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Ministry of Environment, Climate Change
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Republic of Maldives



Assessing Groundwater Resources and Design of Aquifer
Recharge Systems in Selected 17 Islands of Maldives - L1

BASELINE ASSESSMENT REPORT

Ha Filladhoo, Ha Maarandhoo, Ha Muraidhoo
Ha Uligan, and Ha Molhadhoo

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LAMER

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Focus Islands:

- Ha Filladhoo
- Ha Maarandhoo
- Ha Muraidhoo
- Ha Uligan
- Ha Molhadhoo

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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
LAMER	Land and Marine Environmental Resource Group Pvt. Ltd
ME	Ministry of Environment
MHEC	Master Hellie's Engineering Consultants Pvt. Ltd
NBS	National Bureau of Statistic
PMU	Project Management Unit
RIYAN	Riyan Private Limited

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 Baseline Assessment 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 baseline assessment to establish the current status and catchment characterization of 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 five (05) islands of the assignment are: Ha Filladhoo, Ha. Maarandhoo, Ha. Muraidhoo, Ha. Uligan and Ha. Molhadhoo.

The study was conducted as per the conditions and tasks stipulated in the Terms of Reference (ToR) and the report includes a detailed description of the methodologies followed and detailed data collected based on literature sources, and the baseline assessment of geological, hydrological (physiochemical, microbiological, geo-physical) characteristics and land-use investigations conducted for the selected five (05) islands.

The groundwater quality of the freshwater lens was studied based on physiochemical measurements (pH, Dissolved Oxygen (DO), Electrical Conductivity (EC), Turbidity, Temperature, Salinity, Ammonia, Nitrate, and Phosphate) and microbiological parameters (Total coliform and Fecal coliform) to identify the water quality and level of contamination, if any. A comprehensive social and institutional survey was conducted targeting households and local organizations/officials of local councils to gather information on usage characteristics of water for domestic/commercial/agricultural/recreational purposes and root level issues with groundwater and other water sources.

The spatial and volumetric extents of the freshwater lens in each island were estimated based on the geo-physical investigations using Electrical Resistivity (ER) method to establish depths to groundwater table and freshwater-saline water interphase, respectively. A robust assessment of the present impacts on the freshwater lens and quality of other water sources has been carried out based on the information gathered and with an estimation of rates of groundwater recharge and discharge and safe yield for extraction in each island following a freshwater lens water balance approach.

General Findings and Remarks

The selected five (05) islands under this package were located in the northern most atoll, Haa Alifu Atoll. Therefore, all the five (05) islands show some similar features when compared to groundwater parameters. All the five (05) islands are located nearly 290 – 330 km away from the main capital, Male.

The area extent of the islands varies from 41.1 Ha (Ha. Maarandhoo) to 207.08 Ha (Ha. Filladhoo) while the population range between 401 (Molhadhoo) and 1,144 (Filladhoo) as per the council records (Dec., 2021). Ha. Molhadhoo has the least population density of 1.67 per Ha since there exists a large thick vegetation coverage around the island while Ha. Maarandhoo has the highest population density of 26.25 per Ha.

Land use distribution of each island has a significant difference based on each island’s vision and mission. Only Ha. Molhadhoo and Ha. Uligan islands have farmlands where only 2% of the total area extent of both islands has farmlands. Th. Molhadhoo is covered with thick vegetation that covers 78%

of its total land extent (93.64 ha). Although, Ha. Maarandhoo and Ha. Muraidhoo are densely populated, they are covered with thick vegetation of nearly 60% of total land extent of those islands.

More than 47% of each island has a positive perception of ‘use of groundwater for daily uses is safe’ while less than 52% have a negative perception. Furthermore, based on the interviews, more than 39% agreed that the ‘quality of the groundwater is good’ while less than 52% disagreed with that statement.

In all the islands except Ha. Muraidhoo and Ha. Filladhoo, the sewer networks are under construction. Sewer network of Ha. Muraidhoo is already constructed. Ha. Molhadhoo and Ha. Filladhoo do not have island-wide water supply networks and the water supply network is under construction in other islands. More than 95% of the households of these five (05) islands have rainwater harvesting tanks and more than 74% of them use rainwater for drinking purposes. More than 88% use rainwater for cooking. Groundwater is generally used for non-potable use in all the islands while 7% of the Ha. Maarandhoo uses groundwater for cooking purposes.

When water quality data sets collected during both dry and wet periods are compared, there were no significant variations in measured parameters of the tested samples in Ha. Uligan and Ha. Molhadhoo Islands considering all land use types. But in other islands, there were some locations within residential areas where extremely high values of EC and Ammonia were recorded which can be identified generally due to sea water flooding, anthropogenic activities, and excessive groundwater extraction. Agricultural areas in Ha. Filladhoo and Ha. Muraidhoo islands were recorded with augmented values of EC, Ammonia, and Nitrate, which could be attributed to higher extraction of groundwater, leaching of nitrate-based fertilizers, etc.

From these five (05) islands, Ha. Maarandhoo shows the highest average of Electrical Conductivity ($\mu\text{S}/\text{cm}$) of $1625 \mu\text{S}/\text{cm}$ which is higher than the acceptable limit of $1,500 \mu\text{S}/\text{cm}$ for potable water. Ha. Uligan and Ha. Molhadhoo show better water quality with respect to EC and Ammonia values. All the groundwater wells in Ha. Uligan were bottom sealed with a small opening. The average Ammonia concentration of the tested samples remained within the acceptable limit of $1.5 \text{ mg}/\text{L}$.

The freshwater level of each island varies from -0.62 m (below MSL) to 3.26 m (above MSL) and the depth to the top water level from the ground varies from 0.5 m ~ to 1.4 m . The infiltration rate of the subsoils in the islands varies from the least average value of $1.58 \pm 1.4 \text{ m}/\text{day}$ in Ha. Filladhoo to the highest average value of $13.14 \pm 5.24 \text{ m}/\text{day}$ in Ha. Molhadhoo.

All the five (05) islands lie in ‘Semi-pervious’ range of the relative hydraulic conductivity and show ‘Low’ to ‘Moderate’ potential for groundwater recharge. All the five (05) islands have ‘Poor’ to ‘Good’ present aquifer conditions based on the estimated hydraulic conductivity and transmissivity.

Based on the developed water balance and recharge model, Ha. Maarandhoo and Ha. Muraidhoo islands show the most stressed and overexploited freshwater aquifer conditions with the present groundwater extraction rates exceeding their safe yields by 232% and 175%, respectively.

Ha. Filladhoo: This is the largest island in the selected five (5) islands with a land extent of 207 ha. Nearly 75.5% of the land use can be identified as thick vegetation showing good aquifer conditions. Based on the tested WQ samples, elevated values of tested parameters were identified mainly in all land use areas which could be due to higher GW extraction, leaching of Nitrate based fertilizers, and close proximity to the sea. Perception of people on “safeness of GW for daily uses” and “quality of GW” shows positive feedback scoring above 86% agreed percentage. This island is the largest island and shows a higher freshwater volume of $207,859 \text{ m}^3$. The present groundwater extraction rate estimated based on survey data is $94,101 \text{ m}^3$ per year and this is about 53% of the allowable Safe Yield in the island. The relative hydraulic conductivity of the island lies in the ‘Semi-pervious’ state while the present aquifer condition remains at the ‘Poor’ state. Moreover, general status based on transmissivity is ranked as ‘High’ and the potential for groundwater recharge remains ‘Low’ to ‘Moderate’ as per the estimations.

