



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

FEASIBILITY & CONCEPT DESIGN REPORT

Th. Gaadhiffushi, Th. Omadhoo, Th. Vandhoo,
Th. Kandoodhoo, and Sh. Foakaidhoo

May 2022



Project: Supporting Vulnerable Communities in Maldives to Manage Climate Change-Induced Water Shortages Project

Funding Agency: Green Climate Fund (GCF)

Implementing Agency: Ministry of Environment, Climate Change and Technology

Accredited Entity: United Nations Development Programme (UNDP)

Assignment: Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Maldives (Lot 2)

Client: Ministry of Environment, Climate Change and Technology

Consultants: Riyan Pvt. Ltd., Maldives & Master Hellie's Engineering Consultants Pvt. Ltd, Sri Lanka

Deliverable: Feasibility Concept Design Report

Focus Islands:

- Th Gaadhiffushi
- Th Omadhoo
- Th Vandhoo
- Th Kandoodhoo
- Th Dhiyamigili
- Sh Foakaidhoo

Table of contents

EXECUTIVE SUMMARY	VIII
Background and Methodology.....	VIII
General Findings from Baseline Surveys	VIII
Concept of Managed Aquifer Recharge (MAR).....	IX
Roof Water Recharging	IX
Road Runoff Recharging	IX
Recharging Ponds	IX
Contour Drains.....	IX
Application of Aquifer Modifications.....	X
Recommendation for Detailed Design.....	X
1 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Specific Objectives	2
1.3 Structure of the Report.....	2
2 BASIC REQUIREMENTS FOR MANAGED AQUIFER RECHARGE (MAR)	3
2.1 Groundwater Occurrence in the Maldives Islands	3
2.1.1 Seawater and Freshwater Relationship	3
2.1.2 Natural Groundwater Recharge and Variation of Groundwater Level	3
2.1.2.1 Groundwater Level Variation due to Recharge and Discharge Conditions due to Annual Climatic Cycle.....	4
2.1.2.2 Groundwater level variation due to tidal effect	4
2.1.2.3 Addition of wastewater as groundwater.....	4
2.2 Managed Aquifer Recharge and Different Options for Groundwater Recharge	4
2.2.1 Source Water Availability.....	5
2.2.2 Different Options for Groundwater Recharge and Management of Overland Flow	6
2.2.2.1 Roof Water Recharging	7
2.2.2.2 Road Runoff Recharging	8
2.2.2.3 Recharging Ponds	9
2.2.2.4 Contour Drains.....	9
2.2.2.5 Application of Aquifer Modifications.....	9
3 HYDROLOGY AND DRAINAGE	11
3.1 General Overview of Climate in the Maldives Islands	11
3.2 Recent Rainfall Trends in the Maldives Islands	15

3.3	Rainfall Characteristics Data for Recharge Estimation in the Selected Islands.....	17
3.3.1	Distinct Characteristics in Annual Rainfall Series.....	17
3.3.2	Monthly Rainfall Variations in Northern and Southern Islands	17
3.3.3	Rainfall Intensity for Recharge Estimation.....	18
3.4	Runoff Coefficients for Roof Runoff and Overland Flow Estimation.....	19
3.5	Estimating Effective Plan Roof Area & Catchment Area for Rainfall Harvesting.....	21
4	METHODOLOGY AND CALCULATIONS FOR CONCEPTUAL DESINGS.....	22
4.1	Geological and Hydrogeological Aspects for Feasibility and Concept Design	22
4.2	Conceptual Designs of Proposed MAR System (MAR).....	22
4.3	Assumptions and Major Considerations in Conceptual Designs	24
4.4	Calculations for Conceptual Designs of Proposed MAR System (MAR)	25
4.4.1.1	Assessment of Unsaturated Area	25
4.4.1.2	Recharging Using Roof Water.....	26
4.4.1.2.1	Distribution of roof areas and design volume of recharging well.....	26
4.4.1.2.2	Conceptual design of recharging well.....	27
4.4.1.3	Road Runoff Recharging	29
4.4.1.4	Conceptual design of roadside drains and recharging pits.....	31
4.4.1.5	Recharging Pond.....	33
4.4.1.6	Application of Aquifer Modifications.....	35
4.4.1.7	Predicted Groundwater Enhancement in The Island.....	37
4.5	Social and Environmental Feasibility and Impact of Proposed MAR Systems	38
4.5.1	Th. Kandoodhoo	38
4.6	Quantification and Cost Estimation of Proposed Conceptual Designs	41
4.6.1	Roof recharging structures.....	41
4.6.2	Road runoff recharging.....	43
4.6.3	Recharging pond.....	43
4.6.4	Application of Aquifer Modifications.....	44
4.7	Validation of the Proposed Recharge Structures	44
4.7.1	Rational Formula Method.....	44
4.7.2	Soil Conservation Service (SCS) Method.....	46
4.7.3	Capacity Calculation and Sizing of Drain Network.....	47
4.7.3.1	Considering identified catchment area for the whole network would be managed by a single drain.....	48
4.7.3.2	Considering identified catchment area for the whole network would be managed by two parallel drains	48

5	RESULTS AND RECOMMENDATIONS FOR DETAILED DESIGN	49
5.1	Conceptual Designs for Managed Aquifer Recharge (MAR).....	49
5.1.1	Roof Water Recharging Structures	49
5.1.2	Road Runoff Recharging	50
5.1.3	Recharging Using Recharging Ponds	50
5.1.4	Application of Aquifer Modifications.....	51
5.2	Social and Environmental Feasibility and Impact of Proposed MAR Systems.....	51
5.3	Quantification and Cost Estimation of Proposed Conceptual Designs	52
5.4	Validation of the Proposed Recharge Structures	53
5.4.1	Th. Kandoodhoo	53
5.4.2	Th. Vandhoo	54
5.4.3	Th. Omadhoo	55
5.4.4	Th. Gaadhiffushi	56
5.4.5	Sh. Foakaidhoo	57
5.5	Recommendations for Detailed Design	58
	REFERENCES.....	61
	Annex I: Location Map of the Islands	63
	Annex II: Land Use Distribution of Islands.....	65
	Annex III: Water Quality Sample Locations of the Islands.....	71
	Annex IV: Digital Elevation Model of Islands	82
	Annex V: Locations of Permeability and Steady Pumping Tests Maps	88
	Annex VI: Freshwater level, Saline Water Level and Freshwater thickness of the Islands	94
	Annex VII: Assessment of Hydrogeology	110
	Annex VIII: Groundwater Flow Velocity Distribution of the Islands	158
	Annex IX: Spatial Distribution of Unsaturated Areas of the Islands.....	164
	Annex X: Developed IDF Curves and Calculations Carried Out for The SCS Method.....	170
	Annex XI: Conceptual Designs for Recharging Well.....	186
	Annex XII: Conceptual Designs for Road Runoff Recharge.....	188
	Annex XIII: Conceptual Designs for Aquifer Modifications	190

List of Figures

Figure 1-1: Location Map of Selected Six islands in Lot 2	2
Figure 2-1: Ghyben-Herzberg relation for fresh and seawater dynamics (Source: Barlow, 2003).....	3
Figure 2-2: Annual rainfall based on past 30 years of data in Hanimaadhoo and Kadhdhoo islands (1991-2020).....	6
Figure 2-3: Average monthly rainfall and its variation at Hanimaadhoo and Kadhdhoo islands (1991-2020).....	6
Figure 3-1: Rainfall Variation from South to North in Maldives (Wickramagamage, 2017).....	12
Figure 3-2: Average monthly temperature and rainfall in the Maldives, 1991–2019 (CCKP, 2020).....	13
Figure 3-3: Average changes in monsoonal rainfall from IPRC RegCM scenario for time slices (2021-2050) and (2082-2100) from baseline (1980-2000).....	14
Figure 3-4: Monthly rainfall variation in Hanimaadhoo (Left) and Kadhdhoo (Right) from 2015-2020.....	15
Figure 3-5: Annual rainfall variation in Hanimaadhoo (Left) and Kadhdhoo (Right) from 1990 - 2020.....	15
Figure 3-6: Decadal means and trend for rainfall and temperature in Hanimaadhoo (1990 - 2020).....	16
Figure 3-7: Decadal means and trend for rainfall and temperature in Kadhdhoo (1990 - 2020).....	16
Figure 3-8: Annual rainfall based on past 30 years of data in Hanimaadhoo and Kadhdhoo islands.....	17
Figure 3-9: Monthly average rainfall based on past 30 years in Hanimaadhoo and Kadhdhoo islands.....	17
Figure 3-10: Probabilistic plot of Monthly rainfall in Hanimaadhoo (Left) and Kadhdhoo islands (Right) for the Month of January (Dry Period)	18
Figure 3-11: Probabilistic plot of Monthly rainfall in Hanimaadhoo (Left) and Kadhdhoo islands (Right) for the Month of December (Wet Period).....	18
Figure 3-12: Methodology and equations for obtaining the Plan roof area (Source: NBRO, 2021).....	21
Figure 4-1: Spatial distribution of unsaturated areas in Kandoodhoo.....	25
Figure 4-2: Distribution curve for roof areas in Kandoodhoo	26
Figure 4-3: Conceptual drawing for the recharging well (not to scale)	28
Figure 4-4: Selected Roads for Recharging trenches and pits	29
Figure 4-5: Contributory residential area considered for calculation of runoff	30
Figure 4-6: Cross section of the recharging drain.....	31
Figure 4-7: Cross section of the recharge pit	32
Figure 4-8: Location of the recharging pond	34
Figure 4-9: Proposed recharging pond.....	34
Figure 4-10: Proposed impermeable (clay) liner parallel to the road	35
Figure 4-11: Proposed area for the installation of clay liner parallel to the road.....	36
Figure 4-12: Identified catchment areas for the drain capacity calculations	45

List of Tables

Table 2.1: Available types of recharge structures for roof water recharging.....	7
Table 2.2: Categorization of roof types	8
Table 2.3: Proposed recharging well types	8
Table 3.1: Fifty per cent (50%) Probabilistic Monthly Rainfall in Hanimaadhoo and Kadhdhoo Islands with the Monthly Average Rainfall Data (Mean \pm 1 Standard Deviation) for the Northern Islands.....	19
Table 3.2: Runoff coefficients for different roof materials (Source: Thomas and Martinson, 2007).....	20
Table 3.3: Runoff coefficients for different roof materials (Source: Tsutsumi et al., 2009)	20
Table 3.4: Derived runoff coefficients for different roof materials (After: Tsutsumi et al., 2009).....	20
Table 4.1: Average rainfall data used for the northern island (Sh. Foakaidhoo).....	24
Table 4.2: Average rainfall data used for southern islands.....	25
Table 4.3: Distribution of unsaturated areas within Kandoodhoo	26
Table 4.4: Design of recharging volume.....	26
Table 4.5: Potential recharging volume of proposed structures.....	27
Table 4.6: Monthly predicted recharging volume through proposed recharging wells	28
Table 4.7: The potential of the yearly roof recharging volume	28
Table 4.8: Estimated runoff along the roads	30
Table 4.9: The potential recharge through drains and recharging pits.....	32
Table 4.10: Monthly predicted recharging volume through proposed recharging pits and drains	32
Table 4.11: Predicted yearly and monthly recharging volume through the proposed pond	35
Table 4.12: Estimated groundwater enhancement due to aquifer modification in Th. Kandoodhoo	37
Table 4.13: Predicted groundwater enhancing quantities of Th. Kandoodhoo	37
Table 4.14: Comparison of available groundwater amount vs predicted additional recharge from MAR.....	37
Table 4.15: Impact and Social and Environmental Feasibility of Proposed MAR Systems.....	38
Table 4.16: Proposed recharging well types	41
Table 4.17: Required quantities of roof recharging structures in Kandoodhoo	42
Table 4.18: Required quantities of roof recharging structures in Vandhoo.....	42
Table 4.19: Required quantities of roof recharging structures in Omadhoo.....	42
Table 4.20: Required quantities of roof recharging structures in Gaadhiffushi.....	42
Table 4.21: Required quantities of roof recharging structures in Foakaidhoo.....	42
Table 4.22: Required length of the drains and recharging pits	43
Table 4.23: No. of proposed recharging ponds.....	43

Table 4.24: Proposed aquifer modifications of the islands	44
Table 4.25: Rainfall Intensities taken from developed IDF curves	45
Table 4.26: Calculated overland flow quantities (m ³)	45
Table 4.27: Expected runoff per square meter area for the island and residential area	46
Table 4.28: Summary of the comparison of the SCS method and	47
Table 4.29: Calculated width of single drain network for respective scenario	48
Table 4.30: Calculated width of parallel drain network for respective scenario.....	48
Table 5.1: Proposed recharging structures	49
Table 5.2: Dimensions and capacity of proposed roof water recharging wells types	49
Table 5.3: Summary of proposed quantities and yearly recharging potential from recharging wells	49
Table 5.4: Summary of proposed quantities and yearly recharging potential from road runoff recharging systems	50
Table 5.5: Summary of proposed quantities and yearly recharging potential from recharging ponds	50
Table 5.6: Summary of proposed aquifer modification methods and estimated GW enhancement.....	51
Table 5.7: Deviation of the construction cost for proposed aquifer modifications.....	52
Table 5.8: Deviation of estimated total cost and Operation and Maintenance Cost.....	52
Table 5.9: Calculated overland flow quantities (m ³) – Th. Kandoodhoo	53
Table 5.10: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Kandoodhoo	53
Table 5.11: Calculated overland flow quantities (m ³) – Th. Vandhoo	54
Table 5.12: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Vandhoo.....	54
Table 5.13: Calculated overland flow quantities (m ³) – Th. Omadhoo	55
Table 5.14: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Omadhoo.....	55
Table 5.15: Calculated overland flow quantities (m ³) – Th. Gaadhiffushi	56
Table 5.16: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Gaadhiffushi.....	56
Table 5.17: Calculated overland flow quantities (m ³) – Th. Kandoodhoo	57
Table 5.18: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Kandoodhoo	57
Table 5.19: Comparison between predicted recharge amount and available groundwater amount.....	58

List of abbreviations and acronyms

DNP	Department of National Planning
DTM	Digital Terrain Model
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EPA	Environment Protection Agency
FS	Feasibility Study
GCF	Global Climate Fund
ME	Ministry of Environment
NBS	National Bureau of Statistic
PMU	Project Management Unit

EXECUTIVE SUMMARY

Background and Methodology

The Government of Maldives has received funding from the Green Climate Fund (GCF) for the project “Supporting Vulnerable Communities in the Maldives to Manage Climate Change-induced Water Shortages”. This Feasibility Report compiled as a part of the broader project aforementioned and focusing on Groundwater Resource Management and Aquifer Protection in Maldives Project (under GCF Project) submitted to the Ministry of Environment, Climate Change and Technology, Republic of Maldives presents the results of a study of feasibility assessment to establish the viability of potential Managed Aquifer Recharge (MAR) alternatives proposed based on the previous baseline study on the current status and catchment characterization of selected individual islands with the main objective of undertaking an assessment of the existing groundwater quality and recharge rates and develop a groundwater resources management plan with clear recommendations to ensure improved aquifer recharging and protection. The target six (06) islands of the assignment are: Th Gaadhiffushi, Th Omadhoo, Th Vandhoo, Th Kandoodhoo, Sh Foakaidhoo, and Th. Dhiyamigili.

The study was conducted as per the conditions and tasks stipulated in the Terms of Reference (ToR) and the report includes the feasibility assessment of the selected MAR systems with a detailed description of the methodologies followed and detailed data collected based on literature sources, conducted baseline assessment of geological, hydrological (physiochemical, microbiological, geo-physical) characteristics and land-use investigations for 05 islands (geo-physical surveys were not conducted in Th. Dhiyamigili Island due to unexpected reasons beyond the control of the expert team).

The requirement and potential of introducing MAR in individual islands were recognised based on the findings of the geophysical, physiological, and microbiological investigations and social/institutional surveys carried out during the Baseline Study to determine the hydro-geology of the associated aquifer systems, available freshwater quantity and quality, present/predicted future groundwater usage characteristics, groundwater level variations (based on tidal, dry/wet season, and climatic factors), safe yield and the present stress level of the aquifer as per the detailed, island wide water balance model. The types and locations of MAR systems to be introduced were determined based on a multicriteria analysis focusing on the above information, source water availability, space requirements, and optimization of available alternative options. A comprehensive social and institutional survey and cost-benefit analysis were conducted targeting households and local organizations/officials of local councils to gather information on the social, environmental, and financial feasibility of the proposed MAR systems.

The findings of the Feasibility Study will be used in finalizing the alternative MAR options considered and developing conceptual and detailed designs for individual islands.

General Findings from Baseline Surveys

The six (06) islands selected for the study are situated in two separate atolls located in the northern and southern parts of the Maldives islands. Each island shows individual characteristics compared to water usage characteristics, water quality parameters and hydraulic conductivity parameters as discussed in the Baseline Study Report. Based on the variations identified in the groundwater quantity and quality, aquifer hydro-geologic parameters and observations made during the field visits, the identified main reasons for the critical variation on EC, Ammonia, Nitrate and Phosphates are; higher extraction of groundwater, leaching on nitrate based fertilizers, coral stockpiling within the island area, sea water flooding, and contaminants from anthropogenic activities.

Groundwater extraction for daily activities (for domestic, farming, fisheries, industrial and institutional purposes) in selected islands differs from 36,492 ℓ /yr. in Th. Vandhoo to 186,558 ℓ /yr. in Sh. Foakaidhoo. Furthermore, the stress level of the aquifer differs from ‘Not stressed’ (55% of

allowable safe yield of Th. Kandoodhoo) to “Very highly stressed” (514% of allowable safe yield of Th. Gaadhiffushi) which could be related to the land usage and population density. Therefore, immediate actions are warranted to avoid further degrading of groundwater quantity and quality issues for the islands with the ‘Moderately stressed’ to ‘Very highly stressed’ classification.

Concept of Managed Aquifer Recharge (MAR)

Hydrogeological context and source water availability are key areas of focus that drive the success of MAR projects. Investigation, conceptualization, design, construction and maintenance of recharge systems are very important steps in MAR.

Based on the hydrogeological and hydrological conditions of the Maldives islands, different recharging methods could be proposed for the given islands to improve the available groundwater quantity and quality of the island while managing the stormwater.

The roof water collection and recharging, road runoff recharging, recharging ponds, contour drains, and controlling groundwater flow through aquifer modification are mainly selected options for groundwater recharging of selected islands. The selection of method(s) for the groundwater recharging of a particular island is based on the island-specific or characteristic hydrogeological and hydrological conditions of each island, as further elaborated below.

Roof Water Recharging

The collection of roof water for domestic purposes is a common practice in most of the Maldives islands. Further, it was noted that a part of the roof water in some islands has been diverted directly to their own dug wells to improve the quality of well water. However, most of the roof water is being diverted to the free space of the land block and diverting of roof water to the adjacent unlined and lined roads without using them are also commonly encountered.

Available types of recharging structures were reviewed and the recharging well option was selected over recharge through operational wells, recharge through abandoned and existing tube wells, and recharge trenches.

Road Runoff Recharging

In addition, roof water and overland flow of build-up areas are diverted to the adjacent roads of the household in the islands and such water is stagnated at depression areas on the roads and adjoining areas. This water is available for several hours or a couple of days for promoting slow recharge depending on the amount of rainfall received on the island.

The overland flow along the road stretch can be collected to the drain that is to be constructed along one side of the road by using pre-cast “U”-shaped concrete blocks.

Recharging Ponds

The overland flow water is stagnated at depression areas on the roads and adjoining areas and a recharging pond can be designed to control the water stagnation issues. The excess water in the roadside drains can be used as source water for recharging ponds.

Contour Drains

It is noted that a considerable percentage of forest and unused lands are available on some islands. Generally, a less permeable topmost thin layer is common in the forest area and it rests on the permeable sandy layer. The infiltration capacity of these lands can be improved by constructing contour earth drains.

Application of Aquifer Modifications

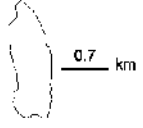
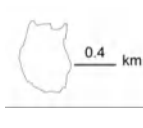
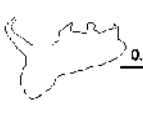

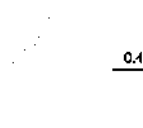
By modification of the aquifer, groundwater retention time could be enhanced and also, the freshwater thickness of the lens could be increased. This method is applied only to islands with uneven groundwater slopes. For the aquifer modification, an impermeable or less permeable vertical layer (liner) will be placed up to the coral layer at selected areas along the rim of the freshwater lens to control the outflow of the aquifer. The suitable areas for the installation of liner and liner height above the ground will be selected based on the existing topographical and hydrogeological conditions of the island. After the installation of the impermeable liner, the formation of a new interface between freshwater and saline water at the rim area of the lens could be expected.

Recommendation for Detailed Design

Based on the findings of the Feasibility Study, the following recommendations could be made.

- Groundwater recharge could be achieved through proposed structures to improve the groundwater quantity and quality in all islands studied.
- Suitable percentage of the roof is to be selected for the roof recharging purposes with the consultation of the client before the detailed designs.
- Small recharging wells are to be installed for the house blocks and large size of wells are to be installed for schools, mosques, and other common places.
- All designs should be finalized after the consultation of all stakeholders such as Power suppliers, Telecom facility providers, Drainage management authorities and respective Councils of the islands.
- The maintenance and monitoring program for the proposed recharging structures should be planned with the help of Island Councils and the local communities.
- It is proposed to incorporate these proposed MAR systems for island development plans if presently available or proposed for the selected islands.

Summary of feasibility and conceptual design findings for proposed recharge structures

Atoll Island	Thaa Kandoodhoo	Thaa Vandhoo	Thaa Omadhoo	Thaa Gaadhiffushi	Shaviyani Foakaidhoo
Shape of the Island					
Proposed Recharge Structures					
Roof Water Recharging	Yes	Yes	Yes	Yes	Yes
Road runoff recharging	Yes	Yes	Yes	Yes	Yes
Recharging pond	Yes	No	Yes	No	No
Aquifer modification/ Barrier wall	Yes	Yes	No	Yes	Yes
Yearly Recharging Potential of Recharge Structures					
Roof Water Recharging Structures					
No. of Type A Recharging Wells	26,050	2,008	7,628	10,904	-
No. of Type B Recharging Wells	117,223	4,561	34,565	49,183	93,514
No. of Type C Recharging Wells	-	8,131	-	-	41,942
Total	143,273	14,700	42,193	60,087	135,456
Road runoff recharging	143,732	26,860	89,465	117,176	102,751
Recharging pond	84,420	-	63,516	-	-
Application Aquifer modification					
Proposed Aquifer Modification Method	Impermeable liner	Impermeable liner	-	Barrier Wall	Impermeable liner
Estimated GW enhancement (m ³)	16,400	5,125	-	360	12,480
Expected Construction Costing for Recharge Structures					
Roof Water Recharging Structures					
Type A Recharging Wells (MVR)	1,080,000	666,000	990,000	558,000	-
Type B Recharging Wells (MVR)	3,000,000	925,000	2,750,000	1,550,000	4,000,000
Type C Recharging Wells (MVR)	-	1,239,500	-	-	2,680,000
Road runoff recharging					
Drain (MVR)	21,303,000	15,665,400	29,403,000	17,309,700	35,640,000
Recharging pit (MVR)	2,003,400	1,549,800	2,835,000	1,682,100	3,364,200
Recharging pond (MVR)	550,000	-	1,100,000	-	-
Application Aquifer modification					
Bentonite/cement slurry / clay rich residual soil (MVR)	1,100,000	866,250	-	-	1,760,000
Rock and earth (MVR)	-	-	-	1,155,000	-
Estimated construction cost (MVR)	29,036,400	20,911,950	37,078,000	22,254,800	47,444,200
Estimated Operation and Maintenance cost (MVR)	871,092	627,359	1,112,340	667,644	1,423,326
Validation of The Proposed Recharge Structures					
Catchment Area for Drain Network (m ²)	70,010	49,869	78,627	52,901	131,480
Aggregate runoff coefficient for the catchment area	0.37	0.30	0.44	0.42	0.48
Max. Return Period than Overland Flow Could Managed					
During Normal Rainfall Event (3 Hr. rainfall)	10 Yr	2 Yr	2 Yr	5 Yr	2 Yr
Extreme Events (30 min rainfall)	32% of 2 Yr	38% of 2 Yr	31% of 2 Yr	28% of 2 Yr	26% of 2 Yr
Extreme Events (1 Hr. rainfall)	59% of 2 Yr	56% of 2 Yr	52% of 2 Yr	52% of 2 Yr	49% of 2 Yr

1 INTRODUCTION

1.1 Background

The Republic of Maldives is a low-lying atoll in the Indian Ocean situated about 670 km southwest of Sri Lanka. The 1,196 coral islets of this archipelagic state which are administratively grouped into 26 atolls spread over an area of 90,000 km² stretching over 760 km in length (from north to south) / approximately 120 km in width (from west to east) with their land area occupying a mere 298 km². With a predicted mid-year total resident population of 557,426 (Statistical Yearbook 2018), the Maldives is one of the world's most geographically dispersed sovereign states (FAO, 2011) as well as the smallest Asian country by land area and the 2nd least populous country in Asia (UNDP, 2019).

The World Bank (WB) classifies the Maldives as having an upper-middle income economy (World Bank, 2015). Fishing has historically been the dominant economic activity, and remains the largest sector by far, followed by the rapidly growing tourism industry and these together contribute nearly 80% of the country's Gross Domestic Product (GDP). The country has an average elevation of 1.5 m above mean sea level (AMSL) and with global warming and the shrinking of the polar ice caps, climate studies have found that the Maldives is directly threatened, as none of its islands rises more than 1.8 m AMSL (World Bank, 2014; BBC, 2018).

According to the Ministry of Environment, Climate Change & Technology, the outer islands of the Maldives experience 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. It has been noted that the Maldivian Government faces constraints in responding to the challenge at hand without assistance, especially in the context of anticipated impacts of climate change.

In response to this climate challenge, the 5-year Green Climate Fund (GCF) funded project targeting 'Supporting Vulnerable Communities in Maldives to Manage Climate Change-Induced Water Shortages' was launched by the Government of Maldives in the year 2015. The accredited entity for the project is the United Nations Development Programme (UNDP) and the implementer is the Ministry of Environment, Climate Change and Technology. The project has the objective to deliver safe and secure freshwater to 105,000 people in the islands of the Maldives in the face of climate change risks. This will be achieved by delivering the following undertakings (Project RFP, Ministry of Environment, 2020):

- 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.

As the first phase of the project Groundwater Resource Management and Aquifer Protection in the Maldives, the compilation of the Baseline Assessment Report of aquifer groundwater conditions was undertaken for 13 islands in 2019 (MoEnv., 2020).

As an integral component of the ongoing project, the Maldivian Government intends to apply part of the proceeds towards procuring the services of Riyan Private Limited (Riyan, Maldives) and Master Hellie's Engineering Consultants Private Limited (MHEC, Sri Lanka) for the Consultancy Services to Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected Islands of Maldives (GCF Project) with the following specific objectives.

1.2 Specific Objectives

The scope of work of this consultancy service is broadly categorized into three (03) areas with specific objectives as outlined below.

- a. Undertake baseline assessment to establish the current status and catchment characterization of each island.
- b. Feasibility study and concept design of Managed Aquifer Recharge (MAR) systems for the islands with a specific emphasis on floodwater management
- c. Detail design of MAR systems

This report outlines the results of the Feasibility Studies and Conceptual Designs of MAR Systems following the Baseline Assessments undertaken in the given five (05) islands during the initial phase of the study. The 6th island, Th. Dhiyamigili was covered only partially due to accessibility issues.

1. Th Gaadhiffushi
2. Th Omadhoo
3. Th Vandhoo
4. Th Kandoodhoo
5. Sh Foakaidhoo

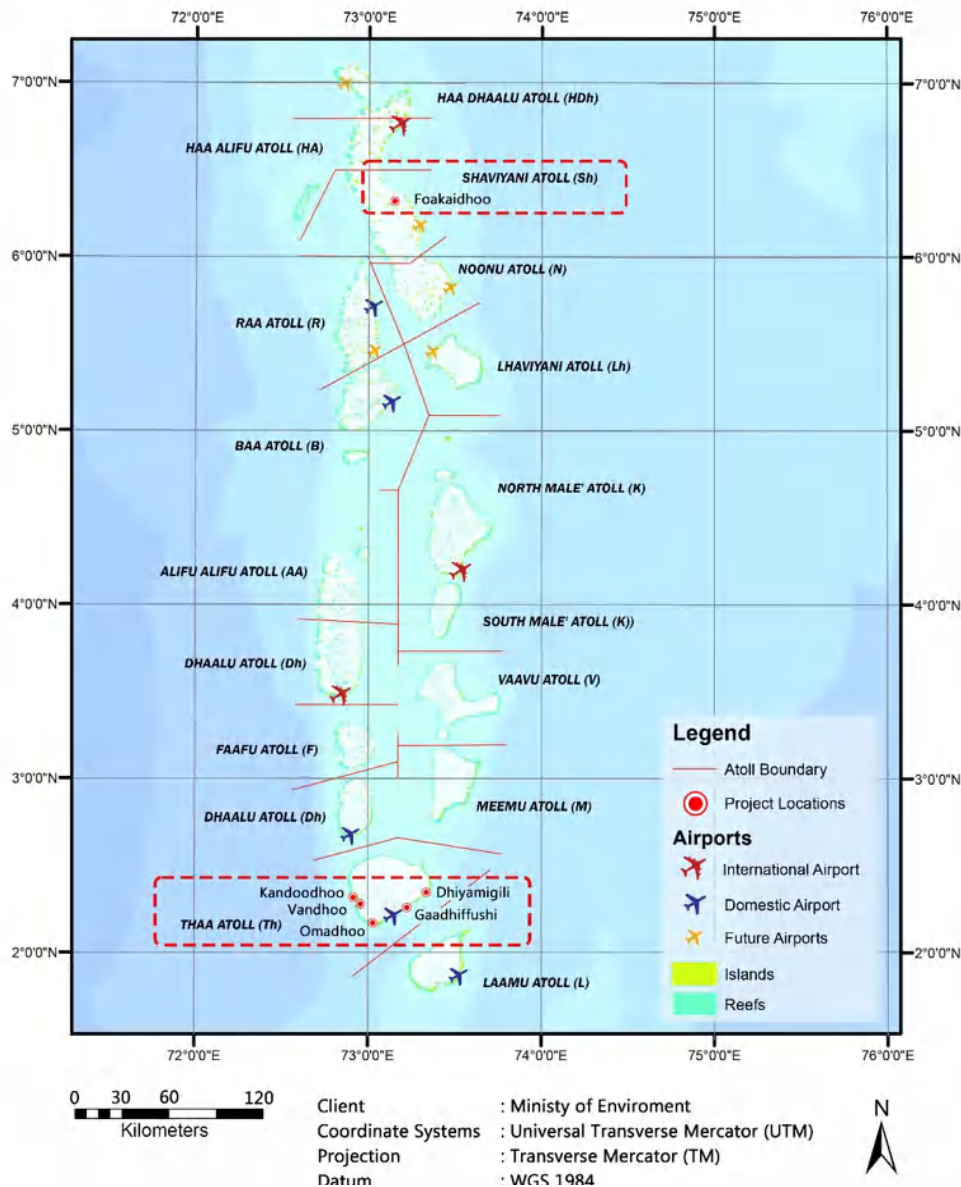


Figure 1-1: Location Map of Selected Six islands in Lot 2

1.3 Structure of the Report

The present report on the Feasibility Studies and Conceptual Designs of MAR Systems has been structured into three broad categories.

First, it provides the reader with a general overview and introduction of the broader project, the objectives and the detailed methodology used to collect data.

The second part of the report will provide an overview of the groundwater, its occurrence and characteristics in the Maldives, which is vital to understand the broader context of water resource management in the Maldives.

Thirdly, the report outlines the Feasibility Studies and Conceptual Designs of MAR Systems based on the findings of the island surveys. For each island, the following information will be provided.

- Basic requirements for Managed Aquifer Recharge (MAR)
 - Groundwater occurrence in the Maldives islands
 - Groundwater occurrence
 - Seawater and freshwater relationship
 - Natural groundwater recharge and variation of groundwater level
 - Managed aquifer recharge and different options for groundwater recharge
 - Concept of Managed Aquifer Recharge (MAR)
 - Source water availability
 - Different options for groundwater recharge and management of the overland flow
- Hydrology and drainage
 - General overview of climate in the Maldives islands
 - Recent rainfall trends in the Maldives islands
 - Rainfall characteristics data for recharge estimation in the selected islands
 - Distinct characteristics in annual rainfall series
 - Monthly rainfall variations in northern and southern islands
 - Rainfall intensity for recharge estimation
 - Runoff coefficients for roof runoff and overland flow estimation
 - Estimating effective plan roof area and catchment area for rainfall harvesting
- Methodology
 - Geological and hydrogeological aspects for feasibility and concept design
 - Assumptions and major considerations in conceptual designs
 - Conceptual designs for Managed Aquifer Recharge (MAR)
 - Assessment of unsaturated area
 - Recharging using roof water
 - Road runoff recharging
 - Recharging ponds
 - Application of aquifer modifications
 - Predicted groundwater enhancement in the island
 - Social and Environmental Feasibility and Impact of Proposed MAR Systems
 - Quantification and cost estimations of proposed MAR Systems
 - Validation of the proposed recharge systems
 - Rational formula method
 - Soil Conservation Service (SCS) method
 - Capacity calculation and sizing of drain network
- Results and Recommendation for detailed design

2 BASIC REQUIREMENTS FOR MANAGED AQUIFER RECHARGE (MAR)

This section briefly outlines the background of groundwater in the Maldives, a vital source of information for the reader in order to understand the broader context of overall water resources management in the island nation. The groundwater occurrence of the islands is discussed based on the available information such as previous reports (Integrated Water Resources Management and Sustainable Sanitation in Maldives (Falkland, 2001), etc.) and recent findings of groundwater surveys.

2.1 Groundwater Occurrence in the Maldives Islands

2.1.1 Seawater and Freshwater Relationship

The freshwater and seawater dynamics in unconfined aquifers are governed by the Ghyben-Herzberg relation (Figure 2-2). Under static conditions, the freshwater is overlaying on seawater as per the low specific gravity in freshwater than the seawater.

If the freshwater level is one meter above mean sea level, the depth to seawater is 40 m below mean sea level, and a unit change of freshwater level will have a 40-fold magnitude of change to the depth to the seawater level. If sea level was constant and recharge from rainfall was uniform, the saltwater/freshwater interface would remain motionless.

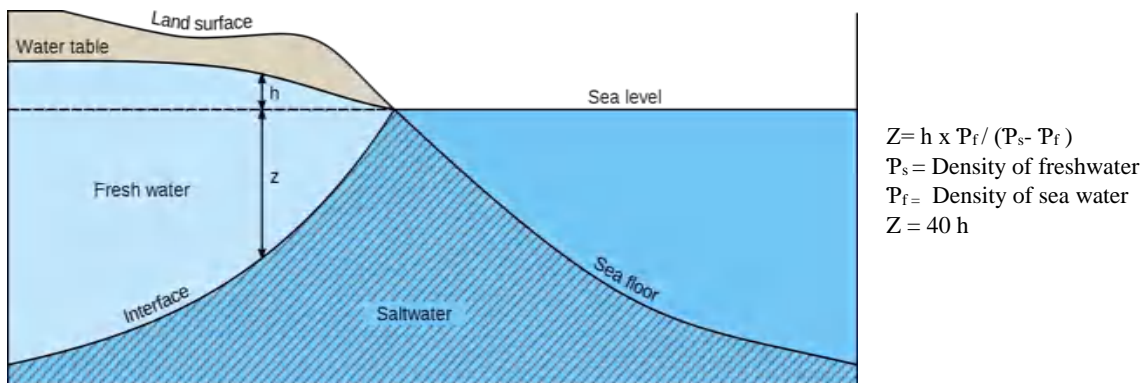


Figure 2-1: Ghyben-Herzberg relation for fresh and seawater dynamics (Source: Barlow, 2003)

2.1.2 Natural Groundwater Recharge and Variation of Groundwater Level

The development of drainage paths or streams is not visible within the islands due to the presence of sandy nature unconsolidated formations. In some islands, the development of marshland and ponds can be seen in the area close to the coastline. Generally, overland flow conditions occur along the road during the rainy period due to the presence of low infiltration capacities in the road and adding of the roof water. As per the information collected, stagnated rainwater is retained in low lying parts of the islands for a few days until the completion of recharge and evaporation of stagnated water.

During the rainy period, a considerable percentage of available rainfall is added to the groundwater body within the island due to the presence of sandy soil within the unsaturated formation. Further, the upper surface of the freshwater and the thickness of the freshwater body within the respective islands are in a certain balance and varies with the inflow and outflow conditions of the lens.

The groundwater level of the Maldives islands fluctuates due to recharging and discharging conditions of the unconfined sandy aquifer due to the annual climatic cycle, tidal effect, and addition of urban wastewater to the groundwater level. However, the impact on the groundwater level from the tidal effect and adding of wastewater are lower compared to the other factors.

2.1.2.1 Groundwater Level Variation due to Recharge and Discharge Conditions due to Annual Climatic Cycle

During the rainy period, the groundwater level is enhanced due to natural recharge scenarios and it drops slowly during the dry period depending on the hydrogeological conditions of the respective island. In addition, a rapid drop in groundwater level just after the heavy rain can be expected due to the outflow conditions of the lens until reaching the balance of inflow and outflow conditions. Therefore, recharge water can be retained for some period within the island and it depends on the hydrogeological conditions of the aquifer.

2.1.2.2 Groundwater level variation due to tidal effect

The height of the tidal zone varies from island to island. The tide level variation of the Maldives island during the day is about 0.96 m as per the record of the tide gauge installed at Gan Island. Due to the tidal action, the groundwater level of the island varies with respect to the tidal pattern of each island. The relatively higher groundwater level change due to the tidal effect can be expected in the area close to the coastline compared to the interior part of the island. During the investigation period, it was noted that groundwater level fluctuation due to tidal effects during the day is less than 0.4 m.

Generally, seawater flooding is common on most of the islands and it occurs at low lying areas close to the coastal line under rough sea conditions resulting in deterioration of the quality of freshwater at the coastal line due to the mixing of seawater with freshwater.

2.1.2.3 Addition of wastewater as groundwater

In most of the investigated islands, groundwater is mainly used for washing, bathing, watering, and agricultural purposes. About 60% to 80% of used water will be infiltrated back into the groundwater depending on the climatic conditions and hydrogeological conditions of the island. It was noted that wastewater management systems for some of the selected islands are under construction and wastewater systems for some islands have already been completed.

After implementation of the wastewater systems in islands (as ongoing projects in most islands), adding of wastewater from houses and other institutes to the groundwater body will be reduced and therefore, the quality of groundwater will be improved with time.

On the other hand, the loss of this additional recycled water input to the groundwater aquifer could lead to the sinking of the freshwater lens causing a vacuum and thus triggering seawater intrusion, adversely impacting groundwater quality, especially during extended dry periods. Therefore, it is important to enhance managed recharge of such aquifers in islands where sewer networks are recently introduced or to be introduced to compensate for this lost component of manmade recharge.

2.2 Managed Aquifer Recharge and Different Options for Groundwater Recharge

Groundwater recharging, mainly Managed Aquifer Recharge (MAR), is a globally proven solution for water shortage, water security, water quality decline, falling water tables, and endangered groundwater-dependent ecosystems. Hydrogeological context and source water availability are key areas of focus that drive the success of MAR projects. Investigation, conceptualization, design, construction and maintenance of recharge systems are very important steps in MAR.

Compared to surface water storage, the Managed Aquifer Recharge significantly reduces the evaporation loss and needs a smaller land requirement. Managed Aquifer Recharge can also be located

close to areas of high demand, can treat water in the aquifer, and can be upscaled to meet the ever-growing water requirements.

In designing aquifer recharge systems, there is a strong link between technical aspects (topography, pollution condition, land availability, climate, hydrology, quality and quantity of source water, geology, hydrogeology, groundwater quality, salinity intrusion, groundwater flux, water balance, current and future stresses) and non-technical information such as demand for water, space availability, and operating mechanism. Linking these two factors is critical for the long-term success of the recharge system.

2.2.1 Source Water Availability

The overland flow conditions in the islands are occurred due to the higher rainfall than the potential infiltration rates and limited space available for recharge within the subsurface formation. A higher infiltration rate could be expected in agricultural and forest lands while a low infiltration rate could be expected within the built-up areas and along the roads.

During the rainy period, overland flow within agricultural lands and forest lands may not be available due to the presence of unconsolidated sandy soil. According to the Baseline Report, the potential infiltration rate of investigated islands ranged from a minimum of 0.53 m/d (22 mm/hr) to a maximum of 24.98 m/d (1,040 mm/hr), with an average of 6.57 m/d (i.e. 275 mm/hr). If the rainfall is more than the infiltration rate, stagnation of rainwater within depressions and overland flow could be available within agricultural and forest lands. But the existence of stagnation of rainwater could be limited for several hours. The probability of the existence of such events per year is low.

The overland flow within the built-up areas and roads may be occurred due to the low infiltration capacities of the areas and rainwater is stagnated at the depressions of the built-up areas for several days depending on the amount of excess precipitation. Overland flow occurs when the depression storage is filled and no more storage is possible, causing spillage to flow over the ground under gravity flow conditions. The main sources of overland flow are roof water and runoff accrued in the road and free space of the land blocks. These water flows could be used for recharging purposes to manage the stormwater within islands.

The annual average precipitation within the Maldives islands decreases from the southern islands to the northern islands. The average annual precipitation in the southern islands and the northern islands are $1,747.1 \pm 283.9$ mm and $2,242.5 \pm 376.5$ mm as per the 30-year historical rainfall data collected at the gauging stations at the Kadhdhoo island and the northernmost Hanimaadhoo island (based on data shared by Maldives Meteorological Service). The total annual rainfall and average monthly rainfall with its variation at Kadhdhoo (southern island) and Hanimadhoo (northern island) based on 30-year (1990 - 2020) are given in Figure 2-2 and Figure 2-3.

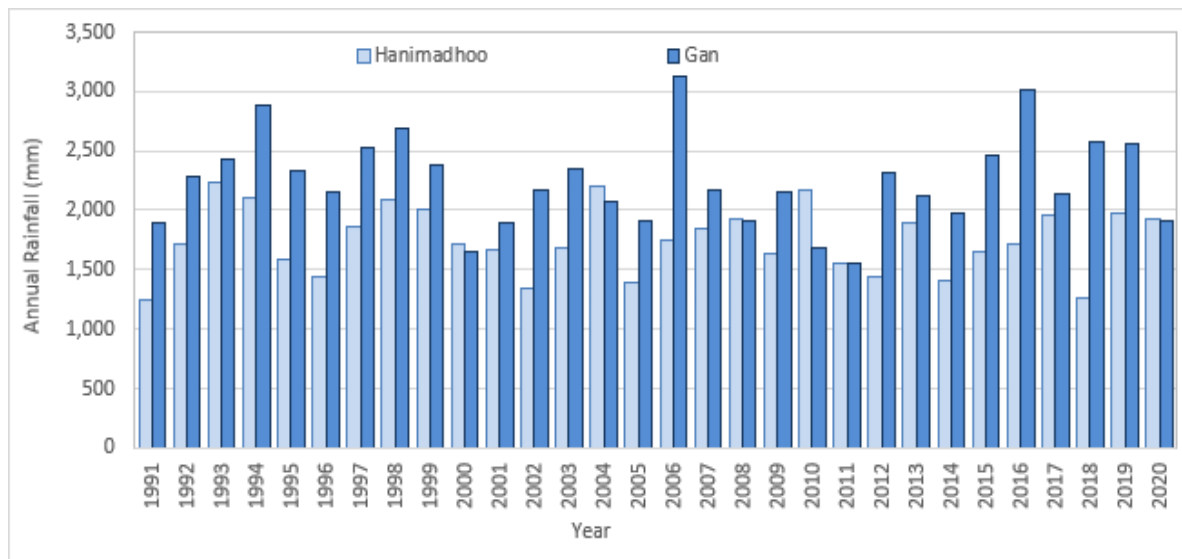


Figure 2-2: Annual rainfall based on past 30 years of data in Hanimaadhoo and Kadhdhoo islands (1991-2020)

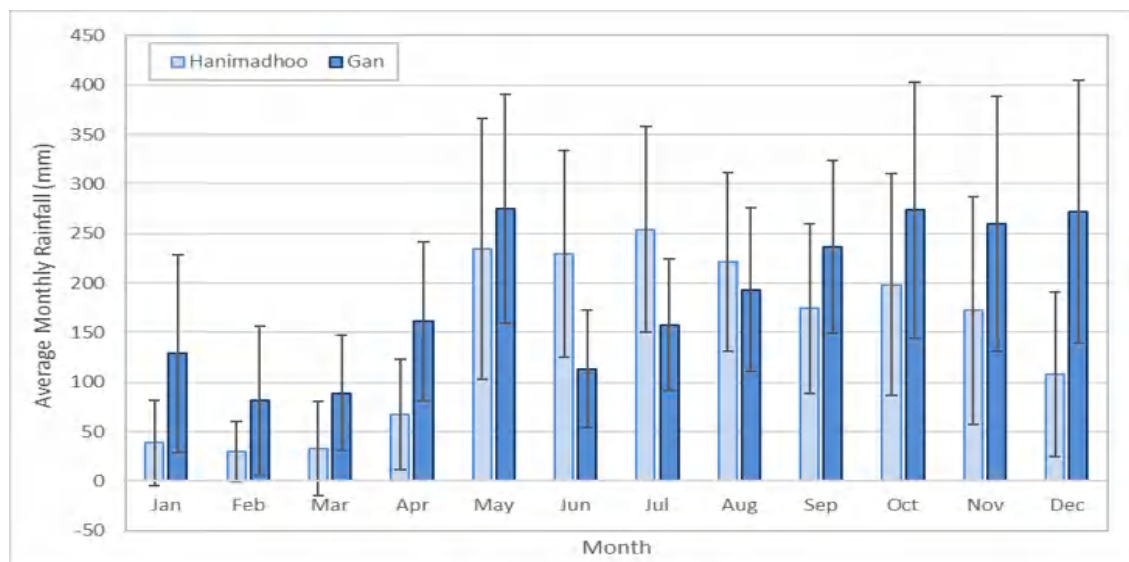


Figure 2-3: Average monthly rainfall and its variation at Hanimaadhoo and Kadhdhoo islands (1991-2020)

Based on the historical rainfall data (30-year rainfall from 1990 to 2020), the daily average rainfall per month is calculated by considering daily rainfall of more than 10 mm. This rainfall is used to estimate daily, monthly, and yearly runoff. The details of hydrology will be discussed in Chapter 5.

2.2.2 Different Options for Groundwater Recharge and Management of Overland Flow

Different approaches can be applied to improve the available groundwater quantity and quality of the Maldives islands and to manage the stormwater. The selection of the approaches is based on the hydrogeological setup of the islands and the availability of source water. The available raw water for groundwater recharge is rainwater in the form of roof water and overland flow.

Based on hydrogeological and hydrological conditions of the Maldives islands, different recharging methods could be proposed for the given islands to improve the available groundwater quantity and quality of the island while managing the stormwater.

The roof water collection and recharging, road runoff recharging, recharging pond, contour drains, and controlling groundwater flow through aquifer modification are mainly selected options for groundwater recharging of Maldives islands. The selection of method(s) for the recharging of a particular island is based on the hydrogeological and hydrological conditions of each island.

2.2.2.1 Roof Water Recharging

Collection of roof water for domestic purposes is a common practice in most of the Maldives islands. Further, it was noted that a part of the roof water in some islands has been diverted directly to their own dug wells to improve the quality of well water. However, most of the roof water is being diverted to the free space of the land block and diverting of roof water to the adjacent unlined and lined roads without using them is also commonly encountered.

Recharging to the groundwater aquifers by roof water can be done through various kinds of structures to ensure the percolation of rainwater into the ground instead of draining away from the surface. The design of the recharging structures is based on the hydrogeological and hydrological conditions of the respective islands. The selection of appropriate recharging structures is mainly based on the availability of space for the construction of recharge structures, useable roof size and its conditions, elevation gap between the outlet of the roof water collecting system and the inlet of the recharging structure, and depth to the groundwater table.

The different types of recharge structures for roof water recharging are available and each method has advantages as well as disadvantages. The details of the methods related to the Maldives islands are given below.

Table 2.1: Available types of recharge structures for roof water recharging

Recharging structure	Remark
Recharge through operational wells	This method is still practised in some islands. Appropriate filtration system is to be introduced before adding rainwater to the operational well. The recharging rate through the operational wells could be low due to conditions of the well structure (wells are constructed for extracting water and not for recharging)
Recharge wells	The use of recharging pits is dependent on the availability of free space within individual land blocks and the depth to the groundwater table. In most cases, free land space for single or multiple pits is available. Therefore, the chances of constructing recharging pits at the household level will be high.
Recharge through abandoned and existing tube wells	It is noted that a limited number of abandoned wells are located within the land blocks. Further, tube wells are not observed in any of the islands. Moreover, the conditions of the existing structures are to be checked before selecting them for recharging purposes. Therefore, this method could not be applied for recharging purposes in the Maldives islands.
Recharge trenches	The recharging trenches are depended on the availability of the free space within individual land blocks. In most cases except in schools and mosques, free land space is not available. Therefore, the chances of construction of recharging trenches are limited.

Recharging structure	Remark
Recharge wells	This is similar to an operational well and the well is not dug up to the general groundwater level. The bottom of the recharging well is unlined and the wall of the well is lined.

As per the above conditions, recharging wells compared to other options is considered the most appropriate option for roof water recharging to enhance the groundwater quantity and quality of freshwater lens within the investigated islands. The diameter of the recharging well is selected based on the size of the useable roof area and the infiltration capacity of the island. The three types of recharging wells are considered and details are given in Table 2.3. The sizes of the roof structures in Maldives islands are different and the categorization of different sizes of structures (Type 1, Type 2, and Type 3) are given below. About 10% loss of rainwater in the roof due to evaporation and spilling is considered.

Table 2.2: Categorization of roof types

Type	Probability Existence
Type 1	25%
Type 2	50%
Type 3	75%

Table 2.3: Proposed recharging well types

Recharging Well Type	Diameter (m)	Depth of the Well (m)	Thickness of Filter Bed (m)	Well Head above Ground Level (m)
Type A	1.0	1.5	0.3	0.2
Type B	1.5	1.5	0.3	0.2
Type C	2.0	1.5	0.3	0.2

A mesh should be provided for the top of the recharging well to avoid the addition of foreign materials to the recharging well. The filter bed (available silty sand within the island) will be provided for recharge well to avoid the adding of fine matters to groundwater. The top layer of the filter bed should be cleaned periodically to maintain the recharge rate. The details of the recharging structure are discussed in Chapter 6.

Before recharging roof water, conditions of the roof and roof area are to be assessed and roof water from the first rain is not suitable for recharging purposes due to the presence of possible high turbid water. It is recommended to use a first flush mechanism to divert this part of roof runoff through an additional filter bed when possible or avoid using it for recharging purposes.

2.2.2.2 Road Runoff Recharging

The occurrence of overland flow is very common in roads in the Maldives islands due to the presence of low infiltration capacity along the compacted road stretch. In addition, roof water and overland flow of build-up areas are diverted to the adjacent roads of the islands and such water is stagnated at depression areas in the roads and adjoining areas. This water is available for several hours or a couple of days for promoting slow recharge depending on the amount of rainfall received on the island.

The overland flow along the road stretch can be collected to the drain that is to be constructed along the one side of the road by using pre-cast “U” shaped concrete blocks.

The collected water in the drain will be diverted to a series of recharging pits to be provided along the drain. The spacing between two recharging pits will be decided based on the recharging potential of the subsurface formation of each island. The bottom of the recharging pit is unlined and a precast concrete slab will be provided to cover the recharging pit.

Road runoff recharging system will be provided for the selected roads. Further, excess water in the recharging pit will be diverted to the recharging ponds or sea or contour drains based on the site conditions. The details of the recharging structure are discussed in Chapter 6.

2.2.2.3 Recharging Ponds

The overland flow water is stagnated at depression areas in the roads and adjoining areas and a recharging pond can be designed to control the water stagnation issues. The excess water in the roadside drains can be used as source water for recharging ponds. The size and depth of such ponds will be decided based on the site conditions. The details of the recharging structure are discussed in Chapter 6.

2.2.2.4 Contour Drains

It is noted that a considerable percentage of forest and unused lands are available on some islands. Generally, a less permeable topmost thin layer is common in the forest area and it rests on the permeable sandy layer. The infiltration capacity of these lands can be improved by constructing contour earth drains. The details of this type of recharging structure are discussed in Chapter 6.

2.2.2.5 Application of Aquifer Modifications

Fresh groundwater occurs in the form of freshwater lenses. There are two types of groundwater lenses mainly identified in the Maldives islands. The first type is the freshwater lens that floats over the saline water and it is very common for homogeneous subsurface conditions. The other type is with the middle part of the freshwater lens resting on the fresh coral formation and the freshwater/saline water interface is observed only at the rim area of the lens. These conditions occur in the subsurface profiles where heterogeneous conditions are dominant.

The thickness of the freshwater lens in the Maldives islands is higher in the middle area of the lens and it decreases towards the coastline. Further, the top surface of the freshwater lens is not flat and it slopes towards the coastline. The slope of the water level is mainly controlled by several factors such as topography, geology, hydrogeological of the islands, groundwater velocity, and aquifer properties.

The slopes of the groundwater level for homogeneous and heterogeneous formations are nearly even for some islands and it is uneven for other islands, respectively. In the islands with uneven slopes, the middle part of the most of islands shows a nearly flat groundwater table compared to the rim area. This results in to have an occurrence of relatively low groundwater flow velocity at the middle part of the island than in the rim area of the groundwater lens. In other means, the retention time of groundwater at the middle part of the lens is comparatively higher than that of the groundwater at the rim area.

By modification of the aquifer, groundwater retention time could be increased and further, the freshwater thickness of the lens could be increased. This method is applied only to the islands with uneven groundwater slopes. For the aquifer modification, an impermeable or less permeable vertical layer (liner) will be placed up to the coral layer at selected areas along the rim of the freshwater lens to control the outflow of the aquifer. The suitable areas for the installation of liner and liner height above the ground will be selected based on the existing topographical and hydrogeological conditions

of the island. After installation of the impermeable liner, the formation of a new interface between freshwater and saline water at the rim area of the lens could be expected.

Another issue commonly encountered is seawater flooding and it is common specifically in most of the islands with low lying areas adjacent to the coastline. Seawater flooding mainly occurs in these low-lying areas close to the coastal line under rough sea conditions. It results in to deteriorate the quality of freshwater along the coastal line due to the frequent mixing of seawater with freshwater. Further, it causes a decrease in the freshwater quantities on the island. Therefore, these issues need to be controlled by applying impermeable liners along the rim area of the freshwater lens.

The details for controlling of seawater flooding and increasing of freshwater thickness at the rim area of the freshwater lens are discussed island wise in order to enhance the groundwater level, retention time and fresh groundwater amount of the lens.

3 HYDROLOGY AND DRAINAGE

This study, conducted as a part of Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected Islands of Maldives, explores the feasibility of roof rainwater harvesting and sourcing excess water from the drainage network during the rainy season and storing it in the aquifer for the benefit of household water use purposes at a later time when the dry period occurs.

The available amount of fresh water in aquifers is affected and become unusable when it contains brackish or high salinity water, due to the mixing of freshwater in the lens with the intrusion of high salinity groundwater or seawater. This may occur in some parts of the islands, particularly in low lying areas and in areas where drops in groundwater hydraulic heads have resulted in, the mixing of saline and freshwater within different layers of aquifers has been observed leading to the degrading of water quality. In areas of excessive groundwater extraction, groundwater hydraulic heads can drop and allow saline water to enter into pumping wells, thereby increasing the salinity levels of the freshwater and resulting in less recovery of the volume of freshwater already available for use.

This can be addressed to a greater extent by promoting Managed Aquifer Recharge (MAR) in small islands which includes the collection and diversion of excess rainfall from impervious areas like roofs, compacted road surfaces, etc., to pervious areas where the natural infiltration can be significantly augmented by incorporating infiltration pits/galleries, contour drains, recharge ponds, etc.

However, the feasibility and applicability of the extent of MAR highly depend on the geomorphological as well as climatic conditions of the individual islands. The diversified hydrological and drainage aspects of the Maldives islands under consideration in the present study are elaborated here while the critical parameters associated with the process are identified and established based on available historical rainfall and land use data.

3.1 General Overview of Climate in the Maldives Islands

The Maldives islands are located in the Indian Ocean in close proximity to the equator and the climate of Maldives is greatly influenced by its tropical monsoon weather where the islands experience a warm and humid climate throughout the year. The historical mean annual temperature of the Maldives is 27.6°C with little inter-seasonal variability and average monthly temperatures vary by at most 1°C throughout the year. The seasonal cycle is strongest in the north recording an average maximum temperature of around 29.3°C just prior to the onset of the southwest monsoons (April-May) and an average minimum temperature of around 27.4°C prior to the onset of the northeast monsoons (December-January) (World Bank/ADB, 2021).

The country has relatively high rates of precipitation while the southern equatorial regions experience precipitation throughout the year and do not experience a very significant dry spell related to the northeast monsoons (World Bank, 2015).

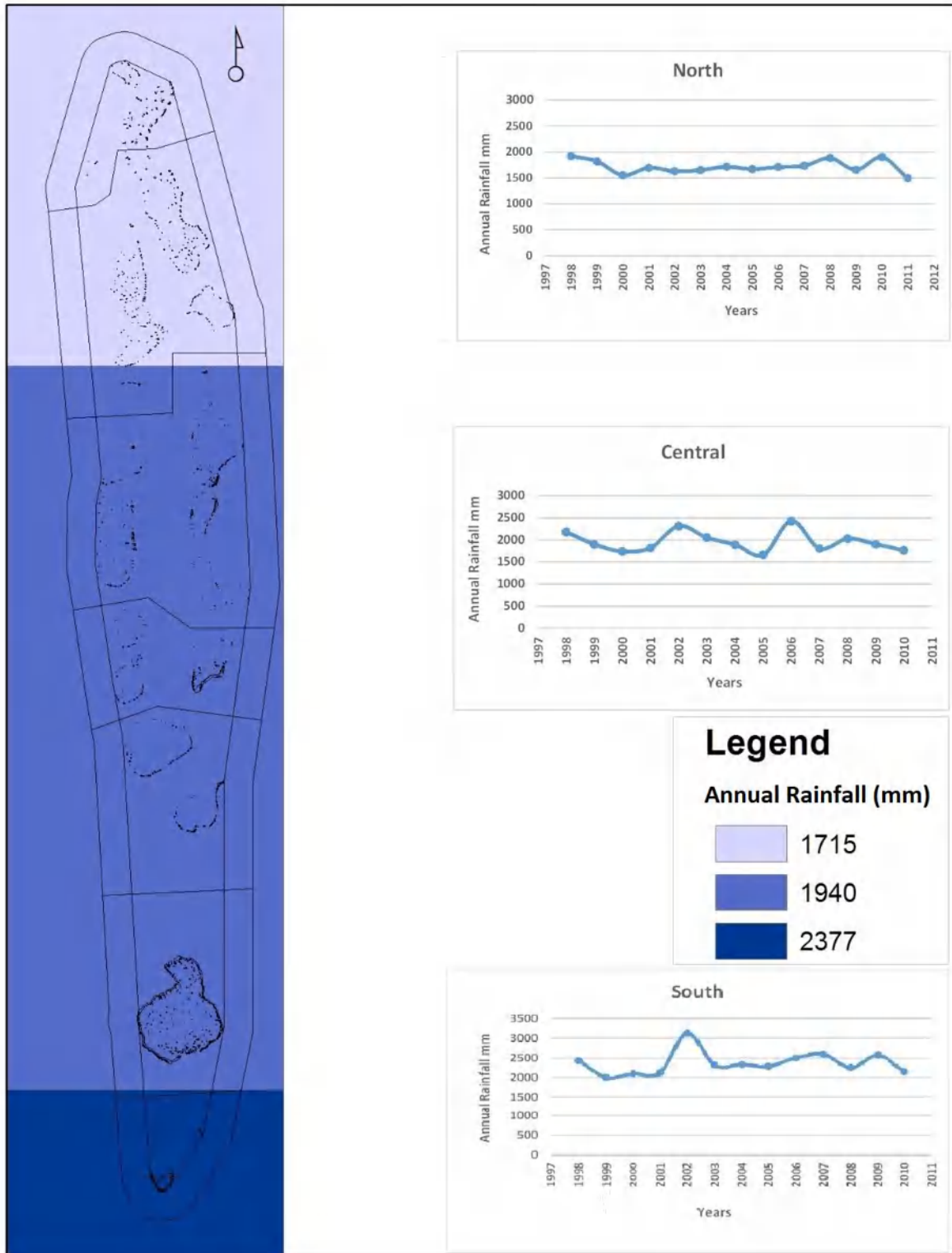


Figure 3-1: Rainfall Variation from South to North in Maldives (Wickramagama, 2017)

Figure 3-1 illustrates the rainfall variation in the Maldives, with annual average rainfall decreasing from 2,377 mm to 1,715 mm from south to north.

Further, the monthly average rainfall follows a clear bi-modal type temporal rainfall distribution as influenced by the tropical monsoonal weather patterns in the region Figure 3-2.

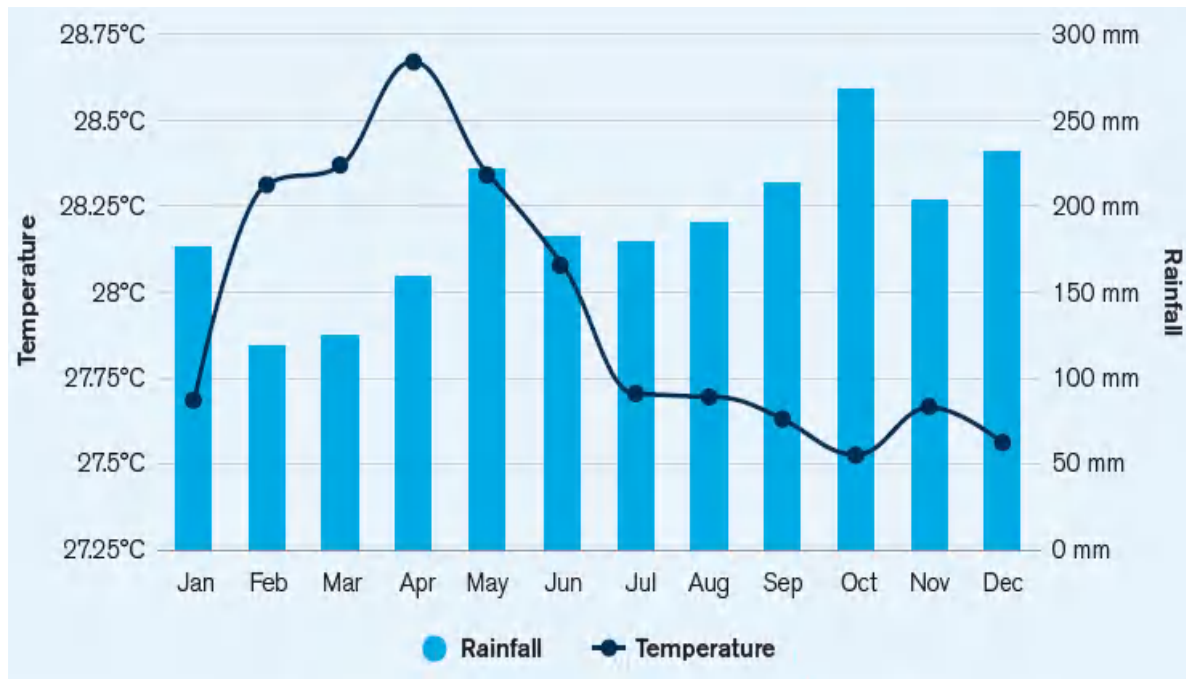


Figure 3-2: Average monthly temperature and rainfall in the Maldives, 1991–2019 (CCKP, 2020)

Based on past studies, the following long-term trends in temperature and precipitation have been identified, as elaborated below.

Trend in Temperature

- From 1969 to 1999, the annual average maximum and annual average minimum temperatures in Malé (central region) show a rising trend of 0.17°C and 0.07°C per decade, respectively.
- A more recent temperature record from 1995-2004 compares the trend in annual average maximum temperatures between the northern, central and southern atolls. An increasing trend is observed in central and northern regions, with the northern atolls showing a more pronounced increase. The southern atolls do not show any visible trend in the short-term record of annual average maximum temperatures (Climate Risk Country Profile: Maldives, 2021).

Trend in Precipitation

- The analysis of annual rainfall totals from 1969-1998 for Malé (Central) and Gan (South) shows a decreasing trend of rainfall of around 2.7 mm/year and 7.6 mm/year, respectively.
- Further, on analyzing the seasonal average precipitation for the same period at Malé (Central), it can be seen that the decreasing trend is visible only during the southwest monsoon season, while no significant trend is observed during the northeast monsoon.

Due to its location over the equatorial region in the Indian Ocean, the Maldives experiences a typical equatorial tropical monsoonal climate with a slightly defined bi-modal rainfall distribution where there is significant rainfall in most months of the latter part of the year. The South-west monsoon (wet season) in the Maldives normally extends from mid-May to November with a stronger influence on northern islands. The North-east monsoon (dry-season) extends from January to March/April and generally quieter with minor showers and infrequent thunderstorms in the afternoon or evening, especially in the southern atolls. The months of December and April are considered as the monsoon transitional periods. The driest period, outside the monsoons, runs from January to April and is felt more on the northern atolls with prevalent water scarcity issues.

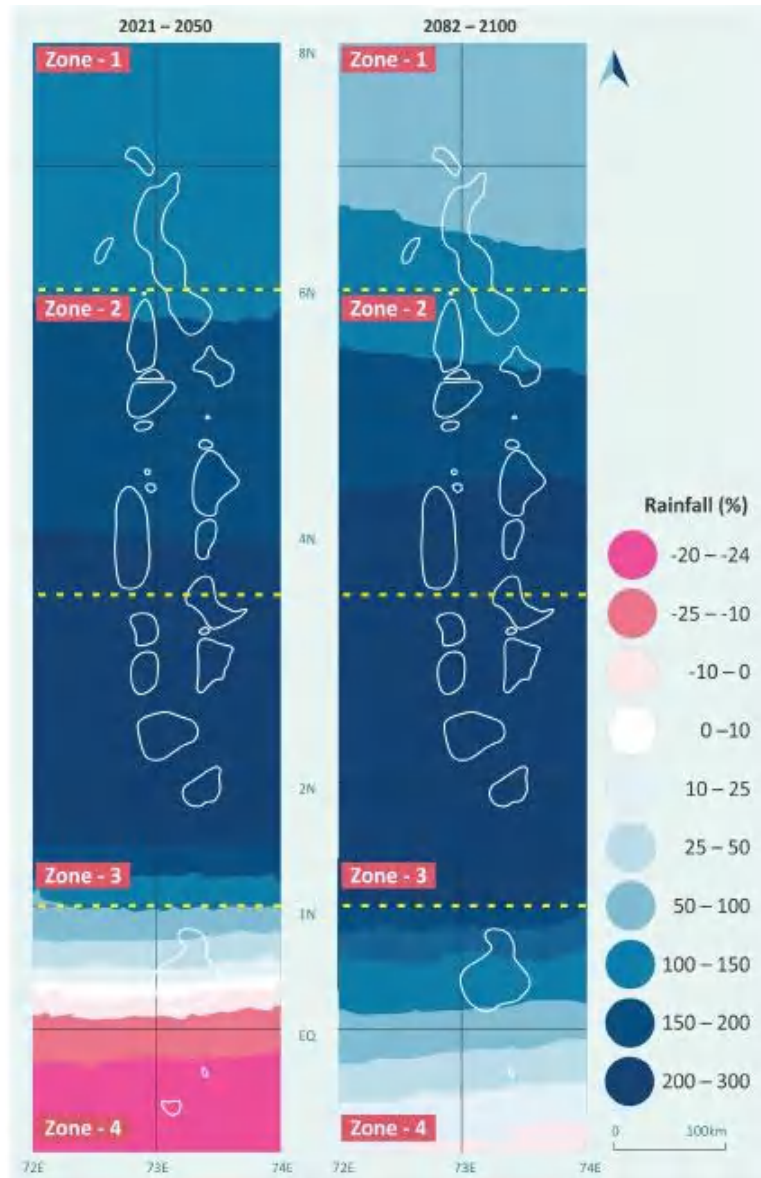


Figure 3-3: Average changes in monsoonal rainfall from IPRC RegCM scenario for time slices (2021-2050) and (2082-2100) from baseline (1980-2000)

The central region of the Maldives has a tropical monsoon climate that is consistent throughout the country. The islands in this zone feature a mix of both wet and dry seasons, with the wet season lasting from May through December and the dry season covering the remaining four months. The islands experience relatively consistent temperatures throughout the course of the year, with an average high of 30 °C and an average low of 26.5 °C, which is equivalent to many equatorial cities' average year-round daily mean. The islands in the Central region receive 2,000 mm of precipitation annually, and this is presumed to be higher for the Sh. Foakaidhoo island (in the Northern part) and lower for the rest of five (05) islands in Lot 2, i.e. Th. Kandoodhoo, Th. Vandhoo, Th. Omadhoo, Th. Dhiyamigili, and Th. Gaadhiffushi, in the Southern part of Maldives.

The predicted average changes in monsoonal rainfall based on the Highly Resolved Regional Climate /Atmospheric Model developed at the International Pacific Research Centre (IPRC RegCM) using selected climate scenarios for time slices (2021-2050) and 2082-2100) from baseline (1980-2000) are presented in Figure 3-3 which clearly indicates the rainfall changes for months MJJASO (May to October during South-West monsoon with heavy rainfall) in percentage values (MEE, 2016; Adopted from MEE, 2015)

3.2 Recent Rainfall Trends in the Maldives Islands

The historical temperature and rainfall data were collected for the present study from the Maldives Meteorological Service for the period 1990 to 2020. Climate data were available for Hanimaadhoo island which is located close to the Sh Foakaidhoo island (in the Northern part) and the Kadhdhoo island (in the Southern part close to Gan) which is situated close to the rest of the five (05) islands in Lot 2 (Th. Kandoodhoo, Th. Vandhoo, Th. Omadhoo, Th. Dhiyamigili, and Th. Gaadhiffushi). All islands in Lot 1 are located close to Hanimaadhoo (Ha. Filladhoo, Ha. Maarandhoo, Ha. Muraidhoo, Ha. Uligan, and Ha. Molhadhoo islands).

