecting it to the island. Crest height for the breakwater is around +2 m above mean sea level. The breakwater is highlighted in orange.
- Revetment: The island has two revetments, one the northern point of the harbor and the other on the northwestern corner of the harbor. The revetment serves as shore protection and prevents erosion at these locations by dissipating wave energy from westerly wind waves generated within the atoll basin. Crest height of northern and southwestern revetment are around +1.8 m and +1.6 m above mean sea level respectively. The revetments are highlighted in green.
- Quay wall: These structures are found within the harbor and are highlighted in yellow. Crest height of quay walls is around +1.3 m above mean sea level.

The southeastern shoreline has undergone severe beach erosion, where the shoreline has regressed to expose vegetation roots and beach rock (aanugandu)

Figure 142: Orthomosaic of Dh. Bandidhoo

9.2.3 Reef

Dh. Bandidhoo is located on the northeast end of the basin of the Dhaalu Atoll, being the only island to be located on this particular reef. The nearest island is uninhabited and to the north of Dh. Bandidhoo. The reef measures roughly 1 km along its longest section. For the major wave direction, which is the northeastern swell waves approaching from the windward side, the shortest buffer zone measures about 120 m.

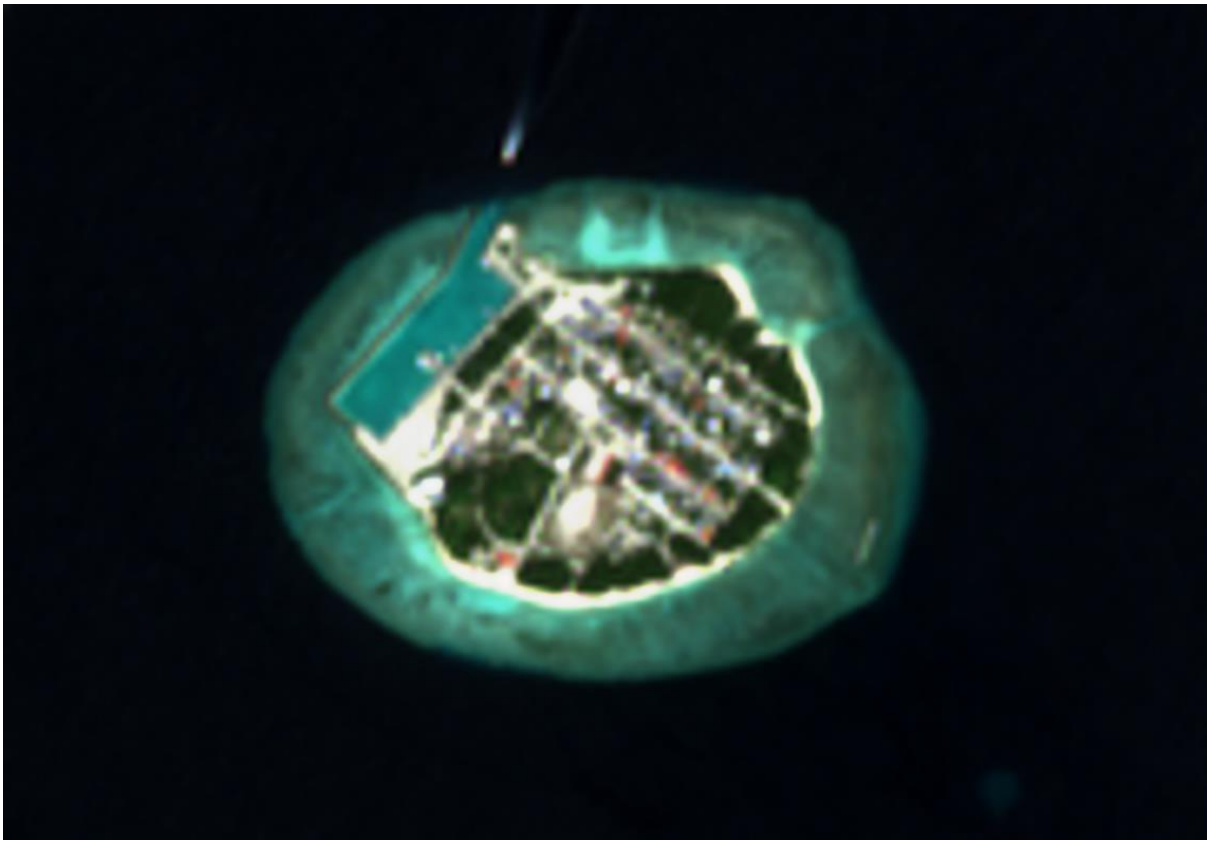


Figure 143 Sentinel 2 imagery of Dh. Bandidhoo reef taken in February 2022

9.3 Socio Economic Status

9.3.1 Demography

The island has a registered population of 714 as per the 2014 census, with a total of 392 males and 322 females. The island population density per hectare is at 41. The population figures have drastically increased over the past years where the total registered local population climbed up to 997. The following table and graph illustrate the demographic breakdown of Dh. Bandidhoo.

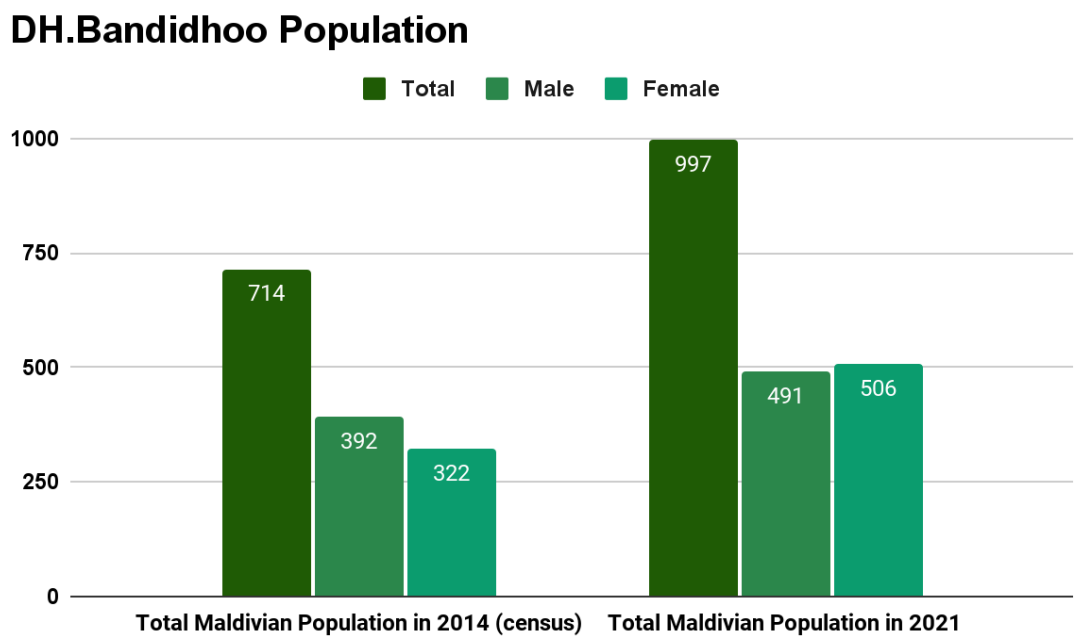


Figure 144: Dh. Bandidhoo Population

Table 144: Dh. Bandidhoo 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
Dh	Bandidhoo	793	466	327	714	392	322	79	74	5

9.3.2 Socio-Economic Activities

Dh. Bandidhoo is an inhabited island in Dhaalu Atoll's administrative unit and physically part of Nilandhe Atoll in the Maldives' southernmost region. It is an administrative constituency on an island in central province, governed by the Dh. Bandidhoo Island Council. The commerce of the island is mostly centered in the fishing (especially yellowfin tuna) and construction industry.

9.3.3 Facilities available

9.3.3.1 Health Care

Dh. Bandidhoo Island has a modest level of healthcare infrastructure which is staffed by 1 doctor and 3 nurses. Currently, they have six beds to cater for the patients.

9.3.3.2 Education

Dh. Bandidhoo has pre-school, primary and secondary education. The total number of students enrolled in the schools total up to 173. There are currently 29 teachers and 6 administrative staff in Bandidhoo school.

9.3.3.3 Utilities

Electricity in the island is provided by state-owned utility company FENAKA Corporation. According to the Ministry of National Planning, Housing and Infrastructure, an ongoing project of water and sanitation system is currently being implemented in Dh. Bandidhoo. The work is expected to finish by the end of June 2022.

9.3.3.4 Transportation

Dh. Bandidhoo has a harbor of 1000ft x 300ft which was constructed by Maldives Transport and Contracting Company (MTCC) in the year 2014. This has enabled faster loading and unloading for both commercial and fishing boats.

9.3.4 Water resources, water usage and water consumption survey

In Dh. Bandidhoo, 69 out of 84 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 145: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	**69/84 households = 82.1%**
Percentage of well fitted with pumps	99%
Ground water	**Usage in percentage**
Source of drinking	0%
Source of cooking	13%

9.3.4.1 Existing water and sanitation

The main form of sanitation is via the use of septic tanks systems and small-bore sewer systems. According to the social survey, 100% of the houses surveyed have septic tanks as their main form of sanitation. A piped water supply system is currently under construction and is expected to finish by 2023. The majority of the surveyed households were reported with less than 49ft distance between septic tank and water well. In Dh. Bandidhoo 91 percent reported to have less than 49ft distance between septic tanks and water well while, 9% reported to have more than 49ft distance between both of them. The households are recommended to 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.

9.3.4.2 Water usage and resources

Based on the survey conducted in Dh. Bandidhoo, all the houses have HDPE rainwater tanks for rainwater storage. 100% of the households use rainwater for drinking and 98% use rainwater for cooking. Rainwater collected from rooftops is stored in water tanks, whether communal or home tanks. Rainwater is the primary source of drinking water. Many homes utilize rainwater from neighboring houses or bottled water when rainwater is scarce during the dry season. The island has traditionally had exceptionally clean groundwater. It is now usually good, but over-extraction generates unpleasant smells sometimes. While groundwater is mainly used for gardening, household cleaning with 99% houses fitted with water pumps.

The following sections outline 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 Dh. Bandidhoo, **209,370** liters of water is used daily in the households. A total of **210** liters of groundwater are consumed per capita per day.

Table 146: Domestic groundwater use data for Dh. Bandidhoo

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
101	27.4	7.48	46.9	1.62	19	3.33	**210**

*All units are in Liters per capita per day

9.3.4.4 Commercial water usage

There is no commercial data available for Dh. Bandidhoo as they do not have any operational guesthouses and cafes at the time of baseline assessment.

9.3.4.5 Industrial water usage

Fishing vessels from Dh. Bandidhoo and nearby islands visit once a week to restock groundwater on the vessels. As per information from the council (2021), 2000 liters of groundwater are extracted from the island by fishing vessels every week and thereby **286** litters of groundwater are extracted from the island every day for industrial purposes.

9.3.4.6 Institutional water usage

Based on the survey conducted in Dh. Bandidhoo, there are currently six institutions that contain groundwater well facilities and use groundwater on this island. A total of 10,252 Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 147: Institutional groundwater use data for Dh. Bandidhoo

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Health Center	149	1440	75	2120	3784
Bandidhoo Council	117	720	11	-	848
Bandidhoo School	1100	1440	86	-	2626
Bandidhoo Pre School	23.5	1080	7	-	1111
FENAKA	117	480	9	-	606
Bandidhoo police	36.3	180	1	1060	1277
					10,252

*All units are in Liters per day

9.3.5 Present & Future water demand

In Dh. Bandidhoo, the present water demand is at **219,908** Liters per day inclusive of domestic, commercial, institutional, and industrial water demand. It is expected that groundwater usage in the island will 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.

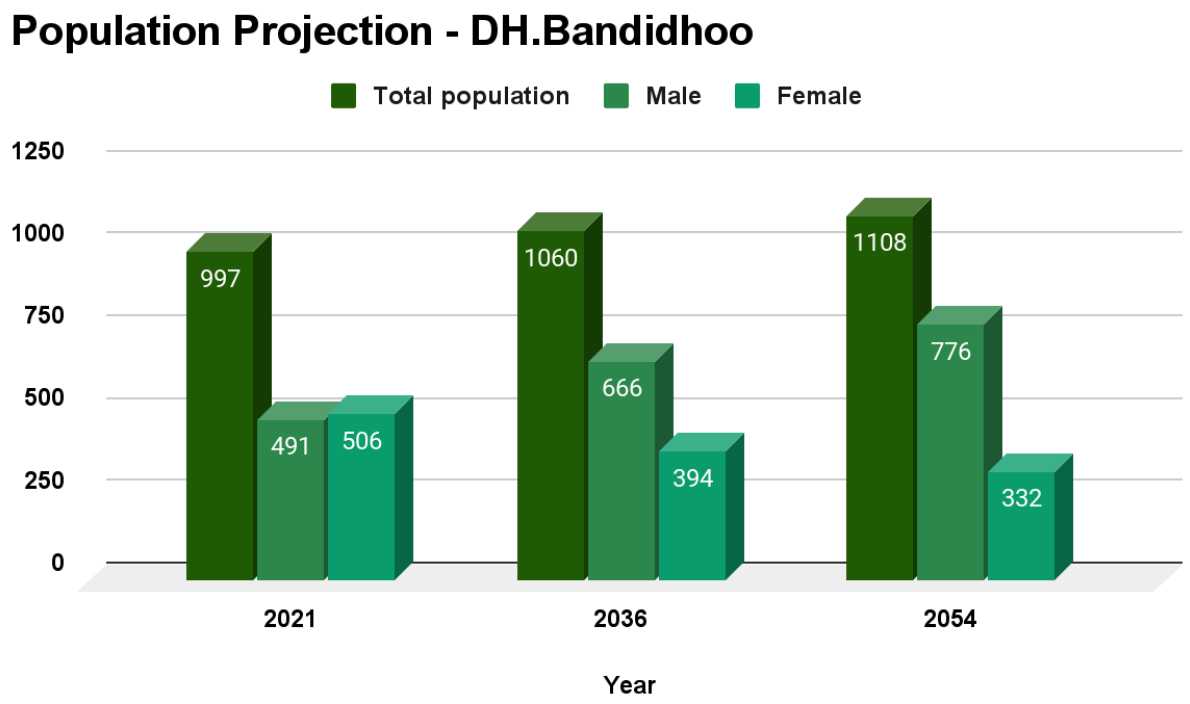


Figure 145: Population Projection - Dh. Bandidhoo

Table 148: Present groundwater demand - Dh. Bandidhoo

Year	Total Population	Domestic water demand	Industrial water demand	Institutional water demand	Groundwater usage
2021	997	209,370	286	10,252	**219,908**

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 210 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 210 Liters, the groundwater demand is expected to be 160 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 1060 is expected to be 169,600 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 210 Liters, the groundwater demand is expected to be 135 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 1108 is expected to be 149,580 Liters per day.

Table 149: Future domestic water demand - Dh. Bandidhoo

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	1060	210	50	160	169,600
2054	1108	210	75	135	149,580

9.3.6 Water related issues

From 69 households surveyed in Dh. Bandidhoo, some houses reported smell and foul taste in their respective wells. However, most of the houses reported having no contamination in their groundwater. According to the social survey, only 4% 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. In Dh. Bandidhoo, groundwater quality was reported good, hence the lower percentage of oxygen pumps in the households.

Table 150: Signs of contamination reported by households

Types of contamination	Data in % out of 69 households surveyed
Smell	28%
Milky	0%
Foul taste	10%
Salty	4%
None	64%

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

Table 151: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 69 households surveyed
Changes with tidal variations	3%
Groundwater quality is better in rainy months	26%
Long periods without rain causes bad smell	20%
Long periods without rain causes bad taste	6%
Rain makes it worse	0%
No change	55%

9.4 Groundwater Quality

9.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 152 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 152: Statistical summary of groundwater physiochemical parameters in Dh. Bandidhoo

	EC (µS/cm)	Turbidity (FNU)	DO (mg/L)	pH	Temp (°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 threshhold <35 Taste threshhold Source[1]	<50 Source[1]	
Mean	619	0.18	5.25	7.47	29.28	0.27	1.44	11.98	0.22
Median	646	0.12	5.44	7.41	29.10	0.29	0.34	8.36	0.18
SD	180	0.21	1.58	0.27	0.95	0.09	2.79	10.03	0.16
Min	159	0.00	2.08	7.03	27.80	0.01	0.04	1.81	0.06
Max	1099	1.04	7.58	8.37	31.60	0.48	10.83	46.24	0.67
CV	0.29	1.18	0.30	0.04	0.03	0.34	1.94	0.84	0.71

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH_3= Ammonia, NO_3^-= Nitrate, PO_4^{3-}=Phosphate,
SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source[1] = WHO Drinking Water Guidelines, 2017. Source[2] = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 619 µS/cm is lower than the WHO Standard for potable water (1500 µS/cm) and the WHO Standard for non-potable water (2500 µS/cm).
- All of the samples had EC lower than 1500 µS/cm. As expected, the EC of the groundwater in the center of the island is lower than the coastal areas of the island. The spatial distribution of EC is shown in Figure 146.
- The mean Turbidity level at 0.18 NTU fall within the URA Guidelines for drinking water (<5 NTU). None of the samples had higher Turbidity than 5 NTU with the maximum turbidity at 1.04 NTU.
- Dissolved Oxygen ranged from 2.08 mg/L to 7.58 mg/L with a mean of 5.25 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 27.8°C to 31.6°C depending on the well characteristics and time of day reading was taken. Mean temperature was 29.3°C.

- Salinity ranged from 0.01ppt to 0.48ppt with a mean of 0.27ppt.
- The mean Ammonia concentration was 1.44 mg/L which is lower than the WHO threshold for odour and well below the threshold for taste. 80% of samples had concentration below 1.5 mg/L, 20% 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 147.
- The mean Nitrate concentration was 11.98 mg/L which falls within 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 0.06 to 0.67 mg/L with a mean concentration of 0.22 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. 9 samples tested were below 0.1 mg/L.
- Ammonia, Nitrate and Phosphate concentration is higher in the East side of the island which is more densely populated.

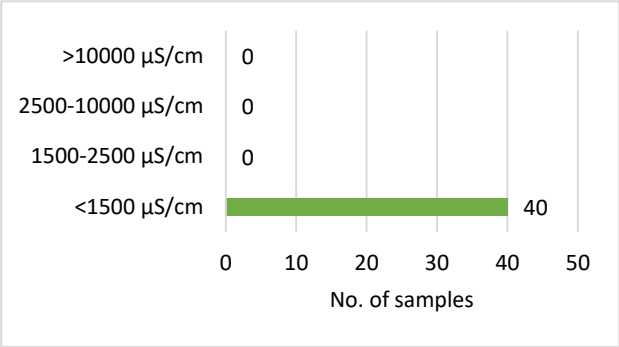


Figure 146: EC Distribution in Dh. Bandidhoo

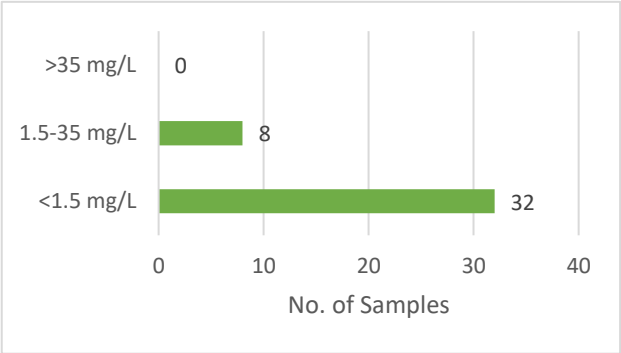


Figure 147: Ammonia Distribution in Dh. Bandidhoo

The spatial distribution of all the parameters measured are shown in Figure 148(a-i).

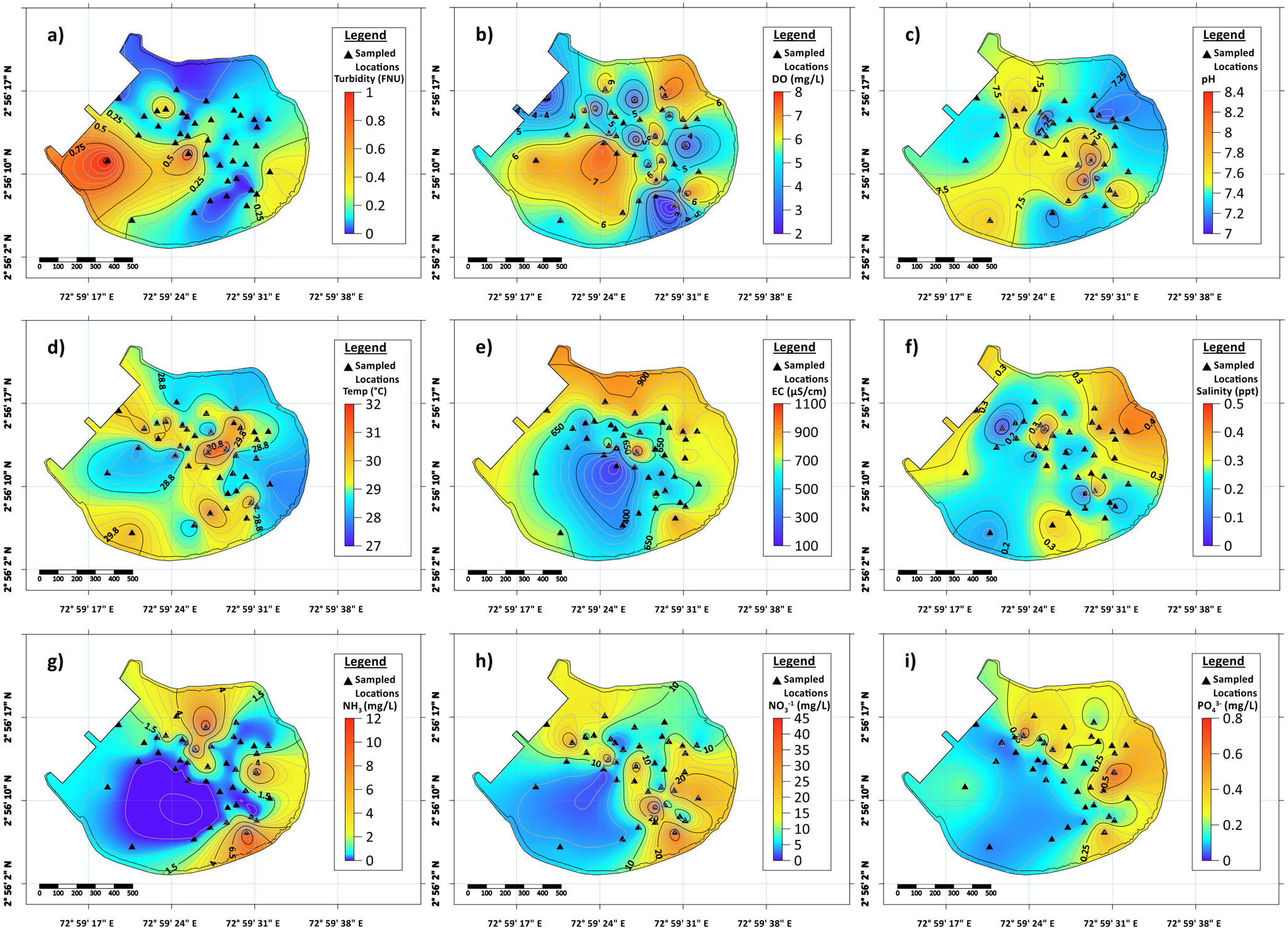


Figure 148: Spatial variation of physiochemical parameters in Dh. Bandidhoo

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 0.0521 and the R-squared of the plot is 0.0027 as indicated from the Figure 149. 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.

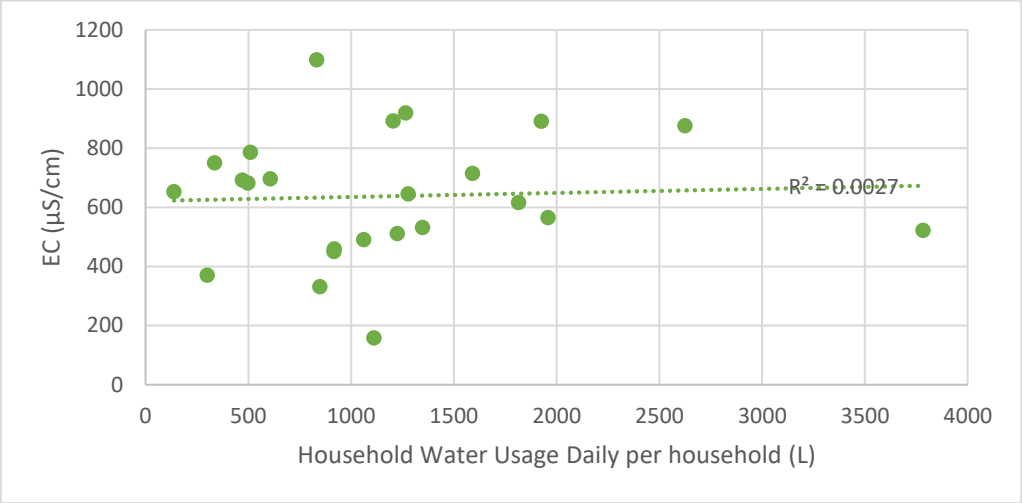


Figure 149: EC against Water Usage in Dh. Bandidhoo

9.4.1.1 Correlation Matrix

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

Table 153: Correlation matrix of the groundwater quality parameters in Dh. Bandidhoo

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)	0.19							
pH	0.13	0.24						
EC (µS/cm)	-0.22	-0.50	-0.14					
Sal (ppt)	-0.10	-0.04	-0.60	***1.00				
Temp (°C)	-0.13	-0.38	-0.03	0.25	-0.09			
NO_3^- (mg/L)	-0.10	-0.33	0.16	0.46	-0.34	0.05		
NH_3 (mg/L)	-0.03	-0.55	-0.09	0.49	-0.09	0.03	0.25	
PO_4^{3-} (mg/L)	0.06	-0.39	-0.06	0.45	0.05	-0.06	0.26	0.65

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation

Table 153 shows a positive correlation coefficient between NH_3/ PO_4^{3-} (r=0.65) and a negative correlation coefficient between DO/EC (r=-0.50) and DO/NH_3 (r=-0.55). There are no other significant correlations observed.

9.4.1.2 Water Quality Index

In this study, the computed WQI ranges from 1.55 to 9.76, with a mean of 4.22. The WQI was divided into four categories and Table 154 shows the categorization of samples. 100% of samples were classified as "Very Good". The spatial distribution of WQI is as per Figure 150.

Table 154: Water Quality Classification based on WQI – Dh. Bandidhoo

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	40	100%
10 to 20	Good	0	0%
20 to 50	Poor	0	0%
>50	Very Poor	0	0%

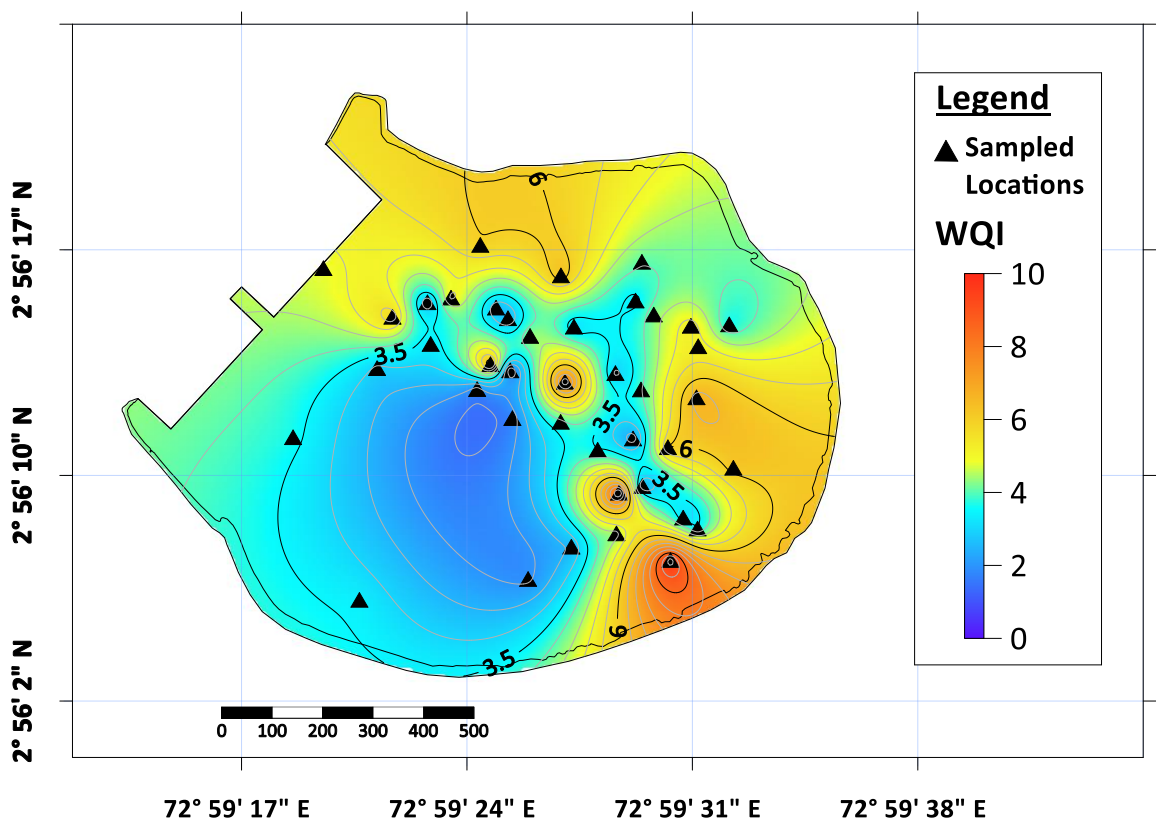


Figure 150: Spatial Distribution of WQI in Dh. Bandidhoo

9.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 155 summarizes the results. Map of locations where groundwater quality points were taken for microbiological analysis is attached to Annex M.

Table 155: Microbiological Parameters of groundwater in Dh. Bandidhoo

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq01	326	53		School
wq02	435	58	50	Septic Tanks. Septic Tank has not been cleaned yet
wq03	>2420	691		Old Mosque
wq04	1553	388	65	Septic Tanks. Septic Tank is buried in other part of household and is cleaned once every 10 years.
wq05	980	152		Police Station
wq06	437	173	20	Septic Tanks. Septic Tank has not been cleaned yet
wq07	189	110	30	Septic Tanks. Septic Tank has not been cleaned yet
wq08	980	149	40	Septic Tanks. Septic Tank has not been cleaned yet
wq09	866	144		Social Survey not carried out
wq10	649	97	30	Septic Tanks. Septic Tank has not been cleaned yet
wq11	548	49		Social Survey not carried out
wq12	281	69		Pre-School
wq13	579	41	10	Septic Tanks. Septic Tank has not been cleaned yet
wq14	236	48		Social Survey not carried out
wq15	548	60		Masjidhul Ameen

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

Both Total Coliform and Faecal Coliform were detected in all 15 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 25 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Total Coliform and Faecal Coliform is given in Figure 151. Moderately even spatial distribution of Total and Faecal Coliform was observed across the island with slightly higher count detected on the West and East side of the island.

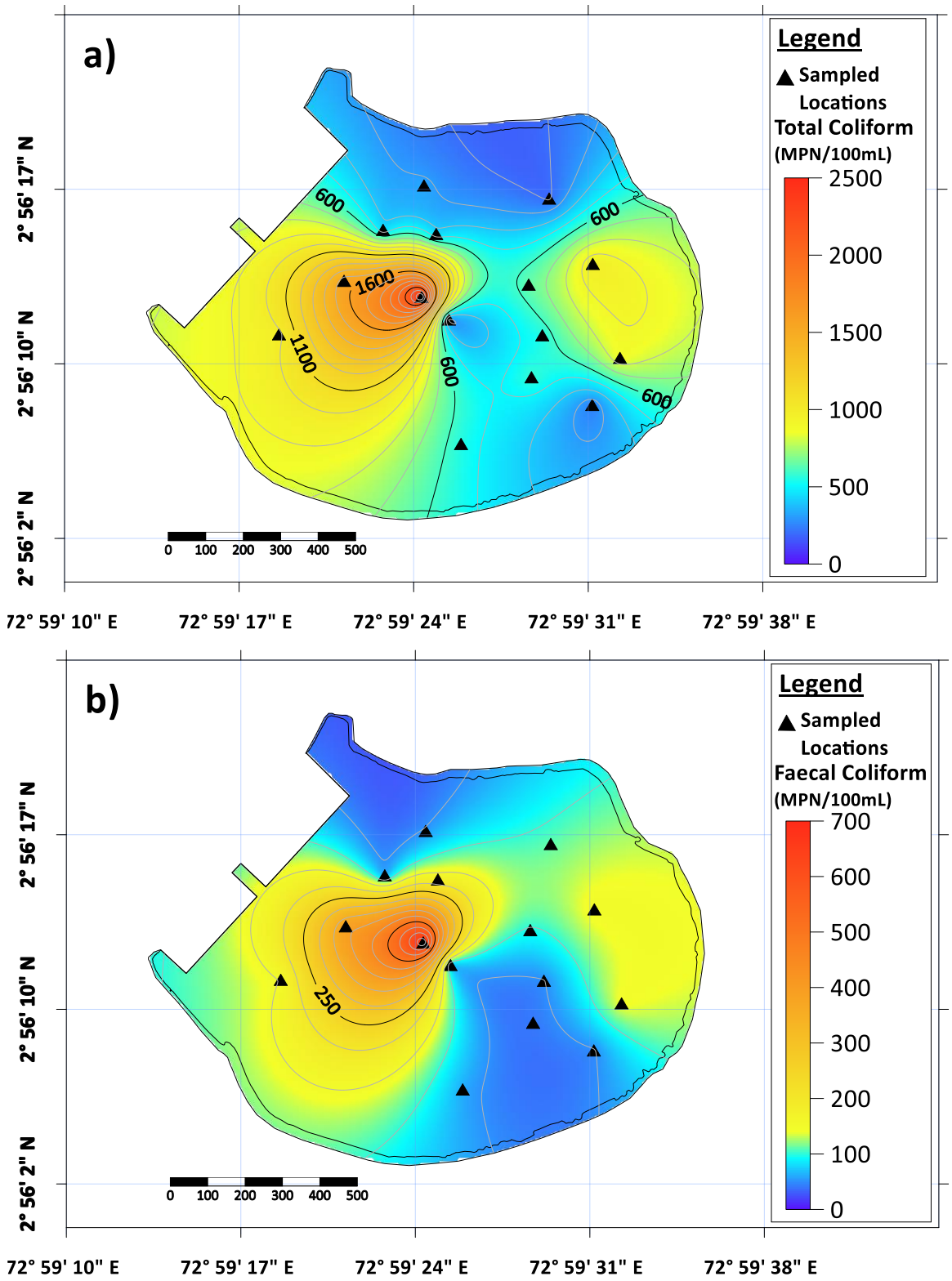
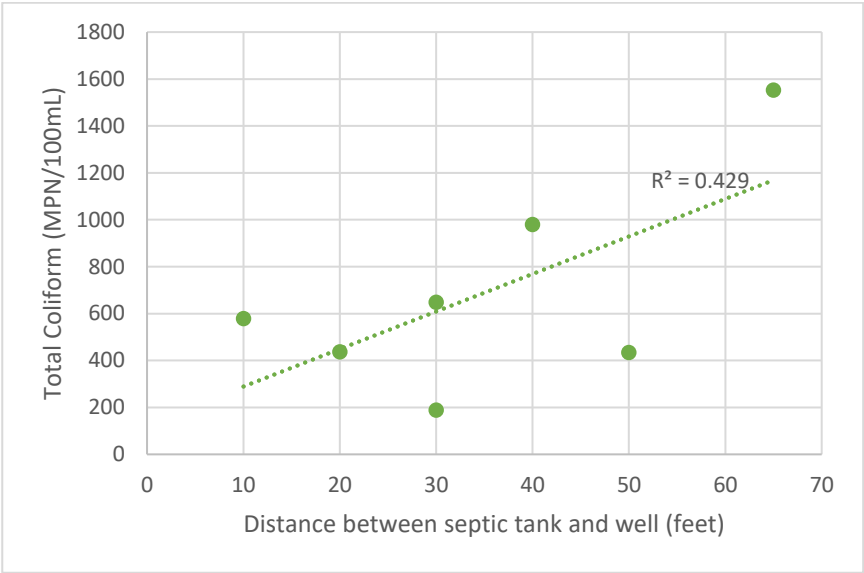


Figure 151: Total (a) and Faecal (b) Contamination Distribution in Dh. Bandidhoo

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.