Ha. Maarandhoo: This is the smallest island in the selected five (5) islands with a land extent of 42 ha where 59% of the land use can be identified as thick vegetation showing poor aquifer conditions due to the high population density of 25.15 per ha. Based on the tested WQ samples, elevated values of tested parameters were identified in residential and bare land areas which could be due to higher GW extraction, close distance to the shoreline from the sample location and anthropogenic activities. Perception of people on “safeness of GW for daily uses” and “quality of GW” shows moderate feedback scoring below 47% agreed percentage. This island is the smallest among the selected and shows a low freshwater volume of 58,262 m³. The present groundwater extraction rate estimated based on survey data is 108,422 m³ per year and this exceeds the allowable Safe Yield in the island by 232%. The relative hydraulic conductivity of the island lies in the ‘Semi-pervious’ state while the present aquifer condition remains at the ‘Poor’ state. The general status based on transmissivity is ranked as ‘High’ and the potential for groundwater recharge remains ‘Low’ to ‘Moderate’ as per the estimations.

Ha. Muraidhoo: This island is famous for banana plantations and the land extent of the island is 42 ha where 62% of the land use can be identified as thick vegetation. Based on the tested WQ samples, elevated values of tested parameters were identified mainly in residential areas which could be due to higher GW extraction and anthropogenic activities. Perception of people on “safeness of GW for daily uses” and “quality of GW” shows moderate feedback scoring below 59% agreed percentage. Freshwater volume is 68,152 m³ and the present groundwater extraction rate estimated based on survey data is 94,101 m³ per year and this exceeds the allowable Safe Yield in the island by 175%. The relative hydraulic conductivity of the island lies in the ‘Semi-pervious’ state while the present aquifer condition remains at the ‘Poor’ state. Moreover, general status based on transmissivity is ranked as ‘High’ and the potential for groundwater recharge remains ‘Low’ to ‘Moderate’ as per the estimations.

Ha. Uligan: The land extent of the island is about 109 ha where 80% of the land use can be identified as thick vegetation. Based on the tested WQ samples, there were no excessively high values of tested parameters in any land use. Perception of people on “safeness of GW for daily uses” and “quality of GW” shows positive feedback scoring above 68% agreed percentage. Freshwater volume is 149,548 m³ and the present groundwater extraction rate estimated based on survey data is 101,422 m³ per year and this exceeds the allowable Safe Yield in the island by 109%. The relative hydraulic conductivity of the island lies in the ‘Semi-pervious’ state while the present aquifer condition remains at ‘Poor’ – ‘Good’ state. Moreover, general status based on transmissivity ranged from ‘Very High’ to ‘High’ and the potential for groundwater recharge remains ‘Low’ – ‘Moderate’ as per the estimations.

Ha. Molhadhoo: The land extent of the island is about 109 ha where 78% of the land use can be identified as thick vegetation and there are farm lands on an extent of 1.75 ha. Based on the tested WQ samples, there were no excessively high values of tested parameters in any land use. Perception of people on “safeness of GW for daily uses” and “quality of GW” shows positive feedback scoring above 96% agreed percentage. Freshwater volume is 211,487 m³ and the present groundwater extraction rate estimated based on survey data is 59,315 m³ per year and this is about 47% of the allowable Safe Yield in the island. The relative hydraulic conductivity of the island lies in the ‘Semi-pervious’ state while the present aquifer condition remains at ‘Poor’ – ‘Good’ state. Moreover, general status based on transmissivity ranged from ‘Very High’ to ‘High’ and the potential for groundwater recharge remains ‘Low’ – ‘Moderate’ as per the estimations.

Evaluation of Hydraulic Properties of Investigated Islands

A comparison of estimated hydraulic conductivity of the islands was carried out as per Bear (1972) and transmissivity of the formation was compared as per Krany (1993). The distribution of hydraulic conductivity and transmissivity of the islands are given below.

Hydraulic conductivity (cm/s)	10 ²	10	1	10 ⁻¹	10 ⁻²	10 ⁻³	10 ⁻⁴	10 ⁻⁵	10 ⁻⁶	10 ⁻⁷	10 ⁻⁸	10 ⁻⁹	10 ⁻¹⁰
Relative hydraulic conductivity	Pervious				Semi-Pervious				Impervious				
Aquifer condition	Good				Poor				None				
Islands													
Filladhoo	 0.00054-0.00446												
Maarandhoo	 0.00334-0.00672												
Uligan	 0.00358-0.0106												
Molhadhoo	 0.0089-0.0248												
Muraindhoo	 0.000513-0.0174												

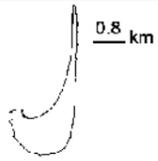
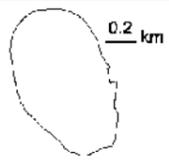
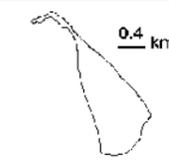
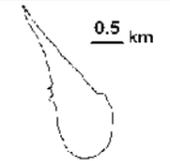
Therefore, all the five islands lie in the range of “Semi-pervious” based on the Relative hydraulic conductivity while they show “Poor” to “Good” Aquifer conditions. Moreover, as shown below, the Transmissivity show “High” to “Very High” conditions.

Transmissivity (m ² /d)	>1000	1000-100	100-10	10-1	1-0.1	<0.1
General Status	Very high	High	Intermediate	low	Very low	impermeable
Islands						
Filladhoo		High (328-440)				
Maarandhoo		High (509-769)				
Uligan		High (440-786)				
Molhadhoo	Very high to high (691-4752)					
Muraindhoo	Very high to high(432-1036)					

The vertical hydraulic conductivity of surficial deposits and other strata in a recharge area of the aquifer determines the volume of recharged water capable of moving downward into the aquifer from the recharge pits, diverted or accumulated drainage paths, ponds, etc., and the transmissivity of the aquifer and potentiometric gradient determine how much water can move away from the recharge area. Therefore, the optimal conditions for recharge are produced when the hydraulic conductivity of the aquifer lies in the Good region and the transmissivity is limited to Intermediate to Low.

A complete summary of island characteristics and observed/measured geo-physical and hydraulic parameters are presented below.

Summary of Island Characteristics and Observed/Measured Geo-physical and Hydraulic Parameters