The observed temporal variation of monthly rainfall and temperature data and time series of total annual rainfall for the islands Hanimaadhoo and Kadhdhoo are illustrated in Figure 3-4 & Figure 3-5 below.

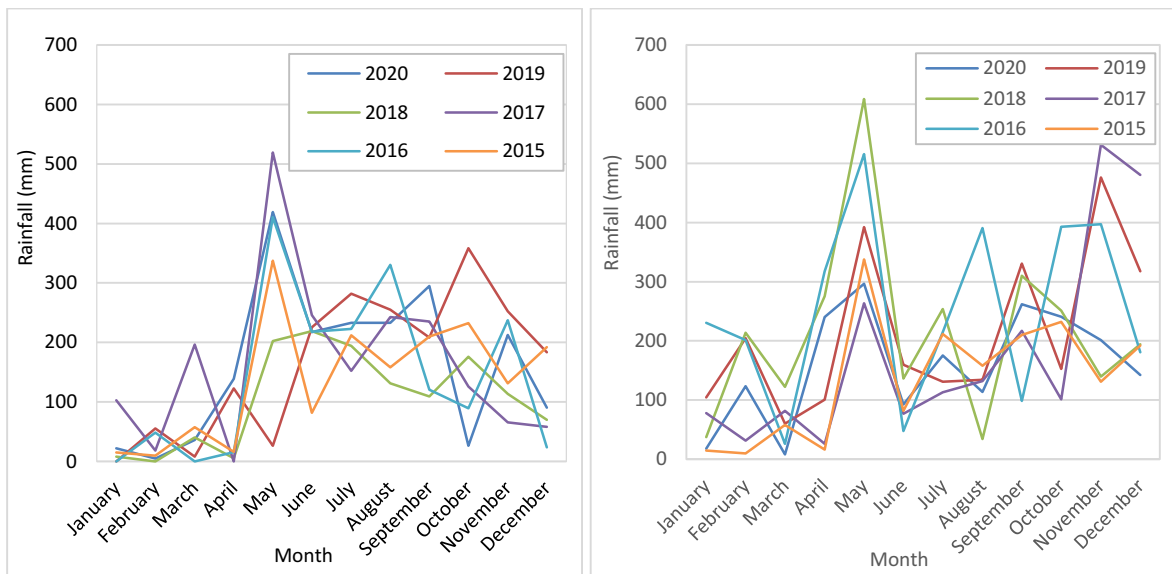


Figure 3-4: Monthly rainfall variation in Hanimaadhoo (Left) and Kadhdhoo (Right) from 2015-2020

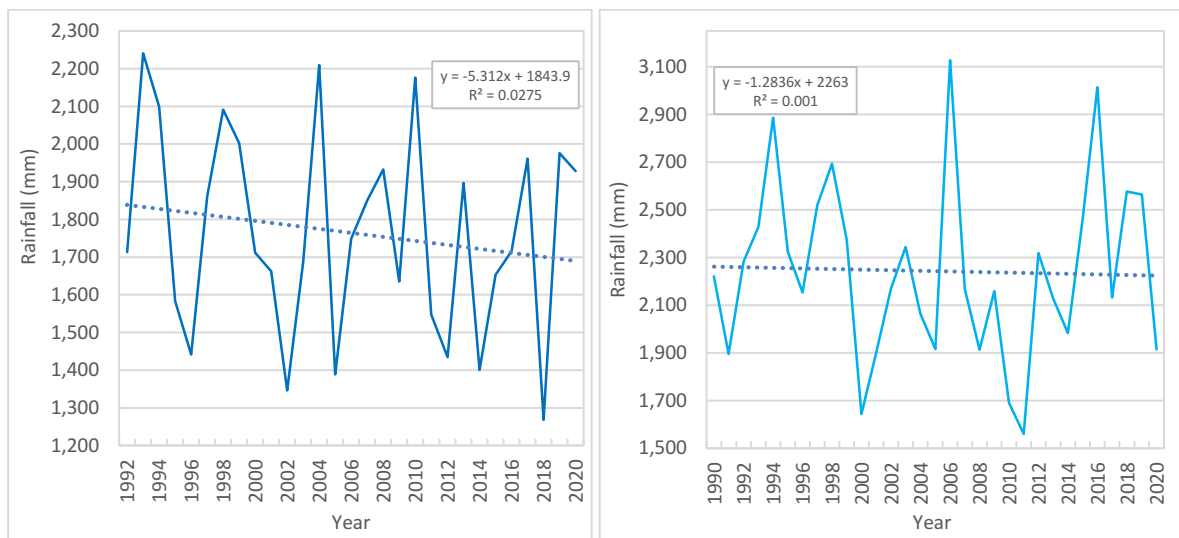


Figure 3-5: Annual rainfall variation in Hanimaadhoo (Left) and Kadhdhoo (Right) from 1990 - 2020

In order to derive medium-term climate trends in the observed data series (30 years of data), the decadal means were plotted based on the observed temporal variation of annual rainfall and temperature data for the islands Hanimaadhoo and Kadhdhoo as illustrated in Figure 3-6 and Figure 3-7.

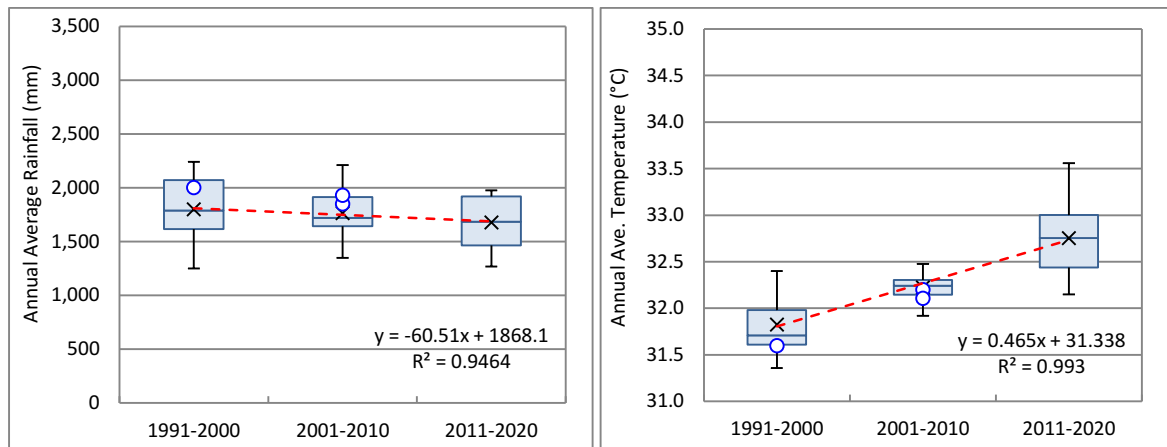


Figure 3-6: Decadal means and trend for rainfall and temperature in Hanimaadhoo (1990 - 2020)

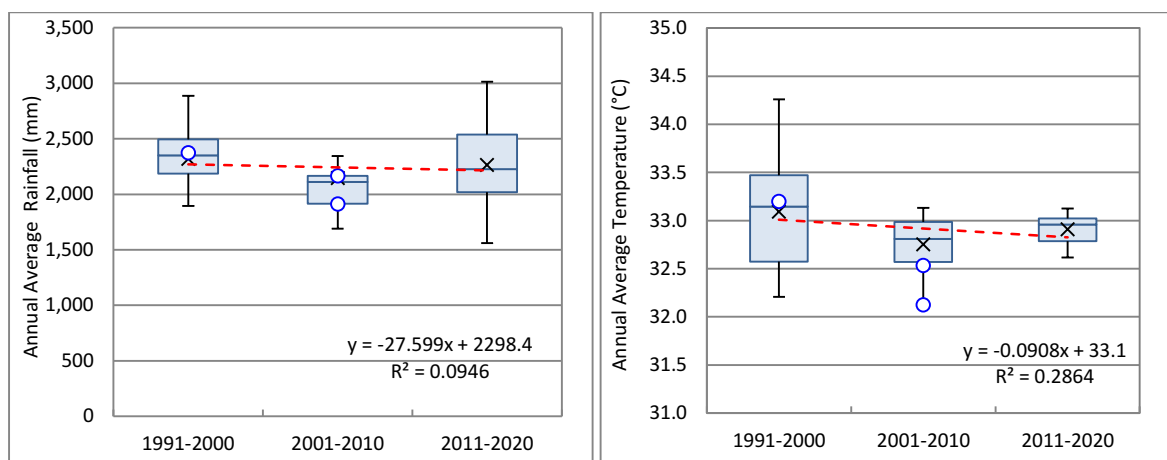


Figure 3-7: Decadal means and trend for rainfall and temperature in Kadhdhoo (1990 - 2020)

Preliminary climate trend analyses indicate that the annual average rainfall data over the last 30 years in both Hanimaadhoo and Kadhdhoo islands display a clear trend of declining rainfall over time with higher variability in rainfall temporal (and presumably spatial) distribution which is on par with climate change impact predictions in the region, hence raising further concerns about groundwater resources management and flood control in Small Island Developing States (SIDS).

However, while the annual average temperature data in Hanimaadhoo island illustrates a clear increasing trend, the temperature data in Kadhdhoo island shows a declining trend. This could have only been possible if the last severe El Niño in 1997/98 had caused a worse impact on equatorial Kadhdhoo island (Latitude 01° 51' N) than its influence on Hanimaadhoo island which is located to further north (Latitude 06° 45' N).

The World Meteorological Agency (WMO) has recommended to perform long term climate trend analyses based on historical time series data sets for over 50 years or more to avoid the effect of local extremes, maxima and minima on global trend patterns. However, the lack of data availability for long term climate trend analyses is a common observation in data scarce South Asian regions as in the case of the Maldives.

It is noted that high spatial and temporal resolution observed data sets are not available for any of the islands and a reasonable extrapolation approach based on available methods and literature will be adopted in estimating extreme storm events which could lead to short term inundation in the majority of the islands. The same design rainfall intensities will be applied in stormwater drainage and MAR design purposes as well.

3.3 Rainfall Characteristics Data for Recharge Estimation in the Selected Islands

The required rainfall intensity values for estimating the overland flow and infiltration components for determining the potential recharge volume in the selected islands were carried out based on the historical rainfall data collected in the above two northern and southern islands (Hanimaadhoo and Kadhdhoo islands) for the past 30 year period from 1990 to 2020.

3.3.1 Distinct Characteristics in Annual Rainfall Series

The annual average rainfall based on the past 30 years of data in Hanimaadhoo and Kadhdhoo islands were found to be $1,747.1 \pm 283.9$ mm and $2,242.5 \pm 376.5$ mm, respectively (Figure 3-8).

The observed data in the two respective stations show that the rainfall in the Southern islands is approximately 32.6% higher than that of the Northern islands, clearly indicating the spatial variability of precipitation over the Maldives islands.

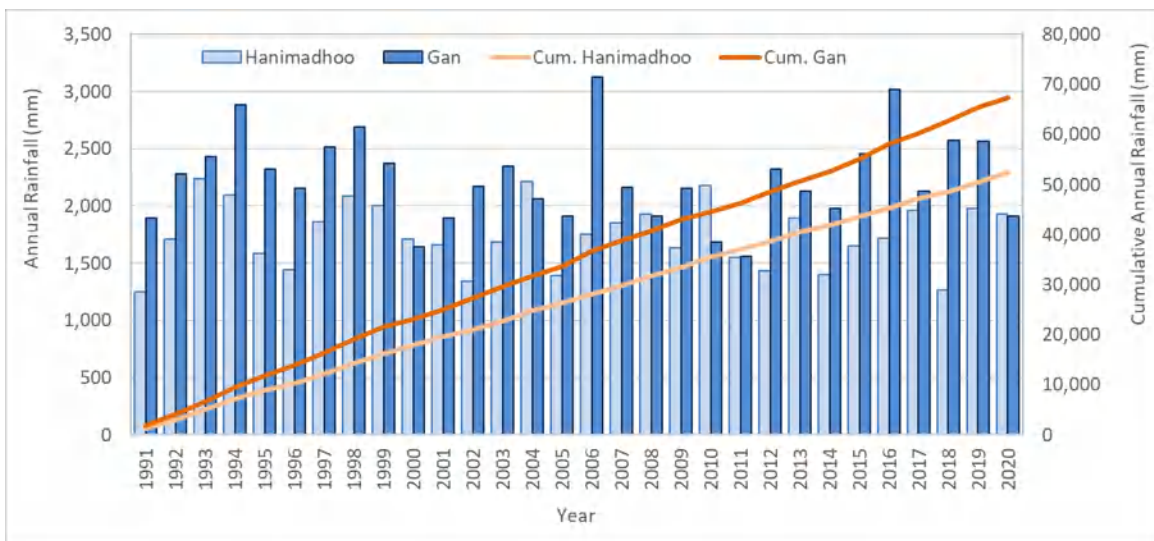


Figure 3-8: Annual rainfall based on past 30 years of data in Hanimaadhoo and Kadhdhoo islands

3.3.2 Monthly Rainfall Variations in Northern and Southern Islands

The monthly average rainfall based on the past 30 years of data in Hanimaadhoo and Kadhdhoo islands are presented in Figure 3-9.

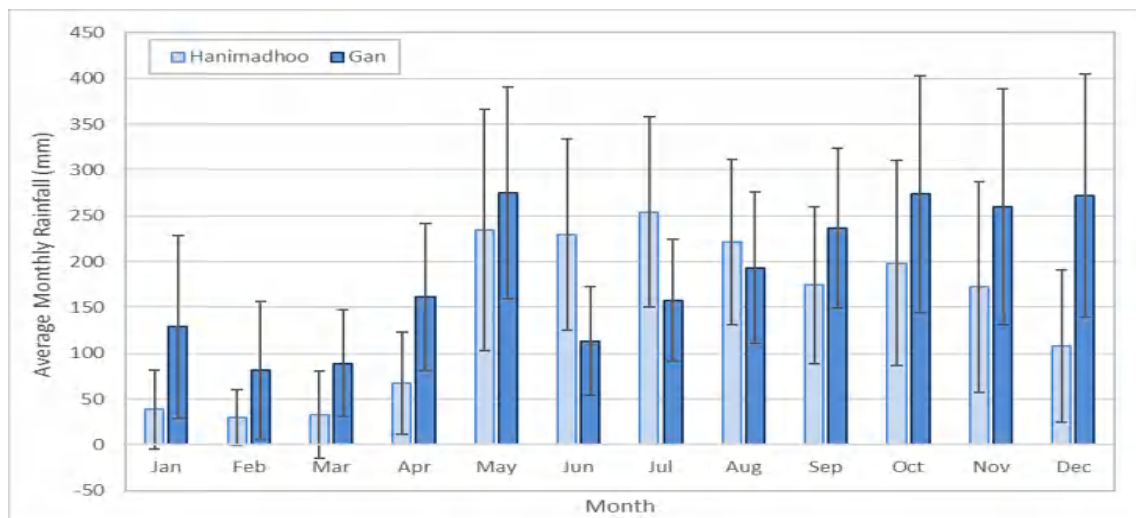


Figure 3-9: Monthly average rainfall based on past 30 years in Hanimaadhoo and Kadhdhoo islands

The observed data in the two respective stations show that the rainfall in the Southern islands is relatively higher than that of the Northern islands, with a distinct four month dry period in the Southern islands from January to April with monthly average rainfall values lower than 100 mm.

3.3.3 Rainfall Intensity for Recharge Estimation

The rainfall intensity values for overland flow calculations are achieved by three different methods:

1. Based on Intensity-Duration-Frequency (IDF) curves
2. Based on Daily/Monthly Average Rainfall Intensity values
3. Based on Probabilistic Rainfall Intensity Values

However, when it comes to the Maldives islands and the selected Lot 1 and Lot 2 set of islands, the available rainfall data resolutions and a higher percentage of occurrence of missing/erroneous data in data series do not allow reliable estimation of design return period rainfall intensity values based on IDF curves. Further, the higher seasonal variability in the data series does not warrant the use of simple mean or monthly average rainfall intensity values for above calculations. Therefore, the 50 per cent (50%) probabilistic monthly rainfall has been estimated in the present study based on the past 30 years of monthly rainfall data and to be used for recharge estimation purposes (Figure 3-10 & Figure 3-11).

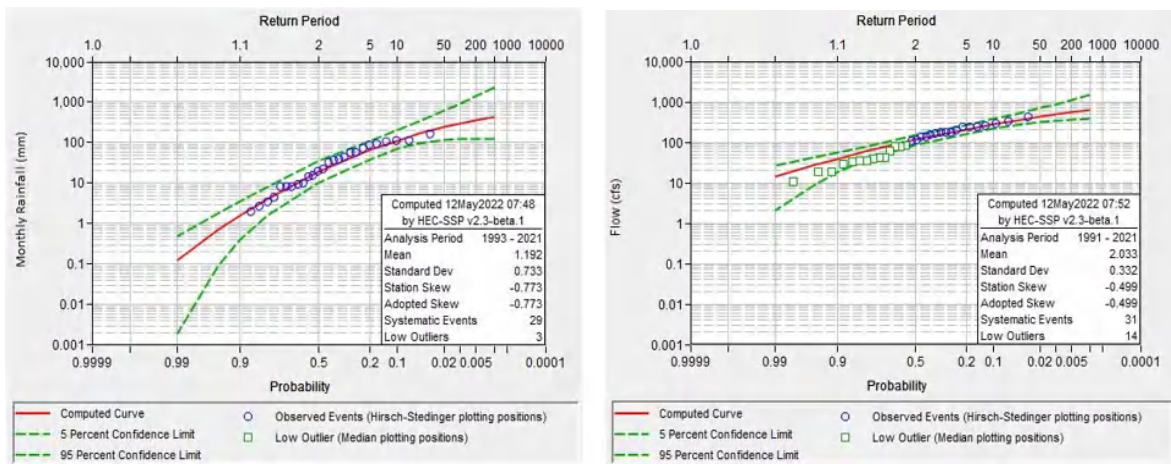


Figure 3-10: Probabilistic plot of Monthly rainfall in Hanimaadhoo (Left) and Kadhdhoo islands (Right) for the Month of January (Dry Period)

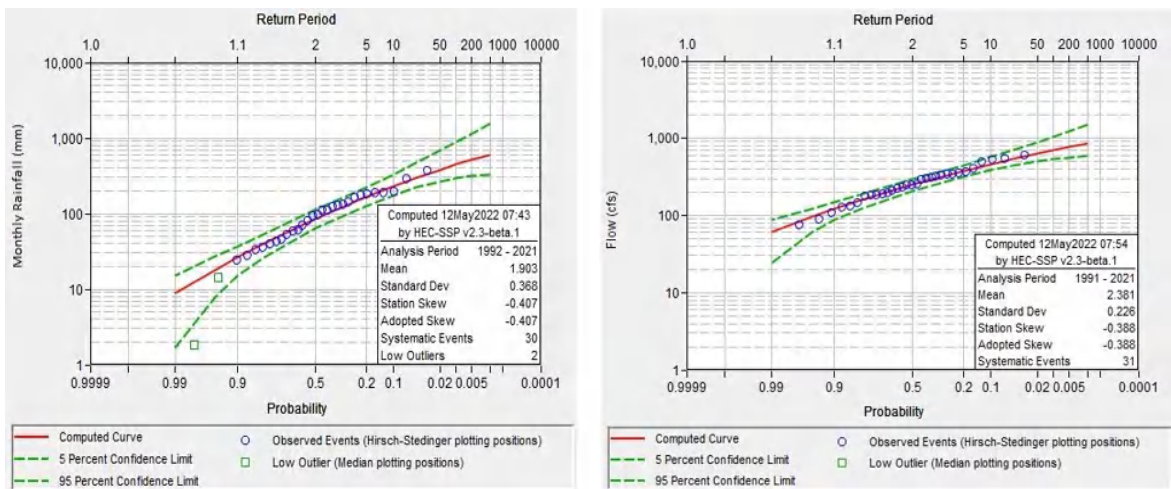


Figure 3-11: Probabilistic plot of Monthly rainfall in Hanimaadhoo (Left) and Kadhdhoo islands (Right) for the Month of December (Wet Period)

The occurrence of extreme rainfall events is a serious factor to be considered as it can have a significant impact on the sustainability of the rainwater harvesting and MAR systems. There can be instances where extreme rainfall may deliver a larger fraction of rainfall without changing the total annual rainfall. The maximum rainfall, 99th or 95th percentiles of rainfall are good indications to analyse the risk of extreme events and the reliability of the system (Figure 3-10 & Figure 3-11).

The 50 per cent (50%) probabilistic monthly rainfall intensities in Hanimaadhoo and Kadhdhoo islands for the months of January to December, with the monthly average rainfall data (Mean \pm 1 Standard Deviation) are presented in Table 3.1.

Table 3.1: Fifty per cent (50%) Probabilistic Monthly Rainfall in Hanimaadhoo and Kadhdhoo Islands with the Monthly Average Rainfall Data (Mean \pm 1 Standard Deviation) for the Northern Islands

Month	Monthly Average Rainfall (mm)		Fifty Percent (50%) Probabilistic Monthly Rainfall (mm)	
	Hanimaadhoo	Kadhdhoo	Hanimaadhoo	Kadhdhoo
January	38.7 \pm 43.2	128.8 \pm 99.6	21.8	128.3
February	29.4 \pm 30.5	81.7 \pm 75.2	26.5	56.2
March	32.7 \pm 47.3	89.0 \pm 58.4	19.0	87.8
April	67.2 \pm 55.7	161.7 \pm 80.0	59.1	155.2
May	234.5 \pm 131.8	275.3 \pm 115.3	208.2	244.8
June	229.2 \pm 104.5	113.3 \pm 59.3	219.0	95.6
July	254.1 \pm 103.9	157.8 \pm 66.3	250.5	155.7
August	221.5 \pm 90.4	193.1 \pm 82.7	211.3	182.5
September	174.3 \pm 86.1	236.3 \pm 87.2	177.3	235.0
October	198.5 \pm 112.4	273.8 \pm 129.0	176.7	240.9
November	172.4 \pm 114.8	259.8 \pm 128.8	188.6	251.7
December	108.0 \pm 83.3	271.9 \pm 132.8	96.2	246.0

These seasonal characteristics can be confirmed in accordance with the mean monthly rainfall observed data over the north, central and southern atolls published by the Maldives Meteorological Service where looking across the length of the Maldives, the amount of annual rainfall received increases from the north to the south. Further, it is noted that normally rainfall occurs in showery form and does not last longer and there will be sunny periods in between.

3.4 Runoff Coefficients for Roof Runoff and Overland Flow Estimation

The roof runoff and direct overland flow, equivalent to the resultant excess rainfall used to estimate the accumulation of potential recharge volume over an impervious or partially impervious area, are calculated based on the above 50% probabilistic rainfall incidence (in mm) falling on top of a particular area of concern (in m²) and by applying the concept of runoff coefficient.

The distinct runoff coefficients used for different roof materials (Thomas and Martinson, 2007) and different land use types (Tsutsumi et al., 2009) for estimating runoff volume calculations are presented in Table 3.2 to Table 3.3.

Table 3.2: Runoff coefficients for different roof materials (Source: Thomas and Martinson, 2007)

Roof Type	Runoff Coefficient
Galvanized iron sheets	> 0.9
Tiles	0.6 - 0.9
Aluminium sheets	0.8 - 0.9
Flat cement roofs	0.6 - 0.7
Organic (e.g. thatched)	0.2
Asbestos	0.8

Table 3.3: Runoff coefficients for different roof materials (Source: Tsutsumi et al., 2009)

Type of ground surface	Coefficient of surface runoff, F_{rc}
Road:	
Pavement	0.70–0.90
Permeable pavement	0.30–0.40
Gravel road	0.30–0.70
Shoulder or top of slope:	
Fine soil	0.40–0.65
Coarse soil	0.10–0.30
Hard rock	0.70–0.85
Soft rock	0.50–0.75
Grass plot of sand:	
Slope 0–2%	0.05–0.10
Slope 2–7%	0.10–0.15
Slope 7%	0.15–0.20
Grass plot of clay:	
Slope 0–2%	0.13–0.17
Slope 2–7%	0.18–0.22
Slope 7%	0.25–0.35
Roof	1.00
Unused bare land	0.20–0.40
Athletic field	0.40–0.80
Park with vegetation	0.10–0.25
Mountain with a gentle slope	0.30
Mountain with a steep slope	0.50
A paddy field or water	0.70–0.80
Farmland	0.10–0.30

Table 3.4: Derived runoff coefficients for different roof materials (After: Tsutsumi et al., 2009)

Land use Type	Runoff Coefficient
Roof cover	1.00
Vegetation	0.15
Bare lands	0.30
Farm Lands	0.20
Roads	0.50
Playground	0.60
Wetlands	0.13

3.5 Estimating Effective Plan Roof Area & Catchment Area for Rainfall Harvesting

The following methodology and equations can be used to obtain the plan roof area requirement for known rainfall depth and demand (Figure 3-12).

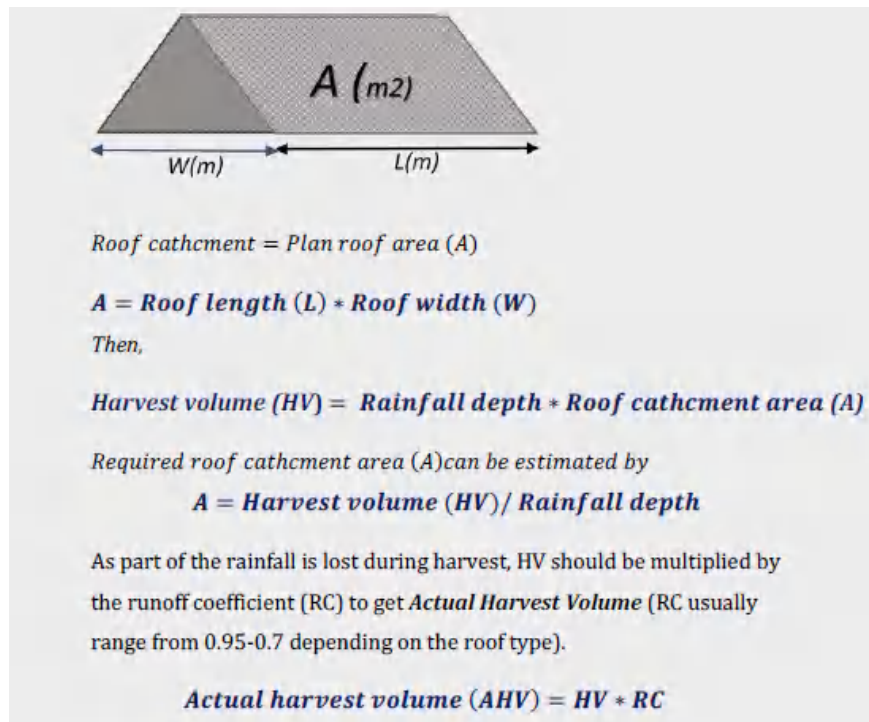


Figure 3-12: Methodology and equations for obtaining the Plan roof area (Source: NBRO, 2021)

The same procedure may be applied for any surface drainage flow or volume estimates as necessary by referring to Table 3.2 and Table 3.3.

4 METHODOLOGY AND CALCULATIONS FOR CONCEPTUAL DESIGNS

Summary of the Methodology Carried out for the Baseline Assessment

- Required hydrological and hydrogeological data for the study was collected through Physiochemical (parameter: pH, Dissolved, Oxygen, Electrical Conductivity, Turbidity, Temperature, Salinity, Ammonia, Nitrate, Phosphate) and microbiological tests (total coliform and faecal coliform), Electrical Resistivity tests, soil permeable tests, and soil profiling.
- Freshwater level and saline water surfaces were developed based on the ER test data and the Digital Elevation Model was developed with the aid of UAV data and Topographic survey data.
- Areas with critical water quality degradation were identified by mapping the Physiochemical and microbiological test results.
- The Water Balance model was developed for each island considering aggregate runoff coefficient, crop water requirement, water usage by each development type, land usage and rainfall data.
- Sea water flooding areas were identified based on field observations and stakeholder consultation.

4.1 Geological and Hydrogeological Aspects for Feasibility and Concept Design

- The geology of each island was studied based on the geological sections which elaborate on the subsurface geological characteristics (Annex VII).
- Hydrogeology was studied and the nature of the fresh groundwater lens was identified considering the $EC < 1500 \mu\text{s}/\text{cm}$. Then groundwater storage was calculated considering 15% porosity (Annex VII).
- Groundwater chemistry and its variation were monitored based on the collected water samples and critical locations with contamination (increment with measured parameters) were identified and mapped (Annex VII).
- The transmissivity value of water bearing formation for each island was estimated based on the pumping test results.
- The hydraulic conductivity of each island was compared based on the permeability test values and considered for estimation of the groundwater flow velocities and recharging volume of the island.
- Groundwater flow velocity maps were developed by using the calculated average hydraulic conductivity of the island and assuming a porosity of 15% to identify the feasible locations for MAR systems
- Seawater flooding areas were identified during the field surveys and considered during proposed aquifer modification applications for islands.

4.2 Conceptual Designs of Proposed MAR System (MAR)

- The rainfall intensity values for overland flow calculations are achieved by three different methods;
 - Based on Intensity-Duration-Frequency (IDF) curves
 - Based on Daily/Monthly Average Rainfall Intensity values
 - Based on Probabilistic Rainfall Intensity Values

However, when it comes to the Maldives islands and the selected Lot 1 and Lot 2 set of islands, the available rainfall data resolutions and a higher percentage of occurrence of missing/erroneous data in data series do not allow reliable estimation of design return period rainfall intensity values based on IDF curves. Further, the higher seasonal variability in the data series does not warrant the use of simple mean or monthly average rainfall intensity values for the above calculations. Therefore, the 50 percent (50%) probabilistic monthly rainfall has been estimated in the present study based on the past 30 years of monthly rainfall data and is to be used for recharge estimation purposes. Since the 50% probabilistic monthly rainfall also shows some issues with the intensities (intensities were very much higher in the wet period and very much low in dry period), average daily rainfall data was latterly used for the calculations.

- Unsaturated depth of soil was identified and mapped (with aid of ArcMap and Surfer software) based on the freshwater level and the DEM. Selected recharging zones is the upper part of the geological profile depending on the groundwater level of the particular area.
- Considering cost effective environment friendly structures, four types of MAR systems were proposed for islands based on the hydrological and hydrogeological characteristics.
- Roof water recharging;
 - The probability existence of roof area was identified and three types of roof areas were selected for the calculation on each island. The daily, monthly and yearly recharge potential of each type of recharging well was calculated based on the rainfall.
- Road Runoff Recharging;
 - Roads having a width > 6 m have been considered and a road network was identified for the calculation of overland flow along the road and recharge structures. Contributory area (residential area) was identified and overland flow was calculated considering roof area and drain area. Daily, monthly and yearly recharge potential of road runoff recharging systems were calculated based on the rainfall.
- Recharging Ponds;
 - A vacant area located away from the residential area was selected for recharging ponds considering the GW chemistry, unsaturated depth, and topography of the island. Recharging ponds were feed by the road runoff recharging network and daily, monthly and yearly recharge potential was calculated based on the rainfall.
- Aquifer modifications;
 - Locations for aquifer modification applications were identified based on the enhancement in physio-chemical and microbiological parameters and seawater flooding extents.
- The possible Impact and Social and Environmental Feasibility of Proposed MAR Systems were investigated based on household and institutional questionnaire surveys for data collection.
- Quantification, construction cost estimation, operation and maintenance cost for each type of recharging structure was carried out based on the nature and extent of each structure/ network.
- Expected runoff is calculated using the Rational Formula and SCS method and compared with the results of the two approaches. Thereafter, an assessment of the road runoff recharging system was done to manage the overland flow of the residential area using the Continuity equation and Manning's equation.
- Validation for the calculation recharge calculations was carried out based on the rational formula method and Soil Conservation Service (SCS) method and compared both results. Then estimation of drain capacities was carried out following the Continuity equation and Manning's Equation.

4.3 Assumptions and Major Considerations in Conceptual Designs

The following assumptions are made during the conceptual design of Managed Aquifer recharging systems.

2. The sizes of the roof structures in Maldives islands are different and different sizes of structures have been categorized into three based on the distribution of roof sizes of each island.
3. The measured average hydraulic conductivity and transmissivity in each island were assigned considering different land uses.
4. $EC > 2,500 \mu\text{s/cm}$ was considered as freshwater.
5. Porosity of the top layer (unconsolidated sand and completely weathered formation) and the partly weathered formation have been assumed as 15% and 5%, respectively.
6. The elevation of the ground level has been interpolated based on spot height obtained from drone surveys and land surveys. These elevations are used for the conceptual and detailed design of the recharging structures.
7. Height of the seawater flooding with respect to beach line $< 0.5 \text{ m}$ was assumed for each island.
8. The average depth to rock level in each island which were obtained through indirect measurement of geophysical techniques were used for the installation of impermeable liners along the proposed lines.
9. The average rainfall (from 30-year average) for the northern and southern part of the Maldives islands were considered during conceptual design for the northern and southern islands, respectively.
10. Runoff coefficients of 0.9, 0.6, and 0.5 are considered for the calculation of runoff for the roof, road, and residential areas including the playground, respectively.
11. The area with a thickness of unsaturated zone $> 0.75 \text{ m}$ was considered for roof water recharging, road runoff recharging, and recharging ponds.
12. The retention of the recharging wells is not considered for the roof recharge calculation. However, 1/3 of the volume along the roadside drains and 20% of the volume of the recharging pits are considered as retention volume on daily basis.
13. Roads having a width $> 6 \text{ m}$ have been considered for the calculation of overland flow along the road and recharging structures.
14. It is assumed that household wastewater/ domestic wastewater would not be dumped to roads and into land blocks.
15. Based on the rainfall data (30-year rainfall from 1990 to 2020), daily average rainfall per month is calculated by considering daily rainfall of more than 10 mm. This rainfall is used to estimate daily, monthly, and yearly runoff. Details are given below in Table 4.1.

Northern islands (Sh Foakaidhoo)

Table 4.1: Average rainfall data used for the northern island (Sh. Foakaidhoo)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average daily rainfall (mm)	38.7	29.4	32.7	33.6	39.08	32.74	36.3	31.64	34.86	33.08	34.48	36
Monthly rainfall	38.7	29.4	32.7	67.2	234.5	229.2	254.1	221.5	174.3	198.5	172.4	108

Note: Daily maximum for year = 39.08 mm.

Southern islands (Th Gaadhiffushi, Th Omadhoo, Th Vandhoo, and Th Kandoodhoo)

Table 4.2: Average rainfall data used for southern islands

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average daily rainfall (mm)	32.2	40.8	29.66	32.2	34.41	28.32	31.56	32.18	33.75	34.22	32.47	38.84
Monthly rainfall	128.8	81.7	89	161.7	275.3	113.3	157.8	193.1	236.3	273.8	259.8	271.9

Note: Daily maximum for year = 40.85 mm.

4.4 Calculations for Conceptual Designs of Proposed MAR System (MAR)

Methodology followed for the Conceptual Designs of Proposed MAR Systems of Th. Kandoodhoo Island is discussed under this chapter.

Based on the hydrogeology, topography, and geology of the island, four methods can be proposed for groundwater recharging to improve the groundwater quality and groundwater quantity. The possible methods are roof water recharging, road runoff recharging, recharging ponds, and aquifer modification. When the recharging structures are proposed, the availability of sufficient space within the unsaturated layer/zone above the groundwater table is a key factor in all islands.

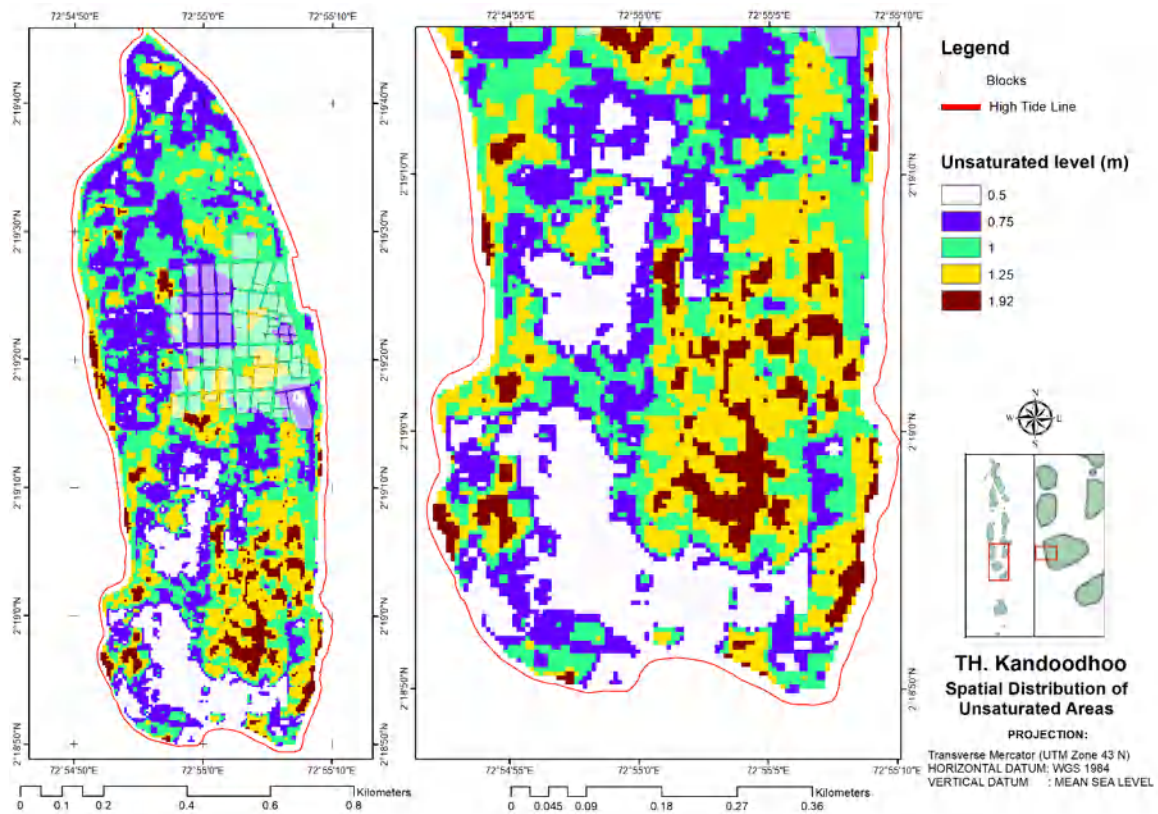


Figure 4-1: Spatial distribution of unsaturated areas in Kandoodhoo

4.4.1.1 Assessment of Unsaturated Area

The selected zone for groundwater recharging is the upper part of the geological profile depending on the groundwater level of the particular area. The distribution of thickness of the unsaturated zone of the Kandoodhoo island is given in Figure 4-1 and Table 4.3.

Table 4.3: Distribution of unsaturated areas within Kandoodhoo

Thickness of the Unsaturated Zone (m)	Area (m ²) and Percentages (%)
Less than 0.5	77,934 (10.7%)
0.5-0.75	218,981 (30.0%)
0.75-1.0	258,600 (35.5%)
1.0-1.25	136,392 (18.7%)
More than 1.25	37,152 (5.1%)

About 59.3% of land area (thickness of unsaturated zone > 0.75 m) in the island is available for the groundwater recharging activities through roof water recharging, road runoff recharging, and recharging ponds.

4.4.1.2 Recharging Using Roof Water

The residential plots are located at the north-eastern part of the island close to the harbour. Some rainwater is currently used (rainwater harvesting) for domestic purposes and the balance amount is either diverted to the free space of land block or to the adjoining roads.

4.4.1.2.1 Distribution of roof areas and design volume of recharging well

The roof sizes of the island vary from 4 m² to 544 m² and three different roof sizes (Type 1: 30 m², Type 2: 85 m², Type 3: 175 m²) have been selected for the conceptual design using probability exceedance (75%, 50% and 25%) curves (Figure 4-2).

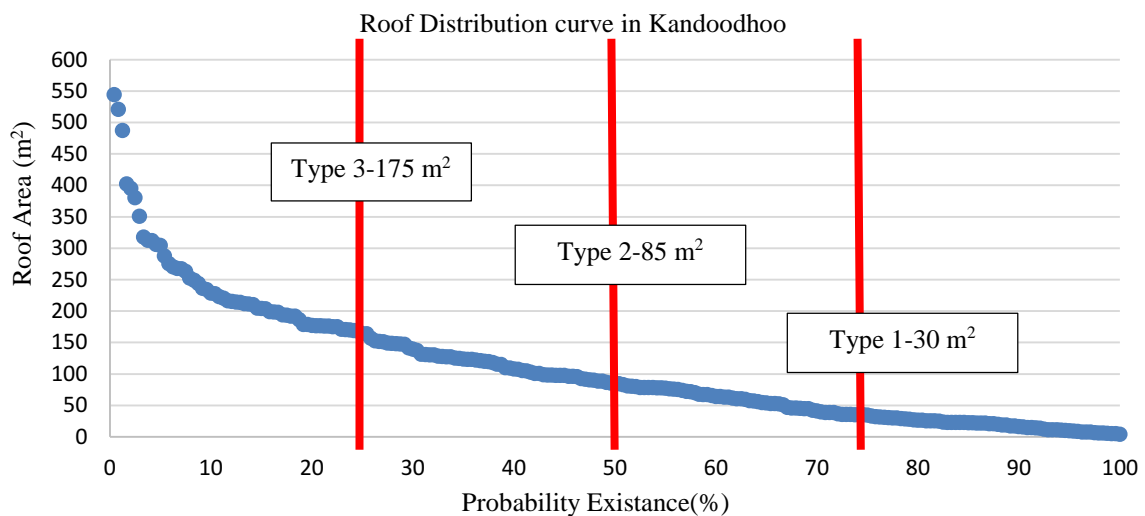


Figure 4-2: Distribution curve for roof areas in Kandoodhoo

As per the roof runoff estimation, Type 1, Type 2, and Type 3 roofs generate a volume of about 1.10 m³, 3.13 m³, and 6.43 m³ respectively per day event (rainfall-40.85 mm). The design volume of recharging wells is given in Table 4.4.

Table 4.4: Design of recharging volume

Type	Roof Area (m ²)	Design Volume (m ³ /d)
Type 1 (75 % of roof area)	30	1.10
Type 2 (50% of roof area)	85	3.13
Type 3 (25% of roof area)	175	6.43

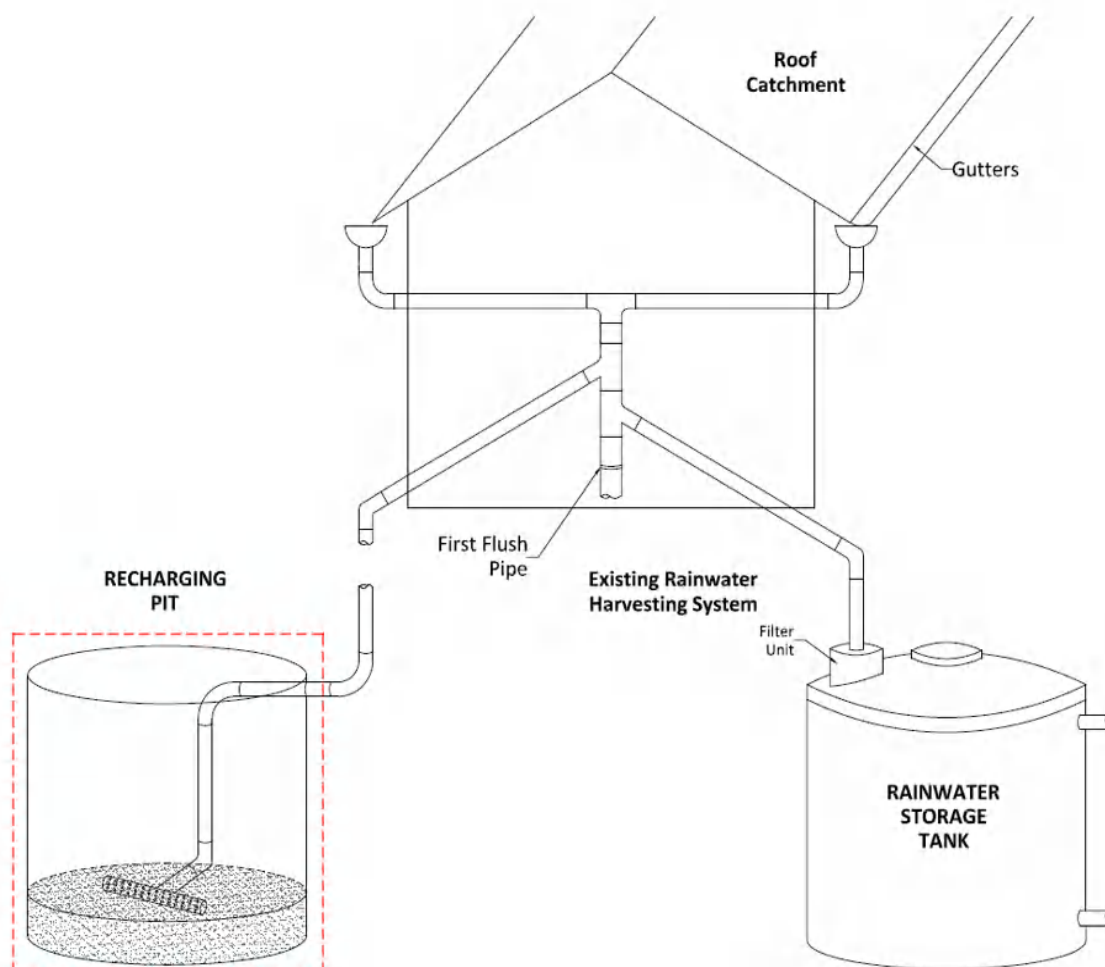
4.4.1.2.2 Conceptual design of recharging well

The average hydraulic conductivity (8.26 m/d) was considered to estimate the potential recharging volume of the proposed size of the recharging well and the number of recharging wells for the island. The potential recharging volumes of proposed structures are given in Table 4.5.

Table 4.5: Potential recharging volume of proposed structures

Type	Roof Area (m ²)	Proposed Recharging Well Details				Total Storage of the Well (m ³)	Total Daily Recharge Volume (m ³)
		Well Type	Depth (m BGL)	Diameter (m)	No. of Recharging Wells		
Type 1	30	A	1.5	1	1	0.78	6.48
Type 2	85	B	1.5	1.5	1	1.76	14.58
Type 3	175	B	1.5	1.5	1	1.76	14.58

The hydraulic conductivity will be reduced with the increasing soil moisture. Therefore, design volume from the roofs can be managed with proposed Type A and Type B recharging wells effectively. The conceptual drawing of the recharging wells is given in Figure 4-3. The excess water in the recharging wells will be diverted to the roadside recharging drains if available.



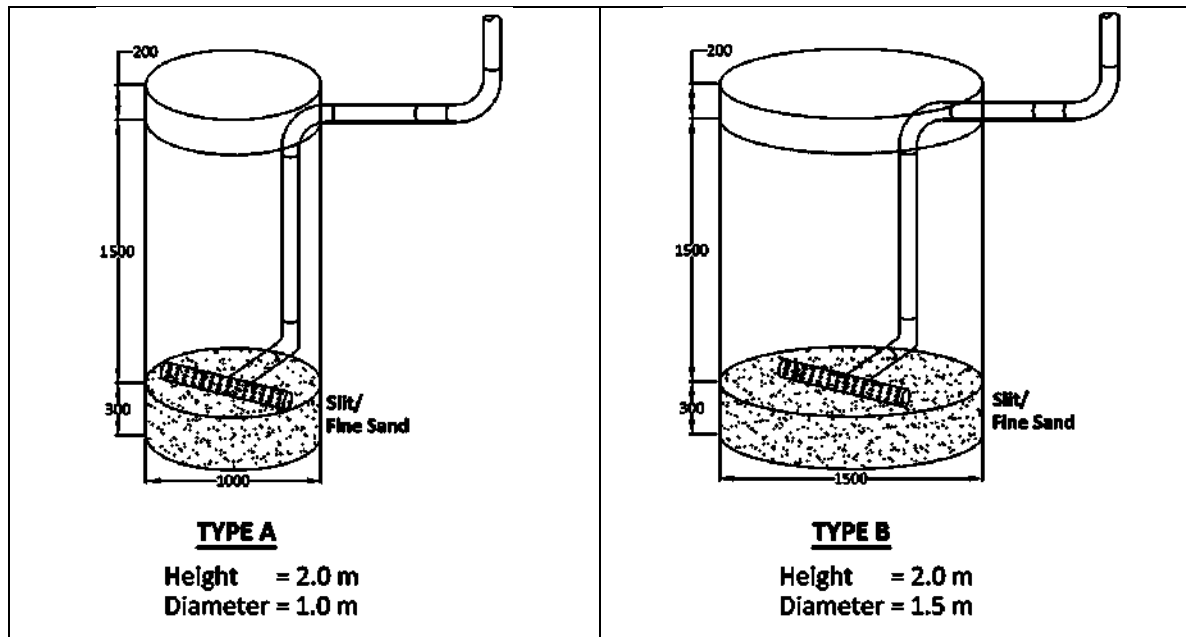


Figure 4-3: Conceptual drawing for the recharging well (not to scale)

The predicted monthly and yearly groundwater recharging volumes through two well types are given in Table 4.6 and Table 4.7.

Table 4.6: Monthly predicted recharging volume through proposed recharging wells

Month	Recharging Volume for Type A (m ³)	Type B (m ³)
January	60 x 4 x 6.48 = 1,555.2	120 x 4 x 14.58 = 6,998.4
February	60 x 2 x 6.48 = 777.6	120 x 2 x 14.58 = 3,499.2
March	60 x 3 x 6.48 = 1,166.4	120 x 3 x 14.58 = 5,248.8
April	60 x 5 x 6.48 = 1,944	120 x 5 x 14.58 = 8,748
May	60 x 8 x 6.48 = 3,110.4	120 x 8 x 14.58 = 13,996.8
June	60 x 4 x 6.48 = 1,555.2	120 x 4 x 14.58 = 6,998.4
July	60 x 5 x 6.48 = 1,944	120 x 5 x 14.58 = 8,748.0
August	60 x 6 x 6.48 = 2,332.8	120 x 6 x 14.58 = 10,497.6
September	60 x 7 x 6.48 = 2,721.6	120 x 7 x 14.58 = 12,247.2
October	60 x 8 x 6.48 = 3,110.4	120 x 8 x 14.58 = 13,996.8
November	60 x 8 x 6.48 = 3,110.4	120 x 8 x 14.58 = 13,996.8
December	60 x 7 x 6.48 = 2,721.6	120 x 7 x 14.58 = 12,247.2
Total	26,050	117,223

Table 4.7: The potential of the yearly roof recharging volume

Category of Recharging Well	No. of Recharging Structures Proposed	Total Recharging Volume per year (m ³)
Type A	60	26,050
Type B	120	117,223
Total	180	143,273

4.4.1.3 Road Runoff Recharging

The infiltration rates along the road areas are very low due to the presence of consolidated and compacted soil formations in the road stretches. As a consequence, rainwater is stagnated in the depression areas on the roads and adjoining lands. The stagnated water would be available for several hours or even a few days depending on the intensity of rainfall received on the island.

Under this method, rainwater along selected roads having a width > 6 m has been considered for the calculation of overland flow along the road and recharging structures. The selected roads for recharging structures are given in Figure 4-4.

The runoff volumes along the selected road are calculated by considering the runoff coefficient (0.6) and daily maximum average rainfall per month (40.85 mm). The estimated total runoff volumes along each road are given in Table 4.8.



Figure 4-4: Selected Roads for Recharging trenches and pits

Table 4.8: Estimated runoff along the roads

Selected Road	Road Area (m ²)	Length of the Road (m)	Design Runoff in the Road (m ³ /d)
Road-1	7,290	810	7,290 x 0.6 x 0.04085 = 178.68
Road-2	4,050	450	4,050 x 0.6 x 0.04085 = 99.26
Road-3	2,160	240	2,160 x 0.6 x 0.04085 = 52.94
Road-4	1,920	240	1,920 x 0.6 x 0.04085 = 47.06
Road-5	2,880	320	2,880 x 0.6 x 0.04085 = 70.59
Road-6	1,920	240	1,920 x 0.6 x 0.04085 = 47.05
Road-7	2,970	330	2,970 x 0.6 x 0.04085 = 72.79
Total	23,190	2,630	568

The runoff from the contributory residential area covered with drains (Figure 4-5) is estimated by considering the runoff coefficient (0.5) and daily maximum average rainfall per month (40.85 mm).

$$\begin{aligned} \text{Total contributory residential area} &= \text{Total area (103,000 m}^2\text{)} - (\text{roof area and drain area}) \\ &= 103,000 \text{ m}^2 - 28,000 \text{ m}^2 = 75,000 \text{ m}^2. \end{aligned}$$

$$\text{The estimated run off volume} = 75,000 \times 0.04085 \times 0.5 = 1,532 \text{ m}^3/\text{d}$$

$$\text{The estimated run off volume from drains and contributory residential area} = 2,100 \text{ m}^3/\text{d}$$



Figure 4-5: Contributory residential area considered for calculation of runoff

4.4.1.4 Conceptual design of roadside drains and recharging pits

The overland flow along the selected road stretch will be collected to the drain that is to be constructed along the one side of the road by using pre-cast “U”-shaped concrete blocks.

The collected water in the drain will be diverted to a series of recharging pits to be constructed along the drain. The spacing between two recharging pits will be 25 m. The bottom of the recharging pit is unlined and a precast concrete slab will be used to cover the recharging pit.

Road runoff recharging system will be provided for the selected roads. Further, excess water in the recharging pit will be diverted to the recharging pond.

The details of the proposed drain and recharging pit are given below.

Proposed drain

Width (m)	0.5
Depth (m)	0.6
Remark	A total of 18 holes (diameter of each hole is 60 mm) per one-meter section of the drain will be provided for the bottom surface of the drain. Further, both bottom edges (15 cm for each side) of the block is 10 cm higher than the normal level to trap silt materials. The cross section of the recharging drain is given in Figure 4-6.

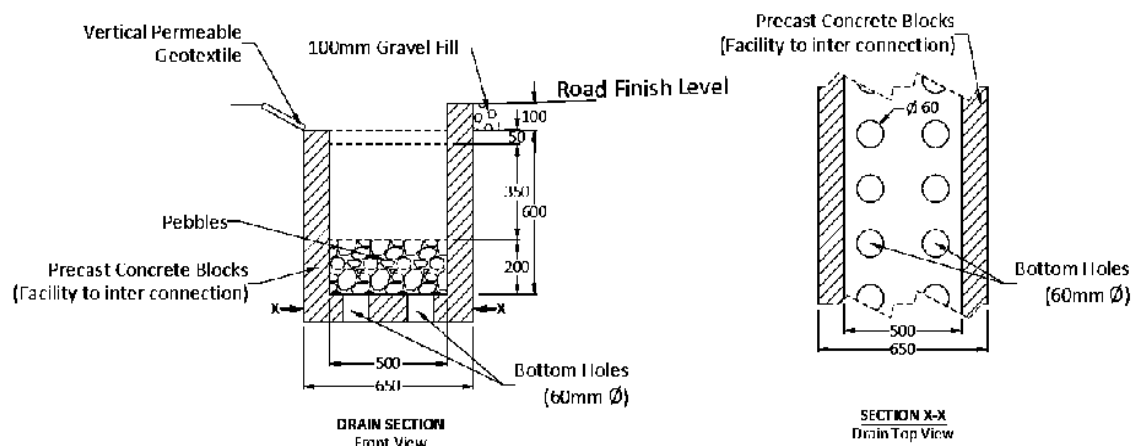


Figure 4-6: Cross section of the recharging drain

Proposed recharging pit

Width (m)	1.0
Length (m)	1.0
Depth (m)	1.5
Remark	The recharging pit will be filled with layers of pebble, sand, and silt to filter the stormwater before it is added to groundwater. Once the recharging pit is filled, excess water will flow to the adjoining pit through the open drain. The top of the recharging pit is 20 cm above the ground level and a concrete cover will be used for the recharging pit. The cross section of the recharging drain is given in Figure 4-7.

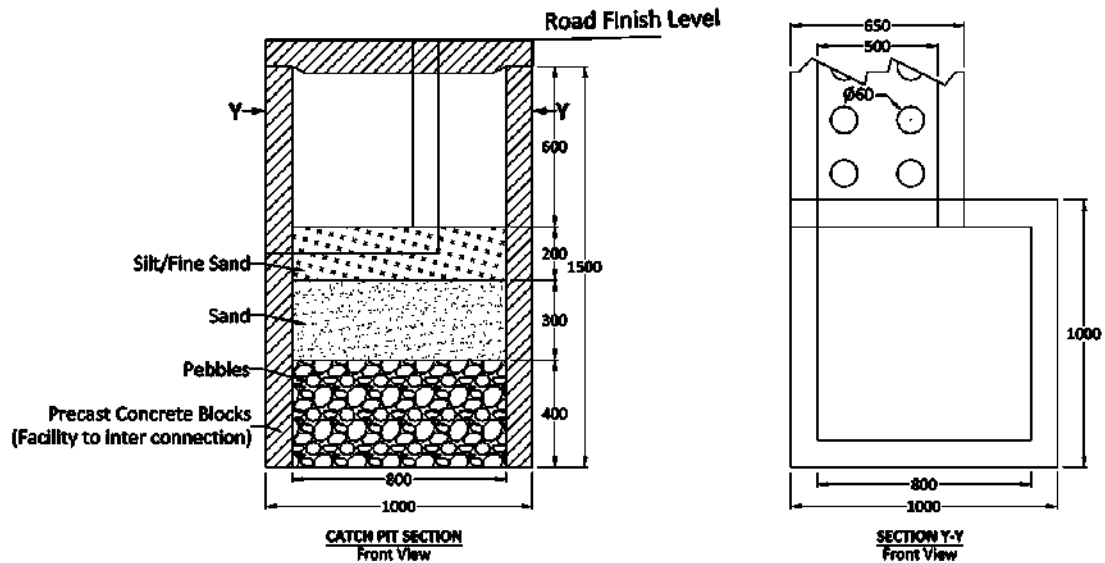


Figure 4-7: Cross section of the recharge pit

The required recharging pits and drains for the selected roads are given in Table 4.9.

Table 4.9: The potential recharge through drains and recharging pits

Selected Road and Length (m)	Number of Recharging Pits	Recharging Holes along the Drain (60 mm Ø)	Daily Recharging Volume (m ³)		Total Retention Volume (m ³) in Drains and Recharging Pits	Total Managed Potential Daily Volume (m ³)
			Drains	Recharging Pits		
Road 1 (810 m)	32	14,004	320	264	77.8+4.48 = 82.28	666.00
Road 2 (450 m)	18	7,776	177	148	2.52+43.2 = 45.72	370.72
Road 3 (240 m)	10	4,140	94	83	1.4+23 = 24.40	201.40
Road 4 (240 m)	10	4,140	94	83	1.4+23 = 24.40	201.40
Road 5 (320 m)	13	5,526	114	107	1.82+30.7 = 32.52	253.52
Road 6 (240 m)	10	4,140	94	83	1.4+23 = 24.40	201.40
Road 7 (330 m)	13	5,526	119	107	1.82+31.7 = 33.53	259.52
Total	106	45,202	1,012	875	267.25	2,154

The proposed drains, recharging ponds, and recharging pits are capable of handling more volume than the predicted water accumulation along the roads and contributory residential areas covered by drains. The predicted monthly and yearly recharging volume through proposed drains and recharging pits are given in Table 4.10.

Table 4.10: Monthly predicted recharging volume through proposed recharging pits and drains

Month	Drains and Recharging Pits (m ³)
January	2,154.26 x 4 = 8,617.04
February	2,154.26 x 2 = 4,308.52
March	2,154.26 x 3 = 6,462.78

Month	Drains and Recharging Pits (m ³)
April	2,154.26 x 5 = 10,771.3
May	2,154.26 x 8 = 17,234.08
June	2,154.26 x 4 = 8,617.04
July	2,154.26 x 5 = 10,771.3
August	2,154.26 x 6 = 12,925.56
September	2,154.26 x 7 = 15,016.82
October	2,154.26 x 8 = 17,234.08
November	2,154.26 x 8 = 17,234.08
December	2,154.26 x 7 = 15,016.82
Total for year	143,732

4.4.1.5 Recharging Pond

The overland flow water at the playground, other contributory residential areas around and excess water in the roadside drains will be diverted to the recharging pond (Figure 4-8). The details of the recharging pond are given below.

Width (m)	10.0
Length (m)	15.0
Depth (m)	1.0 below ground level
Height of the Gabion Wall	1.5 m (0.5 m above the ground level)
Remark	Gabion wall will be constructed for the recharging pond to avoid the direct mixing of the play groundwater to the recharging pond. About 0.25 m thick sand layer will be laid to filter stormwater before it is added to groundwater.
Retention Volume of the Pond (m ³)	30 m ³
Daily Recharging Volume (m ³)	1,239 m ³
Total (m ³)	1,260 m ³



Figure 4-8: Location of the recharging pond

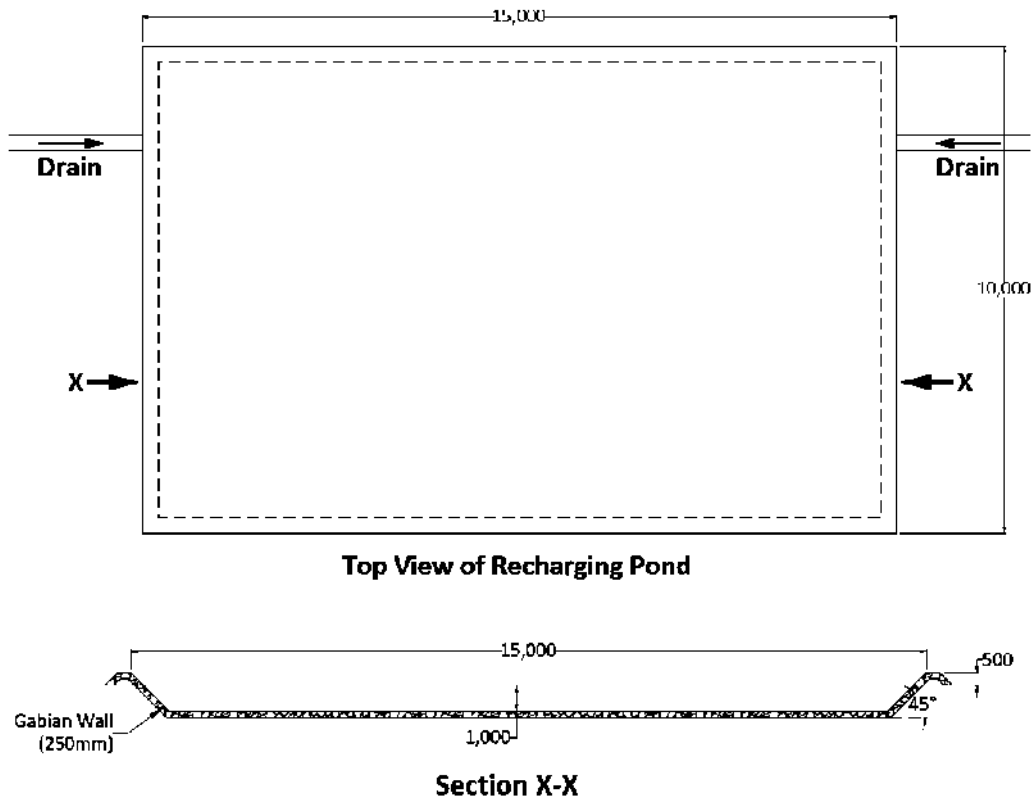


Figure 4-9: Proposed recharging pond

The Predicted yearly and monthly recharging volumes through the proposed recharging pond is given in Table 4.11.

Table 4.11: Predicted yearly and monthly recharging volume through the proposed pond

Month	Recharging Volume (m ³)
January	1,260 x 4 = 5,040
February	1,260 x 2 = 2,520
March	1,260 x 3 = 3,780
April	1,260 x 5 = 6,300
May	1,260 x 8 = 10,080
June	1,260 x 4 = 5,040
July	1,260 x 5 = 6,300
August	1,260 x 6 = 7,560
September	1,260 x 7 = 8,820
October	1,260 x 8 = 10,080
November	1,260 x 8 = 10,080
December	1,260 x 7 = 8,820
Yearly total	84,420

4.4.1.6 Application of Aquifer Modifications

It is noted that the waterlogged area is situated at the southern end of the island. During the rainy period, overland flow and seepages flow to the sea through the waterlogged area while seawater flows into the waterlogged area as a result of tidal action. The depth to bedrock in the southern part of the island is shallow with compared to the northern part of the island. Therefore, the fresh water quantity of the waterlogged area (southern part) and its surrounding could be improved by the aquifer modification method.

It is proposed to install an impermeable liner on the fresh coral layer inside the land parallel to the road and the proposed area for the impermeable liner is given in Figure 4-10.

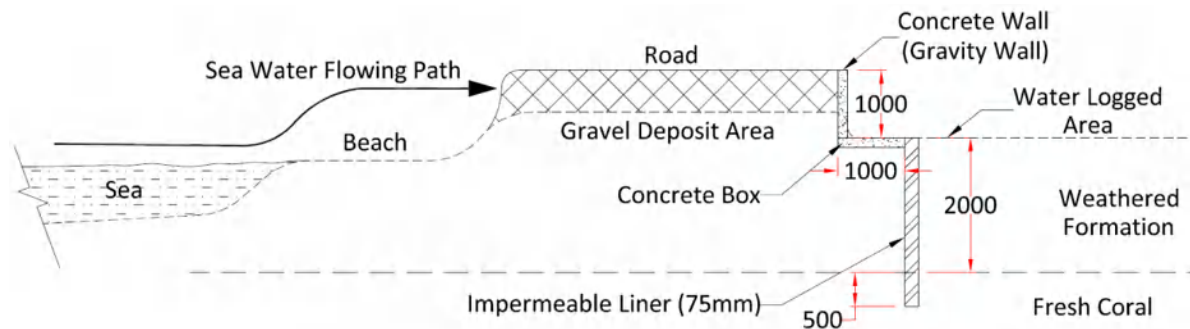


Figure 4-10: Proposed impermeable (clay) liner parallel to the road



Figure 4-11: Proposed area for the installation of clay liner parallel to the road

A concrete wall will be proposed in the area between the road and the impermeable liner bordering the road. The level of the existing road and concrete wall along the proposed liner is proposed to increase by about 1.0 m to control the seawater flooding into the waterlogged area. The details of the liner and road are given below.

Width of liner	- 0.75 m
Length of liner	- 800 m
Average depth of the liner below ground level	- 2.5 m
Proposed liner material	- Bentonite/cement slurry / clay rich residual soil

Remark: A gate will be proposed to discharge excess stormwater to the sea by considering the 0.50 m average water column in the waterlogged area.

After placing of the liner, groundwater level, as well as groundwater flow velocity, will be changed in waterlogged areas and intermediate surroundings. The groundwater level will be increased in close to waterlogged areas and the incremental amount will be decreased in the areas away from the waterlogged area. The groundwater velocity will be decreased and retention time will be increased close to the waterlogged area. The groundwater quality of the waterlogged area could be improved slowly. The predicted groundwater level increase within 50 m and 100 m buffer area are assumed as 0.4 m and 0.2 m, respectively, for estimating the increased groundwater quantity.

Table 4.12: Estimated groundwater enhancement due to aquifer modification in Th. Kandoodhoo

	50 m Buffer Area	100 m Buffer Area
Groundwater level increased by (m)	0.4	0.2
Buffer area (m ²)	40,000	40,000
Enhanced groundwater storage (m ³) assuming a 5% porosity	800	400
Enhanced freshwater thickness (m) as per Ghyben – Herzberg relation	16	8
Enhanced groundwater storage (m ³) assuming a 5% porosity and weathered thickness of 3.8 m	7,600	7,600
Total groundwater storage enhancement (m ³)	16,400	

The minimum groundwater storage enhancement as per assumed conditions due to aquifer modification is 16,400 m³.

4.4.1.7 Predicted Groundwater Enhancement in The Island

The predicted groundwater enhancement volume after the proposed MAR schemes are given below.

Table 4.13: Predicted groundwater enhancing quantities of Th. Kandoodhoo

Recharging Method	Predicted Groundwater Enhancing Quantity (m ³ /year)
Roof recharging system	143,272
Road runoff recharging system	143,732
Recharging pond	84,420
Aquifer modification	16,400
Total	387,825

As per the Baseline Report, the available groundwater amount within the island was estimated by using two approaches and the comparison is given below.

Table 4.14: Comparison of available groundwater amount vs predicted additional recharge from MAR

Approaches	Predicted Groundwater Quantity (m ³ /year)
Natural Recharge	
Water balance method	192,803
Indirect investigation through resistivity method	125,297
MAR Schemes	
Predicted additional recharge from the roof, road runoff, recharging pond, and aquifer modification	387,825

Similar methodology was followed and the results gained for the remaining Islands were illustrated in Chapter 5.

4.5 Social and Environmental Feasibility and Impact of Proposed MAR Systems

4.5.1 Th. Kandoodhoo

The possible Impact and Social and Environmental Feasibility of Proposed MAR Systems were investigated based on household and institutional questionnaire surveys for data collection. A selected sample of household community and Council officials were elaborated on the proposed MAR systems and structures and interviewed for acquiring their feedback, as summarized below.