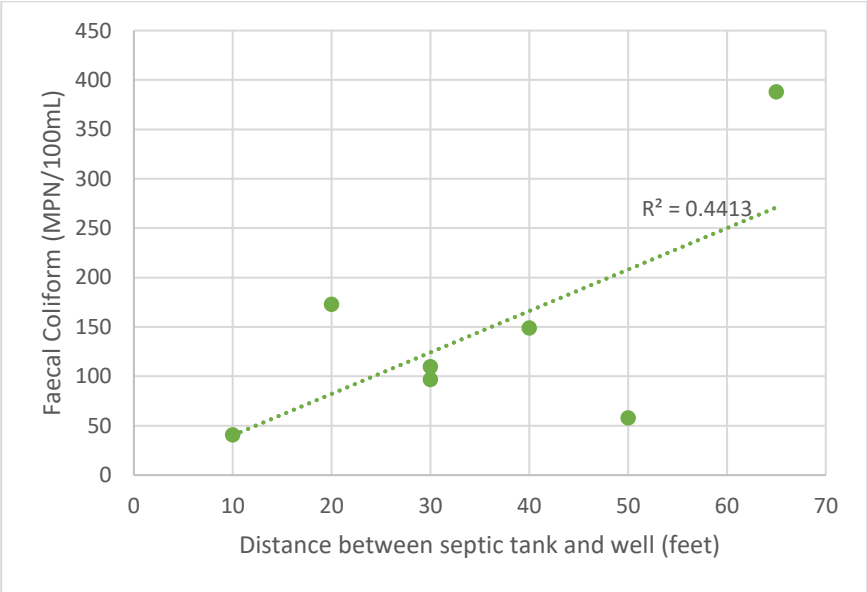


Figure 152: Microbiological Contamination against Septic Tank distancing - Bandidhoo

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.105 and the R-squared of the plot is 0.011 as indicated from the Figure 152. The correlation coefficient of Faecal Coliform to distance between septic tank and well is -0.100 and the R-squared of the plot is 0.01 as indicated from the Figure 152. Therefore, there isn't a significant relationship observed between the parameters.

9.5 Pumping Test

9.5.1 Test location

A well without a base was not available in Dh. Bandidhoo. Therefore, it was decided to carry out the test at the new mosque as the mosque well would be unused for most parts of the day. The chosen well had 2 inlets of approximately 1 ½ inches' diameter at the concrete base plate. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 153 below shows the location for the pumping test at Dh. Bandidhoo.

Figure 153: Pumping test location - Dh. Bandidhoo

9.5.2 Pumping rate, pumping hours, and collected data

A step-drawdown pumping test was carried out. The test began at 0730 hours on 30 August 2021 and lasted for 95 minutes. A flowrate of 30 LPM was maintained for 0-35th minute of the test. The flow was then gradually increased to 50 LPM for 36th-45th minute, 70 LPM for 46th-65th minute, and 75 LPM for 66th-75th minute. The recovery phase of the test lasted from 76th-95th minute for more than 98% 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 using the software, AQTESOLV. The Aquifer Transmissivity (T) value was estimated to be 1.06×10^{-3} m^2/s (92.00 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.2107 for Dh. Bandidhoo. The full data set of the pumping test at Dh. Bandidhoo has been annexed at Annex XI.

9.6 Permeability Test

9.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 154 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 154: Permeability Test Locations - Dh. Bandidhoo

9.6.2 Measured data

Table 156: Permeability Test Measured Data - Dh. Bandidhoo

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m^3/s)	K (m/s)	K (m/day)
BND-PMB1	0.600	1.235	35	12.0	14.00	0.000233	1.93E-04	16.65
BND-PMB2	0.600	1.160	35	12.0	11.00	0.000183	1.61E-04	13.93
BND-PMB3	0.600	0.970	35	12.0	21.00	0.000350	3.68E-04	31.79
BND-PMB4	0.635	1.270	35	12.7	11.00	0.000183	1.48E-04	12.81
BND-PMB5	0.640	1.450	35	12.8	12.00	0.000200	1.41E-04	12.19

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 Dh. Hulhudheli is 17.47 m/day, with permeability values ranging from 12.19 m/day to 31.79 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)).

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 155 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 155: Soil Profile Survey Locations - Dh. Bandidhoo

9.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 156 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.

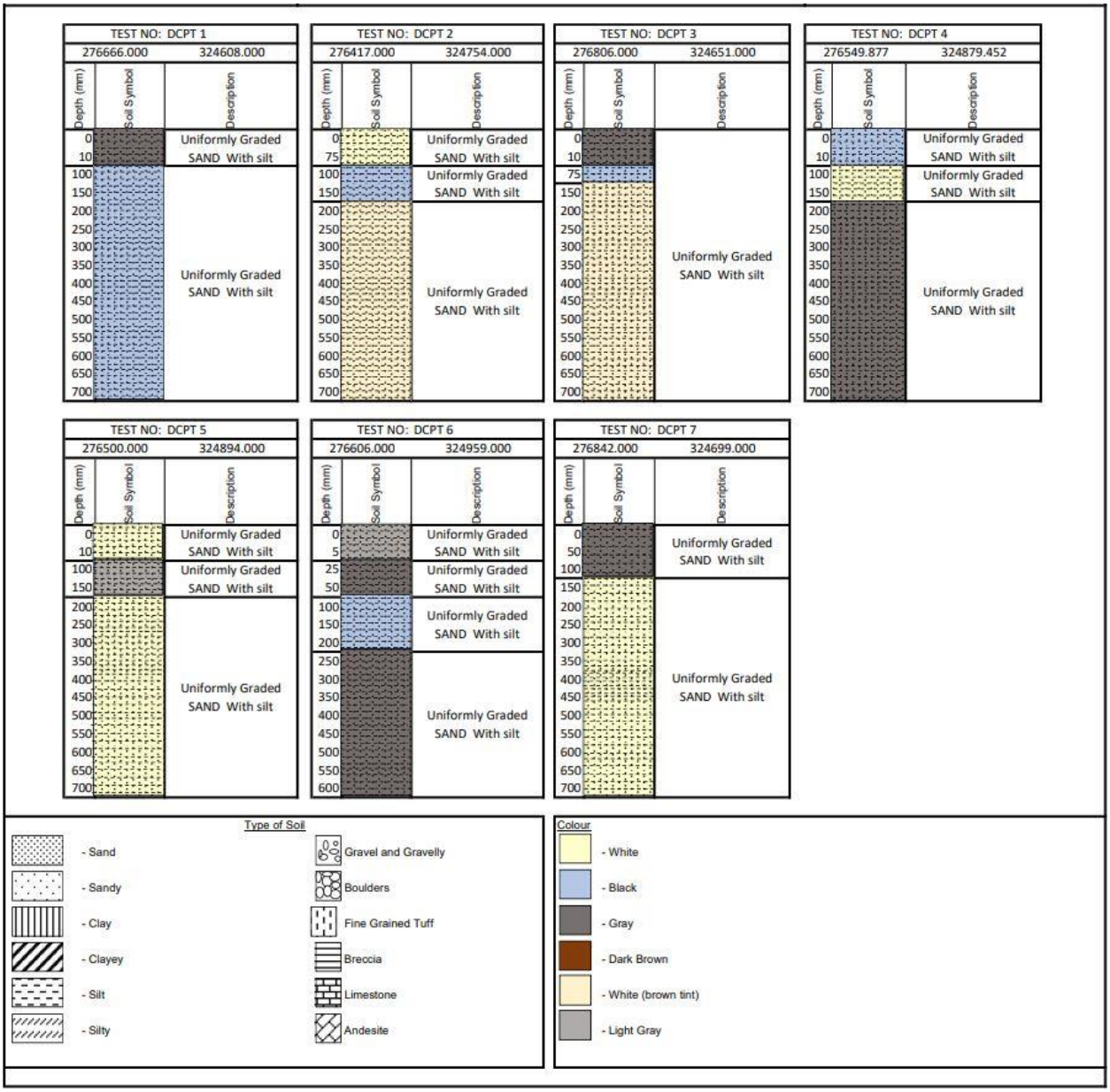


Figure 156: Soil Profile – Dh. Bandidhoo

9.8 Flood Assessment and Inundation Survey

9.8.1 Flood occurrence and flood impact

Dh. Bandidhoo has no major issues of flooding and only reported common ponding areas. Only 17% of the households reported that ponding occurs only when there is a heavy rainfall. On the same note, 68% of the households' report flooding as an acceptable problem (refer to flood severity component of Flood Maps in Annex XII). This can be due to the island's topography and continuous flood mitigation efforts by residents.

The ponding originates mostly from roof runoff (46%) as per the Social Survey. Most responses state multiple sources for the flooding within their properties such as from neighbors' 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 157: Perceived causes of flooding – Dh. Bandidhoo

Perceived causes of flooding				
Roof run off	**Neighbours' roof**	**Off the road**	**General run off in the area**	**No flooding within the plot**
46%	6%	4%	4%	52%

From the social survey, 45% 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 which include overflow 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 158: Discharge of rainwater overflow – Dh. Bandidhoo

Discharge of rainwater overflow			
Ground	**Roads**	**Open area within the plot**	**Drained to well**
45%	3%	39%	3%

Some households reported that there are trenches built to direct rainfall runoff to coconut trees rather than the sea, resulting in relatively minimal loss of rainwater runoff to the sea.

9.8.2 Inundation area identification

Ponding occurs mainly near the mosque, football field, school, council, Health Center and near the police station (refer to Annex XII: Flood Maps). Based on the social survey responses, an average of 1.17ft is estimated as the flooding depth when there is a heavy rainfall. Majority of the respondent's indicated flooding does not happen often in the island. Therefore, the flood depth accumulated was reported by only 10% of the surveyed respondents.

9.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 70% observe that the water drains during the rainfall itself, 27% observe that the water drains in less than 4 hours, 0% observe that the water drains in less than 4-24 hours and 3% observe that it takes more than 24 hours for water to drain.

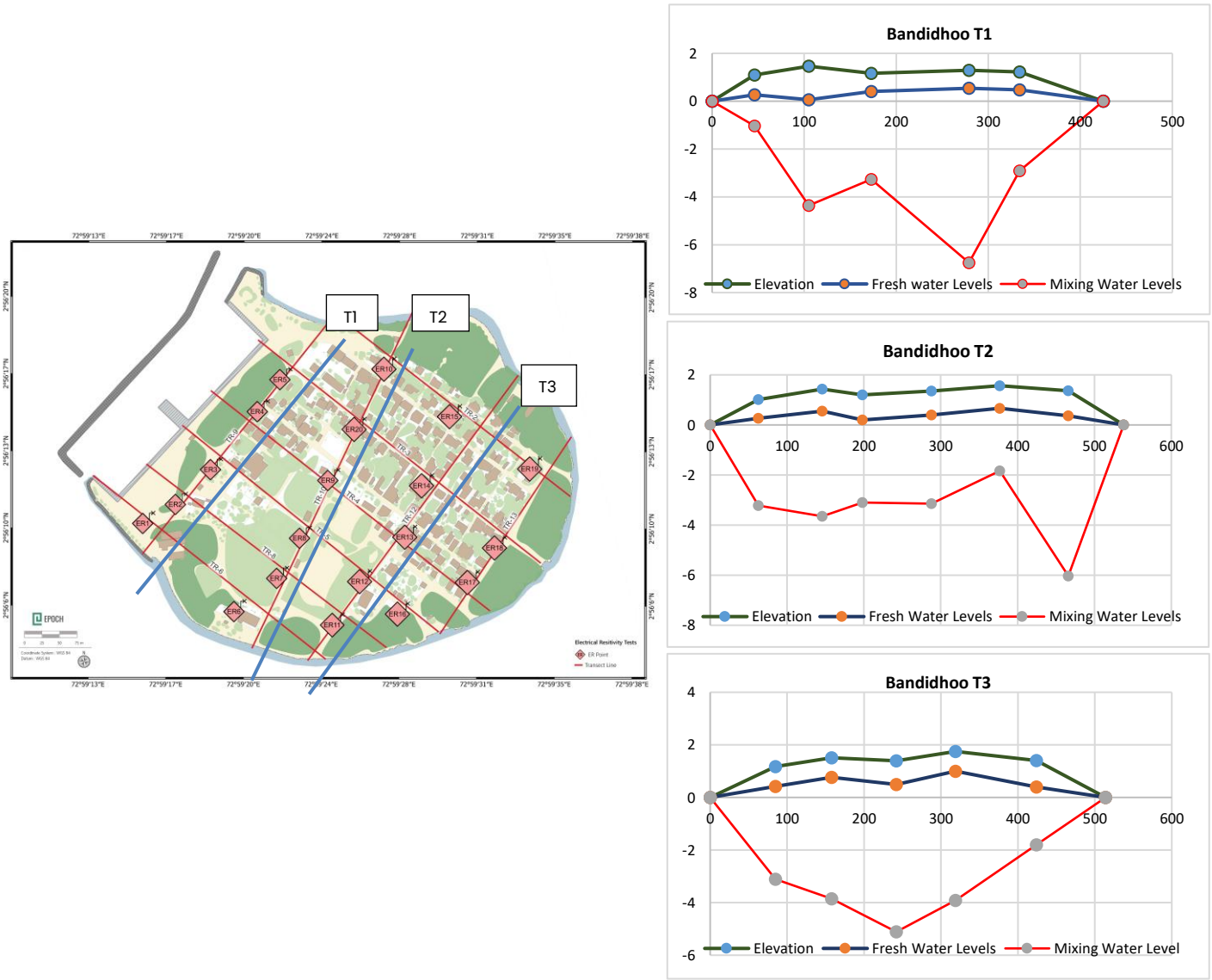
Table 159: Draining period – Dh. Bandidhoo

Draining period			
only while raining	**drains less than 4hrs**	**takes 4-24 hrs**	**more than 24hrs**
70%	27%	0%	3%

9.9 Geophysical Survey

9.9.1 Surveyed locations

Locations where ER sounding measurements were taken at Bandidhoo island are shown in Figure 105 with transect lines. There are 21 ER measurement locations and the number of transects in this island is



10.

Figure 157: ER surveyed locations and transect lines – Dh. Bandidhoo 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 135 below shows the estimated levels at ER surveyed locations of Dh. Bandidhoo Island and freshwater lens thickness.

Table 160: Freshwater lens levels and thickness – Dh. Bandidhoo island

No	Location	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	5	1.22	0.47	-2.91	3.38
2	20	1.57	0.67	-1.83	2.50
3	14	1.75	1.00	-3.91	4.91
4	18	1.73	0.77	-6.13	6.90
5	4	1.29	0.54	-6.75	7.29
6	9	1.35	0.40	-3.15	3.55
7	3	1.16	0.40	-3.27	3.67
8	8	1.20	0.20	-3.10	3.30
9	7	1.43	0.55	-3.65	4.20
10	6	1.01	0.26	-3.23	3.49
11	11	1.17	0.42	-3.11	3.53
12	12	1.51	0.76	-3.85	4.61
13	16	1.31	0.46	-3.32	3.78
14	2	1.46	0.06	-4.36	4.42
15	1	1.09	0.27	-1.04	1.31
16	13	1.39	0.49	-5.11	5.60
17	17	1.46	0.46	-6.64	7.10
18	19	1.37	0.27	-0.87	1.14
19	15	1.40	0.40	-1.80	2.20
20	10	1.37	0.37	-6.03	6.40

Average freshwater thickness of Dh. Bandidhoo island is 4.16m. Maximum recorded thickness of freshwater lens of the Island by ER survey is 7.29 m & minimum is 1.14m.

Data in Table 135 were used to plot freshwater lens cross sections along 10 transects. Of these sectional plots 2 were given in Figure 157 and they represent the transect plots along the longitudinal section of the island.

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 158.

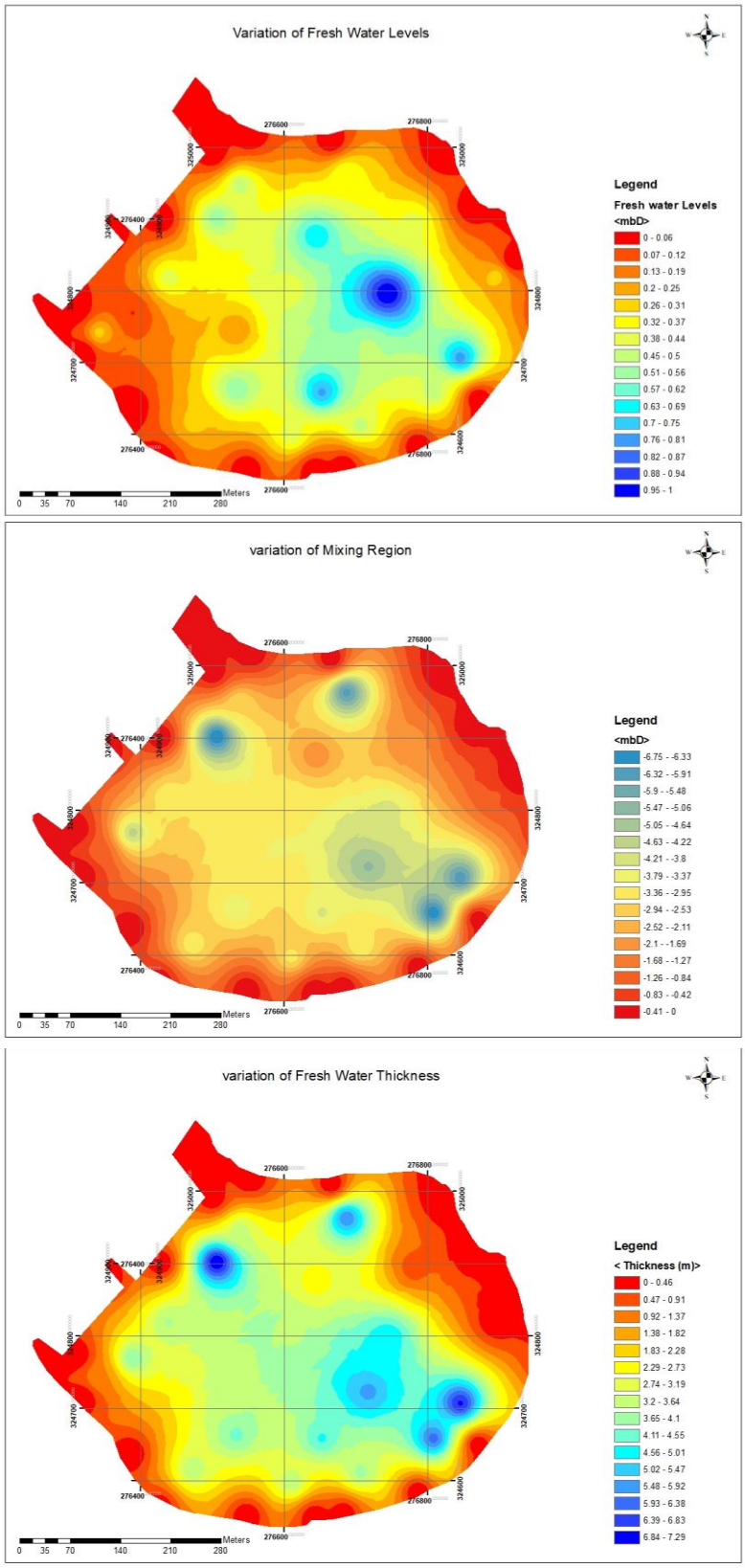


Figure 158: Top: Contours of Freshwater lens upper level,
Middle: Contours of Freshwater lens lower level,
Bottom: Spatial distribution of thickness of freshwater lens in Dh. Bandidhoo

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. Tools in ArcGIS software were used to perform this computation.

Stress level on freshwater aquifer of Dh. Bandidhoo 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 161.

Table 161: Freshwater lens volume and aquifer stress level – Dh. Bandidhoo island

Item	Value	Unit
Freshwater lens volume - ArcGIS	436,921	m^3
Groundwater abstraction	80,266	m^3/yr
Freshwater lens volume/ Groundwater abstraction	5.4	-
Aquifer stress level	Not Stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 9.48m. This deviates by 30% from the maximum measured value of 7.29m, which is more reliable as it results from a more comprehensive, site-specific methodology.

9.10 SWB Modelling

9.10.1 Land use categorization and area estimation

Table showing land classification and their respective areas are shown in Table 162.

Table 162: Land Use Classification - Dh. Bandidhoo

	Area (m^2)	% of total area
Roof cover	32,767	13%
Vegetation (Thick)	79,673	33%
Vegetation (Thin)	43,442	18%
Bare Lands	86,482	36%
Total	242,862	100%

9.10.2 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 Table 163). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 40,163m^3, 1,049,304m^3 and 221,587m^3 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 1983 mm
- Variation among the monthly average recharge value is very high. It is lowest on month of January and highest in May.

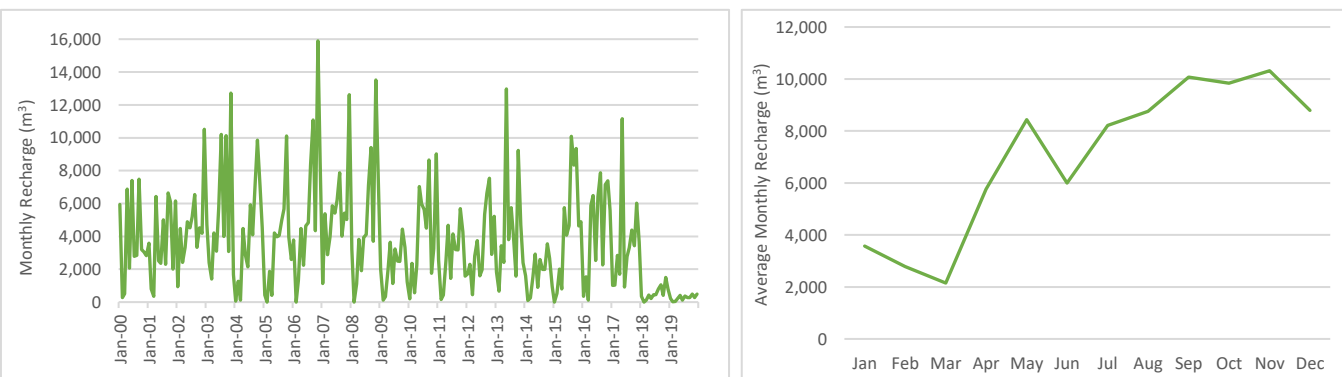


Figure 159: Monthly and annual recharge distribution - Dh. Bandidhoo

Table 163: Monthly recharge estimated by SWB model - Dh. Bandidhoo Island

Year	Monthly Recharge (m^3)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2000	11,306	531	984	13,089	3,918	14,074	5,322	5,419	14,225	6,077	5,838	5,370
2001	6,828	1,531	653	12,227	4,784	4,501	9,529	4,360	12,651	11,627	3,833	11,724
2002	1,785	8,520	4,584	6,340	9,291	8,593	9,866	12,470	6,359	8,588	7,959	20,035
2003	8,979	4,565	2,682	7,993	5,886	10,934	19,435	7,608	19,298	5,847	24,209	3,189
2004	132	2,409	219	8,535	5,516	4,077	11,276	7,784	13,821	18,767	13,519	8,593
2005	814	-	3,560	766	8,022	7,574	7,705	9,510	10,788	19,250	7,520	4,921
2006	7,198	-	2,512	8,544	4,262	8,808	9,208	15,914	21,083	8,281	30,262	16,153
2007	2,142	10,224	5,501	7,608	11,149	10,312	11,839	14,964	7,631	10,306	9,551	24,042
2008	6,119	-	2,135	7,263	3,623	7,487	7,827	13,527	17,921	7,039	25,723	13,730
2009	3,807	226	629	3,705	6,947	2,139	6,160	4,752	4,718	8,450	6,337	2,335
2010	386	4,480	1,081	4,263	13,367	11,398	10,722	8,574	16,457	3,345	6,188	17,152
2011	4,881	289	806	4,750	8,906	2,742	7,898	6,092	6,049	10,833	8,124	2,993
2012	3,283	4,383	864	5,324	7,125	3,027	3,732	10,176	12,604	14,338	5,527	9,949
2013	3,485	1,250	6,527	4,610	24,702	7,222	10,948	7,661	2,993	17,591	8,950	4,557
2014	3,045	181	503	2,964	5,558	1,711	4,928	3,802	3,774	6,760	5,070	1,868
2015	-	1,019	3,838	1,525	10,925	7,734	8,878	19,189	15,873	17,780	8,844	9,327
2016	681	2,945	208	11,195	12,329	4,808	12,185	14,980	4,292	13,623	14,038	10,616
2017	1,941	1,965	5,402	3,225	21,241	1,728	5,272	6,319	8,342	6,536	11,451	6,927
2018	684	-	239	812	405	837	875	1,512	2,003	787	2,875	1,535
2019	427	25	71	416	779	240	691	533	529	948	514	925

9.10.3 Water Balance

As per estimation, annual recharge estimated by the SWB model is 128,987 m^3 and it is 24% of annual average rainfall (refer Figure 160).

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	541,281	6310	254,816	128,987	146,146	80,266
%	100%	1.17%	48%	24%	27%	14.8%

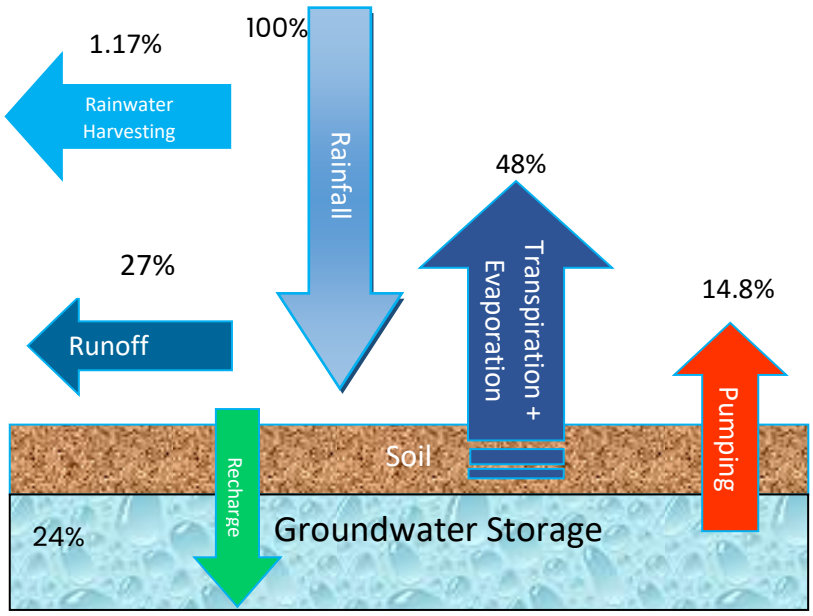


Figure 160: Annual water balance – Dh. Bandidhoo Island

9.10.4 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 (6689 m^3/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 164: Deficit percentage - Dh. Bandidhoo

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	131	54.6

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 Dh. Bandidhoo island depend 54.6% 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 (80,266 m^3/yr) with safe abstraction volume (48,702 m^3/yr) shows that present withdrawal is 64.8% higher than the safe yield. Therefore, it could be inferred that present groundwater abstraction is high and it would lead to up-coning freshwater-saline water interface in future.

9.11 SUTRA Modelling

9.11.1 Model representation and mesh production

SUTRA modelling requires mode domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island. The other boundary defined in the model was island outline which can be referred as shoreline most of the cases except at harbour area and the inner part of the island was subdivided to several polygons representing different land use and it was accomplished by importing GIS shape files of island land use and then drawing polygon 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.

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 161 shows the pressure boundary defined for Dh. Bandidhoo island.

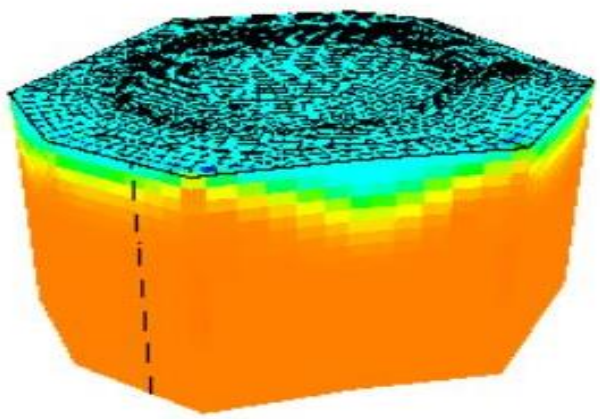


Figure 161: Pressure boundary at SUTRA model – Dh. Bandidhoo island

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.

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.

9.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20 yr period is shown in Figure 162. The section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0357 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top.

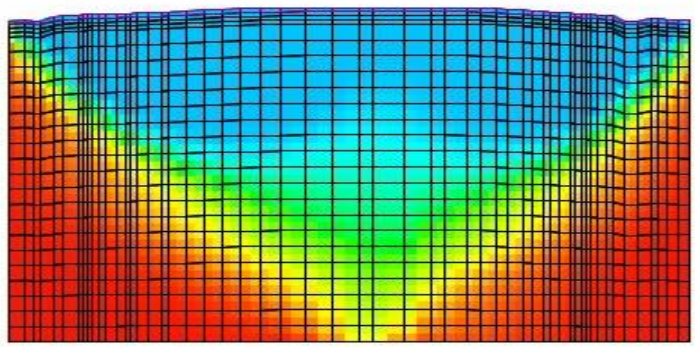


Figure 162: Saltwater distribution - Dh. Bandidhoo island

9.12 Summary of Baseline Assessment

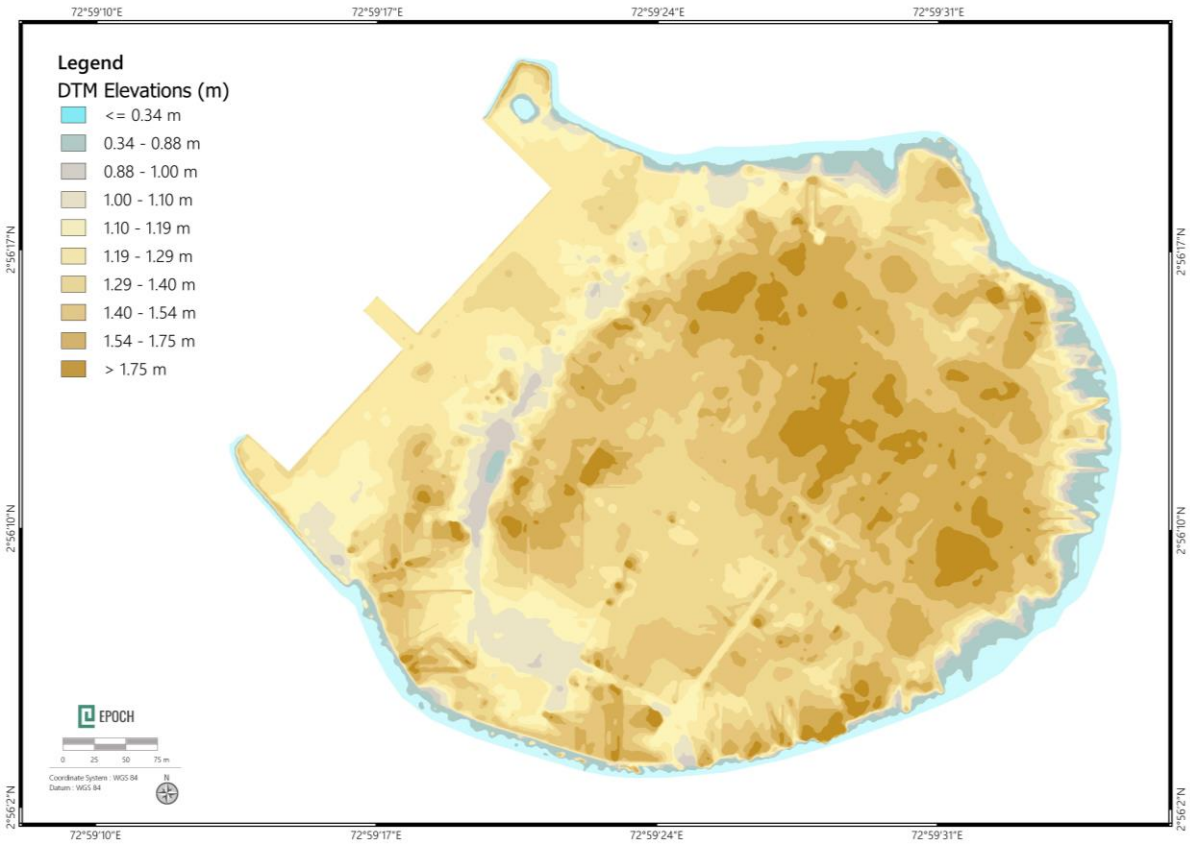
Summary of findings extracted from field works, laboratory test, modelling and analysis are presented below.