Atoll	Haa Alifu	Haa Alifu	Haa Alifu	Haa Alifu	Haa Alifu
Island	Filladhoo	Maarandhoo	Muraidhoo	Uligan	Molhadhoo
Shape of the Island					
Latitude	6°52'31"N	6°51'7 "N	6°50'16"N	7°5'0" N	7° 00'42" N
Longitude	73°13'45"E	72°59'3"E	73°10'0"E	72°55'36"E	72°59'52" E
General Overview of the Island and Demography					
Area (Ha)	207.08	42.91	48.10	109.06	119.50
Length (m)	2,980	1,090	1,010	2,420	2,700
Width (m)	1,570	530	600	780	890
Distance to Male (km)	300	302	297	328	318
Population	1,144	1079	909	547	401
Pop. density (per /hectare)	5.52	25.15	18.90	5.02	3.36
Land Cover and Built up Area (As a percentage of total land area)					
Roof area (%)	3.20 ha (1.5%)	2.94 ha (6.9%)	3.01 ha (6.3%)	3.48 ha (3.2%)	1.75 ha (1.5%)
Thick Vegetation (%)	156.37 ha (75.5%)	25.39 ha (59.2%)	29.93 ha (62.2%)	88.21 ha (80.9%)	93.64 ha (78.4%)
Thin Vegetation (%)	5.05 ha (2.4%)	8.61 ha (20.1%)	3.24 ha (6.7%)	1.35 ha (1.2%)	2.71 ha (2.3%)
Bare lands (%)	40.24 ha (19.4%)	5.96 ha (13.9%)	11.93 ha (24.8%)	12.36 ha (11.3%)	19.66 ha (16.4%)
Farm lands (%)	0.00 ha (0.0%)	0.00 ha (0.0%)	0.00 ha (0.0%)	1.23 ha (1.1%)	1.75 ha (1.5%)
Socio-economic Condition					
Number of Households	148	144	98	72	68
Number of institutions	7	9	7	6	5
Perception on "use of GW for daily uses is safe"	47% - Agree 52% - Disagree	92% - Agree 4% - Disagree	59% - Agree 26% - Disagree	68% - Agree 22% - Disagree	96% - Agree 2% - Disagree
Perception on "quality of GW for is good"	41% - Agree 52% - Disagree	86% - Agree 6% - Disagree	39% - Agree 51% - Disagree	68% - Agree 16% - Disagree	98% - Agree 2% - Disagree
Present Sanitation and Water-use Characteristics					
Presence of Sewer Network	No	Under Construction	Yes	Under Construction	Under Construction
Presence of Water Supply	No	Under Construction	Under Construction	Under Construction	No
Households with RW tanks	98%	100%	99%	97%	95%
Rainwater use for drinking	99%	84%	97%	98%	74%
Rainwater use for cooking	100%	88%	100%	100%	98%
Groundwater as a drinking source	0%	1%	0%	0%	0%
Groundwater use for cooking	0%	7%	0%	0%	0%
Groundwater use for non-potable use	100%	98%	96%	100%	98%
Water Quality Aspects (Selected Parameters; please refer to respective chapters for other details and data)					
Elect. Conductivity (µS/cm)	687.14 ± 422.13	1625.08 ± 791.95	1496.69 ± 1268.27	572.65 ± 371.97	572.06 ± 346.44
Ammonia (mg/L)	0.47 ± 0.86	0.20 ± 0.37	0.81 ± 2.19	0.14 ± 0.09	0.16 ± 0.06
Faecal Contamination	Yes	Yes	Yes	Yes	Yes
Groundwater Availability, Usage, Water Balance and Recharge Potential					
Freshwater Lens Volume (m ³) & Thickness (m)	207,859 0.64 ± 0.91	58,262 1.13 ± 1.13	68,152 1.33 ± 1.27	149,548 2.90 ± 0.83	211,487 1.18 ± 1.19
Rainwater Harvesting (m ³ /year)	1,890	1,734	1,217	1,236	0,810
Groundwater Extraction (m ³)	94,101 /yr (257.8 /day 1.7 /day/HH)	108,422 /yr (297.0 /day 2.1 /day/HH)	91,526 /yr (250.8 /day 2.6 /day/HH)	101,944 /yr (279.3 /day 3.9 /day/HH)	59,315 /yr (162.5 /day 2.4 /day/HH)
Available Overland Flow (m ³ /year)	676,178	189,493	206,740	374,038	390,949
Safe Yield M1 & M2 (m ³ /day)	485 & 993	128 & 206	143 & 231	255 & 523	346 & 573
Usage / Safe Yield (%)	53% & 26%	232% & 144%	175% & 109%	109% & 53%	47% & 28%
Relative hydraulic conductivity	Semi-pervious	Semi-pervious	Semi-pervious	Semi-pervious	Semi-pervious
Present Aquifer Condition	Poor	Poor	Poor	Poor - Good	Poor - Good
Potential for GW Recharge	Low - Moderate	Low - Moderate	Low - Moderate	Low - Moderate	Low - Moderate

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 are administratively grouped into 26 atolls spread over an area of 90,000 km² stretching over 760 km in length (from north to south) and 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 the 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) and Land and Marine Environmental Resource Group Private Limited (LAMER, Maldives) 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 baseline assessment surveys undertaken in the following five (05) islands.

1. Ha Filladhoo
2. Ha Maarandhoo
3. Ha Muraidhoo
4. Ha Uligan
5. Ha Molhadhoo

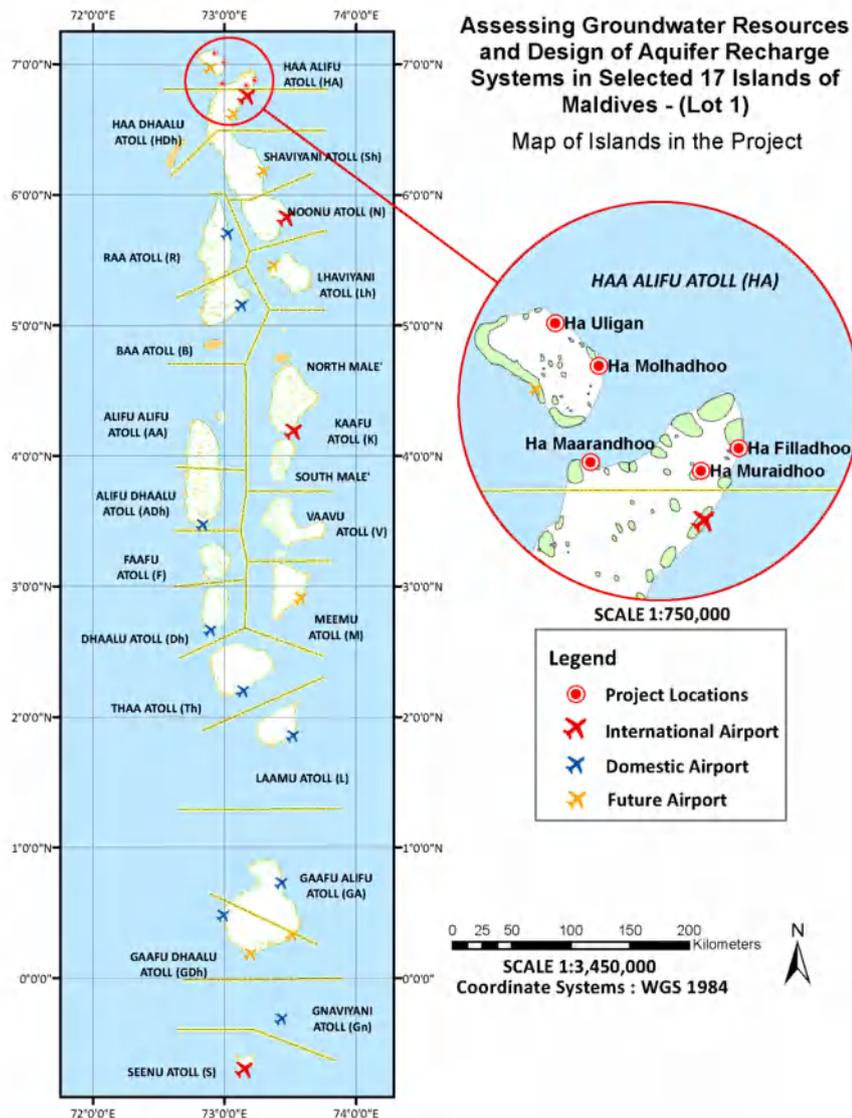


Figure 1-1: Location Map of Selected Six islands in Lot 1

1.3 Structure of the Report

The report has been structured into three broad categories.

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

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

Thirdly, the report outlines the findings of the surveys in the islands. For each island, the following information will be provided.

- General overview of the island including location and geography
- Geology and vegetation
- Topography
- Climate
- Demography
- Socio-economic condition and findings from the Institutional surveys
- Existing water and sanitation situation
- Results of the Baseline Surveys
 - o Water sources and water use
 - Domestic water use situation
 - Commercial water use situation
 - Institutional water use situation
 - o Groundwater quality
 - o Geophysical surveys
 - o Aerial surveys
 - o Freshwater lens
 - o Water demand
 - o Water balance and recharge
 - o Sustainable yield of the lens
 - o Ground permeability
 - o Steady pumping test results
 - o Groundwater availability
- Conclusive Remarks and Recommendations

The findings of the Baseline Assessment Report(s) will provide essential background and existing condition data for the subsequent studies and Managed Aquifer Recharge (MAR) designs as prescribed under Specific Objectives b) and c) in Section 1.2 above.

1.4 Methodology of Data Collection

The baseline surveys were undertaken by visiting each island to gather all the required data as outlined in the TOR.