Table 4.15: Impact and Social and Environmental Feasibility of Proposed MAR Systems

Proposed Recharging Structures	Details of MAR Systems	Feasibility and Other Remarks
<p>Recharging well for house units</p> <p>Recharging well (Depth: 1.5 m, Maximum diameter: 2.0 m).</p>	<p>Diameter will be selected based on the roof size.</p> <p>Condition of the roof and height of the roof to be assessed.</p>	<ul style="list-style-type: none"> • Are there lands available for these structures? <ul style="list-style-type: none"> ○ Most houses will have land available for a recharging well ○ The council institutions also have land available – but roof area might be an issue ○ Depends on the house – most houses have water tanks and land available • Can there be any safety issues, especially for children? <ul style="list-style-type: none"> ○ If the well is covered and if it is underground with 200 mm above from ground – So, there should not be an issue • Will they use these structures for wastewater diversion? <ul style="list-style-type: none"> ○ Almost all households have septic tank arrangements for wastewater disposal ○ Sewer network with islandwide coverage is also under construction, so this is unlikely • Will they clean the roof periodically and especially before the rainy season? <ul style="list-style-type: none"> ○ House owners already clean their roofs and gutters before using water so we do not think that there will be an issue • Can these wells be maintained properly? <ul style="list-style-type: none"> ○ Will not have to clean as much since it is covered ○ Most houses also already have covered wells or underground, so no such requirement to clean often • Any other impacts? <ul style="list-style-type: none"> ○ Should not be an issue if houses have space-might have some issues making space in the households. ○ If placed on the road, this will require more planning as it could create complications in any possible relocation

Proposed Recharging Structures	Details of MAR Systems	Feasibility and Other Remarks
<p>Road runoff recharging structures</p> <p>1) Installation of “U” shaped precast concrete drains along the one side of the road.</p> <p>2) Series of recharging wells will be connected to drains.</p> <p>3) Size of the recharging structure (Depth: 1.5 m, Width: 1.0 m, Length: 1.0 m).</p>	<p>1) Drain is open and the depth is 0.6 m.</p> <p>2) Cover slab will be provided for drains for road crossings.</p> <p>3) Cover slab will be provided to cover the recharging pit.</p> <p>4) Top level of the recharging pit is 0.3 m above the ground level.</p> <p>5) Excess water in the drain will be diverted to recharging ponds or the sea.</p>	<ul style="list-style-type: none"> • Will Road authorities give permission to build these structures along the roads? <ul style="list-style-type: none"> ○ Council will be able to give required permissions ○ Sewerage network is in the middle of the road, One side has water lines and the other side has electricity wires already ○ Roads are already very narrow, so space and safety issues • Can there be any safety issues, especially for children/cyclists/ pedestrians? <ul style="list-style-type: none"> ○ Might face issues if it is above ground level ○ Already get complaints about junctions being above ground level • Will they use these structures for wastewater diversion and solid waste disposal? <ul style="list-style-type: none"> ○ No • Impact on existing services including electricity, water, cable TV, telecommunication, etc? <ul style="list-style-type: none"> ○ Will not be difficult in wide roads but do not think there will be space in narrow roads ○ Require careful planning ○ Electricity, TV cables are laid usually 1-3 ft away from sidewalls (one third of the road distance generally) ○ Yellow mark- vertical – 18 ft, other is 30 ft, the horizontal is also 30 ft ○ The long yellow marked roads (on map) already have other services established, probably 1 m from the roadside is available • Can they be well maintained? <ul style="list-style-type: none"> ○ Yes, if it is covered, but there is a chance of it being blocked by debris leaves and fines/sand ○ A lot of trees on the road • Who will maintain them? <ul style="list-style-type: none"> ○ Council will supervise; Council will award a third party contract to maintain • Any other impacts? <ul style="list-style-type: none"> ○ Do not know/There may be not

Proposed Recharging Structures	Details of MAR Systems	Feasibility and Other Remarks
<p>Contour drains Earth drains will be provided to control the overland flow.</p>	<p>Earth drains will be provided for agricultural lands.</p>	<ul style="list-style-type: none"> • Are there lands available for these structures? <ul style="list-style-type: none"> ○ Yes - available around the red marked area • Any impact on agricultural practices and will it limit or affect land available for agriculture. <ul style="list-style-type: none"> ○ No issues since it will be on the road - on the red marked area ○ Will probably help agriculture since it will help to improve the water quality - the residents are mostly engaged in agriculture so believe it can help ○ Land allocation will not affect the farmers but need careful installation of the system • Will any safety issues arise? <ul style="list-style-type: none"> ○ Do not believe so but if it is kept on the roads, it is important to level it with the ground • Can they be properly maintained? <ul style="list-style-type: none"> ○ If it is given to the Council, they will have to get a third party to maintain them ○ Near Kandoofaa/wetland, so do not believe mosquitoes will breed • Any other impacts? <ul style="list-style-type: none"> ○ Do not believe so ○ If it is on land, it should be fine but water is salty in that area
<p>Aquifer modification Installation of liner for subsurface and construction of earth bunt or road up to required level.</p>	<p>Concrete or bentonite or weathered clayey soil is used as liner.</p>	<ul style="list-style-type: none"> • Land ownership issues of council/private lands? <ul style="list-style-type: none"> ○ Have to talk to residents of the nearby houses to determine it better • Will there be any impact on agricultural practices? <ul style="list-style-type: none"> ○ Do not think any negative impact will be there • Will there be any negative impact due to the rise in the groundwater table (this is common to all)? <ul style="list-style-type: none"> ○ Difficult to say – need to survey ○ Do not think it will have a negative impact • Any other impacts? <ul style="list-style-type: none"> ○ Difficult to say – need to survey

Summary on the institutional survey and write up was included under the Chapter 5 for all the islands.

4.6 Quantification and Cost Estimation of Proposed Conceptual Designs

Based on the hydrogeological, and hydrological settings of the selected islands, different recharging methods are proposed for the given islands to improve the available groundwater quantity and quality of the island while managing the storm water. The available raw water for groundwater recharge is rainwater in the form of roof water and overland flow.

The roof water collection and recharging, road runoff recharging, recharging ponds, contour drains, and controlling groundwater flow through aquifer modification are mainly selected options for groundwater recharging of selected islands. The estimated cost of each recharge method is given in the table below.

Table 4.2: Estimates of costs

Proposed recharging method		Unit	Unit Rates for Construction (MVR)
Recharging Well	Type A	No.	18,000.00
	Type B	No.	25,000.00
	Type C	No.	33,500.00
Road runoff recharging	Drain	m	8,100.00
	Recharging pit	No.	18,900.00
Recharging pond		No.	550,000.00
Aquifer modification / Barrier wall	Bentonite/cement slurry/clay rich residual soil	m ²	550.00
	Rock and earth	m ²	350.00

4.6.1 Roof recharging structures

For the analysis, it is assumed that all roofs, gutters, and other accessories are in good condition.

The roof structures are categorized into three groups based on the probability existence of 25% (type:1), 50% (type:2) and 75% (type:3). The roof water in different roof structures is proposed to infiltrate through different recharging well structures. The proposed sizes of well structures are given in Table 4.16. A mesh should be provided for the top of the recharging well to avoid the addition of foreign materials to the recharging well. The excess water will be diverted to the road side drain through 90/160 mm PVC pipes.

Note: It is assumed that all roofs, gutters, and other accessories are in good condition and

Table 4.16: Proposed recharging well types

Recharging well type	Diameter (m)	Depth of the well (m)	Thickness of filter bed (m)	Well head above ground level (m)
Type A	1	1.5	0.3	0.2
Type B	1.5	1.5	0.3	0.2
Type C	2	1.5	0.3	0.2

The required quantities of roof recharging structures are given in island wise in Table 4.17 to Table 4.21.

Table 4.17: Required quantities of roof recharging structures in Kandoodhoo

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type A	60	1	60	13%
Type B	120	1	120	85%
Total	180		180	95%

Note: Roof area <35 m² is not covered with recharging structures. About 95% roof of areas are covered with proposed recharging structures.

Table 4.18: Required quantities of roof recharging structures in Vandhoo

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type A	37	1	37	12.6%
Type B	37	1	37	26.3%
Type C	37	1	37	57.2
Total	111		111	96.1%

Note: Roof area <36m² is not covered with recharging structures. About 96.1% roof of areas are covered with proposed recharging structures.

Table 4.19: Required quantities of roof recharging structures in Omadhoo

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type A	55	1	55	15%
Type B	110	1	110	80%
Total	165		165	95%

Note: Roof area <42 m² is not covered with recharging structures. About 95% roof of areas are covered with proposed recharging structures.

Table 4.20: Required quantities of roof recharging structures in Gaadhiffushi

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type A	31	1	31	17.2%
Type B	62	1	62	80.5%
Total	93		93	97.7%

Note: Roof area <61 m² is not covered with recharging structures. About 97.7% roof of areas are covered with proposed recharging structures.

Table 4.21: Required quantities of roof recharging structures in Foakaidhoo

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type B	160	2	160	41.2%
Type C	80	1	80	52.8%
Total	240		240	94%

Note: Roof area <65 m² is not covered with recharging structures. About 94% roof of areas are covered with proposed recharging structures.

4.6.2 Road runoff recharging.

The overland flow along the selected road stretch is collected to the drain that is to be constructed along one side of the road by using pre-cast “U”-shaped concrete blocks. The collected water in the drain is diverted to a series of recharging pits to be provided along the drain. The bottom of the recharging pit is unlined and a precast concrete slab will be provided to cover the recharging pit. Also, a cover slab is considered for road crossing.

Proposed drain: Width - 0.5 m, depth – 0.6 m, 18(60 mm) holes per one-meter section at bottom of the drain.

Proposed recharging pit: Width-1 m. Lenth-1 m, depth-1.5 m, the thickness of filter layer-0.3 m, spacing between two pits – 25 m.

The required length of the drains and recharging pits for selected islands are given in the following table.

Table 4.22: Required length of the drains and recharging pits

Number of selected roads	Total length of selected road(m)	Required Pre-cast concrete structures		Required recharging pits with cover slabs
		If length is 1 m	If length is 2 m	
Kandoodhoo				
7	2630	2524	1262	106
Vandhoo				
9	1934	1852	926	82
Omadhoo				
12	3630	3490	1740	150
Gadhiffushi				
11	2137	2048	1024	89
Foakaidhoo				
9	4400	4422	2111	178

4.6.3 Recharging pond

The proposed recharging ponds are connected with recharging drains to increase the recharging amounts. These systems are proposed only for two islands such as Kandoodhoo and Omadhoo.

Table 4.23: No. of proposed recharging ponds

Island	Number of ponds proposed
Kandoodhoo	1
Omadhoo	2

Details of the recharging pond: width-10 m, length-15 m, depth-1, gabion wall for avoiding the direct mixing of the play groundwater to the recharging pond, and filter bed of about 0.25 m thick sand layer at the bottom.

4.6.4 Application of Aquifer Modifications

Under aquifer modification, controlling groundwater flow within the island and sea water flooding is considered. These systems are proposed for four islands and details are given below.

Table 4.24: Proposed aquifer modifications of the islands

Island	Details
Kandoodhoo	Impermeable liner to control the sea water flooding and to increase groundwater thickness.
Vandhoo	Impermeable liner to control the sea water flooding and to increase groundwater thickness.
Gaadhiffushi	Impermeable liner to control the sea water flooding.
Foakaidhoo	Impermeable liner to control the sea water flooding.

4.7 Validation of the Proposed Recharge Structures

Excess water from the proposed roof water recharging systems was added to the proposed recharge trenches along the road. Hence, validation was carried out for the road runoff recharging system. The two approaches such as SCS and rational formula are used to estimate the possible runoff amount for different rainfall durations and different return periods.

Rational Formula; $Q = CIA$

Where;

Q = Design Discharge (m³/s)

C = Runoff Coefficient

I = Rainfall Intensity (m/s)

A = Catchment Area (m²)

Soil Conservation Service (SCS) equation (Equations are available for general condition, wet condition and dry condition)

General Condition;

$$Pe(\text{inch}) = (P - 0.2S)^2 / (P + 0.8S)$$

$$Fa = P - Pe - Ia.$$

Where: Pe= Excess rainfall for direct run off, S =Maximum soil storage, P = Total Precipitation, Ia = Initial abstraction, Fa = Continuous abstraction/soil retention.

For dry condition: $CN(\text{dry}) = 4.2 CN(\text{normal}) / (10 - 0.58 CN(\text{normal}))$

For wet condition: $CN(\text{wet}) = 23 CN(\text{normal}) / (10 + 0.13 CN(\text{normal}))$

The aforementioned two approaches were tested for all the islands and a sample calculation performed for Kandoodhoo Island is presented below.

4.7.1 Rational Formula Method

Following table illustrates the summary of the rainfall intensity values for the Southern Islands taken from the developed IDF curves. IDF curves developed for the Southern and Northern Islands with use of 30 year rainfall data of Kandhoo Island and Hanimadhoo island are attached under Annex X.

Table 4.25: Rainfall Intensities taken from developed IDF curves

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	59.0	61.4	65.4	77.3
1	44.6	48.8	53.0	64.0
3	28.5	33.7	37.8	46
6	17.9	20.9	23.8	27.1

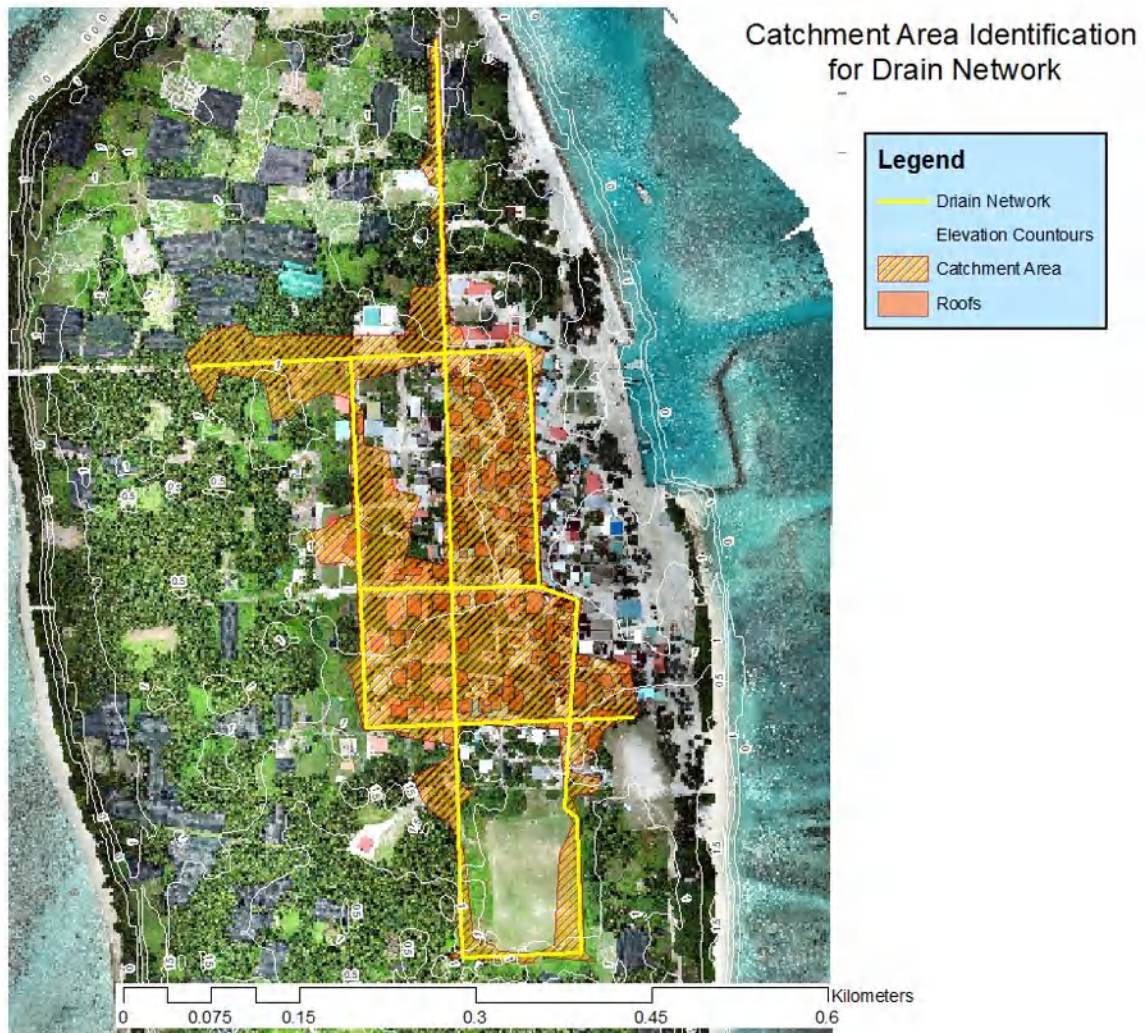


Figure 4-12: Identified catchment areas for the drain capacity calculations

Catchment area for the recharge trench network = 70,010 m²

Aggregate runoff coefficient for the identified catchment area = 0.37

Following table illustrates the calculated overland flow quantities.

Table 4.26: Calculated overland flow quantities (m³)

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	1,478	1,538	1,639	1,937
1	1,117	1,223	1,328	1,603

3	714	844	947	1,152
6	448	524	596	679

4.7.2 Soil Conservation Service (SCS) Method

All the calculations and assumptions are given in Annex X and summarised generated runoff per square meter for residential area and the whole island is given in the following table. The results show that runoff generation is mainly expected in residential areas with compared to other areas. Therefore, recharging drains were mainly proposed for residential areas.

Table 4.27: Expected runoff per square meter area for the island and residential area

Duration (Hour)	SCS method					
	General		Wet		Dry	
	Runoff per square meter for land (m ³)	Runoff per square meter for resident (m ³)	Runoff per square meter for land (m ³)	Runoff per square meter for resident (m ³)	Runoff per square meter for land (m ³)	Runoff per square meter for resident (m ³)
Two- years return period						
0.5	1.19 x 10 ⁻²	1.7 x 10 ⁻²	2.74 x 10 ⁻²	3.40 x 10 ⁻²	10.16 x 10 ⁻²	0.4 x 10 ⁻²
1	0.56 x 10 ⁻²	1 x 10 ⁻²	1.67 x 10 ⁻²	2.22 x 10 ⁻²	-	0.09 x 10 ⁻²
3	0.1 x 10 ⁻²	0.27 x 10 ⁻²	0.6 x 10 ⁻²	1 x 10 ⁻²	-	-
6	0.004 x 10 ⁻²	0.02 x 10 ⁻²	0.2 x 10 ⁻²	0.35 x 10 ⁻²	-	-
9	-	-	0.05 x 10 ⁻²	0.12 x 10 ⁻²	-	-
Five -years return period						
0.5	1.32 x 10 ⁻²	2.02 x 10 ⁻²	2.92 x 10 ⁻²	3.65 x 10 ⁻²	0.17 x 10 ⁻²	0.47 x 10 ⁻²
1	0.74 x 10 ⁻²	1.22 x 10 ⁻²	1.97 x 10 ⁻²	2.57 x 10 ⁻²	0.05 x 10 ⁻²	0.17 x 10 ⁻²
3	0.25 x 10 ⁻²	0.47 x 10 ⁻²	0.97 x 10 ⁻²	1.37 x 10 ⁻²	-	-
6	0.02 x 10 ⁻²	0.07 x 10 ⁻²	0.31 x 10 ⁻²	0.22 x 10 ⁻²	-	-
9	-	-	0.10 x 10 ⁻²	-	-	-
Ten-year return period						
0.5	1.48 x 10 ⁻²	2.29 x 10 ⁻²	3.2 x 10 ⁻²	3.94 x 10 ⁻²	0.27 x 10 ⁻²	0.70 x 10 ⁻²
1	0.73 x 10 ⁻²	1.15 x 10 ⁻²	2.26 x 10 ⁻²	2.92 x 10 ⁻²	0.07 x 10 ⁻²	0.25 x 10 ⁻²
3	0.37 x 10 ⁻²	0.65 x 10 ⁻²	1.22 x 10 ⁻²	1.67 x 10 ⁻²	-	0.02 x 10 ⁻²
6	0.06 x 10 ⁻²	0.15 x 10 ⁻²	0.44 x 10 ⁻²	0.70 x 10 ⁻²	-	-
9	-	0.02 x 10 ⁻²	0.16 x 10 ⁻²	0.32 x 10 ⁻²	-	-

The results of the above two approaches are compared and illustrated in the below table. The results obtained for lower rainfall durations for respective return periods taken from the Rational Formula Method are higher compared to that of the SCS method. Therefore, the results of the Rational Formula Method are considered for the capacity calculation and sizing of recharge drains (trenches) using the Continuity equation and Manning's Equation.

Table 4.28: Summary of the comparison of the SCS method and

Duration (Hour)	Rainfall (mm)	Total catchment (m ²)	SCS method						Rational Equation Method (m ³)
			General		Wet		Dry		
			Rainfall depth % for runoff	Total runoff (m ³)	Rainfall depth % for runoff	Total runoff (m ³)	Rainfall depth % for runoff	Total runoff (m ³)	
Two- years return period									
0.5	59	70,010	31.4	1297	58.4	2412	6.7	277	1478
1	44.6		22.5	703	50	1561	1.7	53	1117
3	28.5		9.6	192	35.1	700	-	-	714
6	17.9		1.4	17	19.4	218	-	-	448
Five -years return period									
0.5	61.4	70,010	32.9	1414	59.3	2549	7.7	331	1538
1	48.8		25.1	857	52.8	1804	3.6	123	1223
3	33.7		14.1	333	40.7	960	-	-	844
6	20.9		3.6	53	25	366	-	-	524
Ten-year return period									
0.5	65.4	70,010	35.1	1607	61	2793	9.2	421	1639
1	53		27.8	1031	55.1	2044	4.5	167	1328
3	37.8		17.2	455	44.3	1172	1	17	947
6	23.8		6.3	105	29.5	491			596

4.7.3 Capacity Calculation and Sizing of Drain Network

Capacity estimations of drain sections were carried out using Continuity Equation and Manning's Equation shown below.

Continuity Equation: $Q = AV$ Where; Q = Design Capacity (m ³ /s) A = Cross Sectional Area of Flow (m ²) V = Flow Velocity (m/s)	Manning's Equation: $V = \frac{1}{n} R^{2/3} S^{1/2}$ Where; V= Velocity of Flow (m/s) n = Manning's Roughness Coefficient R = Hydraulic Radius (m) S = Channel Slope $R = A/P$ Where; A = Cross Sectional Area of Flow (m ²) P = Wetted Perimeter (m)
---	---

Proposed slope for the drain network (%) = 0.8

Considering the depth to the freshwater level, 350 mm depth drain was considered with a free board of 15% (50 mm).

4.7.3.1 Considering identified catchment area for the whole network would be managed by a single drain

Following table shows the calculated drain width for the considered 0.350 m depth for each scenario based on return period and rainfall duration.

Table 4.29: Calculated width of single drain network for respective scenario

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	0.709	0.731	0.767	0.871
1	0.577	0.616	0.655	0.754
3	0.418	0.471	0.511	0.590
6	0.303	0.337	0.368	0.403

Therefore, the required width of the drain for the 25 year return period scenario is nearly 0.9 m which will need additional space for covering and turfing from the available road space. And also, a single road network is inability collect water and recharge rainwater in adjacent road areas. Hence, it was considered that the drain network should be consists of parallel drains. Drain capacity calculation for two parallel drain network considered for Kandoodhoo island is discussed in the following chapter.

4.7.3.2 Considering identified catchment area for the whole network would be managed by two parallel drains

Table below illustrates the calculated width of the parallel drain network with respect to scenarios based on return period and rainfall duration.

Table 4.30: Calculated width of parallel drain network for respective scenario

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	0.428	0.440	0.461	0.519
1	0.352	0.375	0.397	0.454
3	0.259	0.290	0.314	0.360
6	0.190	0.211	0.230	0.251

Therefore, a drain network with 0.5 m width would be satisfied the requirement for the 30-minute rainfall duration for 25-year return period. Hence parallel drain network with cross section of 0.5 m width x 0.35 m depth will be selected.

Similarly, for the remaining islands calculations were carried out in the same way and selected the feasible drain network for each island.

5 RESULTS AND RECOMMENDATIONS FOR DETAILED DESIGN

5.1 Conceptual Designs for Managed Aquifer Recharge (MAR)

The selection of method/s for the recharging of a particular island is based on the hydrogeological and hydrological conditions of each island (Table 5.1).

Table 5.1: Proposed recharging structures

Visited Island	Selected recharging methods				
	Roof water recharging	Road runoff recharging	Recharging pond	Aquifer modification/ Barrier wall	Contour drain
Kandoodhoo	Yes	Yes	Yes	Yes	No
Vandhoo	Yes	Yes	No	Yes	No
Omadhoo	Yes	Yes	Yes	No	No
Gaadhiffushi	Yes	Yes	No	Yes	No
Foakaidhoo	Yes	Yes	No	Yes	No

5.1.1 Roof Water Recharging Structures

Three types of recharging wells were selected based on the average hydraulic conductivity and roof area distribution of each island. The dimensions and capacity of each selected type of well are illustrated in the following table.

Table 5.2: Dimensions and capacity of proposed roof water recharging wells types

Type	Proposed Recharging Well Details				Total Storage of the Well (m ³)
	Well Type	Depth (m BGL)	Diameter (m)	No. of Recharging Wells	
Type 1	A	1.5	1	1	0.78
Type 2	B	1.5	1.5	1	1.76
Type 3	C	1.5	2.0	1	3.14

A summary of the proposed quantities of recharging wells and their potential recharging volume per year is illustrated in the following table from the calculations done for each island based on the hydraulic conductivity and roof area distribution of each island.

Table 5.3: Summary of proposed quantities and yearly recharging potential from recharging wells

Island		Type A	Type B	Type C	Total
Kandoodhoo	No of Recharging Structures Proposed	60	120	-	180
	Total Recharging Volume per year (m ³)	26,050	117,223	-	143,273

Island		Type A	Type B	Type C	Total
Vandhoo	No of Recharging Structures Proposed	37	37	37	111
	Total Recharging Volume per year (m ³)	2,008	4,561	8,131	14,700
Omadhoo	No of Recharging Structures Proposed	55	110	-	165
	Total Recharging Volume per year (m ³)	7,628	34,565	-	42,193
Gaadhiffushi	No of Recharging Structures Proposed	31	62	-	93
	Total Recharging Volume per year (m ³)	10,904	49,183	-	60,087
Foakaidhoo	No of Recharging Structures Proposed	-	160	80	240
	Total Recharging Volume per year (m ³)	-	93,514	41,942	135,456

5.1.2 Road Runoff Recharging

A summary of the selected road length of each island and daily & yearly recharging potential is mentioned in the following table.

Table 5.4: Summary of proposed quantities and yearly recharging potential from road runoff recharging systems

Island	Selected Road Length (m)	Daily Recharging Potential (m ³)	Yearly Recharging Potential (m ³)
Kandoodhoo	2,630	2,154	143,732
Vandhoo	1,934	401	26,860
Omadhoo	3,630	1,335	89,465
Gaadhiffushi	2,137	1,749	117,176
Foakaidhoo	4,400	1,868	102,751

5.1.3 Recharging Using Recharging Ponds

Recharging ponds were proposed only for Kandoodhoo and Omadhoo island considering the depth to the water table, topography, hydraulic conductivity of the Island.

Table 5.5: Summary of proposed quantities and yearly recharging potential from recharging ponds

Island	No. of Proposed Recharging Ponds	Daily Recharging Potential (m ³)	Yearly Recharging Potential (m ³)
Kandoodhoo	1	1,239	84,420
Omadhoo	2	888	63,516

5.1.4 Application of Aquifer Modifications

Aquifer modification structures were proposed for the Kandoodhoo, Vandhoo, Gaadhiffushi, and Foakaidhoo islands and the following table illustrates the summary of the aquifer modification methods and predicted groundwater enhancement.

Table 5.6: Summary of proposed aquifer modification methods and estimated GW enhancement

Island	Proposed Aquifer Modification Method	Estimated GW enhancement (m ³)
Kandoodhoo	Impermeable (clay) liner	16,400
Vandhoo	Impermeable (clay) liner	5,125
Gaadhiffushi	Barrier wall (earth bund)	360
Foakaidhoo	Impermeable (clay) liner	12,480

5.2 Social and Environmental Feasibility and Impact of Proposed MAR Systems

Four types of recharging structures for the MAR system (Recharging wells, Road runoff recharging structures, Recharging pond, and Aquifer modification) have been proposed based on the physical condition of the island. Recharging wells and road runoff recharging systems are placed mainly within the residential areas while recharging ponds and aquifer modification structures are mainly placed within non-residential areas. Major changes expected due to these proposed structures are raising the groundwater table, increasing the soil moisture content and creating temporary surface water bodies/wells for increased groundwater recharge.

Possible impacts on residents due to proposed recharging systems were assessed by interviewing the Council representatives and information on social impacts were collected based on questionnaire surveys conducted representing the communities on the island. However, according to the feedback received from surveys on the social impact due to the proposed recharging structures, there will be minimal negative impacts on the social environment as the proposed structures are simple and environmentally friendly. Because Further, it was found that there will be no considerable impact on day to day lifestyles of the people, safety aspects, economic activities, etc. As per health issues raised, it can be considered that open surface water bodies will be vulnerable to becoming mosquito breeding sites. As these water retention in these structures is temporally limited to a short period, the such impact may also not be much significant. Other major changes expected are increased water table and higher soil moisture content of topsoil. There will be some impact on agricultural practices due to this and there can also be positive impacts due to reduced requirement for watering. Another impact of the increased groundwater table expected is the change in the geotechnical properties of subsurface soil layers. But fluctuation of the groundwater table in these islands is a very common phenomenon in a tropical country and there is a greater impact due to the tidal effect on the groundwater table. Therefore, it is hard to expect extraordinary changes in the geotechnical properties of the subsurface soil layers due to proposed recharging structures.

According to the feedback obtained, the proposed MAR structures do not show considerable negative impacts on the social and natural environment and as they are simple and manageable, they will be feasible to implement on the island. Further, as these structures are simple and need only minor regular maintenance processes with low-cost methods, there will be no issues with maintaining the proposed structures.

5.3 Quantification and Cost Estimation of Proposed Conceptual Designs

Table 5.2: Estimates costs

Proposed recharging method		Unit	Unit Rates for Construction (MVR)
Recharging Well	Type A	No.	18,000.00
	Type B	No.	25,000.00
	Type C	No.	33,500.00
Road runoff recharging	Drain	m	8,100.00
	Recharging pit	No.	18,900.00
Recharging pond		No.	550,000.00
Aquifer modification / Barrier wall	Bentonite/cement slurry/clay rich residual soil	m ²	550.00
	Rock and earth	m ²	350.00

The total construction cost based on the concepts is provided below.

Table 5.7: Deviation of the construction cost for proposed aquifer modifications

Island		Kandoodhoo	Vandhoo	Omadhoo	Gaadhifushi	Foakaidhoo
Recharging Well	Type A	1,080,000	666,000	990,000	558,000	-
	Type B	3,000,000	925,000	2,750,000	1,550,000	4,000,000
	Type C	-	1,239,500	-	-	2,680,000
Road runoff recharging	Drain	21,303,000	15,665,400	29,403,000	17,309,700	35,640,000
	Recharging pit	2,003,400	1,549,800	2,835,000	1,682,100	3,364,200
Recharging pond		550,000	550,000	-	1,100,000	-
Aquifer modification / Barrier wall	Bentonite/cement slurry/clay rich residual soil	1,100,000	866,250	-	-	1,760,000
	Rock and earth	-	-	-	1,155,000	-

Table 5.8: Deviation of estimated total cost and Operation and Maintenance Cost

Island	Estimated construction cost MVR	Estimated Operation and Maintenance cost (estimated as 3% of capital cost) MVR
Kandoodhoo	29,036,400.00	871,092.00
Vandhoo	20,911,950.00	627,358.50
Omadhoo	37,078,000.00	1,112,340.00
Gaadhifushi	22,254,800.00	667,644.00
Foakaidhoo	47,444,200.00	1,423,326.00

5.4 Validation of the Proposed Recharge Structures

5.4.1 Th. Kandoodhoo

Catchment area for the recharge trench network = 70,010 m²

Aggregate runoff coefficient for the identified catchment area = 0.37

The following table illustrates the calculated overland flow quantities.

Table 5.9: Calculated overland flow quantities (m³) – Th. Kandoodhoo

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	1,478	1,538	1,639	1,937
1	1,117	1,223	1,328	1,603
3	714	844	947	1,152
6	448	524	596	679

Table 5.10: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Kandoodhoo

Recharging option	Daily Recharge Volume (m ³)	Hourly Recharge Volume (m ³)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m ³)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m ³)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m ³)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m ³)
Roof Recharging	1,069	45	45	89	178	312
Road Runoff	2,154	90	90	180	359	628
Recharging pond	1,239	52	52	103	207	361
Provision for storage = 288 m ³						
Total Recharge and Storage Volume (m ³)	4,750	474	474	660	1,032	1,589

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that for normal rainfall events the overland flow would be managed for 10 year return period. And in extreme events (30 min rainfall) 32% of the generated overland flow would be managed for the 2-year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1-hour rainfall duration, 59% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.4.2 Th. Vandhoo

Catchment area for the recharge trench network = 27,428 m²

Aggregate runoff coefficient for the identified catchment area = 0.30

The following table illustrates the calculated overland flow quantities.

Table 5.11: Calculated overland flow quantities (m³) – Th. Vandhoo

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	481	500	533	630
1	363	398	432	522
3	232	275	308	371
6	146	170	194	221

Table 5.12: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Vandhoo

Recharging option	Daily Recharge Volume (m ³)	Hourly Recharge Volume (m ³)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m ³)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m ³)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m ³)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m ³)
Roof Recharging	154	6	6	13	26	45
Road Runoff	401	17	17	33	67	117
Provision for storage = 159 m ³						
Total Recharge and Storage Volume (m³)	714	182	182	205	252	321

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that for normal rainfall events the overland flow would be managed for 2 year return period. And in extreme events (30 min rainfall) 38% of the generated overland flow would be managed for the 2-year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1-hour rainfall duration, 56% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.4.3 Th. Omadhoo

Catchment area for the recharge trench network = 51,108 m²

Aggregate runoff coefficient for the identified catchment area = 0.44

The following table illustrates the calculated overland flow quantities.

Table 5.13: Calculated overland flow quantities (m³) – Th. Omadhoo

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	1,320	1,373	1,463	1,729
1	998	1,092	1,186	1,432
3	638	754	846	1,018
6	400	468	532	606

Table 5.14: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Omadhoo

Recharging option	Daily Recharge Volume (m ³)	Hourly Recharge Volume (m ³)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m ³)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m ³)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m ³)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m ³)
Roof Recharging	441	18	18	37	73	129
Road Runoff	1,335	56	56	111	223	389
Recharging pond	888	37	37	74	148	259
Provision for storage = 288 m ³						
Total Recharge and Storage Volume (m ³)	2,960	407	407	518	740	1,073

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that for normal rainfall events the overland flow would be managed for 2 year return period. And in extreme events (30 min rainfall) 31% of the generated overland flow would be managed for the 2 year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1 hour rainfall duration, 52% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.4.4 Th. Gaadhiffushi

Catchment area for the recharge trench network = 34,385 m²

Aggregate runoff coefficient for the identified catchment area = 0.42

The following table illustrates the calculated overland flow quantities.

Table 5.15: Calculated overland flow quantities (m³) – Th. Gaadhiffushi

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	845	879	936	1,107
1	639	699	759	916
3	408	483	541	652
6	256	299	341	388

Table 5.16: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Gaadhiffushi

Recharging option	Daily Recharge Volume (m ³)	Hourly Recharge Volume (m ³)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m ³)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m ³)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m ³)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m ³)
Roof Recharging	628	26	26	52	105	183
Road Runoff	1,749	73	73	146	292	510
Provision for storage = 288 m ³						
Total Recharge and Storage Volume (m ³)	2,510	232	232	331	529	827

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that, for normal rainfall events the overland flow would be managed for 5 year return period. And in extreme events (30 min rainfall) 28% of the generated overland flow would be managed for the 2 year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1 hour rainfall duration, 52% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.4.5 Sh. Foakaidhoo

Catchment area for the recharge trench network = 85,462 m²

Aggregate runoff coefficient for the identified catchment area = 0.48

The following table illustrates the calculated overland flow quantities.

Table 5.17: Calculated overland flow quantities (m³) – Th. Kandoodhoo

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	2,278	2,583	2,888	3,498
1	1,546	1,729	1,993	2,522
3	895	1,110	1,273	1,493
6	517	622	704	809

Table 5.18: Summary of recharge estimations and storage of each recharging option for respective rainfall events – Th. Kandoodhoo

Recharging option	Daily Recharge Volume (m ³)	Hourly Recharge Volume (m ³)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m ³)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m ³)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m ³)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m ³)
Roof Recharging	1,859	77	77	155	310	542
Road Runoff	2,154	90	90	180	359	628
Provision for storage = 288 m ³						
Total Recharge and Storage Volume (m ³)	4,436	590	590	757	1,091	1,593

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that, for normal rainfall events the overland flow would be managed for 2 year return period. And in extreme events (30 min rainfall) 26% of the generated overland flow would be managed for the 2 year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1 hour rainfall duration, 49% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.5 Recommendations for Detailed Design

Fresh groundwater occurs in the form of ‘freshwater lenses’ in medium to large scale Maldivian islands and these lenses play an important role as a source of water supply. Further, they are highly susceptible to saline water intrusions due to over pumping and are vulnerable to pollution from the surface and sub-surface waste disposal, particularly from sanitation systems.

The fresh groundwater lenses show some inflow and outflow conditions. However, changes in groundwater level, shape of the lense and groundwater quality could be observed which are due to several processes such as tidal effect, annual climatic cycle, and addition of wastewater to groundwater. Therefore, groundwater enhancement within the islands is vital for sustainable management of groundwater sources.

The feasibility studies for enhancement of groundwater quality and quantity of the islands studied are conducted based on hydrological, hydrogeological and social/environmental conditions. Further, several assumptions were made to generalize and quantify the recharging structures to suit practical situations.

Several recharging methods have been proposed for the islands studied to improve the available groundwater quantity and quality while managing the stormwater based on the space availability, topography, land use and subsurface conditions. The main source of available raw water for groundwater recharge is rainwater in the form of roof water and overland flow (runoff).

The methods applied in the proposed MAR systems are mainly roof water collection and recharging, road runoff recharging, recharging pond, contour drains, and controlling groundwater flow through aquifer modification for the islands studied. The predicted recharge through proposed structures and available groundwater amounts (water balance model and geophysical method) have been compared and details are given in Table 5.19.

Table 5.19: Comparison between predicted recharge amount and available groundwater amount

Island	Recharging Method or Methods Used for Assessment of Existing Groundwater Amounts	Groundwater Amount/Predicted Recharge (m ³ /year)	Predicted Recharge as a Percentage to Existing Groundwater Amount (%)
Kandoodhoo	Recharging method		
	Roof recharging system	143,272	
	Road runoff recharging system	143,732	
	Recharging pond	84,420	
	Aquifer modification	16,400	
	Total	387,825	
	Groundwater quantification approaches		
	Water balance method	192,803	200%
	Indirection investigation through resistivity method	125,297	309%
Vandhoo	Recharging method		
	Roof recharging system	14,700	
	Road run off recharging system	26,860	

Island	Recharging Method or Methods Used for Assessment of Existing Groundwater Amounts	Groundwater Amount/Predicted Recharge (m ³ /year)	Predicted Recharge as a Percentage to Existing Groundwater Amount (%)
	Aquifer modification	5,125	
	Total	46,685	
	Groundwater quantification approaches		
	Water balance method	31,320	149%
	Indirection investigation through resistivity method	31,617	147%
Omadhoo	Recharging method		
	Roof recharging system	42,193	
	Road run off recharging system	89,465	
	Recharging ponds	63,516	
	Total	195,174	
	Groundwater quantification approaches		
	Water balance method	37,787	516%
	Indirection investigation through resistivity method	36,622	532%
Gaadhiffushi	Recharging method		
	Roof recharging system	60,087	
	Road run off recharging system	117,176	
	Aquifer modification	360	
	Total	177,623	
	Groundwater quantification approaches		
	Water balance method	9,953	1784%
	Indirection investigation through resistivity method	14,634	1213%
Foakaidhoo	Recharging method		
	Roof recharging system	135,456	
	Road run off recharging system	102,751	
	Aquifer modification	12,480	
	Total	250,687	
	Groundwater quantification approaches		
	Water balance method	77,663	322%
	Indirection investigation through resistivity method	68,776	364%

As per the comparison, the predicted recharging amount through proposed structures in Omadhoo and Gaadhiffushi islands is more than 500% higher than the available groundwater amount during the period of investigation from the selection of a large number of roofs (94% of roof area) as well as long road lengths for groundwater recharge.

The groundwater quantity and quality will be improved in these islands with the increase of recharge. In the terms of environmental and social feasibility, the proposed structures are mostly feasible as they are very simple, environmentally friendly and easy/low cost to maintain. However, from the social concerns raised, the space availability for proposed recharging wells within the land blocks is a concern and there may be some issues and restrictions.

Based on the findings of the Feasibility Study, the following recommendations could be made.

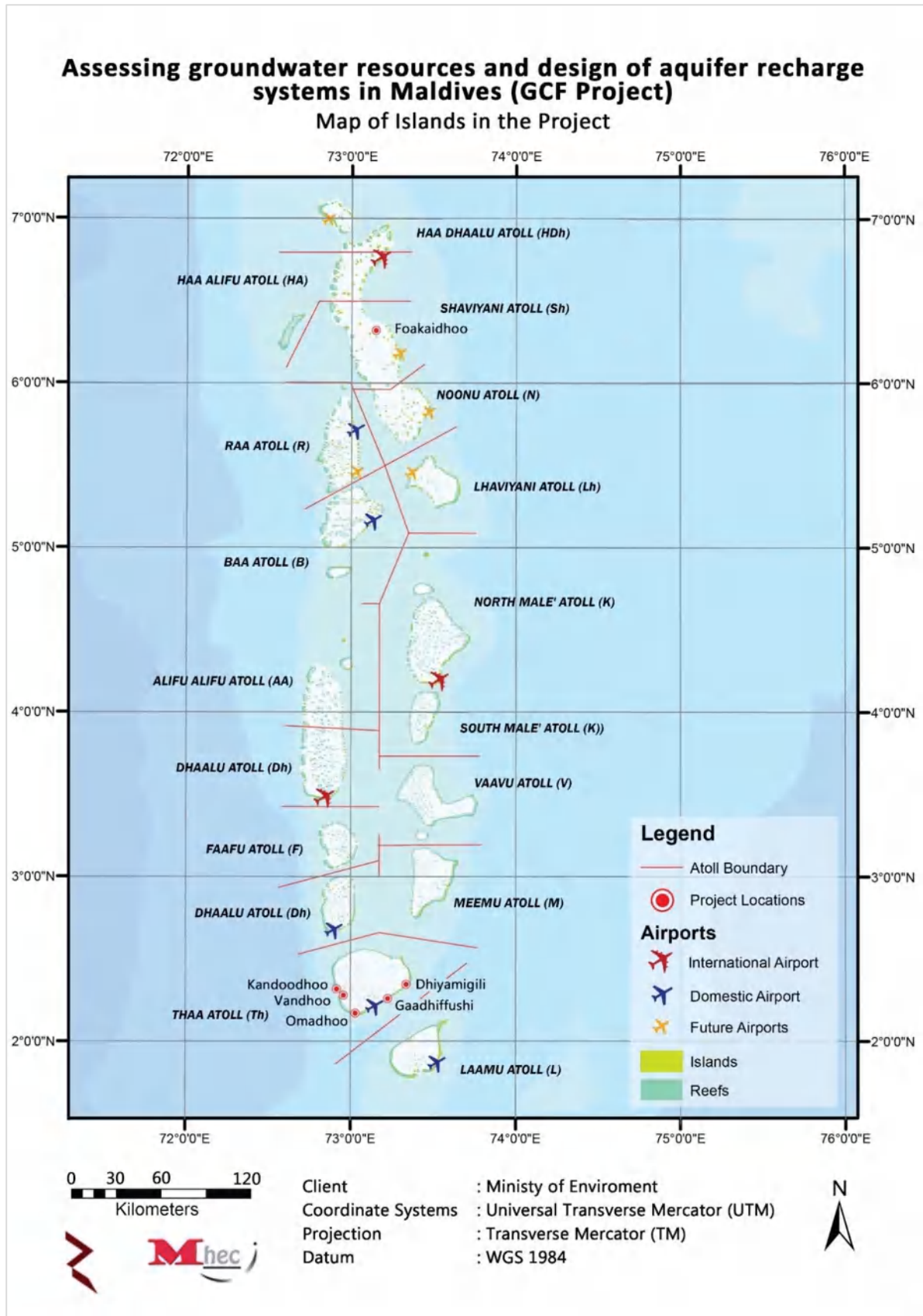
- Groundwater recharge could be carried out through proposed structures to improve the groundwater quantity and quality in all islands studied.
- Suitable percentage of roof is to be selected for the roof recharging purposes with the consultation of the client/stakeholders before the detailed designs.
- Small recharging wells are to be installed for the house blocks and large size of wells are to be installed for schools, mosques, and other common places.
- All designs should be finalized after liaising with and consultation of all stakeholders such as Power suppliers, Telecom facility providers, Drainage Management Authorities and respective Councils/Farmer or Community organizations of the islands.
- The maintenance and monitoring program for the proposed recharging structures should be planned with the help of Island Councils and the local communities.
- It is proposed to incorporate these proposed MAR systems for island development planes if presently available or proposed to the islands.

REFERENCES

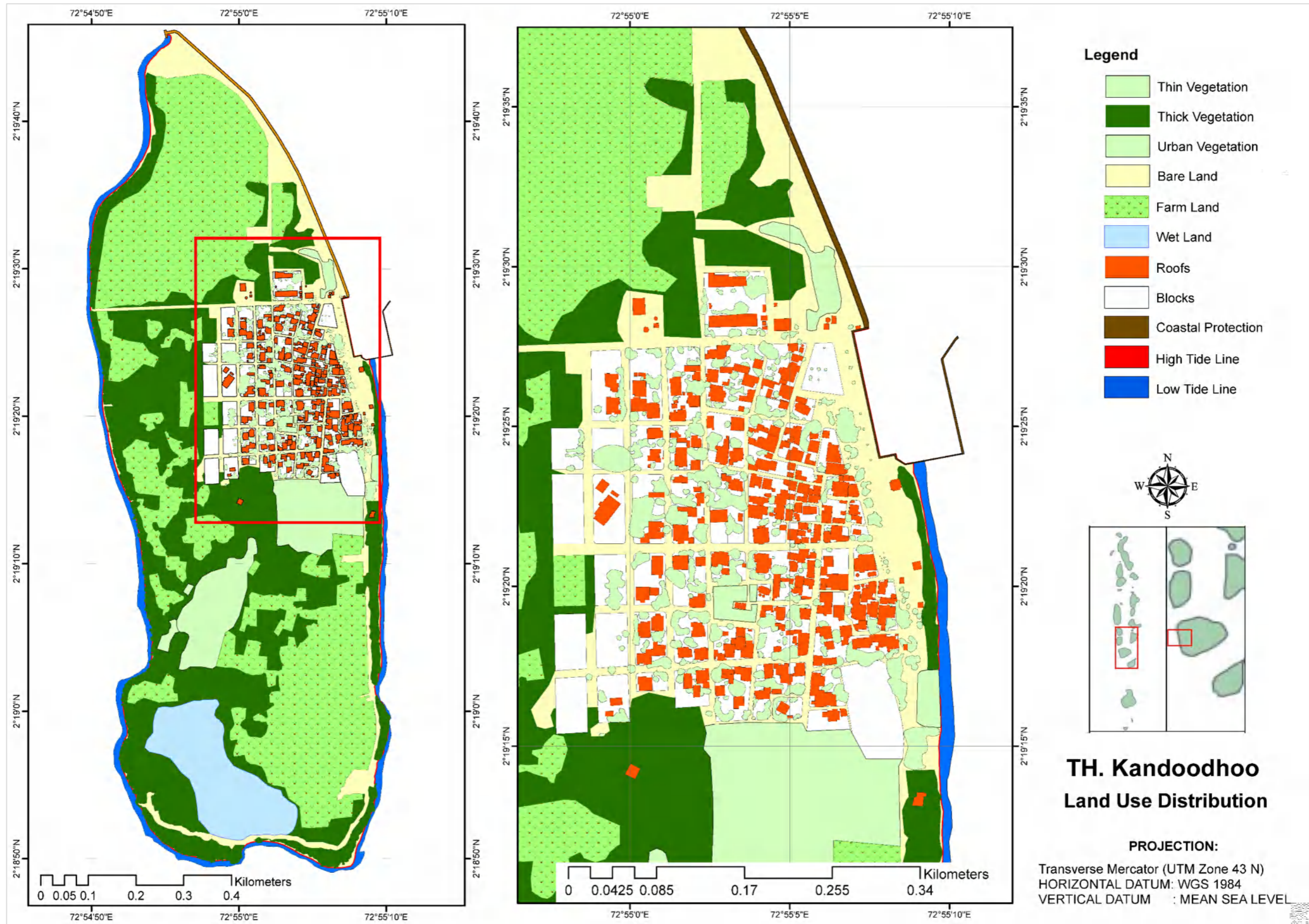
1. Allen, D. A. (2007). A THESIS FOCUSED ON THE MURRAY DARLING BASIN, AUSTRALIA. University of Technology.
2. Barlow, P. M. (2003). Ground Water in Freshwater-saltwater Environments of the Atlantic Coast. U.S. Department of the Interior, U.S. Geological Survey.
3. BBC (2018). Maldives country profile, British Broadcasting Corporation. URL: <https://www.bbc.com/news/world-south-asia-12651486> [Accessed: 21/03/2021].
4. CCKP (2020). WBG Climate Change Knowledge Portal (CCKP, 2020). Maldives Climate Data: Historical. URL: <https://climateknowledgeportal.worldbank.org/country/maldives/climate-data-historical>.
5. Climate Risk Country Profile: Maldives (2021). The World Bank Group and the Asian Development Bank.
6. d'Ozouville, N., Auken, E., Sørensen, K. I., Violette, S., Marsily, G. D., Deffontaines, B., and Merlen, G. (2008), Extensive perched aquifer and structural implications revealed by 3D resistivity mapping in a Galapagos volcano: Earth and Planetary Science Letters, 269, 518–522.
7. Edworthy, K.J. (1985) Groundwater Development for Oceanic Island Communities, Hydrogeology in the Service of Man, Memoirs of the 18th Congress of the International Association of Hydrogeologists, Cambridge.
8. F. K. J. Oberle, P. W. Swarzenski, C. D. Storlazzi (2017). Atoll groundwater movement and its response to climatic and sea-level fluctuations. Water 9, 650.
9. Falkland, A. C. (1993). Hydrology and water management on small tropical islands, Hydrology of Warm Humid Regions (Proceedings of the Yokohama Symposium, July 1993). n, IAHS Publ. No. (216).
10. Falkland, T. (2001). Integrated water resources management & sustainable sanitation for 4 islands Republic of Maldives, (September).
11. FAO (2011). Irrigation in Southern and Eastern Asia in figures – AQUASTAT Survey – 2011: Maldives. URL: http://www.fao.org/nr/water/aquastat/countries_regions/MDV/MDV-CP_eng.pdf [Accessed: 20/03/2021].
12. Garofalo, F. (2014). Physically constrained joint inversion of seismic and electrical data for near-surface application.
13. Ibrahim, S. A., M. R. Bari, and L. Miles, (2014). Water resources management in Maldives with an emphasis on desalination, Maldives Water and Sanitation Authority, Maldives.
14. Jaleel, Mohamed I.; Ibrahim, Shaheeda A.; Hussain, Afsal; Mustafa, Mohamed; Pathirana, Assela (2020). A Screening Approach for Assessing Groundwater Quality for Consumption in Small Islands: Case Study of 45 Inhabited Islands in the Maldives. Water 12, no. 8: 2209. <https://doi.org/10.3390/w12082209>
15. MEE. (2016). State of the Environment 2016, Ministry of Environment and Energy, Maldives.
16. MEE. (2017). National Water and Sewerage Policy, Ministry of Environment and Energy, Maldives.
17. Metai, E. (2002) 'Vulnerability of freshwater lens on Tarawa – the role of hydrological monitoring in determining sustainable yield' Water Engineering Unit, Ministry of Works and Energy, Republic of Kiribati.

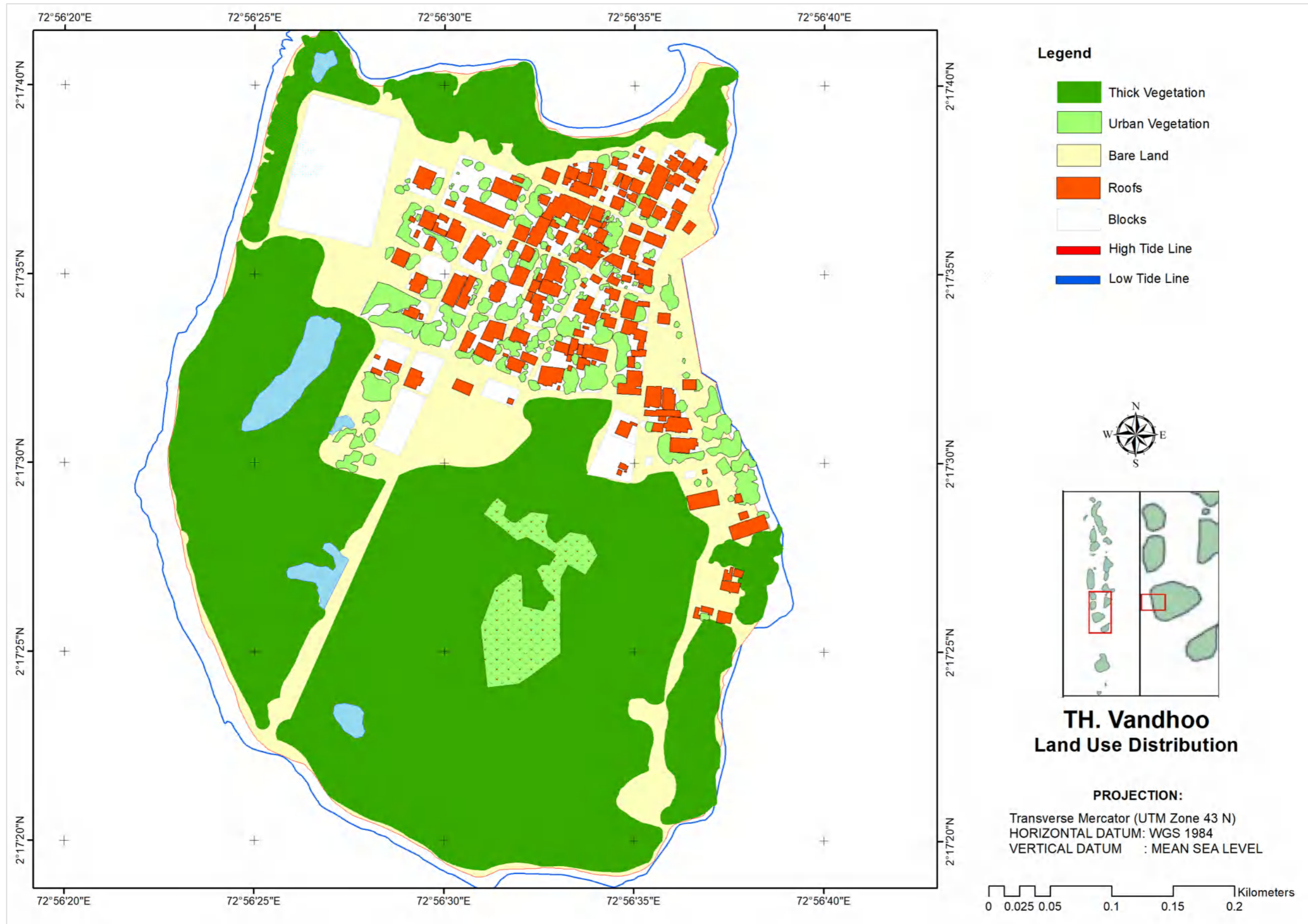
18. MHE. (2011). An Assessment of Rainwater Catchment & Storage Capacity in the Maldives, (March), Ministry of Housing and Transport, Maldives.
19. Ministry of Environment, (2021). A Guide to Groundwater Protection & Improvement Measures in the Maldives. Ministry of Environment, Male', Maldives
20. MoEnv. (2020). Groundwater Resource Management and Aquifer Protection in the Maldives, Baseline Assessment Report. Ministry of Environment, Male', Maldives.
21. MoEnv. (2020b). National Strategic Framework to Mobilize International Climate Finance to Address Climate Change in the Maldives 2020 – 2024. Ministry of Environment, Male', Maldives.
22. Musthafa, M. (2016). Maldives Country Paper Overview of Sanitation in Maldives, (Sacosan Vi), 1–12.
23. Ryan T. Bailey and Saman Tavakoli Kivi (2017). Method for estimating available groundwater volume of small coral islands, Hydrological Sciences Journal, 62:14, 2381-2392, DOI: 10.1080/02626667.2017.1382703
24. Sukhija B. (2007). Geophysical methods. - Proceedings of the International Workshop, Groundwater for emergency situations, Tehran, 29-31 October 2006, IHP/2007/GW-15-UNESCO.
25. T.N.O. (1984). Application of a Permanent Electrode System for Groundwater Salinity Inspection. Delft, Netherlands.
26. Tsutsumi, A., Jinno, K., & Berndtsson, R. (2004). Surface and subsurface water balance estimation by the groundwater recharge model and a 3-D two-phase flow model/Estimation de bilan hydrologique de surface et de subsurface à l'aide de modèles de recharge de nappe et d'écoulement diphasique 3-D. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques - HYDROLOG SCI J, 49. <https://doi.org/10.1623/hysj.49.2.205.34837>
27. WHO (2006). Final Report on water resources assessment in Addu Atoll and sustainable water supply and sanitation strategies for Maldives water and sanitation authority.
28. World Health Organization (2017). Guidelines for drinking-water quality: fourth edition incorporating first addendum, 4th ed.st add. World Health Organization. <https://apps.who.int/iris/handle/10665/254637>. License: CC BY-NC-SA 3.0 IGO.

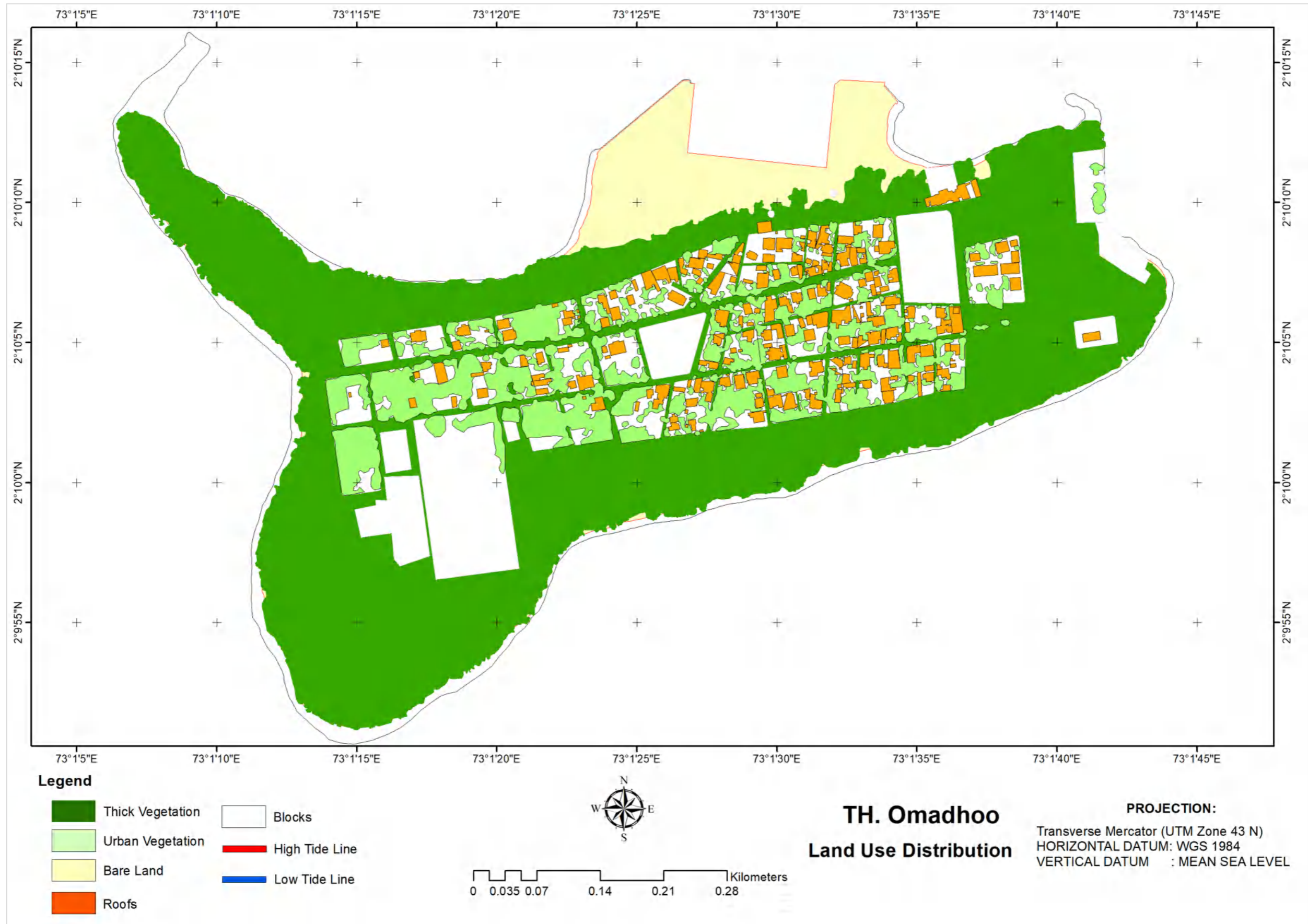
Annex I: Location Map of the Islands

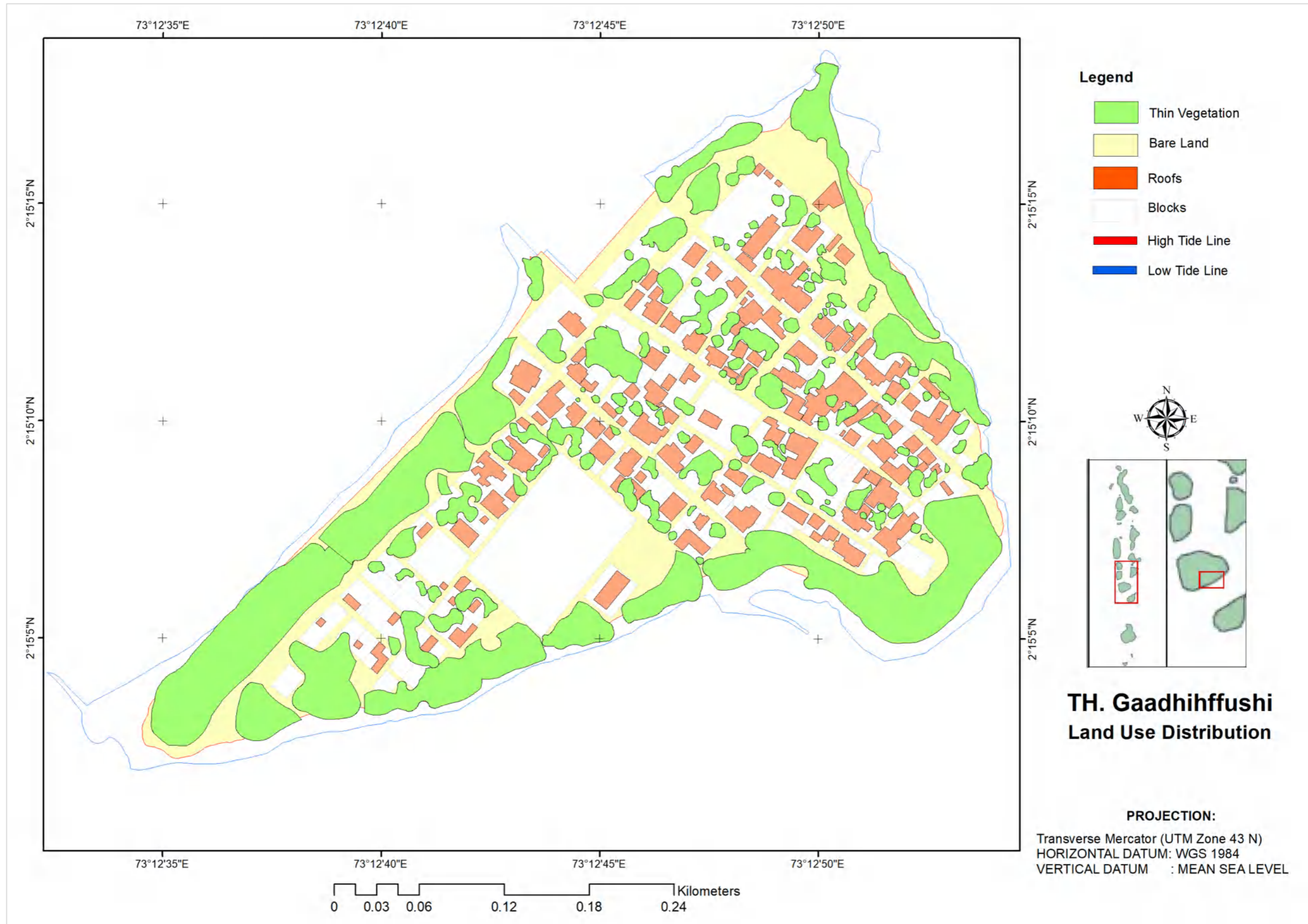


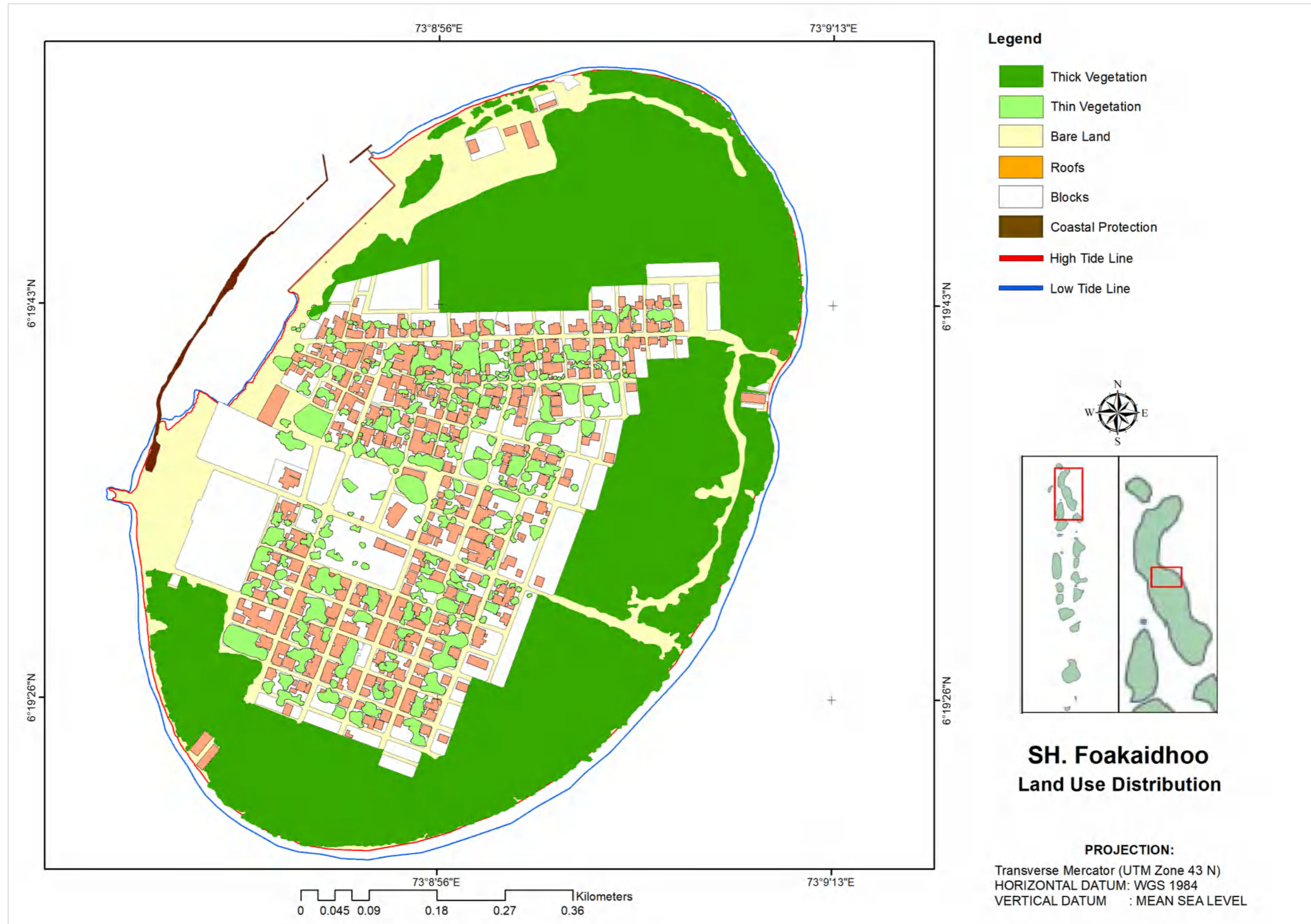
Annex II: Land Use Distribution of Islands