- General overview, demography, and climatology

Item	Details
Atoll	Nilandhe Atholhu Dhekunuburi Atoll
Length	0.62 km
Width	0.53 km
Area	24.2 ha
Population	997
Population/area	41.20 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use

Topographical map



Land use map

Average elevation = 1.396 m above MSL

Shoreline length = 2278 m

	% of total area
Roof cover	13%
Vegetation (Thick)	33%
Vegetation (Thin)	18%
Bare Lands	36%
Farmlands	0%
Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Industrial	Institutional	Total
Rate (m^3/d)	209	-	0.29	10.25	220

- Water quality parameters – Physiochemical
  Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	619 ± 180	1500
Turbidity (FNU)	0.18 ± 0.21	5
DO (mg/L)	5.25 ± 1.58	
pH	7.47 ± 0.27	6.5-8.5
Temp (°C)	29.28 ± 0.95	
Sal (ppt)	0.27 ± 0.09	
NH_3 (mg/L)	1.44 ± 2.79	1.5 (Odour Threshhold)
NO_3^- (mg/L)	11.98 ± 10.03	50
PO_4^{3-} (mg/L)	0.22 ± 0.16	

- Water quality parameters – Microbiological
  Number of samples tested = 15

Parameter	Value range	Average value	Remarks *(on permit limit)*
Total Coliform (MPN/100ml)	189 - >2420	735.13	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	41 – 691	152.13	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	92.00	m^2/day
Storativity	1	0.2107	-
Permeability	7	12.19 – 31.79 Average – 17.47	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m^2)	Inundation depth (m)
34	4,890	0.356

- Electric Resistivity survey
  - Measurement taken at 21 locations.
  - Average freshwater thickness in the island is 1.48 m.
  - Freshwater lens volume and aquifer stress level

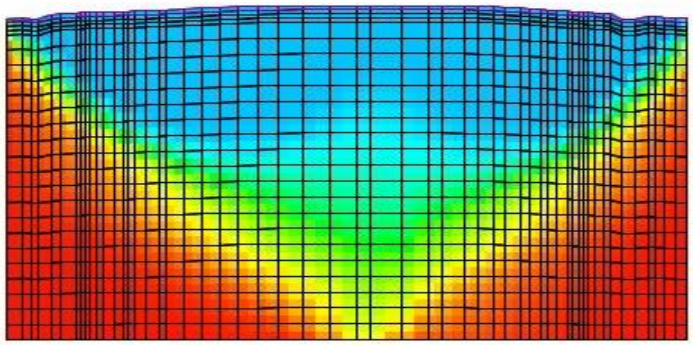
Item	Value	Unit
Freshwater lens volume - ArcGIS	436,921	m^3
Groundwater abstraction	80,266	m^3/yr
Freshwater lens volume/ Groundwater abstraction	5.4	-
Aquifer stress level	Not Stressed	-

- SWB modelling
  - Annual recharge is 128,987 m^3 and it is 24% of annual rainfall (2242 mm)
  - Annual water balance

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	541,281	6310	254,816	128,987	146,146	80,266
%	100%	1.17%	48%	24%	27%	14.8%

  - Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 54.6% in an average year, and it is compensated by ground water storage.
  - Ground water withdrawal (80,266m^3/yr) is 64.8% higher than the safe abstraction (48,702/yr).

- SUTRA modelling
  - Average monthly recharge assigned to SUTRA model
  - Freshwater lens prediction (allowable concentration for potable use is 0.001)



10 M. Naalaafushi

10.1 Island Overview and Location

The Island of M. Naalaafushi, belonging to Mulaku Atoll, is in the Southern Central region of Maldives at 2°53'45"N and 73°34'45"E. It is approximately 142 km South of the capital Male'.

Table 165: Island Geographical Data

Island	M. Naalaafushi
Atoll	Mulaku Atoll
Location	2°53'45"N and 73°34'45"E

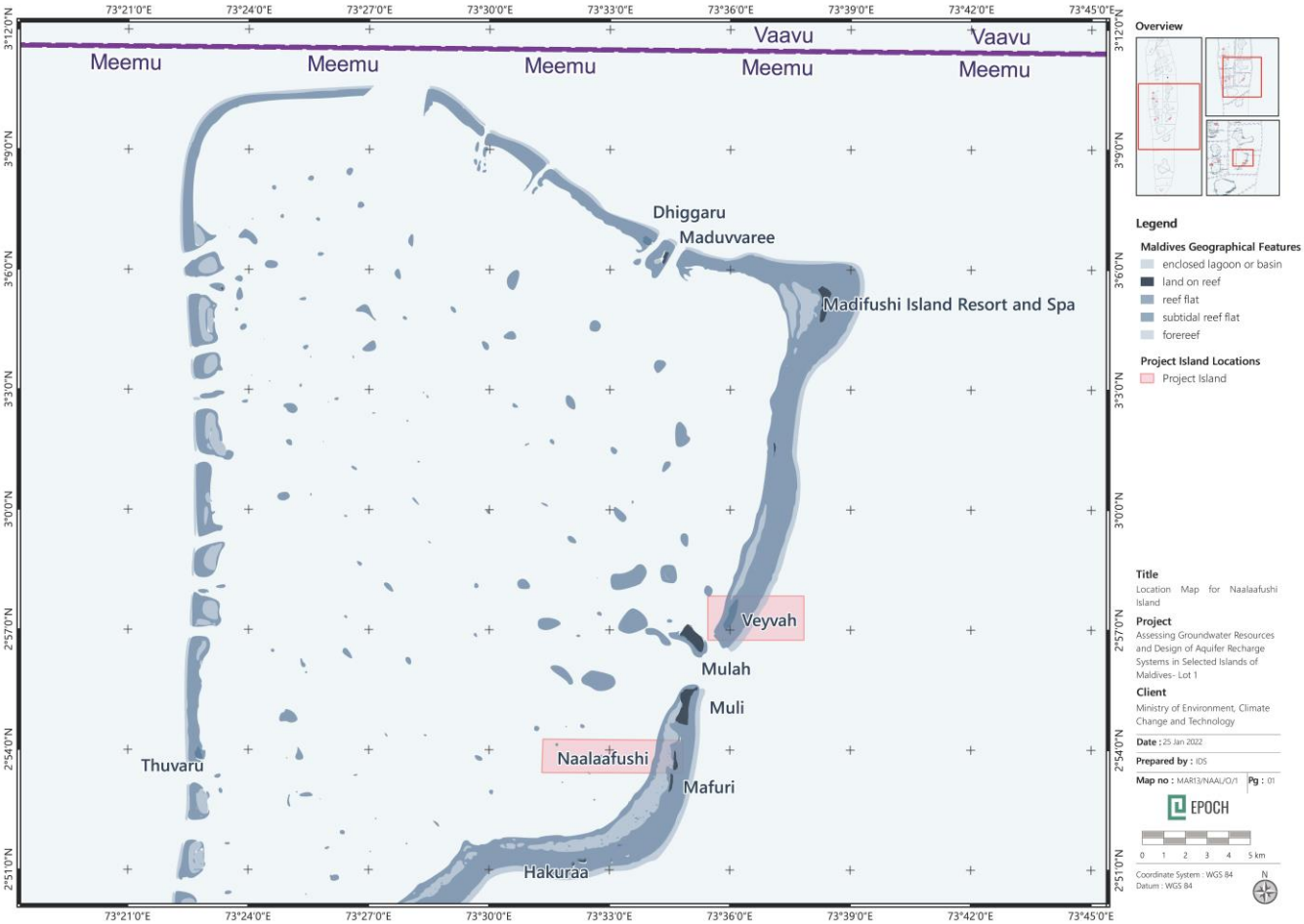


Figure 163: Location map – M. Naalaafushi

10.1.1 Island features

The island is geographically located in the southeast side of Meemu atoll. The island extends up to 0.92 km in length and has a width of 0.21 km from toe to toe. The island mostly has bare lands, and the farmlands only cover 0.2% of the total area of the island. M. Naalaafushi has an old mosque which is adjacent to the island cemetery and is considered a historical site. The island also has a famous surf point, locally known as Boa huraa.

The island has a harbour at its west side of the island. About one-third of the island's surface is vegetation. Thin vegetation is mostly located in the centre and south side of the island. The north side and outer edge of the south side of the island is covered mostly by thick vegetation. About one-third of the island is populated, which is mostly in the south side of the island. The Land Use Characterization map is attached to Annex II.

Table 166: Area Distribution in M. Naalaafushi

Area	12.5 ha	
Length	0.92 km	
Width	0.21 km	
	Area (m^2)	**% of total area**
Roof cover	16,776	13%
Vegetation (Thick)	36,478	29%
Vegetation (Thin)	21,843	17%
Bare Lands	49,740	40%
Farmlands	226	0.2%
Total	125,129	100%

10.2 Topographical Features

Permanent Survey Marks PSM 0307, PSM 0308 and PSM 0309 were used as benchmarks for M. Naalaafushi 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 918 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.27 cm per pixel. 14 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 167: GCP Statistics for M. Naalaafushi

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	0.000257	-0.000308	-0.002747
Sigma [m]	0.0161	0.0191	0.0290
RMS Error [m]	0.0161	0.0191	0.0292

M. Naalaafushi is a relatively low-lying island, with no surface elevation exceeding 1 m above mean sea level throughout the island. The northern end of the island has greater elevations of 0.7 m to 0.9 m. On the other hand, the southern side of the island shows a distinct variation, where natural ground surfaces have elevations between 0.6 to 0.7, while some of the main roads used within the residential area ranges between 0.7 m to 1.1 m, indicating some road levelling and height increase works carried out on the road surfaces. Also of note is the significant deforestation undergone in the late 2000s, alongside reclamation next to the northern harbour. There has also been a beach replenishment and coastal protection project in the form of revetments on the eastern shoreline in recent years.

Roof elevations generally do not exceed 5-7 m and very few houses have multi-storey buildings in M. Naalaafushi. For visualisation purposes all elevations above 10 were given the same colour in the DSM. Vegetation is very limited on M. Naalaafushi, limited to a few patches on the north and centre of the island along with a few stretches along the southern periphery of the island. Thick vegetation with heights greater than 10 m are seen in patches in the north and in the vegetation line along the southern shoreline. Roughly all the vegetation found of the island exceeds 10 m in height.

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 M. Naalaafushi. The DTM slightly overestimates the elevations with a mean of 3.29 cm.

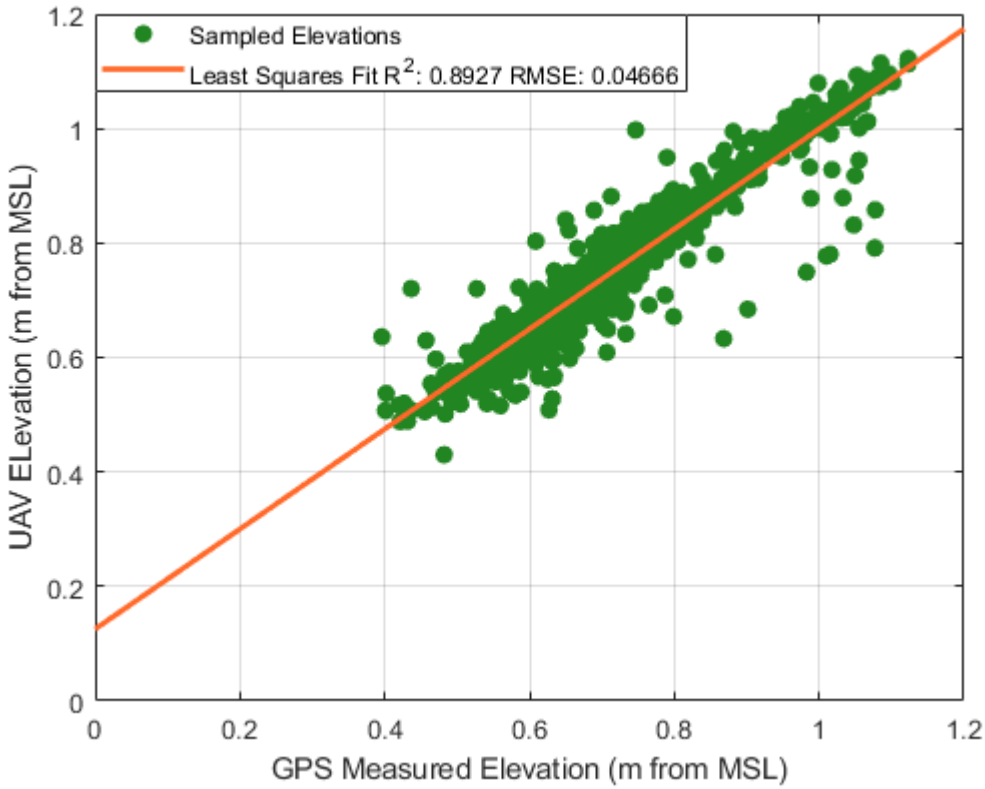


Figure 164: Linear Regression Plot for M. Naalaafushi Sample UAV elevations

Table 168: Error Statistics for M. Naalaafushi DTM

Parameter	*Value (cm)*
Mean	3.29
Standard Error	0.18
Median	3.31
Mode	#N/A
Standard Deviation	5.05
Sample Variance	25.52
Kurtosis	9.19
Skewness	-1.24
Range	56.92
Minimum	-28.54
Maximum	28.38
Sum	2625.52
Count	798.00

10.2.1 Level changes

M. Naalaafushi has an average elevation of 0.733 m with a standard deviation of 0.382. Digital Terrain Model elevations range from -0.6 to 1.7 m from MSL. The distribution of elevations has a symmetrical bimodal distribution with 0.7 m being the highest frequency for elevations. A second peak is observed near -0.4 m from MSL.

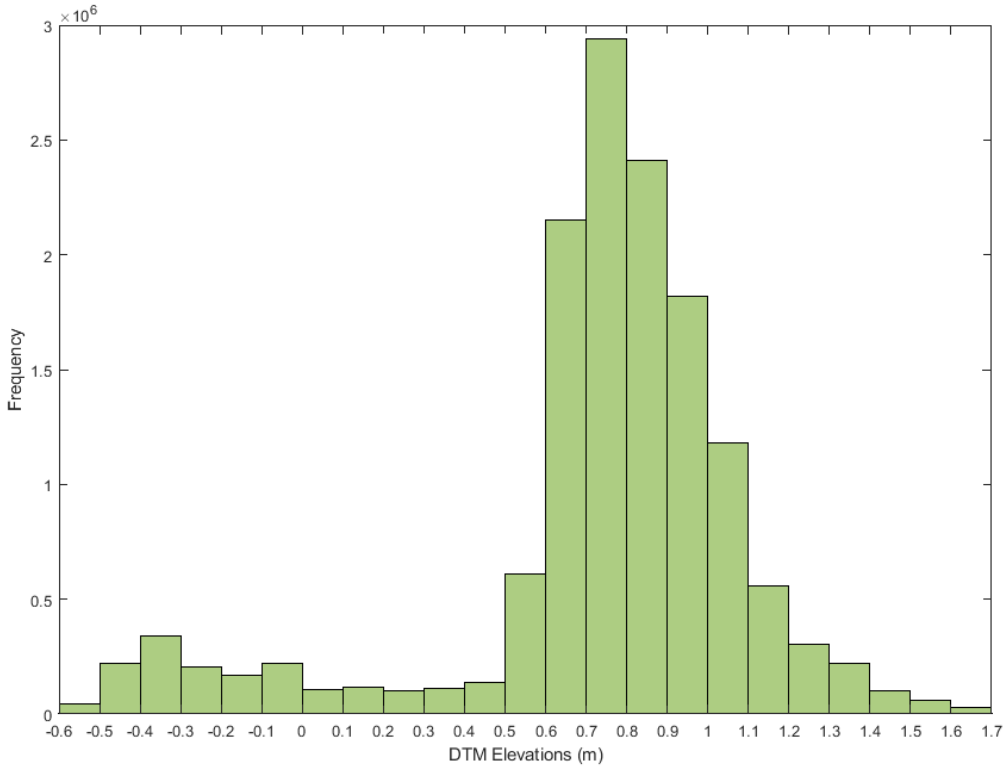


Figure 165: Raster Histogram created for M. Naalaafushi DTM

Profile 1, which goes from north to south, has a number of peaks along its length. There is a ridge formed at the start of this profile, which is on the eastern shoreline. This ridge is the result of eastern swells approaching the island, which is the main wave incident wave direction for M. Naalaafushi. The first depression comes at 200 m, followed by a peak at roughly 400 m. The profile then starts declining towards the shoreline, where it terminates as a ridge on the southern shoreline with an elevation of 1.5 m.

Profile 2 spanning west to east shows little to no variation along its length, with elevation averaging 0.75 m. Profile 3, spanning in the same direction in the south side of the island, has a peak in the middle of elevation 1 m, with both ends only showing a slight decrease in elevation of 0.75 m. Profile 4, which also goes from west to east, is found at the northern side of the island. This profile has a near constant height

of 0.75 m from start to 80 m, after which it starts to incline up to 1.1 m, which is due to the beach replenishment and revetment works carried out at this end.

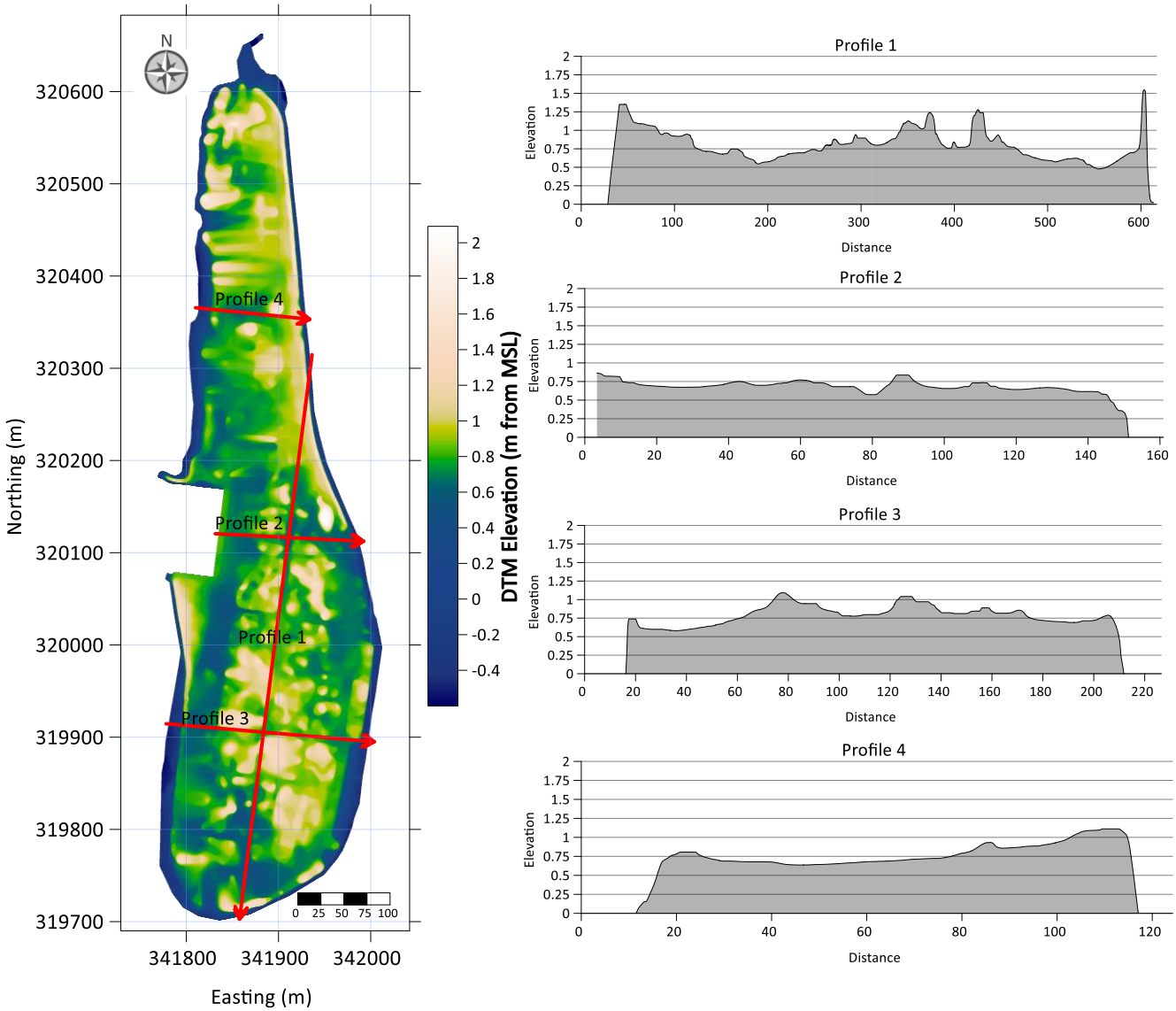


Figure 166: Digital Terrain Model Elevations and Profiles for M. Naalaafushi Island

10.2.2 Shoreline

M. Naalaafushi has a shoreline length of 2225 m. The shore protection features around the island are as follows:

- Breakwater: There are two rubble mound breakwaters on M. Naalaafushi, both found on the west side of the island. Western wind waves generated within the atoll basin is absorbed and dissipated by this breakwater to offer protection to berthed vessels within the harbor. The breakwater is detached from the island itself and does not have any access platforms connecting it to the island. Crest height for both breakwaters vary between +1.2 m and +1.4 m above mean sea level. The breakwaters are highlighted in orange.
- Revetment: There are three revetments, one on the north and one the south side of the harbor, and the last one covering a stretch of the northeastern shoreline. The harborside and northeastern revetments serves as shore protection and prevents erosion behind it by dissipating wave energy from western wind waves generated within the atoll basin and northeastern swell waves respectively. Crest height for the revetments is as follows.
    - Revetment north of harbor: +1 m to +1.2 m above mean sea level
    - Revetment south of harbor: +1.4 m to +1.6 m above mean sea level
    - Revetment on northeastern shoreline: +1.4 m to 2 m above mean sea level

  The revetments are highlighted in green.
- Quay wall: These structures are found within the harbor and are highlighted in yellow. Crest height of quay walls is around +1 m above mean sea level.
- Rock revetment dumped by island residents: This revetment like structure is found along the southwestern and southeastern shoreline, which is made of near vertically stacked rock. This structure does not have much consistency and has crest height varying between +0.4 m and +0.8 m above mean sea level.

The southwestern shoreline has undergone severe beach erosion, where the shoreline has regressed to expose vegetation roots.

Figure 167: Orthomosaic of M. Naalaafushi

10.2.3 Reef

M. Naalaafushi is located on the south-eastern periphery of the Meemu Atoll, with a number of other major islands located on the same reef. To the north, the nearest major island is Muli, with a Finolhu located in between. To the south, Mafuri is located close by with less than 200 m between both islands. For the major wave direction, which for M. Naalaafushi is the North-eastern swell waves, the buffer zone can be roughly 500 m on its shortest length.

Figure 168: Sentinel 2 imagery of M. Naalaafushi reef taken in February 2022

10.3 Socio Economic Status

10.3.1 Demography

The island has a registered population of 406 as per the 2014 census, with a total of 198 males and 208 females. In 2021, the island population as per the council is 535. The island population density is 42.8 people per hectare. The total number of households is 81. The following table and graph illustrate the demographic breakdown of M. Naalaafushi.

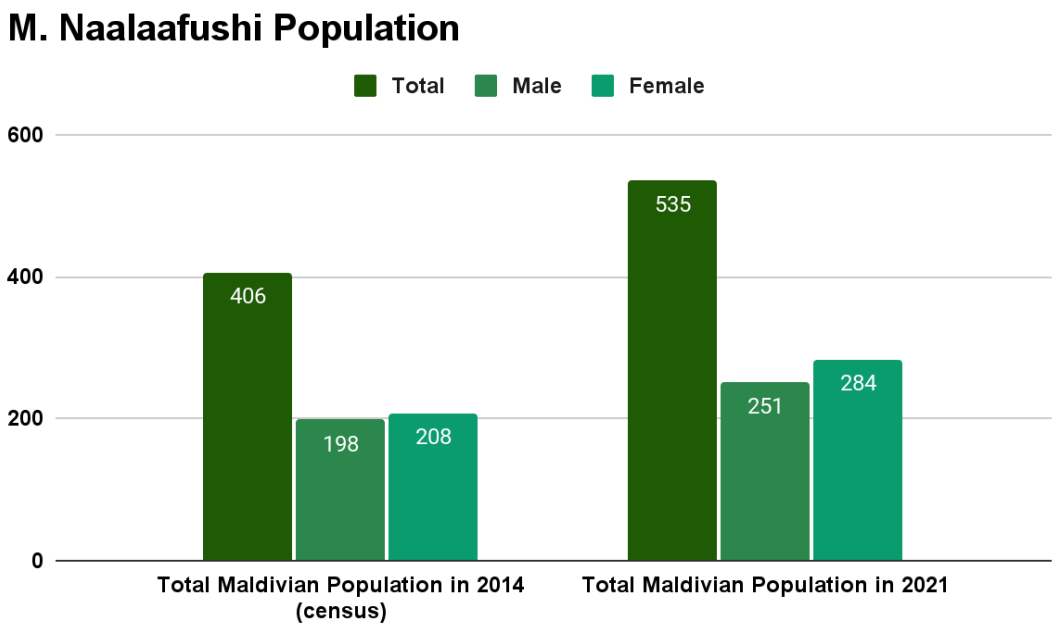


Figure 169: M. Naalaafushi Population

Table 169: M. Naalaafushi 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
M	Naalaafushi	424	216	208	406	198	208	18	18	-

10.3.2 Socio-Economic Activities

M. Naalaafushi is an inhabited island in Meemu Atoll's administrative unit and physically part of Mulaku Atoll in the Maldives'. The people in M. Naalaafushi work mostly in tourism jobs and the fishing industry. The women of the island are proficient rope makers and are well known for thatch weaving. Following the 2004 Tsunami, the island was categorized as one of the worst affected islands with more than 80% of the population of the island left without habitable homes.

10.3.3 Facilities available

10.3.3.1 Health Care

M. Naalaafushi Health Center is equipped with 4 beds and a pharmacy. Currently, 15 staff including one doctor and three nurses are working at the Health Center to ensure basic medical care is provided for the residents.

10.3.3.2 Education

M. Naalaafushi has one school which is named as Naalaafushi School. A total of 22 staff are working and 68 students are enrolled in primary and lower secondary schools.

10.3.3.3 Utilities

Currently, the main form of sanitation in the island is local outfall pipes. Government has tendered more than MVR 18 million budget for the water and sewerage project planned on the island. The island also has one powerhouse and 4 industrial buildings.

10.3.3.4 Transportation

M. Naalaafushi has a harbor of 310ft x 150ft which was constructed by Maldives Transport and Contracting Company (MTCC) in the year 2015.

10.3.4 Water resources, water usage and water consumption survey

In M. Naalaafushi, there are a total of 81 households in habited currently. 67 out of 81 households were surveyed, while maintaining a 95% confidence interval and geo-coordinated sampling points. A map of households surveyed is attached in Annex V. A map of households surveyed is attached in Annex H.

Table 170: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	**67/81 households = 82.7%**
Percentage of well fitted with pumps	97%
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 local outfall pipes and septic tanks. Based on the survey, 96 percent of the survey households have connected their sanitation to a local outfall pipe. While the remaining 4 percent use septic tanks as sanitation facilities.

In M. Naalaafushi 36 percent reported to have less than 49ft distance between septic tanks and groundwater well. While the remaining 64% reported that they do not know an exact distance between them. 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 (49.2 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.

10.3.4.2 Water usage and resources

Based on the survey conducted in M. Naalaafushi, 63 houses have HDPE rainwater tanks for rainwater storage. 100% of the households use rainwater for cooking and 93% use rainwater for drinking. Rainwater collected from rooftops is stored in water tanks, whether communal or home tanks. During dry season, many households go by 3-4 months without being able to obtain any rainwater. Many homes utilize rainwater from neighboring houses or bottled water when rainwater is scarce during the dry season. After the tsunami the council had to continuously request for RO water for 4-5 years. While most houses reported groundwater is mainly used for gardening, household cleaning, toilet flushing and showering with 97% of the houses fitted with water pumps.

The following sections highlight 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 M. Naalaafushi, **92,555** liters of groundwater is used daily in the households. A total of **173** liters of groundwater are consumed per capita per day.

Table 171: Domestic groundwater use data for M. Naalaafushi

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
87.5	33	10.5	19.5	1.06	16.4	4.61	**173**

*All units are in Liters per capita per day

10.3.4.4 Commercial water usage

Based on the survey conducted in M. Naalaafushi, there are currently two operational café'/restaurant and no guesthouses on this island. A total of 263 Liters of groundwater are used by commercial entities and their detailed breakdown is given in the table below.

Table 172: Commercial groundwater use data for M. Naalaafushi

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Iramaa Cafe	93.8	-	-	75	169
Finihiyaa Cafe	93.8	-	-	-	93.8
					263

*All units are in Liters per day

10.3.4.5 Industrial water usage

The total groundwater usage for industrial purposes incorporating the groundwater used for farming and for fish processing is 199 Liters per day.

Groundwater in the farming area was reported as bad and so groundwater is brought to farming area from households to give water to the crops.

Table 173: Groundwater use for farming in for M. Naalaafushi

No. of farms	Type of plantation	Farming period	Plantation size (sqft)	Total water usage daily (Liters)
1	Fruit & Vegetable	Throughout the year	2500	100
				100

In M. Naalaafushi, out of the 2 fish processing units surveyed, both the fish processing units use groundwater for cutting and cleaning, while rainwater is used for rest of the activities such as cooking, smoking and rihaakuru production.

Table 174: Groundwater use for fish processing in for M. Naalaafushi

Number of fish processing unit	Fish processing activities	Total water usage daily (Liters)
1	Cutting and Cleaning, Cooking and Smoking, Rihaakuru Production	33
2	Cutting and Cleaning, Cooking and Smoking, Rihaakuru Production	66
		99

10.3.4.6 Institutional water usage

Based on the survey conducted in M. Naalaafushi, there are currently five institutions that contain groundwater well facilities and use groundwater on this island. A total of 2102 Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 175: Institutional groundwater use data for M. Naalaafushi

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
M. Naalaafushi School	438	360	40	-	838
Health Centre	117	360	1	74.2	553
Council	133	120	140	-	393
FENAKA	93.9	120	7	-	221
Naalaafushi Court	23.5	73	1	-	97
					2102

*All units are in Liters per day

10.3.5 Present & Future water demand

In M. Naalaafushi the present water demand is at **95,119** Liters per day inclusive of domestic, commercial, institutional, and industrial water demand. It is expected that groundwater usage will 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.

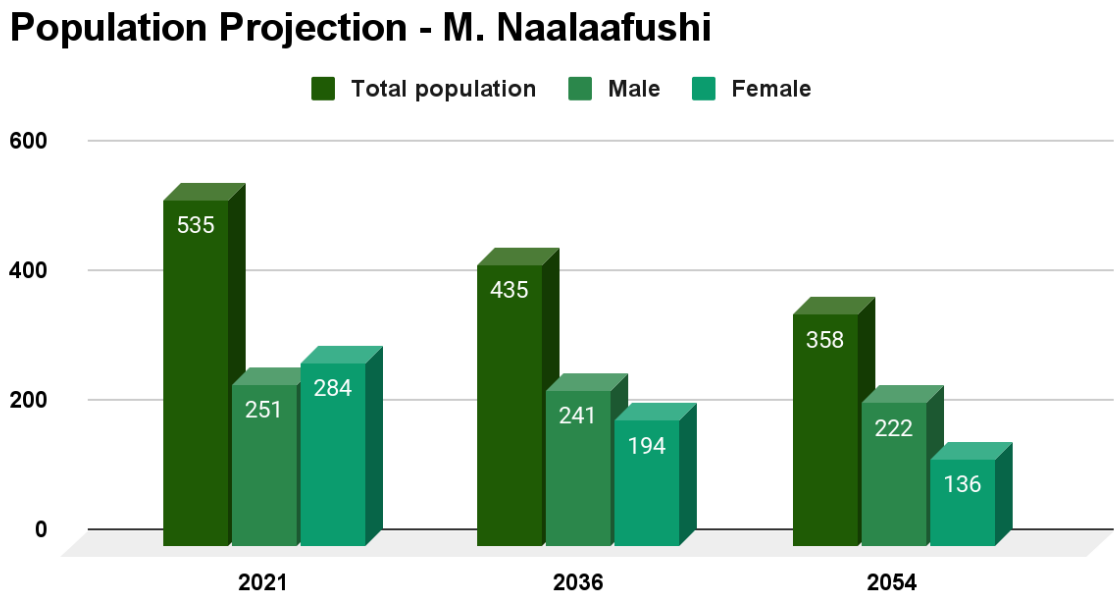


Figure 170: Population Projection - M. Naalaafushi

Table 176: Present groundwater demand - M. Naalaafushi

Year	Total Population	Domestic water demand	Commercial water demand	Industrial water demand	Institutional water demand	Groundwater usage
2021	535	92,555	263	199	2102	**95,119**

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 173 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 173 Liters, the groundwater demand is expected to be 123 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 435 is expected to be 53,505 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 173 Liters, the groundwater demand is expected to be 98 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 358 is expected to be 35,084 Liters per day.

Table 177: Future domestic water demand - M. Naalaafushi

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	435	173	50	123	53,505
2054	358	173	75	98	35,084

10.3.6 Water related issues

From 67 households surveyed in M. Naalaafushi, most houses reported smell, milky texture and foul taste in their respective wells. According to the social survey, 78 percent reported having a smell, 46 percent reported having a milky texture and 43 percent reported having a foul taste in their groundwater. In M. Naalaafushi, oxygen pump usage is common in most households because of foul smell. The island Health Center has no records of health issues related to groundwater. As per social survey, 34% of the houses have oxygen pumps connected to their wells. Oxygen pumps are usually connected to counteract pollution and gasses such as hydrogen sulphide which cause unpleasant smells. The water at school was reported to be significantly bad and has a foul odor. As per social survey, water in the farming areas was also reported as significantly bad and because of this groundwater is usually taken from households to the farming area to water the crops.

Many households also report that during dry season, generally 3-4 months go without being able obtain rainwater. The council also indicated that after tsunami they have been continuously requesting RO water for 4-5 years.

Table 178: Signs of contamination reported by households

Types of contamination	Data in % out of 67 households surveyed
Smell	78%
Milky	46%
Foul taste	43%
Salty	37%
None	13%

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 67 households surveyed
Changes with tidal variations	19%
Groundwater quality is better in rainy months	58%
Long periods without rain causes bad smell	36%
Long periods without rain causes bad taste	25%
Rain makes it worse	7%
No change	1%

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 - M. Naalaafushi

	EC (µS/cm)	Turbidity (FNU)	DO (mg/L)	pH	Temp (°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 threshhold <35 Taste threshhold Source[1]	<50 Source[1]	
Mean	3608	3.32	3.80	7.54	29.5	1.82	5.90	16.7	0.30
Median	1427	0.86	3.30	7.51	29.4	0.65	2.04	6.24	0.19
SD	5031	6.49	1.47	0.27	0.86	2.75	8.28	23.3	0.29
Min	322	0.02	1.64	7.15	27.8	0.14	0.19	1.11	0.05
Max	25,584	32.28	7.73	8.07	32.0	14.2	36.9	123	1.42
CV	1.39	1.95	0.39	0.04	0.03	1.52	1.40	1.40	0.97

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH_3= Ammonia, NO_3^-= Nitrate, PO_4^{3-}=Phosphate,
SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source[1] = WHO Drinking Water Guidelines, 2017. Source[2] = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 3608 µS/cm is higher than both the WHO Standard for potable water (<1500 µS/cm) and the WHO Standard for non-potable water (<2500 µS/cm). The maximum value for EC (25,584 µS/cm at WQ40) was observed at the fisheries work area which is located away from the inhabited areas at the Northernmost tip of the island.
- Thirteen samples had higher EC than 2500 µS/cm with three samples having EC higher than 10000 µS/cm. Six samples had EC between 1500 µS/cm and 2500 µS/cm while 21 samples had EC lower than 1500 µS/cm. The EC distribution is shown in Figure 171.
- As expected, the EC of the groundwater in the center of the island is lower than the coastal areas of the island which indicate saltwater intrusion at the periphery of the island.
- The mean Turbidity level at 3.32 NTU fall within the URA Guidelines for drinking water (<5 NTU). Five samples had higher Turbidity level than 5 NTU.
- Dissolved Oxygen ranged from 1.64 mg/L to 7.73 mg/L with a mean of 3.80 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 7.15.
- Temperature ranges from 27.8°C to 32°C depending on the well characteristics and time of day reading was taken. Mean temperature was 29.5°C.
- Salinity ranged from 0.14 ppt to 14.2 ppt with a mean of 1.82 ppt. As expected, the salinity of the groundwater in the center of the island is lower than the peripheral areas of the island
- The mean Ammonia concentration was 5.9 mg/L which is higher than the WHO threshold for odour but well below the threshold for taste. 40% of samples had concentration below 1.5 mg/L, 57.5% 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 172.
- The maximum value for Ammonia (36.86 mg/L at WQ40) was observed at the fisheries work area which is located away from the inhabited areas at the Northernmost tip of the island.
- The mean Nitrate concentration was 16.7 mg/L which falls within the WHO Standard for Nitrate concentration (<50 mg/L). Only 1 sample (WQ40) which is the sample taken at the Fisheries Work Area had Nitrate concentration higher than the WHO standard.
- The maximum value for Nitrate concentration (123.4 mg/L at WQ40) was observed at the fisheries work area which is located away from the inhabited areas at the Northernmost tip of the island.
- Phosphate concentration ranges from 0.05 to 1.42 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. 5 samples tested were below 0.1 mg/L.
- Phosphate concentration is generally higher in residential area.