In each island, eight (8) different types of surveys (investigations) were undertaken. They are;

- 1) Groundwater assessment (Physiochemical and microbiological tests for groundwater quality).
- 2) Geo-physical surveys (Depth to the groundwater table, Depth to the freshwater-saline water interphase to estimate thickness of the freshwater lens based on collected Electrical Resistivity (ER) data)
- 3) Socio-economic surveys (Household/Institutional surveys with water usage survey to establish Water demand and recharge-depletion pattern and meetings with the Local Councils to assess the Existing water use, Recharge, Flood extent/frequency data, Present impacts on the freshwater lens and the Quality of other water sources, etc.)
- 4) Rainwater catchment and infiltration survey (To establish natural recharge and drainage pattern)
- 5) Topographic surveys and UAV Mapping (Contributory catchment identification to estimate rates of groundwater recharge and discharge)
- 6) Groundwater level survey (To monitor groundwater table depletion and study aquifer water balance and depletion-recovery)
- 7) Soil permeability tests and Soil profiling (To estimate infiltration and recharge characteristics)
- 8) Steady pumping tests (To recognize well drawdown and recovery and aquifer parameters)

The following sections outline the detailed methodology of how the above surveys and data collection procedures were undertaken in the field or on each island.

1.4.1 Groundwater well survey – (Physiochemical and Microbiological)

The scope of the assessment required the collection of data on the physiochemical and microbiological status of groundwater. Thus, in each of the islands, groundwater quality was tested for the selected physicochemical parameters outlined in the TOR.

The aim of the survey was to provide a structured and consistent approach to collect data on the existing quality of groundwater in each island covering in its entirety. Since each household, mosque and in most cases, institutions had shallow dug wells where groundwater can be sampled and tested, this was the preferred method to test the water quality. In islands where there are large vegetated areas or barren land with no wells, groundwater was extracted by digging a small hole and extracting the water using a manual pump. Digging was undertaken using a fuel driven mechanical auger.

1.4.1.1 Sampling methodology

For the physicochemical survey of the groundwater, as per the TOR, a minimum of 40 or a representative adequate number of samples should be collected for all physiochemical tests and 15 or a representative adequate number of samples should be collected for all microbiological tests. Population, housing and land use for various activities are not evenly distributed throughout the island, making this method unpractical and biased. Some islands have large unused/undeveloped areas with tree cover segregated from the main residential areas. Other islands are more saturated with houses evenly distributed throughout the island. Hence, testing water from existing wells only would not provide a complete picture of the groundwater quality of the entire island. The proximity of contamination sources such as septic tanks would affect the quality of groundwater in localized areas. Type of land usage, amount of water extraction from the ground, type of plantation in the area, proximity to the shoreline, etc. are all factors which could affect the quality of groundwater in localized areas in each island. Therefore, sampling locations were selected in a way to represent the whole island with various land use areas.

Sampling was undertaken from pre-determined random points throughout the island (refer to the results section of each island that includes the sampling locations). Selecting sampling points in this manner ensured that the entire island's groundwater quality was evenly represented.

The sampling points were selected keeping in mind the following factors:

- Stratified random sampling points throughout the island to cover the entire aerial extent,
- Sampling points were proximal to where the ER surveys have been undertaken for comparison,
- Cross-sectional profiles of the island to the extent of the shoreline vegetation, and covering
 - Residential areas,
 - Agricultural areas,
 - Industrial areas
 - Forest type vegetated areas,
 - Barren lands, and
 - Areas of other specific land use (existing reclamation, newly reclaimed, industrial areas, etc.)

1.4.1.1.1 Parameters tested

The following physiochemical parameters were measured for each island:

- Temperature (°C)
- pH
- Salinity (mg/L)
- Electrical Conductivity (EC) ($\mu\text{S}/\text{cm}$)
- Dissolved Oxygen (DO) (mg/L)
- Turbidity (NTU)
- Ammonia (mg/L)
- Nitrate (mg/L)
- Phosphate (mg/L)

The electrical conductivity measurements were used to determine the areal extent and depth spread (depth to freshwater-saline interphase) of the freshwater lens. For the survey, the practical limit of EC for freshwater was considered to be 2,500 $\mu\text{S}/\text{cm}$, which approximately correlates to a concentration of 600 mg/l Cl, a salinity of which has a discernible salty taste (GWP).

The sampling was conducted such that the whole island was covered and a detailed overview of the groundwater quality and quantity of each island was obtained. The minimum requirements of the physiochemical and microbiological studies as per the TOR are as follows:

- o Physiochemical: The following parameters were tested for each island: pH, Dissolved Oxygen (DO), Electrical Conductivity (EC), Turbidity, Temperature, Salinity, Ammonia, Nitrate, and Phosphate (at least 40 samples per island, from existing groundwater wells)
- o Microbiological: The following parameters were tested for each island: Total coliform and Faecal coliform (at least 15 samples per island, from existing groundwater wells)

Samples for laboratory testing were collected using properly decontaminated and labelled High Density Poly Ethylene (HDPE) sampling containers or Standard Thio-bags. Samples were preserved as required and stored at 4 ± 2 °C until they were transported to the laboratory for testing.

All groundwater samplings and water quality testing were conducted following the standard methods as stipulated by US EPA Standards and Guidelines for Groundwater Sampling (US EPA, 2013); ASTM D4448: Standard Guide for Sampling Ground-Water Monitoring Wells (ASTM, 2007/2019).

1.4.1.1.2 Equipment used

The following methods and equipment were used for water quality sampling and testing purposes.

1.4.1.1.2.1 Equipment for sampling

A mechanical earth auger drill was used to drill holes deep enough to obtain the groundwater from areas where there were no dug wells, such as non-residential and vegetated areas. The holes drilled had a diameter wide enough to obtain water through, either by a pipe or a pump (~ 10 cm - 15 cm). In situations where the auger could not be used, the hole was dug manually using a spade or hand auger.

1.4.1.1.2.2 Instruments for water quality testing

Temperature, pH, salinity, DO, EC and turbidity have been tested in-situ using Hanna Multiprobe Test Meter (HI 9829). Hanna Multiprobe has been calibrated using the calibration solution prior to commencement of testing (each day or as necessary). The quick calibration solution was used to calibrate all physical parameter sensors.

Chemical parameters (Ammonia, Nitrate and Phosphate) have been analysed through the Water Quality Assurance Laboratory (MWSC) or National Health Laboratory (NHL) of Maldives Food and Drug Authority (MFDA).

1.4.1.2 Sampling methodology – Microbiological surveys

To understand the severity and extent of microbiological contamination of the groundwater, Total coliform and Faecal coliform were measured at selected sampling locations for each island. Similar to the physical parameters, sampling was undertaken from household wells and wells at identified institutions/locations.

Unlike the physiochemical surveys, the number of samples tested for microbiological contamination was less and the locations concentrated more on the residential areas due to higher risk.

Water samples were collected and labelled in Standard Thio-bags for the coliform tests. Samples were kept in dry ice until delivered to the laboratory for testing. Coliform and faecal coliform tests were performed at Male' Water & Sewerage Company Pvt. Ltd. (MWSC) after transferring the bottles to Male' within 24 hours. The samples were transferred in a cool box. Ideal temperature for the sample to be stored is between 4 and 10 degrees Celsius and hence, this temperature was maintained throughout its transit. The details of test procedures are briefly explained below and a summary is provided in Table 1.1.

Table 1.1: Summary details of Physiochemical and Microbiological parameters measured

Physiochemical Parameters				
Parameter	Test Method	Unit	MDL	Reference
pH	In-situ Multi-probe	Standard Units	0.1	HI 9829
DO	In-situ Multi-probe	mg/L or %	±0.1 mg/L	HI 9829
EC	In-situ Multi-probe	mS/cm	±0.5%	HI 9829
Turbidity	In-situ Multi-probe	NTU	±2.0%	HI 9829
Temperature	In-situ Multi-probe	°C	±0.2°C	HI 9829
Salinity	In-situ Multi-probe	mg/L or ppt	±0.1	HI 9829
Ammonia	In-situ Multi-probe	mg/L as N	0.01 mg/L	HATCH method
Nitrate	In-situ Multi-probe	mg/L as N	0.01 mg/L	HATCH method
Phosphate	Laboratory	mg/L as P	0.01 mg/L	HATCH method

Microbiological Parameters				
Parameter	Test Method	Unit	MDL	Reference
Total coliform	Laboratory	MPN/100 mL		MWSC Lab
Faecal coliform	Laboratory	MPN/100 mL		MWSC Lab

1.4.1.2.1 Data entry

Groundwater sampling locations have been mapped by recording the house/plot names or if in an open area, by using GPS coordinates. The GPS coordinates of the plots have been derived from the survey map. The resultant data has been tabulated for entry into a GIS database as given below. Since some of the water wells are expected to be covered by the roof, the estimated location with the plot has been derived by measuring offsets from walls. The name of the house or data point has been entered into the filename of the water test meter (Logger HI 9829).