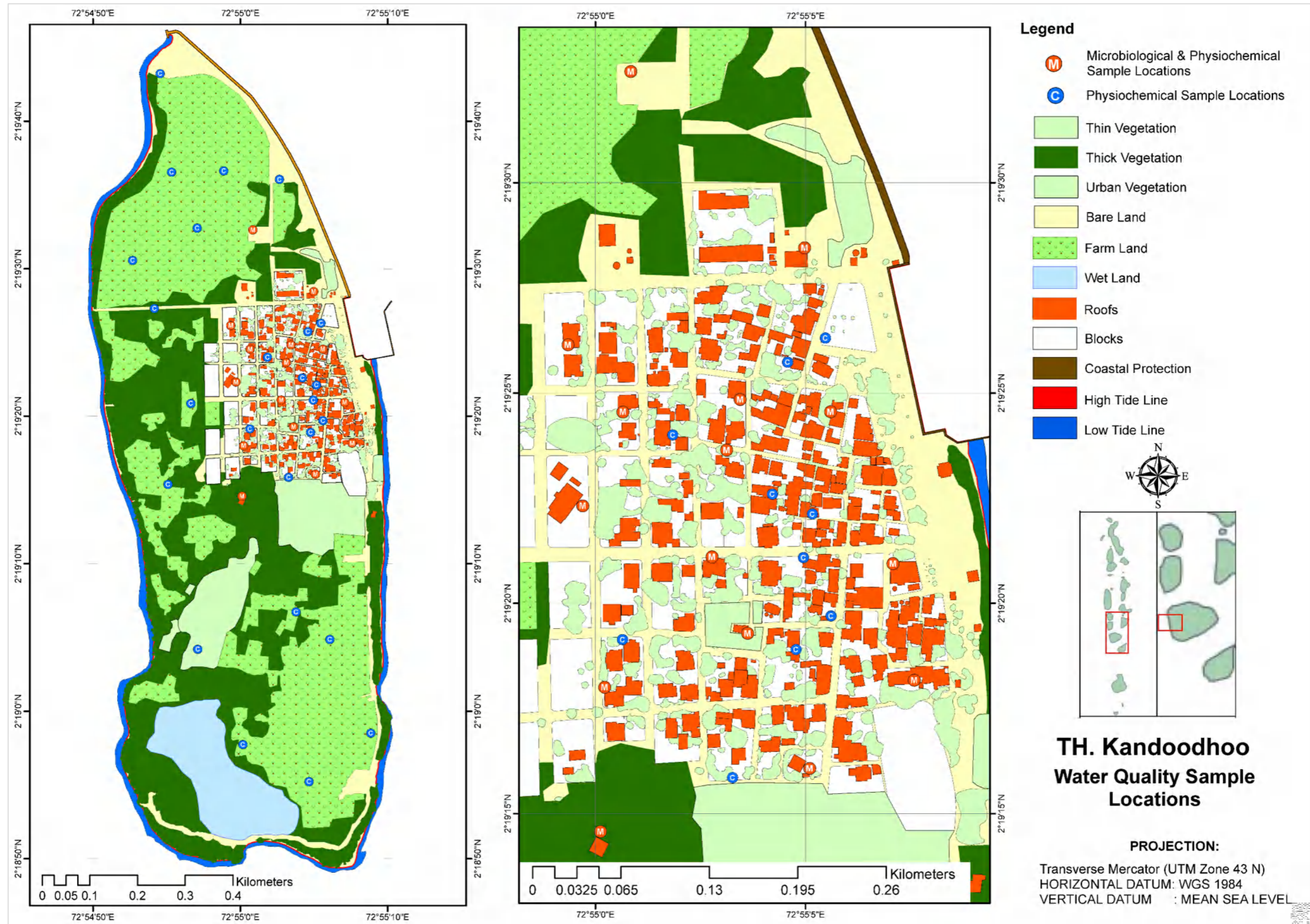


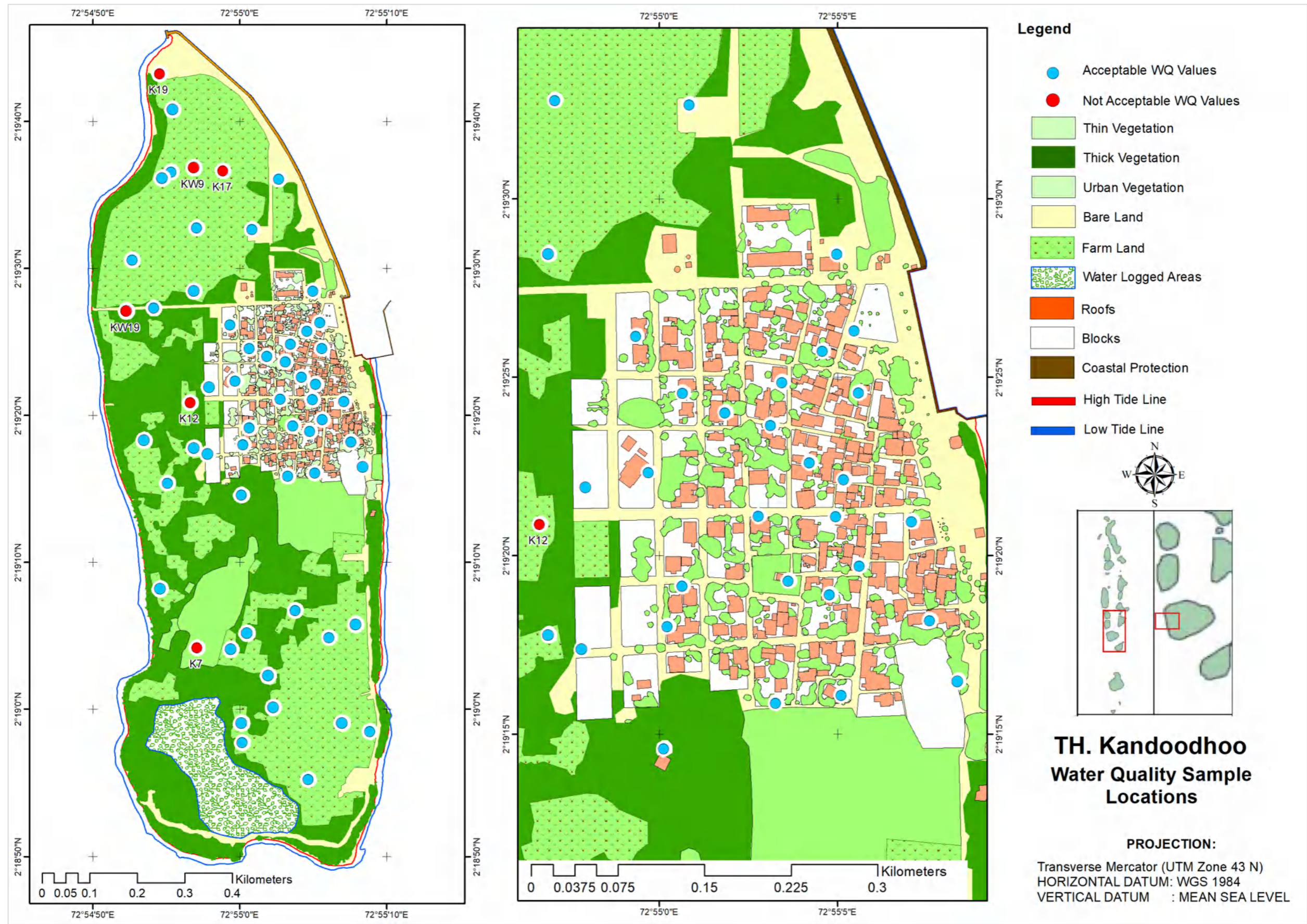


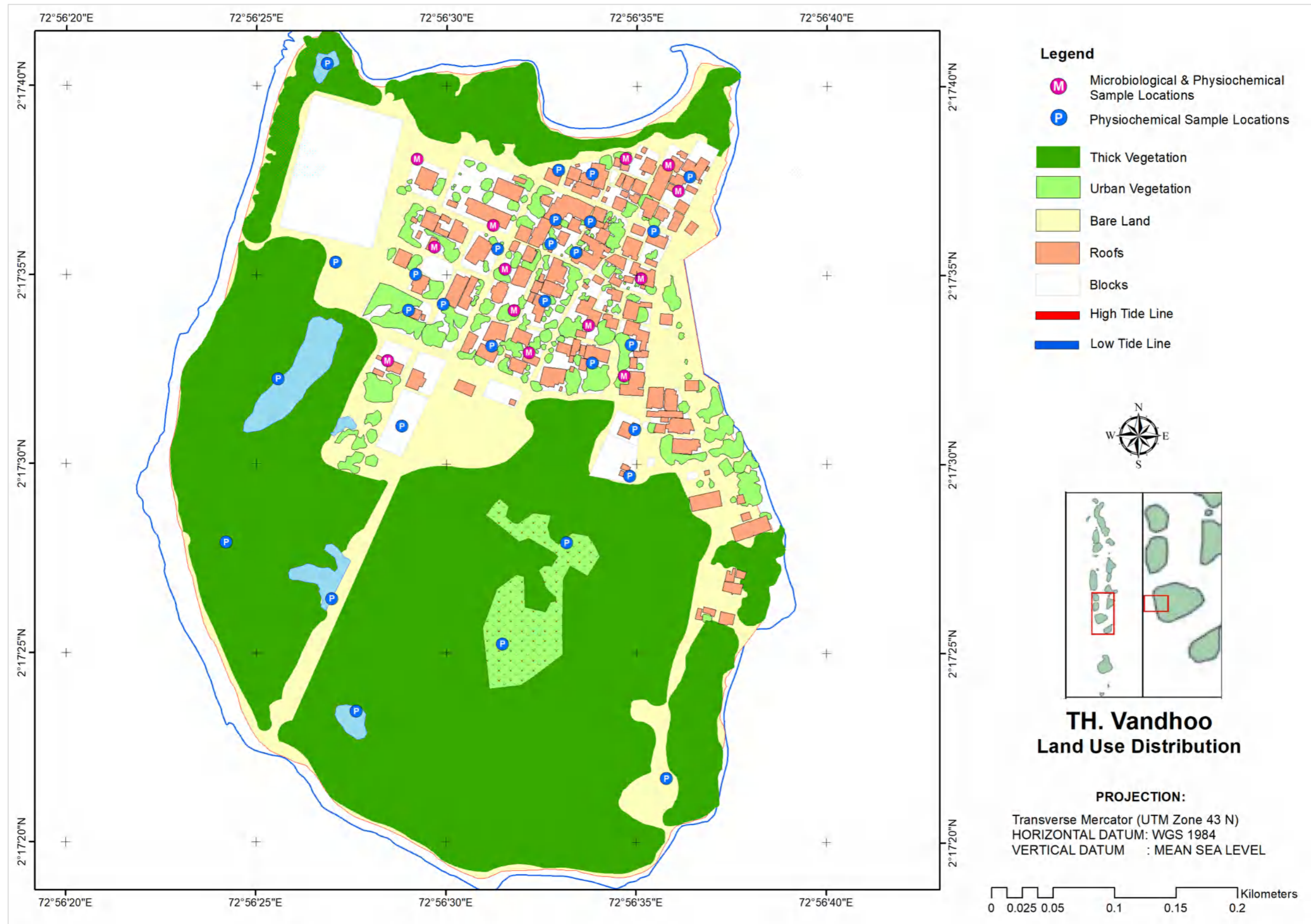


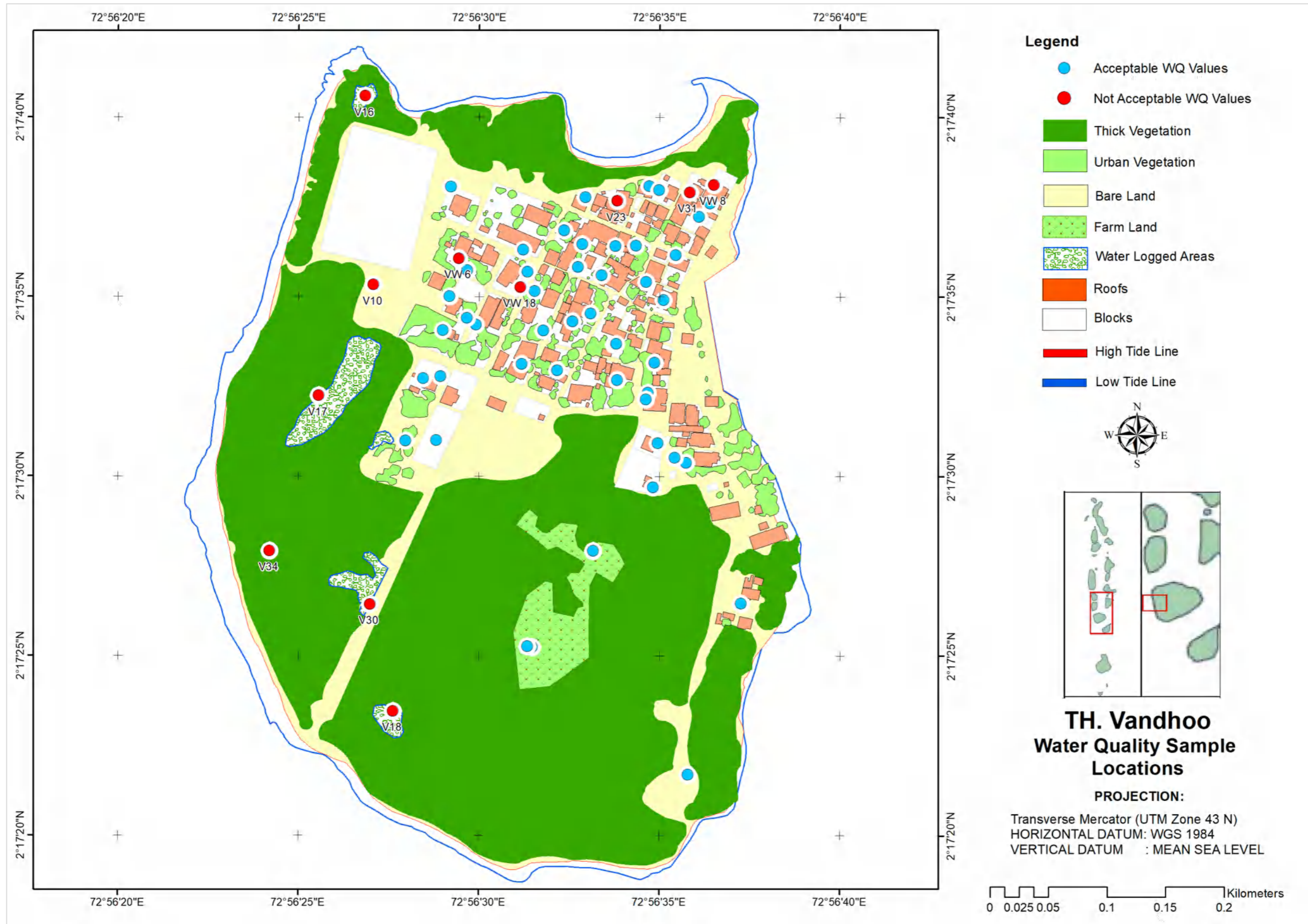


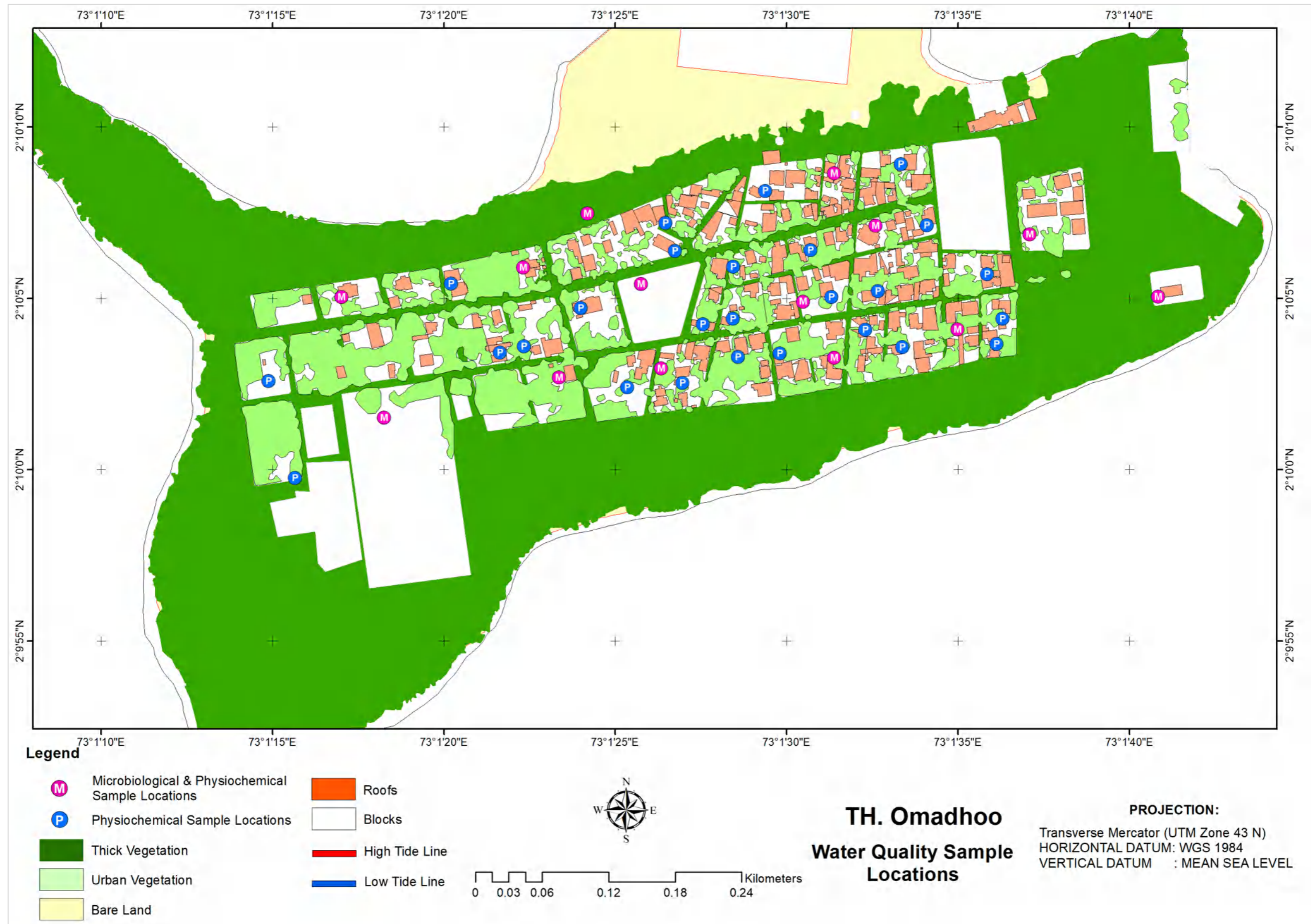
Annex III: Water Quality Sample Locations of the Islands

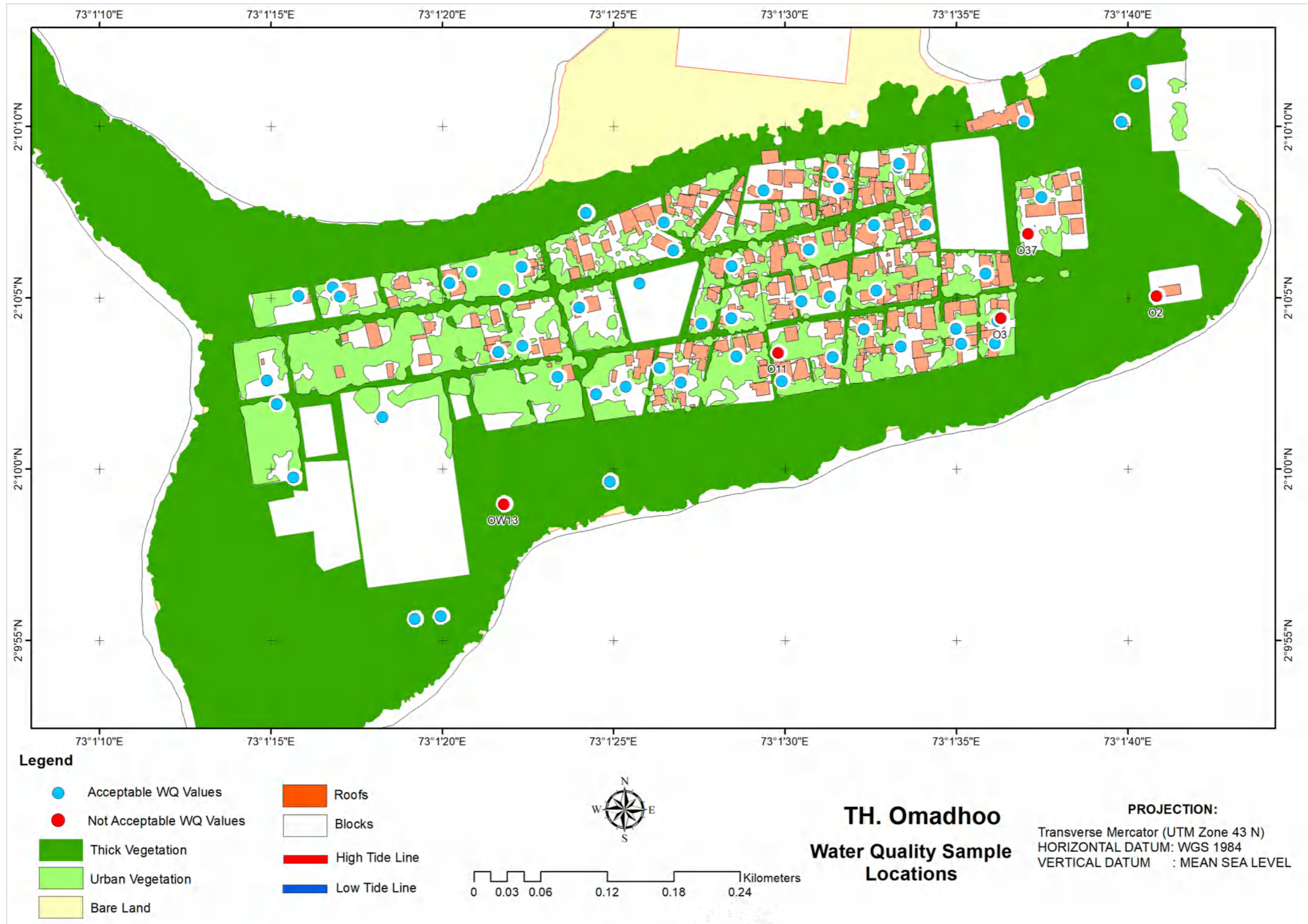


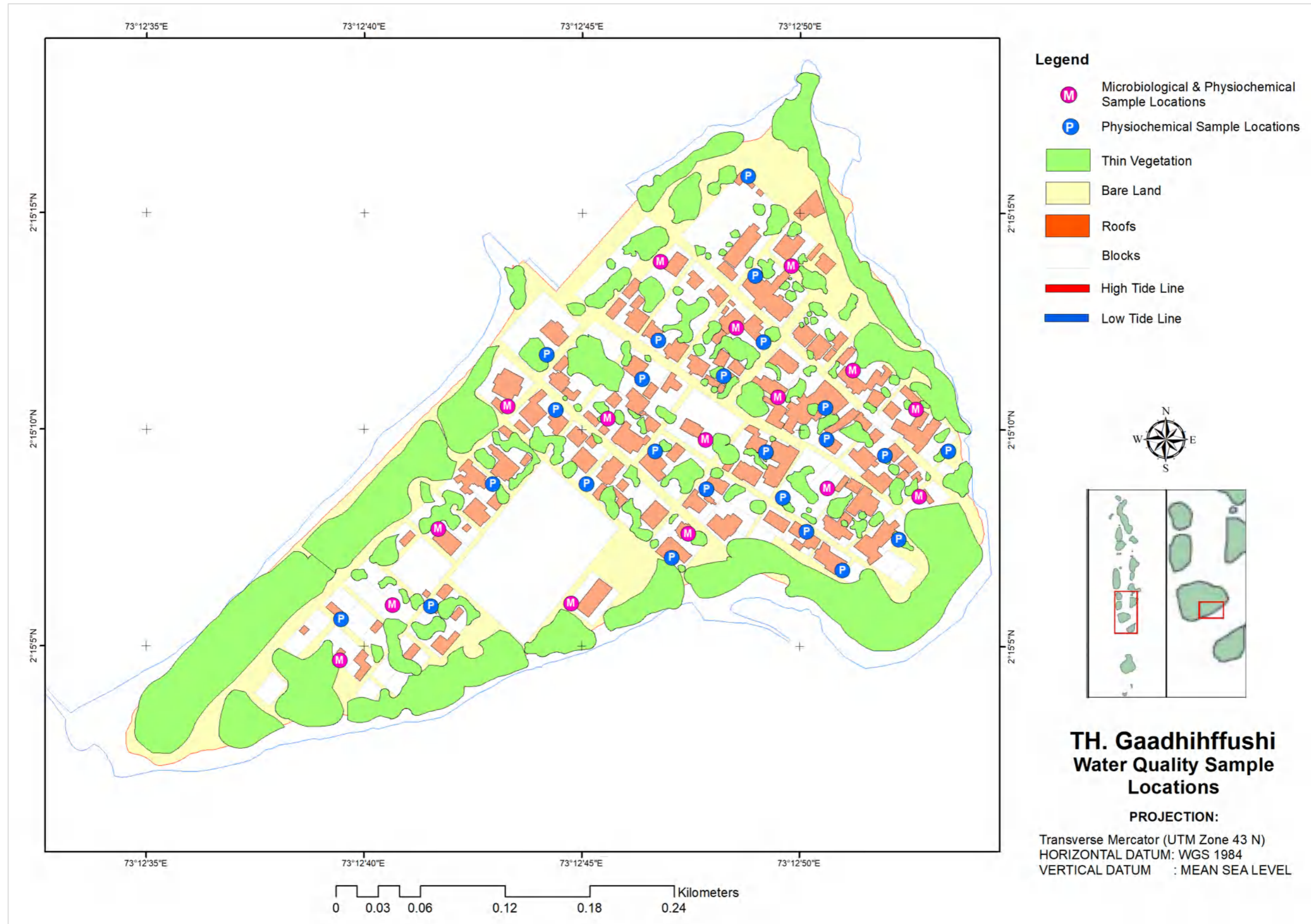


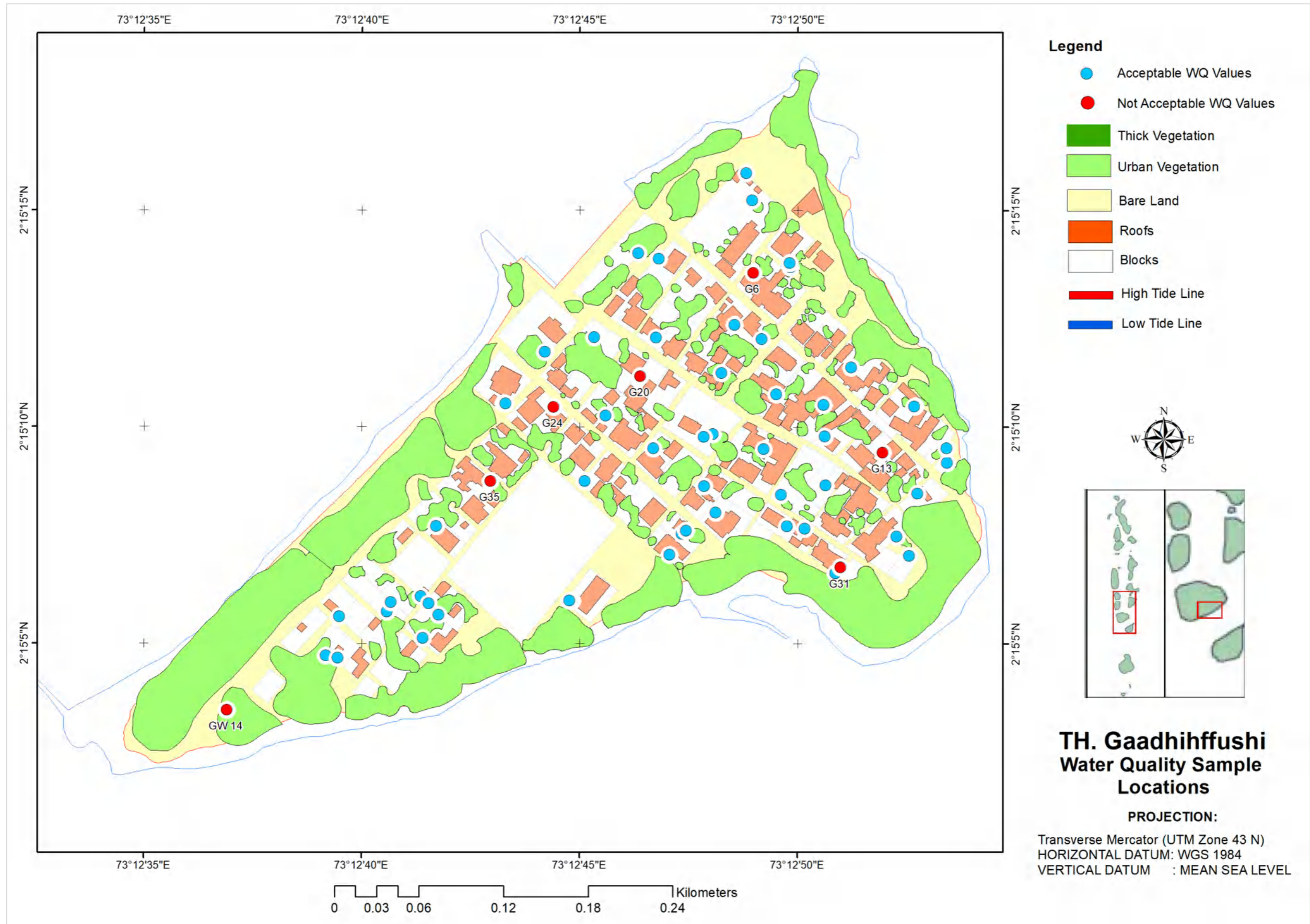


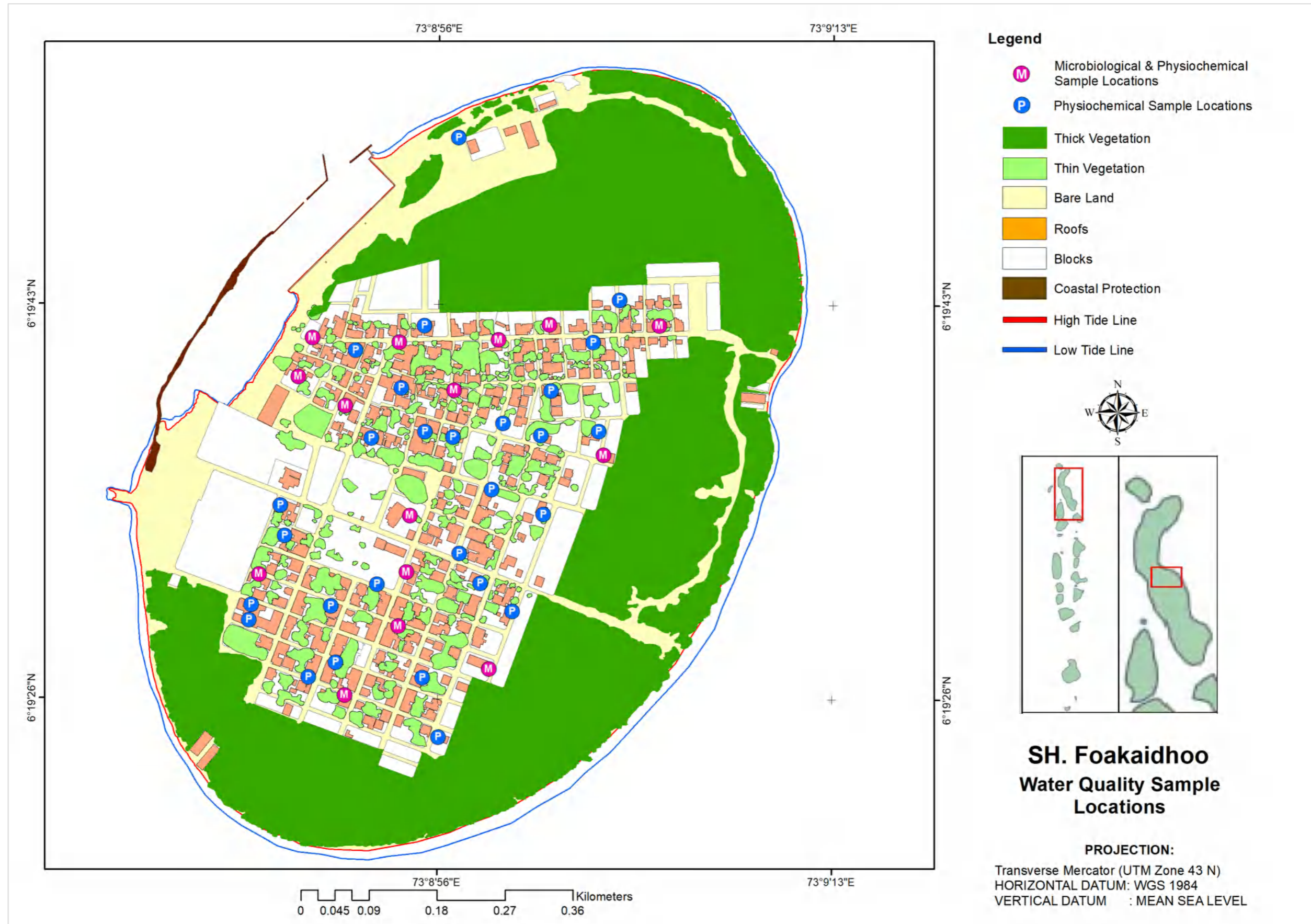


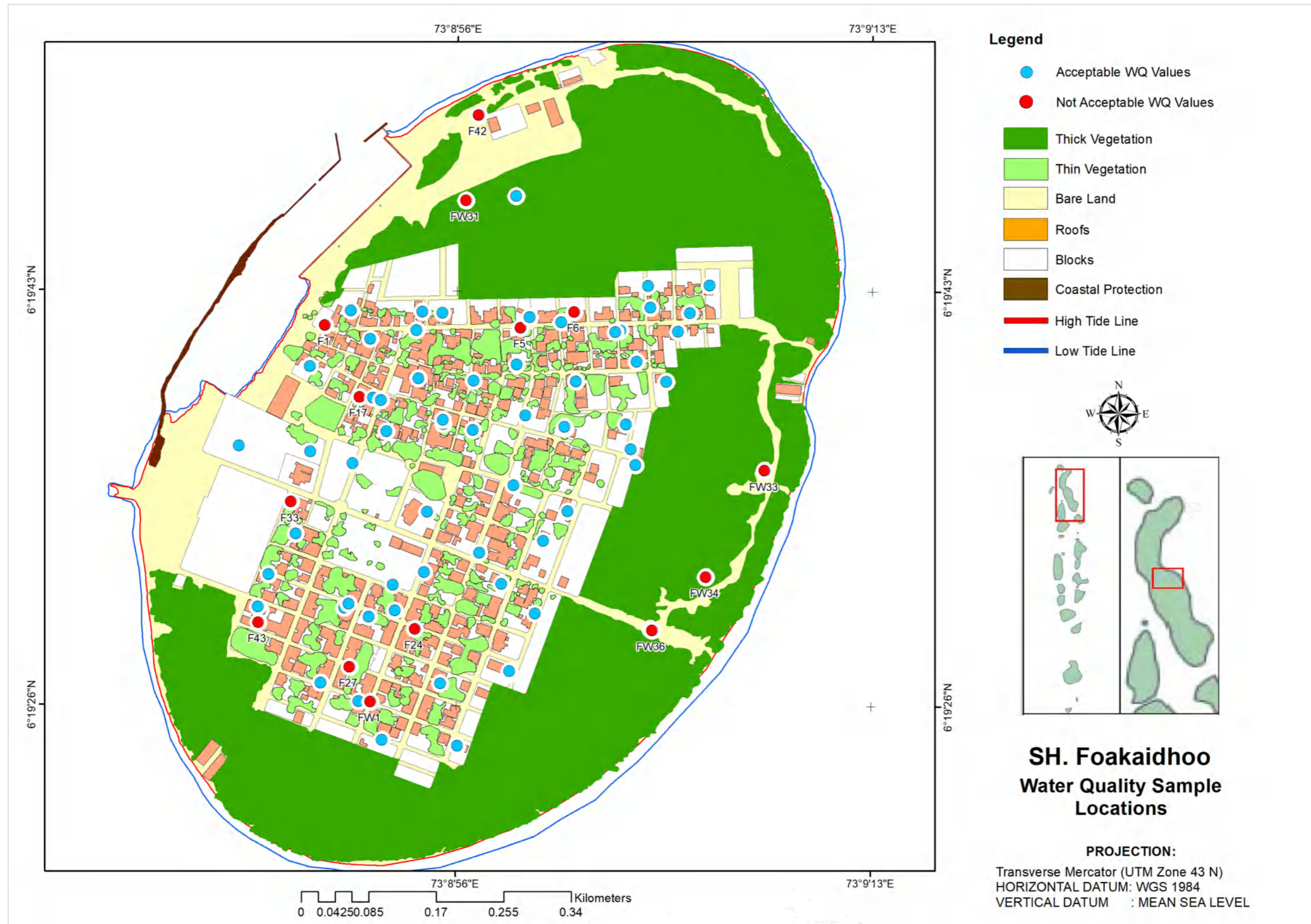




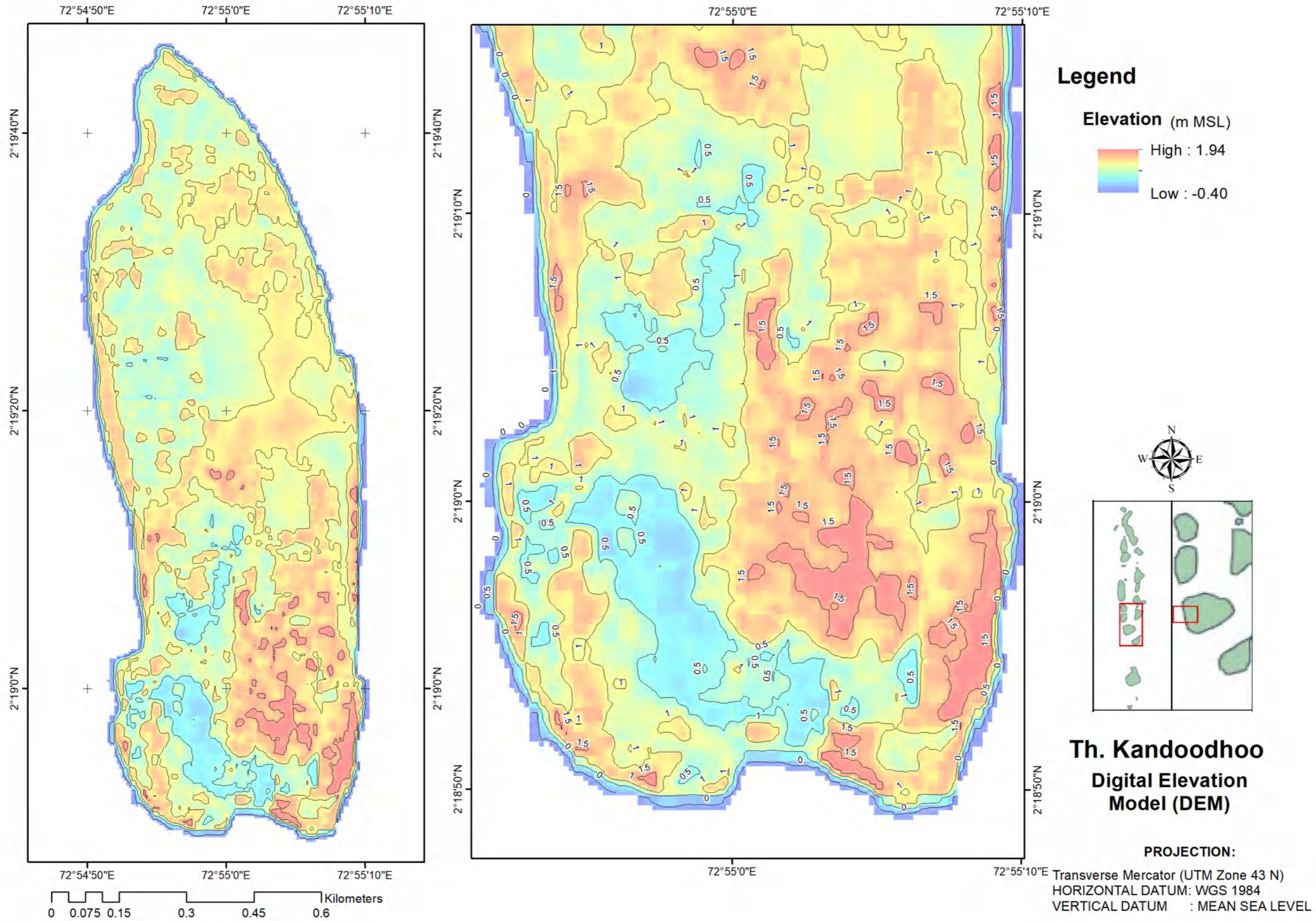


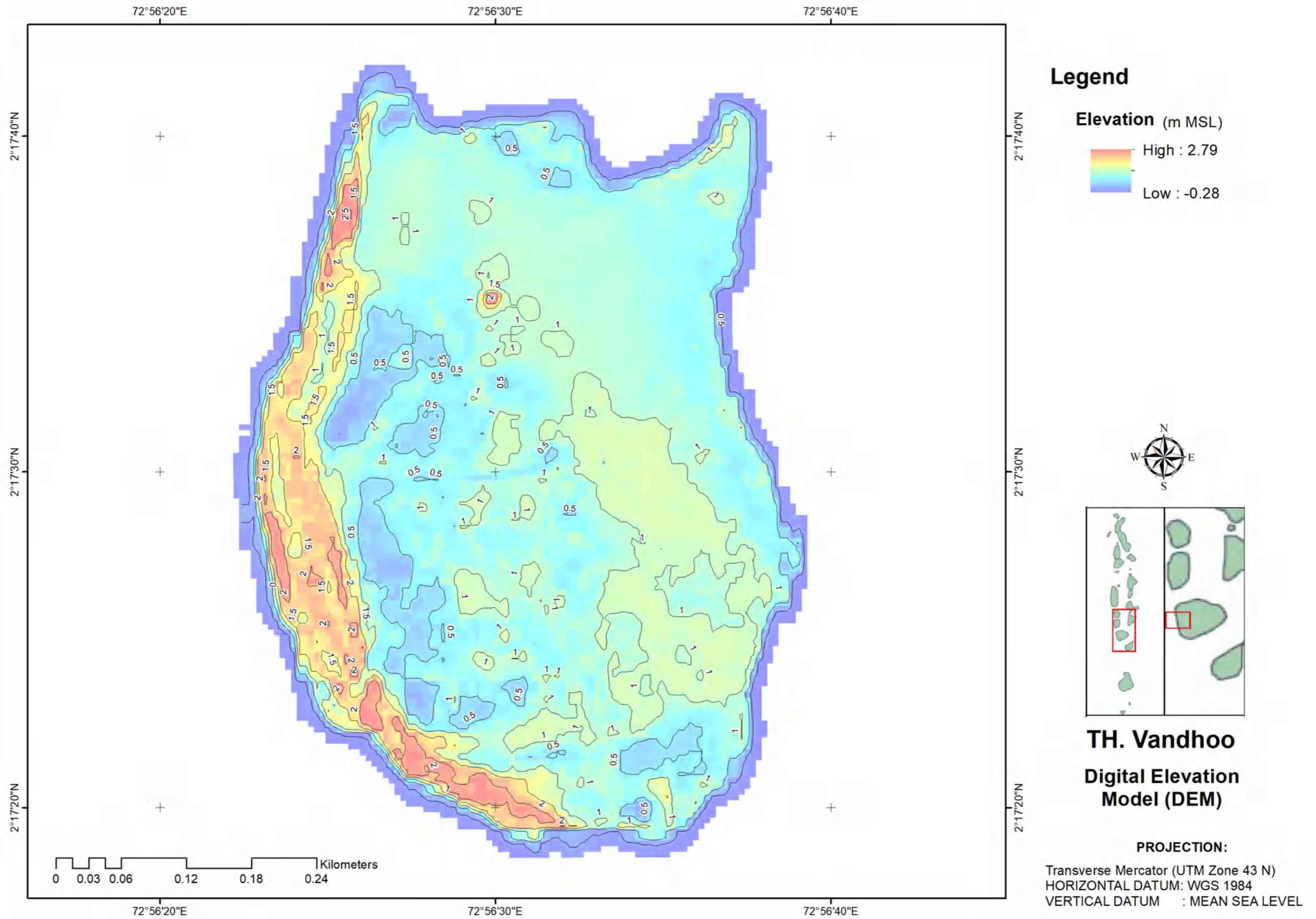


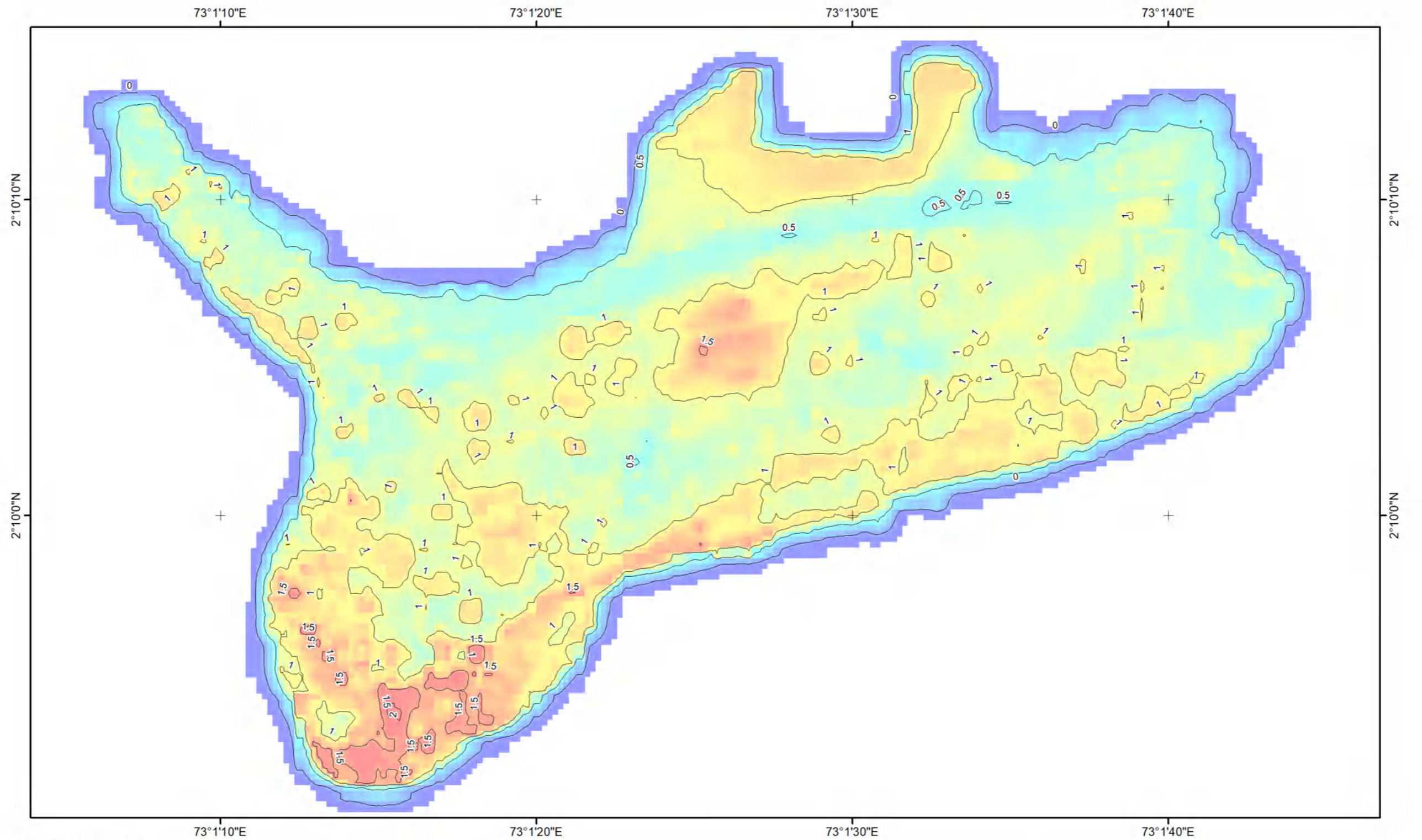




Annex IV: Digital Elevation Model of Islands

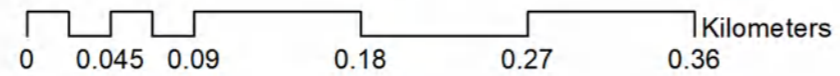
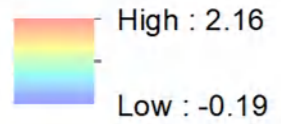






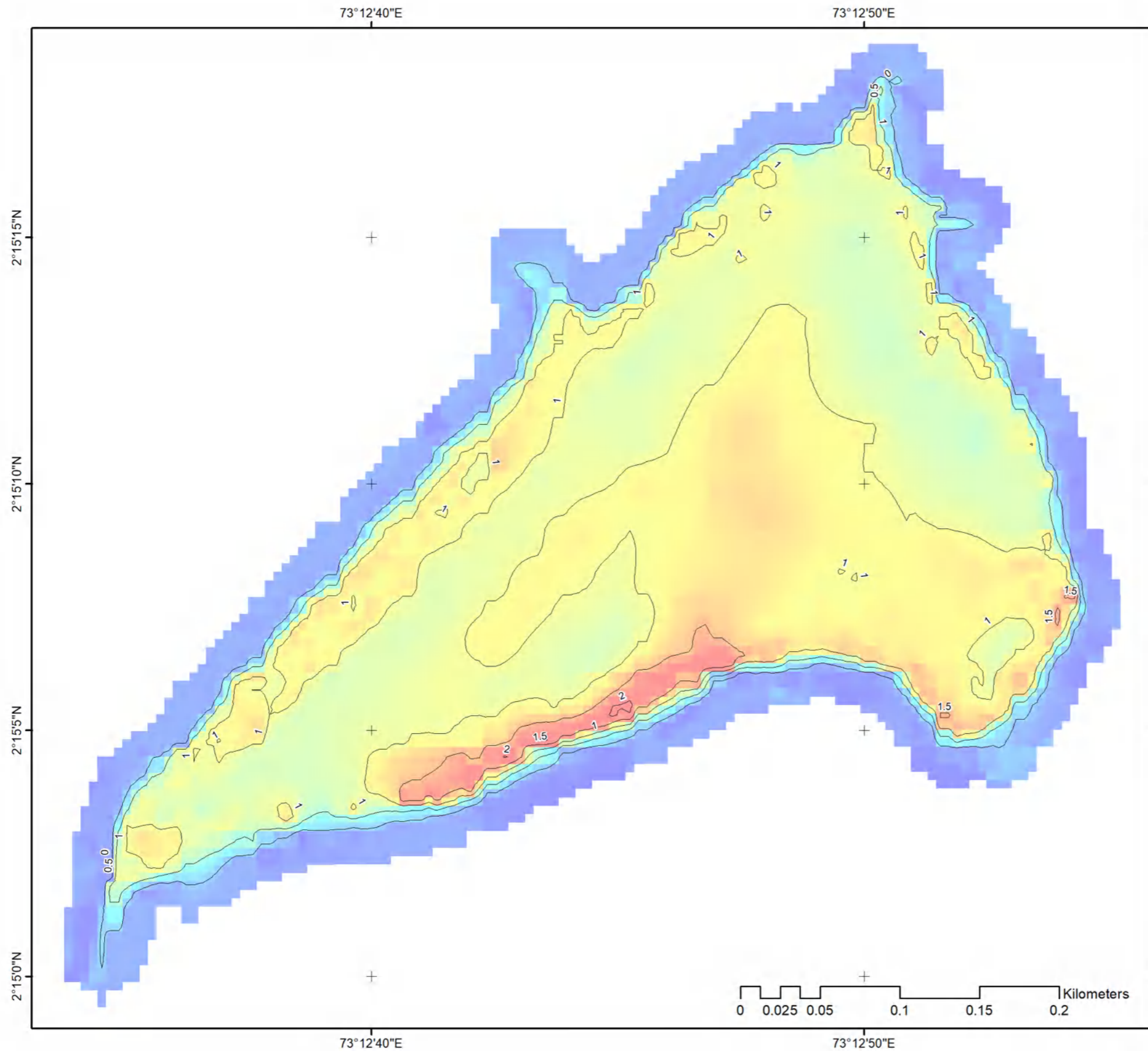
Legend

Elevation (m MSL)

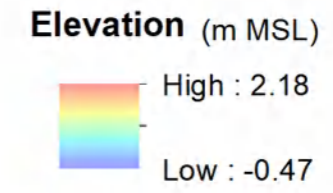


**Th. Omadhoo
Digital Elevation
Model (DEM)**

PROJECTION:
 Transverse Mercator (UTM Zone 43 N)
 HORIZONTAL DATUM: WGS 1984
 VERTICAL DATUM : MEAN SEA LEVEL



Legend

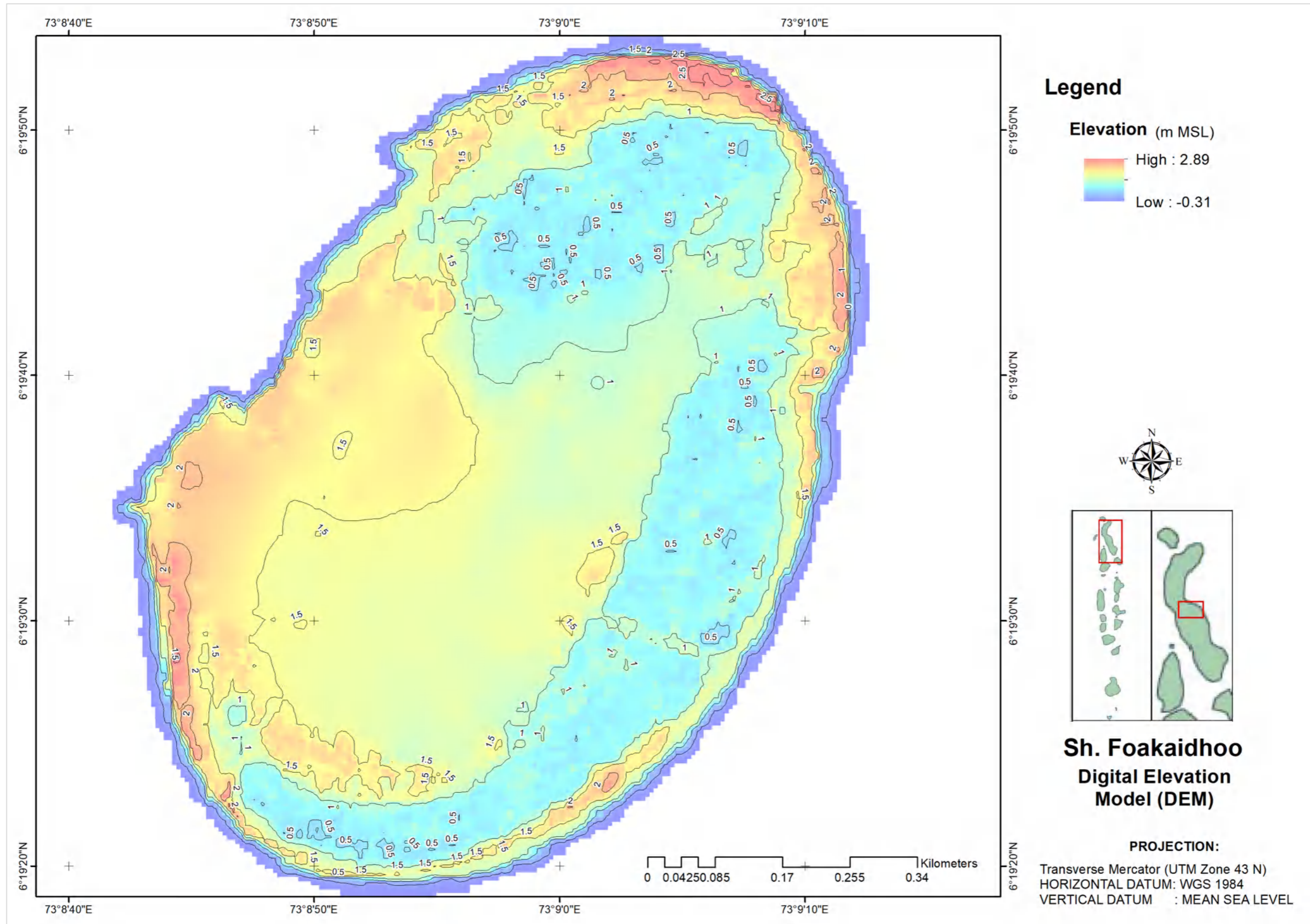


TH. Gaadhiffushi

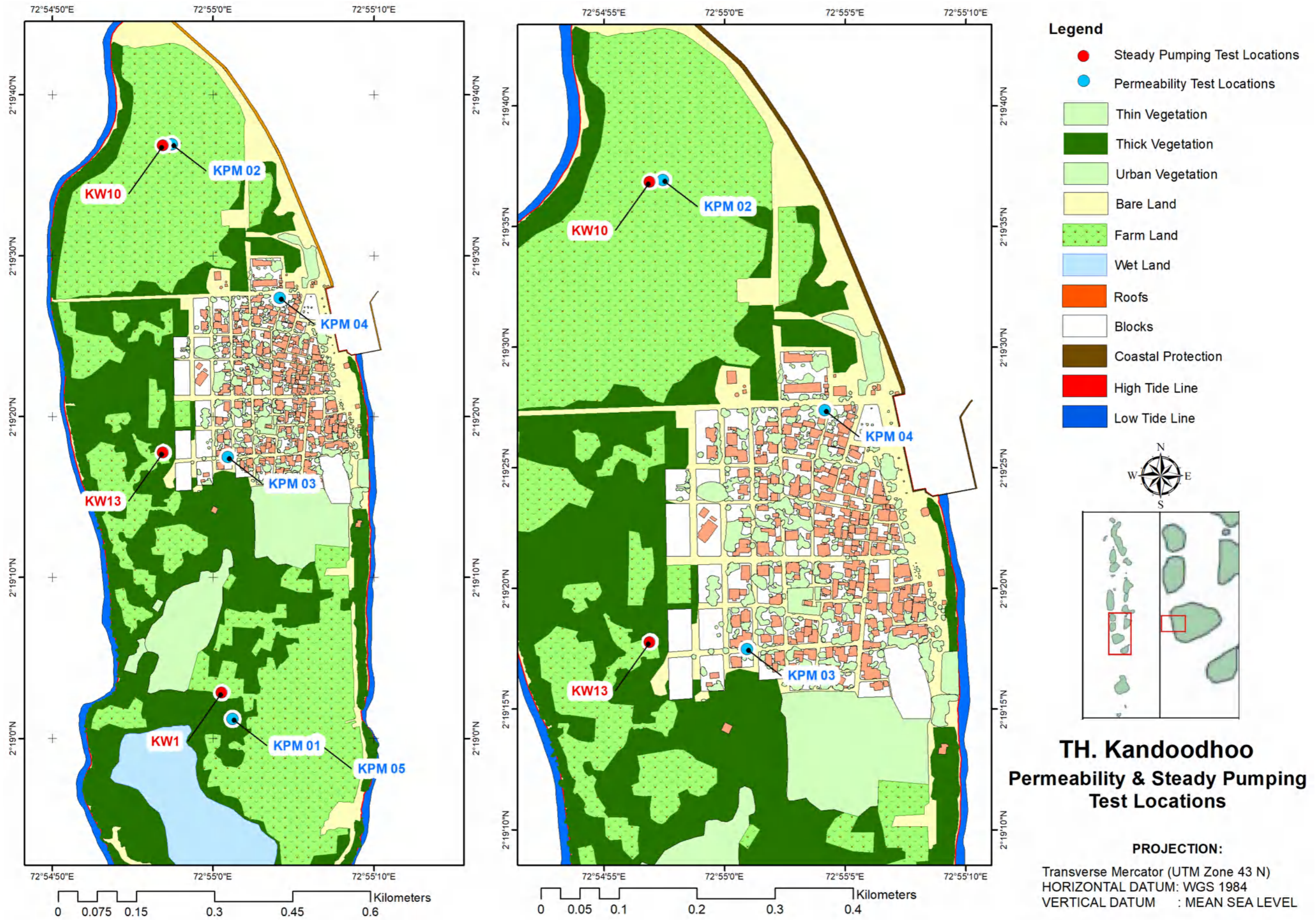
Digital Elevation Model (DEM)

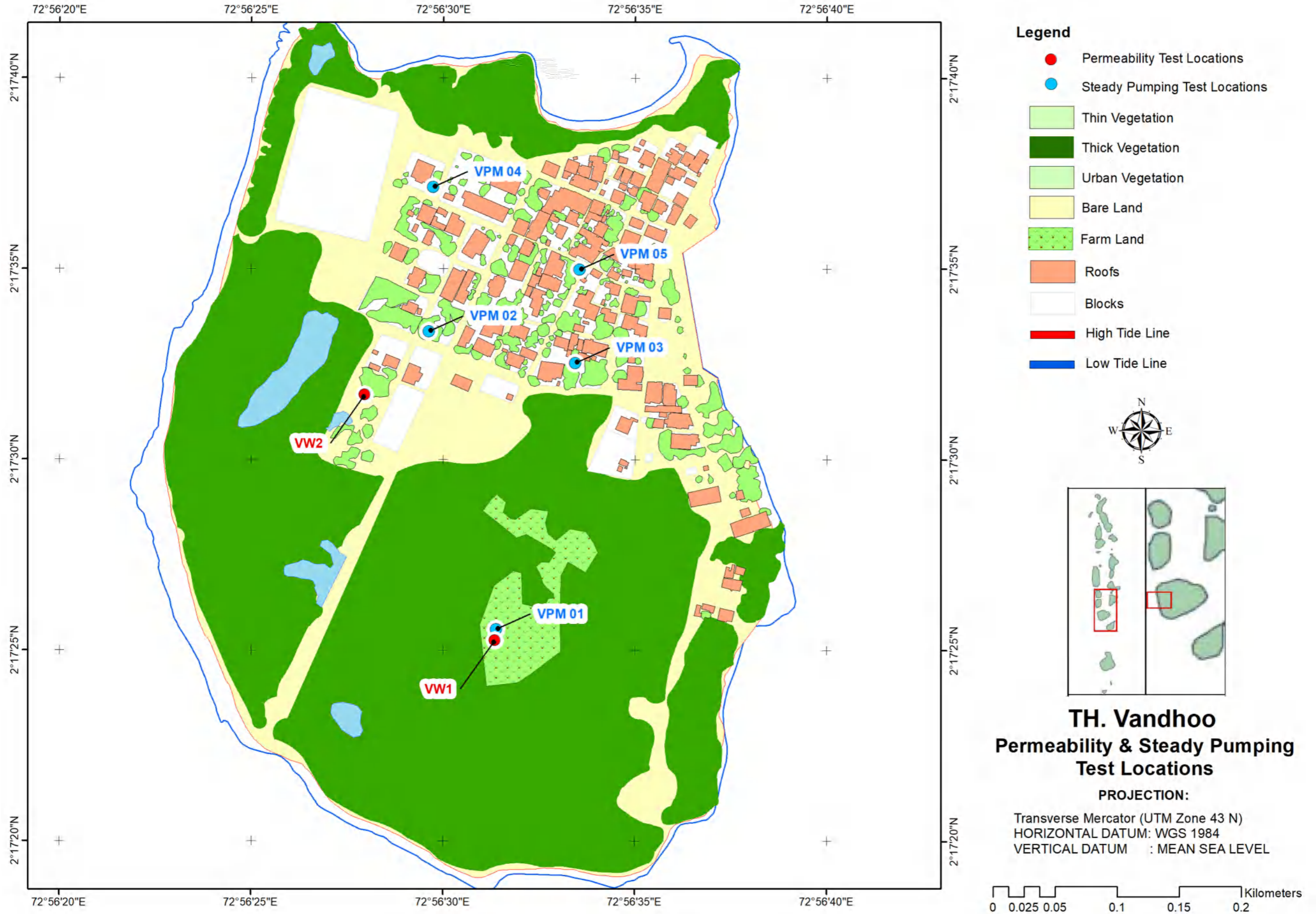
PROJECTION:

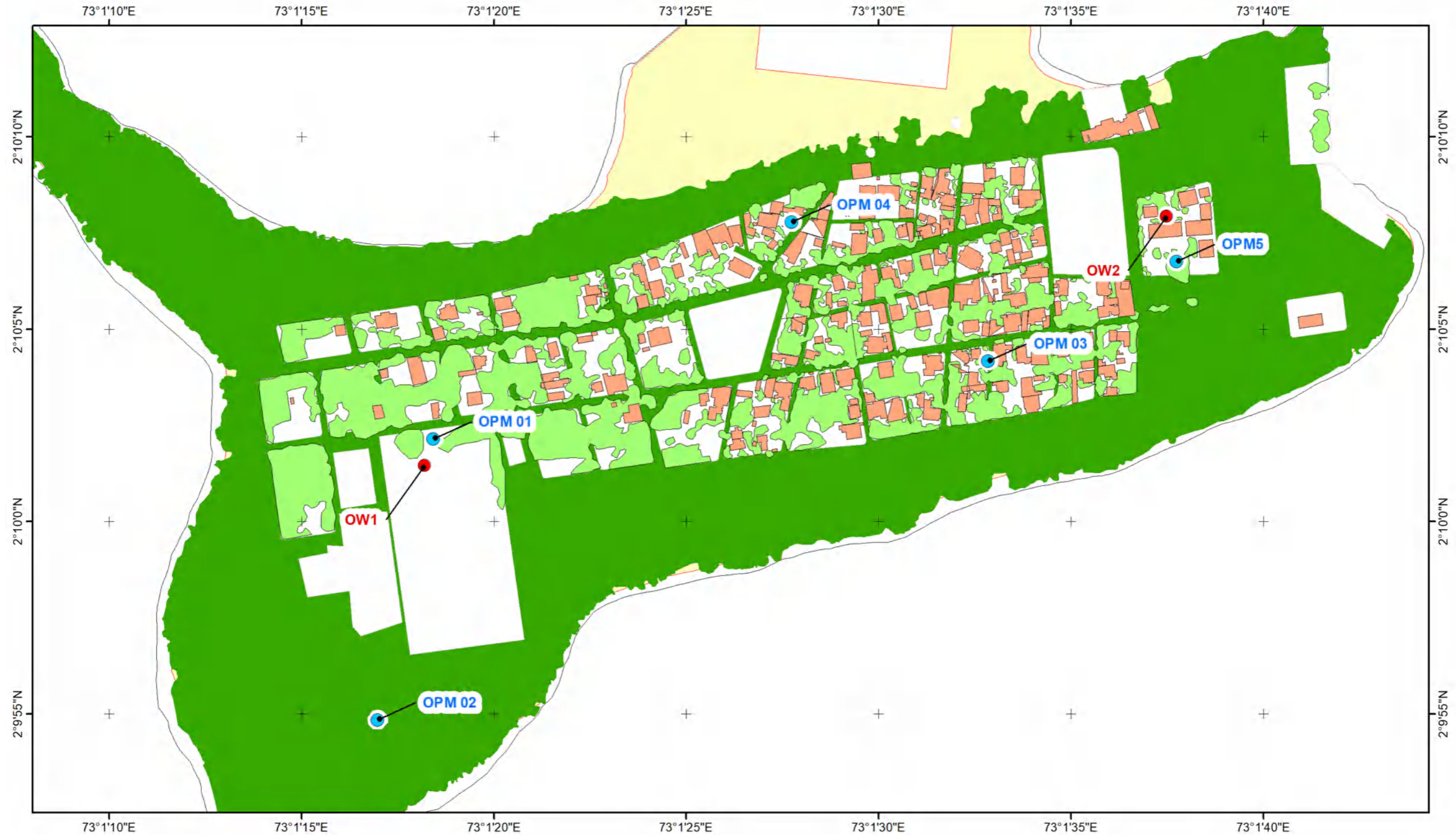
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL