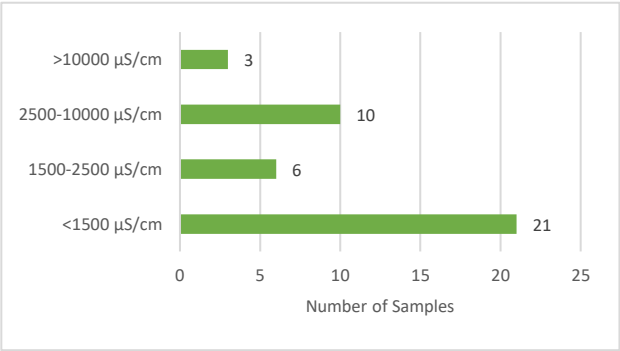


Figure 171: EC Distribution in M. Naalaafushi

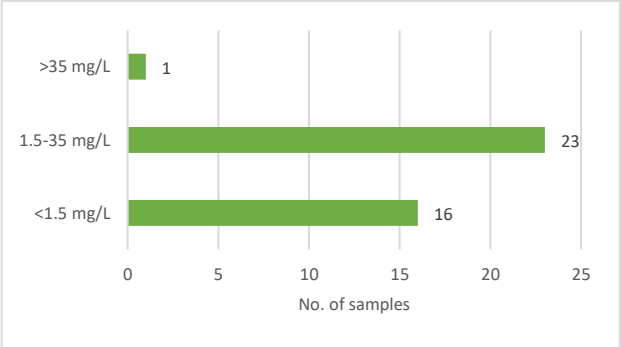


Figure 172: Ammonia Concentration Distribution in M. Naalaafushi

The spatial distribution of all the parameters measured are shown in Figure 173 (a-i).

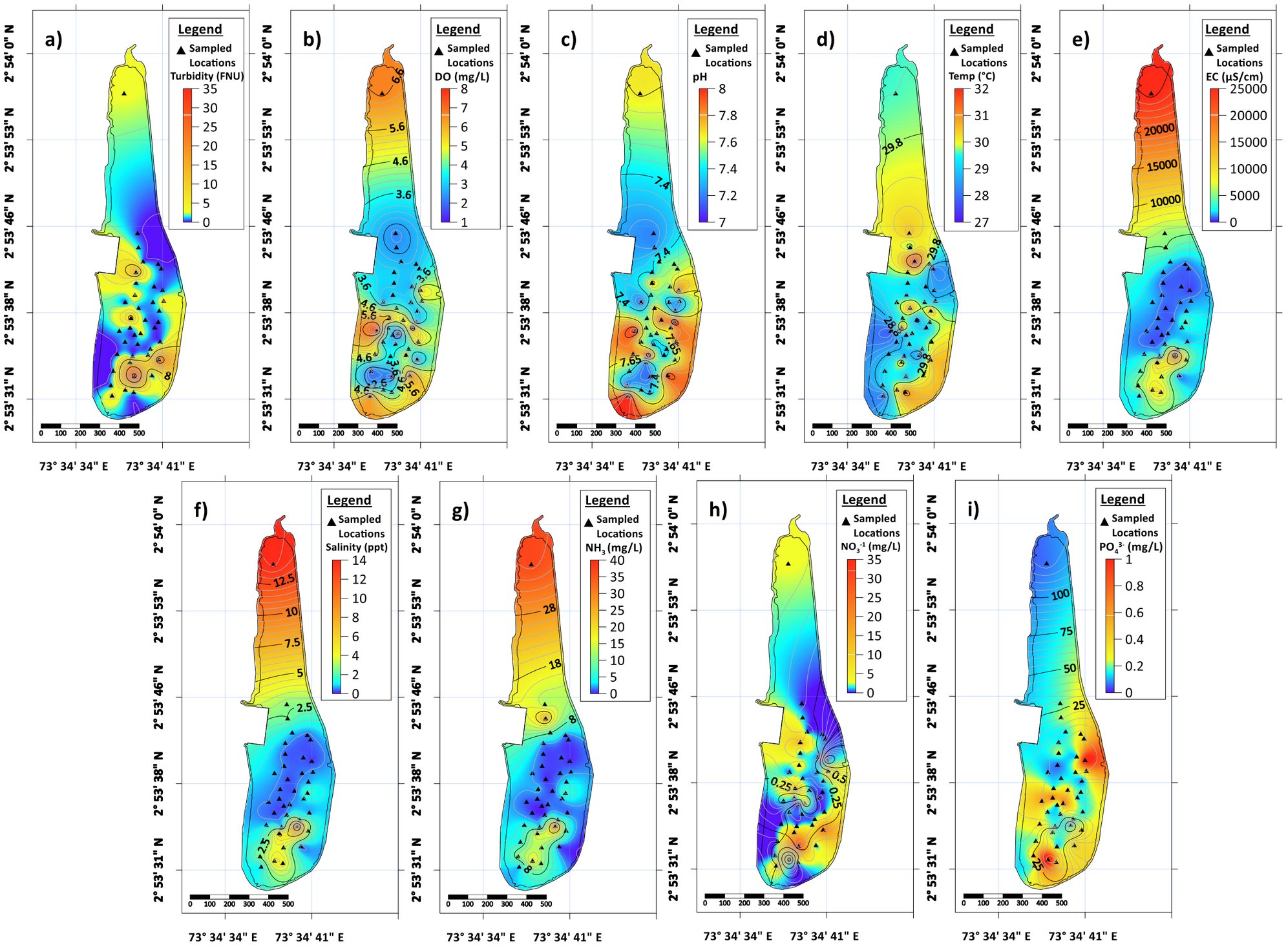


Figure 173: Spatial variation of physiochemical parameters in M. Naalaafushi

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 0.189 and the R-squared of the plot is 0.0357 as indicated from the Figure 174. 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.

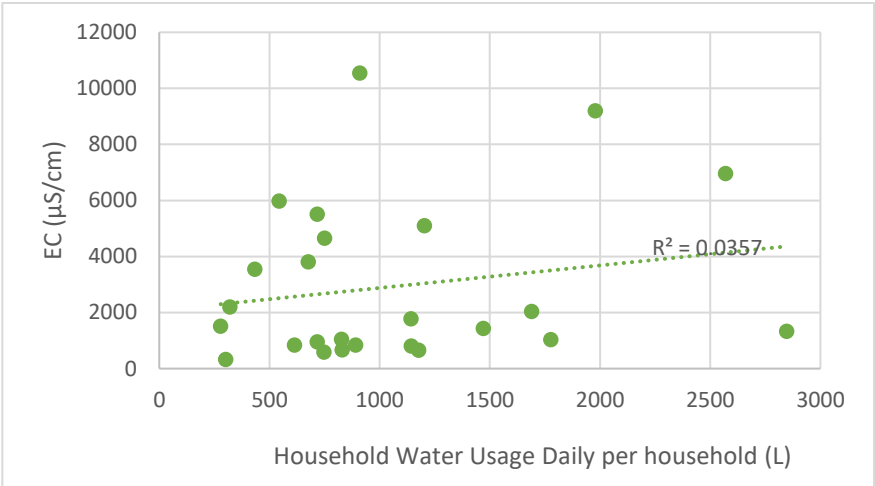


Figure 174: EC against Water Usage in M. Naalaafushi

10.4.1.1 Correlation Matrix

The correlation matrix for M. Naalaafushi 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 M. Naalaafushi

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)	-0.17							
pH	-0.26	0.59						
EC (µS/cm)	0.19	0.15	-0.24					
Sal (ppt)	0.17	0.17	-0.22	***1.00				
Temp (°C)	0.06	-0.32	-0.33	0.09	0.07			
NO_3^- (mg/L)	0.18	0.17	-0.20	0.99	0.99	0.09		
NH_3 (mg/L)	0.14	0.05	-0.31	0.93	0.93	0.14	0.93	
PO_4^{3-} (mg/L)	-0.10	0.12	0.13	-0.04	-0.05	-0.01	-0.05	-0.02

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation

Table 181 shows a strong positive correlation coefficient between EC/Sal (r=1.00), EC/NO_3^- (r=0.99), EC/NH_3 (r=0.93), Sal/NO_3^- (r=0.99), Sal/NH_3 (r=0.93) and NO_3/NH_3 (r=0.93). As the parameter salinity is calculated by the instrument from conductivity and temperature readings, the positive correlation 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 from 2.39 to 184, with a mean of 27.8. The WQI was divided into four categories and Table 182 shows the categorization of samples. 37.5% of samples were classified as "Very Good", 30% of samples were classified as "Good", 15% of samples were classified as "Poor" and 17.5% of samples were classified as "Very Poor". The high value of WQI at some locations has been found to be mainly from the high EC at most locations. High Ammonia concentration and Nitrate concentration also contribute to high WQI at two locations (WQ29 and WQ40). The spatial distribution of WQI is as per Figure 175.

Table 182: Water Quality Classification based on WQI – M. Naalaafushi

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	15	37.5%
10 to 20	Good	12	30.0%
20 to 50	Poor	6	15.0%
>50	Very Poor	7	17.5%

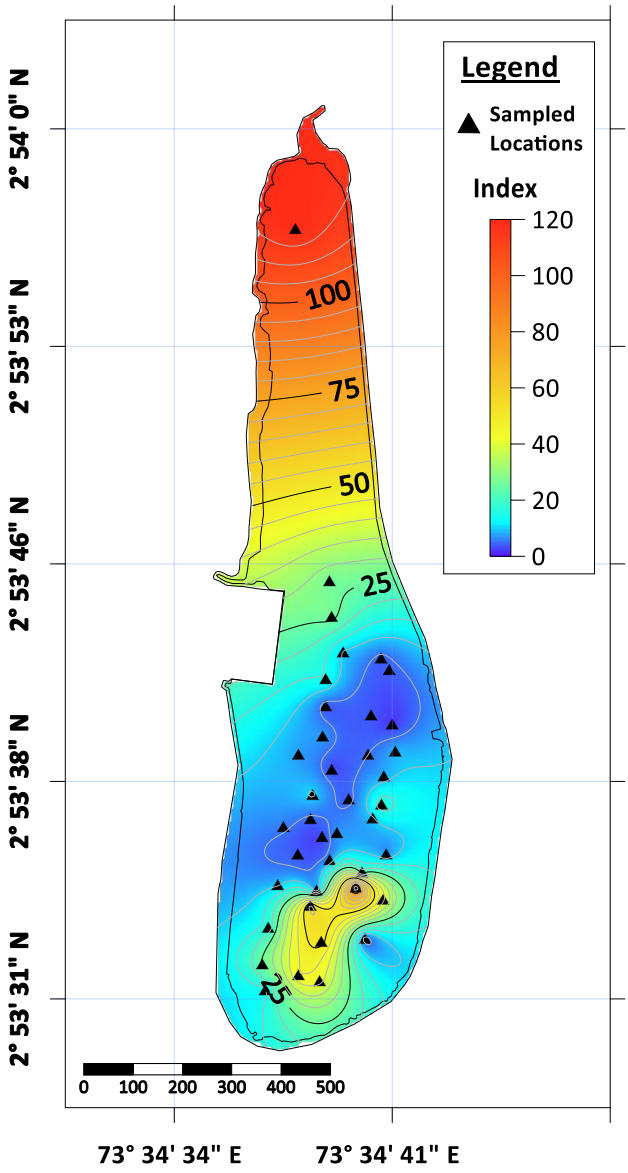


Figure 175: Spatial Distribution of WQI in M. Naalaafushi

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 M. Naalaafushi

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq01	3	Not detected		Connected to a local outfall pipe
wq02	921	Not detected		Social Survey not carried out
wq03	225	Not detected		Connected to a local outfall pipe
wq04	165	Not detected		Connected to a local outfall pipe
wq05	64	2		Connected to a local outfall pipe
wq06	308	Not detected		School
wq07	276	Not detected		Nooru Mosque
wq08	2420	Not detected		Social Survey not carried out
wq09	613	1		Social Survey not carried out
wq10	1553	Not detected		Cemetery
wq11	1046	1	40	Connected to a local outfall pipe
wq12	>2420	8		Connected to a local outfall pipe
wq13	>2420	2	6	Connected to a local outfall pipe
wq14	>2420	20		Connected to a local outfall pipe
wq15	>2420	1		Health Centre

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

Faecal Coliform was detected in 7 samples and Total Coliform were detected in all 15 samples. Total Coliform count higher than 2400 MPN/100ml were detected in 4 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 17 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Total Coliform and Faecal Coliform is given in Figure 176. 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.

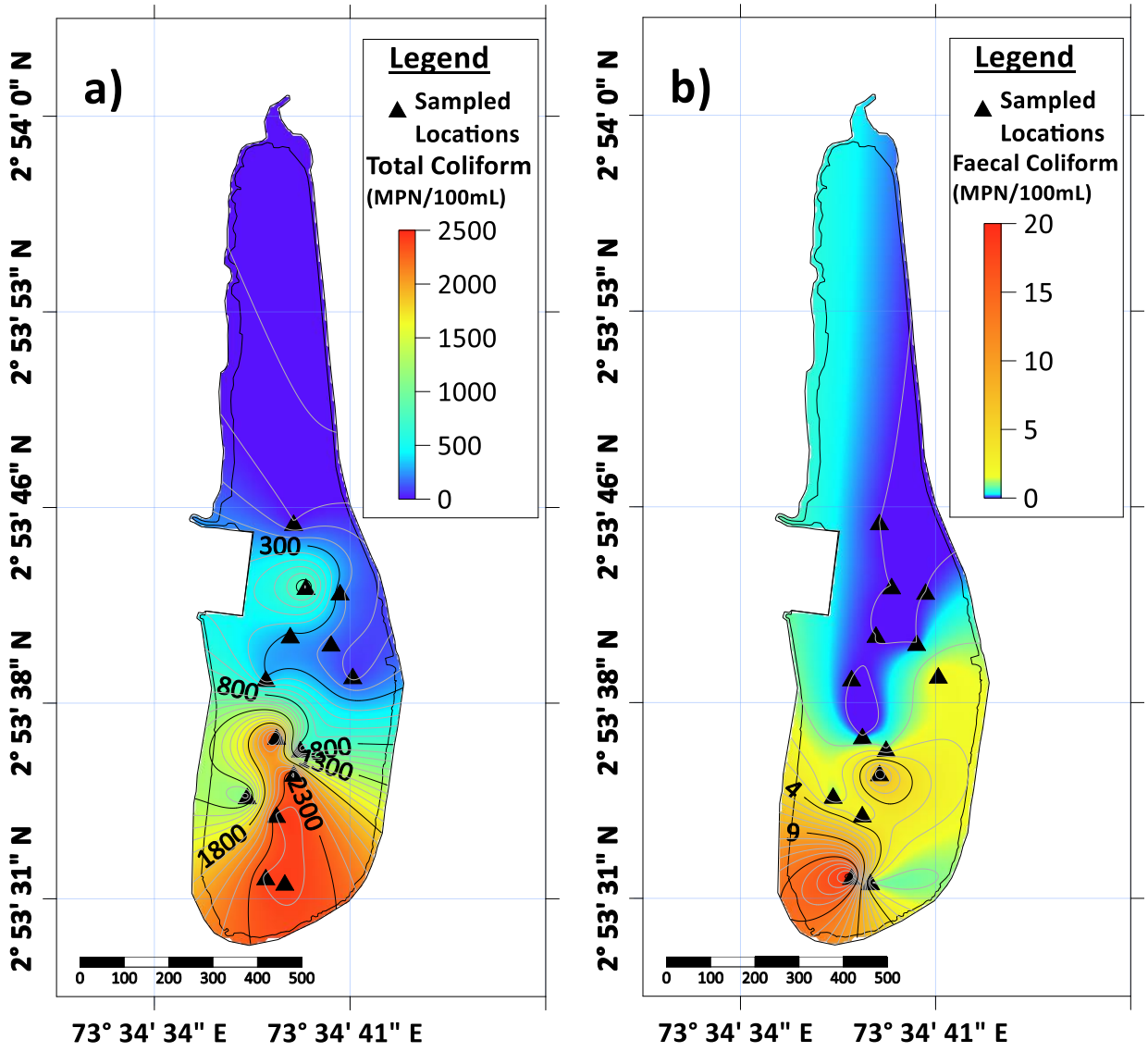
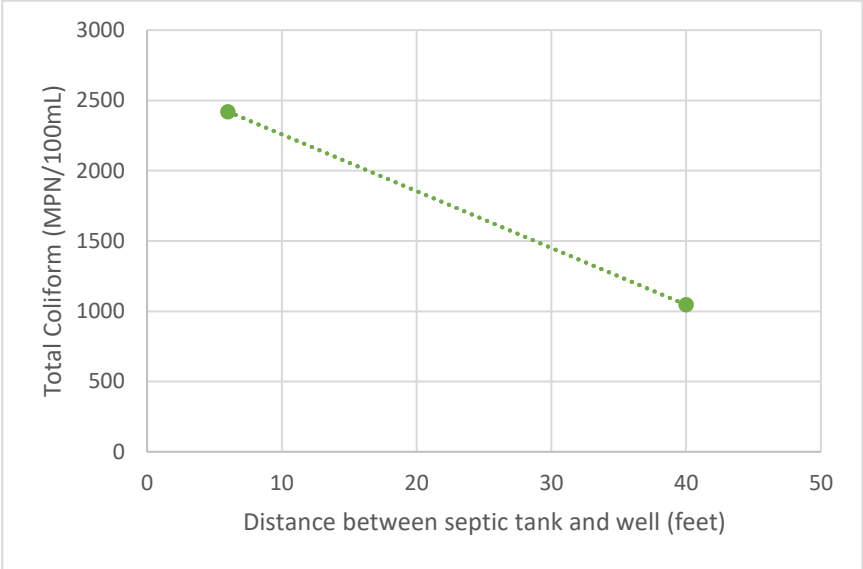


Figure 176: Total (a) and Faecal (b) Contamination Distribution in M. Naalaafushi

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.



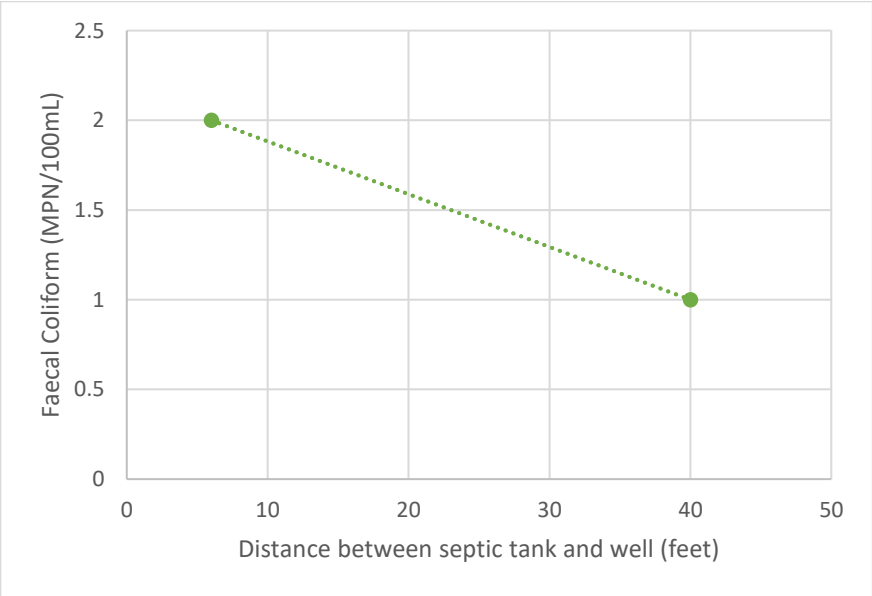


Figure 177: Microbiological Contamination against Septic Tank distancing - Naalaafushi

Since out of the fifteen samples taken for microbiological analysis, only two samples were taken from households where social survey was carried out and an answer was obtained for the distance between septic tank and well, any resulting statistical analyses cannot be considered robust and does not show an accurate relationship between the parameters. However, a negative co-relation is observed based on the two readings taken.

10.5 Pumping Test

10.5.1 Test location

A well without a base was not available in M. Naalaafushi. Therefore, it was decided to carry out the test at the old mosque as the mosque well would be unused for most parts of the day. The chosen well was built using coral stones, hence there were small gaps between that acted as inlets. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 178 below shows the location for the pumping test at M. Naalaafushi.

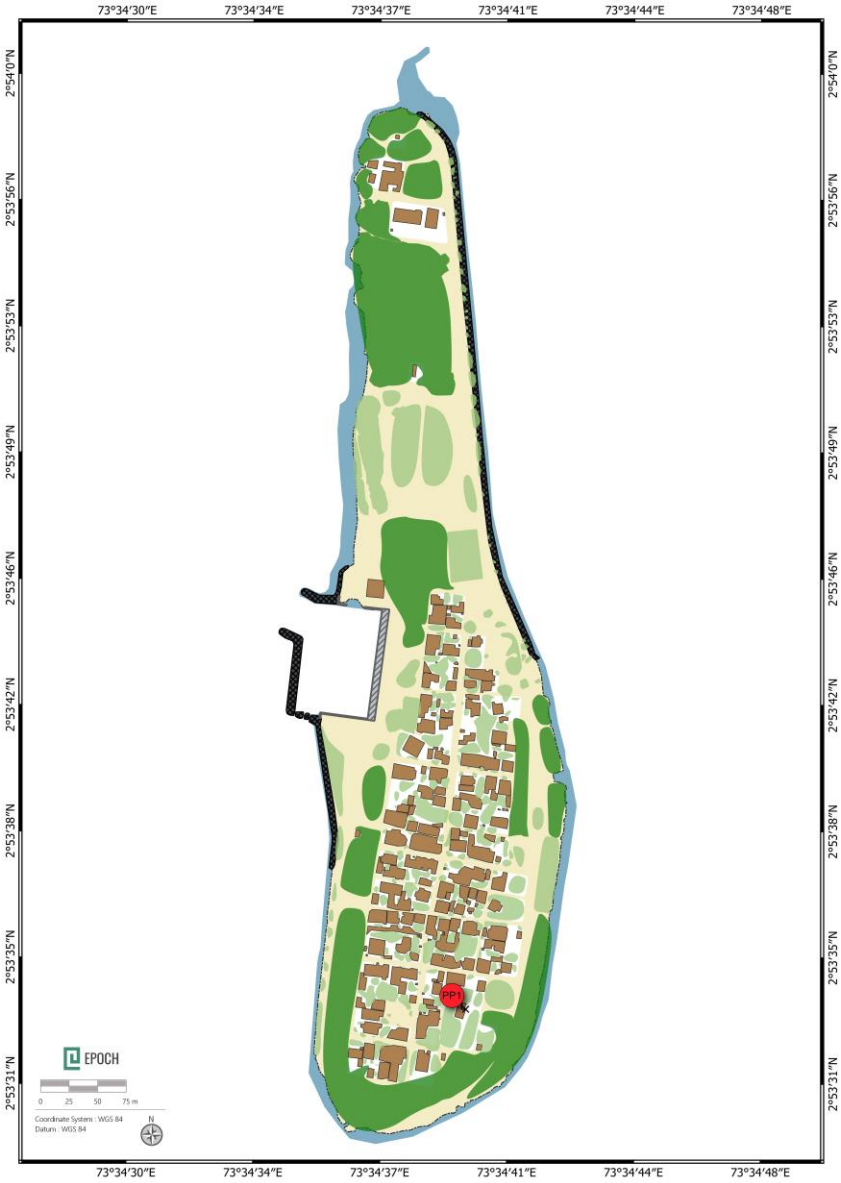


Figure 178: Pumping test location – M. Naalaafushi

10.5.2 Pumping rate, pumping hours, and collected data

A constant rate pumping test was carried out at M. Naalaafushi. The test began at 1557 hours on 01 September 2021 and lasted for 61 minutes. A flowrate of 20 LPM was maintained for the pumping phase which lasted from the 0-31st minute. The recovery phase of the test lasted from 31st-61st minute for more than a 98% recovery.

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 3.14×10^{-4} m^2/s (27.09 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.2021 for M. Naalaafushi. The full data set of the pumping test at M. Naalaafushi has been annexed at Annex XI.

10.6 Permeability Test

10.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 179 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.

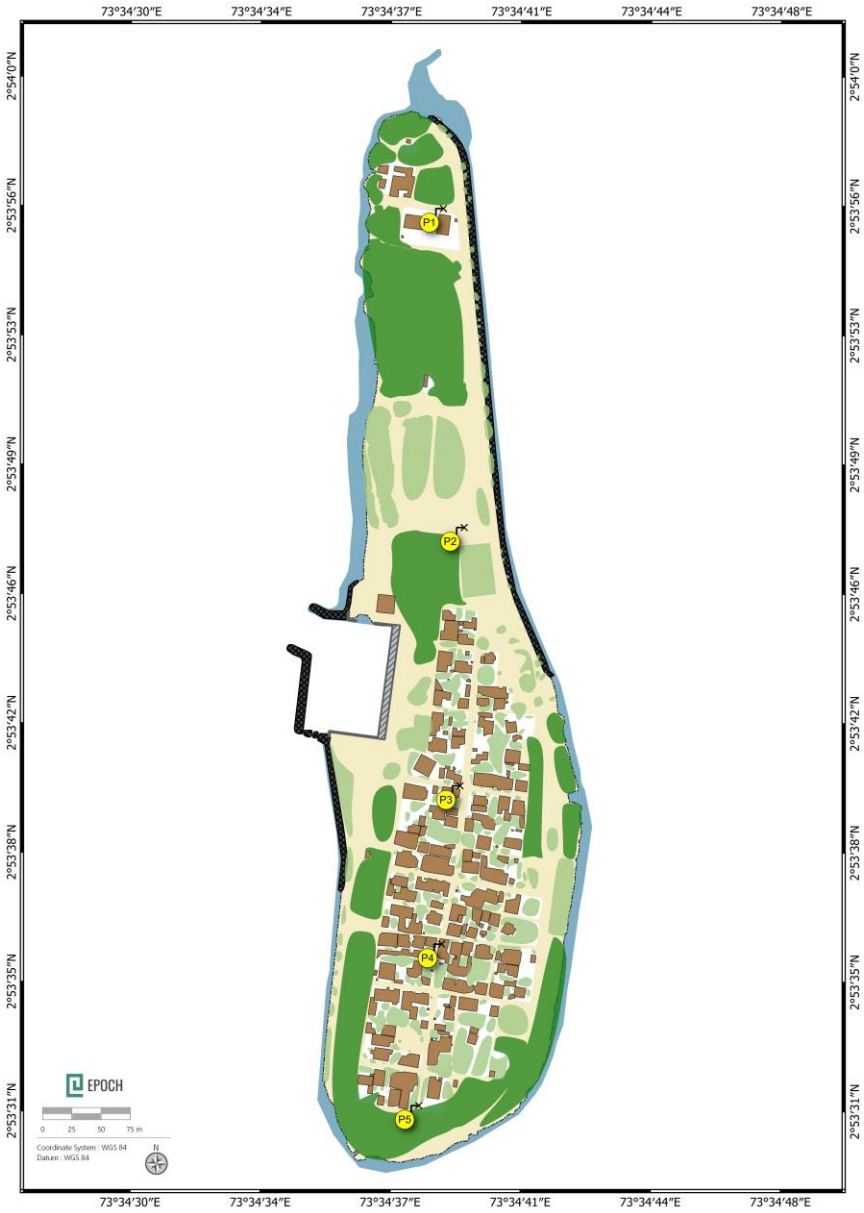


Figure 179: Permeability Test Locations – M. Naalaafushi

10.6.2 Measured data

Table 184: Permeability Test Measured Data - M. Naalaafushi

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m^3/s)	K (m/s)	K (m/day)
NLF-PMB1	0.600	0.540	35	12	5.50	0.000092	1.73E-04	14.96
NLF-PMB2	0.600	0.650	35	12	4.50	0.000075	1.18E-04	10.17
NLF-PMB3	0.600	0.805	35	12	0.25	0.000004	5.28E-06	0.46
NLF-PMB4	0.600	0.660	35	12	9.20	0.000153	2.37E-04	20.47
NLF-PMB5	0.600	0.900	35	12	0.25	0.000004	4.72E-06	0.41

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 M. Naalaafushi is 9.29 m/day, with permeability values ranging from 0.41 m/day to 20.47 m/day. As highlighted in Section **10.7 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)).

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 180 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.

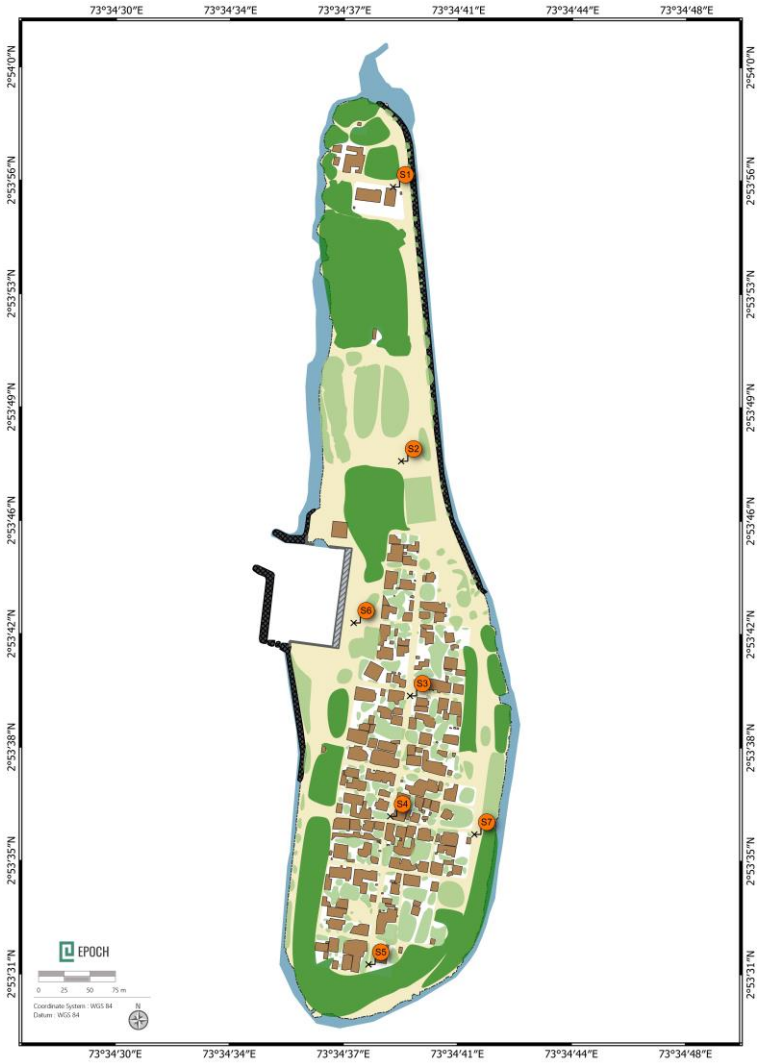


Figure 180: Soil Profile Survey Locations – M. Naalaafushi

10.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 181 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.

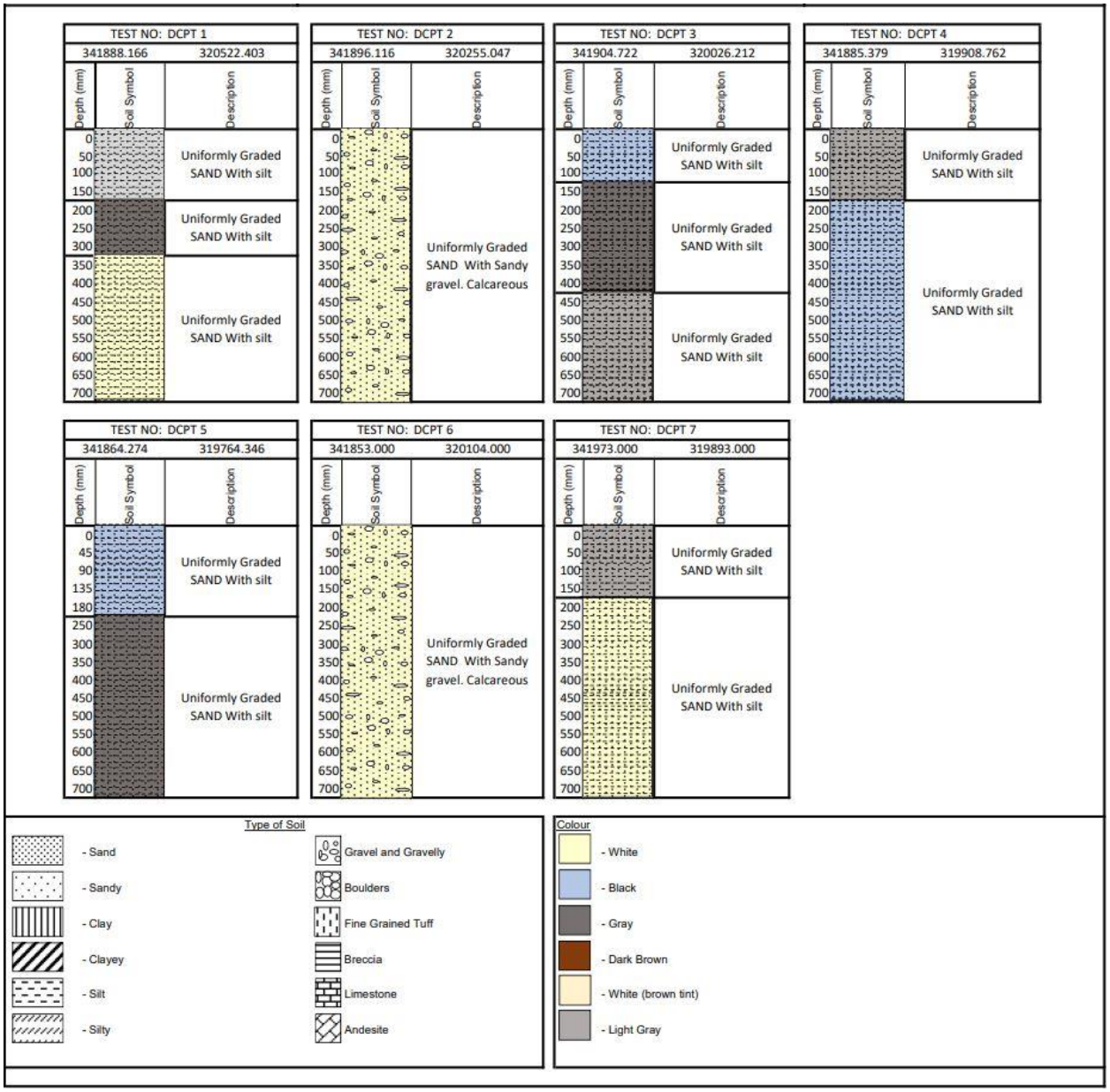


Figure 181: Soil Profile - M. Naalaafushi

10.8 Flood Assessment and Inundation Survey

10.8.1 Flood occurrence and flood impact

In M. Naalaafushi ponding originates mostly because of catchment of flood from roof tops and some water catchment is also observed near the school especially after the construction of harbor but it's not very significant or problematic. Many respondents reported that harbor construction and island reclamation work had a major impact on the flooding pattern of the island. As per survey, 39% of the households reported flooding occurs only when there is a heavy rainfall. 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.