Each point had a set of attributes including all the parameters to be tested as well as the name of the house/institution/place. At each sampling point, water quality data has been entered as attribute values on-site, minimizing manual data recording.

1.4.1.2.2 Quality assurance

Quality assurance during the groundwater well survey minimized the uncertainties during data collection and provided accurate and unbiased results. Below is a list of quality control measures that were followed during the survey.

- 1). The water quality equipment was calibrated before use.
- 2). When existing wells were sampled, the probe was directly dipped in the water for measurements. Probe was immersed in mid water to ensure that the water being tested was an accurate representation of well conditions.
- 3). If water was drawn from a well using a pump or other means, it was carried out using a clean container and the sensors were washed at least twice with the sample water.
- 4). The sensors were immersed in the water completely.
- 5). While testing, recordings were taken after the reading stabilized.
- 6). At least two readings were recorded from each well as a cross-check measure.

For microbiological parameters:

- 1). Hands were thoroughly washed before collecting samples.
- 2). If the sample was drawn from a dug well, a clean container was used to draw water.
- 3). The rinsing of Thio bags with sample water was avoided as this would remove some or all of its preservatives and ruin the sample.
- 4). Touching the inside or the lip of the sampling bag was avoided, to ensure the sample does not get contaminated.
- 5). The bag was tightly sealed immediately after collecting enough water.

1.4.2 Geophysical surveys

1.4.2.1 General background

For developing groundwater conservation strategies and aquifer management plans, it is crucial to estimate the extent and volumes of the freshwater lens in the islands. The TOR further stipulates the requirement for assessing the present impacts on the freshwater lens and the quality of other water sources. The freshwater lens configuration was evaluated by using electrical conductivity (or resistivity) data while groundwater levels, topographical and geological features were also discussed in the detailed evaluation process. Further during this process, the thickness of the freshwater lens was required to be assessed in the field by measurements and it was further verified by providing reasons. Thickness of the groundwater aquifer in the islands depends on the net rainfall recharge, size of the island and permeability of the soil column and required data for verification was collected during the course of the project (twice during the water quality measurements and at the time of geophysical surveys; i.e. towards the end of the dry period and end of the wet period, respectively).

In addition, these baseline conditions related to presently existing groundwater resources at individual islands were properly established in order to have a better insight into the rates of groundwater recharge and discharge, as well as targeting assessment of potential improvements due to implementation of proposed interventions in future under the present study. The quantitative volumetric estimates of the groundwater resource availability were derived based on the identified extents and thickness of the freshwater lens following Electrical Resistivity (ER) surveys as described below and verified with the help of existing literature and generated maps which were produced using available data and the other supplementary data collected during the course of the present study. These established baseline conditions will help develop groundwater extraction/recharge monitoring protocols and other groundwater and aquifer management strategies and methodologies to be developed following the water balance approach or numerical modelling to simulate the behaviour of the freshwater lens in each island.

1.4.2.1.1 Selection of methodology

Geophysical methods for groundwater exploration (mainly, Electrical Resistivity or ER) methods based on conductance and Electro-Magnetic (EM) methods based on penetration/reflectance) are useful for providing relatively quick and cheap assessments of freshwater lens locations, extents and thicknesses. Both ER and EM methods have been widely applied in groundwater explorations under different conditions. However, the results from ER and EM surveys are subject to differing interpretations and require independent calibration to be used with confidence.

The emerging EM methods are based on the electrical properties of sub-surface layers while it overcomes the problem of establishing good galvanic (electrical) contact between the source of current and (earth) media, such as encountered in resistivity measurements. This enables the use of airborne EM technologies which are relatively faster and easier in application over wider areas. With presently available helicopter-borne and drone mounted sensors, groundwater studies can be designed to obtain a high resolution three-dimensional (3-D) view of the internal resistivity structure. However, the choice of method is entirely dependent on the availability of time and funds and the degree of accuracy required. Further, the relatively small dimensions and extents of the islands involved in comparison to the ranges of detectable depths (Fig. 1-2) and the specific need for differentiating saline groundwater from fresh groundwater to identify saline-freshwater interphase to detect lens thickness in this project exclude the use of EM methodologies in the present study. The ER based equipment and methodologies have been adopted in the first part of the project focusing on the assessment of baseline conditions in selected 13 islands (Min Env, 2020).

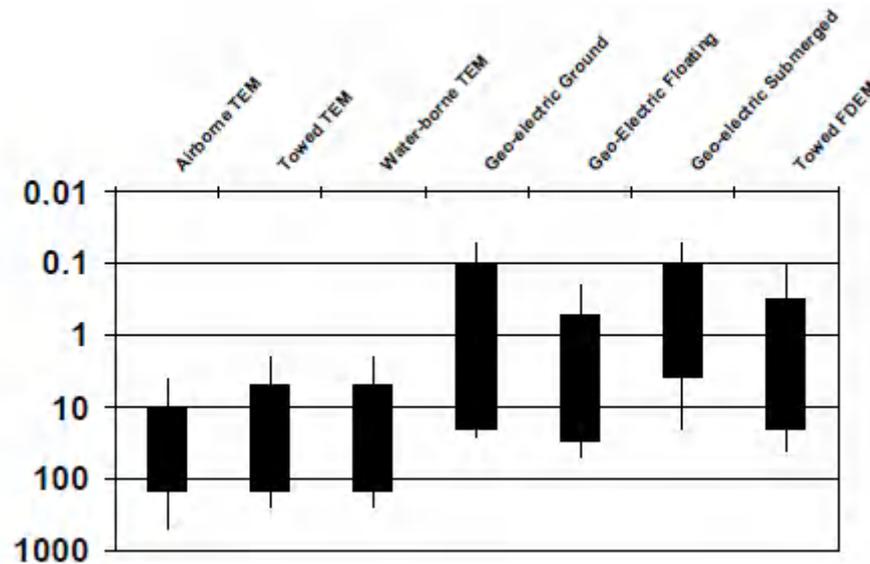


Figure 1-2: Ranges of detectable depths of various ER/EC imaging devices (in metres). Note that airborne FDEM (not shown) has a range similar to but shallower than airborne TEM (Source: Allen, 2007)

On the contrary, Electrical Resistivity (ER) based methods can be effectively used to estimate depth to groundwater table as well as to delineate saltwater and freshwater interphase. With proper survey design with ER methods, 2-D as well as 3-D pictures of the subsurface profiles can be obtained. The ER surveys are normally conducted in conjunction with a drilling program to assess freshwater lens locations and thicknesses on atolls and sand islands, however, in Maldives Islands, drilling is not viable due to the unavailability of required heavy machinery and equipment for drilling and/or excessive mobilizations costs. Therefore, the possibility of utilizing water level records from existing dug wells in household/community/institutional premises was considered and verified during pilot tests and adopted for the rest of the study.

For the past studies, pilot tests had been carried out in three selected islands with the assistance of the Earth Resources Engineering Department of University of Moratuwa, Sri Lanka to assess the capability of ER and EM approaches for effective assessment of freshwater lens (FWL). Further, the technology service providers Geonics, SkyTEM were also consulted to establish the most suited ER/EM based application while additional information was referred from the available literature.

Based on further considerations and following pilot tests carried out, the ER based method was selected as the most suited application for identifying and mapping of FWL in selected atoll islands.