Annex V: Locations of Permeability and Steady Pumping Tests Maps

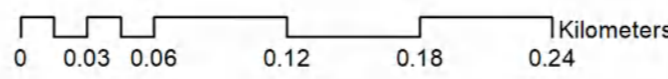






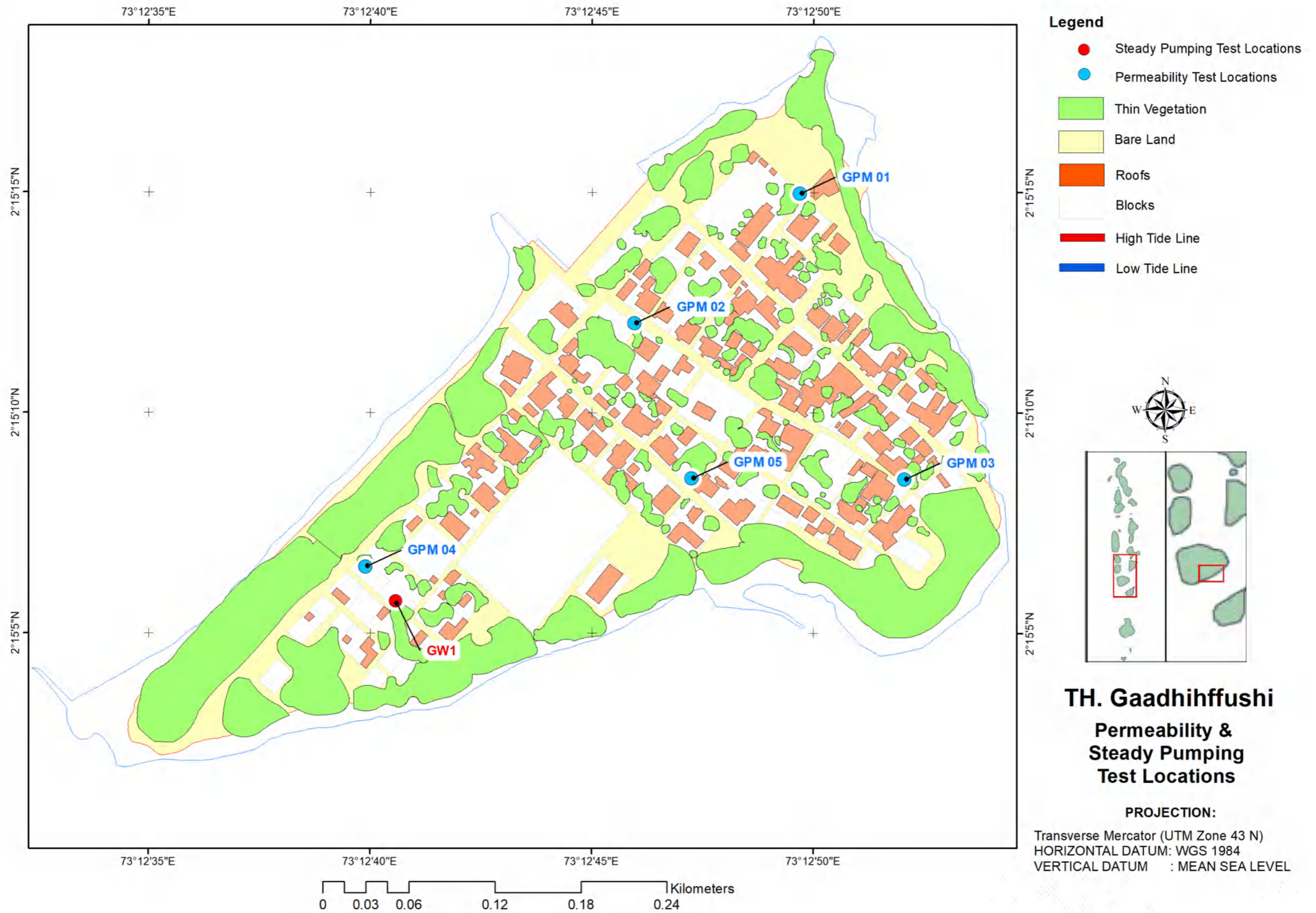
Legend

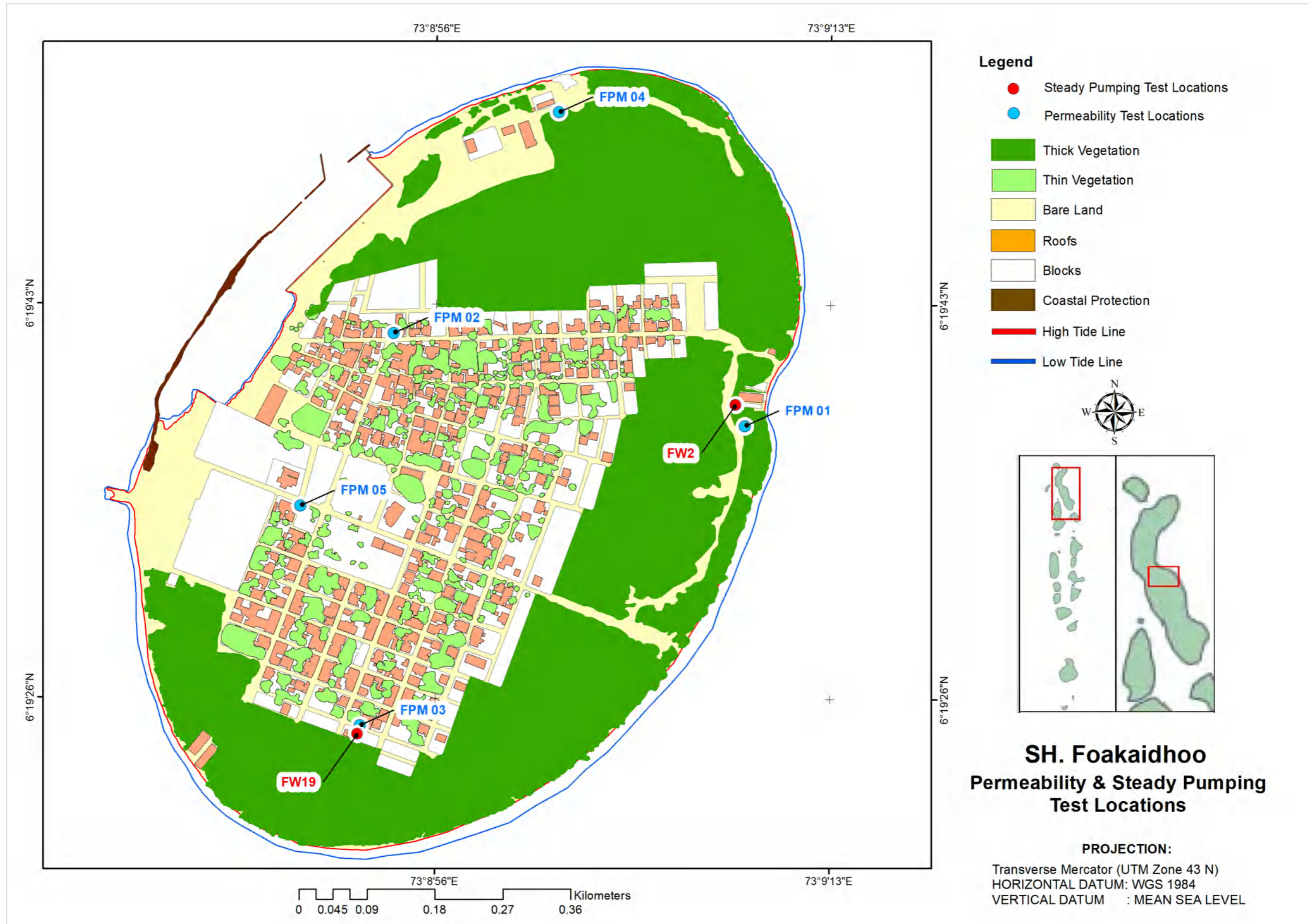
- Steady Pumping Test Locations
- Permeability Test Locations
- Thick Vegetation
- Urban Vegetation
- Bare Land
- Roofs
- Blocks
- High Tide Line
- Low Tide Line



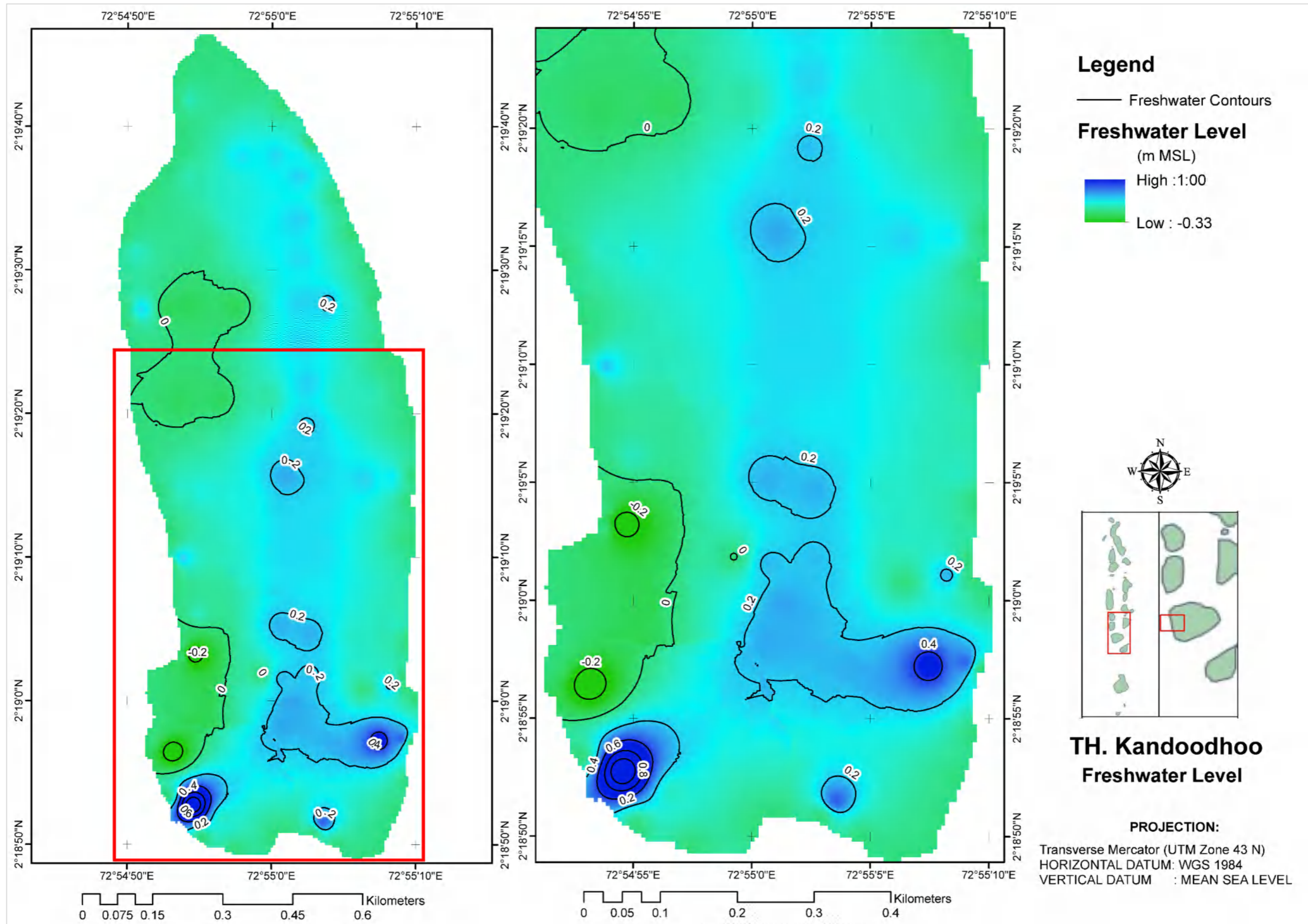
TH. Omadhoo
Permeability & Steady Pumping Test Locations

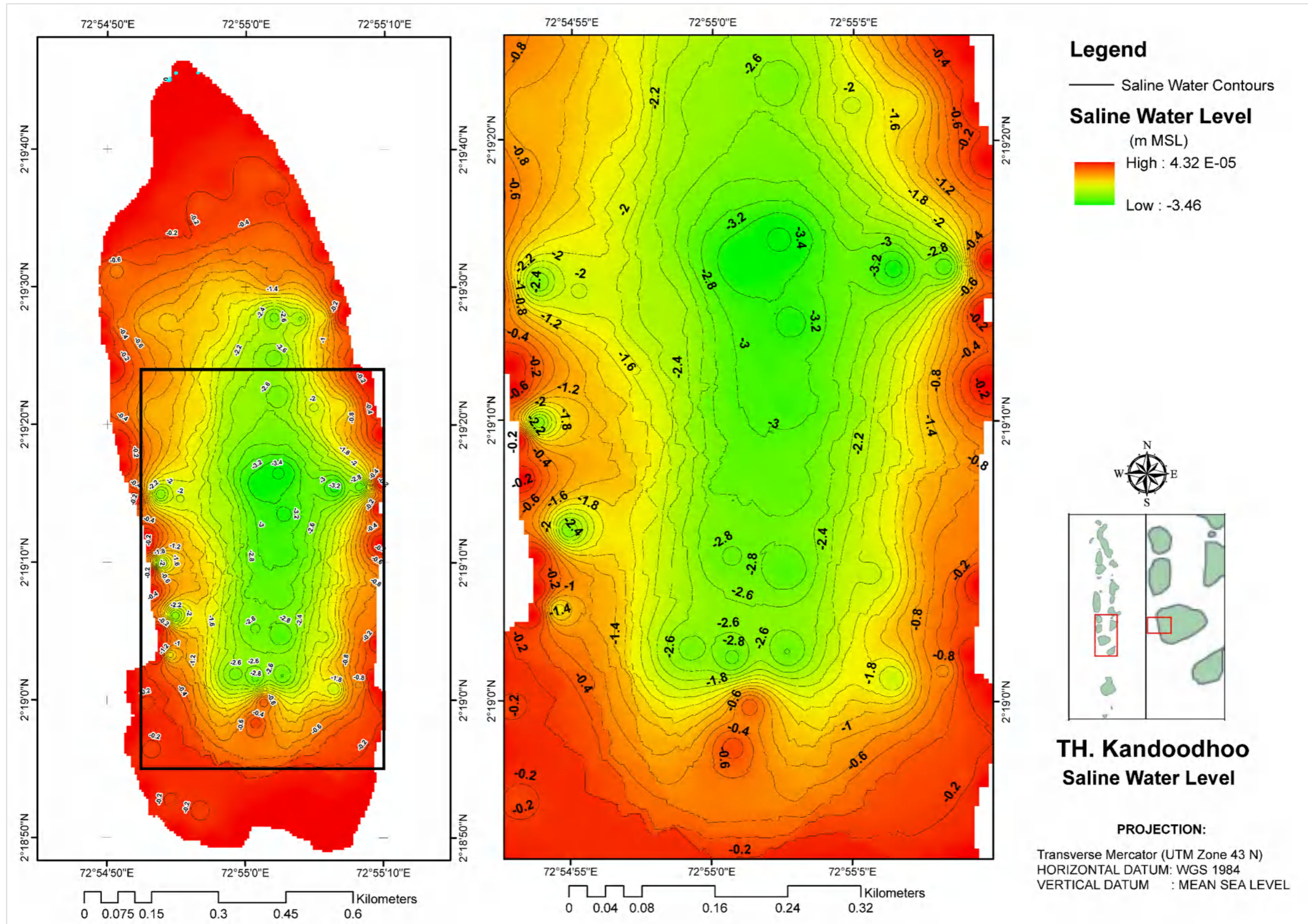
PROJECTION:
 Transverse Mercator (UTM Zone 43 N)
 HORIZONTAL DATUM: WGS 1984
 VERTICAL DATUM : MEAN SEA LEVEL

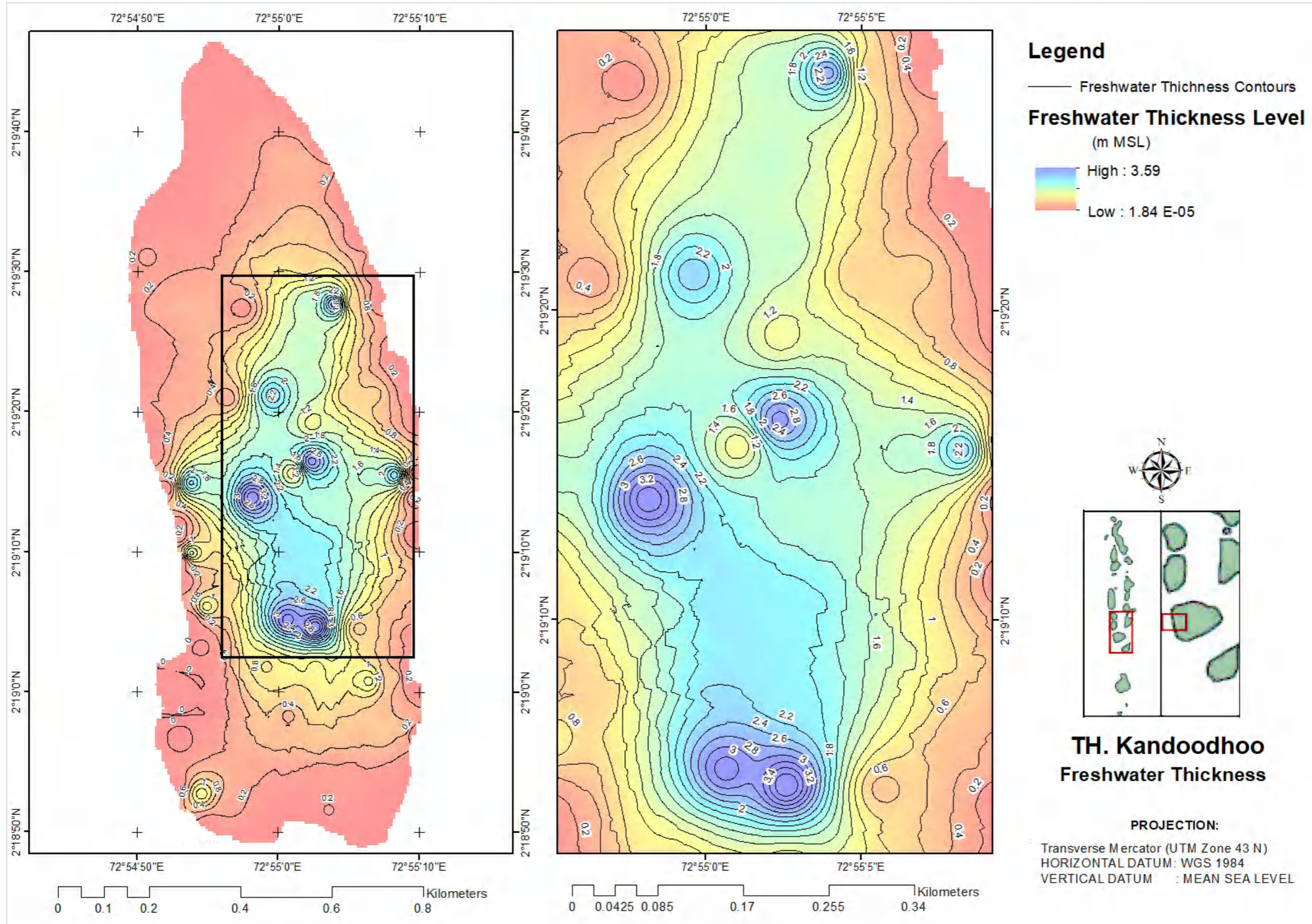


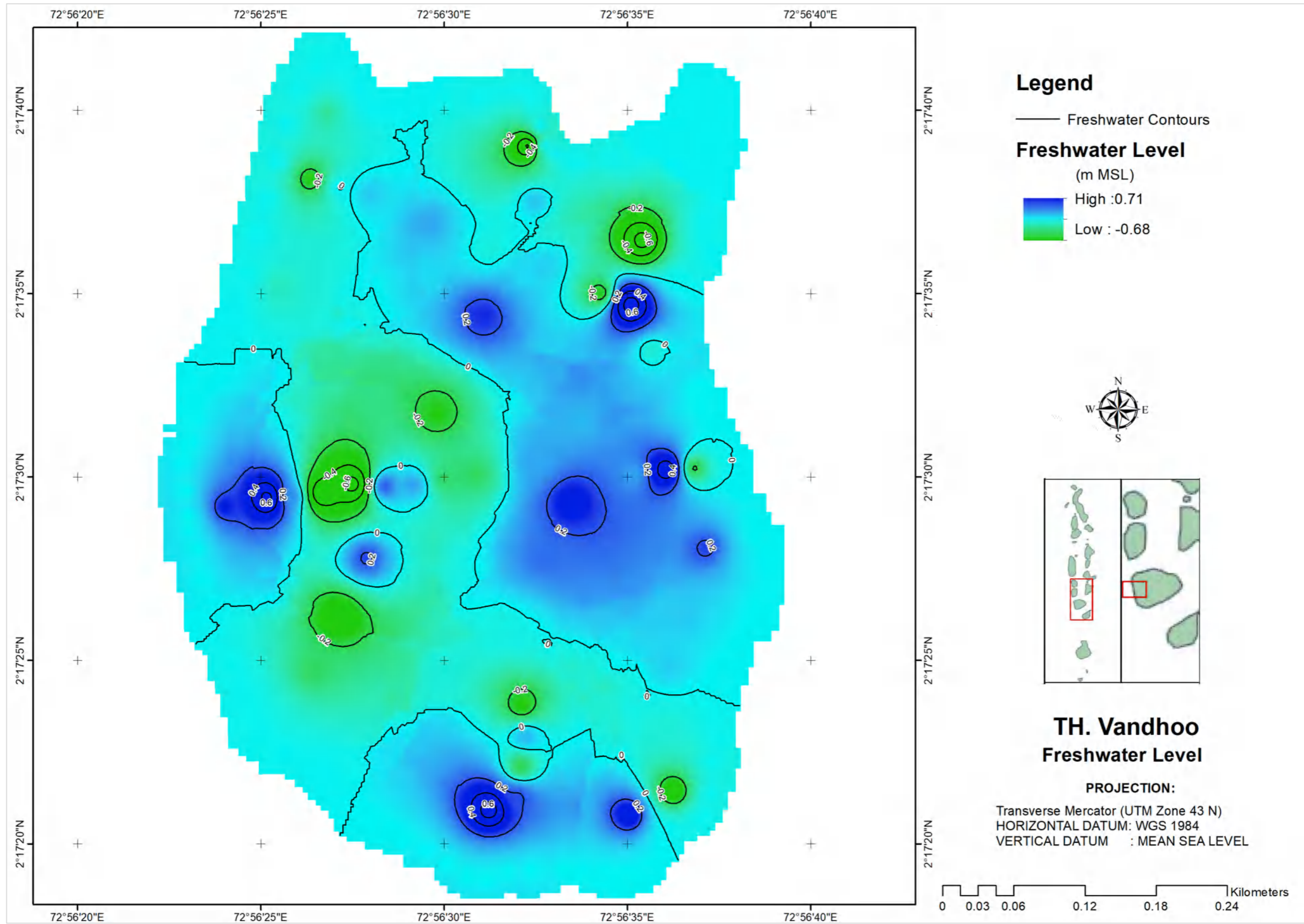


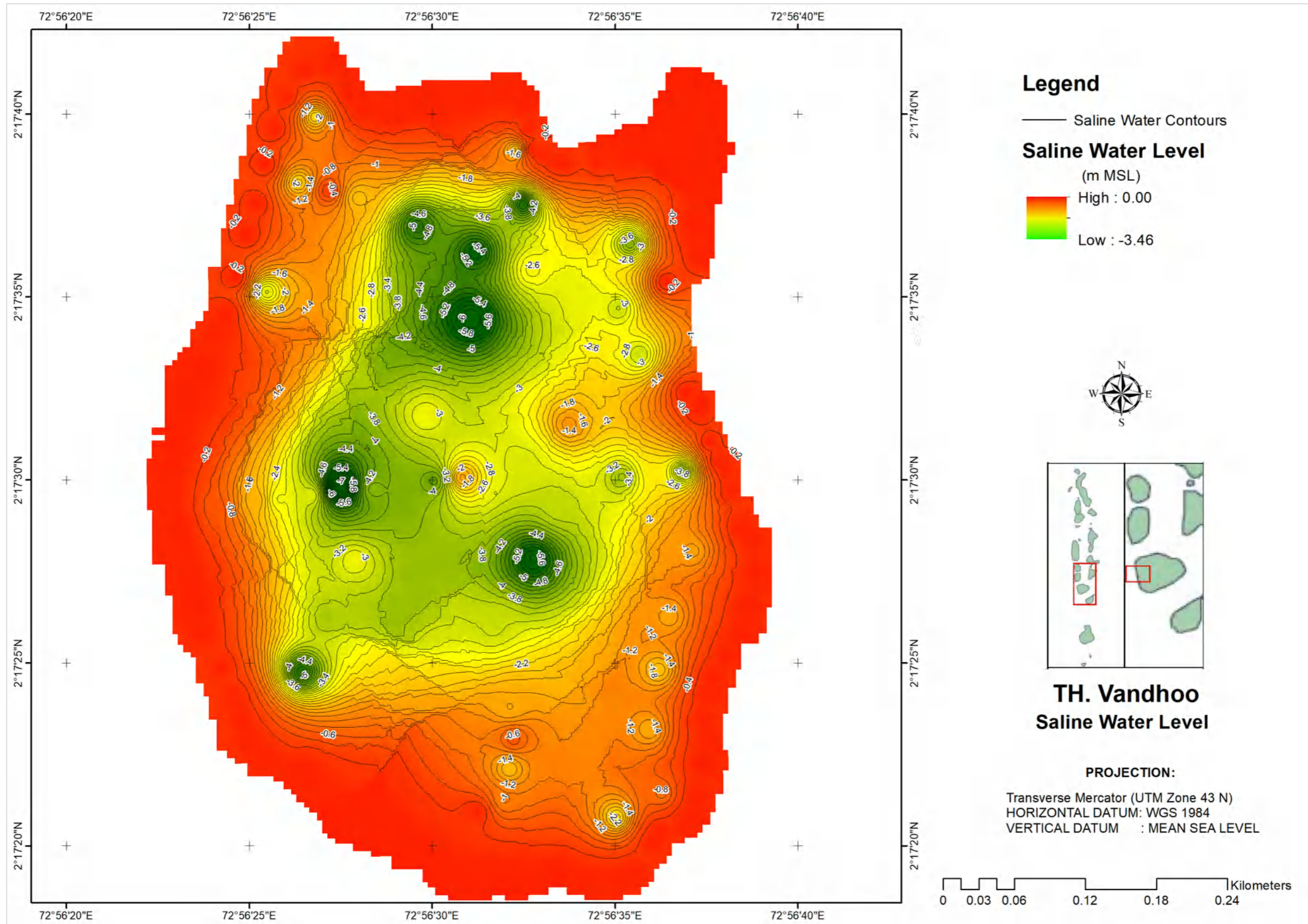
Annex VI: Freshwater Level, Saline Water Level and Freshwater Thickness of the Islands

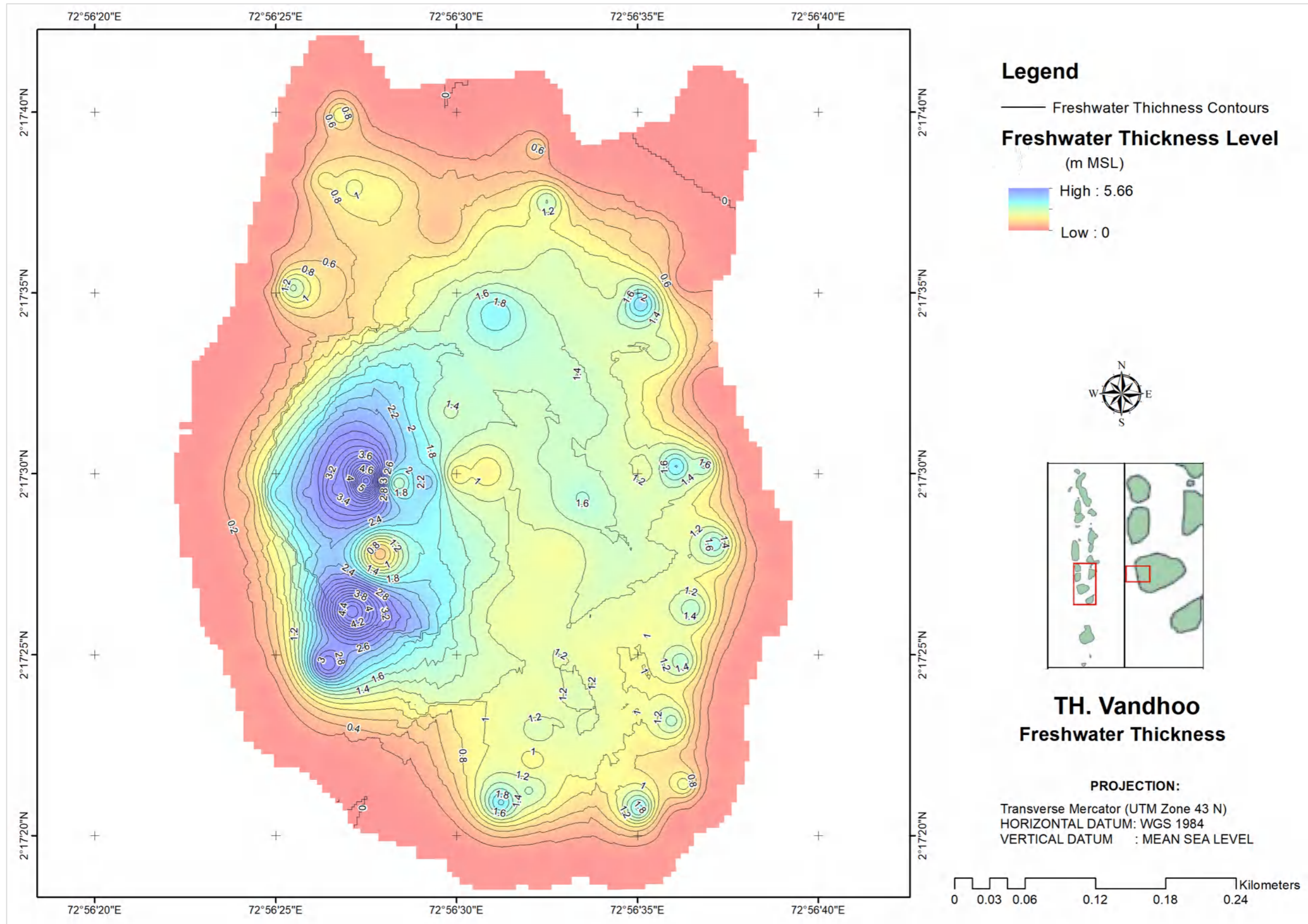


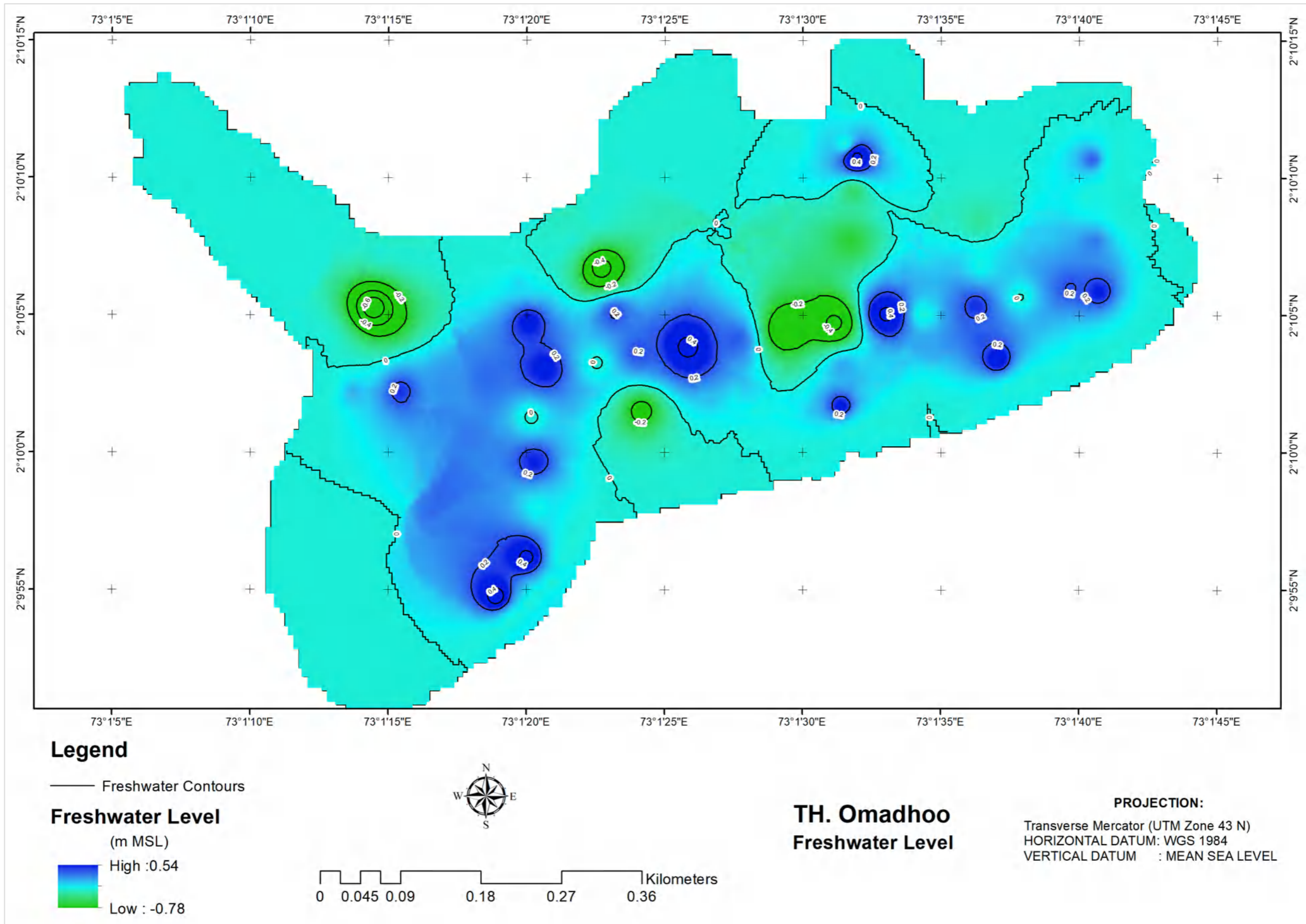


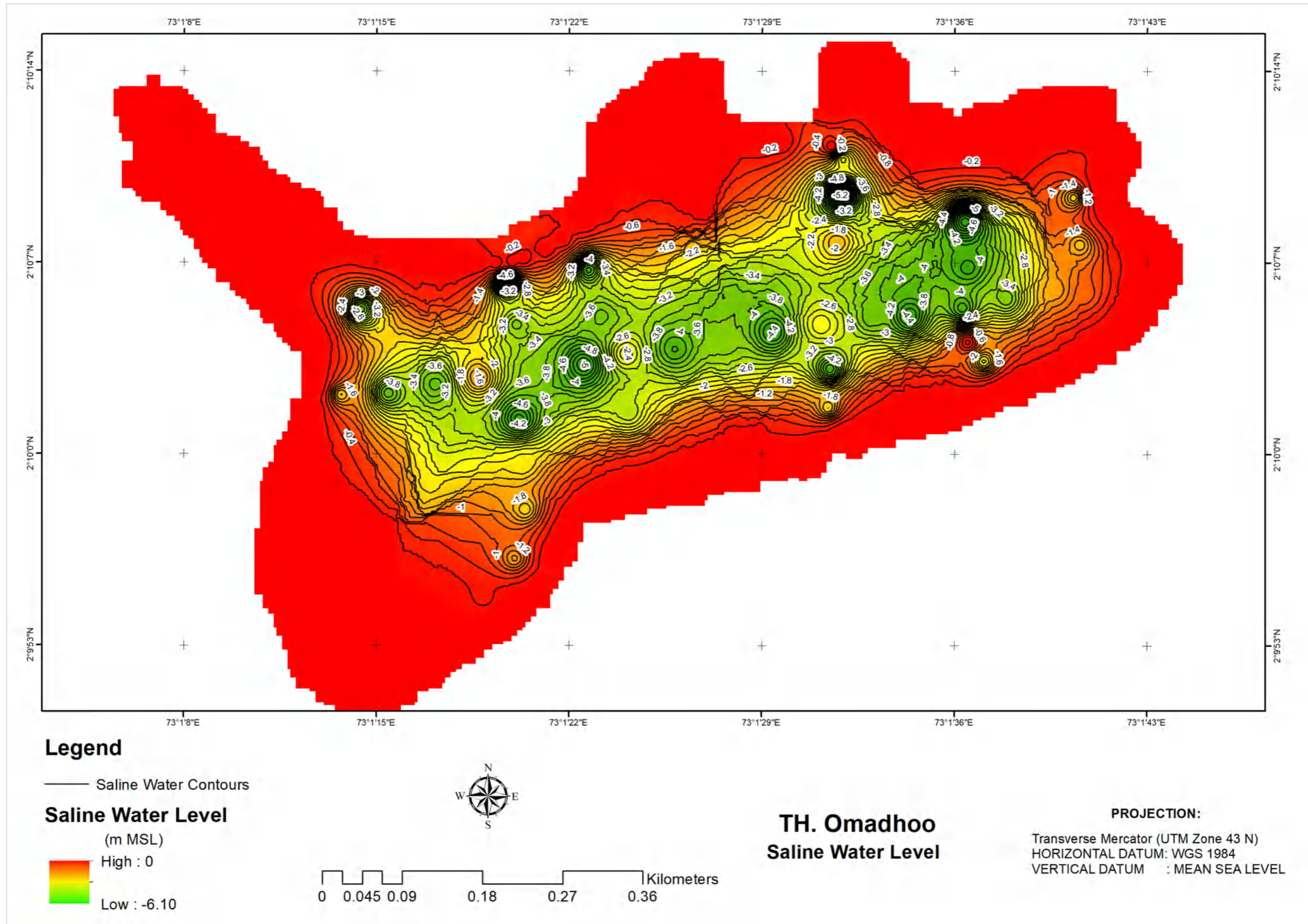


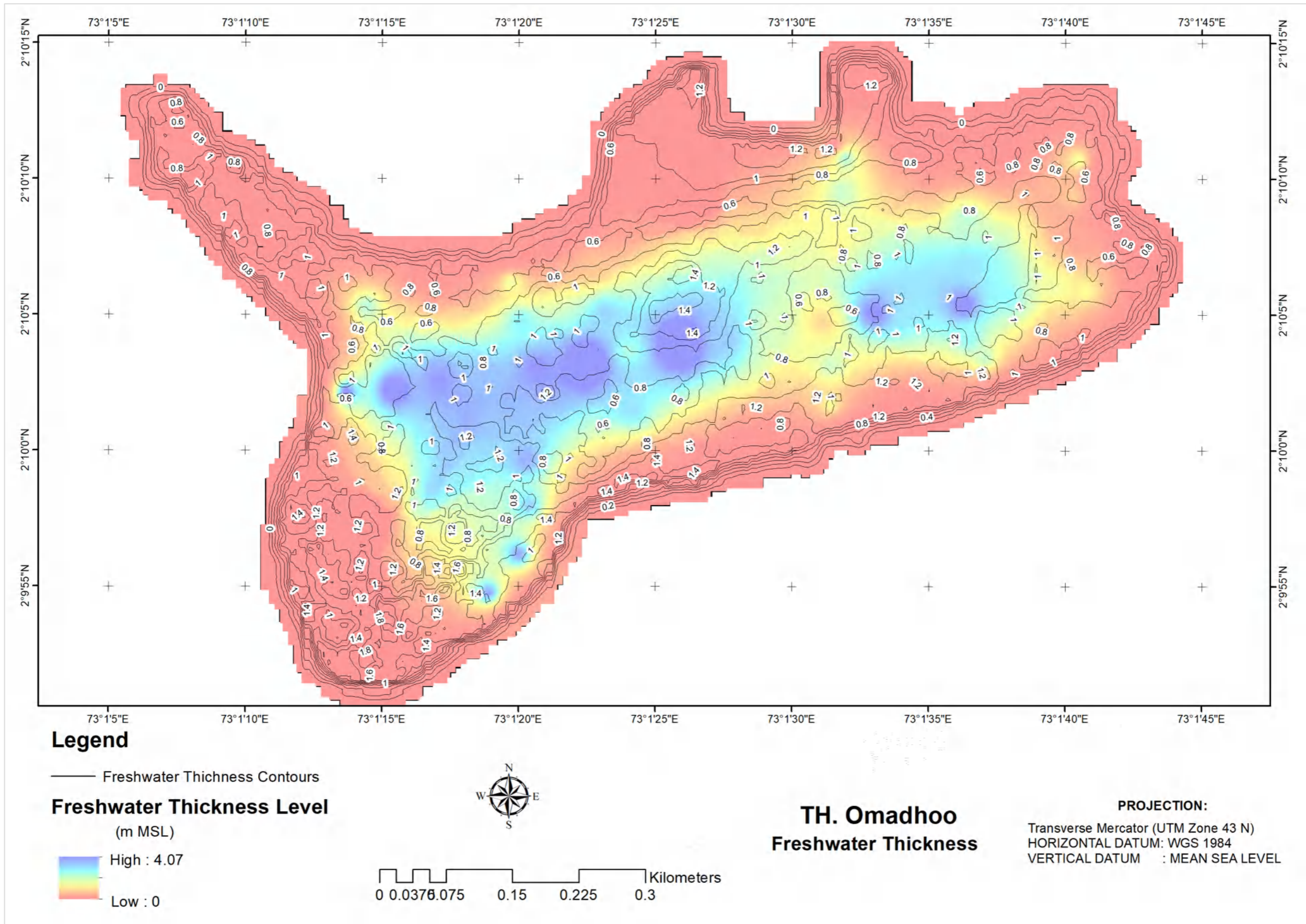


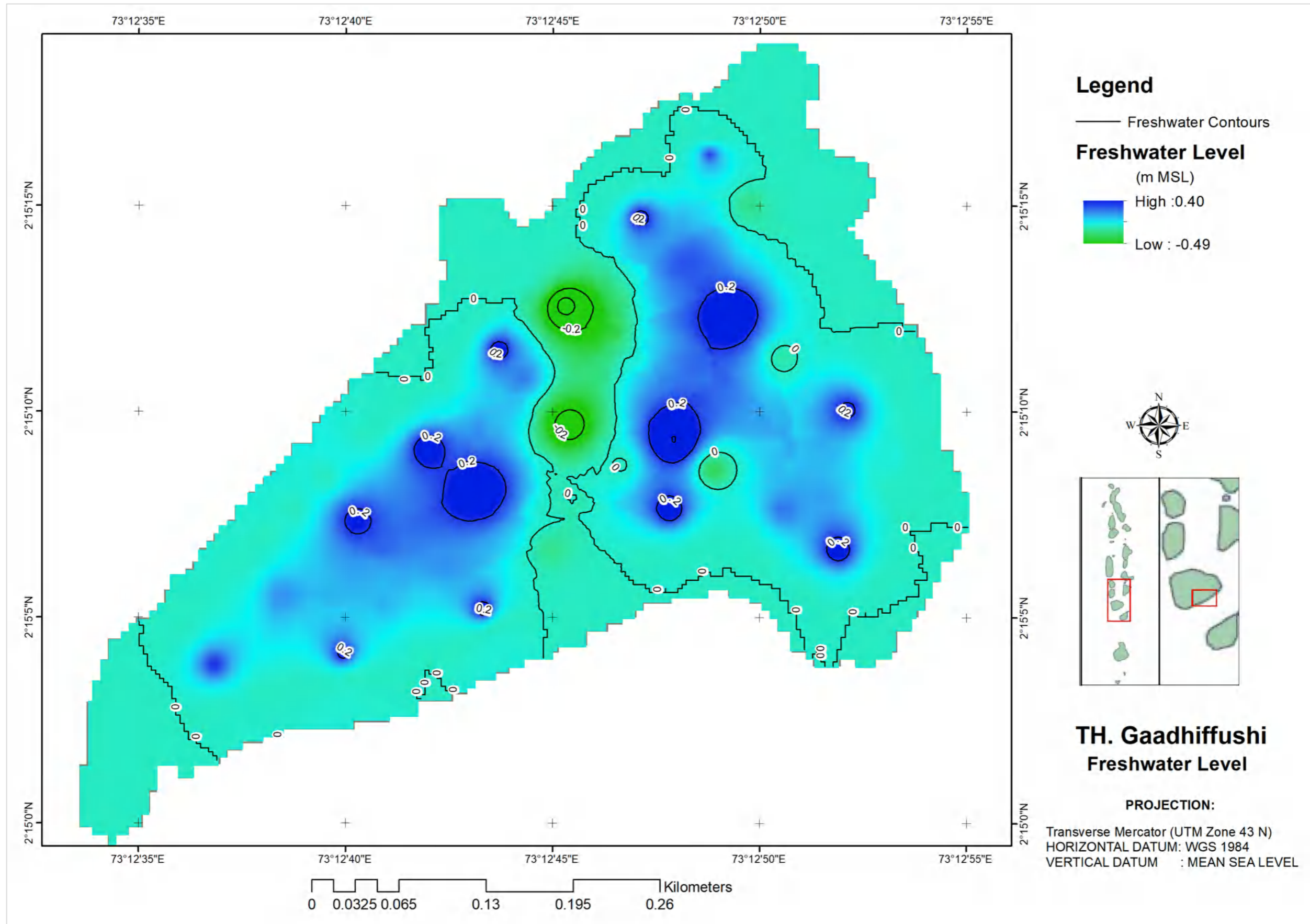


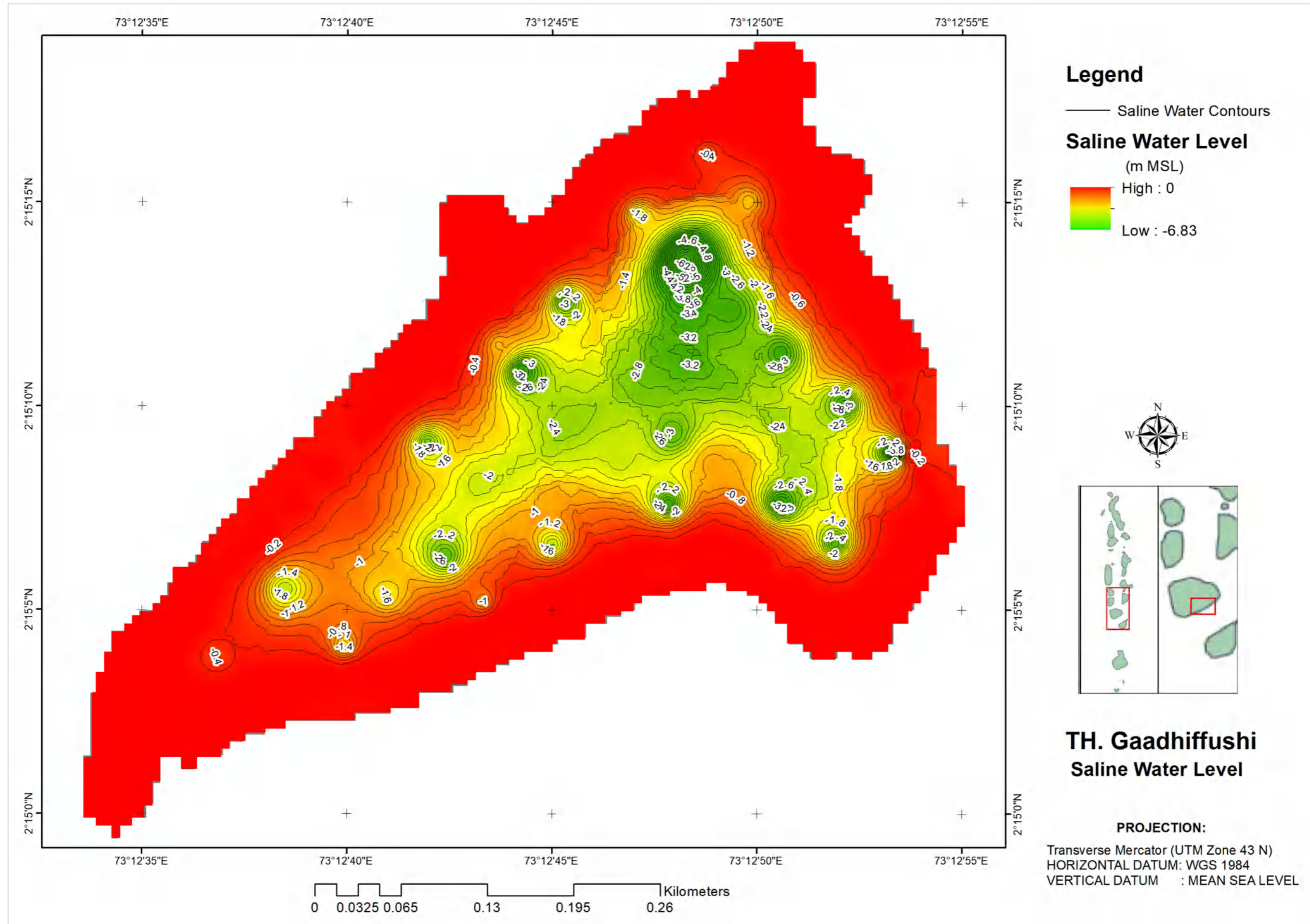


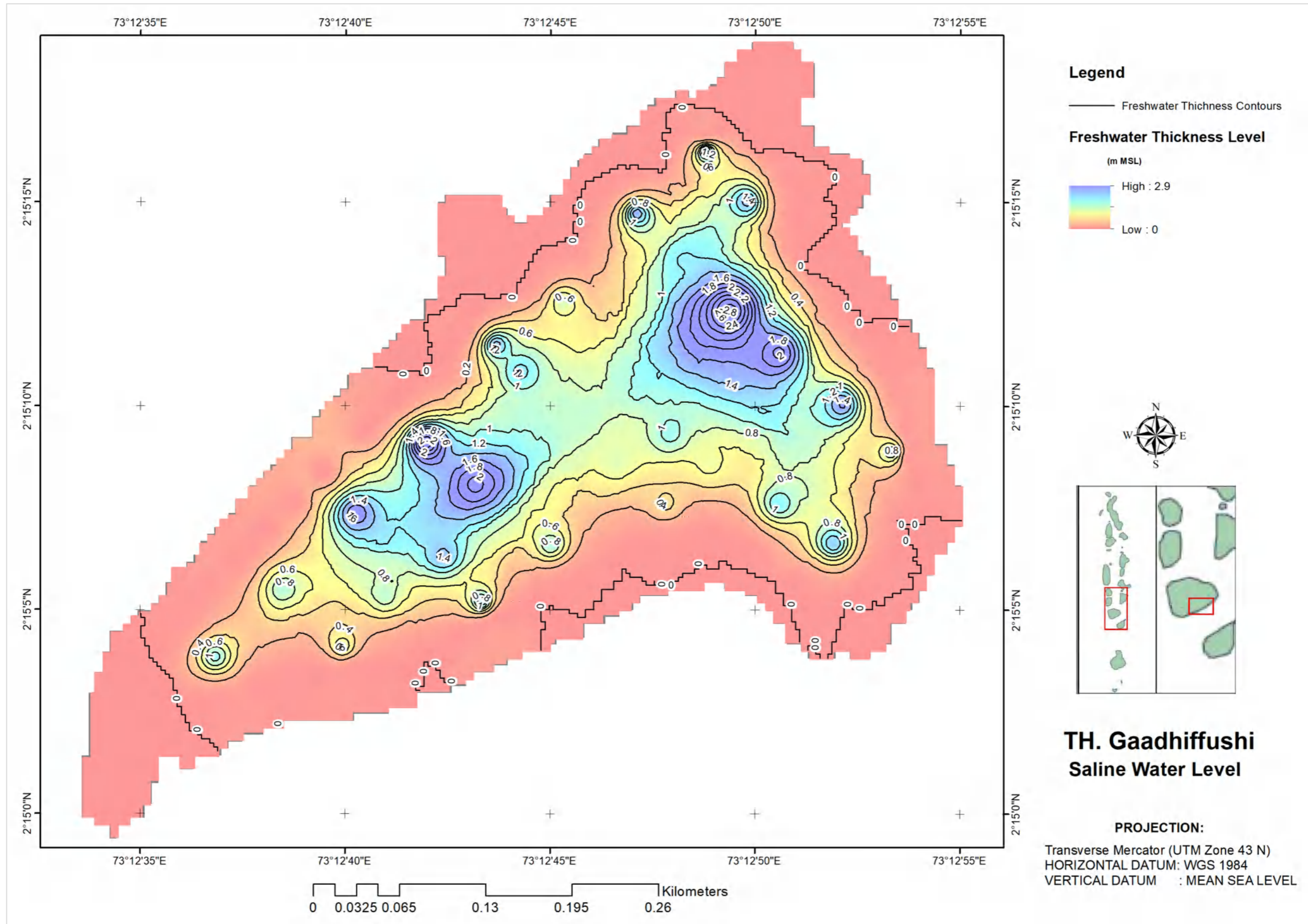


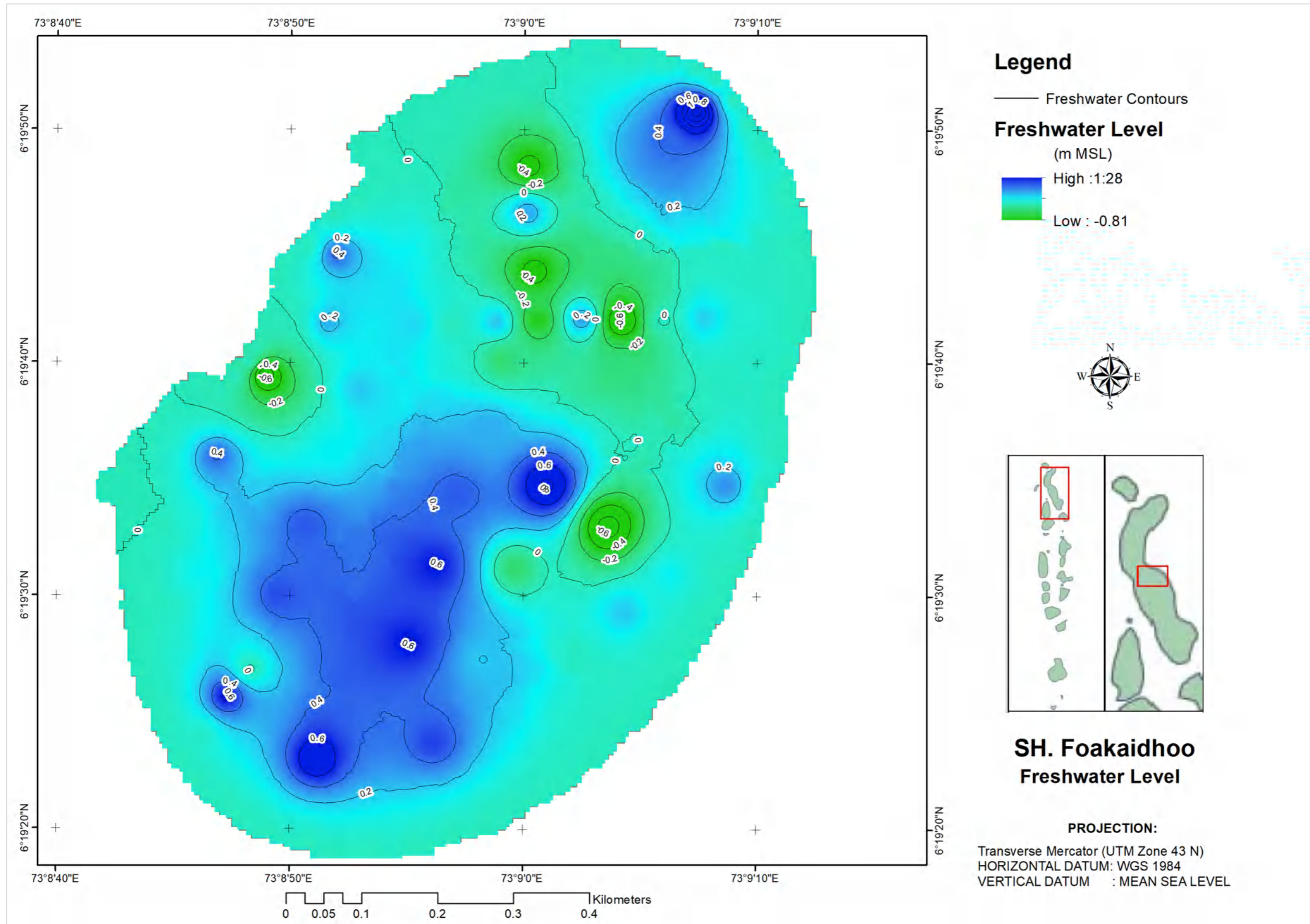


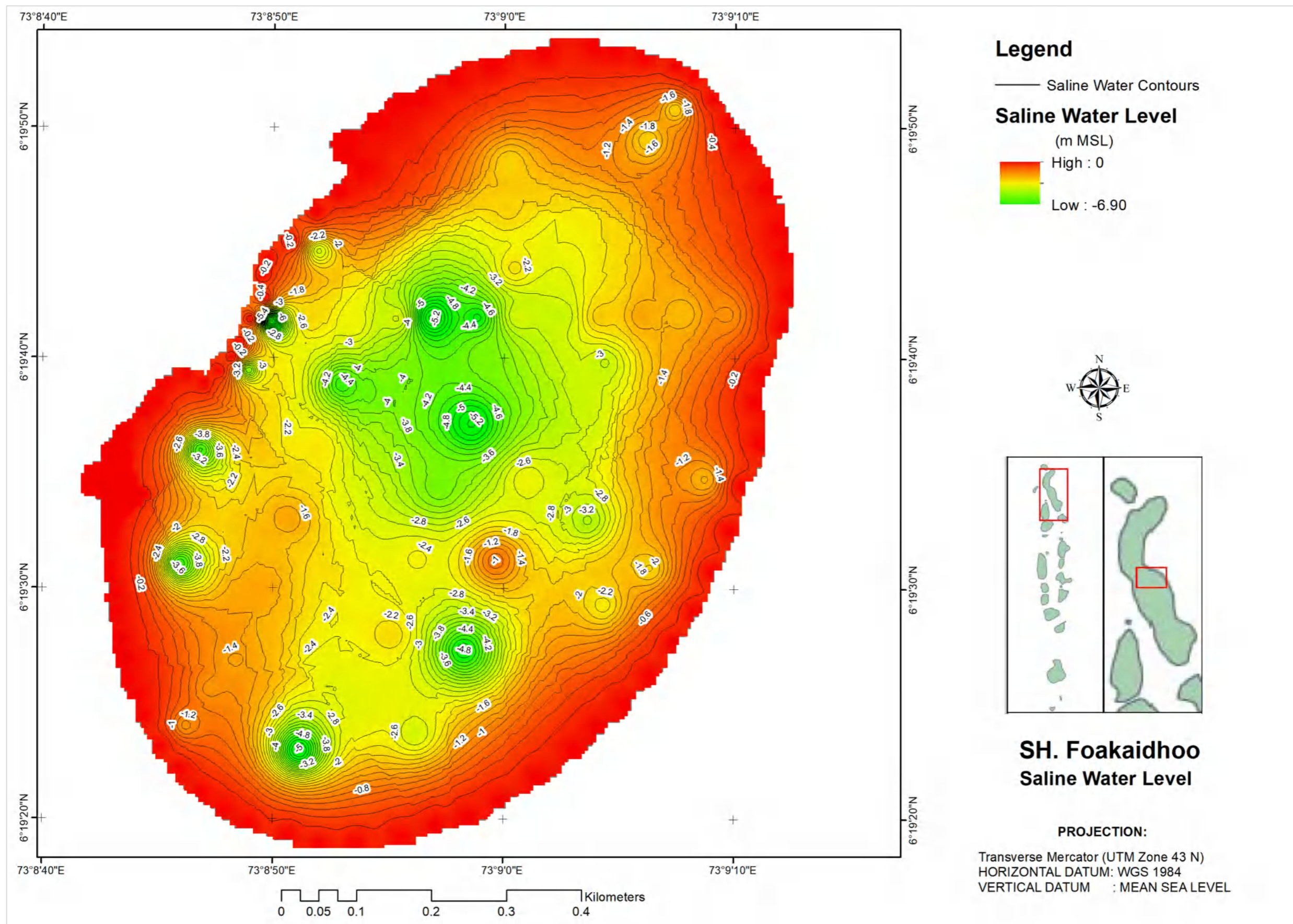


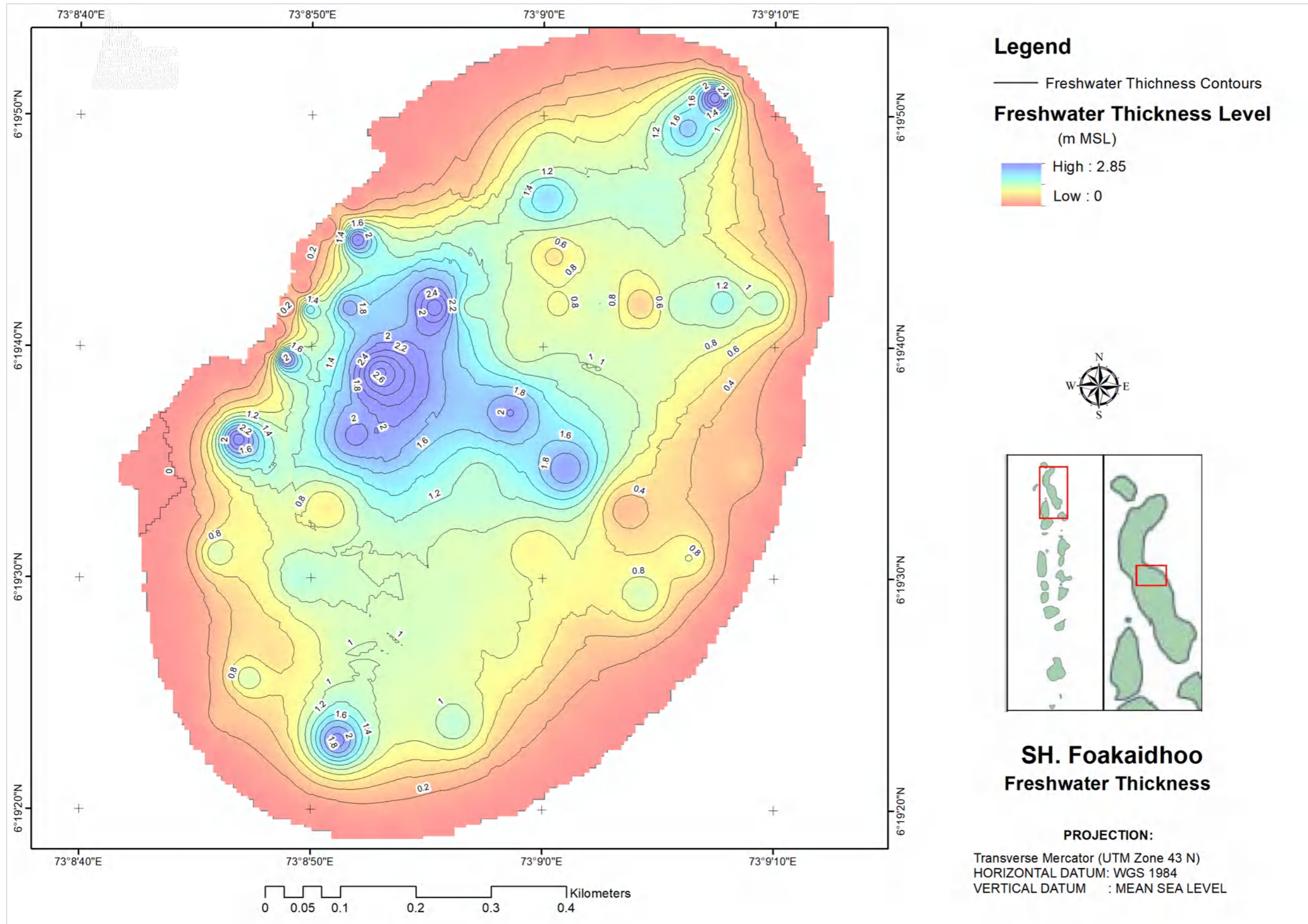












Annex VII: Assessment of Hydrogeology

Th. Kandhoodoo

Geology and Hydrogeology of the Island

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation. The thickness of the overburden (unconsolidated layer and weathered layer) within Kandoodhoo island varies from place to place with a maximum of 5.9 m and shallow overburden occurs in the southern part of the island.

The summarized details of the geological profile are given below.

- Thickness of the beach sand and top layer varies from 0.3 m to 0.4 m
- Thickness of the sandy coral layer varies from 0.5 m to 1.8 m
- Thickness of the weathered coral layer varies from 0.5 m to 3.8 m.

According to the compositional and structural differences in coral formation, differential weathering could be observed on the island. However, the general trend is that the central part of the island shows higher weathering compared to the coastal area and some deep weathered zones could also be found sporadically located on the island.

The occurrence of weak layers is common in the fresh coral formations at different depth horizons due to the occurrence of different types of coral formations within subsurface formations. The depth to the fresh coral layer varies along the coastal area with a maximum of 4 m based on indirect measurements.

Hydrogeology

The lower part of the overburden (lower part of unconsolidated formation, weathered layer, and partly weathered layer) is water bearing. The lower part of the unconsolidated formation is a completely weathered layer, and the partly weathered layer behaves as a single unit and acts as an unconfined aquifer.

The aquifer properties of the three layers are different and geologically, the completely weathered layer and unconsolidated layer show relatively more homogeneous behaviour than the partly weathered layer. Porosity of the completely weathered layer and unconsolidated layer is higher than the porosity of the partly weathered layer.

Fresh groundwater of the island occurs as a lens. Middle part of the freshwater lens rests on the fresh coral formation and its outer area rests on saline water. Basically, the geometry of the freshwater lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 1 m above MSL at the middle parts of the island. The maximum thickness of the freshwater lens is about 3.59 m by considering the $EC > 1500 \mu\text{s/cm}$ and it reduces toward the rim area of the lens. During the rainy period, groundwater seepage could be expected at the low elevated area (Waterlogged area located in the southern part of the island).

As per the report, calculated groundwater storage by considering the 15% porosity is about 192,803 m^3 .

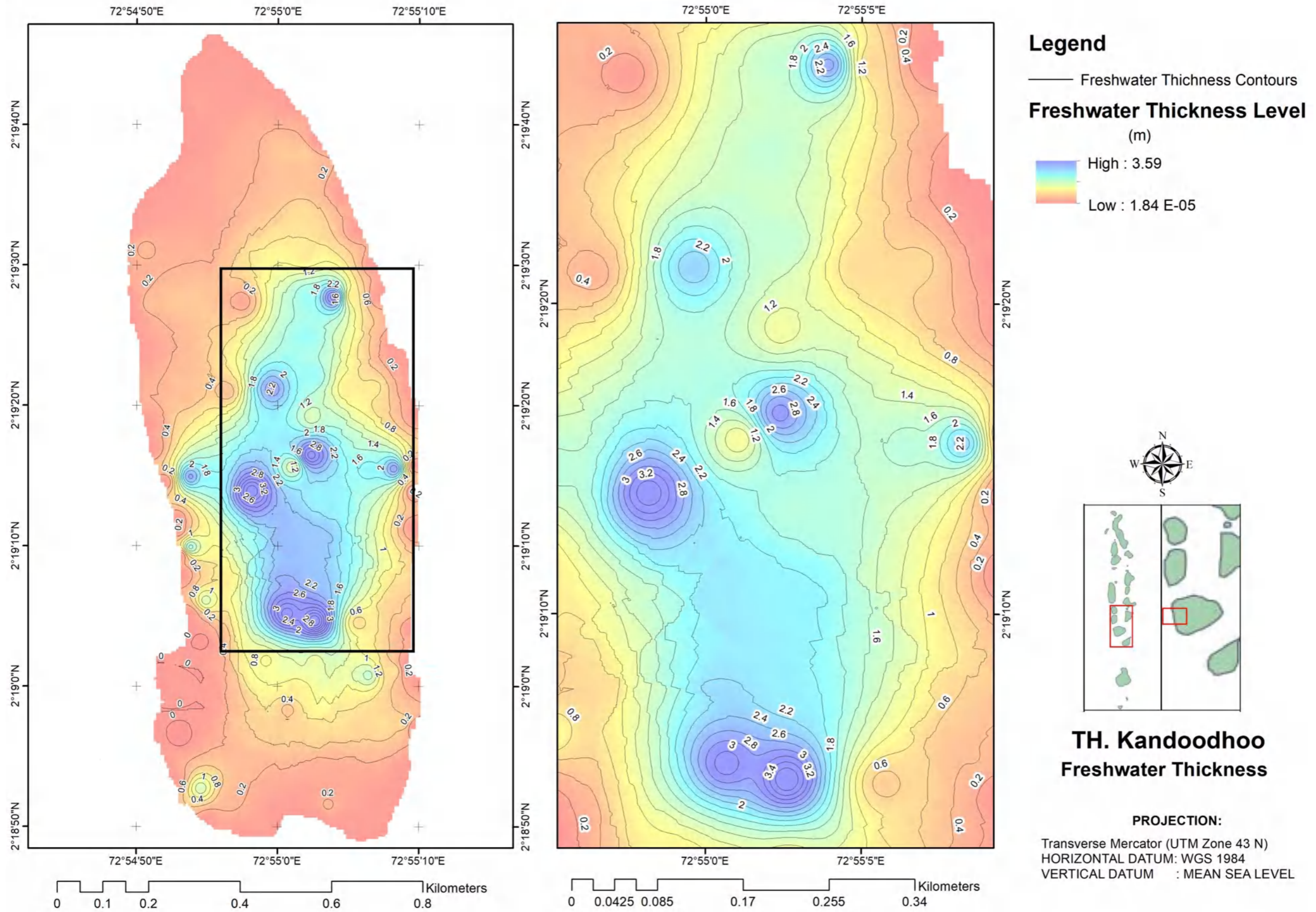


Figure 1: Fresh water thickness map of Kandoodhoo Island

Groundwater Chemistry and its Variation

Groundwater quality measurements have been made in selected places for selected physical, chemical, and microbiological parameters. All data with relevant information were presented in the submitted Baseline Assessment Report (Ref?). Further interpretation is discussed under this sub topic.

About 40 water samples have been analysed for EC ($\mu\text{s}/\text{cm}$), pH, Turbidity (NTU), DO (ppm), Temperature ($^{\circ}\text{C}$), Salinity (PSU), Nitrate (mg/l), Ammonia (mg/l), and Phosphate (mg/l). Bacteriological analysis was done in 15 places and results revealed that all wells are contaminated with coliform in different proportions (total coliform – [172 – 2,420] MPN/100 ml, faecal coliform – [6 – 1,300] MPN/100 ml) as per the WHO guidelines. In addition, field EC was measured for 18 samples. The sampling points are given in following figure.

The summarized results of the selected physical and chemical parameters are given in Table 1.

Table 0.1: Comparison of WQ results based on land usage

Land Use	No. of Samples	Results are Lined with Conditions	Increment of Measured Parameters	Remarks
Residential area	28	28		
Industrial Areas	1	1		
Agricultural area	30	24	K7, K12, K17, K19, KW9, KW19	K7-Located an Agricultural area and higher EC could be due to higher extraction. K12 and K17-Higher ammonia and nitrate are due to leaching of nitrate base fertilizers. K19-High EC due to it is close to sea. KW 9 and KW 19 –Higher EC is due to higher extraction.
Total	58	52	6	

Note:

- 1) $\text{EC} > 2,500 \mu\text{s}/\text{cm}$ (water could be used for potable and non-potable use depending on EC).
- 2) Nitrate ($> 50 \text{ mg}/\text{l}$), Phosphate ($> 5 \text{ mg}/\text{l}$), and ammonia ($> 0.5 \text{ mg}/\text{l}$) as per WHO guidelines.

The water quality records of contaminated points as per Note 1 and 2 are given in following figure.