The flooding originates mostly from roof runoff (45%) 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 185: Perceived causes of flooding – M. Naalaafushi

Perceived causes of flooding				
Roof run off	**Neighbors' roof**	**Off the road**	**General run off in the area**	**No flooding within the plot**
45%	13%	3%	12%	54%

From the social survey, 61% 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 which include overflow 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 – M. Naalaafushi

Discharge of rainwater overflow			
Ground	**Roads**	**Open area within the plot**	**Drained to well**
61%	3%	22%	13%

In M. Naalaafushi, 62% of the household's report flooding as an acceptable problem (refer to flood severity component of Flood Maps in Annex XII). This can be due to topography of the island and continuous flood mitigation efforts.

10.8.2 Inundation area identification

M. Naalaafushi has no flooding issues, but ponding is mostly observed in the school, main road, Health Centre and mosque (refer to Annex XII: Flood Maps). Based on the social survey responses, an average of 0.94ft is estimated as the flooding depth when there is a heavy rainfall. Majority of the respondent's indicated flooding does not happen often in the island. Therefore, the flood depth accumulated was reported by only 12% of the surveyed respondents.

10.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 53% observe that the water drains during the rainfall itself, 28% observe that the water drains in less than 4 hours, 16% observe that the water drains in less than 4-24 hours and 3% observe that it takes more than 24 hours for water to drain.

Table 187: Draining period – M. Naalaafushi

Draining period			
only while raining	**drains less than 4hrs**	**takes 4-24 hrs**	**more than 24hrs**
53%	28%	16%	3%

10.9 Geophysical Survey

10.9.1 Surveyed locations

Locations where ER sounding measurement taken at M. Naalaafushi island are shown in Figure 182 together with transect lines. There are 19 ER measurement locations and the number of transects in this island is 9.

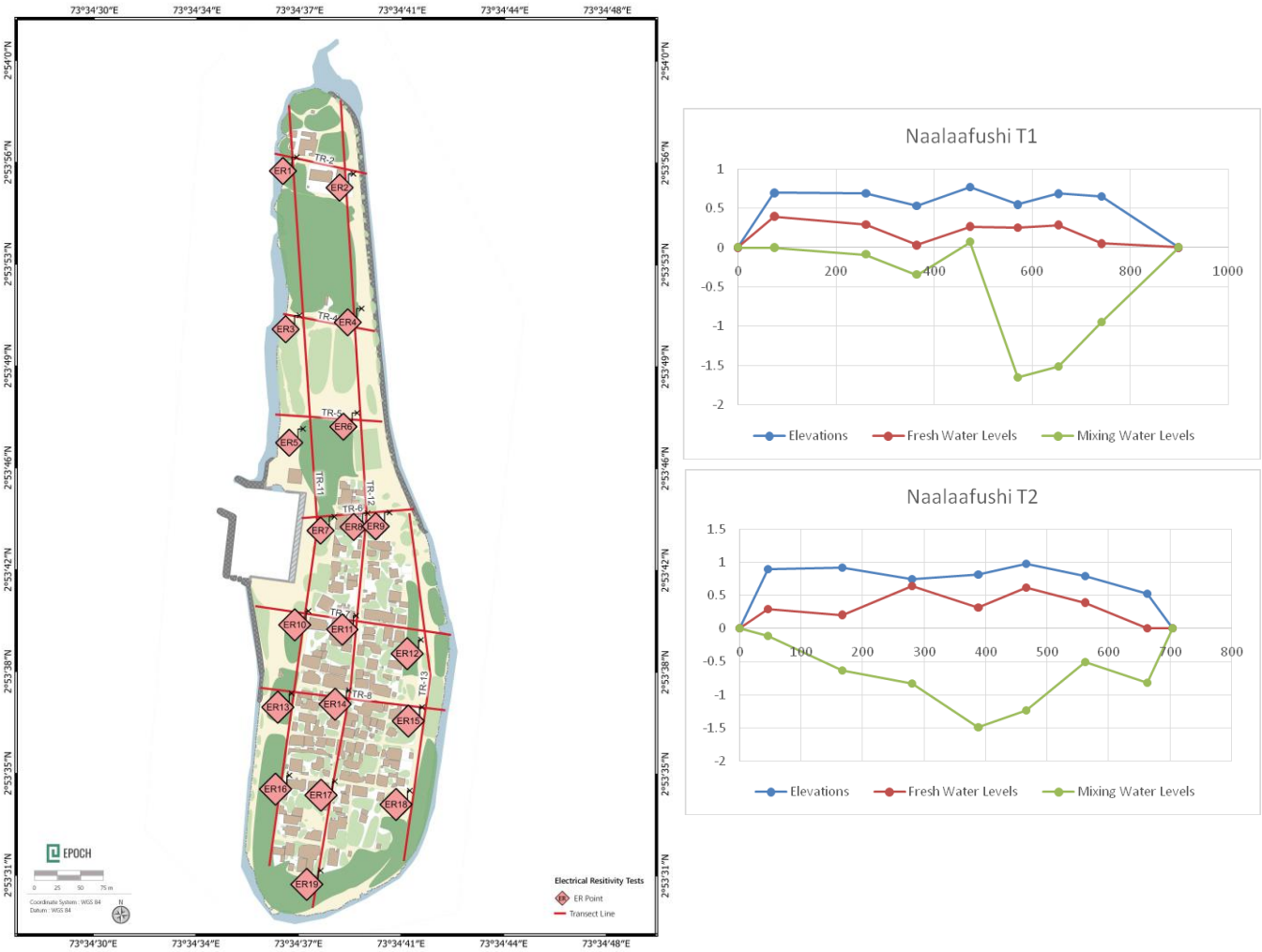


Figure 182: ER surveyed locations and transect lines – M. Naalaafushi Island

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 M. Naalaafushi Island and freshwater lens thickness.

Table 188: Freshwater lens levels and thickness – M. Naalaafushi island

No	Location	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	19	0.52	0.00	-0.82	0.82
2	17	0.79	0.39	-0.51	0.90
3	14	0.97	0.62	-1.24	1.86
4	11	0.81	0.31	-1.49	1.80
5	8	0.74	0.64	-0.83	1.47
6	6	0.91	0.20	-0.64	0.84
7	4	0.89	0.29	-0.11	0.40
8	2	0.94	0.64	-0.01	0.65
9	1	0.70	0.40	0.00	0.40
10	3	0.69	0.29	-0.09	0.38
11	5	0.53	0.03	-0.35	0.38
12	9	0.64	0.14	-0.76	0.90
13	12	0.66	0.61	-0.19	0.80
14	15	0.76	0.69	-0.11	0.80
15	18	0.80	0.70	-0.10	0.80
16	16	0.65	0.05	-0.95	1.00
17	13	0.69	0.29	-1.51	1.80
18	10	0.55	0.25	-1.65	1.90
19	7	0.77	0.27	0.07	0.20

Average freshwater thickness of M. Naalaafushi island is 0.95m. Maximum recorded thickness of freshwater lens of the Island by ER survey is 1.90 m & minimum is 0.20 m

Data in Table 188 were used to plot freshwater lens cross sections along 9 transects. Of these sectional plots 2 were given in Figure 182 and they represent the transect plots along the longitudinal section of the island.

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 183.

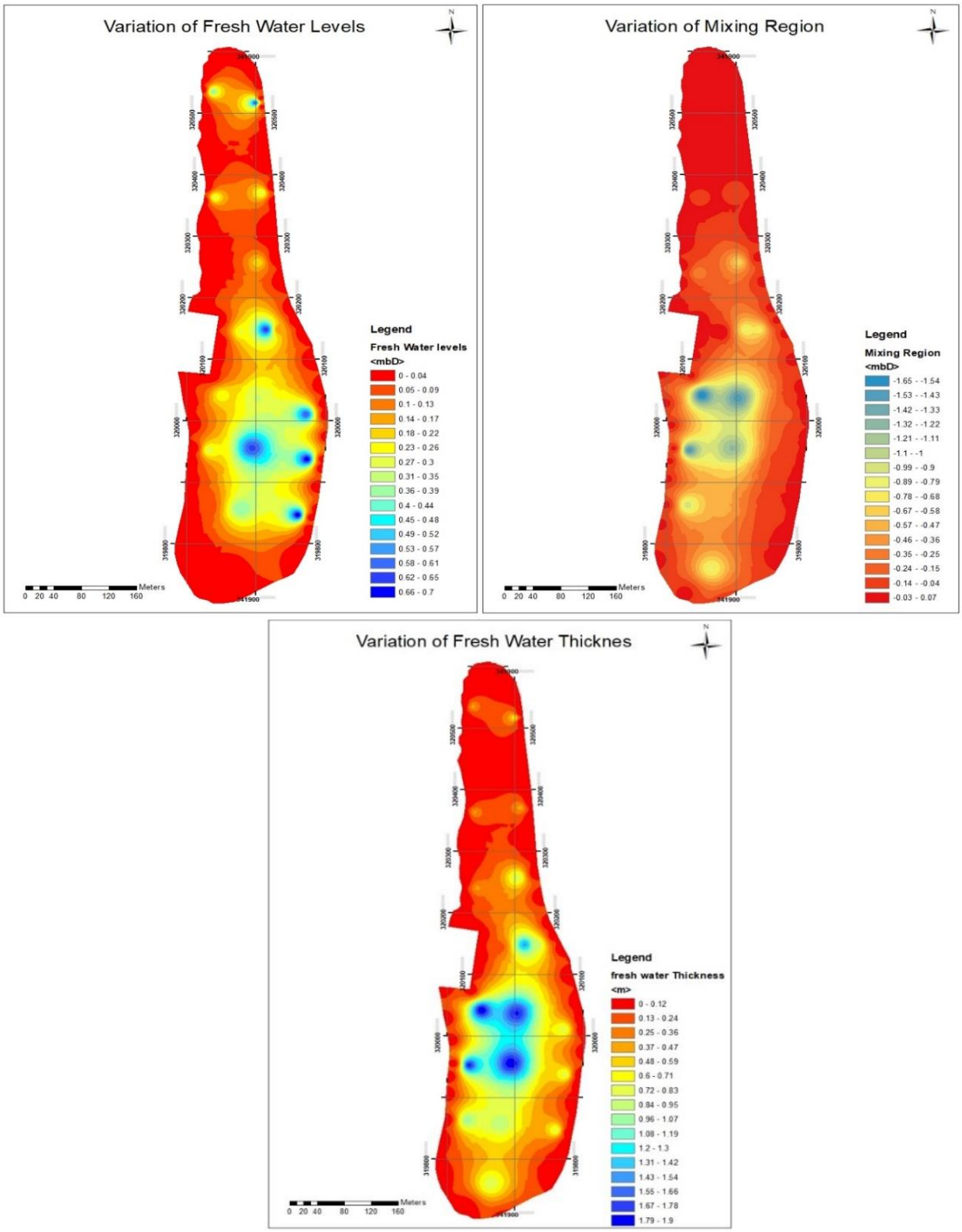


Figure 183: Top Left: Contours of Freshwater lens upper level, Top Right: Contours of Freshwater lens lower level, Bottom: Spatial distribution of thickness of freshwater lens – M. Naalaafushi

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. Tools in ArcGIS software were used to perform this computation.

Stress level on freshwater aquifer of M. Naalaafushi 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 – M. Naalaafushi island

Item	Value	Unit
Freshwater lens volume - ArcGIS	100,468	m^3
Groundwater abstraction	34,718	m^3/yr
Freshwater lens volume/ Groundwater abstraction	2.89	-
Aquifer stress level	Not Stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 3.22m. This deviates by 73.1% from the maximum measured value of 1.86m, which is more reliable as it results from a more comprehensive, site-specific methodology.

10.10 SWB Modelling

10.10.1 Land use categorization and area estimation

Table showing land classification and their respective areas are shown in table below

Table 190: Land Use Classification - M. Naalaafushi

	Area (m^2)	% of total area
Roof cover	16,776	13%
Vegetation (Thick)	36,478	29%
Vegetation (Thin)	21,843	17%
Bare Lands	49,740	40%
Farmlands	226	0.2%
Total	125,129	100%

10.10.2 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 184 and Table 191). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 21,097m^3, 551,198m^3 and 116,399m^3 respectively over a 20 year period.
- There is a good relationship between annual rainfall and annual recharge, but it is not linear instead an inverse exponential.
- Annual average rainfall is around 2242 mm.
- Variation among the monthly average recharge value is very high. It is lowest on month of January and highest in May.

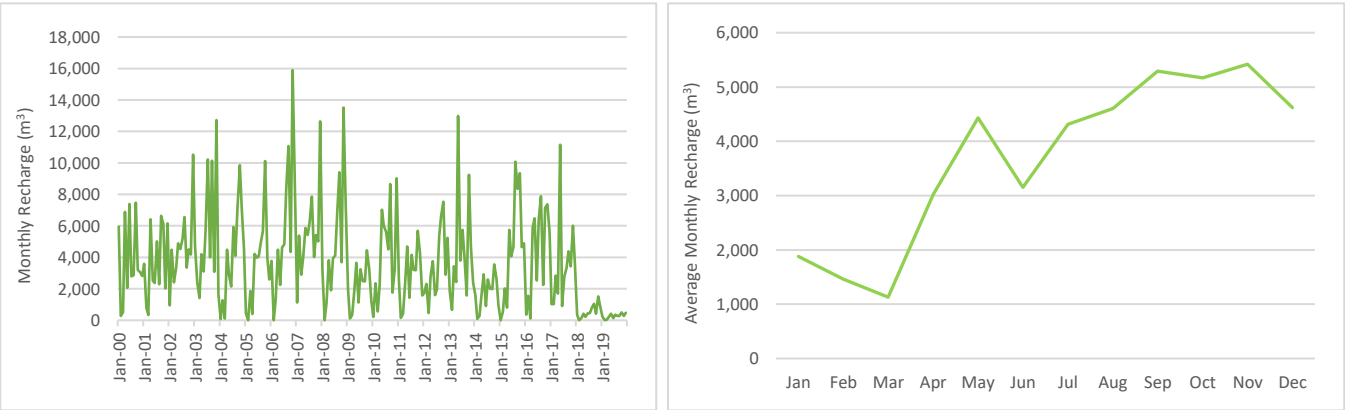


Figure 184: Monthly and annual recharge distribution in M. Naalaafushi

Table 191: Monthly recharge estimated by SWB model - M. Naalaafushi Island

Year	Monthly Recharge (m^3)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2000	5,939	279	517	6,876	2,058	7,393	2,795	2,847	7,472	3,192	3,067	2,821
2001	3,587	804	343	6,423	2,513	2,365	5,006	2,290	6,645	6,108	2,014	6,159
2002	938	4,476	2,408	3,330	4,880	4,514	5,183	6,551	3,341	4,511	4,181	10,524
2003	4,716	2,398	1,409	4,199	3,092	5,744	10,209	3,997	10,137	3,072	12,717	1,675
2004	69	1,266	115	4,483	2,897	2,142	5,923	4,089	7,260	9,858	7,102	4,514
2005	428	-	1,870	402	4,214	3,979	4,048	4,996	5,667	10,112	3,950	2,585
2006	3,781	-	1,319	4,488	2,239	4,627	4,837	8,359	11,075	4,350	15,897	8,485
2007	1,125	5,371	2,890	3,996	5,856	5,417	6,219	7,861	4,009	5,414	5,017	12,629
2008	3,214	-	1,121	3,815	1,903	3,933	4,111	7,106	9,414	3,698	13,512	7,212
2009	2,000	119	330	1,946	3,649	1,123	3,236	2,496	2,478	4,439	3,329	1,226
2010	203	2,353	568	2,239	7,022	5,987	5,632	4,504	8,645	1,757	3,251	9,010
2011	2,564	152	423	2,495	4,679	1,440	4,149	3,200	3,177	5,690	4,268	1,572
2012	1,724	2,303	454	2,797	3,743	1,590	1,960	5,346	6,621	7,532	2,904	5,226
2013	1,831	657	3,428	2,422	12,976	3,794	5,751	4,024	1,572	9,241	4,701	2,394
2014	1,600	95	264	1,557	2,919	899	2,589	1,997	1,983	3,551	2,663	981
2015	-	535	2,016	801	5,739	4,062	4,663	10,080	8,338	9,340	4,646	4,899
2016	358	1,547	109	5,881	6,477	2,526	6,401	7,869	2,254	7,156	7,374	5,576
2017	1,019	1,032	2,838	1,694	11,158	908	2,769	3,319	4,382	3,434	6,015	3,639
2018	359	-	125	426	213	440	459	794	1,052	413	1,510	806
2019	224	13	37	218	409	126	363	280	278	498	270	486

10.10.3 Water Balance

As per estimation, annual recharge estimated by the SWB model is 87,120m^3 and it is 18.4% of annual average rainfall (refer Figure 185).

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	284,334	3,858	119,420	87,120	79,614	34,718
%	100.0%	1.36%	42%	18.4%	26%	12.2%

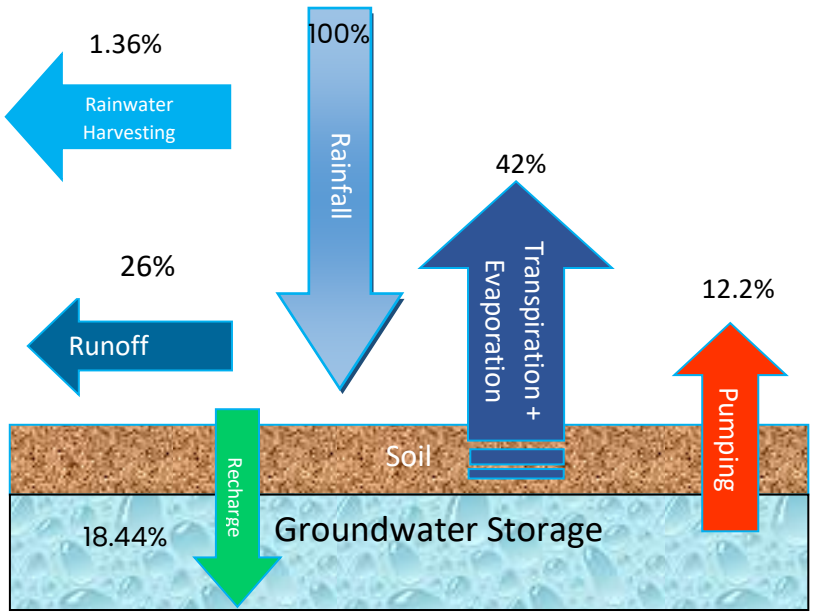


Figure 185: Annual water balance – M. Naalaafushi Island

10.10.4 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 (2893 m^3/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 192: Deficit percentage - M. Naalaafushi

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	113	47.1

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 M. Naalaafushi is 47.1% 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 (34,718 m^3/yr) with safe abstraction volume (52,403 m^3/yr) shows that present withdrawal is 33.75% less than the safe yield. Therefore, it could be inferred that present groundwater abstraction is within the allowable limit and it has insignificant influence in up-coning freshwater-saline water interface in the existing condition.

10.11 SUTRA Modelling

10.11.1 Model representation and mesh production

SUTRA modelling requires mode domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island. The other boundary defined in the model was island outline which can be referred as shoreline most of the cases except at harbour area and the inner part of the island was subdivided to several polygons representing different land use and it was accomplished by importing GIS shape files of island land use and then drawing polygon 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.

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 211 shows the pressure boundary defined for M. Naalaafushi island.

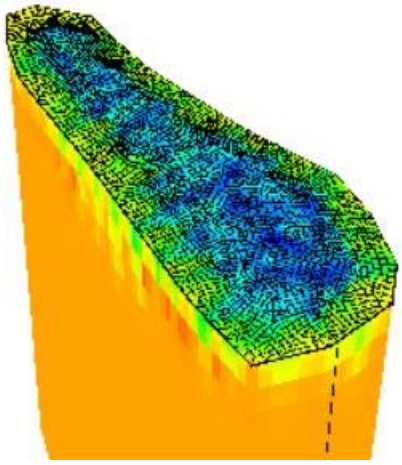


Figure 186: Pressure boundary at SUTRA model - Naalaafushi island

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.

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.

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 84. The section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0357 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top.

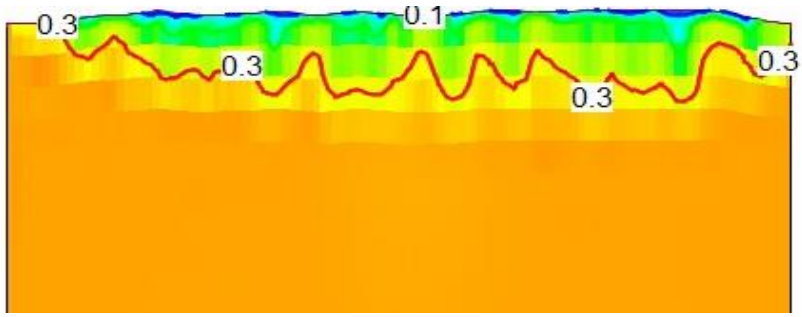


Figure 187: Saltwater distribution - M. Naalaafushi island

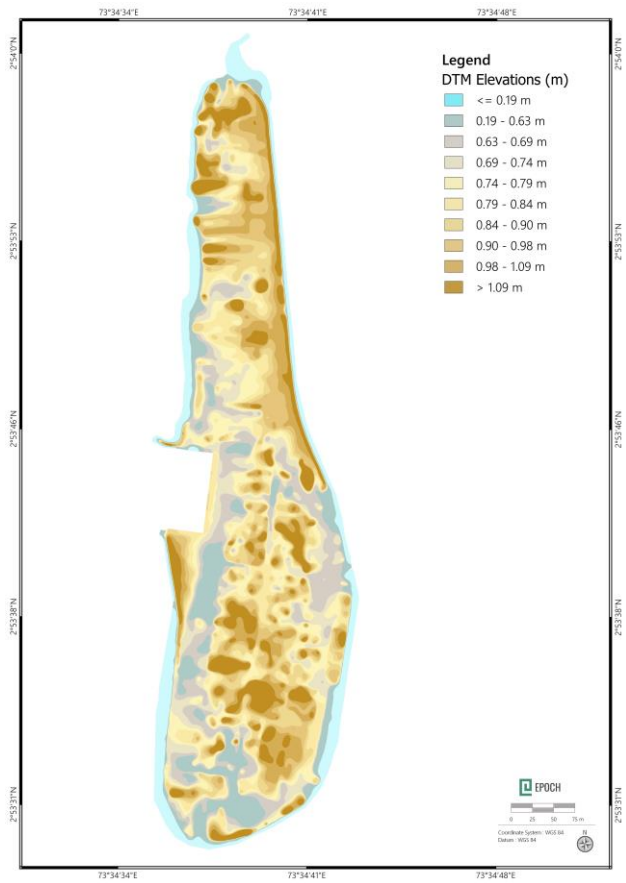
10.12 Summary of Baseline Assessment

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

- General overview, demography, and climatology

Item	Details
Atoll	Mulaku Atoll
Length	0.92 km
Width	0.21 km
Area	12.5 ha
Population	535
Population/area	42.8 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use

Topographical map	Land use map
	

		% of total area
Average elevation = 0.733 m above MSL	Roof cover	13%
	Vegetation (Thick)	29%
Shoreline length = 2225 m	Vegetation (Thin)	17%
	Bare Lands	40%
	Farmlands	0.2%
	Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Industrial	Institutional	Total
Rate (m^3/day)	93	0.26	0.20	2.10	95.1

- Water quality parameters – Physiochemical
  Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	3608 ± 5031	<1500
Turbidity (FNU)	3.32 ± 6.49	<5
DO (mg/L)	3.80 ± 1.47	
pH	7.54 ± 0.27	6.5-8.5
Temp (°C)	29.5 ± 0.86	
Sal (ppt)	1.82 ± 2.75	
NH_3 (mg/L)	5.90 ± 8.28	<1.5 (Odour Threshhold)
NO_3^- (mg/L)	16.7 ± 23.3	<50
PO_4^{3-} (mg/L)	0.30 ± 0.29	

- Water quality parameters – Microbiological
  Number of samples tested = 15

Parameter	Value range	Average value	Remarks *(on permit limit)*
Total Coliform (MPN/100ml)	3 - >2420	1,151.6	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	Not detected – >20	2.33	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	27.09	m^2/day
Storativity	1	0.2021	-
Permeability	7	0.41 – 20.47, Average – 9.29	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m^2)	Inundation depth (m)
64	1,900	0.286

- Electric Resistivity survey
  - Measurement taken at 19 locations
  - Average freshwater thickness in the island is 0.95 m.
  - Freshwater lens volume and aquifer stress level

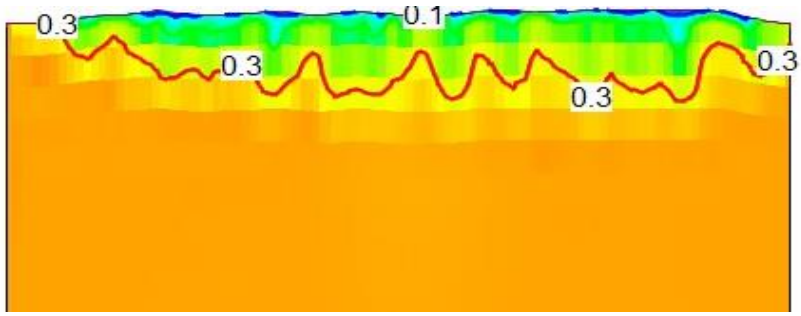
Item	Value	Unit
Freshwater lens volume - ArcGIS	100,468	m^3
Groundwater abstraction	34,718	m^3/yr
Freshwater lens volume/ Groundwater abstraction	2.89	-
Aquifer stress level	Not Stressed	-

- SWB modelling
  - Annual recharge is 87,120m^3 and it is 18.4% of annual rainfall (2242mm)
  - Annual water balance

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	284,334	3,858	119,420	87,120	79,614	34,718
%	100.0%	1.36%	42%	18.4%	26%	12.2%

  - Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 47.1% in an average year, and it is compensated by ground water storage.
  - Ground water withdrawal (34,718m^3/yr) is 33.7% less than the safe abstraction (52,403m^3/yr).

- SUTRA modelling
  - Average monthly recharge assigned to SUTRA model
  - Freshwater lens prediction (allowable concentration for potable use is 0.001)



11 M. Veyvah

11.1 Island Overview and Location

The Island of M. Veyvah, belonging to Mulaku Atoll, is in the Central Southern region of Maldives at 2°57'30.8"N and 73°36'01.7"E. It is approximately 135.25 km south of the capital Male'.

Table 193: Island Geographical Data

Island	M. Veyvah
Atoll	Mulaku Atoll
Location	2°57'30.8"N and 73°36'01.7"E

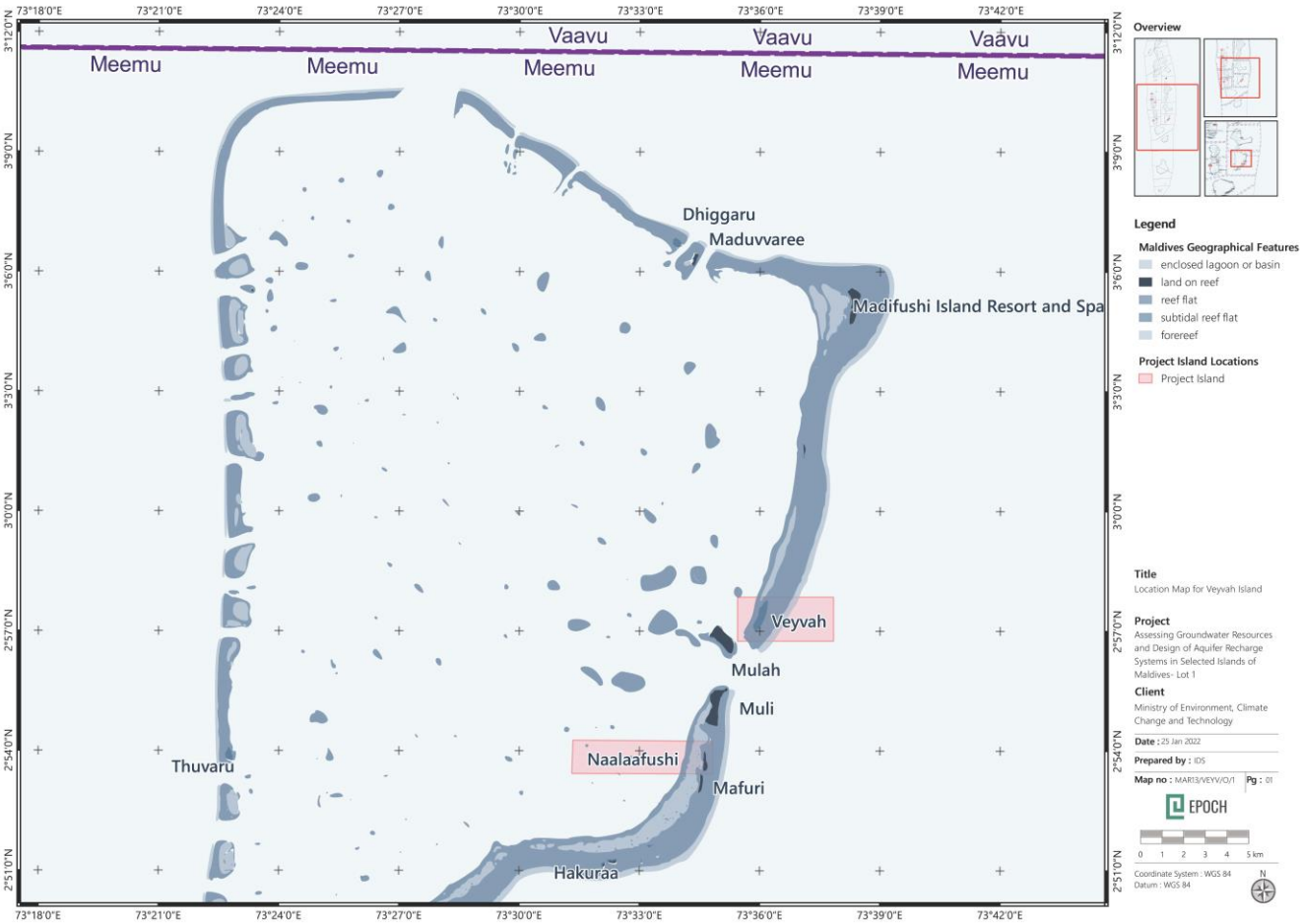


Figure 188: Location Map – M. Veyvah

11.1.1 Island features

M. Veyvah is in the south eastern peripheral reef in Mulaku atoll. The island extends up to 1.54 km in length from toe to toe and a width of 0.35 km from toe to toe. The island is mostly rectangular in shape and has mostly thick vegetation in the southern part of the island. The island is known to have significant historical infrastructure and elements such as Friday Mosque and two wells. The island also has a cemetery and sundial which are to be over 400 years old.

The island has a harbour at its west side of the island. About two-third of the island's surface is vegetation. Thin vegetation is mostly located in the centre and North side of the island. The north side and outer edges of the east side of the island is covered mostly by thick vegetation. About one-third of the island is populated, which is mostly in the northwest and centre of the island. The Land Use Characterization map is attached to Annex II.

Table 194: Area Distribution in M. Veyvah

Area	42.8 ha	
Length	1.54 km	
Width	0.35 km	
	Area (m²)	**% of total area**
Roof cover	16,776	3.9%
Vegetation (Thick)	274,667	64%
Vegetation (Thin)	36,520	8.5%
Bare Lands	99,776	23%
Farmlands	226	0.053%
Total	428,007	100%

11.2 Topographical Features

Permanent Survey Marks PSM 0407, PSM 0408 and PSM 0409 were used as benchmarks for M. Veyvah 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 1928 calibrated UAV photos at an altitude of 75 m resulting in an Average Ground Sampling Distance (GSD) of 2.25 cm per pixel. 9 Ground control points (GCP) were measured using the GPS survey. Error statistics for the GCPs are presented below.

Table 195: GCP Statistics for M. Veyvah

Parameter	Error X[m]	Error Y[m]	Error Z [m]
Mean [m]	-0.0293	0.000375	0.013727
Sigma [m]	0.0832	0.0152	0.0298
RMS Error [m]	0.0882	0.0152	0.0328

M. Veyvah is a relatively low-lying island, with elevation of most of its populated area between 0.6 m to 0.7 m, with it never exceeding 1 m at any point in this area. In contrast, the harbour and newly reclaimed areas all have higher elevations ranging between 1.1 m to 1.4 m. The entire eastern shoreline shows ridge formations with elevations ranging from 1.25 m to 1.75m. Ridge formation of this face is to be expected as it is the windward side of the island, with swell waves approaching from the east having direct impact on this shoreline. With the exception of the harbour, the island does not have any coastal protection structures built. Also of note is the deforestation that has occurred around 2015 on the northern side of the island to make way for the newly built football grounds, which has elevations ranging from 0.6 m to 0.9 m.

Roof elevations do not exceed 5-7 m in M. Veyvah. For visualisation purposes all elevations above 10 were given the same colour in the DSM. The island is mostly covered in jungle, with the populated area being less than half of the island area. The elevation of entire vegetation area is roughly higher than 10 m, with most trees being concentrated in the south side of the island.