1.4.2.1.2 Methodology for ER Based Pilot Tests

The methodology for the ER based pilot tests carried out in selected three islands from 28th February to 05th March 2019 is elaborated as follows.

Geophysical Investigation (Resistivity Survey)

A resistivity survey was carried out on the selected available land section of the Maldives Islands. The ER survey was conducted following a pre-determined set of transverse transects identified based on GIS and UAV maps considering representative land use, accessibility, close proximity to existing dug wells for verification purposes and to adequately comprehend the extents of groundwater layer in the form of the freshwater lens. Therefore, a selected representative number of locations along these pre-identified transects were surveyed to properly understand the depth to groundwater level and the freshwater-saline water interface. Existing unpaved gravel or sandy road traces where possible were selected in the present study for aligning the transects due to easy accessibility to the points.

Resistivity surveying methods available

Generally, resistivity values of geological materials show a wide range varying from $10^{-1} \Omega\text{m}$ to $10^7 \Omega\text{m}$. Moreover, the resistivity range of any given formation can be wider and may overlap with that of other formations. The resistivity of a particular site can vary due to several factors such as properties of the water, soil moisture, temperature, nature of the subsurface material, decomposition level, depth, textural features of different strata, etc. In any given site, the subsurface is not uniform and always shows heterogeneous conditions both laterally and vertically. Therefore, background data and information are collected from the available reports, core log records, and field observation before the field investigations. Types of soil/wastes, thicknesses, the orientation of geological bands, groundwater conditions, man-made structures and climatic conditions of the site are used to plan the layout or outline of resistivity surveys to obtain more realistic values to yield an equivalent model for the electrical performance of the earth.

There are several standard electrode configurations used in resistivity surveys such as the Wenner array and Schlumberger array. The Wenner array is mostly used for profiling to investigate the lateral resistivity variation whereas the Schlumberger array is used for vertical profiling. Schlumberger array is the method used in this study. Figure 1-3 shows the two different electrode arrays.

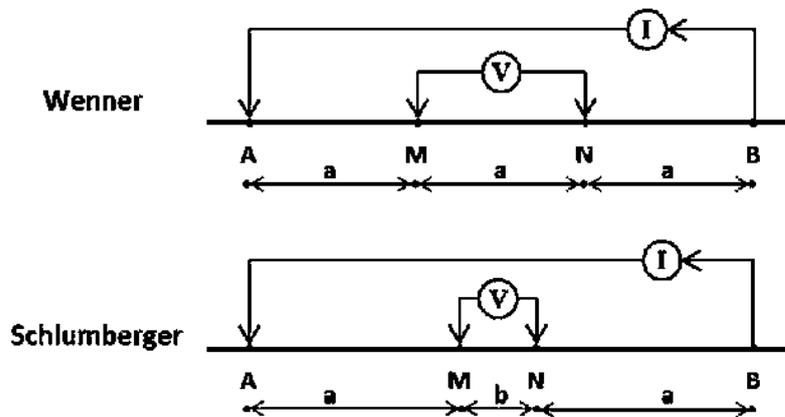


Figure 1-3: Electrode configurations -- Wenner and Schlumberger Arrays (Garofalo, 2014)

Electrode spacing and measurement of test reading

The current and potential electrode spacing used in the field measurements are given in the following table (Table 1.2).

Table 1.2: Electrode Spacing for Schlumberger Array (Vertical Electrical Sounding)

AB/2 (m)	MN/2 (m)	Apparent resistivity (Ωm)
1.5	0.5	Measured in the field
2.1	0.5	
3.0	0.5	
4.4	0.5	
6.3	0.5	
9.1	0.5	
13.2	0.5	
13.2	0.5	
19.0	0.5	

Interpretation of field resistivity data

The field resistance data collected at each electrode spacing was converted to the apparent resistivity using Equation 1 for the Schlumberger array.

$$\rho_a = \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \pi \left(\frac{V}{I}\right) \dots\dots\dots(\text{Equation 1})$$

Note: Apparent Resistivity (ρ_a), Current electrode spacing (AB), Potential electrode separation (MN), Field resistance(V/I).

Standard curve matching and computer modelling along with 1-D/2-D/3-D visualization software with geographic information system (GIS) interphase were used for the interpretation of field sounding curves.

Equipment for the resistivity survey

An ABEM Terrameter (Model SAS 1000) and an IRIS Resistivity Instrument (Model SYSCAL Pro) were used to carry out the islandwide ER surveys in selected atoll islands.



Figure 1-4: Electrical Resistivity (ER) equipment used for the field pilot tests (Sources: Left - ABEM Terrameter LS 2 - User Manual, 2017/ Center, Right - Siqueira Neto & Elis)

1.4.3 Socio-economic surveys (Water-usage survey)

A social or public survey at the island community level was carried out to understand the water usage for different purposes, emphasizing groundwater usage in households, tourism, agriculture, fisheries and other economic sectors of the islands. The communities’ perception of the existing condition of groundwater and support information regarding flooding issues experienced on the island have been assessed during the survey. The results of the surveys have mainly been used to determine the generalised quantification of groundwater usages for different uses for the design of aquifer recharge systems and flood mitigation approaches. The usage was quantified by estimating the volume of groundwater used for various purposes. This was determined based on the method of water extraction practiced in households. For example, if they use taps connected to the well, the water extraction pressure of the pump and the estimated time spent running the tap can be used to calculate an estimated volume. The survey interviews included questions that could assist in carrying out the estimations.

1.4.3.1 Sampling methodology

The sampling was carried out at different levels. This includes identification of water usage at;

1. Household-level,
2. Commercial outlets (café’s/restaurants/guesthouses),
3. Industrial activities (agricultural lands/fish processing centres/others)
4. Institutions (schools, health centres, council, other administrative buildings, etc.)

A Stratified-random sampling method has been used to derive the samples where the sample size was determined at a 95% confidence interval.

Table 1.3 below gives the sample size for the household surveys that have been carried out in the selected five (5) islands of Lot 2.

Table 1.3: Sample size for the household surveys in the islands

Island	Total Number of Households	Sample Size at 95% Confidence Interval	Completed Sample Size	Margin of Error (%)
Ha. Muraidhoo	98	79	78	5
Ha. Filladhoo	148	108	82	5
Ha. Molhadhoo	68	58	58	5
Ha. Uligan	72	61	62	4.7
Ha. Maarandhoo	144	105	96	5

Note: In the case of Ha. Uligan, one additional survey was completed and the data was included in the analysis as it will improve the accuracy of the results

1.4.3.2 Survey methodology

The surveys have been conducted using structured questionnaires. The key areas that were covered in the surveys as per the TOR include:

- Groundwater usage in households (estimates of the quantity of groundwater used per day for various uses (such as drinking, bathing, washing clothes and dishes, flushing toilets, watering plants etc.)
- Perception on groundwater accessibility and quality
- Flooding depths, frequency and causes (this was collected as supporting information to the information collected from the Island Councils)

Given the COVID-19 situation, the surveys have been carried out with the help of enumerators selected from the island communities. A robust sample frame has been obtained to successfully carry out the survey. Enumerators were hired from the island communities and trained to carry out the surveys. The training was conducted in an online session with Google Meet and other platforms based on the convenience of the enumerators. An effort was made to provide equal opportunity for both genders in selecting the enumerators. The training was mainly focused on the following aspects:

- Basic etiquette tips in carrying out a household (HH) survey
- Explain the objective of the survey and the objectives of each question
- Familiarise the enumerators with the questionnaires
- Mock interviews to test interviewing skills of enumerators
- Familiarisation with Google Forms and data entry
- A thorough discussion of the objectives of the survey as well as the objectives of each question was explained during the training process.

1.4.3.3 Data entry and analysis

Data collection was carried out using Google Forms. Once the data collection was completed, the data set was extracted to Microsoft Excel and calculations were performed for individual islands. For each individual island, data for the four (4) categories of water uses were analysed separately. The water usage estimates were calculated based on internationally applied flow rates.