Table 0.2: Water quality records of contaminated points

Sampling Point	EC ($\mu\text{S}/\text{cm}$)	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
K7	2,666	7.22	44.5	0.03	4.94
K12	426	7.55	1.1	1.14	0.44
K17	1,721	7.78	72.7	0.02	0.18
K19	3,683	7.99	0.6	0.07	0.18
KW9	3,450	NM	NM	NM	NM
KW19	3,880	NM	NM	NM	NM

Note: NM- Not measured

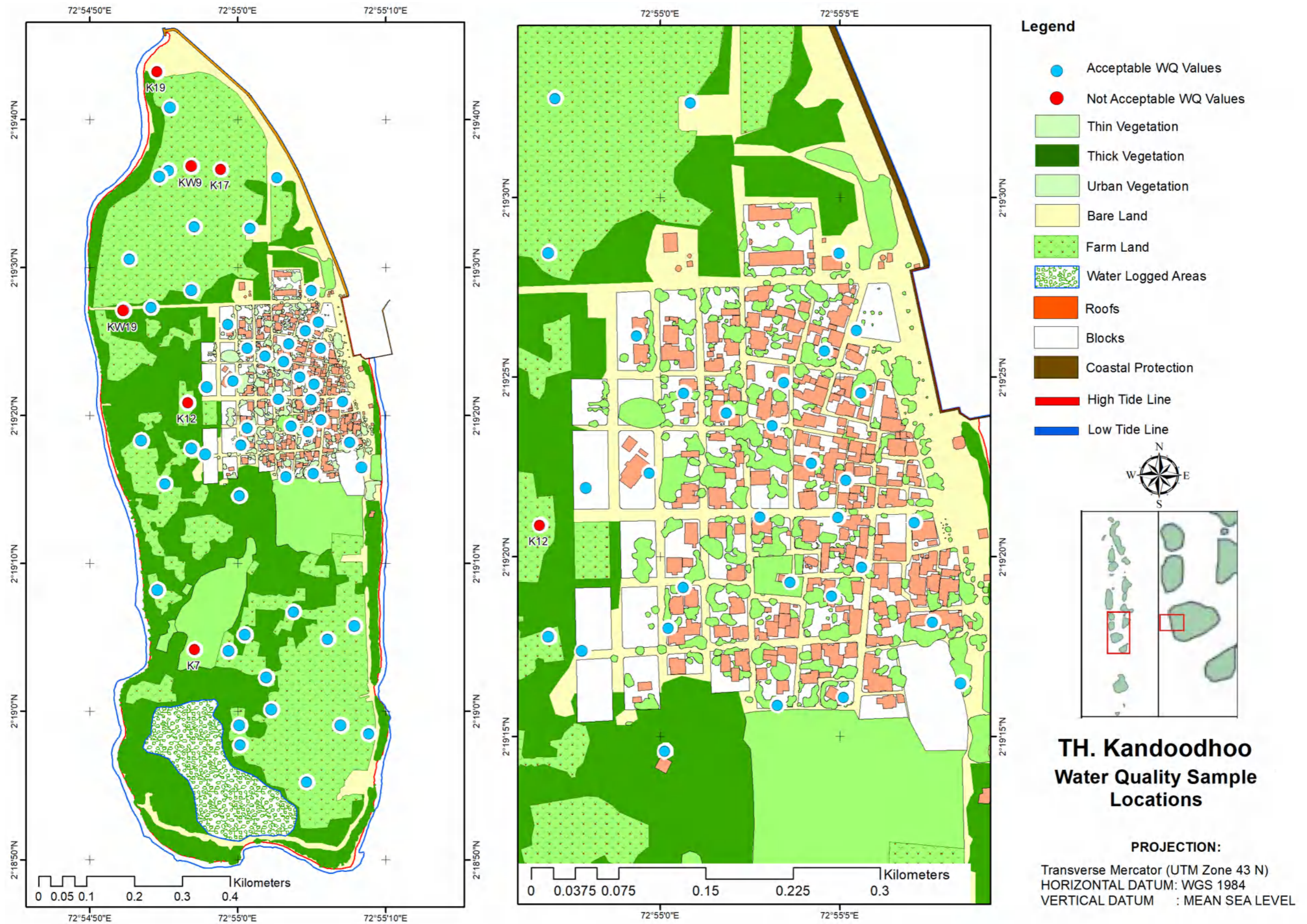


Figure 2: Location of groundwater sampling points in Kandoodhoo Island

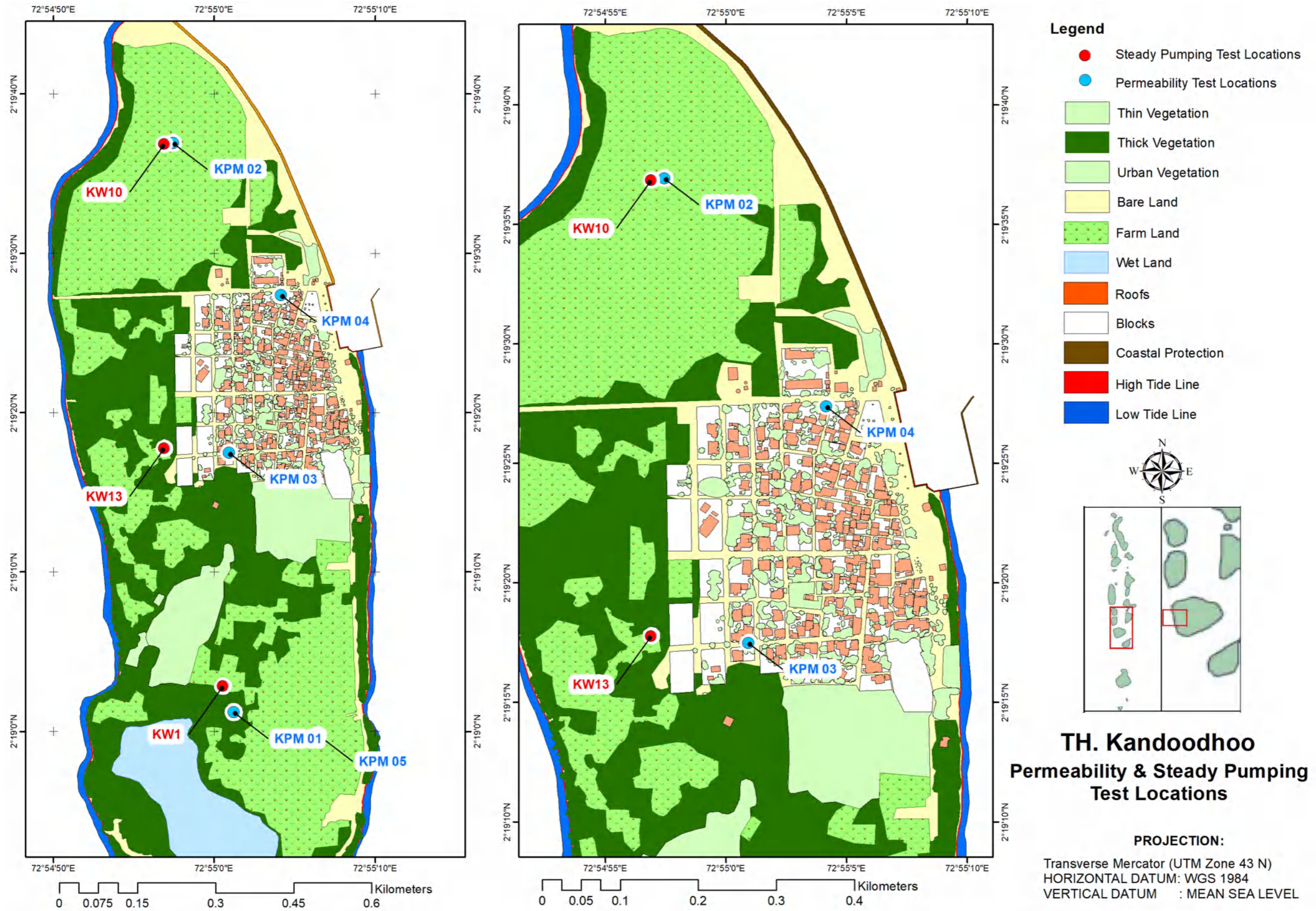


Figure 3: Locations of permeability and steady pumping tests in Kandoodhoo Island

Aquifer Properties

Hydraulic conductivity (permeability) and transmissivity were estimated by conducting permeability tests and pumping tests, respectively. Tested locations are given in above figure.

The porosity of the different subsurface formations is different and decreases towards the bottom. Porosity of the top layer (unconsolidated sand and completely weathered formation) and the partly weathered formation are assumed as 15% and 5%, respectively. The fresh limestone layer is impermeable and some porosity in coral limestone is expected under fractured conditions.

Hydraulic conductivity of the unsaturated formation

Field permeability testing was conducted at five locations as per the Borehole Infiltration Testing Guide (ASTM D 6391-11) using Borehole Infiltration Tests (Constant Head Approach). The estimated hydraulic conductivity values of the unsaturated zone of the soil profile at tested locations are given below.

Table 0.3: Estimated hydraulic conductivity values for Th. Kandoodhoo

Point	Hydraulic Conductivity (m/d)
KMP 1	10.94
KMP 2	8.41
KMP 3	4.50
KMP 4	15.00
KMP 5	2.47

The measured hydraulic conductivity values ranged from a minimum of 2.47 m/d to a maximum of 15.00 m/d, with an average of 8.26 m/d. The results revealed that measured hydraulic conductivity within different land uses does not show significant variation. The average value of 8.26 m/d is considered for estimation of the groundwater flow velocities and recharging volume of the island.

Pumping test

The testing was conducted on dug wells to estimate the transmissivity of the water bearing formation for a 1-hour period (pumping and recovery). The estimated transmissivity value of water bearing formation is given below.

Table 0.4: Pumping test results for Th. Kandoodhoo

Dug well	Transmissivity (m ² /s)	Drawdown (m)	EC - Before Pumping (µs/cm)	EC - End of Pumping (µs/cm)
KW 1	0.011	0.32	700	840
KW 10	0.013	0.42	1,360	3,330
KW 13	0.002	0.62	1,160	1,230

The measured transmissivity (m²/s) values ranged from a minimum of 0.002 m²/s to a maximum of 0.013 m²/s., with an average of 0.0086 m²/s. A clay mixed sand is observed at KW 13 compared to the other two sites.

Groundwater flow and flow velocity

As per the groundwater elevation map, a north-south oriented groundwater lens is observed within the island and a relatively higher head is observed in the southern part of the island. The water level of the freshwater lens is sloping towards the east and west sides.

The groundwater velocity map for the island was developed by using the calculated average hydraulic conductivity of the island and assuming a porosity of 15%. The calculated velocity of the groundwater varies from place to place with a maximum of 7.73 m/day. The flow velocity over 90% of the land area is less than 0.82 m/day.

The estimated maximum retention time of the groundwater within the island for a velocity of 0.3 m/day and 0.82 m/d is about 24.4 months and 8.9 months, respectively. As per the velocity map, the groundwater recharging shall be carried out in the middle part of the island. In addition, recharging structures are to be constructed in order to increase the retention time and to control the seawater flooding. The details of the structures will be discussed under Chapter 6.

Seawater Flooding

It is noted that seawater flooding areas (marked in red) along the coastal line are observed during the field. Further, the waterlogged area is situated at the southern corner of the island. During the rainy period, overland flow and seepages flow to the sea through the waterlogged area while seawater flows into the waterlogged area as a result of tidal action.



Figure 4: Seawater flooding areas in Kandoodhoo Island (marked in red colour)

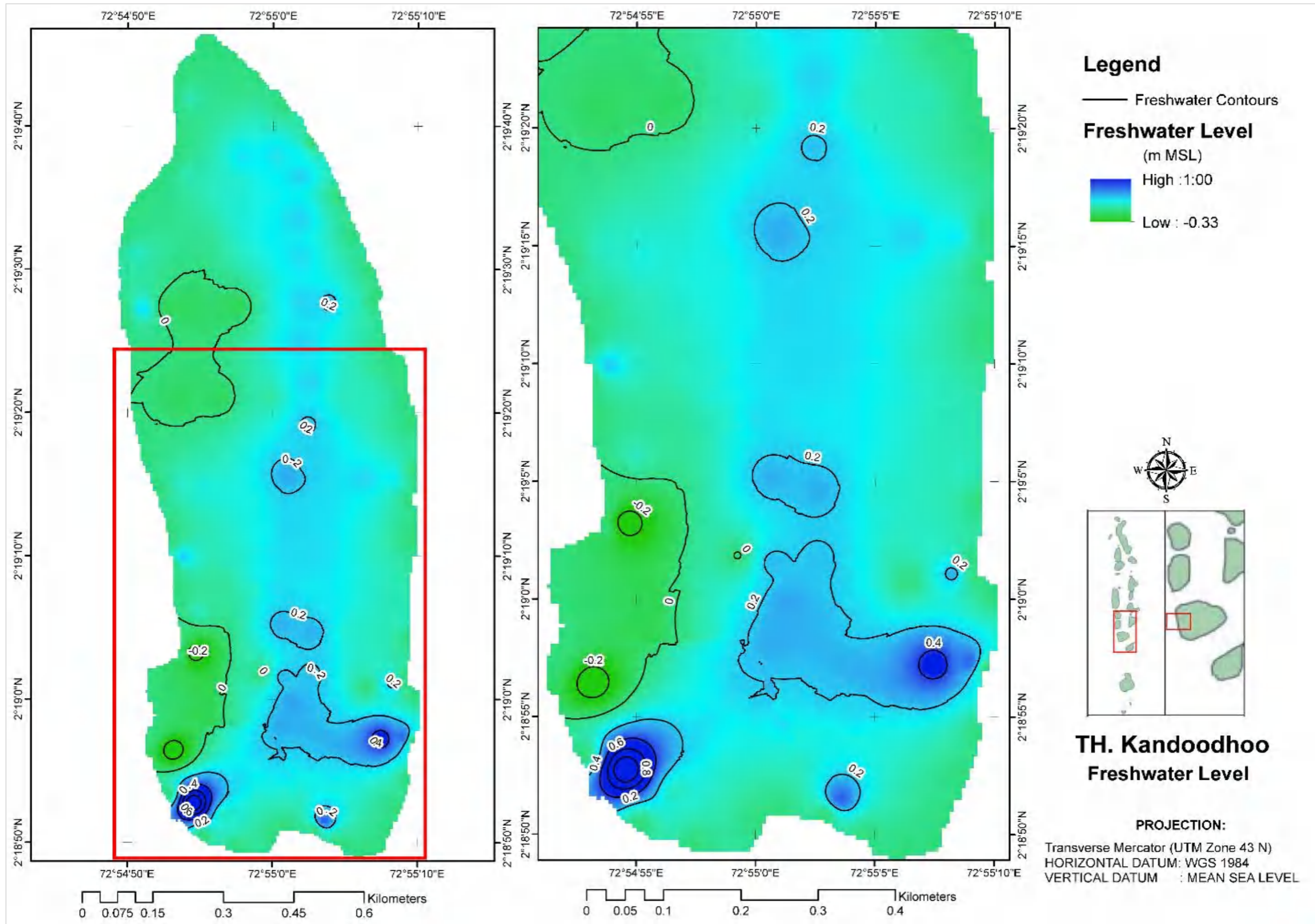


Figure 5: Freshwater Level in Kandoodhoo Island

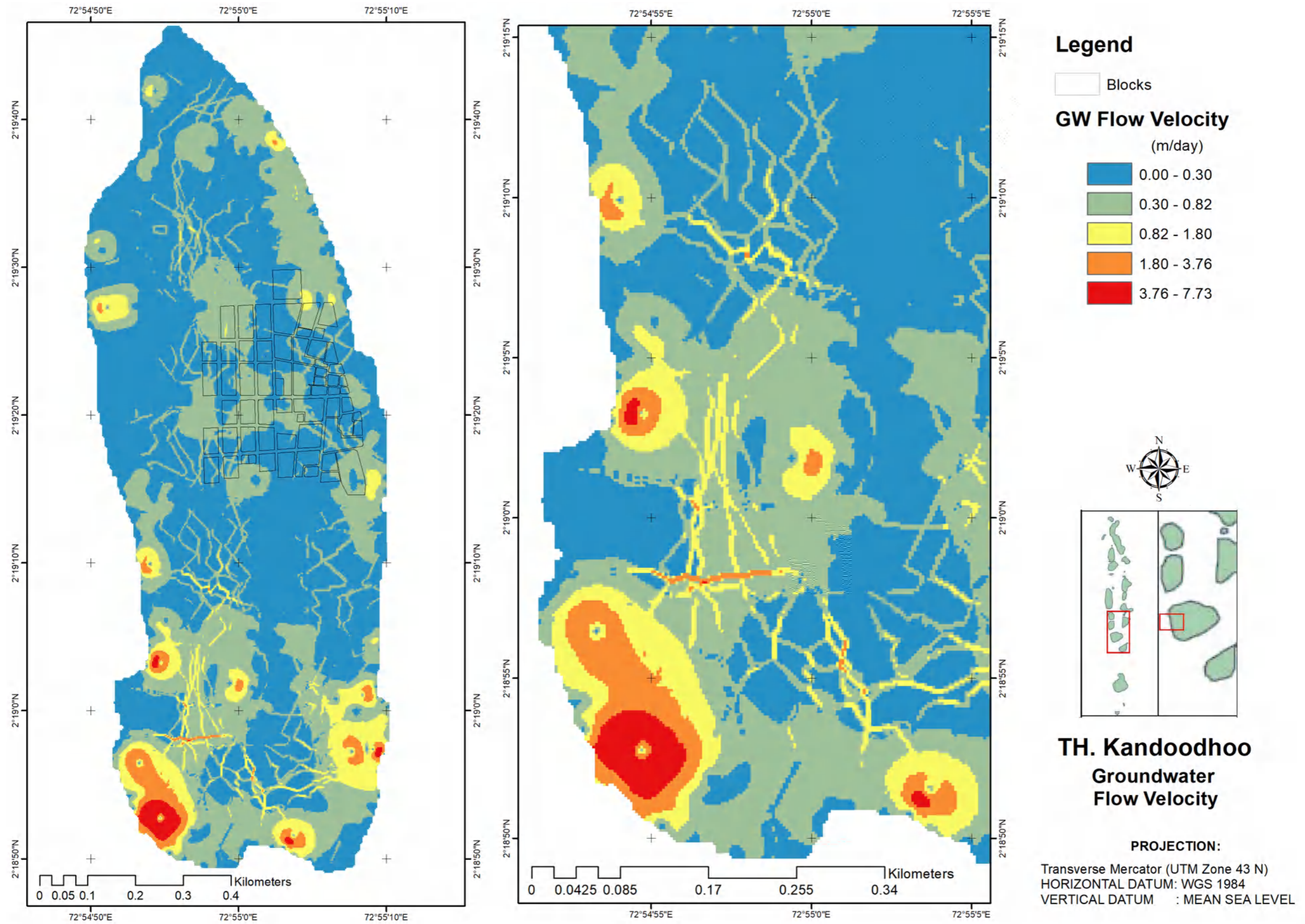


Figure 6: Groundwater Flow velocity map of the Kandoodhoo Island

Th. Vandhoo

Geology and Hydrogeology of the Island

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation. The thickness of the overburden (unconsolidated layer and weathered layer) within Vandhoo island varies from place to place with a maximum of 4.5 m.

The summarized details of the geological profile are given below.

- Thickness of the top layer varies up to 0.5 m
- Thickness of the beach coral sand layer varies from 0.3 m to 1.8 m. The gravel rich depositional areas are observed in the southern stretch of the island along the beach stretch and its interior areas. Sandy formations are observed in the northern stretch of the island. Middle stretch is mainly composed of a mixed formation of gravel and sand.
- Thickness of the weathered coral layer varies from 0.5 m to 4 m.

According to the compositional and structural differences in coral formation, differential weathering could be observed in the island. Along the E-W cross section, the general trend is that the central part of the island shows higher weathering compared to the coastal area. However, the N-S cross section clearly shows some deep weathered zones in northern areas of the island.

The occurrence of weak layers is common in the fresh coral formations at different depth horizons due to the occurrence of different types of coral formations within subsurface formations. The depth to the fresh coral layer varies along the coastal area with a maximum of 2-3 m based on indirect measurements.

Hydrogeology

The lower part of the overburden (lower part of unconsolidated formation, weathered layer, and partly weathered layer) is water bearing. The lower part of the unconsolidated formation is a completely weathered layer, and the partly weathered layer behaves as a single unit and acts as an unconfined aquifer.

The aquifer properties of the three layers are different and geologically, the completely weathered layer shows more homogeneous behaviour than the partly weathered layer and unconsolidated formation. Porosity of the completely weathered layer and unconsolidated layer is higher than the porosity of the partly weathered layer.

Fresh groundwater of the island occurs as a lens. The middle part of freshwater lens rests on the fresh coral formation and its outer area rests on saline water. Basically, the geometry of the freshwater lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 0.71 m above MSL in the middle parts of the island. The maximum thickness of the freshwater lens is about 5.67 m by considering the $EC > 1500 \mu\text{s/cm}$ and it reduces toward the rim area of the lens. During the rainy period, groundwater discharging conditions could be expected at the low elevated area

As per the report, calculated groundwater storage by considering the 15% porosity is about 31,617 m^3 .

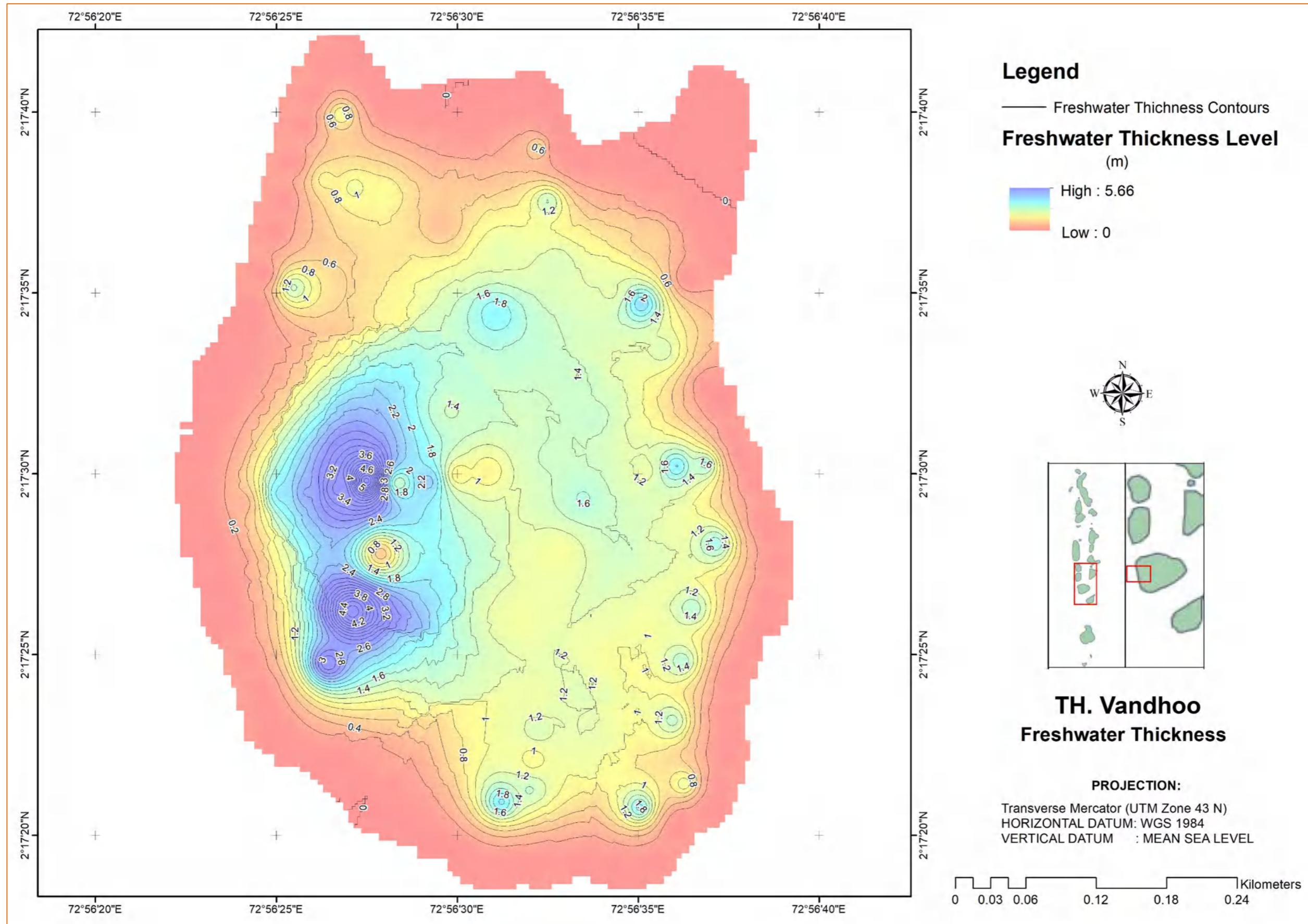


Figure 7: Freshwater thickness map of Vandhoo Island

Groundwater Chemistry and Its Variation

Groundwater quality measurements have been made in selected places for selected physical, chemical, and microbiological parameters. All data with relevant information were presented in the submitted Baseline Assessment Report. Further interpretation is discussed under this sub topic.

About 41 water samples have been analysed for EC ($\mu\text{s}/\text{cm}$), pH, Turbidity (NTU), DO (ppm), Temperature ($^{\circ}\text{C}$), Salinity (PSU), Nitrate (mg/l), Ammonia (mg/l), and Phosphate (mg/l). Bacteriological analysis was done in 13 places and results revealed that all wells are contaminated with coliform in different proportions (total coliform – [248 – 2,420] MPN/100 ml, faecal coliform – [5 – 261] MPN/100 ml) as per the WHO guidelines. The sampling points are given in following figure. In addition, field EC was measured for 19 samples.

The summarized results of the selected physical and chemical parameters are given.

Table 0.5: Comparison of WQ results based on land usage

Land Use	Number of Samples	Results are Lined with Conditions	Increment of Measured Parameters	Remarks
Residential area	48	43	VW6, VW 8, VW18, V23, V31	VW 6 and VW 18-EC extreme values are due to the leaching of salt from a coral stockpiling site. VW 8 and VW 23-EC enrichment due to seawater mixing. VW 18- EC increased vaues are due to water flooding.
Agricultural area	3	2	V10	V10 – Leaching on nitrate-based fertilizers from agricultural lands
Industrial areas	2	2		
Other areas	9	4	V16, V17, V18, V30, V34,	V18, V30, V34-Seawater flooding and adding of contaminants from overland flow. These sites are located in low elevated areas. V17 –Adding of contaminants from anthropogenic activities through overland flow and it is located at water logged area.
Total	60	49	11	

Note:

- 1) EC > 2,500 $\mu\text{s}/\text{cm}$ (water could be used for potable and non-potable use depending of EC.
- 2) Nitrate (> 50 mg/l), Phosphate (> 5 mg/l), and ammonia (> 0.5 mg/l) as per WHO guidelines.

The water quality records of contaminated points as per Note 1 and 2 are given in following table.

Table 0.6: Water quality records of contaminated points

Sampling Points	EC (µS/cm)	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
V10	1,431	7.11	1.3	2.38	0.17
V16	50,263	7.32	0.4	0.73	0.13
V17	2,221	7.70	4.0	0.62	1.24
V18	28,130	7.21	8.3	0.56	1.22
V23	2,872	7.33	18.2	0.08	0.09
V30	3,753	7.45	2.7	0.63	1.28
V31	3,186	7.53	1.1	0.08	0.13
V34	47,248	7.32	3.5	1.30	0.32
VW6	2,730	NM	NM	NM	NM
VW8	7,310	NM	NM	NM	NM
VW18	3,390	NM	NM	NM	NM

Note: NM- Not measured

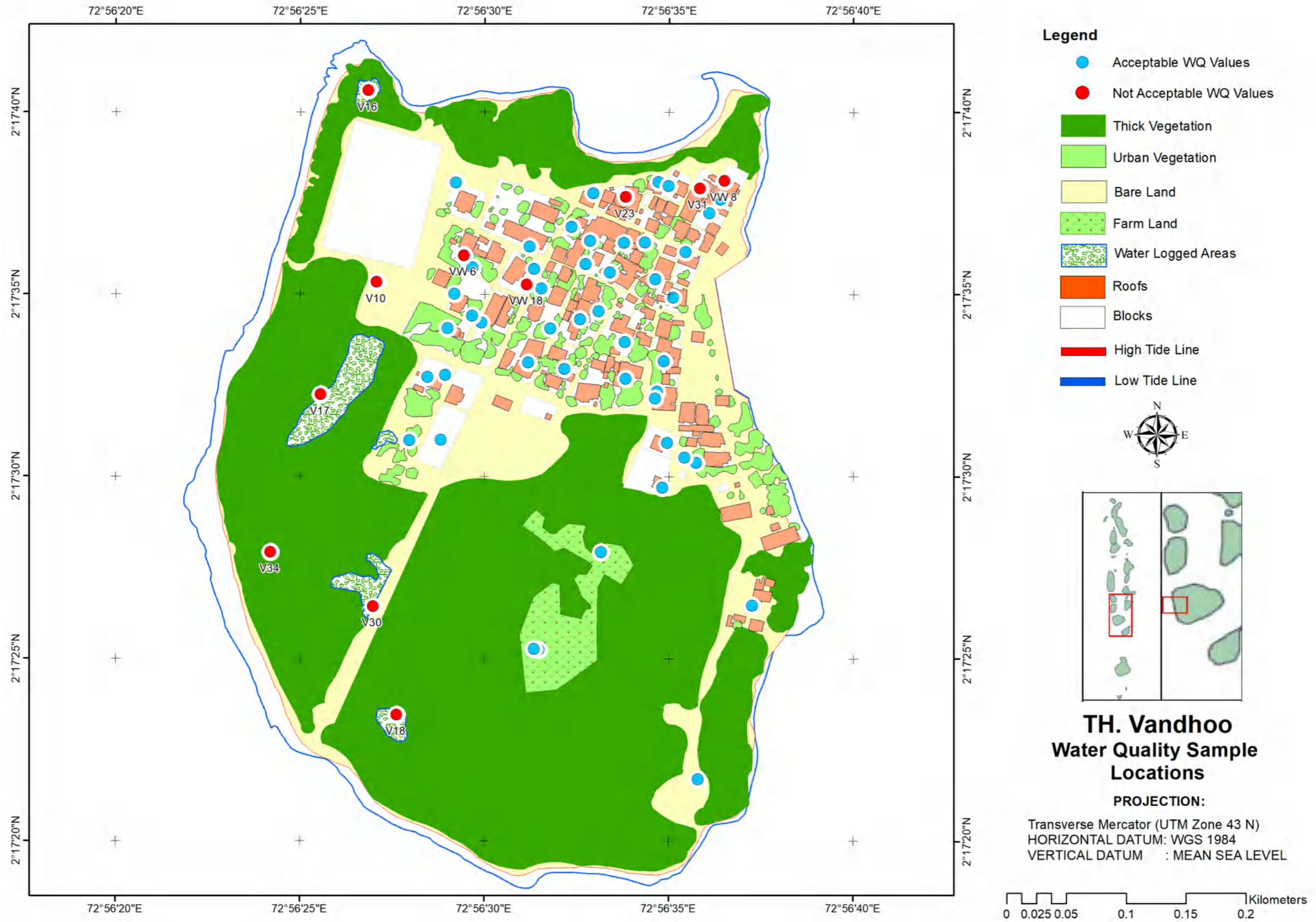


Figure 8: Location of groundwater sampling points in Vandhoo Island

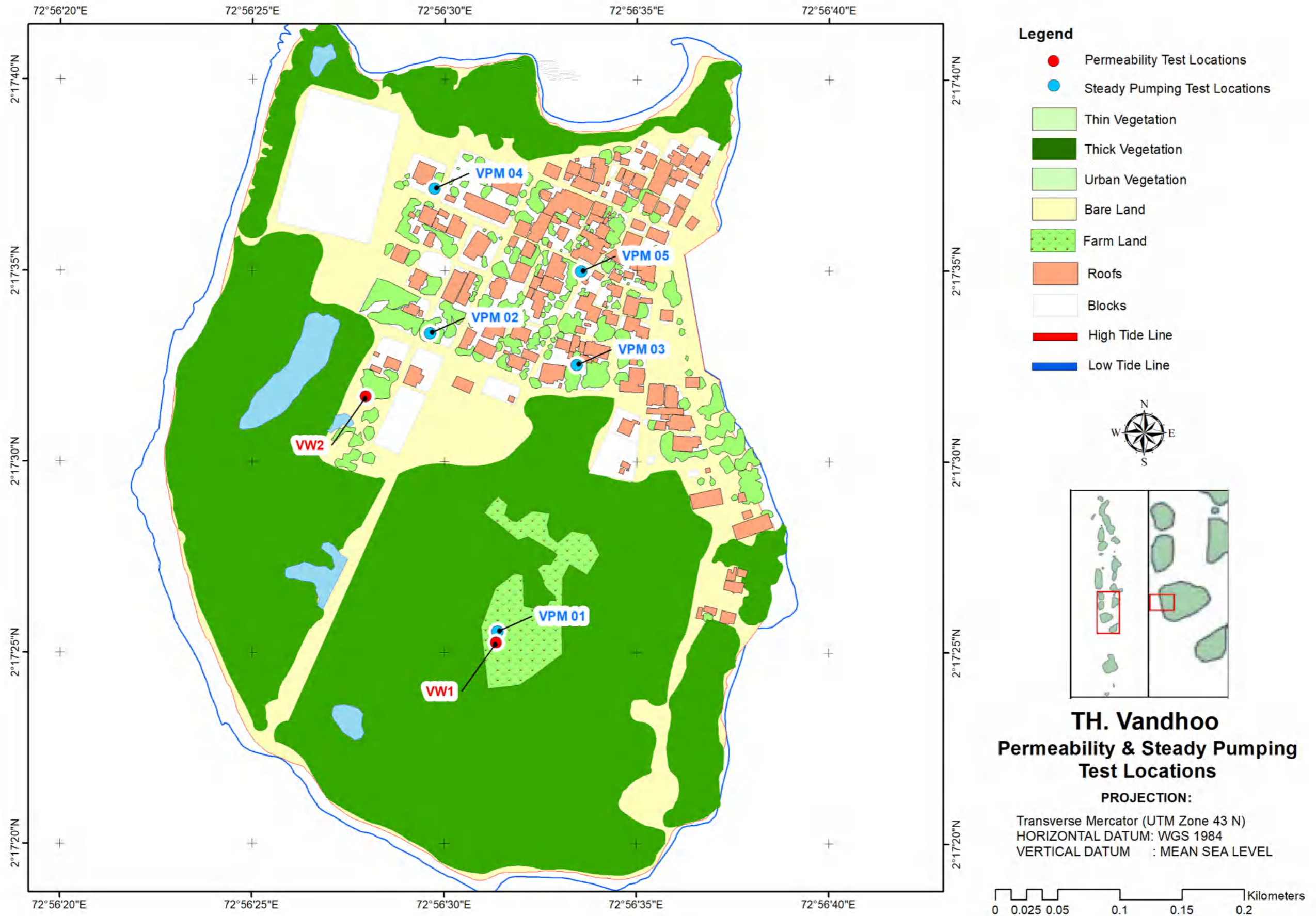


Figure 9: Locations of permeability and steady pumping tests in Vandhoo Island

Aquifer Properties

Hydraulic conductivity(permeability) and transmissivity were estimated by conducting the permeability test and pumping tests respectively. Tested locations are given in above figure.

The porosity of the different subsurface formations is different and decreases towards the bottom. Porosity of the top layer (unconsolidated sand and completely weathered formation) and the partly weathered formation are assumed as 15% and 5%, respectively. The fresh limestone layer is impermeable and some porosity in coral limestone is expected under fractured conditions.

Hydraulic conductivity of the unsaturated formation

Field permeability testing was conducted at five locations as per the Borehole Infiltration Guideline (ASTM D 6391-11) using Borehole Infiltration Tests (Constant Head Approach). The estimated hydraulic conductivity values of the unsaturated zone of the soil profile at tested locations are given below.

Table 0.7: Estimated hydraulic conductivity values for Th. Vandhoo

Point	Hydraulic Conductivity (m/d)
VPM 1	1.59
VPM 2	24.98
VPM 3	0.89
VPM 4	1.00
VPM 5	24.33

The measured hydraulic conductivity values ranged from a minimum of 0.89 m/d to a maximum of 24.98 m/d, with an average of 10.54 m/d. The results revealed that measured hydraulic conductivity within different land uses shows significant variation due to the presence of different formations from gravel to clayey sand. The higher hydraulic conductivities are recorded in gravelly areas (high elevated) and low hydraulic conductivities are recorded at low elevated areas with clayey sand. The average value of 10.54 m/d is considered for estimation of the groundwater flow velocities while 1.16 m/d is considered for estimation of the groundwater recharge volume.

Pumping test

The testing was conducted on dug wells to estimate the transmissivity of the water bearing formation for a 1-hour period (pumping and recovery). The estimated transmissivity values of water bearing formation is given below.

Table 0.8: Pumping test results for Th. Kandoodhoo

Dug well	Transmissivity (m ² /s)	Drawdown (m)	EC - Before Pumping (µs/cm)	EC - End of Pumping (µs/cm)
VW 1	0.0016	0.46	800	810
VW 2	0.0025	0.45	810	1,010

The measured transmissivity (m²/s) values ranged from a minimum of 0.0016 m²/s to a maximum of 0.0025 m²/s., with an average of 0.0021 m²/s.

Groundwater flow and flow velocity

As per the groundwater level map, groundwater zones with a relatively higher head are developed in southern, western and eastern parts of the island at high elevated areas. It is noted that groundwater zones with a low head are developed at the areas between high groundwater level zones and areas close to the coastal line at low elevated areas. The path of groundwater flow within the island is more complex than on other islands and groundwater on part of the eastern side flows to the western part along with the low elevated areas.

The groundwater velocity map for the island was developed by using the calculated average hydraulic conductivity of the island and assuming a porosity of 15%. The calculated velocity of the groundwater varies from place to place with a maximum of 4 m/day. The flow velocity over 80% of the land area is less than 0.5 m/day. It is noted that several small high velocity zones are developed at low elevated areas due to the lowering of groundwater levels.

The estimated maximum retention time of the groundwater within the island for the velocity of 0.5 m/day is about 20 months. As per the velocity map, the groundwater recharging shall be done in the middle part of the island. In addition, recharging structures are constructed in order to increase the retention time and to control the controlling the seawater flooding. The details of the structures will be discussed under Chapter 6.

Seawater Flooding

It is noted that several seawater flooding areas (marked in red) along the coastal line are observed during the field. Further, flooded seawater in the southern part is percolating into interior low elevated land areas and mixed with deteriorate the fresh groundwater.



Figure 10: Seawater flooding areas in Vandhoo Island (marked in red colour)

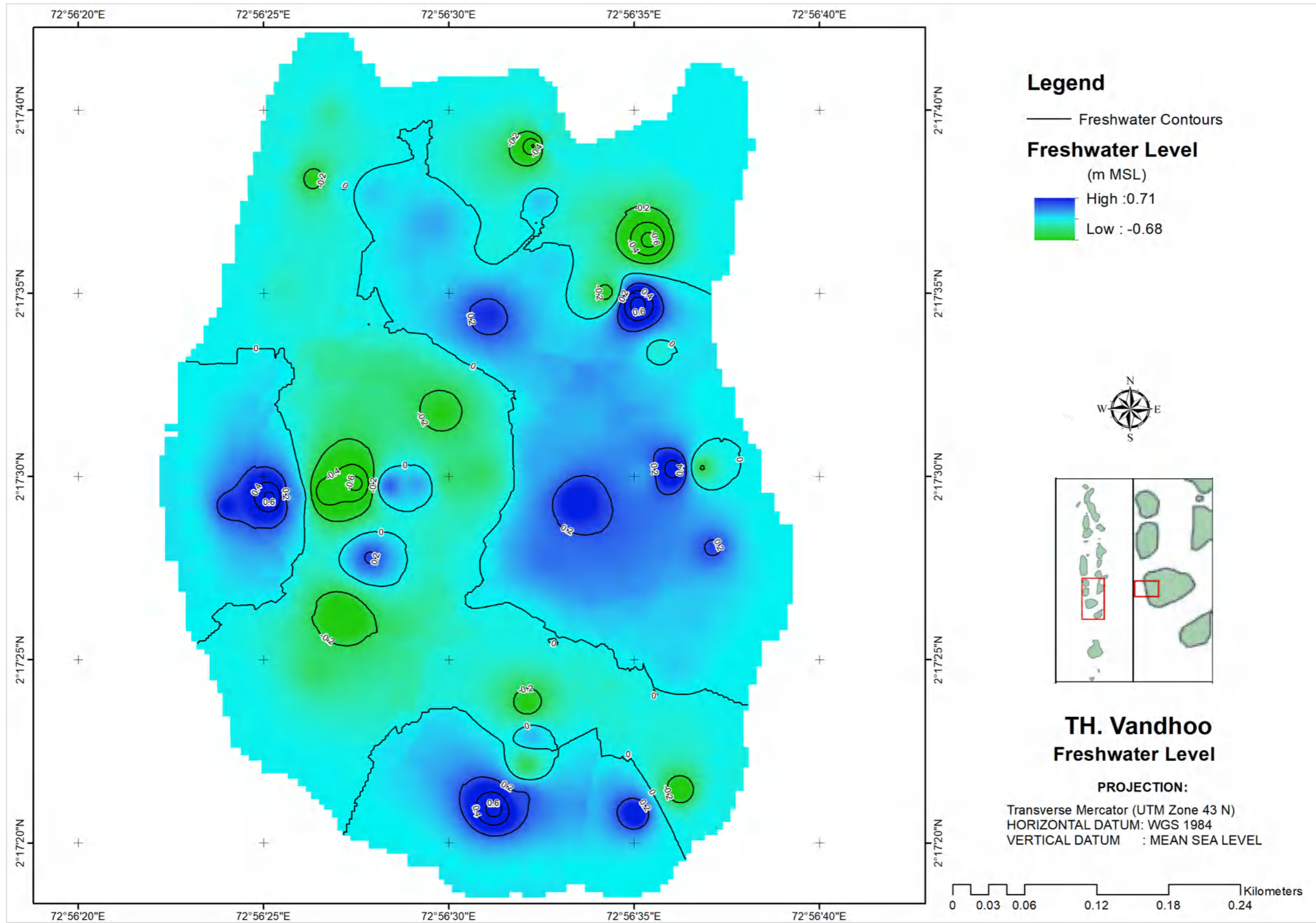


Figure 11: Freshwater Level in Kandoodhoo Island

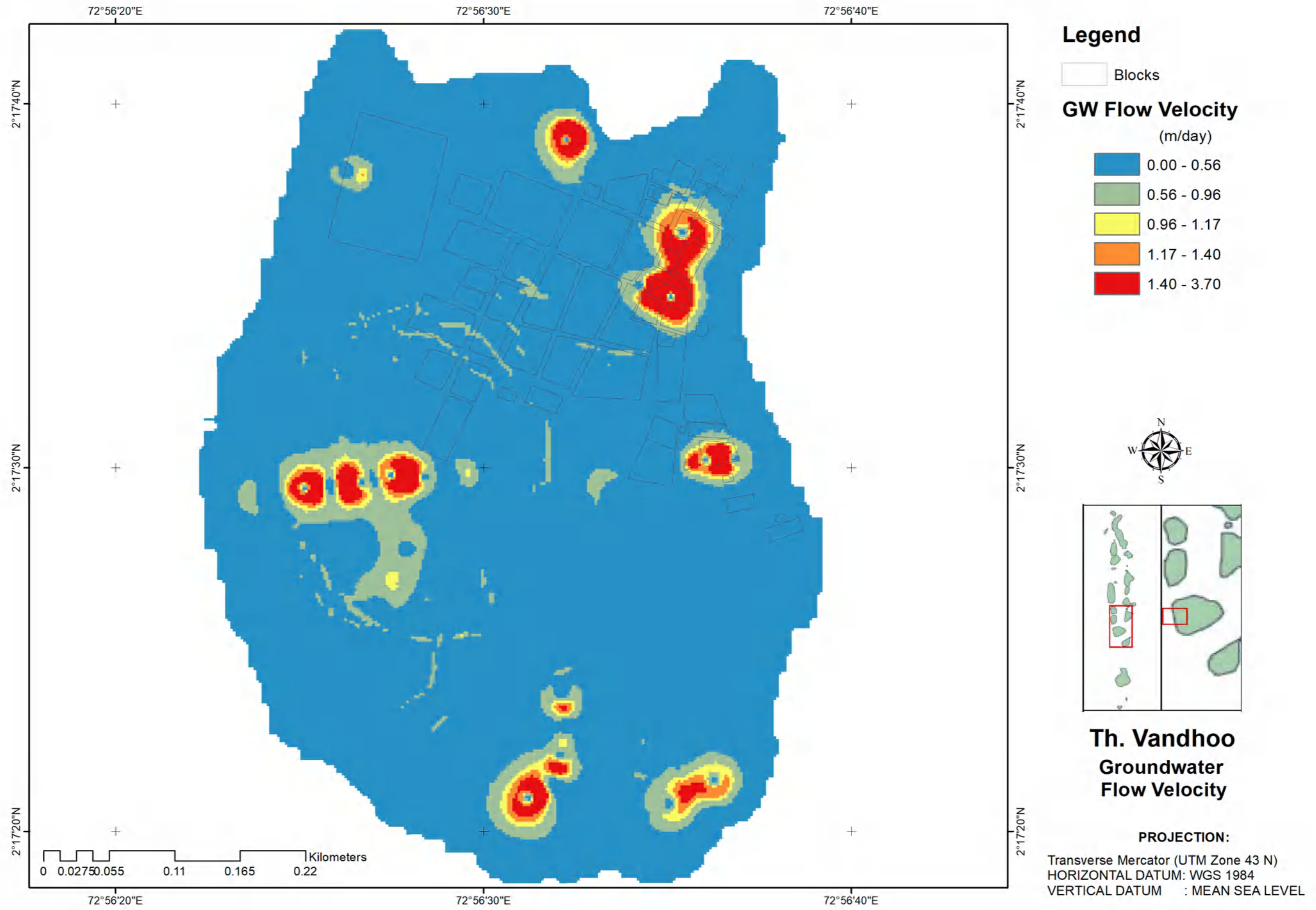


Figure 12: Groundwater Flow velocity map of the Vandhoo Island

Th. Omadhoo

Geology and Hydrogeology of the Island

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation. The thickness of the overburden (unconsolidated layer and weathered layer) within Omadhoo island varies from place to place with a maximum of 9 m.

The summarized details of the geological profile are given below.

- Thickness of the top layer varies up to 0.5 m
- Thickness of the beach coral sand layer varies from 0.3 m to 1.0 m. In beach areas mostly beach coral sand exists as the top layer.
- Thickness of the weathered coral layer varies up to 9 m. Thickness of the weathered layer in the western part of the island is about 9 m while the thickness in the eastern side is about 4-5 m.

According to the compositional and structural differences of coral formation, differential weathering could be observed. Also, deep weathering is observed in the middle part of the island with compared to the coastal area.

The occurrence of weak layers is common in the fresh coral formations at different depth horizons due to the occurrence of different types of coral formations within subsurface formations. The depth to the fresh coral layer varies along the coastal area with a maximum of 2-3 m based on indirect measurements

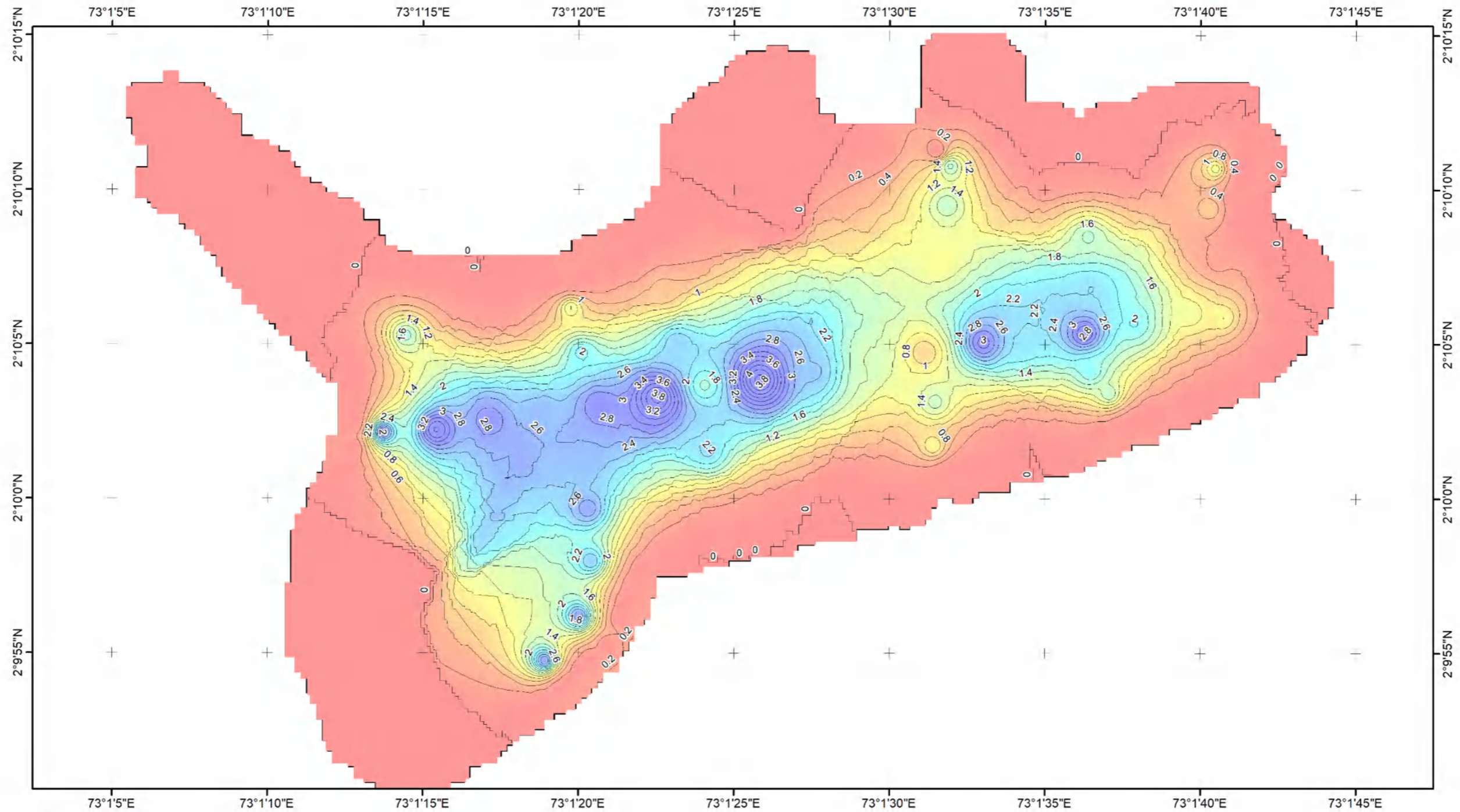
Hydrogeology

The lower part of the overburden (lower part of unconsolidated formation, weathered layer, and partly weathered layer) is water bearing. The lower part of the unconsolidated formation is a completely weathered layer, and the partly weathered layer behaves as a single unit and acts as an unconfined aquifer.

The aquifer properties of the three layers are different and geologically, the completely weathered layer shows more homogeneous behaviour than the partly weathered layer and unconsolidated formation. Porosity of the completely weathered layer and unconsolidated layer is higher than the porosity of the partly weathered layer.

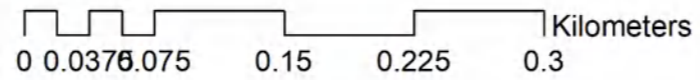
Fresh groundwater of the island occurs as a lens. Middle part of the freshwater lens rests on the fresh coral formation and its outer area rests on saline water. Basically, the geometry of the freshwater lens varies with the groundwater recharge and discharge conditions. As per the Baseline Assessment Report, the standing maximum groundwater level is 0.54 m above MSL in the middle parts of the island. The maximum thickness of the freshwater lens is about 4.7 m by considering the EC > 1500 $\mu\text{s}/\text{cm}$ and it reduces toward the rim area of the lens.

As per the report, calculated groundwater storage by considering the 15% porosity is about 36,622 m^3 .



Legend

- Freshwater Thickness Contours
- Freshwater Thickness Level**
(m)
- High : 4.07
- Low : 0



**TH. Omadhoo
Freshwater Thickness**

PROJECTION:
 Transverse Mercator (UTM Zone 43 N)
 HORIZONTAL DATUM: WGS 1984
 VERTICAL DATUM : MEAN SEA LEVEL

Figure 13: Freshwater thickness map of Omadhoo Island

Groundwater Chemistry and Its Variation

Groundwater quality measurements have been carried out in selected places for selected physical, chemical, and microbiological parameters. All data with relevant information were presented in the submitted Baseline Assessment Report. Further interpretation is discussed under this sub topic.

About 40 water samples have been analysed for EC ($\mu\text{s}/\text{cm}$), pH, Turbidity (NTU), DO (ppm), Temperature ($^{\circ}\text{C}$), Salinity (PSU), Nitrate (mg/l), Ammonia (mg/l), and Phosphate (mg/l). Bacteriological analysis was done in 15 places and results revealed that all wells are contaminated with faecal coliform in different proportions (2- more than 2,420 MPN/100 ml) as per the WHO guidelines. The sampling points are given in following figure. In addition, field EC was measured for 21 samples.

The summarized results of the selected physical and chemical parameters are given.

Table 0.9: Comparison of WQ results based on land usage

Land Use	Number of Samples	Results are Lined with Conditions	Increment of Measured Parameters	Remark
Residential area	53	50	O3, O11, and O37	Extra high values of Ammonia in three wells are due to anthropogenic activities.
Industrial area	1	0	O2	Extra high value of Ammonia is due to anthropogenic activities.
Fish huts	7	6	OW 13	Extra high value of EC due to higher groundwater extraction from thin freshwater lens.
Total	61	56	5	

Note:

- 1) EC > 2,500 $\mu\text{s}/\text{cm}$ (water could be used for potable and non-potable use depending of EC).
- 2) Nitrate (> 50 mg/l), Phosphate (> 5 mg/l), and ammonia (> 0.5 mg/l) as per WHO guidelines.

The water quality records of contaminated points as per Notes 1 and 2 are given in Table 10.

Table 0.10: Water quality records of contaminated points:

Sampling Points	EC ($\mu\text{S}/\text{cm}$)	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
O2	1,060	7.10	1.3	0.55	0.08
O3	599	7.21	8.8	0.51	0.12
O11	717	7.56	14.7	8.25	0.14
O37	328	7.26	1.1	0.86	0.05
OW 13	3,133	NM	NM	NM	NM

Note: NM- Not measured

Aquifer properties

Hydraulic conductivity(permeability) and transmissivity were estimated by conducting the permeability test and pumping tests respectively. Tested locations are given in above figure.

The porosity of the different subsurface formations is different and decreases towards the bottom. Porosity of the top layer (unconsolidated sand and completely weathered formation) and the partly weathered formation are assumed as 15% and 5%, respectively. The fresh limestone layer is impermeable and some porosity in coral limestone is expected under fractured conditions.

Hydraulic conductivity of the unsaturated formation

Field permeability testing was conducted at five locations as per the Borehole Infiltration Guideline (ASTM D 6391-11) using Borehole Infiltration Tests (Constant Head Approach). The estimated hydraulic conductivity values of the unsaturated zone of the soil profile at tested locations are given below.

Table 0.11: Estimated hydraulic conductivity values for Th. Omadhoo

Point	Hydraulic conductivity(m/d)
OPM 1	2.08
OPM 2	4.24
OPM 3	5.88
OPM 4	1.28
OPM 5	1.35

The measured hydraulic conductivity values ranged from a minimum of 1.28 m/d to a maximum of 5.88 m/d, with an average of 2.96 m/d. The average value of 2.96 m/d is considered for the estimation of the groundwater flow velocities and recharging volumes of the island.

Pumping test

The testing was conducted on selected dug wells to estimate the transmissivity of the water bearing formation for a 1-hour period (pumping and recovery). The estimated transmissivity value of water bearing formation is given below.

Table 0.12: Pumping test results for Th. Kandoodhoo

Dug Well	Transmissivity (m ² /s)	Drawdown (m)	EC - Before Pumping (µs/cm)	EC - End of Pumping (µs/cm)
OW 1	0.0012	0.53	490	560
OW 11	0.0018	0.78	360	390

The measured transmissivity (m²/s) values ranged from a minimum of 0.0012 m²/s to a maximum of 0.0018 m²/s., with an average of 0.0016 m²/s

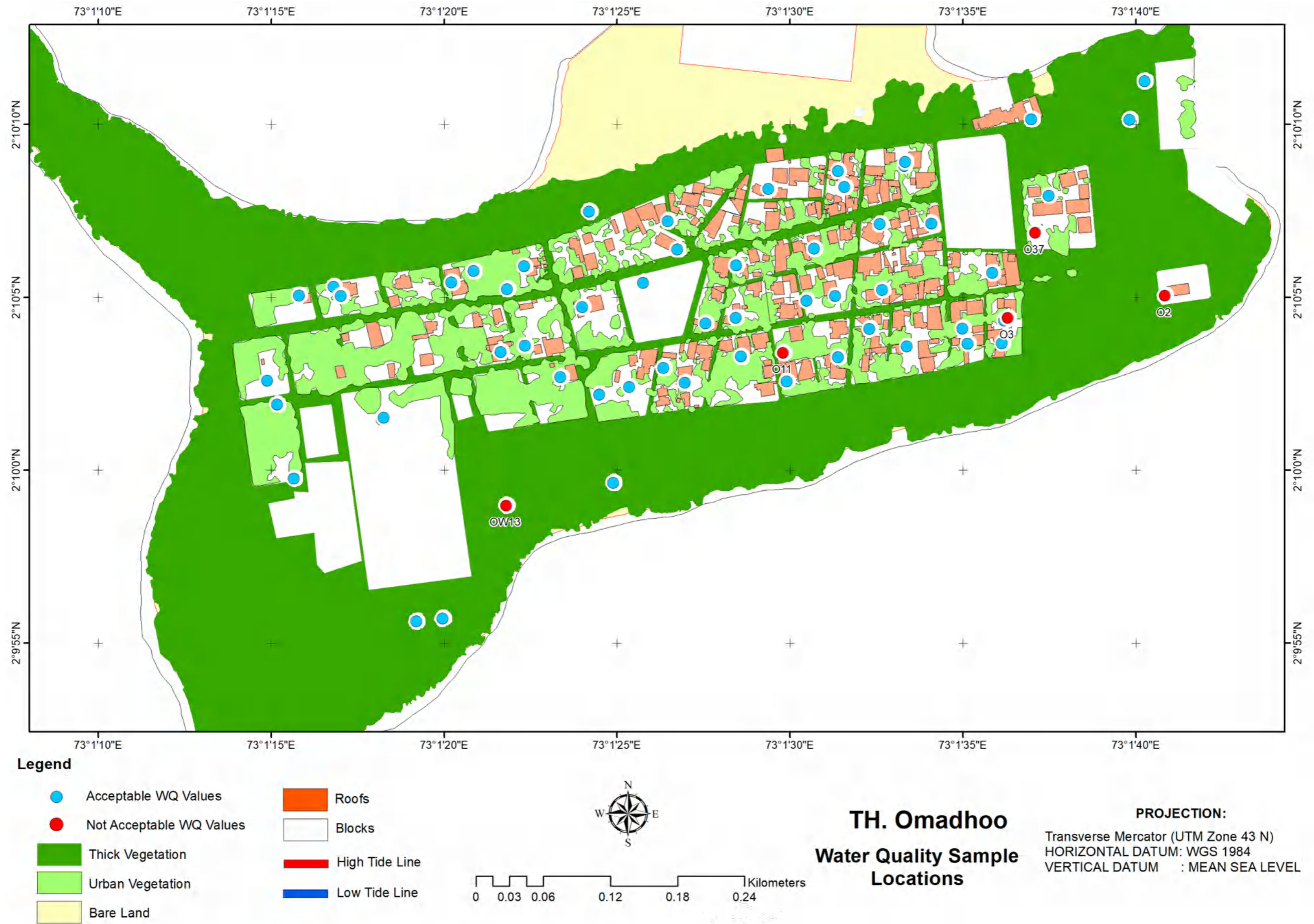


Figure 14: Location of groundwater sampling points in Omadhoo Island

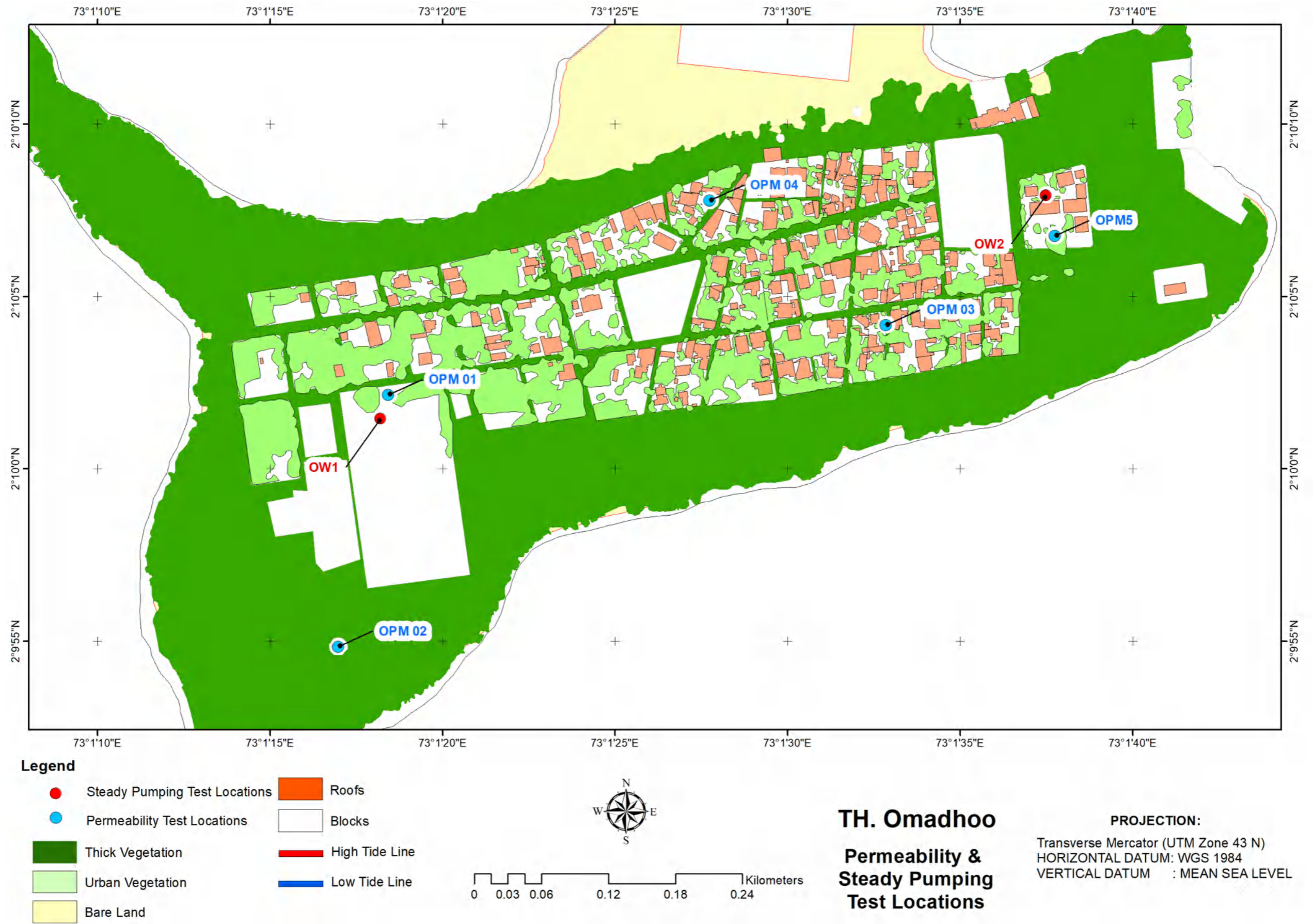


Figure 15: Locations of permeability and steady pumping tests in Omadhoo Island

Groundwater flow and flow velocity

As per the groundwater level map, east west oriented groundwater lens is developed within the island. It is noted that groundwater zones with a low head are encountered in the groundwater lens at the middle section. Some of these low groundwater zones could be occurred due to higher groundwater extraction. The main groundwater flow direction of the island is south to north.

The groundwater velocity map for the island was developed by using the calculated average hydraulic conductivity of the island and assuming a porosity of 15%. The calculated velocity of the groundwater varies from place to place with a maximum of 73 m/day.

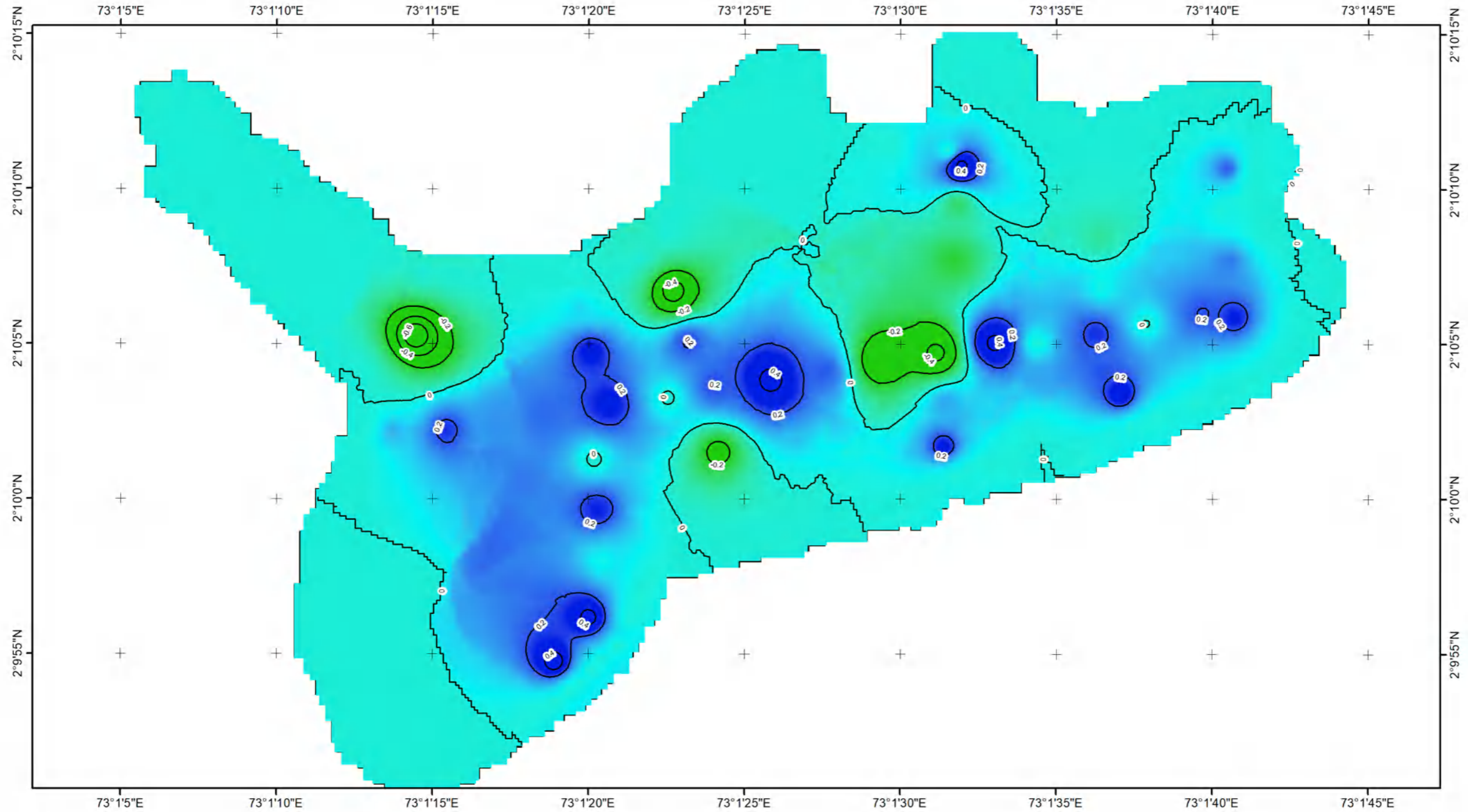
The estimated maximum retention time of the groundwater within the island for a velocity of 1.88 m/day is about 40 days. As per the velocity map, the groundwater recharging shall be carried out in the middle part of the island. In addition, recharging structures are to be constructed in order to increase the retention time and to control the controlling the seawater flooding. The details of the structures will be discussed under Chapter 6.

Seawater Flooding

It is noted that several seawater flooding areas (marked in red) along the coastal line are observed during the field visit. The impact on groundwater quality is low with compared to the island size. It could be due to the presence of impermeable rock barriers along the beach or the existence of low tidal height.



Figure 16: Seawater flooding areas in Omadhoo island (marked in red colour)

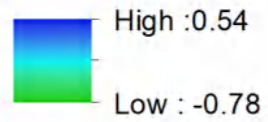


Legend

— Freshwater Contours

Freshwater Level

(m MSL)



**TH. Omadhoo
Freshwater Level**

PROJECTION:

Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

Figure 17: Freshwater Level in Omadhoo Island

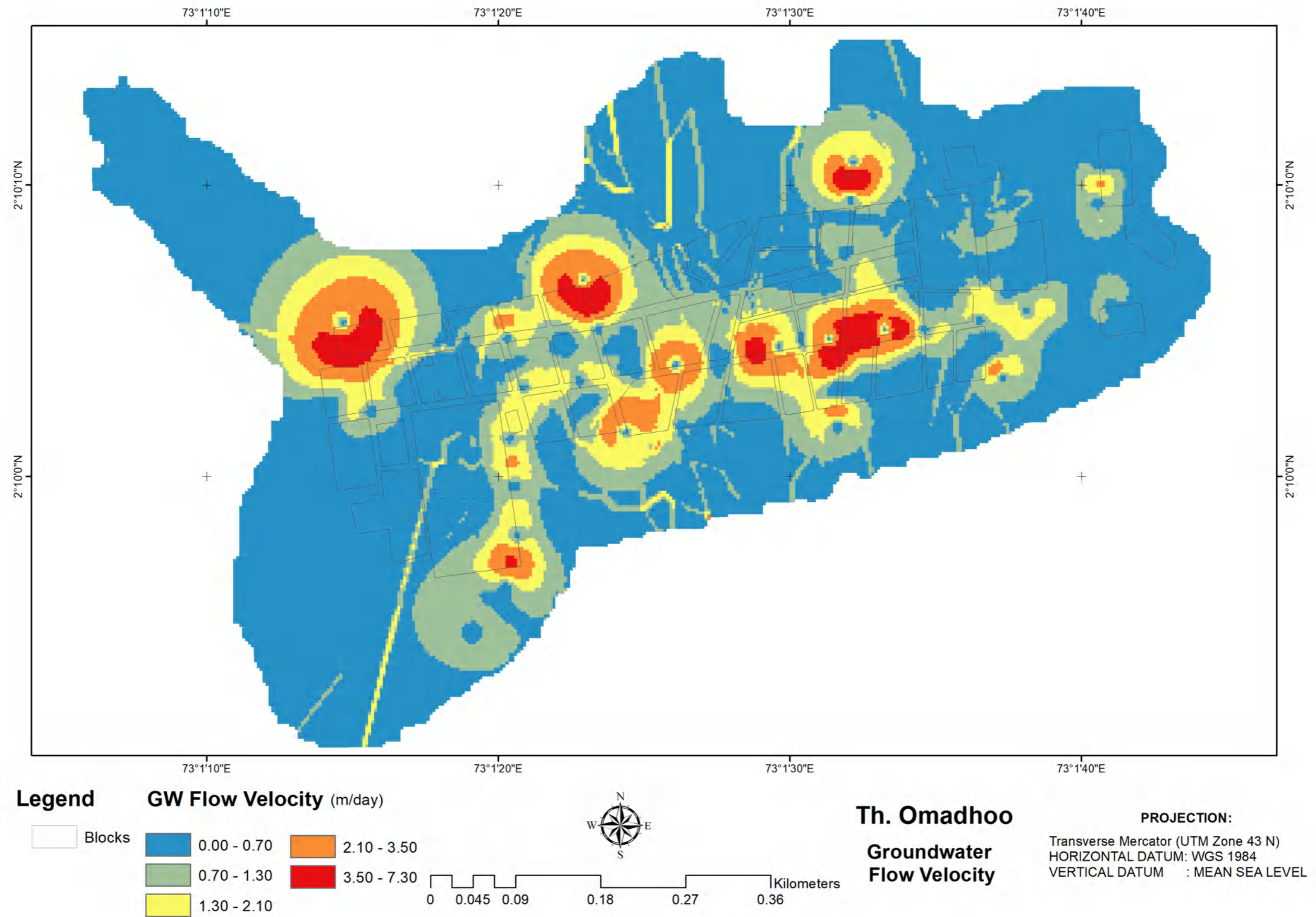


Figure 18: Groundwater Flow velocity map of the Omadhoo island

Th. Gaadhiffushi

Geology and Hydrogeology of the Island

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation. The thickness of the overburden (unconsolidated layer and weathered layer) within Gaadhiffushi island varies from place to place with a maximum of 4 m.