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 M. Veyvah. The DTM slightly underestimates the elevations with a mean of -0.84 cm. The DTM does not contain any elevation information related to the sand filled breakwater of M. Veyvah

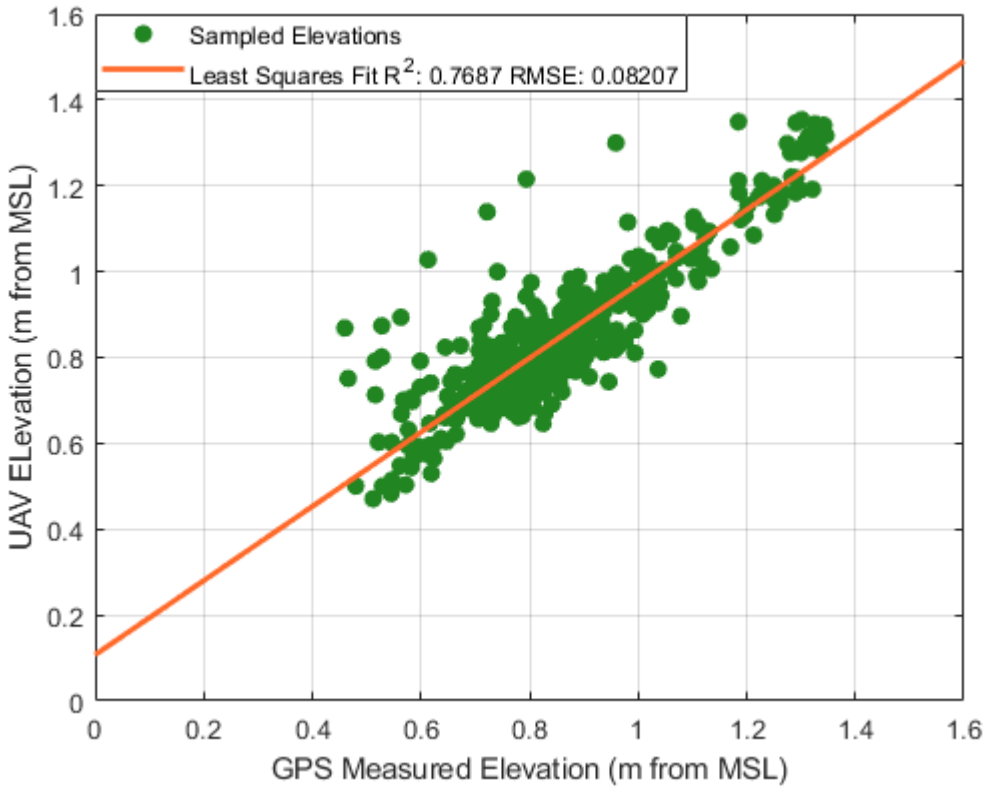


Figure 189: Linear Regression Plot for M. Veyvah Sample UAV elevations

Table 196: Error Statistics for Veyvah DTM

Parameter	*Value (cm)*
Mean	-0.84
Standard Error	0.37
Median	-1.98
Mode	#N/A
Standard Deviation	8.53
Sample Variance	72.76
Kurtosis	7.32
Skewness	1.96
Range	68.56
Minimum	-26.43
Maximum	42.14
Sum	-451.03
Count	539.00

11.2.1 Level changes

M. Veyvah 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 1.2 m being the highest frequency for elevations. A second peak is observed near 0.2 m from MSL.

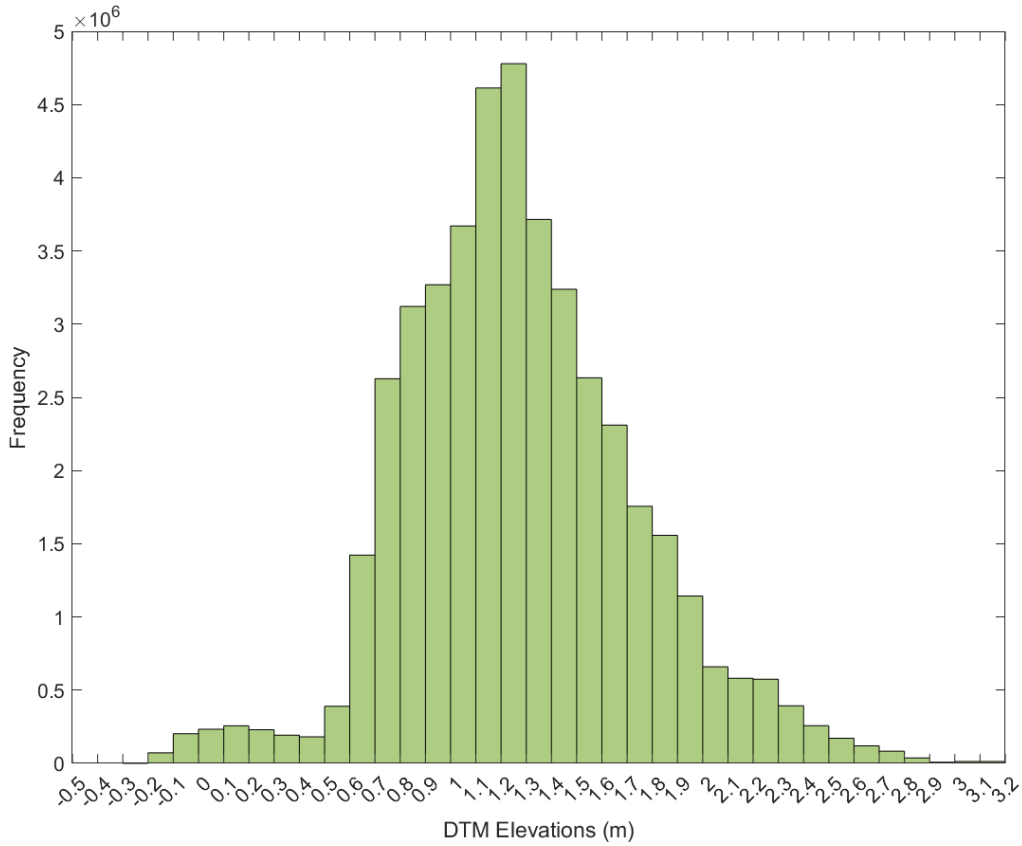


Figure 190: Raster Histogram created for M. Veyvah DTM

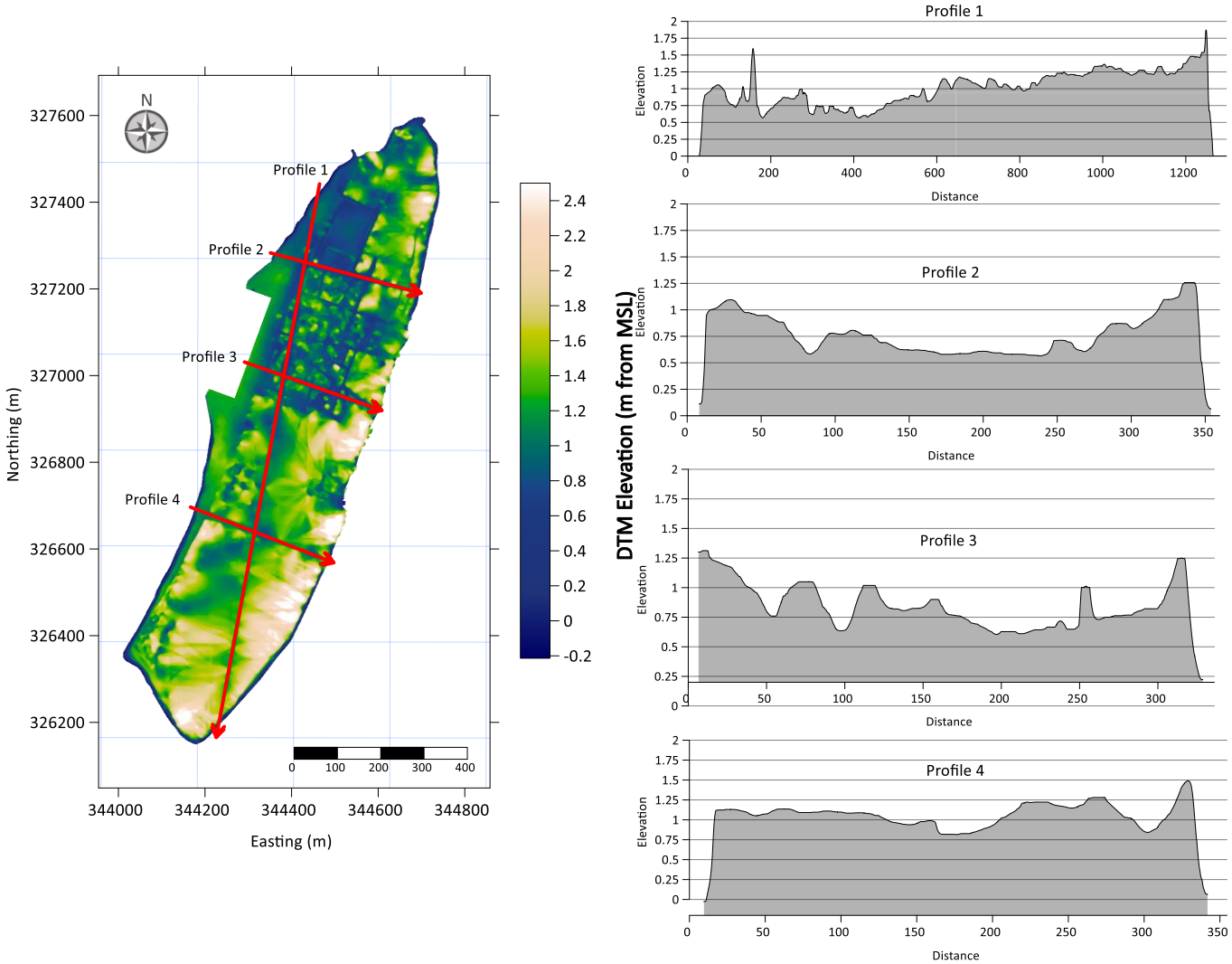


Figure 191: Digital Terrain Model Elevations and Profiles for M. Veyvah Island

The island terrain shows that the residential areas are mostly at lower elevations compared to the vegetated areas. However, the area used for fish processing in the northeast of the island is at the same high elevation as the vegetation, as shown in Profile 2. Profile 2 shows a depression in the middle of the island, with ridges formed on both ends of the profile. The eastern ridge at elevation of 1.25 m is higher than opposite side, which is due to the stronger swell waves approaching eastern shoreline across the reef flat.

Profile 1, which goes from the north to south, shows a decline in elevation up to 400 m, which corresponds to the residential area. The elevation starts to increase and remain at roughly 1.25 m elevation until it reaches the end of the profile. There is a prominent ridge formed here reaching up to 1.8 m in elevation, indicating that this is the shoreline with the most severe wave activity.

Profile 3 shows a number of peaks, which most likely corresponds to locations where there are road intersections. Excluding these peaks, the profile shows a depression in the middle, with one end being the harbor and the other the ridge formed on the eastern shoreline. The harbor area was brought up to an elevation of 1.5 m during the harbor construction project, hence why Profile 3 starts at a high elevation.

Profile 4 remains at roughly the same elevation which can be attributed to this particular profile only passing through the jungle area, which has not been altered for the most part. The slight depression found at the middle of this profile is likely due to the road found here passing through the jungle. The profile ends at a ridge found at an elevation of 1.5 m at the eastern shoreline.

11.2.2 Shoreline

M. Veyvah has a shoreline length of 3938 m. The island has all its coastal protection on its harbor as follows:

- Breakwater: There are two breakwaters on M. Veyvah, one sand filled breakwater and rubble mound breakwater, both found on the west side of the island. Western wind waves generated within the atoll basin is absorbed and dissipated by this breakwater to offer protection to berthed vessels within the harbor. The breakwater is detached from the island itself and has an access platform connecting it to the island. Crest height for the sand filled and rubble mound breakwater is around +1.5 m and +1.4 m above mean sea level respectively. The breakwater is highlighted in orange.
- Revetment: There are two revetments, one on the north and one the south side of the harbor. The revetments serve as shore protection and prevents erosion behind it by dissipating wave energy from western wind waves generated within the atoll basin. Crest height of both revetments vary, ranging between +1.2 m and +1.4 m above mean sea level. The revetments are highlighted in green.
- Quay wall: These structures are found within the harbor and are highlighted in yellow. Crest height of quay walls is around +1.25 m above mean sea level.

The eastern and a section of the northern shoreline has undergone severe beach erosion, where the shoreline has regressed to expose vegetation roots.

Figure 192: Orthomosaic of M. Veyvah

11.2.3 Reef

M. Veyvah is located on the eastern periphery of the Meemu Atoll, sharing the same reef with Raiymandhoo and a few other Finolhu. The nearest inhabited island is Mulah, which is located to the southwest of M. Veyvah on a different reef. For the major wave direction, which is the northeastern swell waves approaching from the windward side, the shortest buffer zone measures about 650 m.

Figure 193: Sentinel 2 imagery of M. Veyvah reef taken in February 2022

11.3 Socio Economic Status

11.3.1 Demography

M. Veyvah has a registered population of 223 as per the 2014 census, with a total of 122 males and 101 females. In 2021, the island population as per the council is 339. The island population density is 7.92 people per hectare. The total number of households is 58. The following table and graph illustrate the demographic breakdown of M. Veyvah.

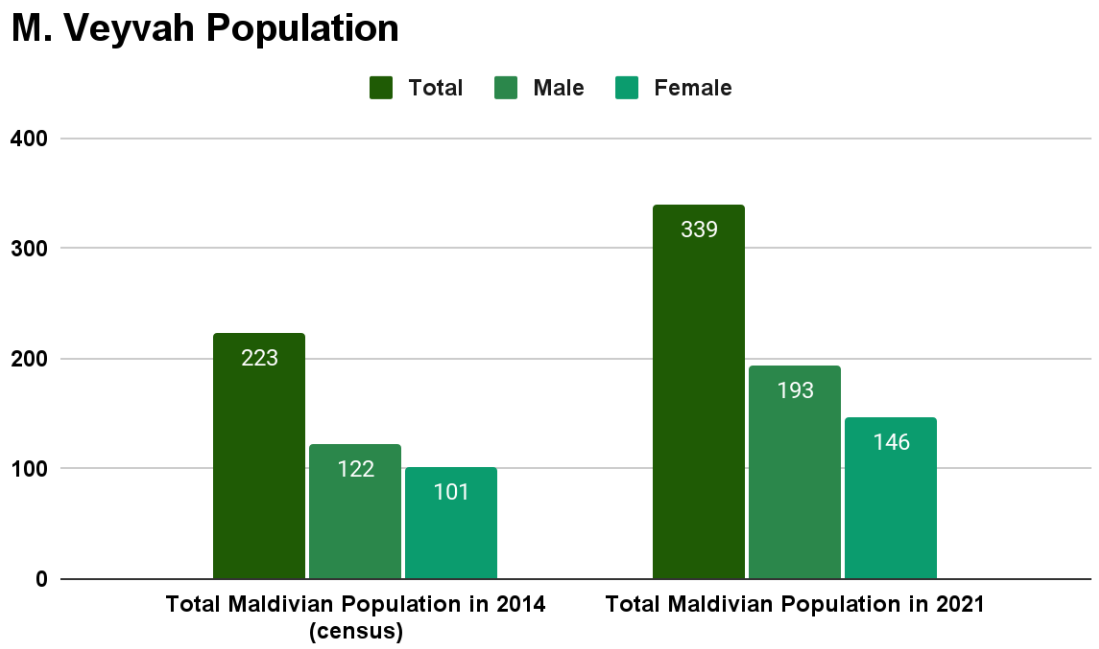


Figure 194: M. Veyvah Population

Table 197: M. Veyvah Population (Census, 2014)

Atoll	Locality	Resident Population according to Census 2014								
		Total			Maldivians			Foreigners		
		Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
M	Veyvah	263	160	103	223	122	101	40	38	2

11.3.2 Socio-Economic Activities

M. Veyvah is an inhabited island in Meemu Atoll's administrative unit and physically part of Mulaku Atoll in the Maldives. It is an island-level administrative constituency in the central province, governed by the M. Veyvah Island Council. The people in M. Veyvah work mostly in the fishing industry. This also includes fish processing activities and production of fish products. They are also involved in farming, fiber work and thatching work.

11.3.3 Facilities available

11.3.3.1 Health Care

M. Veyvah Health Center is equipped with 3 beds. Currently, one doctor and two nurses are working at the Health Center to ensure basic medical care is provided for the residents.

11.3.3.2 Education

M. Veyvah has one school which is named as Veyvah School. A total of 12 teachers and 5 administrative staff are working in the school. There are 48 students enrolled in primary and lower secondary schools.

11.3.3.3 Utilities

Currently, the main form of sanitation in the island is septic tanks and local outfall pipes. Government has budgeted for the water and sewerage project planned on the island which is expected to finish by April 2023. The island also has one powerhouse provided by state-owned utility company FENAKA Corporation.

11.3.3.4 Transportation

The reconstruction of M. Veyvah harbor was finished in 2017. The value of the project was MVR 48.8 million. The island has ferry services and other private speed launches. The speed boats often travel 3-4 times a week.

11.3.4 Water resources, water usage and water consumption survey

In M. Veyvah there are a total of 47 households. 41 out of 47 households were surveyed with geo-coordinated sampling points. Also, 95% confidence interval was maintained with an error margin of 6%. The survey was mainly carried out through phone calls and many households were unresponsive due to many reasons. One of the many reasons include due to incorrect numbers and households not having any occupants. There were also other reasons such as households not wanting to take part in the survey because of unavailability. A maximum of five attempts were made on different occasions to determine unavailability of the participant. A map of households surveyed is attached in Annex V.

Table 198: Groundwater Usage for cooking and drinking

Total no. of household wells surveyed	**41/47 households = 87%**
Percentage of well fitted with pumps	100%
Ground water	**Usage in percentage**
Source of drinking	2%
Source of cooking	20%

11.3.4.1 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, 88 percent of the survey households have connected their sanitation to septic tanks. While the remaining 12 percent has connected to local outfall pipes. In M. Veyvah 51 percent reported to have less than 49ft distance between septic tanks and groundwater well. While 25% reported to have more than 49ft distance and remaining 24% reported that they do not know an exact distance between them. 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.

11.3.4.2 Water usage and resources

Based on the survey conducted in M. Veyvah, 38 houses have HDPE rainwater tanks for rainwater storage. Rainwater collected from rooftops is stored in water tanks, whether communal or home tanks. Many homes utilize rainwater from neighboring houses or bottled water when rainwater is scarce during the dry season. On the same note, 20% of the households use groundwater for cooking and the remaining 78% and 2% use rainwater and bottled water respectively. It has also been observed that most houses using groundwater for cooking have a groundwater filtration system. There was also a rare instance where one household reported that they use groundwater for both cooking and drinking. The same house also reported having no rainwater tank and this could be the main reason for the use of groundwater for drinking and cooking. Nonetheless, most houses reported groundwater is mainly used for non-potable use such as gardening, household cleaning, toilet flushing and showering. The following sections outline further details about various groundwater usage and consumption scenarios in the island.

11.3.4.3 Domestic water usage

Based on household water usage surveys in M. Veyvah, **62,037** liters of groundwater is used daily in the households. A total of **183** liters of groundwater are consumed per capita per day.

Table 199: Domestic groundwater use data for M. Veyvah

Showering	Toilet Flushing	Laundry	Gardening	Mopping	Bathroom faucet usage	Dishwashing	Total
76.1	25	10.1	47.4	1.35	18	4	**183**

*All units are in Liters per capita per day

11.3.4.4 Commercial water usage

Based on the survey conducted in M. Veyvah, there are currently two operational café'/restaurant and 1 guesthouse on this island. A total of 701 Liters of groundwater are used by commercial entities and their detailed breakdown is given in the tables below.

Table 200: Commercial groundwater use data for M. Veyvah

Cafe/ Restaurant	Dishwashing	Toilet Flushing	Gardening	Mopping	Total
Haveeree cafe	7.5	0	130	5	143
Nilamehi Cafe	135	0	1.25	6.43	143
					286

*All units are in Liters per day

Table 201: Guesthouse groundwater use data for M. Veyvah

Guesthouse	Average Occupancy	Total (L/day)
Veyvah Inn Maldives	25%	**415**

11.3.4.5 Industrial water usage

In M. Veyvah, a total of **18,329** Liters of groundwater is used daily for industrial purposes. In the social survey, 10 out of 26 farming plots were surveyed to determine the farming groundwater usage. Majority of the farms have pumpkin, cucumber, watermelon and chillies and they are produced throughout the year. An average of **662.67** Liters of groundwater is used by each farm and the breakdown for 26 farms are given in the table below.

Table 202: Groundwater use for farming in M. Veyvah

Total farms	No. of farms surveyed	Average usage	Total usage for all farms
26	10	662.67	**17,229**

The total groundwater usage for fish processing is **1100** Liters per day. The breakdown for 4 fish processing units is given in the table below

Table 203: Groundwater use for fish processing in M. Veyvah

Number of fish processing unit	Fish processing activities	Total water usage daily (Liters)
1	Cutting and Cleaning, Cooking and Smoking, Rihaakuru Production	400
2	Cooking and Smoking, Rihaakuru Production	200
3	Cutting and Cleaning, Cooking and Smoking, Rihaakuru Production	300
4	Cutting and Cleaning, Cooking and Smoking, Rihaakuru Production	200
		1100

11.3.4.6 Institutional water usage

Based on the survey conducted in M. Veyvah, there are currently five institutions that include groundwater well facilities and use groundwater on this island. A total of **1151** Liters of groundwater are used by these institutions and their detailed breakdown is given in the table below.

Table 204: Institutional groundwater use data for M. Veyvah

Institution	Toilet Flushing	Gardening	Mopping	Laundry	Total
Veyvah School	297	180	20	0	497
Health Center	133	0	20	185	339
Council	133	0	9	0	142
Powerhouse	125.2	0	7	0	132
Veyvah Court	36.3	0	5	0	41
					1151

*All units are in Liters per day

11.3.5 Present & Future water demand

In M. Veyvah, the present water demand is at **64,989** Liters per day inclusive of domestic, commercial, institutional, and industrial water demand. 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.

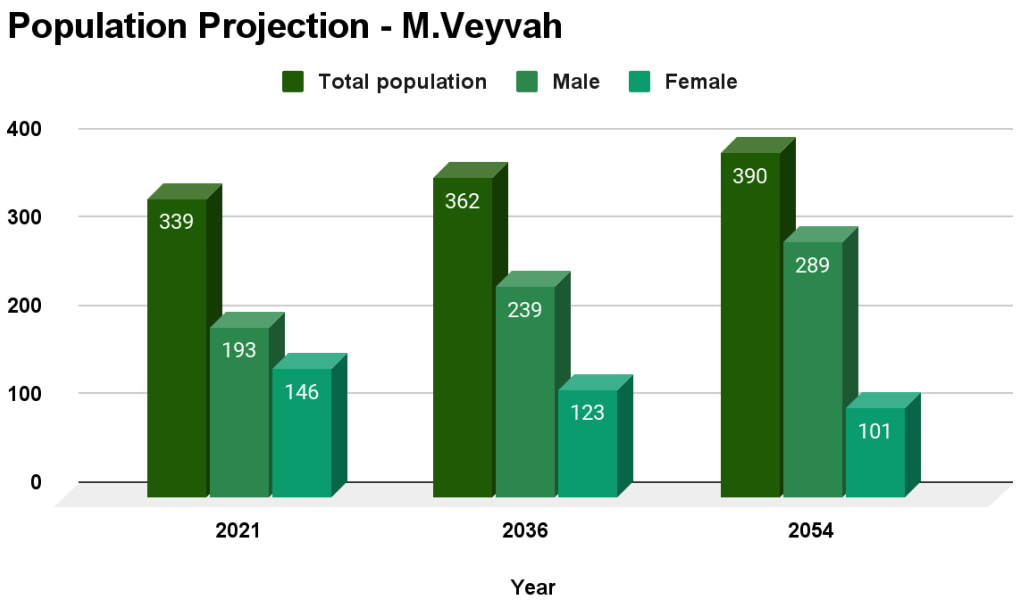


Figure 195: Population Projection - M. Veyvah

Table 205: Present groundwater demand - M. Veyvah

Year	Total Population	Domestic water demand	Commercial water demand	Industrial water demand	Institutional water demand	Groundwater usage
2021	339	62,037	701	1,100	1,151	**64,989**

*All units are in Liters per day

For the year 2036 and 2054, the total domestic water usage is expected to stay consistent at 183 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 183 Liters, the groundwater demand is expected to be 133 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2036 for a population of 362 is expected to be 48,146 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 183 Liters, the groundwater demand is expected to be 108 Liters per capita per day. Therefore, the total domestic groundwater demand for the year 2054 for a population of 390 is expected to be 42,120 Liters per day.

Table 206: Future domestic water demand - M. Veyvah

Year	Projected Population	Total water demand (LPCD)	Expected water supply usage (LPCD)	Groundwater demand (LPCD)	Groundwater demand (L/day)
2036	362	183	50	133	48,146
2054	390	183	75	108	42,120

11.3.6 Water related issues

From 41 households surveyed in M. Veyvah, most houses reported smell and milky texture in their respective wells. 68 percent reported having smell and 34 percent reported having a milky texture in their groundwater. Oxygen pumps are usually connected to counteract pollution and gasses such as hydrogen sulphide which causes unpleasant smells. In M. Veyvah, 34% of the houses reported with oxygen pumps in their wells. From the interview with Veyvah Health Center, they highlighted that there are some cases of skin irritation reported due to groundwater. However, the exact number of health issues pertinent to ground water is not identified or recorded. Especially following the tsunami, groundwater on most of the islands in this atoll showed a higher degree of salinity and faecal contamination.

Table 207: Signs of contamination reported by households

Types of contamination	Data in % out of 41 households surveyed
Smell	68%
Milky	34%
Foul taste	24%
Salty	20%
None	29%

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

Table 208: Changes in groundwater quality during tidal or seasonal changes

Changes in groundwater quality	Data in % out of 41 households surveyed
Changes with tidal variations	10%
Groundwater quality is better in rainy months	54%
Long periods without rain causes bad smell	32%
Long periods without rain causes bad taste	17%
Rain makes it worse	0%
No change	34%

11.4 Groundwater Quality

11.4.1 Physiochemical survey results

Groundwater quality measurements were made at 40 selected locations and the following Table 209 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 209: Statistical summary of groundwater physiochemical parameters in M. Veyvah

	EC (µS/cm)	Turbidity (FNU)	DO (mg/L)	pH	Temp (°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 threshhold <35 Taste threshhold Source[1]	<50 Source[1]	
Mean	2329	3.43	3.12	7.49	27.7	1.16	7.80	21.34	0.26
Median	1144	1.55	2.73	7.44	27.7	0.54	2.97	16.86	0.19
SD	2705	4.89	1.80	0.31	0.92	1.44	12.18	22.96	0.27
Min	138	0.02	0.44	6.89	25.3	0.06	0.18	1.37	0.06
Max	11,691	22.65	8.20	8.28	29.5	6.24	48.49	125.2	1.24
CV	1.16	1.43	0.58	0.04	0.03	1.23	1.56	1.08	1.02

Note: EC=Electrical Conductivity, DO=Dissolved Oxygen, Temp=Temperature, Sal=Salinity NH_3= Ammonia, NO_3^-= Nitrate, PO_4^{3-}=Phosphate,
SD=Standard Deviation, Min=Minimum, Max=Maximum, CV=Coefficient of Variation
Source[1] = WHO Drinking Water Guidelines, 2017. Source[2] = URA Drinking Water Guidelines, 2021.

- The mean Electrical Conductivity at 2329 µS/cm is higher than the WHO Standard for potable water (<1500 µS/cm) but lower than the WHO Standard for non-potable water (<2500 µS/cm). The maximum value for EC (11,691 µS/cm) was observed at the farming area which is located away from the inhabited areas.
- Eleven samples had higher EC than 2500 µS/cm with one sample having EC higher than 10000 µS/cm. Three samples had EC between 1500 µS/cm and 2500 µS/cm while 26 samples had EC lower than 1500 µS/cm. The EC distribution is shown in Figure 197.
- As expected, the EC of the groundwater in the center of the island is lower than the coastal areas of the island which indicate saltwater intrusion at the periphery of the island.
- The mean Turbidity level at 3.43 NTU fall within the URA Guidelines for drinking water (>5 NTU). Eight samples had higher Turbidity level than 5 NTU. Turbidity is generally lower in residential areas and higher in boatyard area and farming area.

- Dissolved Oxygen ranged from 0.44 mg/L to 8.20 mg/L with a mean of 3.12 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 7.49.
- Temperature ranges from 25.3°C to 29.5°C depending on the well characteristics and time of day reading was taken. Mean temperature was 27.71°C.
- Salinity ranged from 0.06ppt to 6.24ppt with a mean of 1.16ppt.
- The mean Ammonia concentration was 7.80 mg/L which is higher than the WHO threshold for odour but well below the threshold for taste. 35% of samples had concentration below 1.5 mg/L, 57.5% of samples had concentration between 1.5 mg/L and 35 mg/L and 7.5% of samples had concentration higher than 35 mg/L. The Ammonia concentration distribution is shown in Figure 196.
- Ammonia concentration is higher in fish processing area and boatyard area compared to residential area.
- The mean Nitrate concentration was 21.34 mg/L which falls within the WHO Standard for Nitrate concentration (<50 mg/L). Only 3 samples had Nitrate concentration higher than the WHO standard.
- Nitrate concentration is higher in fish processing area, boatyard area and powerhouse area compared to residential area.
- Phosphate concentration ranges from 0.06 to 1.24 mg/L with a mean concentration of 0.26 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. 10 samples tested were below 0.1 mg/L.
- Phosphate concentration is higher in boatyard area and farming area compared to residential area.

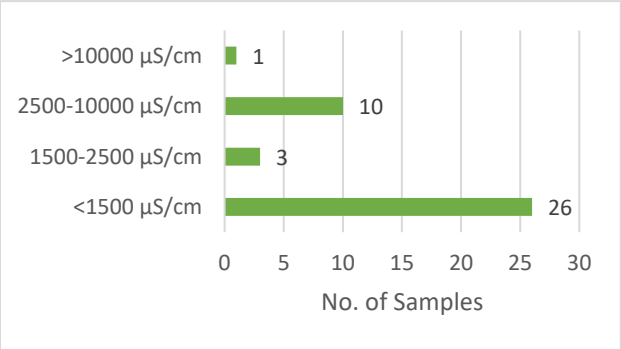


Figure 197: EC Distribution in M. Veyvah

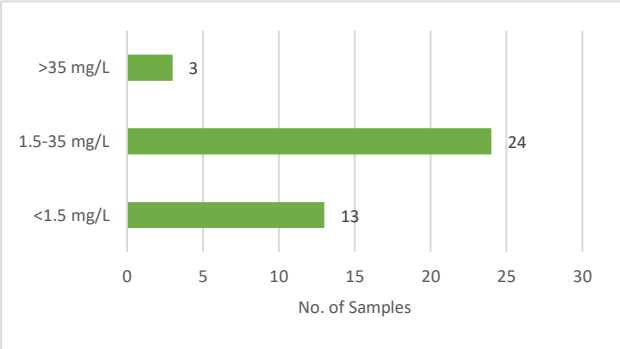


Figure 196: Ammonia Distribution in M. Veyvah

The spatial distribution of all the parameters measured are shown in Figure 198 (a-i).

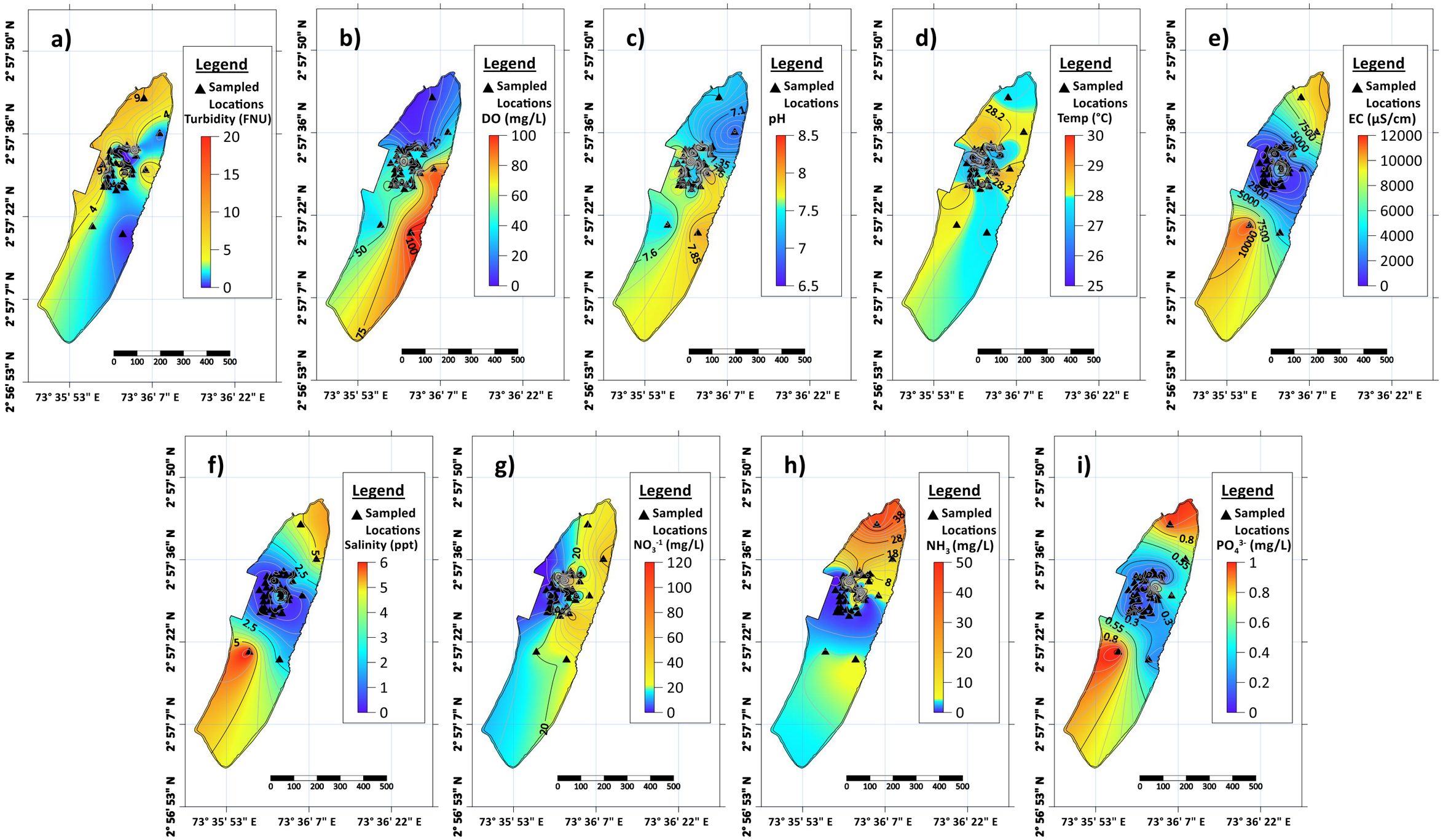


Figure 198: Spatial variation of physiochemical parameters in M. Veyvah

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 0.293 and the R-squared of the plot is 0.0859 as indicated from the Figure 72. 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.