1.4.3.4 Challenges, limitations and mitigation measures adopted

During the data collection process, the survey teams experienced a number of challenges and limitations and the following measures were taken to mitigate the challenges and to ensure the quality of the data collected. The following Table 1.4 summarizes this information in detail.

Table 1.4 Challenges, Limitations and Mitigation Measures during Surveys Conducted

Challenges and Limitation	Details	Mitigation Measures Adopted
Inaccuracy in the sample frame provided by the councils	The councils in each island were requested to provide lists of households, institutions, businesses and the number of people engaged in different business activities in the island. Some of the lists received from the councils were proven as inaccurate during the data collection process. Some councils were also not able to provide the requested data.	The enumerators attempted to correct and update the lists as much as possible
Refusals	Some respondents selected for the survey refused to take part in the survey.	Replacement samples were drawn to achieve the targeted sample as much as possible
Vacant Houses	Some households in the sample were discovered as vacant	Replacement samples were drawn to achieve the targeted sample.
Non-practicing registered farmers	Some of the registered farmers in the island were not practicing farming at the time of data collection. This includes those who have registered land plots for farming as well. Hence, the lists received from the councils did not provide an accurate number of farmers in the island and therefore the survey team was unable to reach the targeted sample which was taken from the lists provided by the council.	The enumerators attempted to correct and update the lists as much as possible and replacement samples were taken to reach the sample size as much as possible. However, due to the limited number of actual farmers, the total sample at 95% confidence level was not reached
Non-practicing fishing vessels and fish processing businesses	Some of the registered fishing vessels and fish processing businesses were not operational at the time of data collection. Hence, the list received from the council did not provide an accurate number of people engaged in these activities in the islands. Consequently, the survey team was unable to reach the targeted samples on these activities, which were taken from the lists provided by the island councils	The data collection team attempted to correct and update the list as much as possible and replacement samples were taken to reach the sample size as much as possible. However, due to the limited number of active businesses (or none in some cases) at the time of data collection, the total sample at 95% confidence level was not reached

Challenges and Limitation	Details	Mitigation Measures Adopted
Missing data in the completed survey forms	There were a lot of missing data in the completed forms, mostly due to respondents not being able to answer them accurately.	Enumerators were advised to probe respondents as much as possible to get an accurate response.
Issues with generalizing the data across some commercial and /or institutional activities as the activities varied in the nature of work and the level of operation	With regard to some commercial activities or institutional water usage, huge differences were observed in the volume of water used as the kind and level of operations varied. For example, there is a big difference in the amount of water used in the island courts compared to that of a health centre. Similarly, water usage in cafes varied based on their capacity and level of operation.	A total amount of water used is provided rather than per capita or average water usage in these activities.

1.4.3.5 Estimation of rainwater catchment/infiltration and runoff

The development of an aquifer management plan requires an understanding of rainfall, catchment characteristics of each island, catchment potential and estimation of infiltration and recharge as a percentage of rainfall for each island. According to Falkland (2000), approximately 30% of the rainfall will infiltrate into the groundwater aquifers as recharge and this has been used as a reasonable estimate in the Maldives and other similar small islands. Falkland also estimates 20% to be used if the area is heavily vegetated and 40% to be used if it is barren. In addition, the total roof area cover and how the water is discharged will be essential to calculate the water balance.

The aggregate runoff coefficient was taken to estimate the overland flow and the following runoff coefficients were considered.

Table 1.5: Considered runoff coefficients for land use type (Source: Tsutsumi et al., 2004)

Land use (type of ground surface)	Runoff Coefficient
Roof cover	0.90
Vegetation	0.15
Bare lands	0.30
Farm Lands	0.20
Roads	0.50
Playground	0.70
Wetlands	0.70

Based on the above facts, it is therefore important to estimate these required values. To estimate the aforementioned factors, Unmanned Aerial Vehicle (UAV) surveys were completed for each island. Through the use of UAV surveys, many required variables for the study were calculated.

1.4.3.5.1 Establishment of Permanent Survey Marks (PSMs)

The PSMs have been established where necessary (project sites where PSMs are not registered at Maldives Land and Survey Authority - MLSA) as per the MLSA guideline of establishing PSMs. Three PSMs were cast on-site as per MLSA guideline (Type A PSM design), while the PSMs were spaced such that best triangulation is achieved (depending on availability of space). The PSMs were placed 10 cm below ground level as recommended in Control Survey Guidelines by MLSA. The PSMs horizontal coordinates were established using Topcon GNSS receivers using the static survey method with horizontal and vertical error within 10 mm. The data was processed using the Magnate Tools Office (TOPCON Inc., USA) software. The vertical level was established using predicted tidal data of the nearest tide station and established using the difference of ellipsoid height method (Figure 1-5 to Figure 1-7).

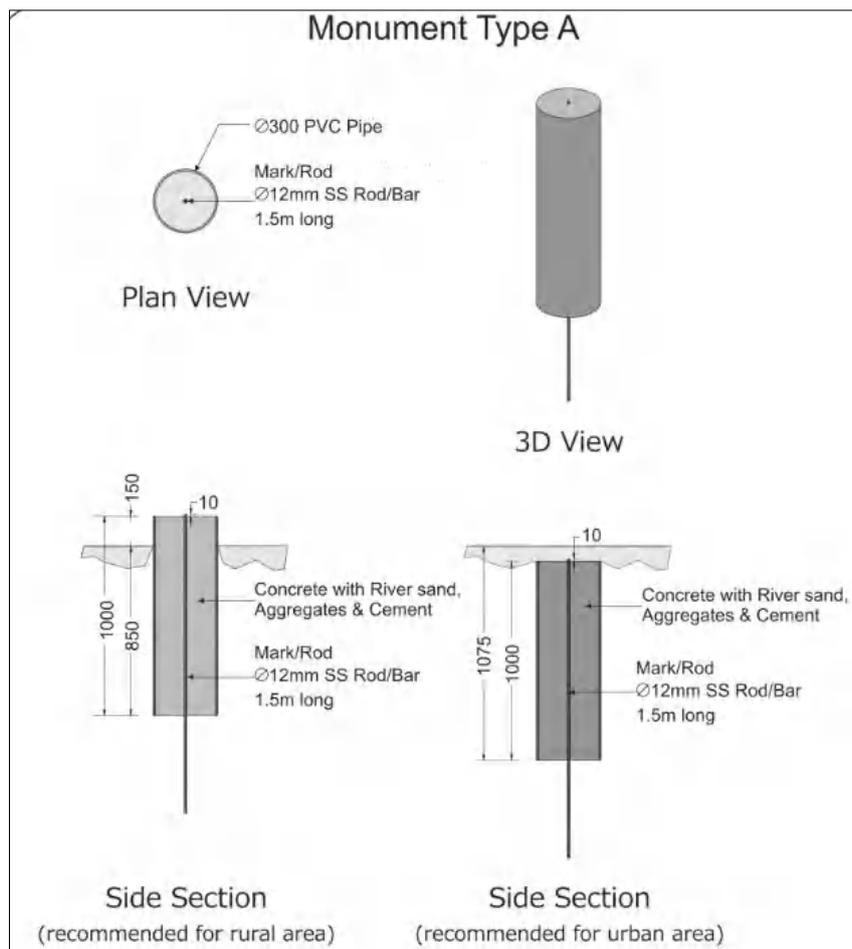


Figure 1-5: Type A PSM design (Source: Maldives Land and Survey Authority, Guideline on the Establishment of Permanent Survey Marks)



Figure 1-6: Example of PSM



Figure 1-7: Example of spacing of PSMs

Two PSMs were located such that both are intervisible to each other while the 3rd was located at a maximum available distance away from intervisible PSMs (and intervisible to both above) as illustrated in Fig. 1-7.

The static survey loop closure was set to a 1 cm error margin, and to attain this accuracy, static survey data was collected for a minimum of 6 hrs on each transect.