The summarized details of the geological profile are given below.

- Thickness of the top layer varies up to 0.5 m
- Thickness of the beach coral sand layer varies from 0.3 m to 1.0 m. In beach areas, mostly beach coral sand exists as the top layer.
- Thickness of the weathered coral layer varies up to 4 m.

According to the compositional and structural differences of coral formation, differential weathering could be observed. Further, deep weathering is observed in the middle part of the island along the longer section with compared to the shorter section.

The occurrence of weak layers is common in the fresh coral formations at different depth horizons due to the occurrence of different types of coral formations within subsurface formations. The depth to the fresh coral layer varies along the coastal area with a maximum of 2-3 m based on indirect measurements.

Hydrogeology

The lower part of the overburden (lower part of unconsolidated formation, weathered layer, and partly weathered layer) is water bearing. The lower part of the unconsolidated formation is a completely weathered layer, and the partly weathered layer behaves as a single unit and acts as an unconfined aquifer.

The aquifer properties of the three layers are different and geologically, the completely weathered layer shows more homogeneous behaviour than the partly weathered layer and unconsolidated formation. Porosity of the completely weathered layer and unconsolidated layer is higher than the porosity of the partly weathered layer.

Fresh groundwater of the island occurs as a lens. Middle part of the fresh water lens rests on the fresh coral formation and its outer area rests on saline water. Basically, the geometry of the freshwater lens varies with the groundwater recharge and discharge conditions. As per the Baseline Assessment Report, the standing maximum groundwater level is 0.4 m above MSL in the middle parts of the island. The maximum thickness of the freshwater lens is about 2.9 m by considering the $EC > 1,500 \mu\text{s/cm}$ and it reduces toward the rim area of the lens.

As per the report, calculated groundwater storage by considering the 15% porosity is about 14,634 m^3 .

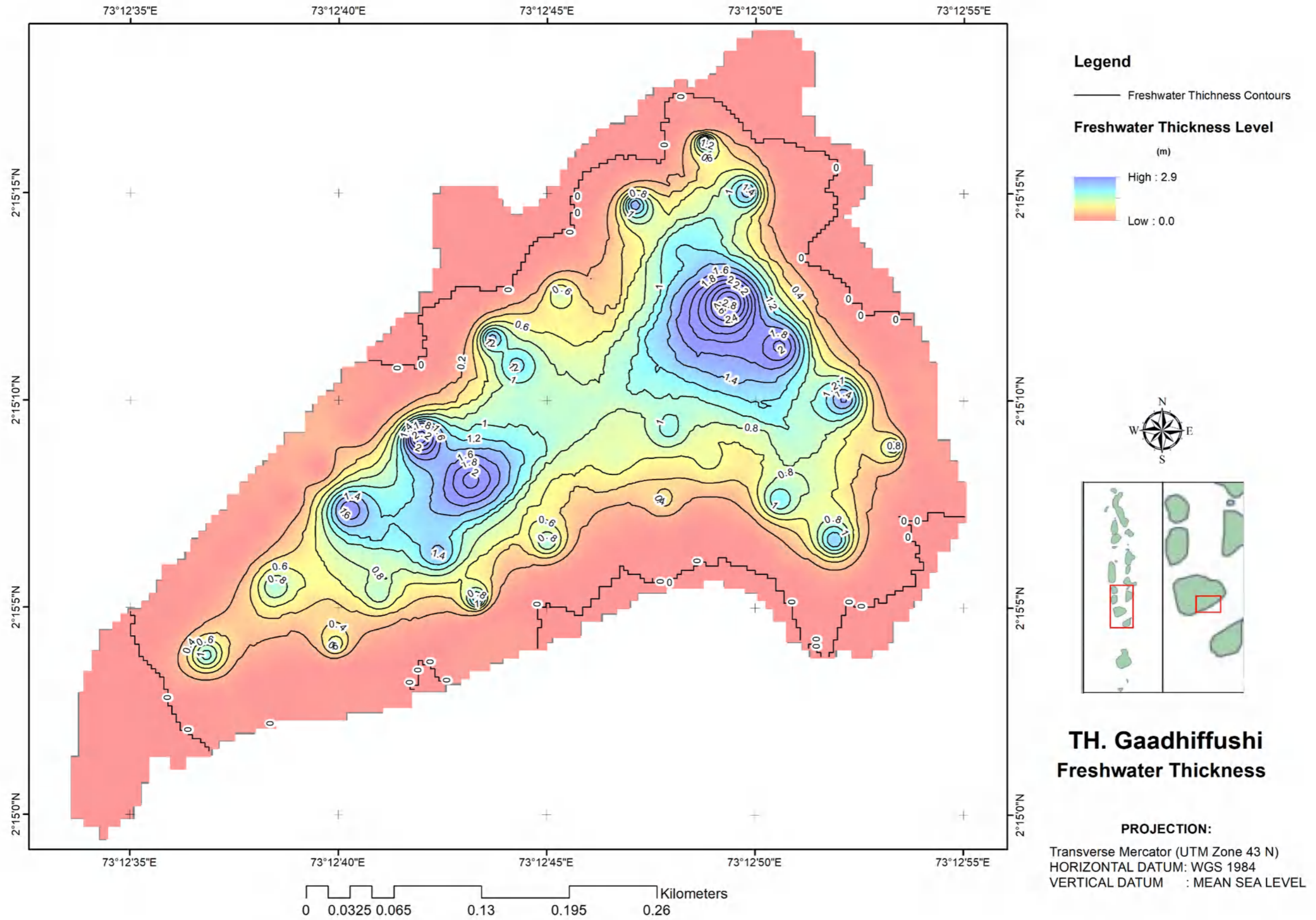


Figure 19: Freshwater thickness map of Gaadhiffushi Island

Groundwater Chemistry and Its Variation

Groundwater quality measurements have been carried out in selected places for selected physical, chemical, and microbiological parameters. All data with relevant information were presented in the submitted Baseline Assessment Report. Further interpretation is discussed under this sub topic.

About 40 water samples have been analysed for EC ($\mu\text{s}/\text{cm}$), pH, Turbidity (NTU), DO (ppm), Temperature ($^{\circ}\text{C}$), Salinity (PSU), Nitrate (mg/l), Ammonia (mg/l), and Phosphate (mg/l). Bacteriological analysis was done in 15 places and results revealed that all wells are contaminated with coliform in different proportions (total coliform – [91 – 2,420] MPN/100 ml, faecal coliform – [2 – 1,415] MPN/100 ml) as per the WHO guidelines. Faecal coliform is not recorded in location G23. The sampling points are given in following figure. In addition, field EC was measured for 21 samples.

The summarized results of the selected physical and chemical parameters are given.

Table 0.13: Comparison of WQ results based on land usage

Land Use	Number of Samples	Results are Lined with Conditions	Increment of Measured Parameters	Remarks
Residential area	59	52	G6, G13, G20, G24, G31, G35, GW14	G6, G13, G20, G24, G31, G35- indicate the pollution due to anthropogenic activities. GW 14-This site is located at the beach line.
Industrial Areas	1	1		
Total	60	53	7	

Note:

- 1) EC > 2,500 $\mu\text{s}/\text{cm}$ (water could be used for potable and non-potable use depending of EC.
- 2) Nitrate (> 50 mg/l), Phosphate (> 5 mg/l), and ammonia (> 0.5 mg/l) as per WHO guidelines.

The water quality records of contaminated points as per Notes 1 and 2 are given in Table 14.

Table 0.14: Water quality records of contaminated points

Sampling Points	EC ($\mu\text{S}/\text{cm}$)	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
G6	0.05	0.36	1073.4	7.02	92.4
G13	0.71	2.20	579.5	7.09	113.6
G20	0.08	0.23	766.4	7.16	130.3
G24	0.13	0.14	703.6	7.11	75.4
G31	2.44	0.12	1182.7	7.10	112.0
G35	4.75	0.11	474.0	7.36	19.4
GW 14	NM	NM	10180.0	NM	NM

Note: NM- Not measured

Aquifer Properties

Hydraulic conductivity (permeability) and transmissivity were estimated by conducting permeability tests and pumping tests, respectively. Tested locations are given in above figure.

The porosity of the different subsurface formations is different and decreases towards the bottom. Porosity of the top layer (unconsolidated sand and completely weathered formation) and the partly weathered formation are assumed as 15% and 5%, respectively. The fresh limestone layer is impermeable and some porosity in coral limestone is expected under fractured conditions.

Hydraulic conductivity of the unsaturated formation

Field permeability testing was conducted at five locations as per the Borehole Infiltration Guideline (ASTM D 6391-11) using Borehole Infiltration Tests (Constant Head Approach). The estimated hydraulic conductivity values of the unsaturated zone of the soil profile at tested locations are given below.

Table 0.15: Estimated hydraulic conductivity values for Th. Gaadhiffushi

Point	Hydraulic Conductivity (m/d)
GPM 1	7.01
GPM 2	11.91
GPM 3	1.38
GPM 4	15.05
GPM 5	2.07

The measured hydraulic conductivity values ranged from a minimum of 1.38 m/d to a maximum of 15.05 m/d, with an average of 7.48 m/d. The relatively low hydraulic conductivities area is located in groundwater discharging area with compared to recharging areas. The average value of 7.48 m/d is considered for the estimation of the groundwater flow velocities of the island.

Pumping tests

The testing was conducted on selected dug wells to estimate the transmissivity of the water bearing formation for a 1-hour period (pumping and recovery). The estimated transmissivity value of water bearing formation is given below.

Table 0.16: Pumping test results for Th. Kandoodhoo

Dug well	Transmissivity (m ² /s)	Drawdown (m)	EC - Before Pumping (µs/cm)	EC - End of Pumping (µs/cm)
GW 1	0.0075	0.37	950	4,950

The measured transmissivity (m²/s) value is 0.0075 m²/s.

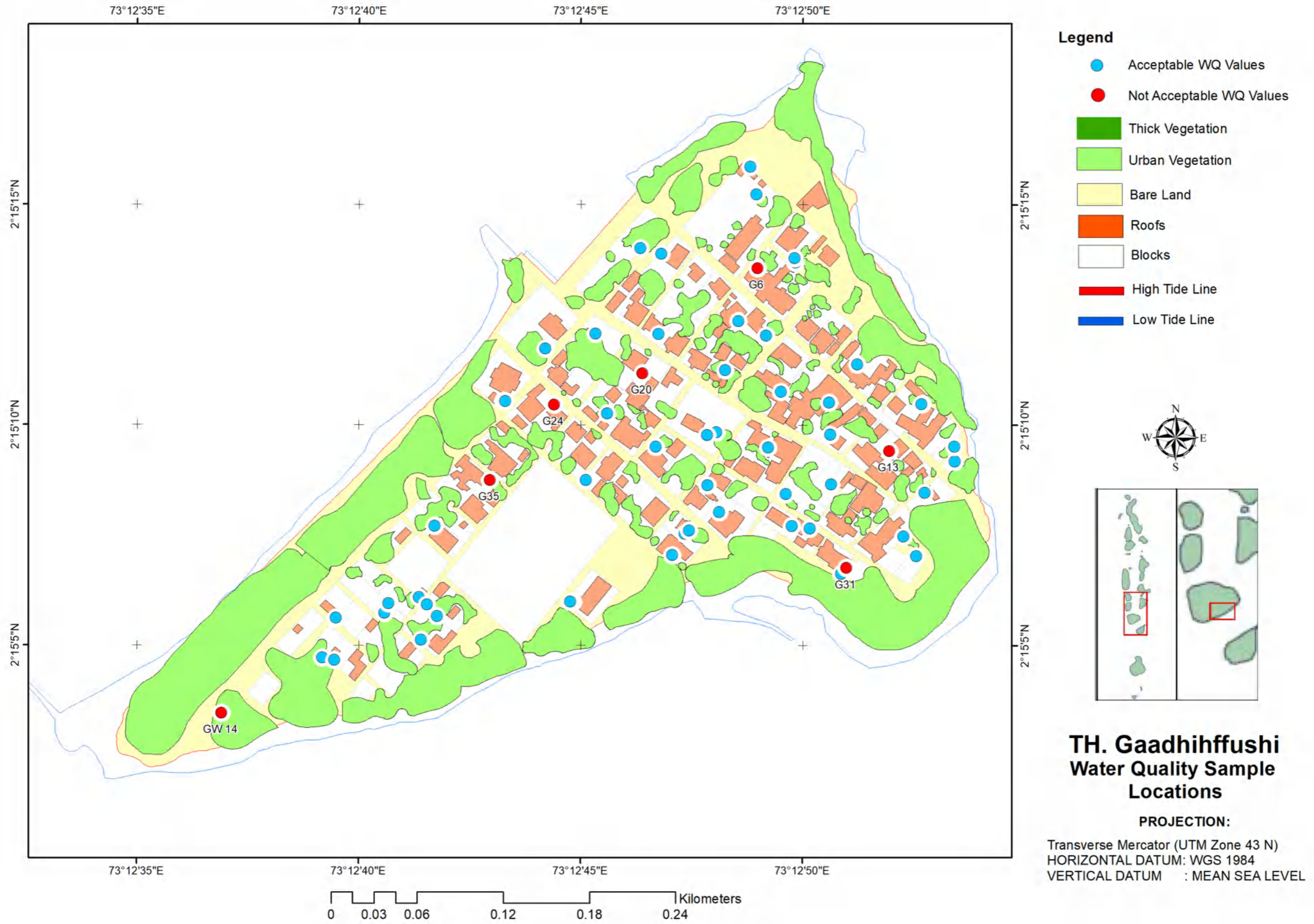


Figure 20: Location of groundwater sampling points in Gaadhiffushi Island

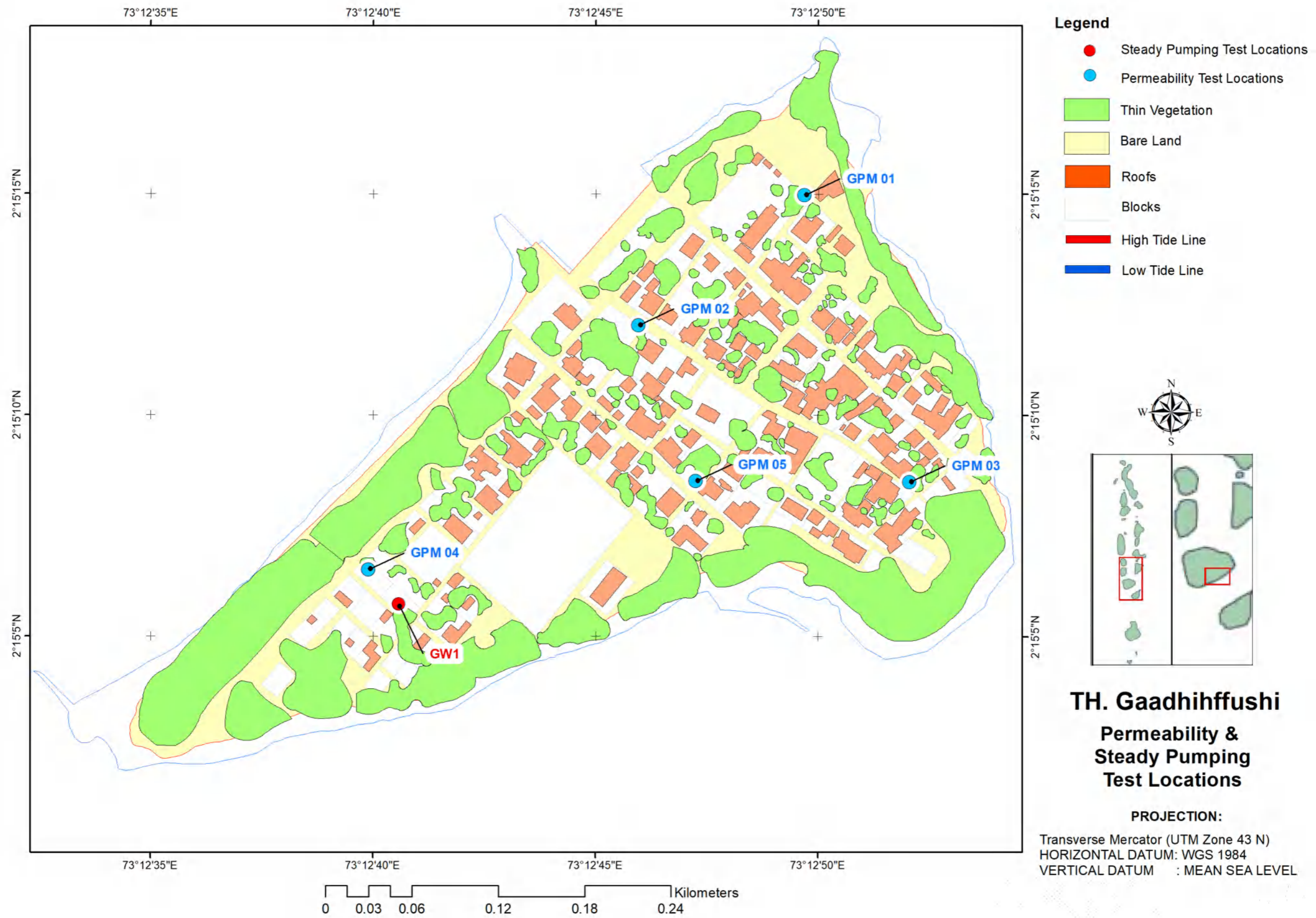


Figure 21: Locations of permeability and steady pumping tests in Gaadhiffushi Island

Groundwater flow and flow velocity

As per the groundwater level map, a zone with a low groundwater head is developed in the middle part of the island in between two groundwater zones with higher head. The low groundwater zones could be occurred due to higher groundwater extraction.

The groundwater velocity map for the island was developed by using the calculated average hydraulic conductivity of the island and assuming a porosity of 15%. The calculated velocity of the groundwater varies from place to place with a maximum of 3.5 m/day and higher velocity zones mainly occur at the rim area of the lens. The flow velocity over 50% of the land area is less than 0.5 m/day.

The estimated maximum retention time of the groundwater within the island for a velocity of 0.5 m/day is about 7.6 months. As per the velocity map, the groundwater recharging shall be done in the middle part of the island. In addition, structures are to be constructed in order to increase the retention time and to control the controlling the seawater flooding. The details of the structures will be discussed under Chapter 6.

Seawater Flooding

It is noted that several seawater flooding areas (marked in red) along the coastal line are observed during the field visit. Further, flooded seawater in the southern part is mixed with fresh water and deteriorates the fresh groundwater. Moreover, it was noted that a temporary earth dam has been constructed along the southeastern coastal line to prevent sea flooding.



Figure 22: Seawater flooding areas in Gaadhiffushi island (marked in red colour)

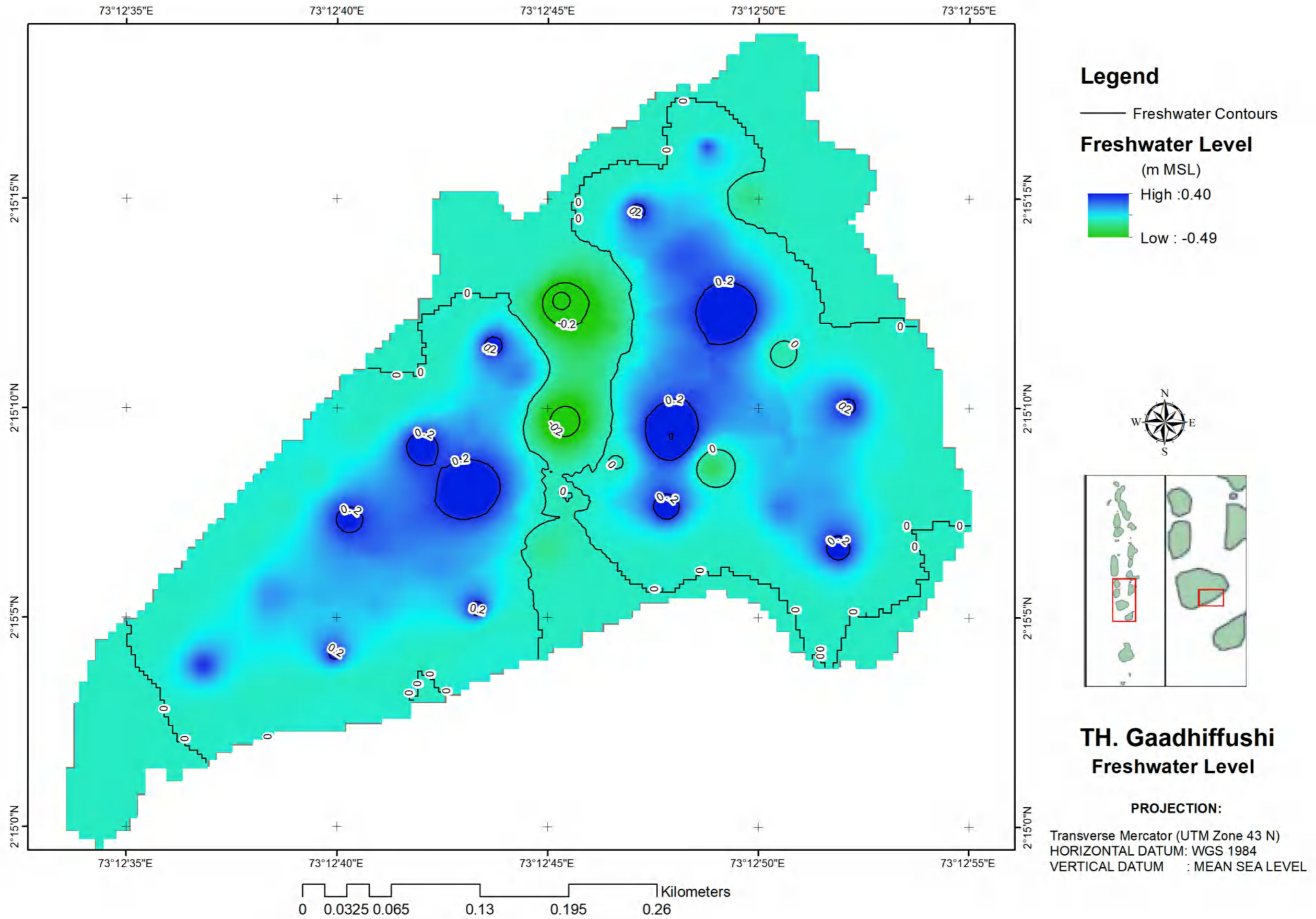


Figure 23: Freshwater Level in Gaadhiffushi Island

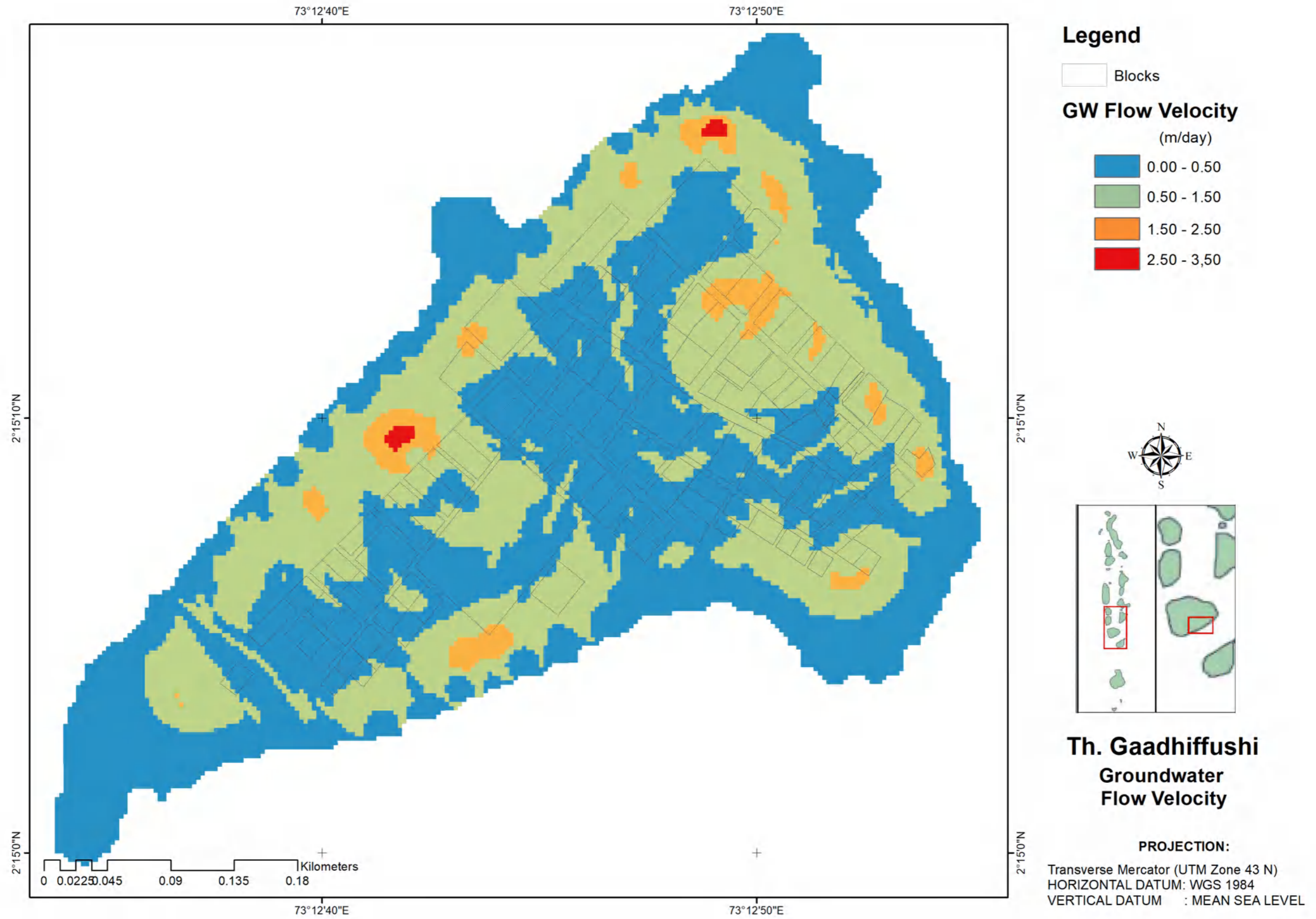


Figure 24: Groundwater Flow velocity map of the Gaadhiffushi Island

Foakaidhoo

Geology and Hydrogeology of the Island

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation. The thickness of the overburden (unconsolidated layer and weathered layer) within Foakaidhoo island varies from place to place with a maximum of 8 m.

The summarized details of the geological profile are given below.

- Thickness of the top layer varies up to 0.5 m
- Thickness of the beach coral sand layer varies from 0.5 m to 1.5 m. In beach areas, mostly beach coral sand exists as the top layer.
- Thickness of the weathered coral layer varies up to 8 m. Thickest area of the weathered layer is located in the middle part of the island.

According to the compositional and structural differences of coral formation, differential weathering could be observed. Further, deep weathering is observed in the middle part of the island with compared to other areas.

The occurrence of weak layers is common in the fresh coral formations at different depth horizons due to the occurrence of different types of coral formations within subsurface formations. The depth to the fresh coral layer varies along the coastal area with a maximum of 2-3 m based on indirect measurements.

Hydrogeology of the Island

The lower part of the overburden (lower part of unconsolidated formation, weathered layer, and partly weathered layer) is water bearing. The lower part of the unconsolidated formation is a completely weathered layer, and the partly weathered layer behaves as a single unit and acts as an unconfined aquifer.

The aquifer properties of the three layers are different and geologically, the completely weathered layer shows more homogeneous behaviour than the partly weathered layer and unconsolidated formation. Porosity of the completely weathered layer and unconsolidated layer is higher than the porosity of the partly weathered layer.

Fresh groundwater of the island occurs as a lens. Middle part of the fresh water lens rests on the fresh coral formation and its outer area rests on saline water. Basically, the geometry of the freshwater lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 1.28 m above MSL in the middle parts of the island. The maximum thickness of the freshwater lens is about 2.85 m by considering the $EC > 1,500 \mu\text{s/cm}$ and it reduces toward the rim area of the lens.

The groundwater level at the eastern part (about 50-75 m from the beach) is close to the surface and water logging conditions are observed. Generally, the groundwater flows along the water logged area and finally flows into the sea through the culvert located at the harbour site. The groundwater in the water logged areas is frequently mixed with seawater due to the tidal effect.

As per the report, calculated groundwater storage by considering the 15% porosity is about 68,776 m^3 .

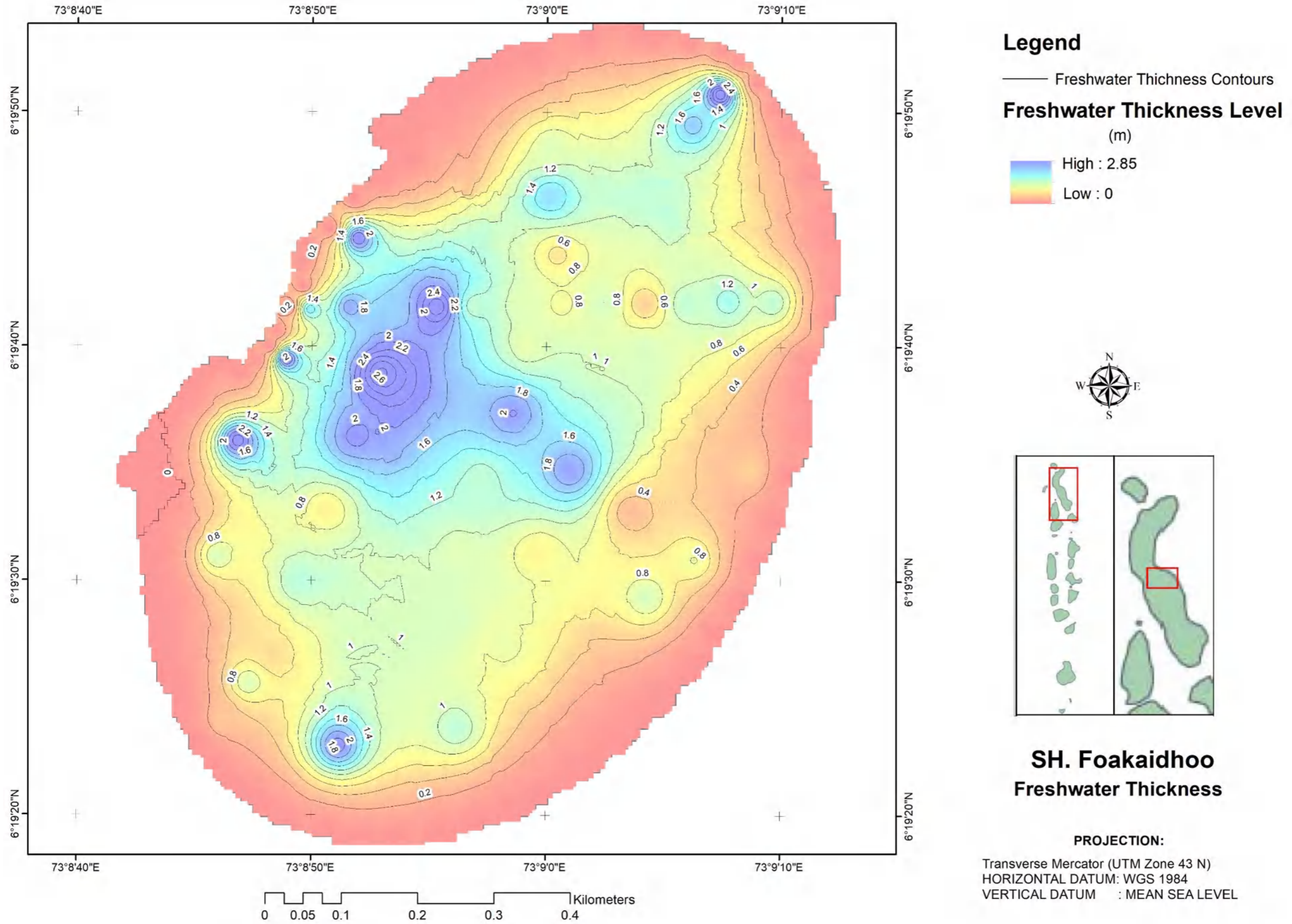


Figure 25: Fresh water thickness map of Foakaidhoo Island

Groundwater Chemistry and Its Variation

Groundwater quality measurements have been carried out in selected places for selected physical, chemical, and microbiological parameters. All data with relevant information were presented in the submitted Baseline Assessment Report. Further interpretation is discussed under this sub topic.

About 43 water samples have been analysed for EC ($\mu\text{S}/\text{cm}$), pH, Turbidity (NTU), DO (ppm), Temperature ($^{\circ}\text{C}$), Salinity (PSU), Nitrate (mg/l), Ammonia (mg/l), and Phosphate (mg/l). Bacteriological analysis was done in 15 places and results revealed that all wells are contaminated with coliform in different proportions (total coliform- (105-2420) MPN/100 ml, faecal coliform – [1 – 980] MPN/100 ml) as per the WHO guidelines. The sampling points are given in following figure. Faecal coliform is not reported in location F 1. In addition, field EC was measured for 37 samples.

The summarized results of the selected physical and chemical parameters are given.

Table 0.17: Comparison of WQ results based on land usage

Land Use	Number of Samples	Results are Lined with Conditions	Increment of Measured Parameters	Remarks
Residential area	75	64	F1, F5, F6, F17, F24, F27, F31, F33, F42, F43, FW1	F1, F5, F6, F17, F24, F27, F31, F33, F42, F43 indicate the pollution due to anthropogenic activities. FW1-Increased EC is due to higher groundwater extraction.
Agricultural area	4	-	FW31, FW33, FW34, FW36	These points are located within water logged area and seawater are mixing with water at water logged area.
Industrial areas	1	-	F42	This place is located along the beach line.
Total	58	52	6	

Note:

- 1) EC > 2,500 $\mu\text{S}/\text{cm}$ (water could be used for potable and non-potable use depending of EC.
- 2) Nitrate (> 50 mg/l), Phosphate (> 5 mg/l), and ammonia (> 0.5 mg/l) as per WHO guidelines.

The water quality records of contaminated points as per Notes 1 and 2 are given in Table 18.

Table 0.18: Water quality records of contaminated points

Sampling Points	EC ($\mu\text{S}/\text{cm}$)	pH	Ammonia (mg/L)	Phosphate (mg/l)	Nitrate (mg/l)
F1	1,281	7.28	19.00	0.12	37.3
F5	1,209	7.08	17.50	0.58	3.7
F6	1,982	7.08	0.90	0.28	42.5
F17	1,629	7.15	53.50	0.83	2.2
F24	953	6.97	0.02	0.05	69.4
F27	1,679	8.18	57.00	0.05	1.3
F31	1,164	6.94	2.20	0.05	113.9

Sampling Points	EC (µS/cm)	pH	Ammonia (mg/L)	Phosphate (mg/l)	Nitrate (mg/l)
F33	948	7.21	5.00	0.05	0.4
F42	28,944	7.46	0.02	0.05	4.7
F43	1,403	7.46	11.50	0.05	59.2
FW 1	2,630	NM	NM	NM	NM
FW31	3,980	NM	NM	NM	NM
FW33	3,540	NM	NM	NM	NM
FW34	3,480	NM	NM	NM	NM
FW36	3,340	NM	NM	NM	NM

Note: NM-Not measured

Aquifer Properties

Hydraulic conductivity(permeability) and transmissivity were estimated by conducting permeability tests and pumping tests, respectively. Tested locations are given in following figure.

The porosity of the different subsurface formations is different and decreases towards the bottom. Porosity of the top layer (unconsolidated sand and completely weathered formation) and the partly weathered formation are assumed as 15% and 5%, respectively. The fresh limestone layer is impermeable and some porosity in coral limestone is expected under fractured conditions.

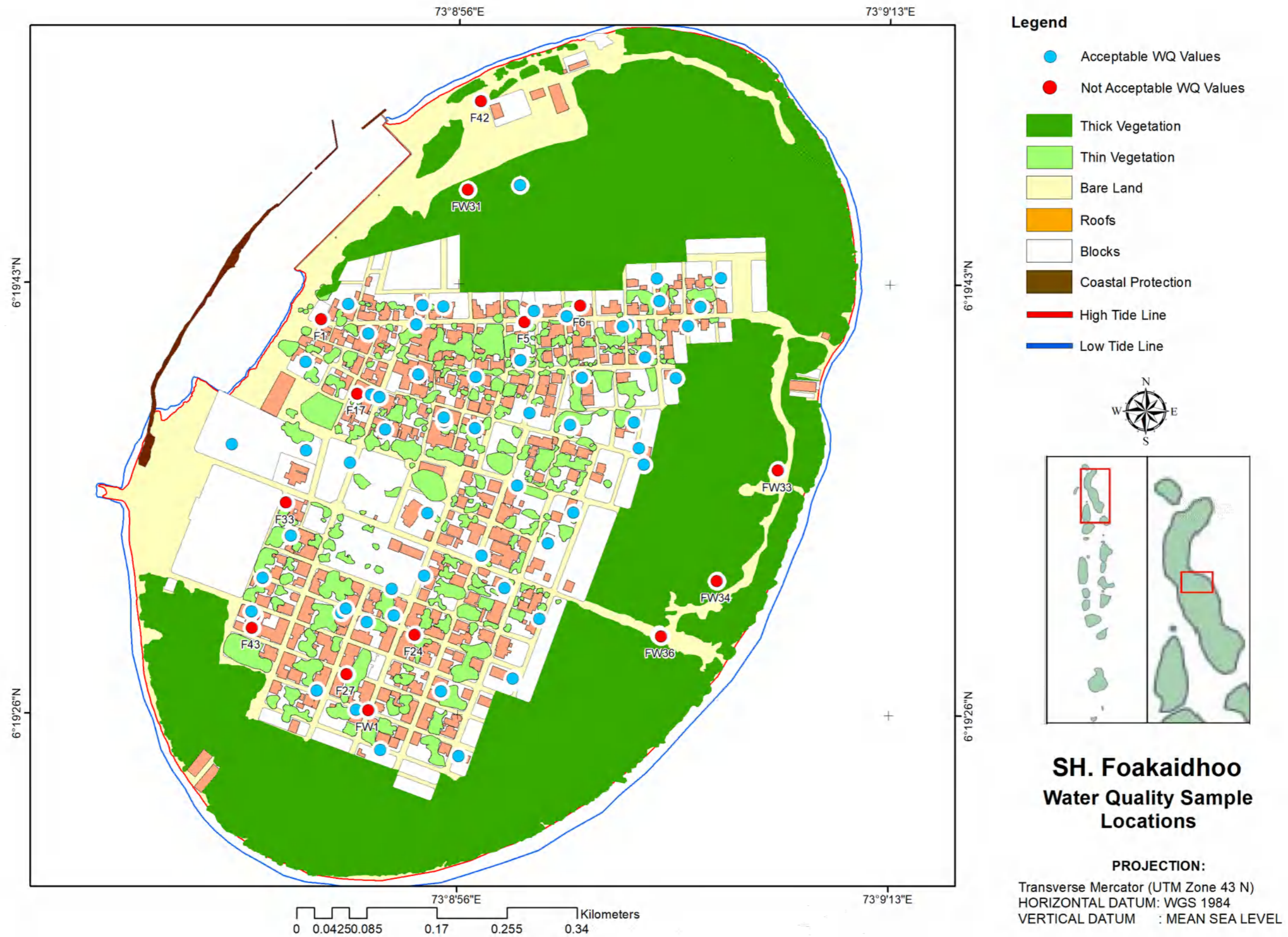


Figure 26: Location of groundwater sampling points in Foakaidhoo Island

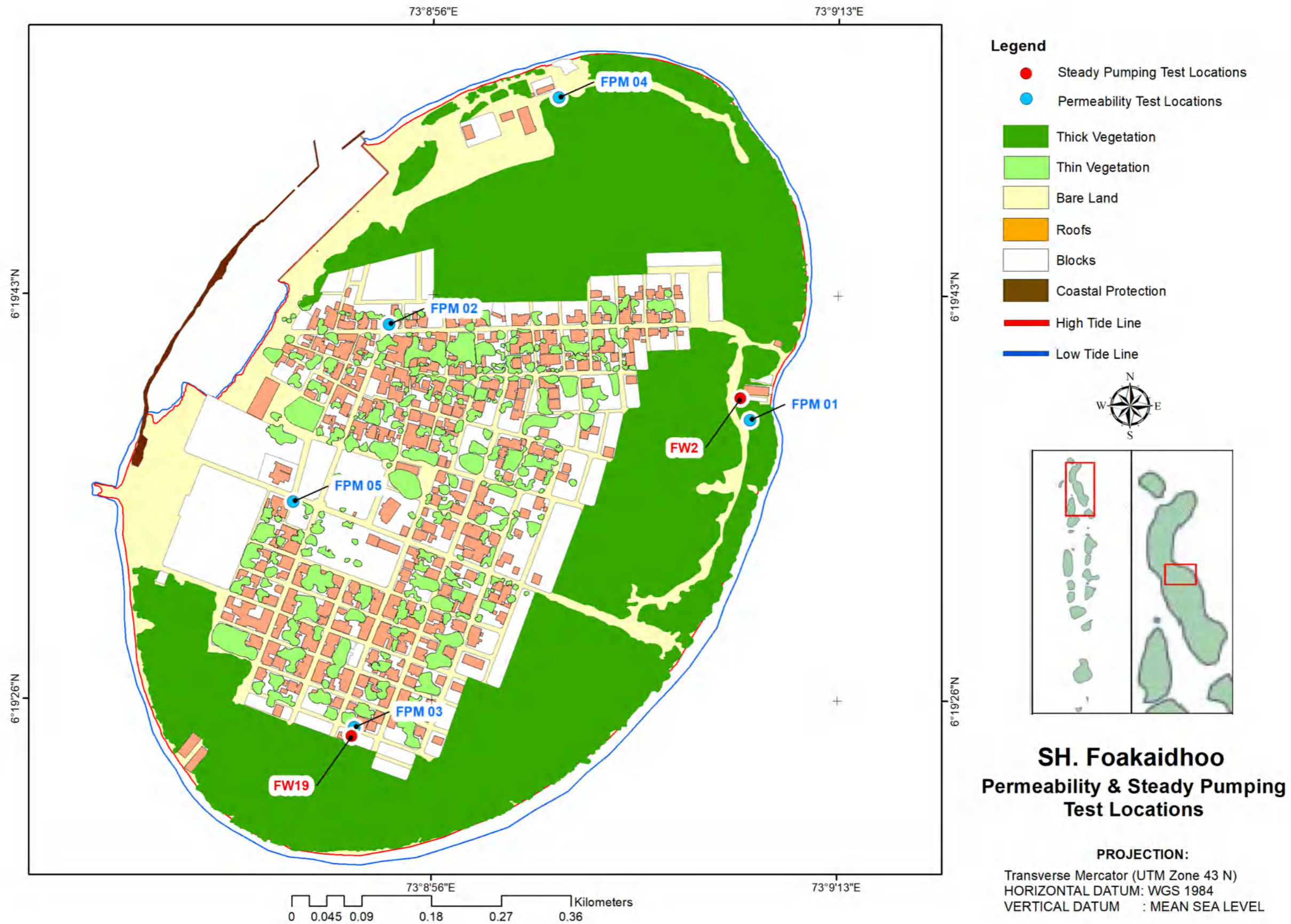


Figure 27: Locations of permeability and steady pumping tests in Foakaidhoo Island

Hydraulic conductivity of the unsaturated formation

Field permeability testing was conducted at five locations as per the Borehole Infiltration (ASTM D 6391-11) and Borehole Infiltration Test (Constant head Approach). The estimated hydraulic conductivity values of the unsaturated zone of the soil profile at tested locations are given below.

Table 0.19: Estimated hydraulic conductivity values for Sh. Foakaidhoo

Point	Hydraulic Conductivity (m/d)
FPM 1	3.05
FPM 2	0.97
FPM 3	0.70
FPM 4	12.88
FPM 5	0.53

The measured hydraulic conductivity values ranged from a minimum of 0.53 m/d to a maximum of 12.88 m/d, with an average of 3.62 m/d. The 1.31 m/d (average hydraulic conductivity except for 12.88 m/d) is considered for estimating the groundwater flow velocities and recharging volume.

Pumping test

The testing was conducted on selected dug wells to estimate the transmissivity of the water bearing formation for a 1-hour period (pumping and recovery). The estimated transmissivity value of water bearing formation is given below.

Table 0.20: Pumping test results for Sh. Foakaidhoo

Dug well	Transmissivity (m ² /s)	Drawdown (m)	EC - Before Pumping (µs/cm)	EC - End of Pumping (µs/cm)
FW 2	0.0023	0.55	3,080	6,200
FW 19	0.0037	0.97	1,050	1,060

Abbreviation: EC- Electrical conductivity

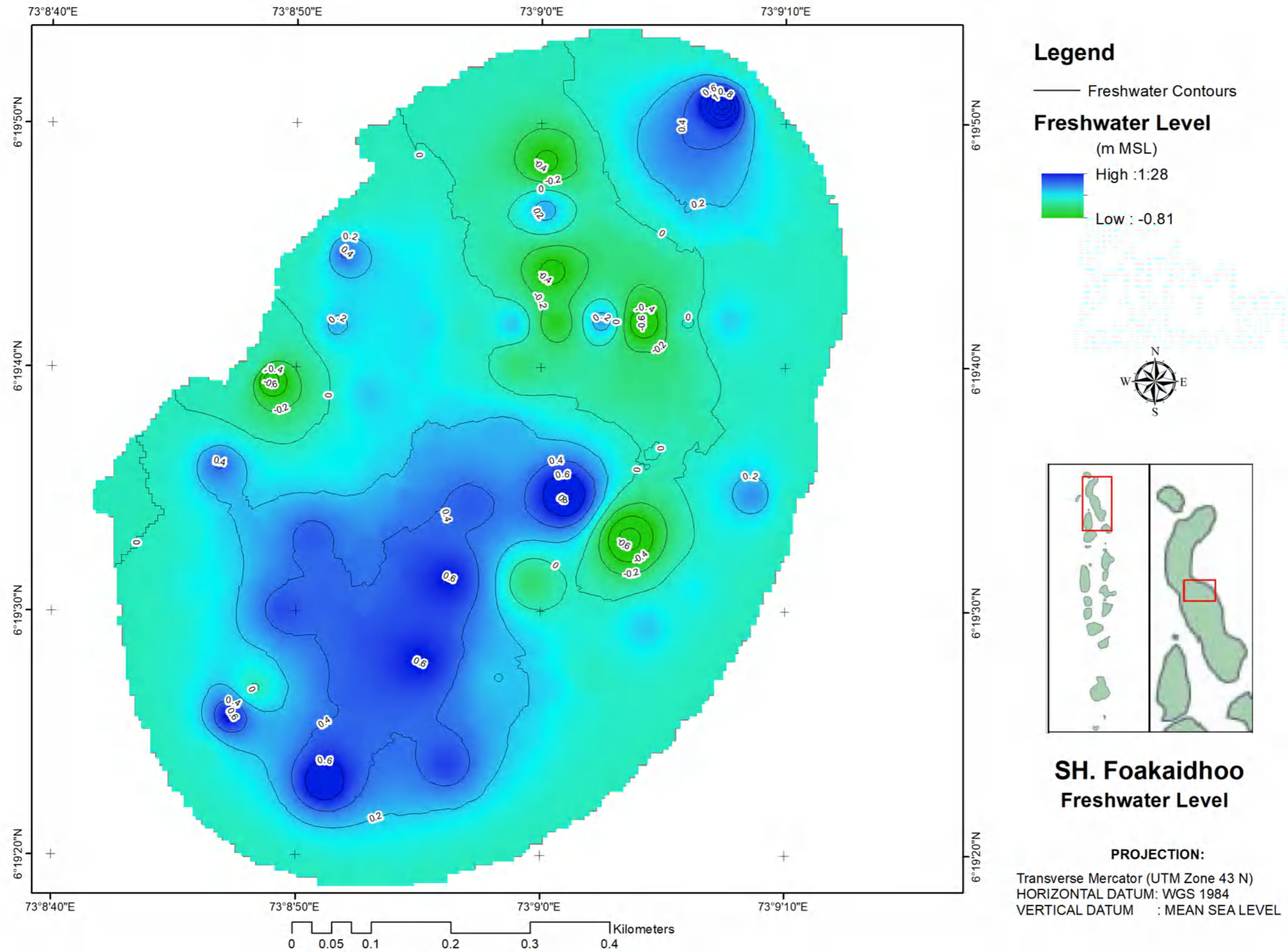
The measured transmissivity (m²/s) values ranged from a minimum of 0.0023 m²/s to a maximum of 0.0037 m²/s., with an average of 0.003 m²/s.

Groundwater flow and flow velocity

As per the groundwater level map, the main groundwater zone with a higher head is developed in the middle part of the island towards the southwest. In addition, several small fresh groundwater patches with a higher head are developed within the low head groundwater zones on the island. Some of low groundwater zones could be occurred due to higher groundwater extraction.

The groundwater velocity map for the island was developed by using the calculated average hydraulic conductivity of the island and assuming a porosity of 15%. The calculated velocity of the groundwater in the island is low and it is up to a maximum of 1.61 m/day. The flow velocity over 85% of the land area is less than 0.4 m/day. It is noted that groundwater zones with a low head are encountered in the groundwater lens in the middle area of the island.

The groundwater flow in the eastern part of the land is towards the east and groundwater in the other part flows along the direction of south-north.



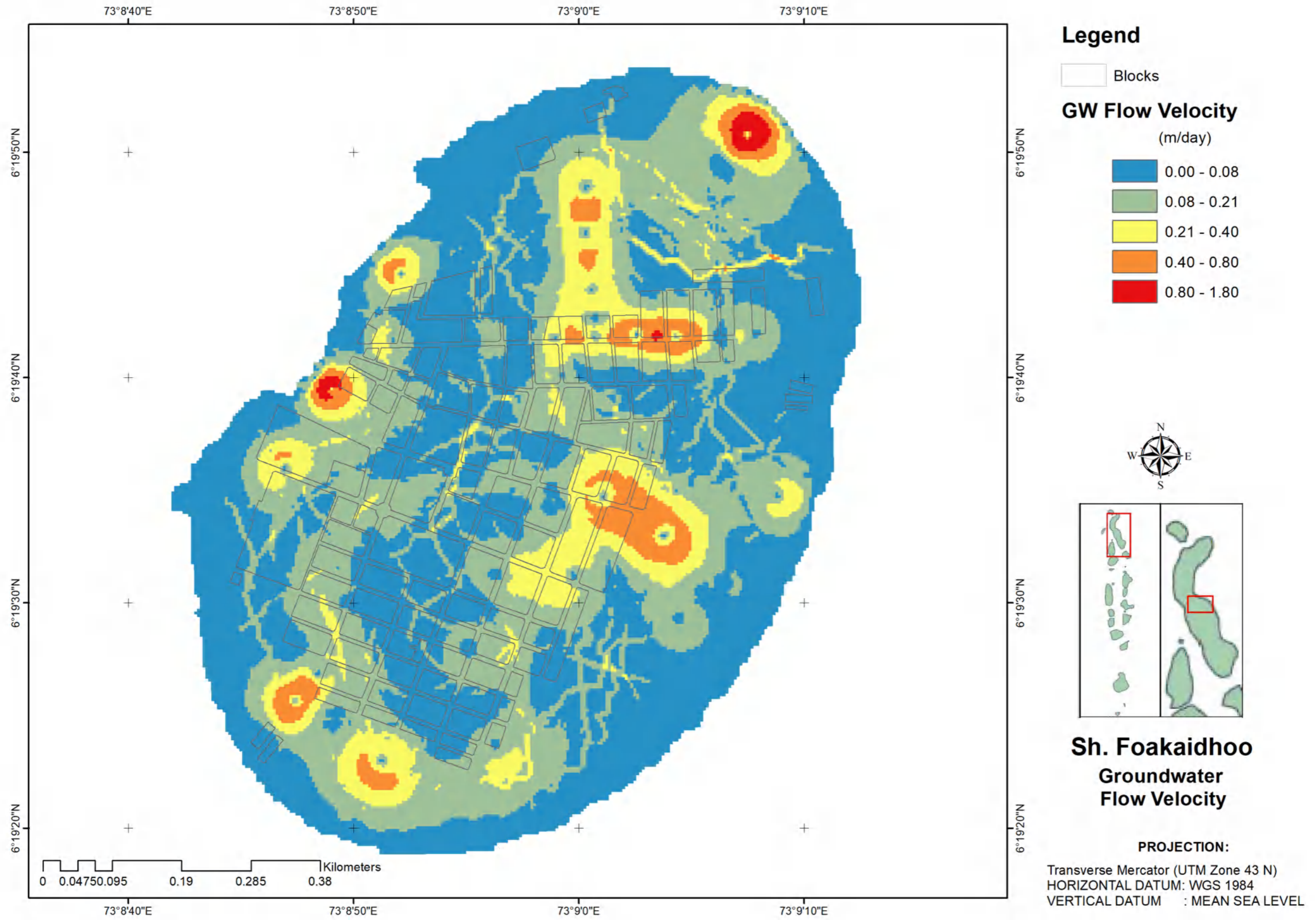


Figure 29: Groundwater Flow velocity map of the Foakaidhoo Island

The estimated maximum retention time of the groundwater within the island for a velocity of 0.4 m/day is about 27 months. As per the velocity map, the groundwater recharging shall be carried out in the middle part of the island. In addition, recharging structures are to be constructed in order to increase the retention time and to control the controlling the seawater flooding. The details of the structures will be discussed under Chapter 6.

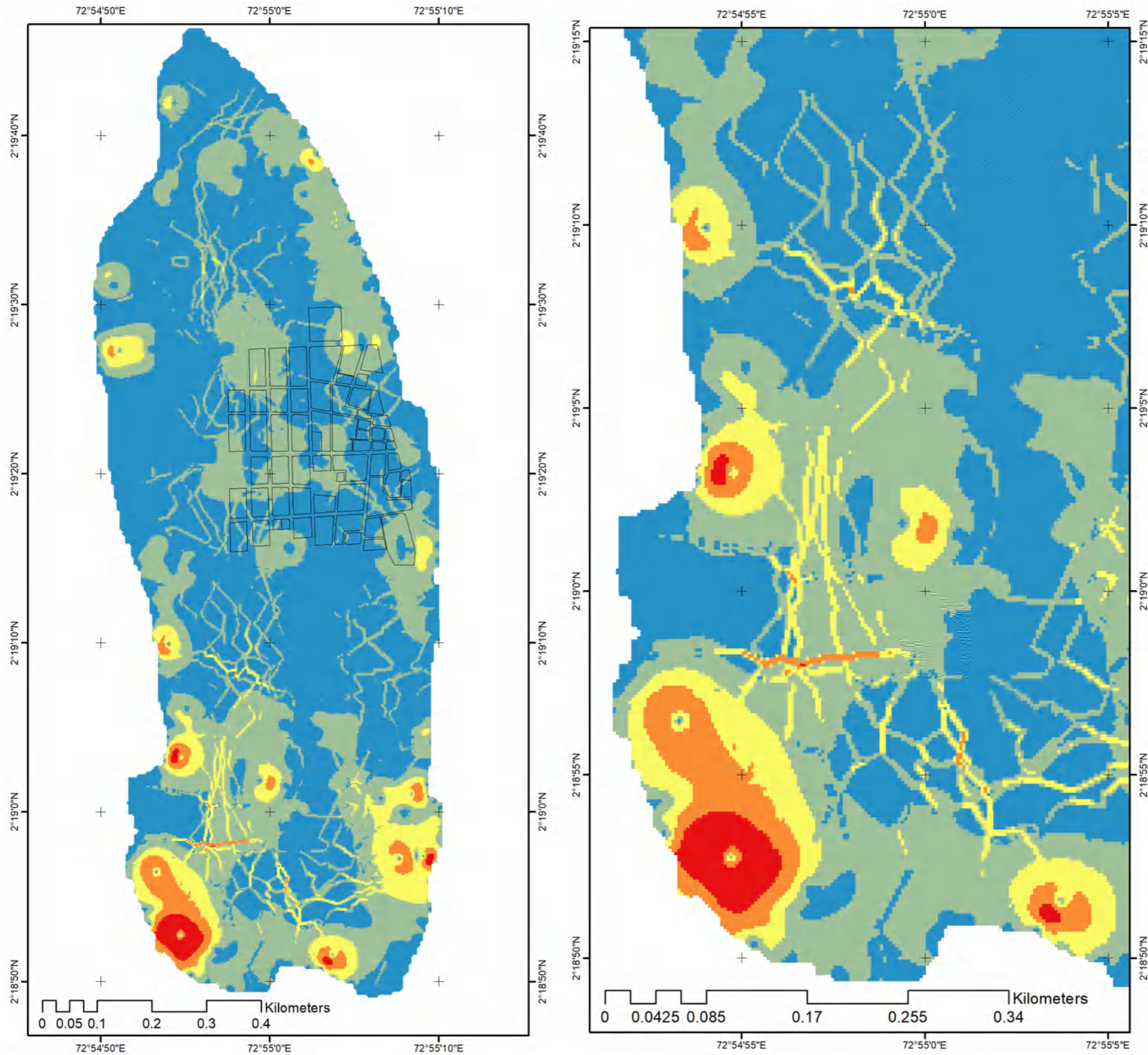
Seawater Flooding

It is noted that several seawater flooding areas (marked in red) along the coastal line are observed during the field visit. Further, flooded seawater in the eastern part is mixed with fresh groundwater and deteriorates the fresh groundwater. The EC concentrations in groundwater in the flooded area are high with compared to the EC values in other areas of the island.









Figure 30: Seawater flooding areas in Foakaidhoo island (marked in red colour)

Annex VIII: Groundwater Flow Velocity Distribution of the Islands



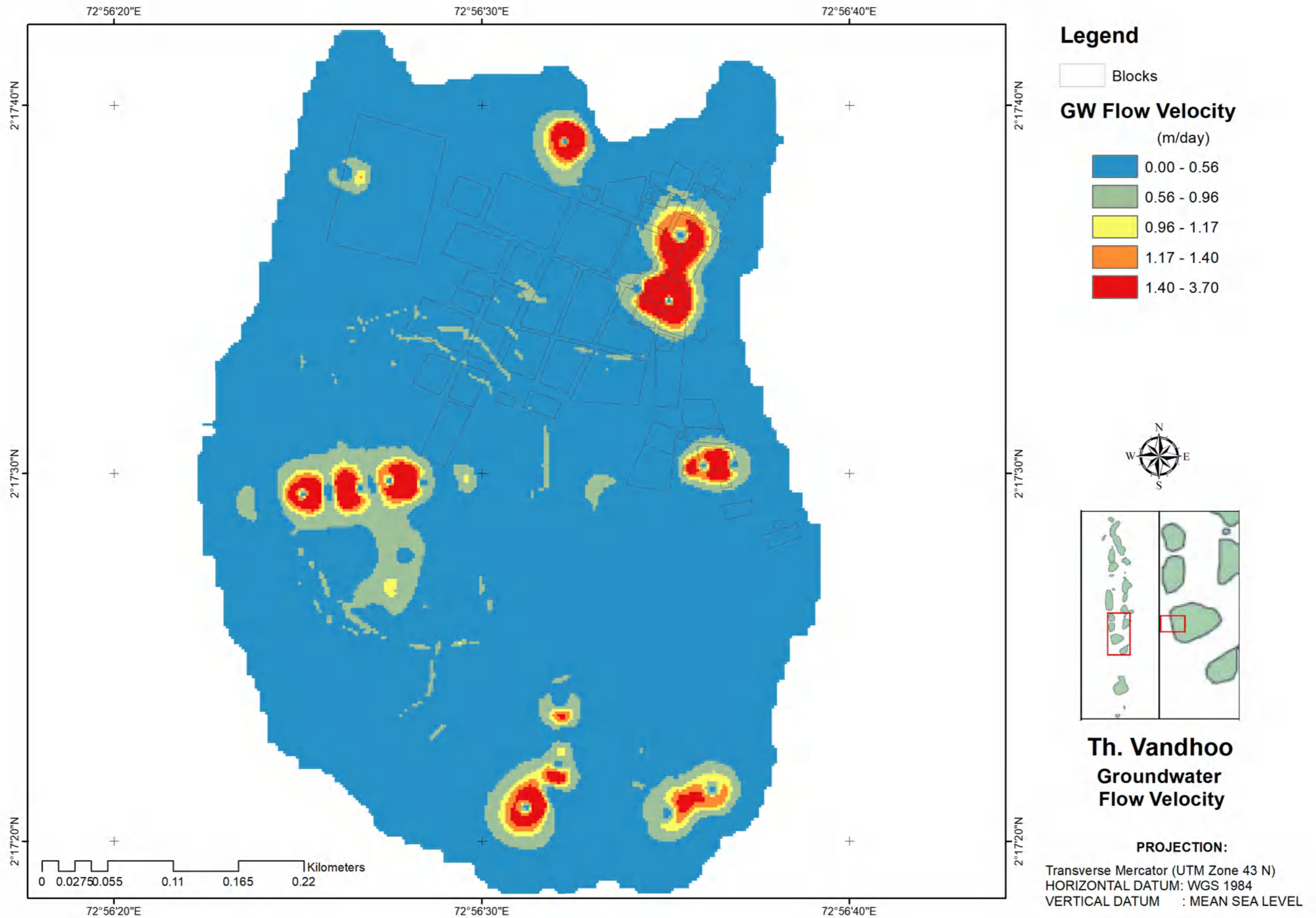
Legend

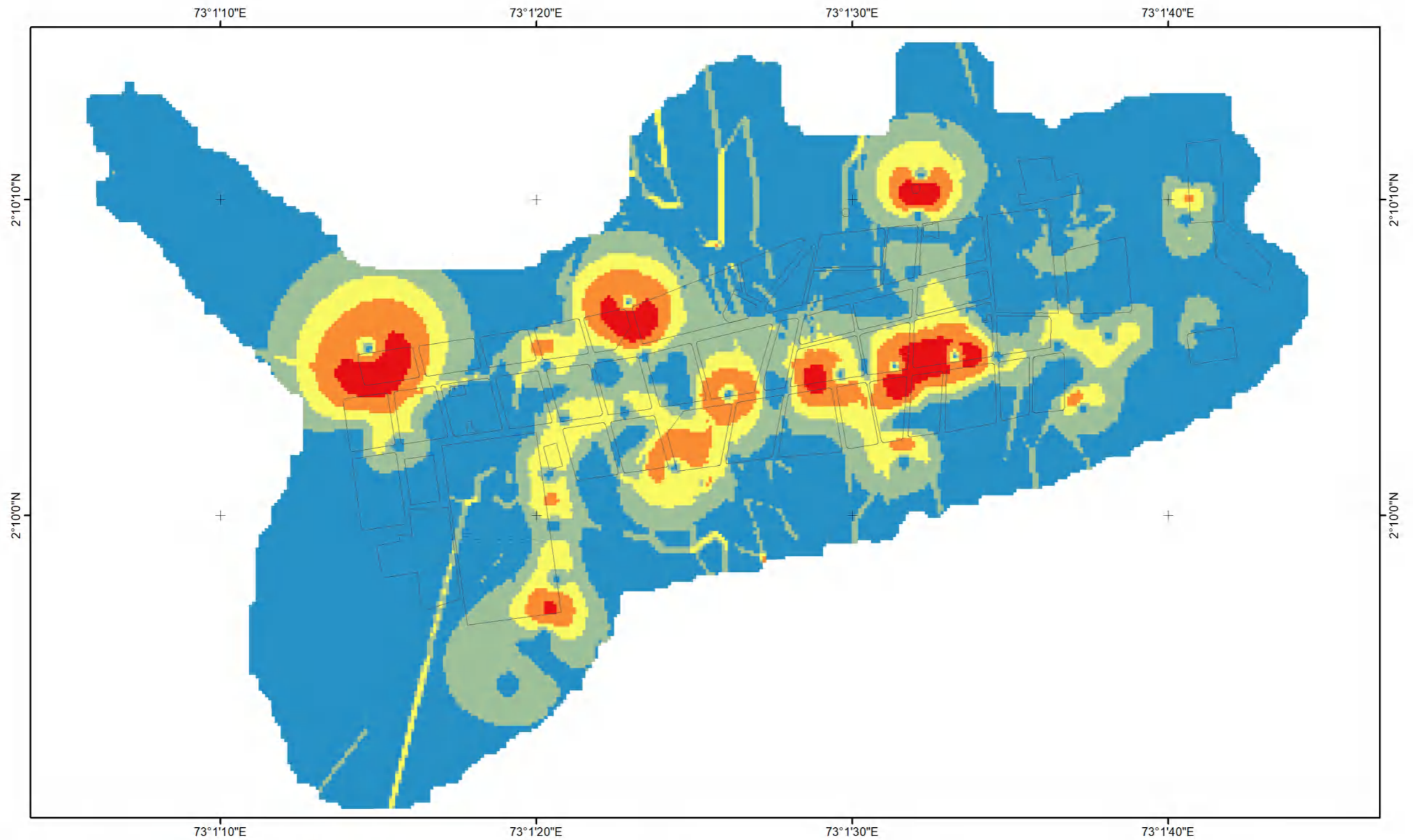
-  Blocks
- GW Flow Velocity (m/day)**
-  0.00 - 0.30
-  0.30 - 0.82
-  0.82 - 1.80
-  1.80 - 3.76
-  3.76 - 7.73



**TH. Kandoodhoo
Groundwater
Flow Velocity**

PROJECTION:
 Transverse Mercator (UTM Zone 43 N)
 HORIZONTAL DATUM: WGS 1984
 VERTICAL DATUM : MEAN SEA LEVEL



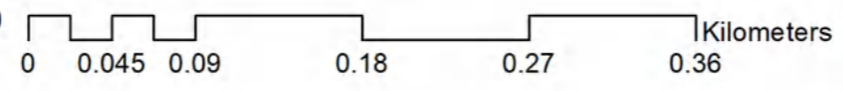


Legend

Blocks

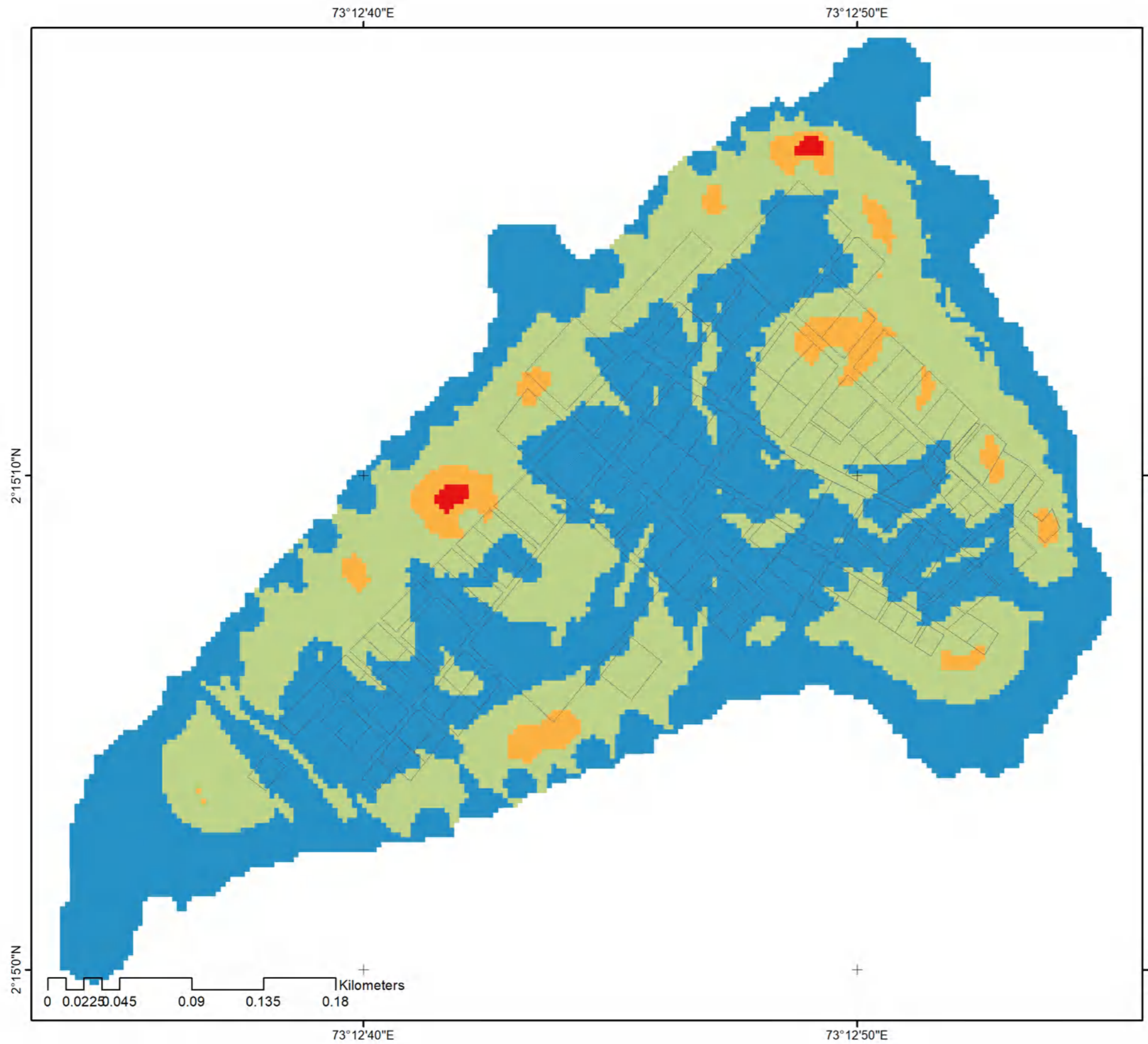
GW Flow Velocity (m/day)