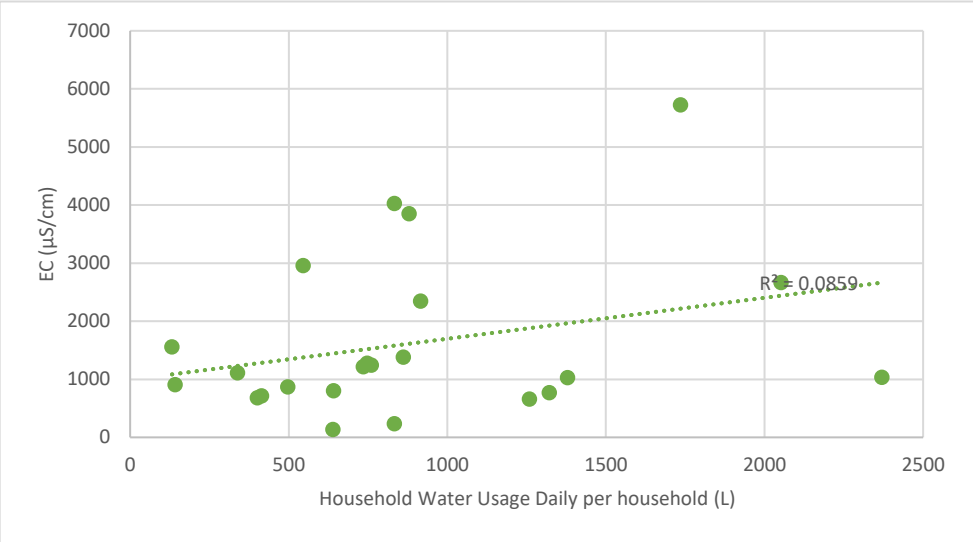


Figure 199: EC against Water Usage in M. Veyvah

11.4.1.1 Correlation Matrix

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

Table 210: Correlation matrix of the groundwater quality parameters in M. Veyvah

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)	-0.23							
pH	-0.13	0.64						
EC (µS/cm)	0.16	-0.25	-0.45					
Sal (ppt)	0.15	-0.25	-0.43	***1.00				
Temp (°C)	0.25	-0.14	-0.30	0.17	0.15			
NO_3^- (mg/L)	0.09	-0.07	-0.31	0.23	0.22	0.25		
NH_3 (mg/L)	0.09	-0.39	-0.35	0.44	0.43	0.22	0.23	
PO_4^{3-} (mg/L)	-0.01	-0.08	-0.08	0.59	0.59	0.10	0.08	0.16

negative correlation	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00	positive correlation

Table 210 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.

11.4.1.2 Water Quality Index

In this study, the computed WQI ranges from 3.04 to 51.48, with a mean of 14.94. The WQI was divided into four categories and Table 211 shows the categorization of samples. 55% of samples were classified as "Very Good", 17.5% of samples were classified as "Good", 25% of samples were classified as "Poor" and 2.5% of samples were classified as "Very Poor". The high value of WQI at some locations has been found to be mainly from the high EC and high Ammonia concentration. The spatial distribution of WQI is as per Figure 200.

Table 211: Water Quality Classification based on WQI – M. Veyvah

WQI Value	Water Quality Classification	Number of samples	Percentage of Samples
0 to 10	Very Good	22	55%
10 to 20	Good	7	17.5%
20 to 50	Poor	10	25%
>50	Very Poor	1	2.5%

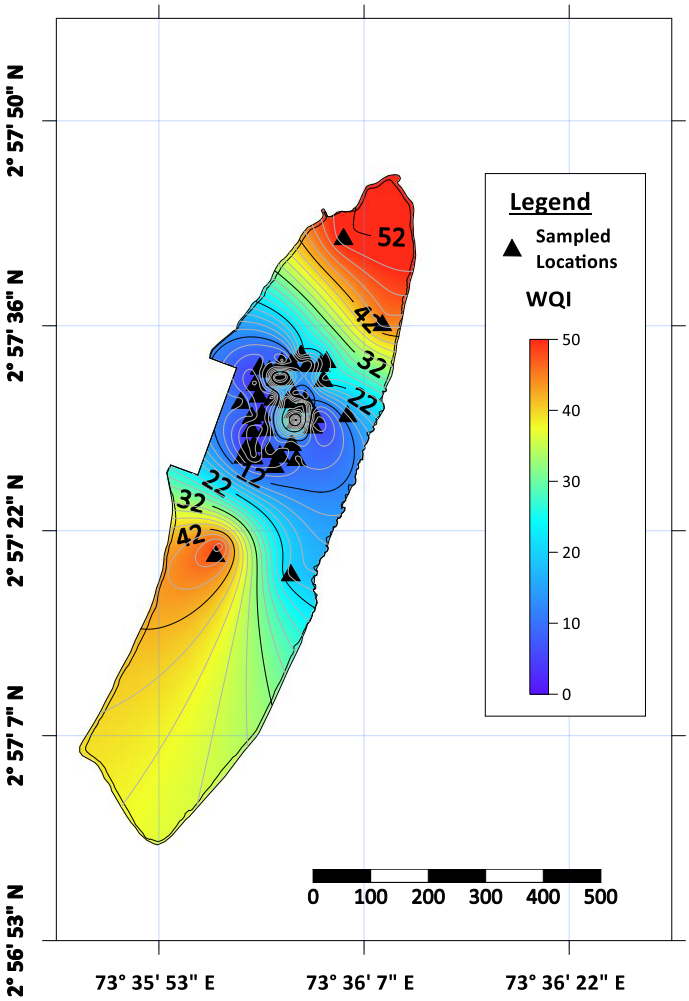


Figure 200: Spatial Distribution of WQI in M. Veyvah

11.4.2 Microbiological survey results

Groundwater samples were taken for microbiological analysis from 15 selected locations and the following Table 212 summarizes the results.

Table 212: Microbiological Parameters of groundwater in M. Veyvah

DATA ID	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)	Distance* (feet)	Remarks
wq31	980	66	70	Septic Tanks - Has not been cleaned yet
wq24	>2420	46	20	Septic Tanks - Has not been cleaned yet
wq04	387	25		Social Survey not carried out
wq15	686	33	45	Septic Tanks. Cleaned once every 5 years. Septic waste buried in house
wq35	>2420	71		Harbour tap
wq30	1203	111		Social Survey not carried out
wq28	>2420	101		Social Survey not carried out
wq12	461	25	3	Septic Tanks. Last time cleaned was 16 years ago. Septic waste pumped out to sea.
wq10	204	27		Connected to a local outfall pipe
wq21	123	57		Mosque
wq33	>2420	121		Connected to a local outfall pipe
wq40	>2420	66		Powerhouse
wq16	141	72	30	Septic Tanks. Cleaned once every 5 years. Septic waste pumped out to sea.
wq09	410	30		Veyvashu School
wq34	1230	72		Social Survey not carried out

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

Both Total Coliform and Faecal Coliform were detected in all 15 samples. 5 samples containing Total Coliform count higher than 2400 MPN/100ml were detected.

As social survey was carried out over the phone on this island due to Covid restrictions there were difficulties in getting responses for all the households where samples were taken for microbiological testing.

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 29 feet between septic tanks and the nearest well as observed from social survey.

The spatial distribution of Total Coliform and Faecal Coliform is given in Figure 201. Moderately even spatial distribution of both Total and Faecal Coliform were observed.

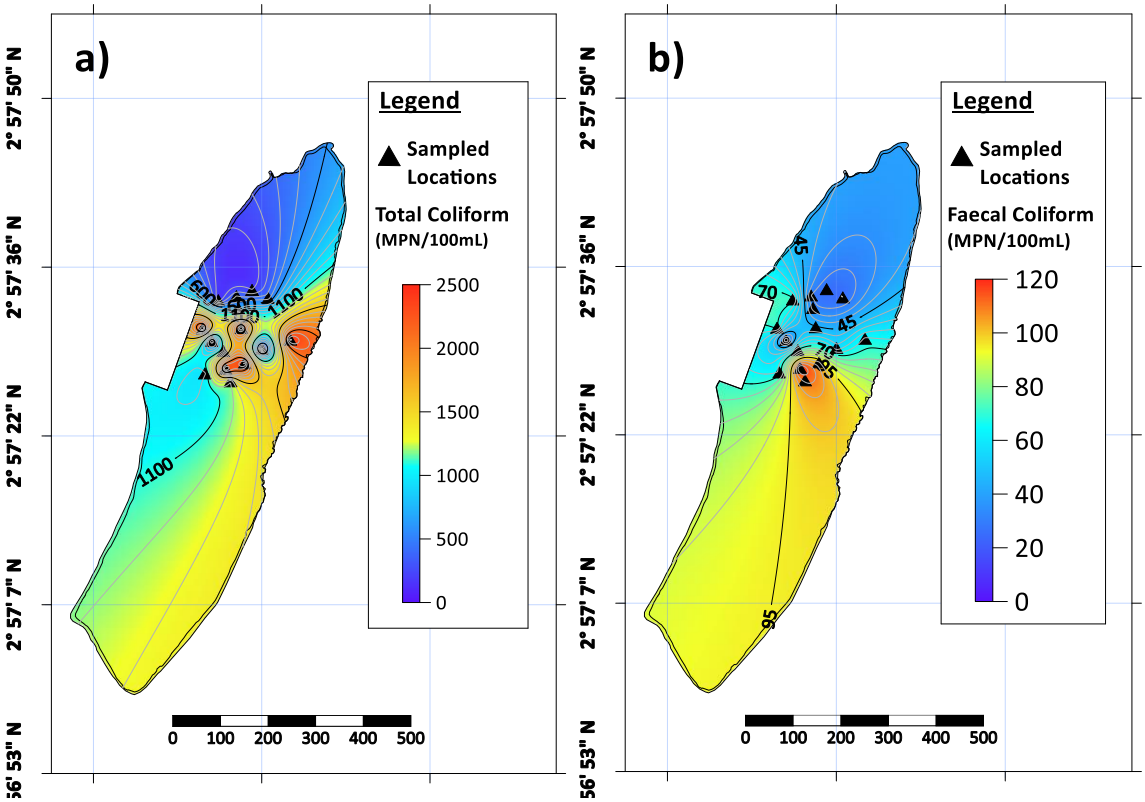
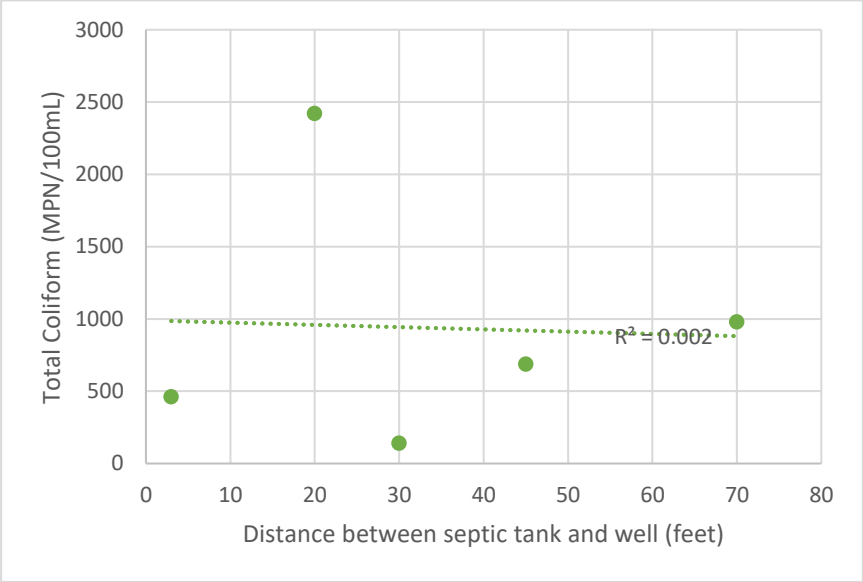


Figure 201: Total (a) and Faecal (b) Contamination Distribution in M. Veyvah

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.



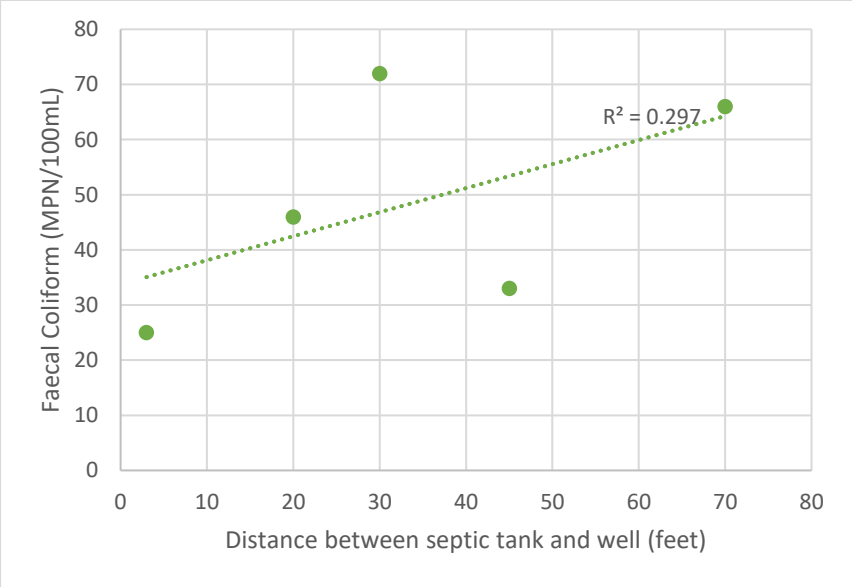


Figure 202: Microbiological Contamination against Septic Tank distancing - Veyvah

The correlation coefficient of Total Coliform to distance between septic tank and well is -0.045 and the R-squared of the plot is 0.002 as indicated from the Figure 202. Therefore, there isn't a significant relationship observed between the parameters.

The correlation coefficient of Faecal Coliform to distance between septic tank and well is 0.545 and the R-squared of the plot is 0.297 as indicated from the Figure 202. Therefore, there is a positive co-relation observed between the parameters.

11.5 Pumping Test

11.5.1 Test location

The well required for pumping should ideally be a well without a base, and the well should not be used for other purposes for the duration of the test. However, a well without a base was not available in M. Veyvah. Therefore, it was decided to carry out the test at the new mosque as the mosque well would be unused for most parts of the day. The chosen well had 3 inlets of approximately 1 inches' diameter at the side walls of the well. Observation well was not used as it was not practical to drill at the chosen location and no other wells were present nearby. Figure 203 below shows the location for the pumping test at M. Veyvah.

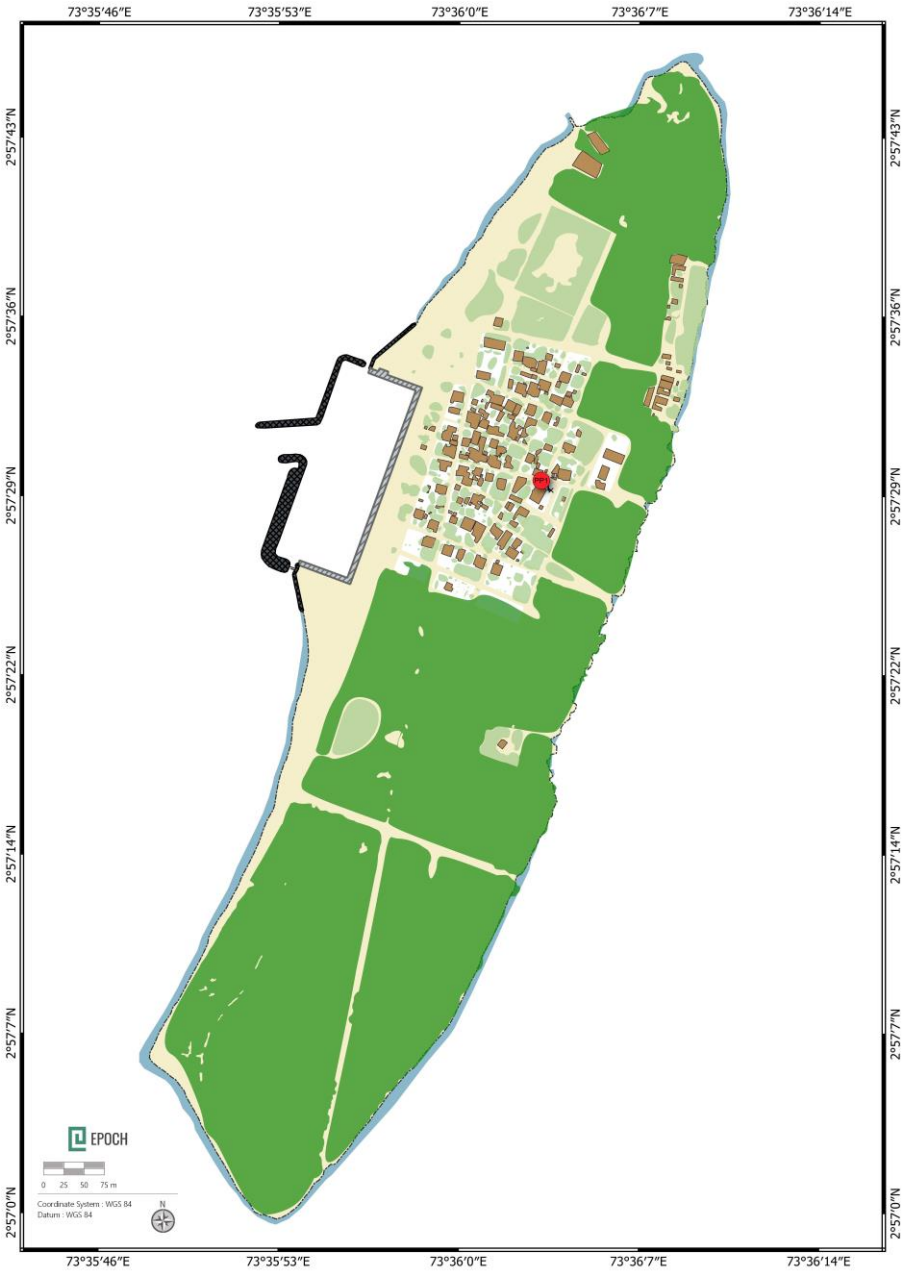


Figure 203: Pumping test location – M. Veyvah

11.5.2 Pumping rate, pumping hours, and collected data

A constant rate pumping test was carried out at M. Veyvah. The test began at 2000 hours on 07 November 2021 and lasted for 225 minutes. A flowrate of 20 LPM was maintained for the pumping phase of the test which lasted from 0-45th minute. The recovery phase of the test lasted from 46th-225th minute for more than an 80% recovery.

11.5.3 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 2.09x10-4 m^2/s (18.07 m^2/day) and the Aquifer Storativity (S) was estimated to be 0.1219 for M. Veyvah. The full data set of the pumping test at M. Veyvah has been annexed at Annex XI.

11.6 Permeability Test

11.6.1 Test locations

Permeability tests were carried out in 5 locations across the island, as outlined in Figure 204 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.

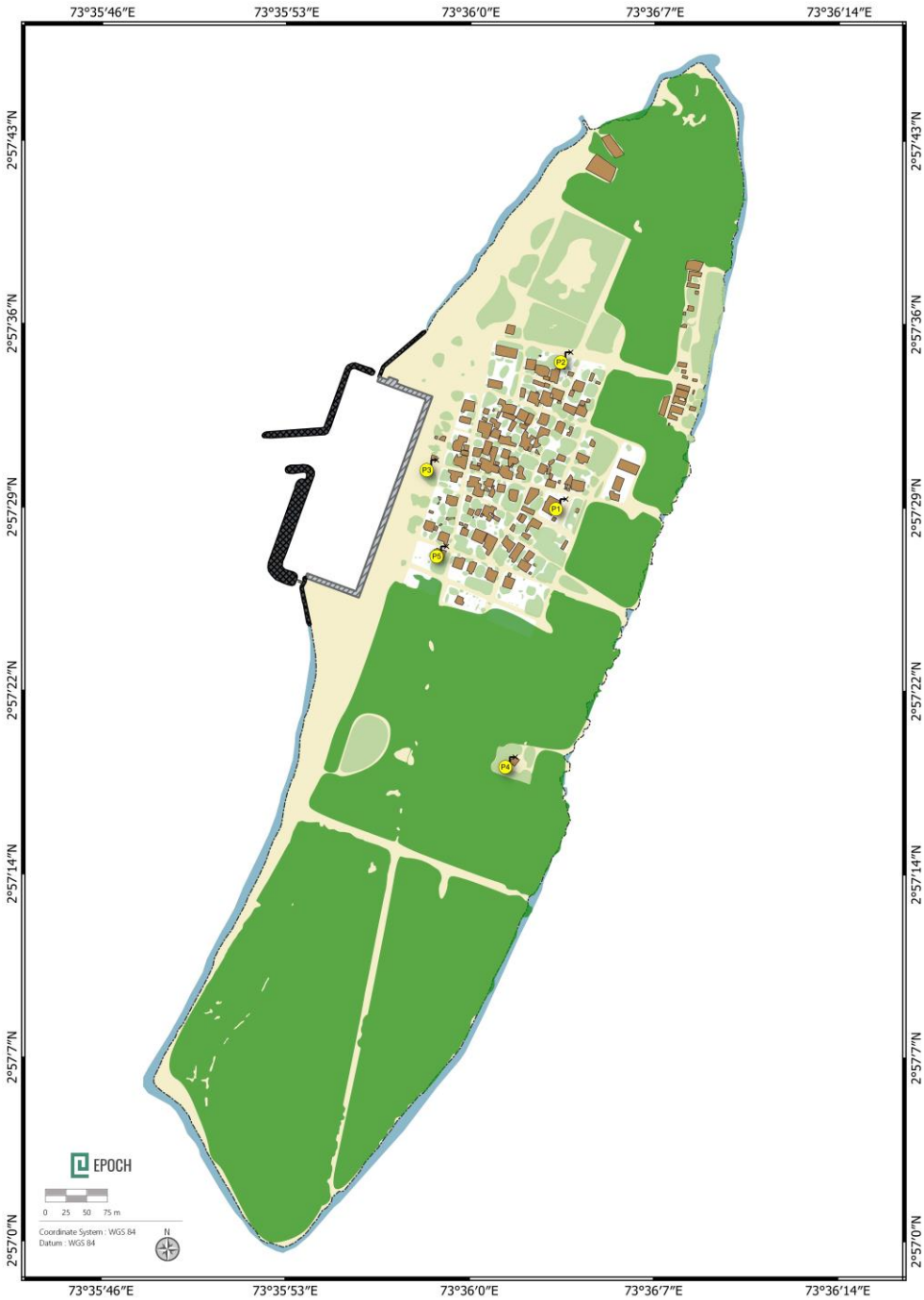


Figure 204: Permeability Test Locations – M. Veyvah

11.6.2 Measured data

Table 213: Permeability Test Measured Data - M. Veyvah

Point ID	H	Tu	Cu	H/r	Q (l/min)	Q (m^3/s)	K (m/s)	K (m/day)
VEY-PMB1	0.600	0.300	35	12	2.00	0.000033	1.13E-04	9.79
VEY-PMB2	0.600	0.495	35	12	0.50	0.000008	1.72E-05	1.483
VEY-PMB3	0.600	0.350	35	12	3.17	0.000053	1.54E-04	13.3
VEY-PMB4	0.600	0.565	35	12	16.00	0.000267	4.81E-04	41.59
VEY-PMB5	0.600	0.400	35	12	0.25	0.000004	1.06E-05	0.918

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.

11.6.3 Permeability estimation and identified features

The average permeability value for the M. Veyvah is 13.42 m/day, with permeability values ranging from 0.92 m/day to 41.59 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)).

11.7 Soil Profile Survey

11.7.1 Test locations

Soil Profile surveys were carried in 7 locations across the island, as outlined in Figure 205 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.

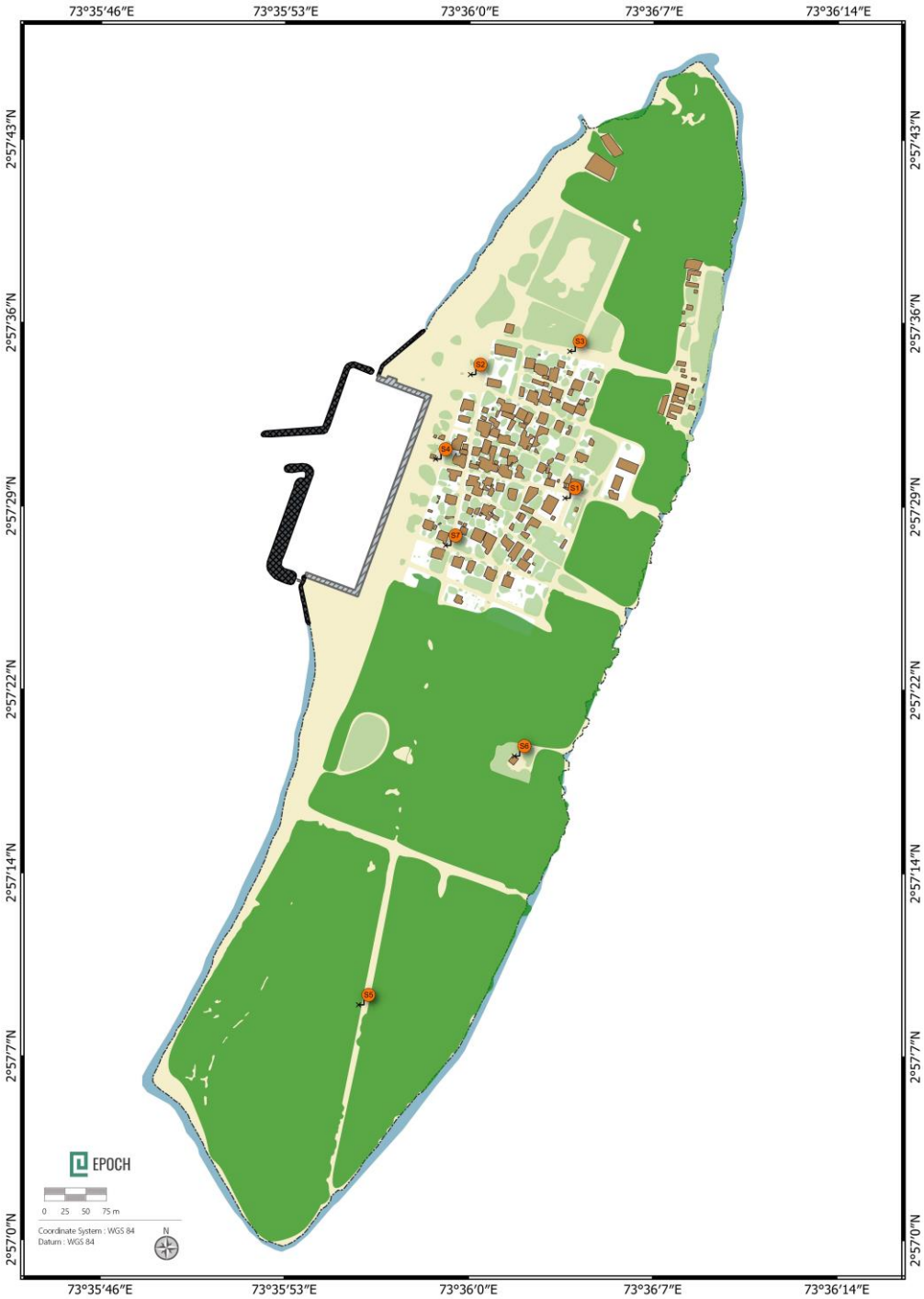


Figure 205: Soil Profile Survey Locations – M. Veyvah

11.7.2 Collected data and observed features

The collected soil profile data and observed features are highlighted in Figure 206 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.

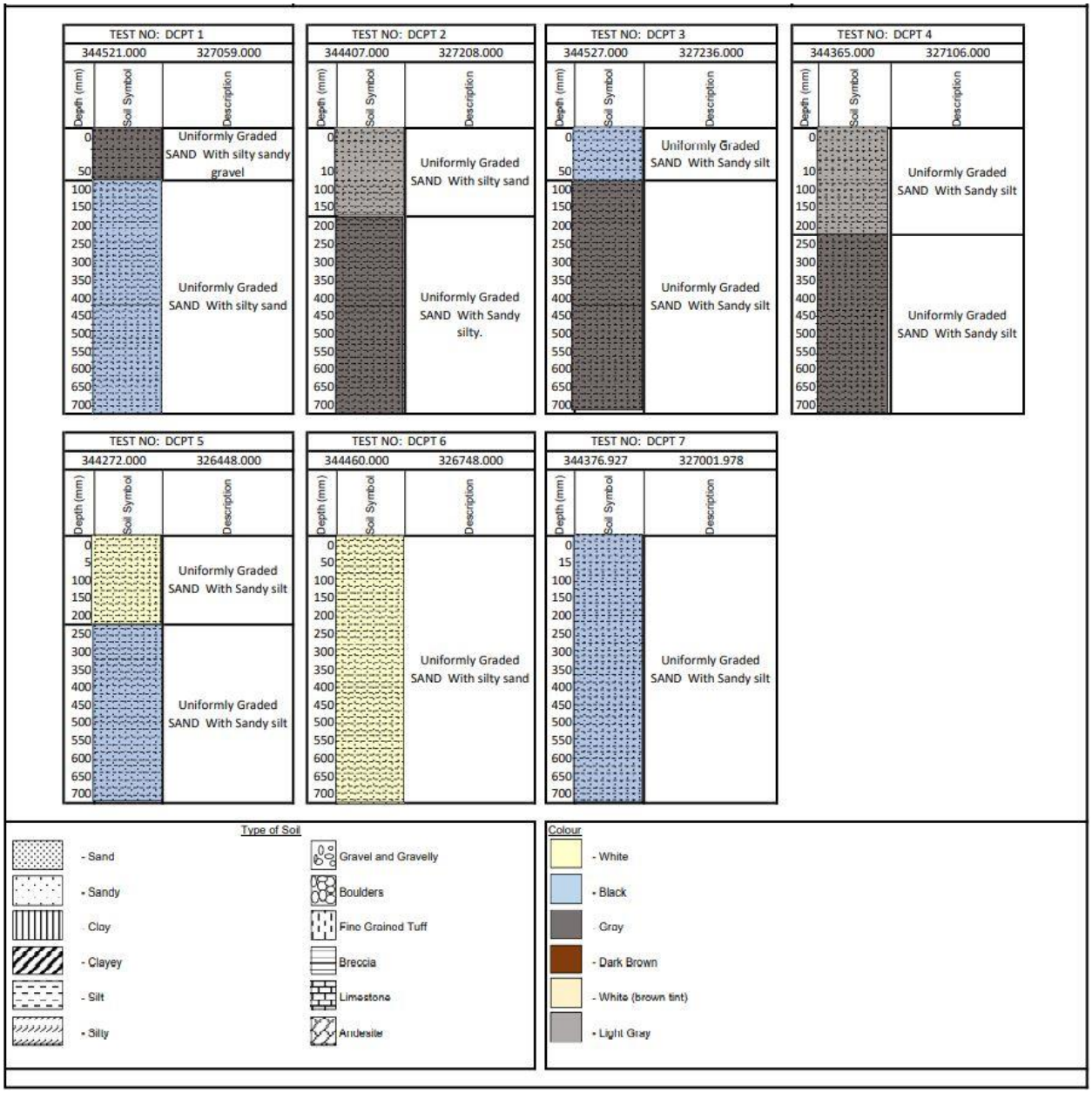


Figure 206: Soil Profile - M. Veyvah

11.8 Flood Assessment and Inundation Survey

11.8.1 Flood occurrence and flood impact

In M. Veyvah, many households report that groundwater has gotten worse after the 2004 Tsunami. Tsunami had a significant impact on this island where a 575 feet jetty was also destroyed. The island also reports frequent tidal swelling during May-July, mainly on the southwest of the harbor near the road intersecting main road.

The council reported that the main road and the road to the west of the football field were filled up to 1 foot with sand in 2021 and some occurrences of floodwater intrusion into households in this region is observed.

Some areas which previously experienced flooding problems such as the Fenaka office and old mosque area were also filled with sand. With these measures, those areas reported less accumulation of water. In M. Veyvah, 54% view flooding as an acceptable problem (refer to flood severity component of Flood Maps in Annex XII).

The flooding originates mostly from roof runoff (46%) 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 214: Perceived causes of flooding – M. Veyvah

Perceived causes of flooding				
Roof run off	**Neighbours' roof**	**Off the road**	**General run off in the area**	**No flooding within the plot**
46%	10%	7%	2%	46%

From the social survey, 59% 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 which include overflow 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 215: Discharge of rainwater overflow – M. Veyvah

Discharge of rainwater overflow				
Ground	**Roads**	**Open area within the plot**	**Drained to well**	**Local outfall pipe**
59%	2%	49%	10%	2%

11.8.2 Inundation area identification

Significant flooding areas include mosque road (commonly referred as Miskiy Magu) and in front of residential houses (refer to Annex XII: Flood Maps). A total of 9 houses were reported with significant flooding issues in front of their house. Based on the social survey responses, an average of 1.36ft is estimated as the flooding depth when there is a heavy rainfall. Also, 42% of the respondents reported that it takes 30 minutes to inundate the area once the heavy rain starts.

11.8.3 Draining flood water

There is no established drainage system within the island. As per the social survey, 48% observe that the water drains during the rainfall itself, 32% observe that the water drains in less than 4 hours, 12% 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 216: Draining period – M. Veyvah

Draining period			
only while raining	**drains less than 4hrs**	**takes 4-24 hrs**	**more than 24hrs**
48%	32%	12%	8%

In M. Veyvah, there were a few circumstances where the flooded water was pumped out and sandbags were used to reduce water level in the vicinity to negate any further damages caused by flooding.

11.9 Geophysical Survey

11.9.1 Surveyed locations

Locations where ER sounding measurement taken at M. Veyvah island are shown in Figure 207 together with transect lines. There are 27 ER measurement locations and the number of transects in this island is 14.