0.00 - 0.70	2.10 - 3.50
0.70 - 1.30	3.50 - 7.30
1.30 - 2.10	








Th. Omadhoo
Groundwater
Flow Velocity

PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL



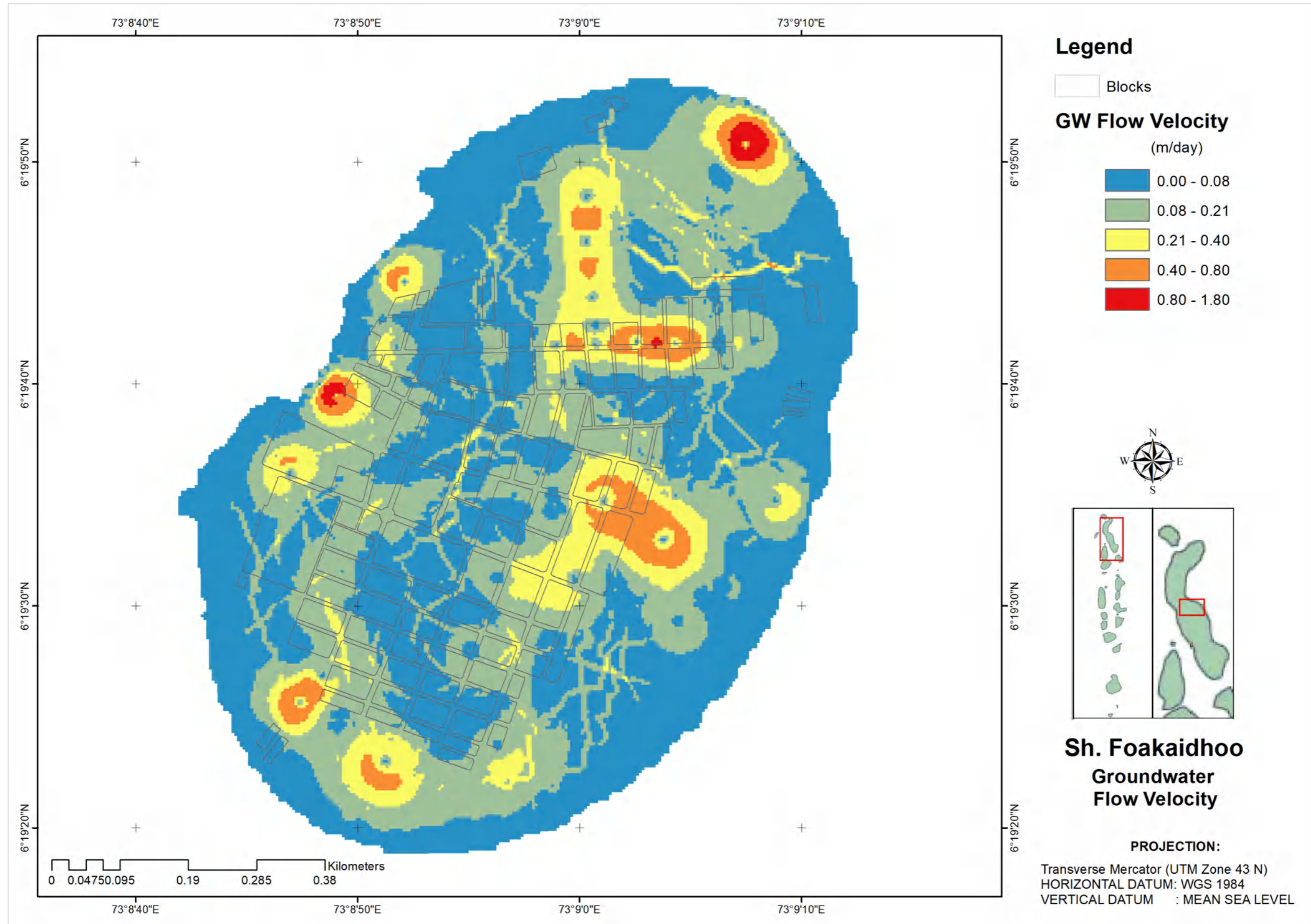
Legend

-  Blocks
- GW Flow Velocity**
(m/day)
-  0.00 - 0.50
-  0.50 - 1.50
-  1.50 - 2.50
-  2.50 - 3,50

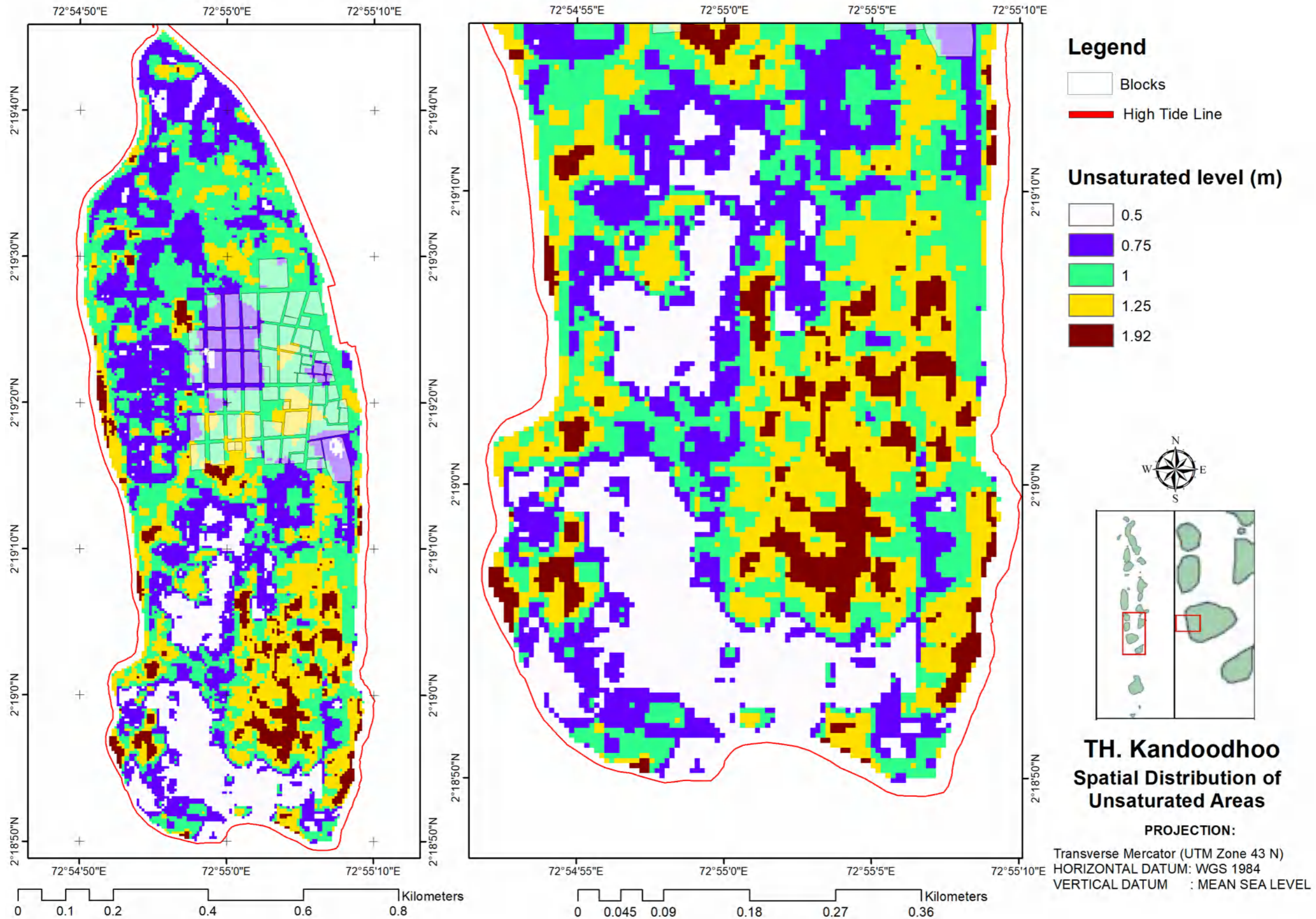


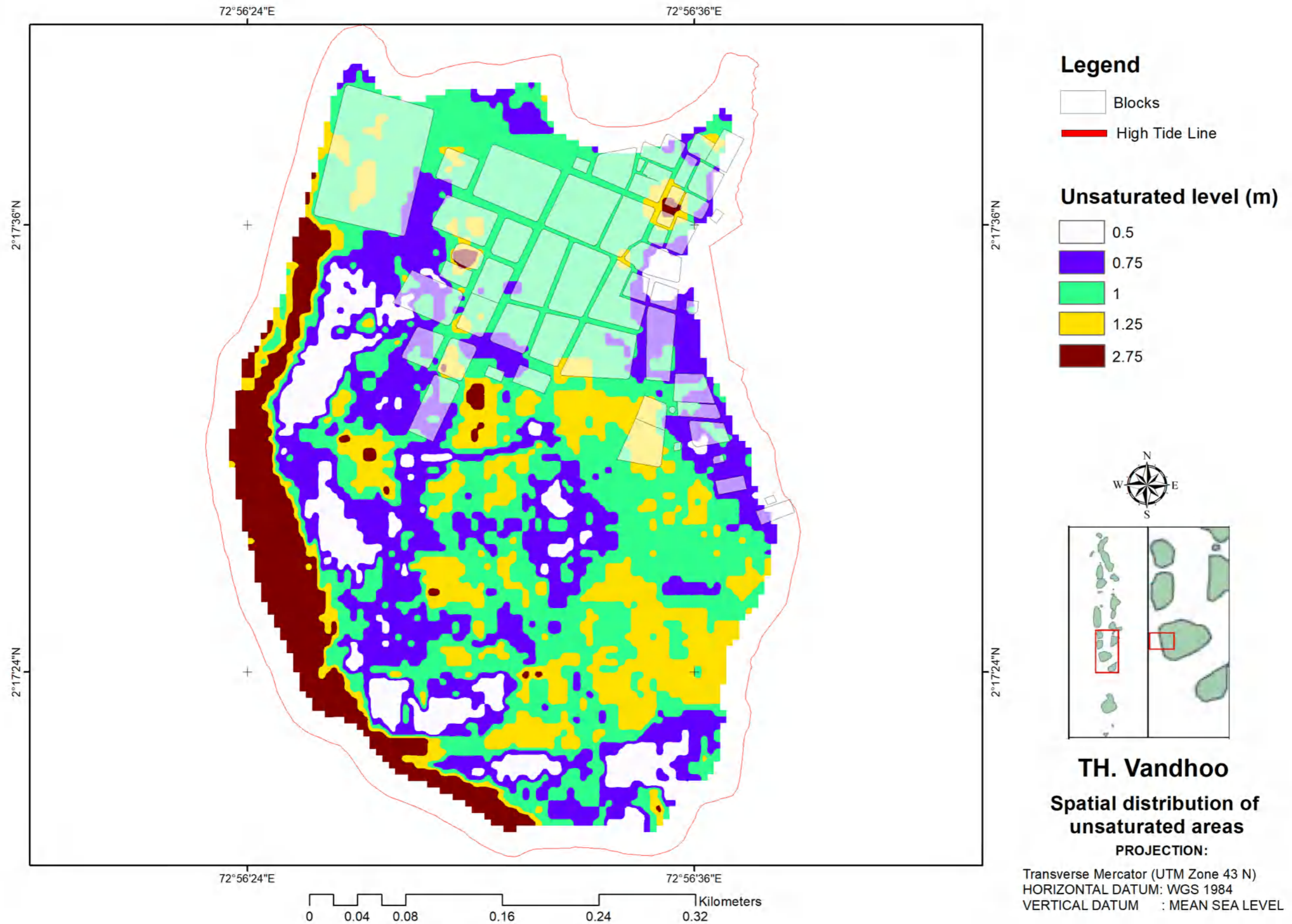
**Th. Gaadhiffushi
Groundwater
Flow Velocity**

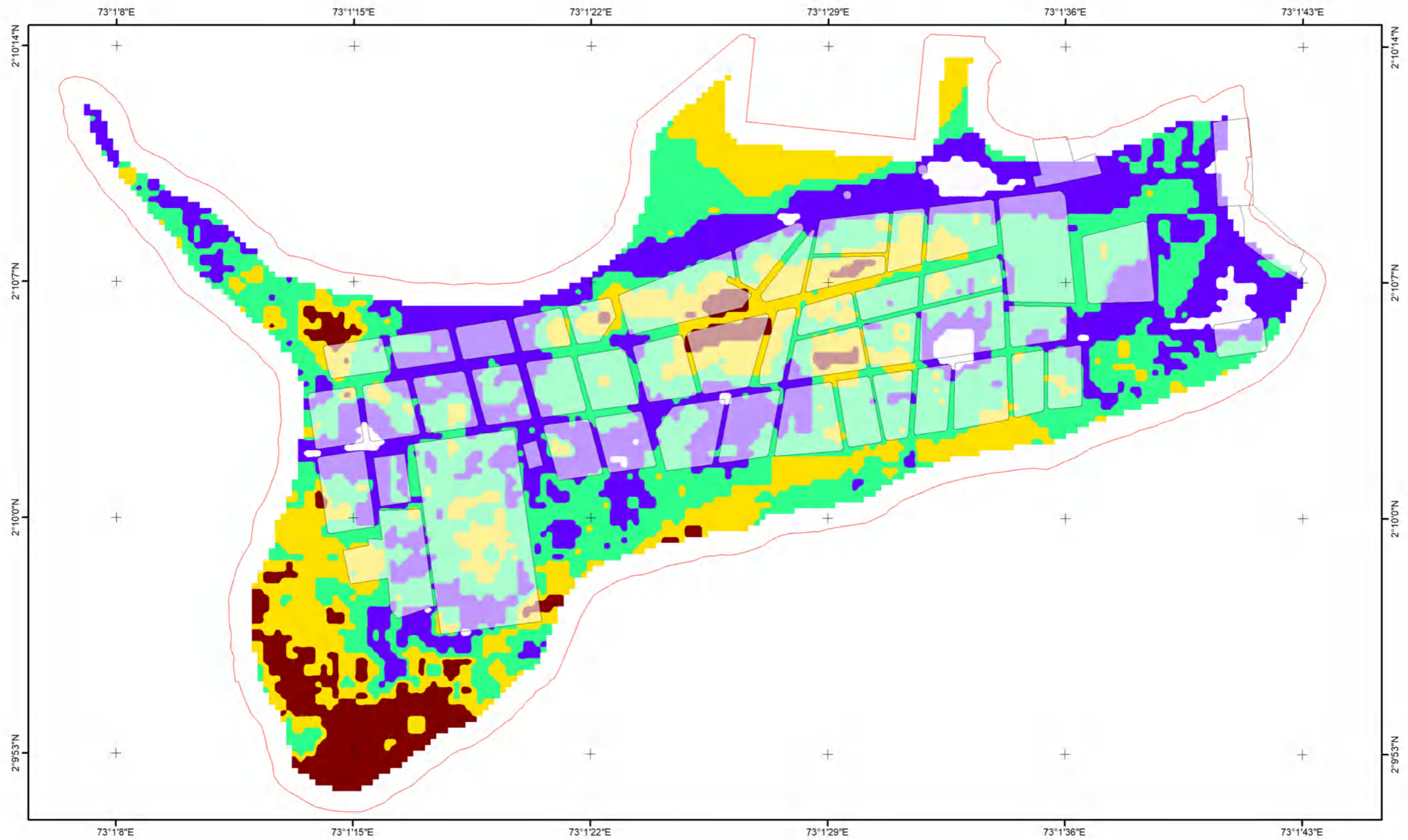
PROJECTION:
 Transverse Mercator (UTM Zone 43 N)
 HORIZONTAL DATUM: WGS 1984
 VERTICAL DATUM : MEAN SEA LEVEL



Annex IX: Spatial Distribution of Unsaturated Areas of the Islands









Legend

-  Blocks
-  High Tide Line

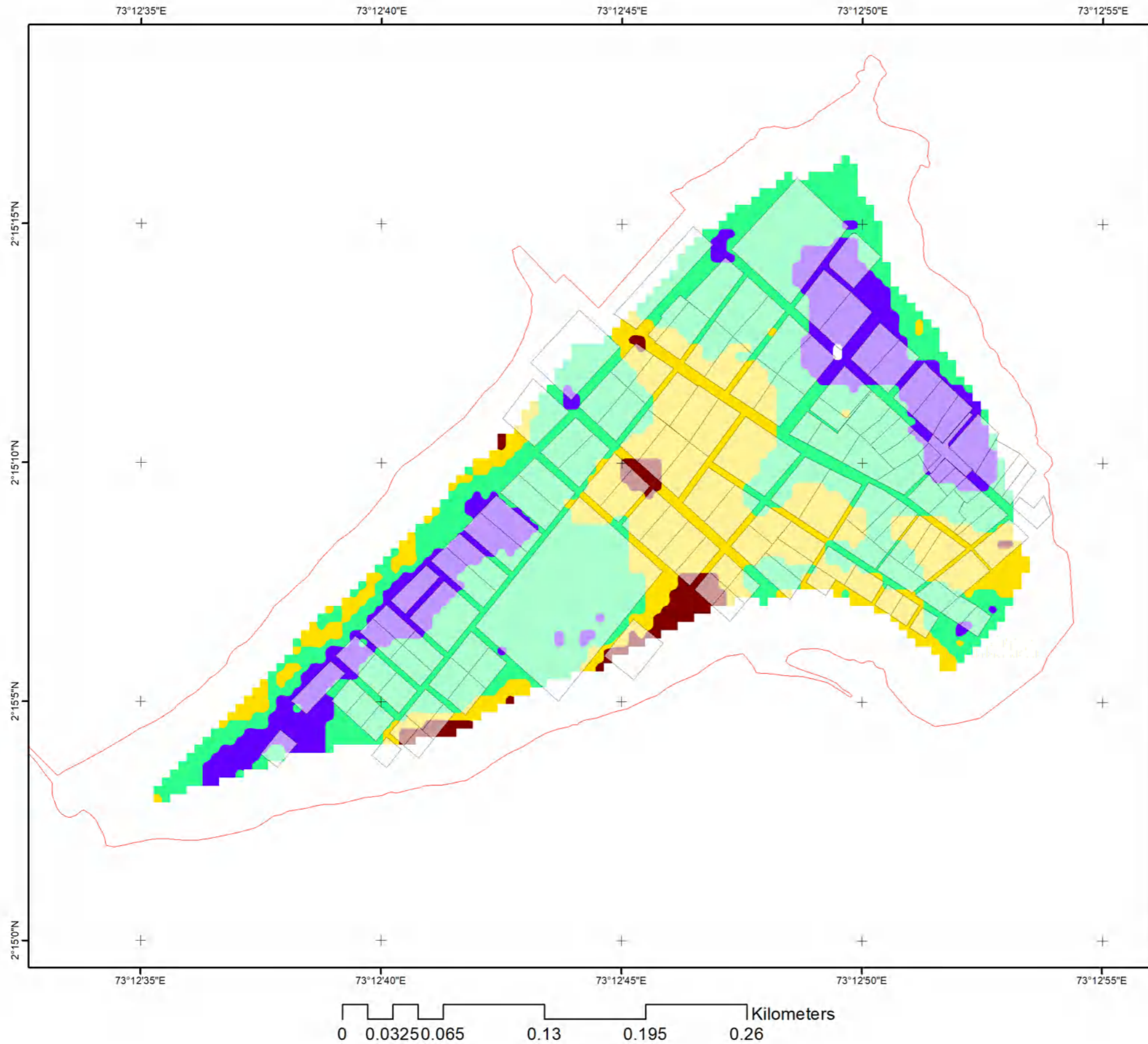
Unsaturated level (m)

- | | |
|--|--|
|  0.5 |  1.25 |
|  0.75 |  2.20 |
|  1 | |



TH. Omadhoo
Spatial Distribution of Unsaturated Areas

PROJECTION:
 Transverse Mercator (UTM Zone 43 N)
 HORIZONTAL DATUM: WGS 1984
 VERTICAL DATUM : MEAN SEA LEVEL



Legend

- Blocks
- High Tide Line

Unsaturated level (m)

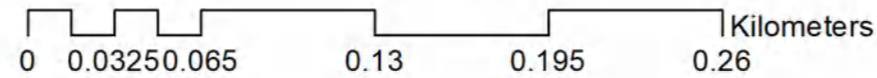
- 0.5
- 0.75
- 1
- 1.25
- 1.61

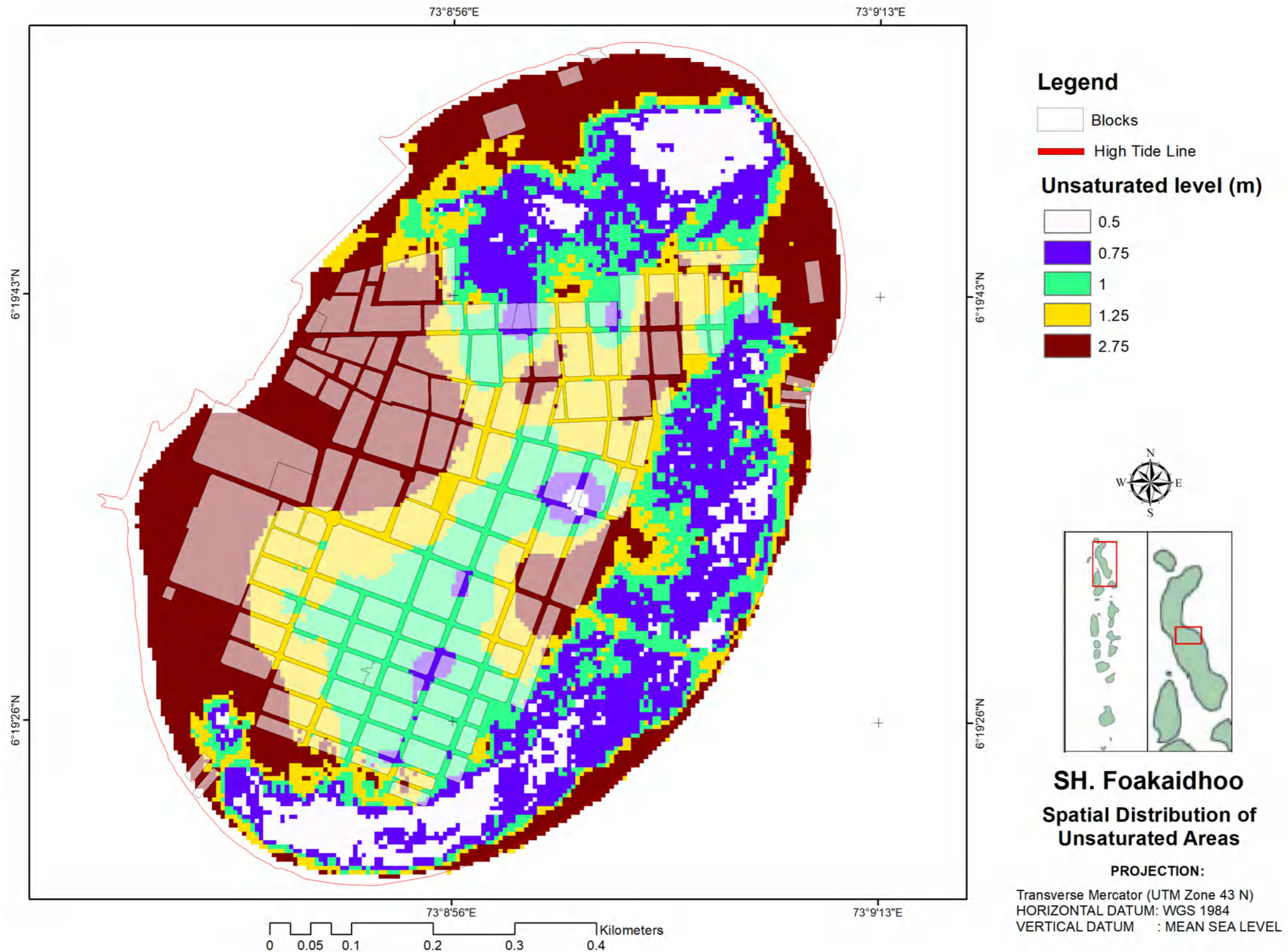


**TH. Gaadhiffushi
Spatial Distribution of
Unsaturated Areas**

PROJECTION:

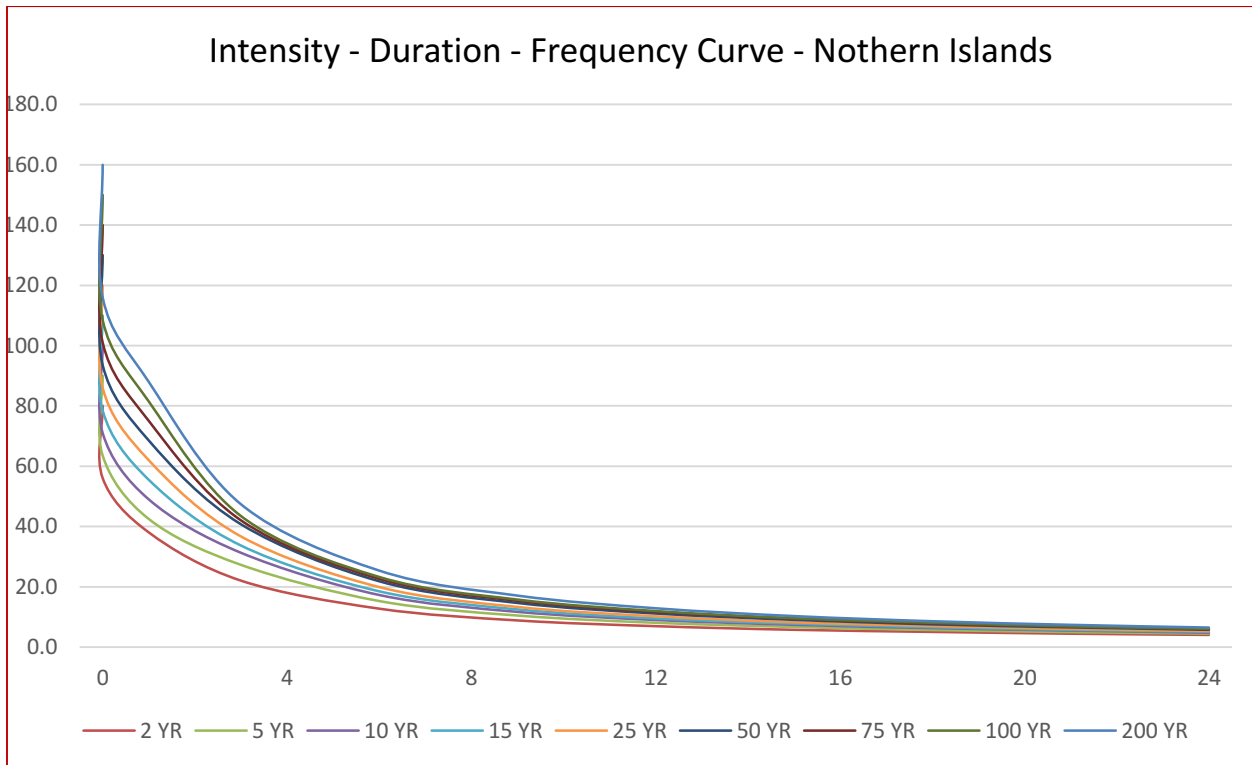
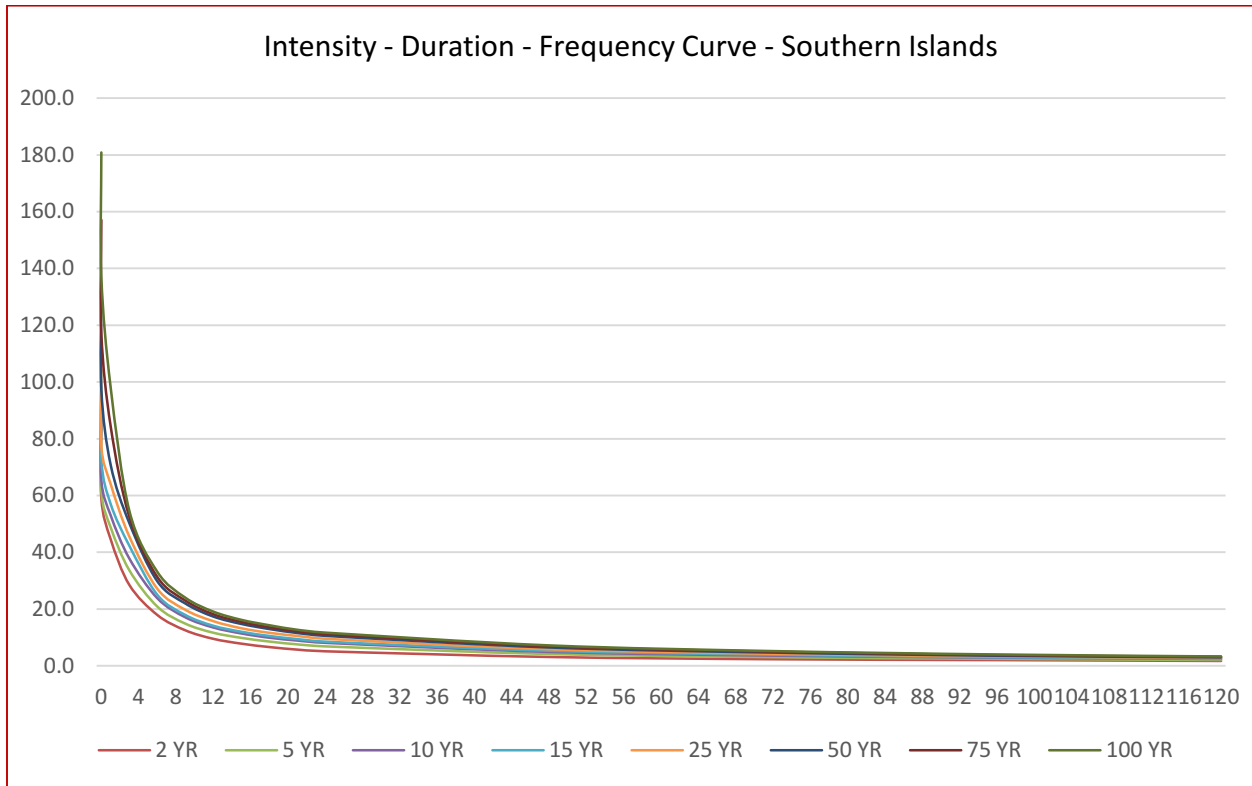
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL





Annex X: Developed IDF Curves and Calculations Carried Out for The SCS Method

Developed IDF Curves for Northern and Southern Islands



Intensity - Duration - Frequency Table (Southern Islands)

Duration (hr)	Return period in years							
	2 YR	5 YR	10 YR	15 YR	25 YR	50 YR	75 YR	100 YR
0.25	88.0	90.8	95.6	104.1	109.8	133.5	157.1	180.8
0.5	59.0	61.4	65.4	72.5	77.3	97.2	117.1	137.0
1	44.6	48.8	53.0	57.0	64.0	70.8	84.4	98.0
3	28.5	33.7	37.8	42.3	46	50.3	52.5	54.6
6	17.9	20.9	23.8	25.0	27.1	29.8	31	33.1
9	12.5	14.9	17.1	17.9	19.7	22.0	23.0	24.0
12	10	11.7	13.5	14.1	15.7	17.4	18.2	19.1
15	7.8	9.9	11.4	12.0	13.2	14.8	15.5	16.2
18	6.6	8.6	9.9	11	11.6	13.0	13.6	14.3
21	5.7	7.6	8.9	9.4	11	11.6	12.2	12.7
24	5.1	6.9	8.1	8.5	9.5	10.6	11.2	11.7
48	3.1	4.2	4.9	5.3	5.8	6.5	6.9	7.2
72	2.3	3.1	3.6	3.9	4.2	4.7	5.0	5.2
96	2.0	3	2.9	3.0	3.3	3.6	3.8	4.0
120	1.7	2.1	2.4	2.6	2.7	3.0	3.2	3.3

Intensity - Duration - Frequency Table (Northern Islands)

Duration (hr)	Return period in years							
	2 YR	5 YR	10 YR	15 YR	25 YR	50 YR	75 YR	100 YR
0.25	80.0	90.0	100.0	110.0	120.0	130.0	140.0	150.0
0.5	56.0	63.5	71.0	78.5	86.0	93.5	101.0	108.5
1	38.0	42.5	49.0	55.5	62.0	68.5	75.0	81.5
3	22.0	27.3	31.3	33.7	36.7	40.7	42.0	43.5
6	12.7	15.3	17.3	18.5	19.9	21.8	22.6	23.3
9	8.8	10.5	11.7	12.5	13.3	14.6	15.3	15.8
12	6.9	8.1	9.0	9.5	10.2	11.1	11.6	12.0
15	5.7	6.7	7.4	7.8	8.2	9.0	9.4	9.6
18	5.0	5.7	6.3	6.6	7.0	7.5	7.8	8.1
21	4.4	5.0	5.5	5.7	6.0	6.5	6.8	6.9
24	4.0	4.5	4.8	5.1	5.3	5.7	5.9	6.1
48	80.0	90.0	100.0	110.0	120.0	130.0	140.0	150.0
72	56.0	63.5	71.0	78.5	86.0	93.5	101.0	108.5
96	38.0	42.5	49.0	55.5	62.0	68.5	75.0	81.5
120	22.0	27.3	31.3	33.7	36.7	40.7	42.0	43.5

Calculation of run off and estimation of recharge from (NRCS) CN method.

Example: Kandhodh0oo island.

Land Use: Five land use types are observed in the island and details of the calculation are given below (see annex:1).

Land use	Area(m ²)	CN value for land use	CN value for soil types	Used CN value for SCS method(results from overlay)
Water/wetland	44626	100	100	100
Agriculture	278016	71	79	75
Bare/Vacant land	27290	69	79	74
Forest/coconut	251537	55	79	67
Residential/ Built	133282	79	79	79

Rain fall: Selected rainfall intensity duration frequency data for southern islands is given in following table.

Duration (hr)	Return period in years							
	2 YR	5 YR	10 YR	15 YR	25 YR	50 YR	75 YR	100 YR
0.25	88.0	90.8	95.6	104.1	109.8	133.5	157.1	180.8
0.5	59.0	61.4	65.4	72.5	77.3	97.2	117.1	137.0
1	44.6	48.8	53.0	57.0	64.0	70.8	84.4	98.0
3	28.5	33.7	37.8	42.3	46	50.3	52.5	54.6
6	17.9	20.9	23.8	25.0	27.1	29.8	31	33.1
9	12.5	14.9	17.1	17.9	19.7	22.0	23.0	24.0
12	10	11.7	13.5	14.1	15.7	17.4	18.2	19.1
15	7.8	9.9	11.4	12.0	13.2	14.8	15.5	16.2
18	6.6	8.6	9.9	11	11.6	13.0	13.6	14.3
21	5.7	7.6	8.9	9.4	11	11.6	12.2	12.7
24	5.1	6.9	8.1	8.5	9.5	10.6	11.2	11.7

SCS equation.

$$Pe(\text{inch}) = (P-0.2S)^2 / (P + 0.8S).$$

$$Fa = P - Pe - Ia.$$

Where: Pe= Excess rainfall for direct run off, S =Maximum soil storage, P = Total Precipitation, Ia = Initial abstraction, Fa = Continuous abstraction/soil retention.

For dry condition: $CN(\text{dry}) = 4.2 CN(\text{normal}) / (10 - 0.58 CN(\text{normal}))$

For wet condition: $CN(\text{wet}) = 23 CN(\text{normal}) / (10 + 0.13 CN(\text{normal}))$

1) Calculation of run off for different return period using (NRCS) CN method.

For two years return Period															
Duration (Hours)	Excess rain fall for run off(inch)														
	General Condition					Wet Condition					Dry Condition				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0.5	2.36	0.57	0.53	0.30	0.74	2.36	1.22	1.18	0.94	1.38	2.36	0.07	0.05	0.00	0.16
1	1.78	0.28	0.25	0.11	0.40	1.78	0.76	0.73	0.54	0.89	1.78	0.00	0.00	-	0.04
3	1.14	0.06	0.05	-	0.11	1.14	0.31	0.29	0.19	0.40	1.14	-	-	-	-
6	0.72	-	-	-	0.01	0.72	0.10	0.09	0.04	0.14	0.72	-	-	-	-
9	0.50	-	-	--	-	0.50	0.03	0.02	0.00	0.05	0.50	-	-	-	-
15	0.31	-	-	-	-	0.31	0.00	0.00	-	0.01	0.31	-	-	-	-
24	0.20	-	-	-	-	0.20	-	-	-	-	0.20	-	-	-	-
For five years return Period															
Duration (Hours)	Excess rain fall for run off(inch)														
	General condition					Wet condition					Dry Condition				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0.5	2.46	0.63	0.58	0.34	0.81	2.46	1.30	1.26	1.01	1.46	2.46	0.09	0.07	0.00	0.19
1	1.95	0.36	0.33	0.16	0.49	1.95	0.89	0.85	0.65	1.03	1.95	0.02	0.01	-	0.07
3	1.35	0.12	0.10	0.02	0.19	1.35	0.45	0.42	0.29	0.55	1.35	-	-	-	0.00
6	0.84	0.01	-	-	0.03	0.84	0.15	0.14	0.07	0.21	0.84	-	-	-	-

9	0.60	-	-	-	-	0.60	0.05	0.05	0.01	0.09	0.60	-	-	-	
15	0.40	-	-	-	-	0.40	0.01	0.01	-	0.02	0.40	-	-	-	
24	0.28	-	-	-	-	0.28	-	-	-	0.00	0.28	-	-	-	
For ten years return Period															
Duration (Hours)	Excess rain fall for run off(inch)														
	General condition					Wet Condition					Dry Condition				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0.5	2.62	0.72	0.68	0.41	0.92	2.62	1.43	1.39	1.13	1.60	2.62	0.13	0.10	0.01	0.24
1	2.12	0.44	0.41	0.21	0.59	2.12	1.02	0.98	0.76	1.17	2.12	0.03	0.02	-	0.10
3	1.51	0.17	0.15	0.05	0.26	1.51	0.56	0.53	0.38	0.67	1.51	-	-	-	0.01
6	0.95	0.02	0.02	-	0.06	0.95	0.21	0.19	0.11	0.28	0.95	-	-	-	-
9	0.68	-	-	-	0.01	0.68	0.08	0.07	0.03	0.13	0.68	-	-	-	-
15	0.46	-	-	-	-	0.46	0.02	0.01	0.00	0.04	0.46	-	-	-	-
24	0.32	-	-	-	-	0.32	0.00	0.00	-	0.01	0.32	-	-	-	-
1) Water body / wetland (CN number-100) 2) Agricultural area (CN number-75) 3) Bare land (CN number-74) 4) Forest / coconut Land (CN number-67) 5) Residential area (CN number-79)															

2) Estimated of continuous abstraction from NRCS method for different return period.

For two years return Period															
Duration (Hours)	Estimated continuous abstraction(inch)														
	General Condition					Wet Condition					Dry Condition				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0.5	0.00	1.12	1.13	1.07	1.09	0.00	0.85	0.87	1.00	0.75	0.00	0.70	0.64	0.02	0.93
1	0.00	0.83	0.83	0.68	0.85	0.00	0.73	0.74	0.82	0.66	0.00	0.19	0.11	-	0.47
3	0.00	0.41	0.39	0.15	0.50	0.00	0.54	0.54	0.53	0.51	0.00	-	-	-	-
6	0.00	0.05	0.02	-	0.18	0.00	0.33	0.32	0.26	0.35	0.00	-	-	-	-
9	0.00		-	-	-	0.00	0.18	0.17	0.08	0.22	0.00	-	-	-	-
15	0.00		-	-	-	0.00	0.02	0.00	-	0.07	0.00	-	-	-	-
24	0.00		-	-	-	0.00	-	-	-	-	0.00	-	-	-	-
For five years return Period															
Duration (Hours)	Excess rain fall for run off(inch)														
	General condition					Wet condition					Dry Condition				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0.5	0.00	1.16	1.18	1.13	1.12	0.00	0.87	0.89	1.03	0.77	0.00	0.78	0.72	0.12	1.00
1	0.00	0.92	0.92	0.80	0.93	0.00	0.77	0.79	0.88	0.69	0.00	0.34	0.27	-	0.61
3	0.00	0.56	0.55	0.34	0.63	0.00	0.61	0.62	0.64	0.57	0.00	-	-	-	0.08
6	0.00	0.16	0.14	-	0.28	0.00	0.40	0.39	0.35	0.40	0.00	-	-	-	-

9	0.00	-	-	-	0.07	0.00	0.26	0.24	0.17	0.28	0.00	-	-	-	-
15	0.00	-	-	-	-	0.00	0.10	0.08	-	0.15	0.00	-	-	-	-
24	0.00	-	-	-	-	0.00	-	-	-	0.05	0.00	-	-	-	-
For ten years return Period															
Duration (Hours)	Excess rain fall for run off(inch)														
	General condition					Wet Condition					Dry Condition				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0.5	0.00	1.23	1.24	1.22	1.17	0.00	0.90	0.92	1.07	0.79	0.00	0.90	0.85	0.27	1.07
1	0.00	1.01	1.01	0.92	1.00	0.00	0.81	0.83	0.94	0.72	0.00	0.50	0.43	-	0.75
3	0.00	0.67	0.66	0.47	0.72	0.00	0.66	0.67	0.71	0.61	0.00	-	-	-	0.23
6	0.00	0.26	0.23	-	0.36	0.00	0.45	0.45	0.42	0.44	0.00	-	-	-	-
9	0.00	0.01	-	-	0.14	0.00	0.31	0.30	0.05	0.32	0.00	-	-	-	-
15	0.00	-	-	-	-	0.00	0.15	0.14	-	0.19	0.00	-	-	-	-
24	0.00	-	-	-	-	0.00	0.03	0.01	-	0.08	0.00	-	-	-	-

3) The total runoff and estimated soil abstraction for the different land use are given below. The run off from water /wet land area is not included into total.

Duration (hours)	General condition		Wet condition		Dry condition	
	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
Land Use: Agriculture_						
For two year return period						
0.5	3534	6969	7564	5270	434	4353
1	1736	5171	4712	4526	-	1190
3	372	2567	1922	3348	-	-
6	-	335	620	2046	-	-
9	-		186	1116	-	-
15	-		-	124	-	-
24	-		-		-	-
For five year return period						
0.5	3906	7217	8061	5394	558	4849
1	2232	5729	5518	4774	124	2121
3	744	3497	2790	3782	-	-
6	62	1017	930	2480	-	-
9	-		310	1612	-	-
15	-		62	620	-	-
24	-		-		-	-

Duration (hours)	General condition		Wet condition		Dry condition	
	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
For ten year return period						
0.5	4464	7651	8867	5580	806	5593
1	2728	6287	6324	5022	186	3113
3	1054	4179	3472	4092	-	-
6	124	1637	1302	2790	-	-
9	--	87	496	1922	-	-
15	-		124	930	-	-
24	-		-	186	-	-
Land Use: Bare land_						
For two year return period						
0.5	362	770	805	596	34	435
1	171	565	498	508	-	74
3	34	265	198	371	-	-
6	-	12	61	221	-	-
9	-		14	119	-	-
15	-		-	3	-	-
24	-		-		-	-

Duration (hours)	General condition		Wet condition		Dry condition	
	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
For five year return period						
0.5	396	804	860	610	48	490
1	225	626	580	542	7	183
3	68	374	287	426	-	-
6	-	94	96	269	-	-
9	-		34	166	-	-
15	-		7	57	-	-
24	-		-		-	-
For ten year return period						
0.5	464	845	948	630	68	579
1	280	688	669	569	14	292
3	102	449	362	460	-	-
6	136	156	130	310	-	-
9	-		48	207	-	-
15	-		7	98	-	-
24	-		-	10	-	-

Duration (hours)	General condition		Wet condition		Dry condition	
	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
Land Use: Forest/Coconut land						
For two year return period						
0.5	1887	6746	5911	6301	-	101
1	692	4296	3396	5169	-	-
3	-	967	1195	3345	-	-
6	-		252	1648	-	-
9	-		-	516	-	-
15	-		-		-	-
24	-		-		-	-
For five year return period						
0.5	2138	7123	6351	6490	-	729
1	1006	5050	4087	5546	-	-
3	126	2161	1824	4037	-	-
6	-	-	440	2214	-	-
9	-	-	63	1082	-	-
15	-	-	-	-	-	-
24	-	-	-	-	-	-

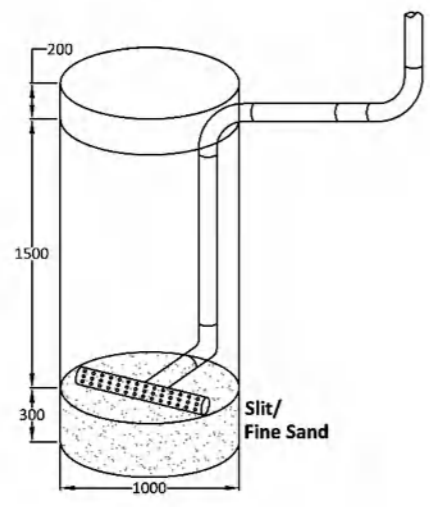
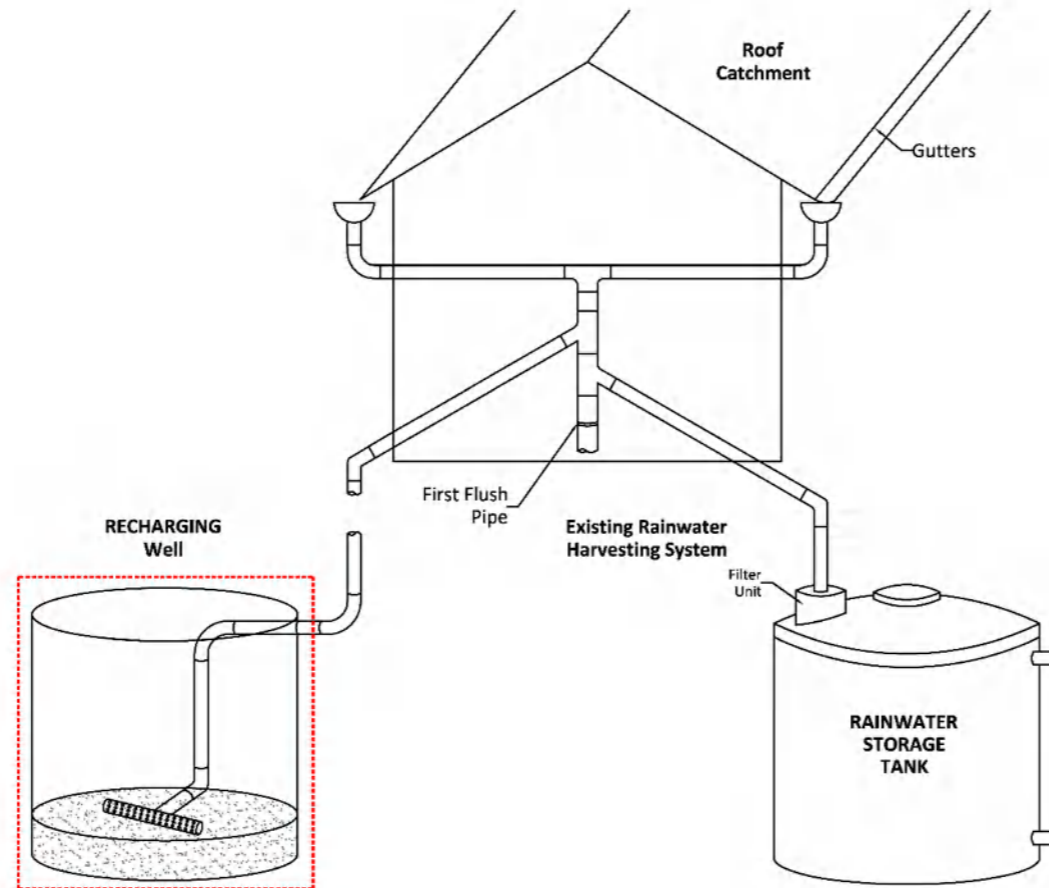
Duration (hours)	General condition		Wet condition		Dry condition	
	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
For ten year return period						
0.5	2578	7688	7106	6741	63	1673
1	1321	5804	4779	5924	-	-
3	314	2977	2390	4477	-	-
6	-		692	2654	-	-
9	-		189	327	-	-
15	-		-		-	-
24	-		-		-	-
Land Use: Residential area_						
For two year return period						
0.5	2466	3625	4598	2492	533	3112
1	1333	2826	2966	2192	133	1579
3	367	1659	1333	1693	-	-
6	33	593	466	1160	-	-
9	-		167	726	-	-
15	-		33	227	-	-
24	-		-		-	-

Duration (hours)	General condition		Wet condition		Dry condition	
	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
For five year return period						
0.5	2699	3725	4865	2559	633	3345
1	1633	3092	3432	2292	233	2046
3	633	2093	1833	1893	-	280
6	100	926	700	1326	-	-
9	-	227	300	926	-	-
15	-		-	493	-	-
24	-		-	160	-	-
For ten year return period						
0.5	3065	3892	5331	2626	933	3579
1	1966	3325	3898	2392	333	2512
3	866	2392	2232	2026	33	780
6	200	1193	933	1459	-	-
9	33	460	433	1060	-	-
15	-		133	626	-	-
24	-		-	260	-	-

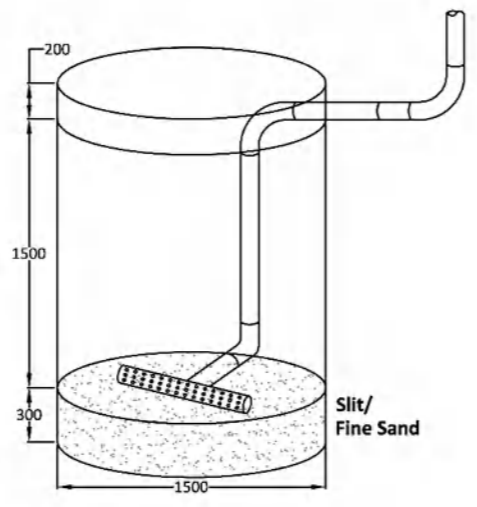
Duration (hours)	General condition		Wet condition		Dry condition	
	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
For island						
For two year return period						
Duration (hours)	General condition		Wet condition		Dry condition	
	Total run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Total run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
0.5	8249	18110	18978	14659	1133	8001
1	3932	12858	11572	12395	-	2843
3	773	5458	4448	8757	-	-
6	33	940	1399	5075	-	-
9	-	227	367	1477	-	-
15	-	-	33	354	-	-
24	-	-	-	-	-	-
For five year return period						
0.5	9139	18864	20137	15053	1239	9413
1	5096	14497	13617	13159	364	4350
3	1759	8124	6734	10138	-	280
6	162	2037	2166	6289	-	-
9	-	227	707	3736	-	-

Duration (hours)	General condition		Wet condition		Dry condition	
	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)	Run off(m ³ /d)	Estimated soil abstraction(m ³ /d)
15	-	-	69	1170	-	-
24	-	-		160	--	-
For ten year return period-						
0.5	10271	20076	22252	15577	1870	11424
1	5095	16104	15640	13907	533	5917
3	2336	9997	8456	11055	33	780
6	460	2986	3057	5213	-	-
9	33	547	1166	3516	-	-
15	-	-	264	1654	-	-
24	-	-	-	456	-	-

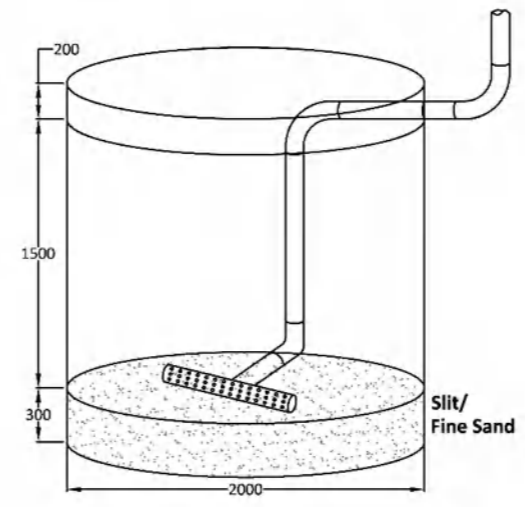
Annex XI: Conceptual Designs for Recharging Well



TYPE A
Height = 2.0 m
Diameter = 1.0 m



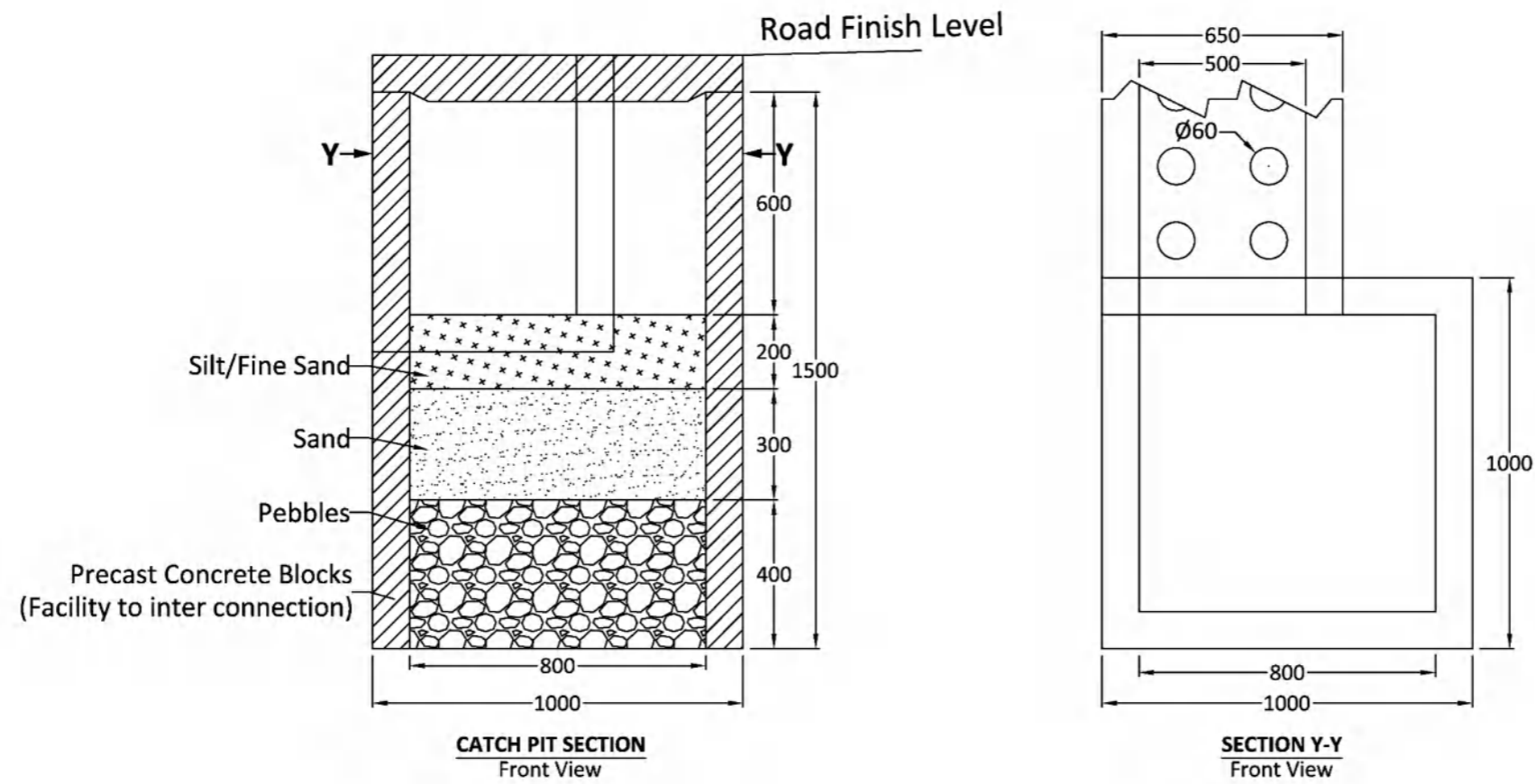
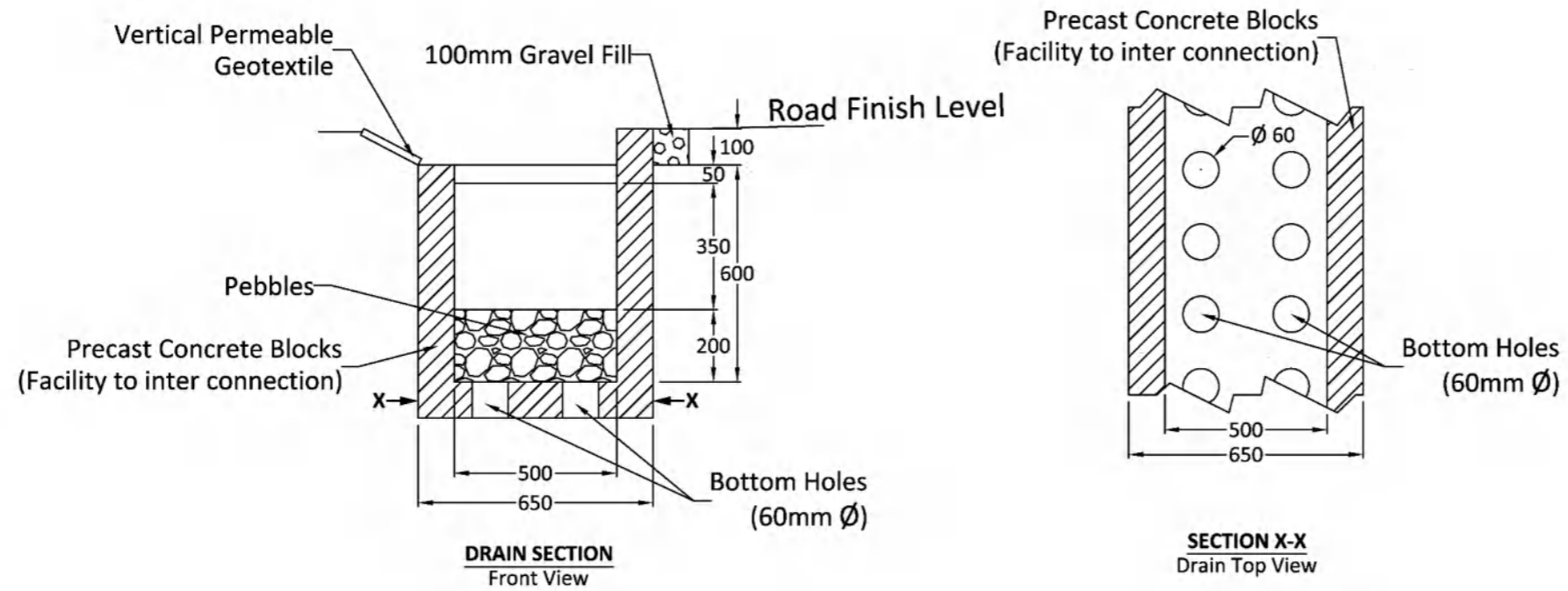
TYPE B
Height = 2.0 m
Diameter = 1.5 m



TYPE C
Height = 2.0 m
Diameter = 2.0 m

<p>Map Title : Conceptual Design For Roof Recharging Wells</p>
<p>Geodetic Parameters : Coordinate Systems :UTM Zone: 43 North Projection :Transverse Mercator (TM) Datum : WGS 1984</p>
<p>Deliverable : Feasibility Concept Design Report</p>
<p>Project : Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Maldives - Lot 2</p>
<p>Client : Ministry of Environment - Maldives</p>
<p>Consultant : </p>
<p>Purpose : Consultation</p>

Annex XII: Conceptual Designs for Road Runoff Recharge



Map Title :
Conceptual Design For Road Runoff
Recharging System

Geodetic Parameters :
Coordinate Systems :UTM Zone: 43 North
Projection :Transverse Mercator (TM)
Datum : WGS 1984

Deliverable :
Feasibility Concept Design Report

Project : Assessing Groundwater Resources and
Design of Aquifer Recharge Systems in
Maldives - Lot 2

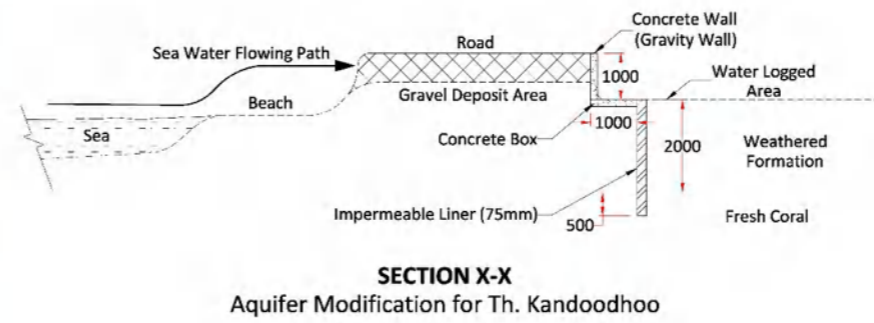
Client : Ministry of Environment - Maldives

Consultant :

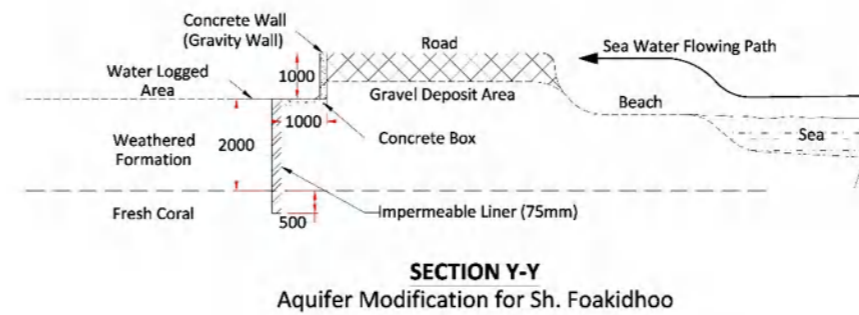
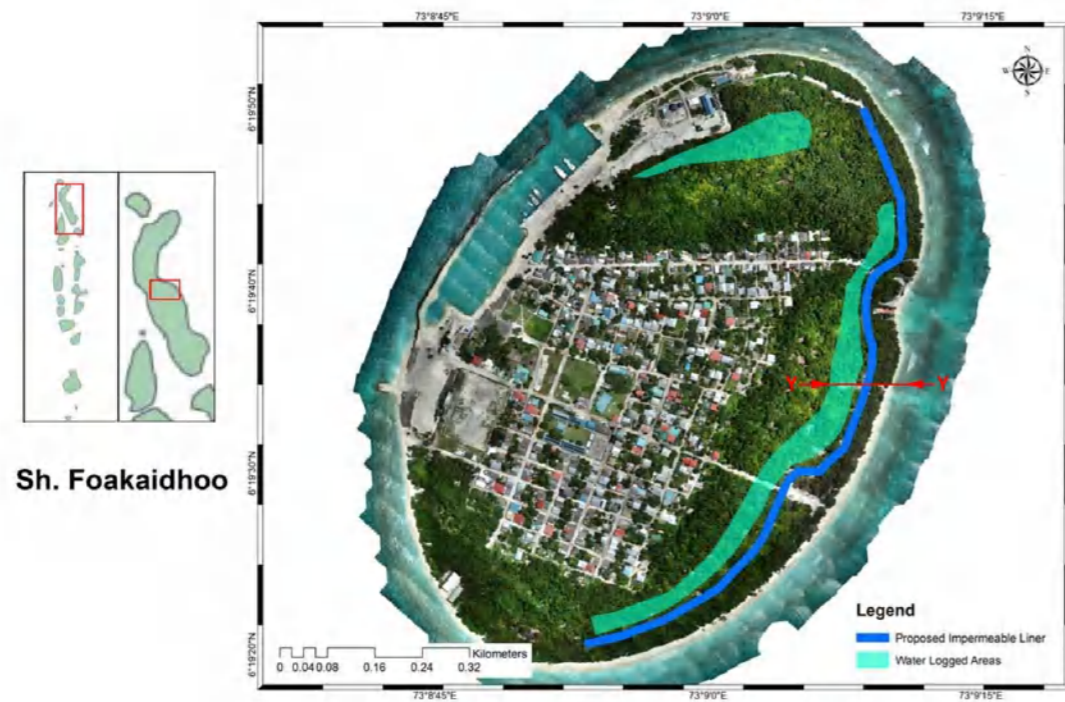
Purpose : Consultation

Annex XIII: Conceptual Designs for Aquifer Modifications

Proposed Managed Aquifer Recharge (MAR) Systems for Th. Kandoodhoo



Proposed Managed Aquifer Recharge (MAR) Systems for Sh. Foakaidhoo



Map Title :

Proposed Managed Aquifer Recharge (MAR) Systems for the Selected Islands

Geodetic Parameters :

Coordinate Systems :UTM Zone: 43 North
Projection :Transverse Mercator (TM)
Datum : WGS 1984

Deliverable :

Feasibility Concept Design Report

Project : Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Maldives - Lot 2

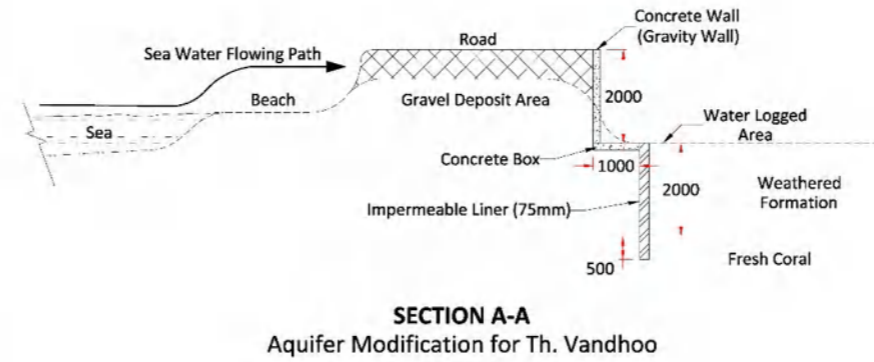
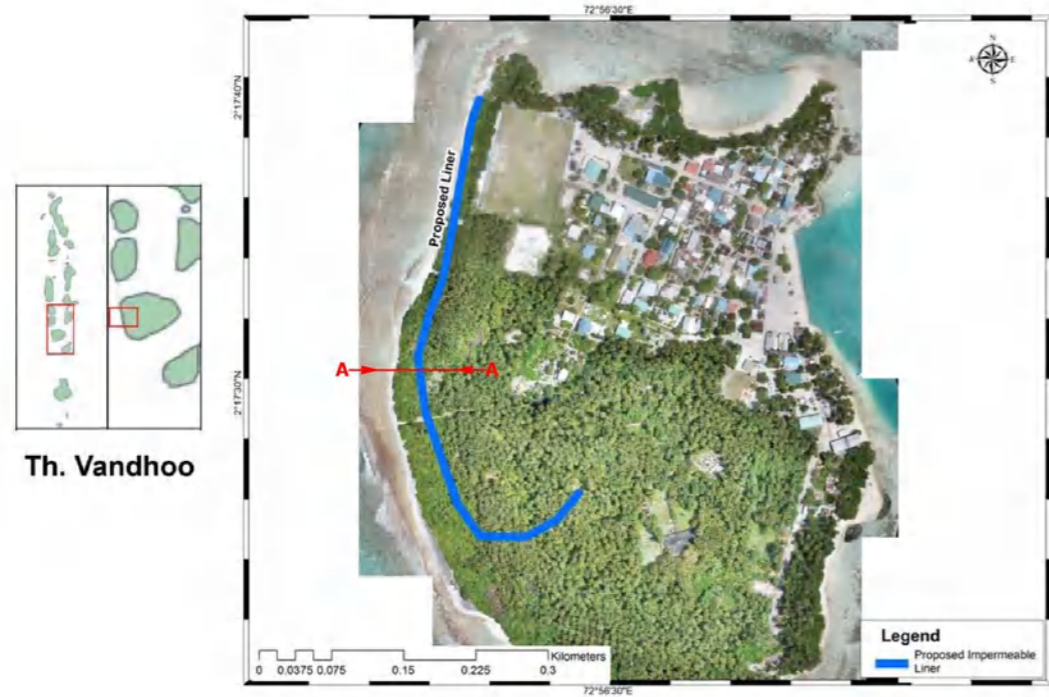
Client : Ministry of Environment - Maldives

Consultant :

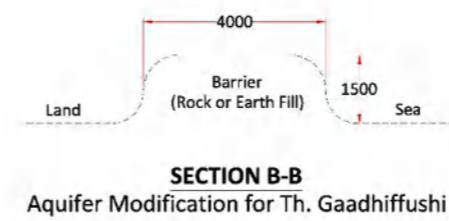


Purpose : Consultation

Proposed Managed Aquifer Recharge (MAR) Systems for Th. Vandhoo



Proposed Managed Aquifer Recharge (MAR) Systems for Th. Gaadhiffushi



Map Title :

Proposed Managed Aquifer Recharge (MAR) Systems for the Selected Islands

Geodetic Parameters :

Coordinate Systems :UTM Zone: 43 North
Projection :Transverse Mercator (TM)
Datum : WGS 1984

Deliverable :

Feasibility Concept Design Report

Project : Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Maldives - Lot 2

Client : Ministry of Environment - Maldives

Consultant :



Purpose : Consultation