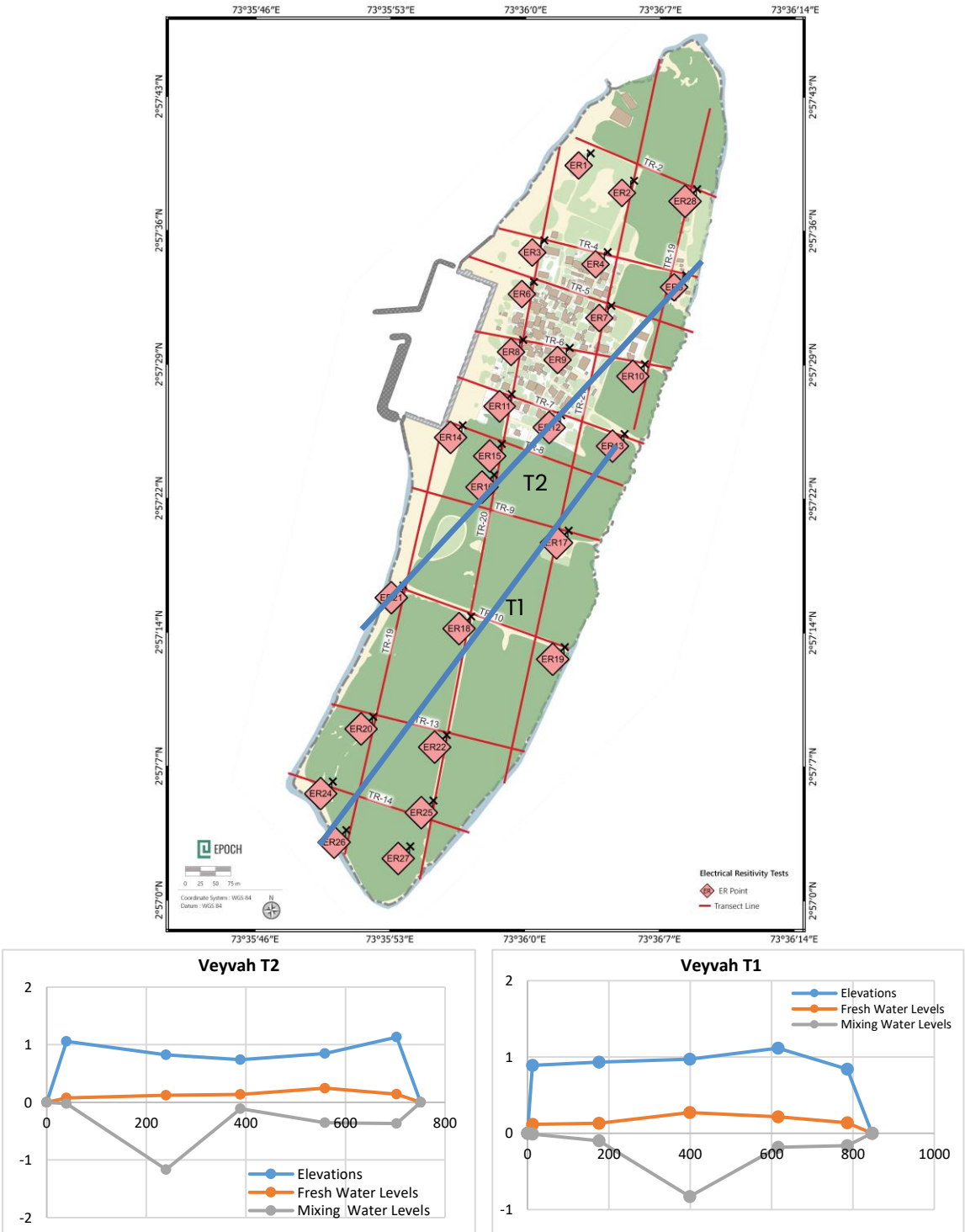


Figure 207: ER surveyed locations and transect lines – M. Veyvah Island

11.9.2 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 217 below shows the estimated levels at ER surveyed locations of M. Veyvah Island and freshwater lens thickness.

Table 217: Freshwater lens levels and thickness – M. Veyvah island

No	Location	Level (m AMSL)			Freshwater lens thickness (m)
		Ground	Freshwater	Saline water	
1	1	0.72	0.02	-0.07	0.09
2	2	0.57	0.07	-0.93	1.00
3	3	0.64	0.09	-0.16	0.25
4	4	0.61	0.06	-0.89	0.95
5	5	1.13	0.14	-0.37	0.51
6	6	0.93	0.13	-0.37	0.50
7	7	0.61	0.11	-0.79	0.90
8	8	0.69	0.09	-0.88	0.97
9	9	0.71	0.11	-0.89	1.00
10	10	0.85	0.25	-0.35	0.60
11	11	0.60	0.20	-0.42	0.62
12	12	0.74	0.14	-0.11	0.25
13	13	0.84	0.14	-0.16	0.30
14	14	1.09	0.19	0.06	0.13
15	15	0.86	0.09	-0.01	0.10
16	16	0.83	0.13	-1.16	1.29
17	17	1.12	0.22	-0.18	0.40
18	18	0.97	0.27	-0.83	1.10
19	19	1.41	0.21	-0.09	0.30
20	20	0.93	0.13	-0.10	0.23
21	21	1.06	0.08	-0.02	0.10
22	22	1.30	0.51	-0.60	1.11
23	24	0.89	0.12	-0.01	0.13
24	25	1.26	0.38	-0.84	1.22
25	26	1.12	0.22	-0.08	0.30
26	27	0.90	0.17	-0.30	0.47
27	28	0.96	0.15	-0.06	0.21

Average freshwater thickness of M. Veyvah island is 0.56m. Maximum recorded thickness of freshwater lens of the Island by ER survey is 1.29 m & minimum is 0.09 m.

Data in Table 217 were used to plot freshwater lens cross sections along transects. Of these 2 sectional plots are given in Figure 207 and they represent the transect plots along the diagonal sections of the island as per Figure 207.

11.9.3 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 208.

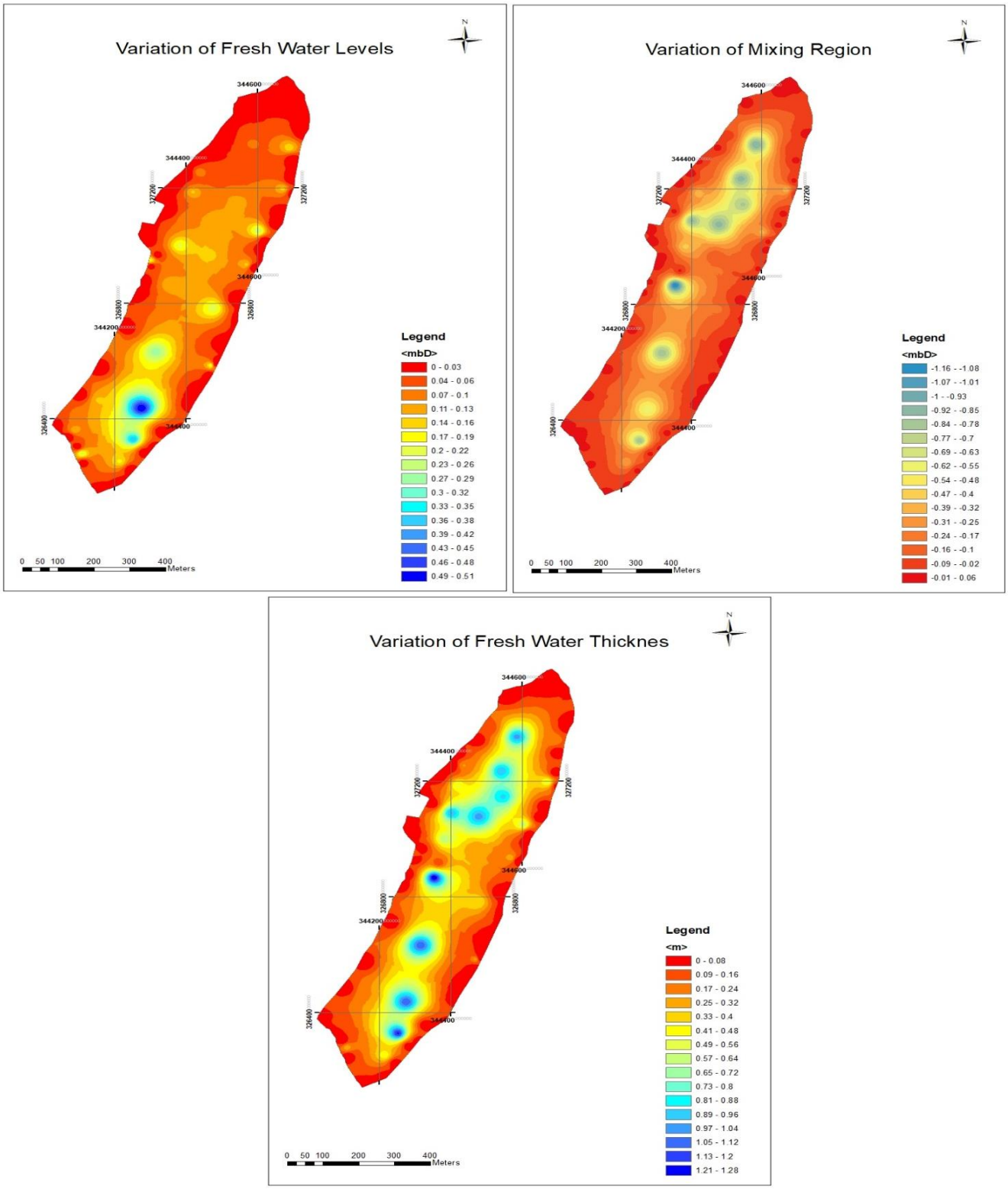


Figure 208: Top Left: Contours of Freshwater lens upper level,
Top Right: Contours of Freshwater lens lower level,
Bottom: Spatial distribution of thickness of freshwater lens – M. Naalaafushi

11.9.4 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. Tools in ArcGIS software were used to perform this computation.

Stress level on freshwater aquifer of M. Veyvah 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 218.

Table 218: Freshwater lens volume and aquifer stress level – M. Veyvah island

Item	Value	Unit
Freshwater lens volume - ArcGIS	275,827	m^3
Groundwater abstraction	80,266	m^3/yr
Freshwater lens volume/ Groundwater abstraction	11.7	-
Aquifer stress level	Not Stressed	-

The estimation of freshwater lens thickness from Falkland (1994) equation come to 6.7m. This deviates by 419% from the maximum measured value of 1.29m, which is more reliable as it results from a more comprehensive, site-specific methodology.

11.10 SWB Modelling

11.10.1 Land use categorization and area estimation

Table showing land classification and their respective areas are shown in Table 137.

Table 219: Land Use Classification - M. Veyvah

	Area (m^2)	% of total area
Roof cover	16,776	3.9%
Vegetation (Thick)	274,667	64%
Vegetation (Thin)	36,520	8.5%
Bare Lands	99,776	23%
Farmlands	226	0.053%
Total	428,007	100%

11.10.2 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 209 and Table 138). Followings were noted from the estimated recharge values.

- Annual minimum, maximum and average recharge values are 75,412m^3, 1,970,252m^3 and 410,068m^3 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 2242 mm.
- Variation among the monthly average recharge value is very high. It is lowest in month of January and highest in May.

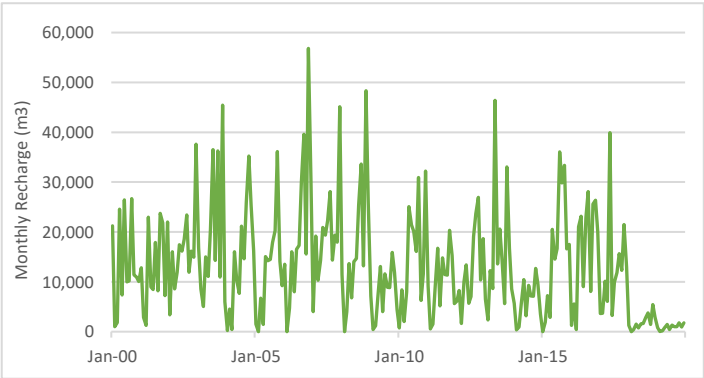


Figure 209: Monthly and annual recharge distribution - M. Veyvah

Table 220: Monthly recharge estimated by SWB model - M. Veyvah Island

Year	Monthly Recharge (m^3)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	21,229	997	1,848	24,578	7,357	26,426	9,992	10,175	26,710	11,410	10,962	10,084
2001	12,820	2,875	1,227	22,958	8,983	8,452	17,893	8,187	23,754	21,831	7,198	22,014
2002	3,352	15,998	8,608	11,904	17,445	16,135	18,525	23,415	11,941	16,126	14,945	37,618
2003	16,859	8,571	5,037	15,009	11,053	20,531	36,492	14,286	36,236	10,979	45,458	5,988
2004	247	4,524	412	16,026	10,357	7,656	21,172	14,615	25,952	35,238	25,384	16,135
2005	1,529	-	6,685	1,438	15,063	14,222	14,468	17,857	20,256	36,144	14,120	9,240
2006	13,516	-	4,716	16,044	8,003	16,538	17,289	29,881	39,588	15,549	56,822	30,329
2007	4,022	19,198	10,330	14,285	20,934	19,362	22,230	28,098	14,329	19,351	17,934	45,142
2008	11,489	-	4,009	13,637	6,802	14,058	14,696	25,399	33,649	13,217	48,299	25,780
2009	7,148	424	1,180	6,957	13,044	4,016	11,567	8,923	8,859	15,866	11,899	4,384
2010	725	8,412	2,030	8,004	25,099	21,401	20,132	16,098	30,900	6,282	11,620	32,206
2011	9,164	543	1,513	8,919	16,723	5,148	14,829	11,439	11,357	20,340	15,255	5,620
2012	6,164	8,231	1,623	9,998	13,379	5,683	7,007	19,108	23,667	26,922	10,379	18,682
2013	6,544	2,348	12,255	8,656	46,382	13,560	20,558	14,385	5,620	33,030	16,805	8,557
2014	5,718	339	944	5,566	10,435	3,213	9,254	7,138	7,087	12,692	9,519	3,507
2015	-	1,913	7,206	2,864	20,513	14,521	16,670	36,031	29,804	33,384	16,606	17,513
2016	1,278	5,529	390	21,021	23,151	9,029	22,879	28,127	8,058	25,580	26,359	19,933
2017	3,644	3,689	10,143	6,055	39,884	3,245	9,898	11,865	15,663	12,273	21,501	13,008
2018	1,284	-	448	1,524	760	1,571	1,642	2,839	3,761	1,477	5,398	2,881
2019	802	48	132	780	1,463	450	1,298	1,001	994	1,780	965	1,737

11.10.3 Water Balance

As per estimation, annual recharge estimated by the SWB model is 116,377m^3 and it is 20.3% of annual average rainfall (refer Figure 210).

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	456,380	6,878	237,318	116,377	95,840	23,721
%	100.0%	1.5%	52%	20.3%	21%	5.2%

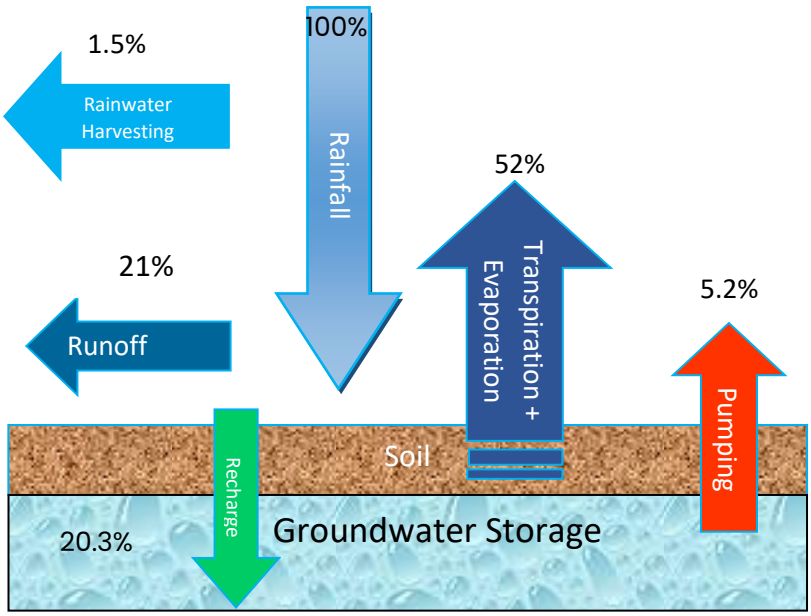


Figure 210: Annual water balance – M. Veyvah Island

11.10.4 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 (1977 m^3/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 221: Deficit percentage – M. Veyvah

Total Month (Nos)	Month with deficit (Nos)	Deficit (%)
240	42	17.5

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 M. Veyvah island depend 17.5% 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 (23,721 m^3/yr) with safe abstraction volume (92,655 m^3/yr) shows that present withdrawal is 74.4% less than the safe yield. Therefore, it could be inferred that present groundwater abstraction is within the allowable limit and it has insignificant influence in up-coning freshwater-saline water interface in the existing condition.

11.11 SUTRA Modelling

11.11.1 Model representation and mesh production

SUTRA modelling requires mode domain to be defined in the first step and it was achieved by drawing a polygon along the reef end of the island. The other boundary defined in the model was island outline which can be referred as shoreline most of the cases except at harbour area and the inner part of the island was subdivided to several polygons representing different land use and it was accomplished by importing GIS shape files of island land use and then drawing polygon 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.

11.11.2 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 211 shows the pressure boundary defined for M. Veyvah island.

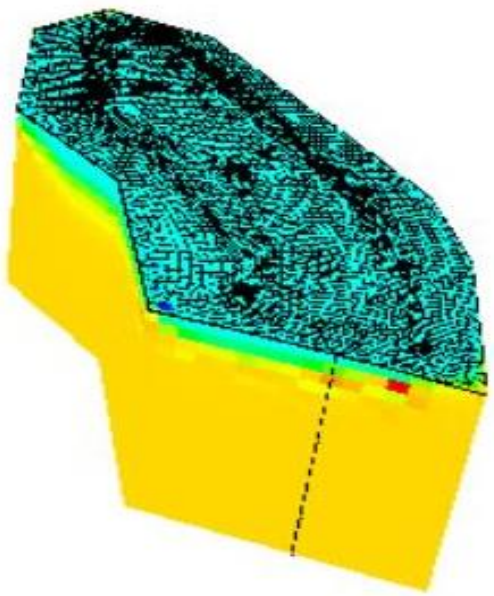


Figure 211: Pressure boundary at SUTRA model - Veyvah island

11.11.3 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.

11.11.4 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.

11.11.5 Prediction of freshwater lens

The simulated delineation of the freshwater lens from the SUTRA model over a 20 yr period is shown in Figure 212. The section view shows contours of saltwater concentration at the vertical section. Sea water concentration is 0.0357 (= 35.7 g/l) and allowable saltwater concentration in potable water is 0.001 which can be seen on island top.

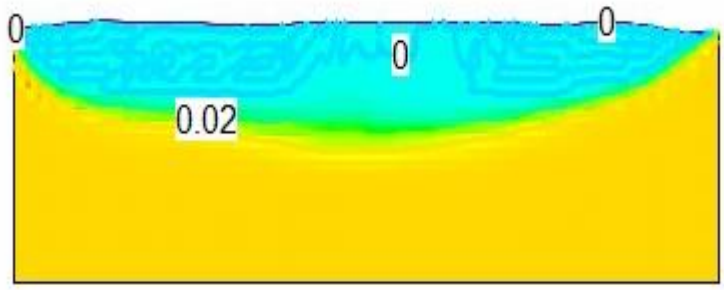


Figure 212: Saltwater distribution - M. Veyvah island

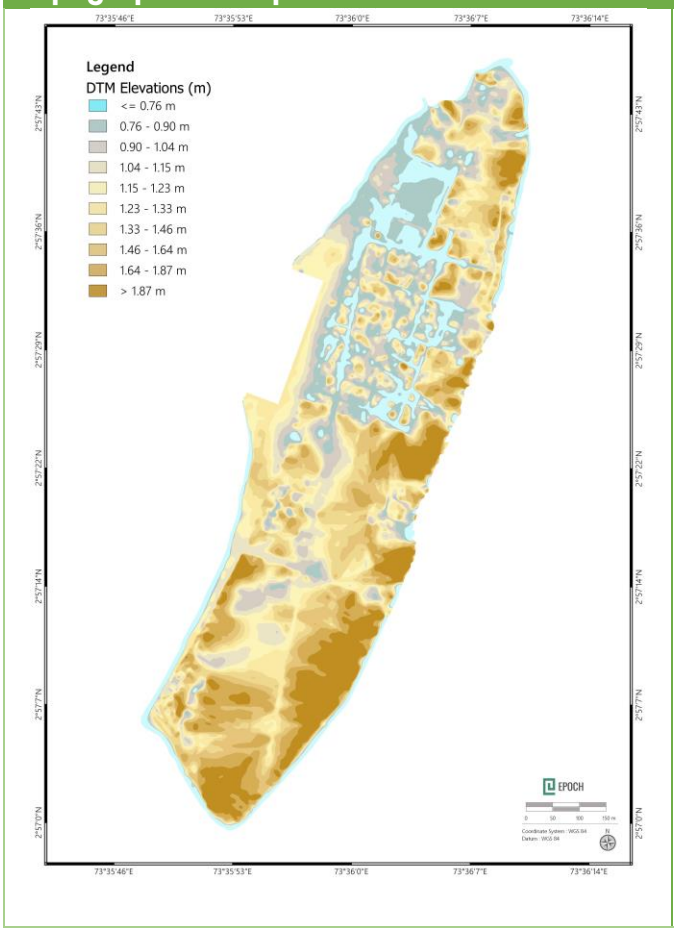
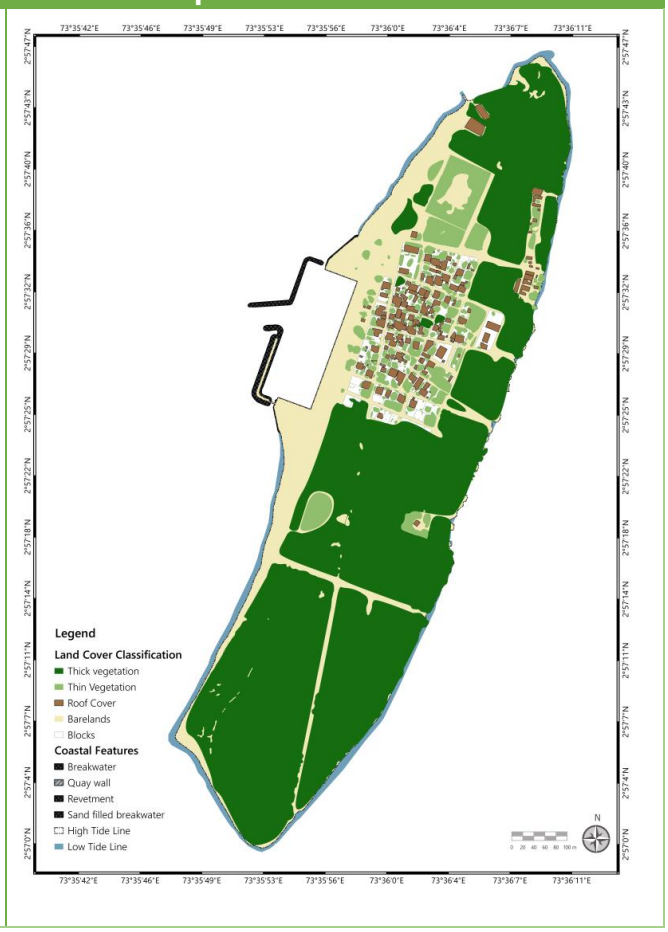
11.12 Summary of Baseline Assessment

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

- General overview, demography, and climatology

Item	Details
Atoll	Mulaku Atoll
Length	1.54 km
Width	0.35 km
Area	42.8 ha
Population	339
Population/area	7.92 per ha
Pipe borne water supply	Nil
Pipe borne Sanitation	Construction in progress/Nil

- Topography and land use
  Data from level survey, drone survey and photometric survey

Topographical map	Land use map
	

	% of total area	
Average elevation = 1.160 m above MSL	Roof cover	3.9%
	Vegetation (Thick)	64%
Shoreline length = 3938 m	Vegetation (Thin)	8.5%
	Bare Lands	23%
	Farmlands	0.053%
	Wetlands	0%

- Water consumption

Category	Domestic	Commercial	Industrial	Institutional	Total
Rate (m^3/d)	62	0.70	18.3	1.15	82.2

- Water quality parameters – Physiochemical
  Number of samples tested = 40

Parameters	Value	Allowable limit for drinking water
EC (µS/cm)	2329 ± 2705	1500
Turbidity (FNU)	3.43 ± 4.89	5
DO (mg/L)	3.12 ± 1.80	
pH	7.49 ± 0.31	6.5-8.5
Temp (°C)	27.7 ± 0.92	
Sal (ppt)	1.16 ± 1.44	
NH_3 (mg/L)	7.80 ± 12.18	1.5 (Odour Threshhold)
NO_3^- (mg/L)	21.34 ± 22.96	50
PO_4^{3-} (mg/L)	0.26 ± 0.27	

- Water quality parameters – Microbiological
  Number of samples tested = 15

Parameter	Value range	Average value	Remarks *(on permit limit)*
Total Coliform (MPN/100ml)	123 - >2420	1,195	Total Coliform should not be detected
Faecal Coliform (MPN/100ml)	25 – >121	61.53	Faecal Coliform should not be detected

- Pumping test, permeability, and soil profile

Item	No. of samples	Value range	Unit
Transmissivity	1	18.07	m^2/day
Storativity	1	0.1219	-
Permeability	7	0.92 – 41.59 Average – 13.42	m/day
Soil profile	5	Mostly uniformly graded sand	

- Flooding

Flooding days per year	Inundation area (m^2)	Inundation depth (m)
83	3700	0.414

- Electric Resistivity survey
  - Measurement taken at 27 locations.
  - Average freshwater thickness in the island is 0.56 m.
  - Freshwater lens volume and aquifer stress level

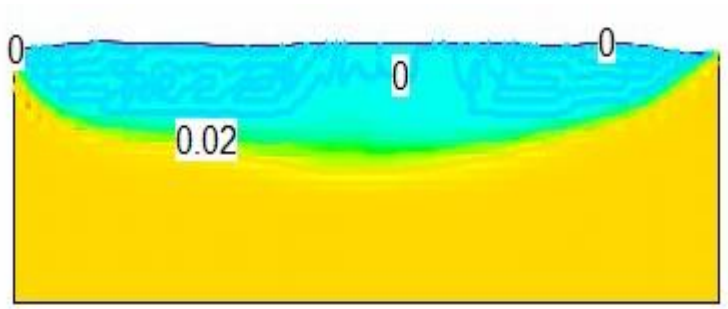
Item	Value	Unit
Freshwater lens volume - ArcGIS	275,827	m^3
Groundwater abstraction	80,266	m^3/yr
Freshwater lens volume/ Groundwater abstraction	11.7	-
Aquifer stress level	Not Stressed	-

- SWB modelling
  - Annual recharge is 116,377m^3 and it is 20.3% of annual rainfall (2242 mm)
  - Annual water balance

Unit	Component					
	Rainfall	**Rainfall Harvesting**	**Evapotranspiration**	**Recharge**	**Runoff**	**Pumping**
m^3	937,320	6,878	237,318	116,377	95,840	23,721
%	100.0%	1.5%	52%	20.3%	21%	5.2%

  - Comparison of monthly recharge rate verse ground water extraction rate shows that pumping is exceeding recharge by 17.5% in an average year, and it is compensated by ground water storage.
  - Ground water withdrawal (23,721 m^3/yr) is 74.4% less than the safe abstraction (92,655m^3/yr).

- SUTRA modelling
  - Average monthly recharge assigned to SUTRA model
  - Freshwater lens prediction (allowable concentration for potable use is 0.001)



12 Conclusion and Recommendations

The field surveys and investigations together with the groundwater modelling carried out for the baseline assessment of the islands reveal an urgent need for recharge and replenishment of the freshwater lens.

The social surveys carried in the islands indicate that domestic groundwater usage is in the expected range for all the islands ranging from 156 to 210 LPCD.

Based on the water quality testing carried for the physiochemical parameters, the water quality is found to vary considerably across all the islands. The water quality of Dh. Bandidhoo was classified as "Very Good", ADh. Kunburudhoo was classified as "Very Poor" based on physiochemical parameters and the remaining islands water quality was classified as "Good". As the groundwater consumption in Dh. Bandidhoo is considerably high as compared to the rest of the islands, it is recommended to conduct awareness programs to encourage and educate people about the role of the freshwater lens and to reduce their groundwater consumption.

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 213. 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.

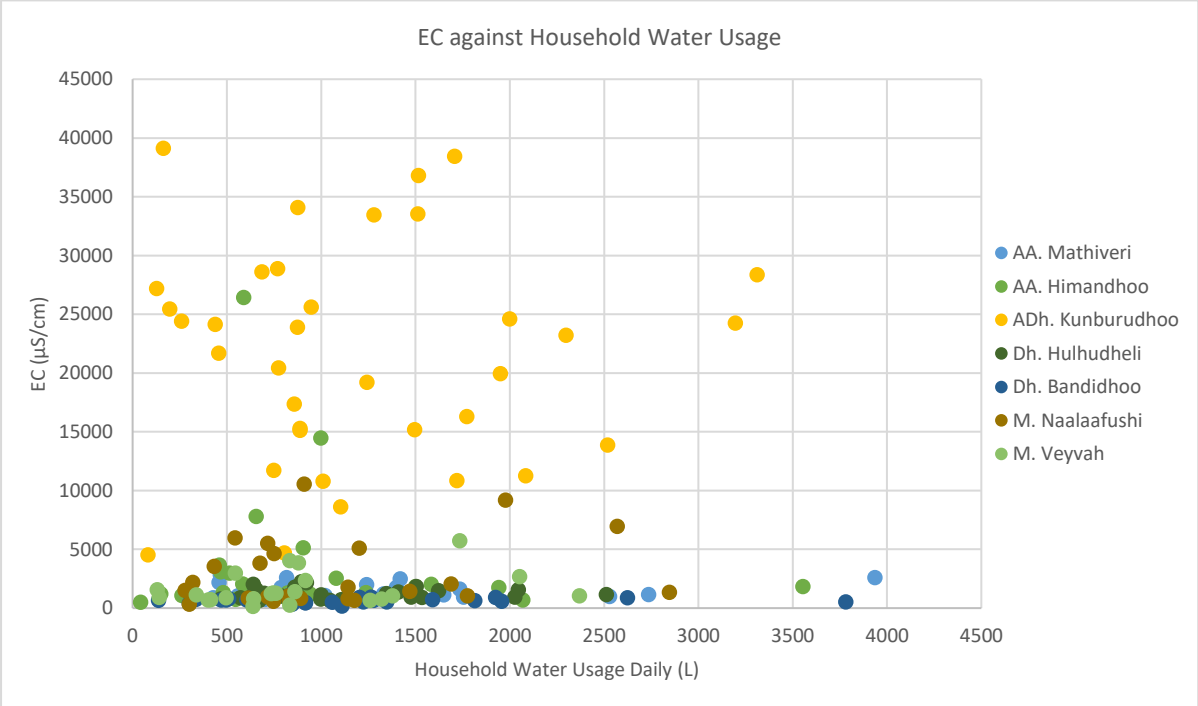


Figure 213: Electrical Conductivity against Household Water Usage for all islands

The microbiological testing carried on samples indicate 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. There is no significant relationship observed between Total Coliform, Faecal Coliform and distance between septic tank and nearest well.

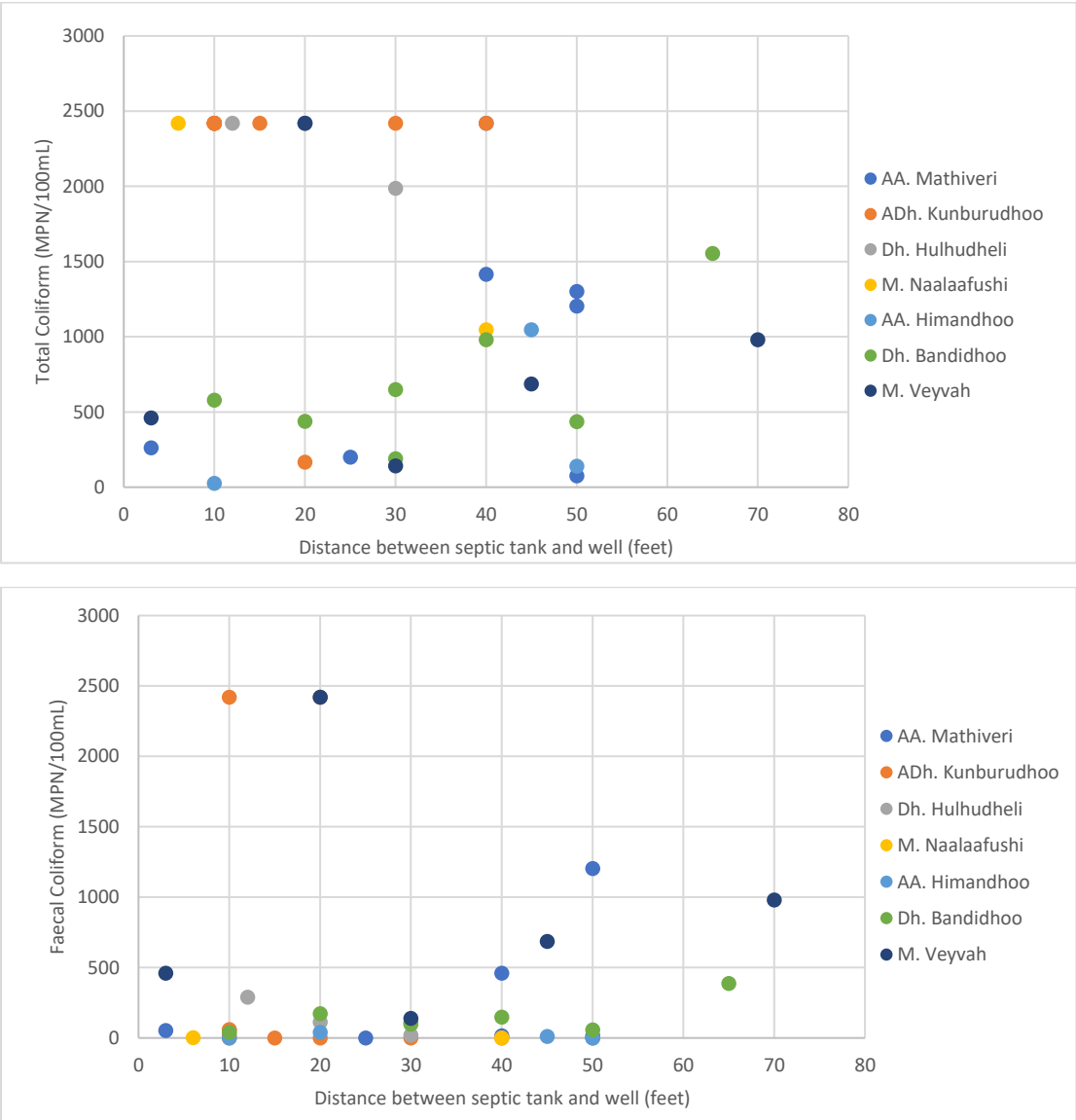


Figure 214: Co-relation between microbiological contamination and distance between septic tank and well

The geophysical surveys carried indicate that AA. Himandhoo has a highly stressed aquifer, ADh. Kunburudhoo has a stressed aquifer and remaining islands' aquifers are not stressed.

The SWB modelling carried indicates that recharge percentages for the islands ranges from 18% to 33% 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 exceed the safe yields of the aquifer in AA. Mathiveri, Dh. Bandidhoo and ADh. Kunburudhoo. The SUTRA modelling that was

carried out 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, the islands that exceed the safe yield 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 with other social, environmental, and economic factors during feasibility study.

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14 Annex I: Stakeholder consultation and meeting

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18 Annex V: Map of households surveyed

19 Annex VI: Water Quality Location Map

20 Annex VII: Water Quality Data

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25 Annex XI: Pumping test data and parameter estimations

26 Annex XII: Flood Maps