1.4.3.5.2 UAV survey

Unmanned Aerial Vehicle (UAV) survey was undertaken using DJI Phantom 4 RTK drone (DJI Inc., China/USA/Europe) with GNSS base station, using RTK correction. Mapping was undertaken at a constant 60 m altitude with reference to the ground with images overlapping at 75% at the front and 65% at the side. At islands with communication towers, flight elevation was decided based on the minimum safe flight elevation possible. Ground Control Points (GCPs) were established around the island (set such that maximum length and width is covered). The GCPs were established using Topcon GNSS receivers in RTK mode with errors fixed to 15 mm (Vertical and Horizontal). Depending on the size of the island, a minimum of 10 GCPs were used for processing the image and georeferencing.

The images captured have been processed using Drone Deploy online service (DroneDeploy business subscription) with GCPs. The final maps were exported in UTM coordinate system WGS 1984, Zone 43N. Further checks were carried out to verify the accuracy of Orthomosaic images with established GCPs (Fig. 1-8).

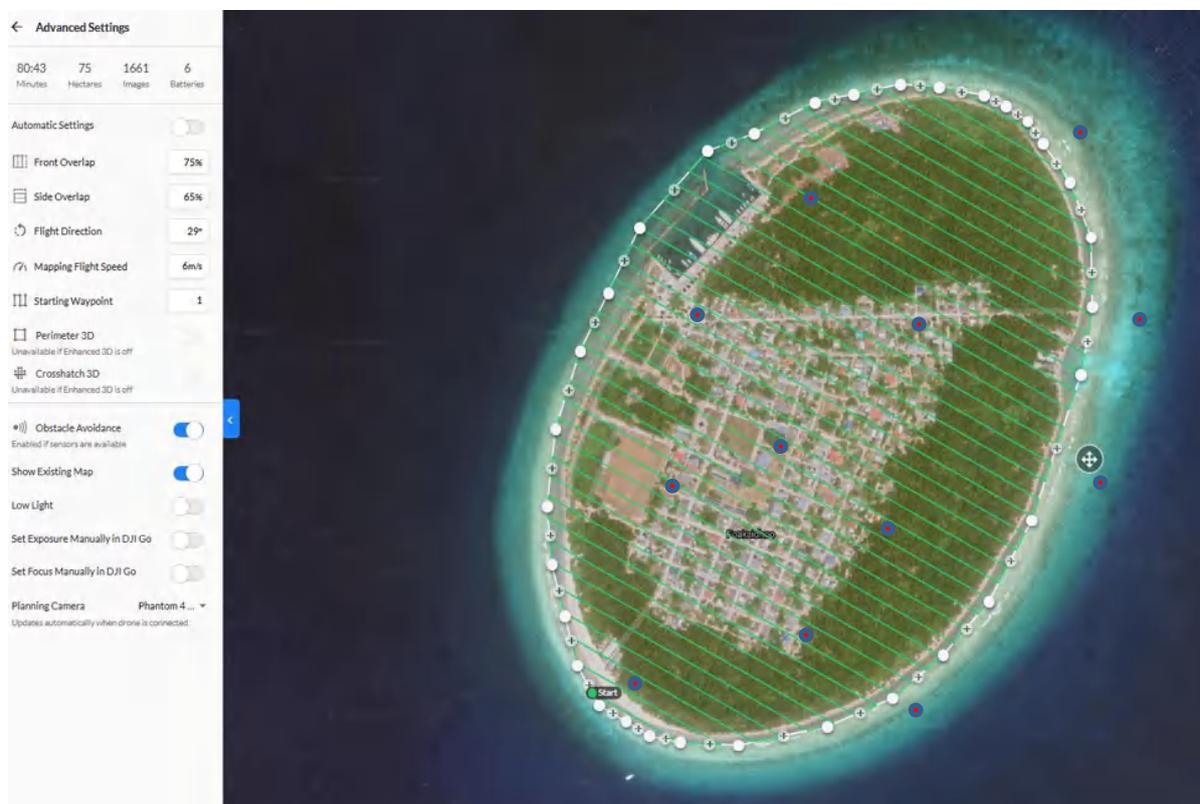


Figure 1-8: Example of a Flight Plan using Drone Deploy application and an example of spacing of Ground Control Points (GCPs) (red points) – Sh. Foakaidhoo Island.

1.4.3.5.2.1 Outputs from UAV mapping

The main outputs from UAV mapping are the Orthomosaic and Digital Surface Model (DSM). The Orthomosaic can be produced in very high resolutions at 2 cm per pixel. This data can be used in a GIS application to extract multiple data sets such as buildings, roof cover, roof aspect, land cover, change detection, shoreline, etc. The following image illustrates all the roof areas (in red) on an island extracted using a UAV survey (Fig. 1-9). The total roof areas can then be easily calculated without having to measure them individually from house to house. The results can be used to accurately estimate the rainwater catchment potential, how much water is discharged into the ground, etc.

Similarly, all empty areas, vegetated areas and other similar land use and terrain features can be extracted. These data will help hydrogeologists to accurately model rainfall-runoff and rainwater infiltration, and provide vital estimates on groundwater recharge.



Figure 1-9: Calculation of Roof Cover in an island using UAV survey in the Maldives (Ha. Uligan)

1.4.4 Present impacts on the Freshwater lens and Quality of other water sources

The assessment of the present impacts on the freshwater lens was carried out based on the findings of the geophysical surveys, social surveys and using water balance based groundwater modelling approach for the freshwater lens in each island, considering its present subsurface volumetric extent together with associate gains (recharge) and losses (discharge).

This procedure involves the use of measured Electrical Resistivity (ER) data to estimate depths to groundwater table and saline-freshwater interphase in each cross-section and along the longitudinal transect and the existing freshwater volume at the time of investigation can be extracted as the difference between the two respective subsurface terrain layers using ArcGIS software (ESRI, USA, ArcGIS/ArcMap version 10.8).

A robust modelling approach to estimate the volume of available groundwater in the freshwater lens in each island under steady-state conditions was developed based on the approach presented in ‘Method for estimating available groundwater volume of small coral islands’ by Bailey and Kivi (2017). Model inputs include average annual rainfall depth, island width for cross-sections along the ER transects and length of the island based on longitudinal ER transect, aquifer hydraulic conductivity, aquifer porosity, depth to the contact between the upper sand aquifer and the lower limestone aquifer (based on estimated depth to groundwater table and saline-freshwater interphase as per ER measurements). The required land use data including vegetation cover, road/bare-land/farmland/built-up area composition in each island were derived from the digitized land cover GIS maps and the impermeable layer extents and roof cover were extracted from high resolution UAV drone maps using Agisoft Metashape Professional image processing software.

The methodology proposed by Bailey and Kivi (2017) has been tested for nine islands of varying sizes in the Maldives and Micronesia during the course of the initial study (Min Env, 2020). According to the sensitivity analysis carried out in the study, the lens volume on large islands is typically governed by the depth to the discontinuity (freshwater-saline water interphase), whereas lens volume for smaller islands is governed by rainfall rate and hydraulic conductivity. Volume curves, which relate lens volume to lens thickness, have been developed for each of the nine islands studied and for three generic island shapes to allow rapid estimation of lens volume given field-estimated lens thickness and the methods presented in the study have been recommended for any small atoll island.

Instead of using the proposed empirical equations for the maximum freshwater lens thickness which depends on the recharge rate and island width, the estimated layer thickness based on ER measurements was used in the model estimates in the present study for generating volumetric estimates of the freshwater lens using 3D Analyst Tools of ArcGIS (version 10.8) software (ESRI, USA). Furthermore, it is noted that the above algebraic equations can be effectively used in estimating the possible growth of freshwater lens following the replenishment due to the recharge generated from the monsoonal rainy period. The social surveys were conducted in the islands during the period from February to March towards the end of the dry period in the Maldives while initial ER measurements in the islands were carried out in October towards the end of the monsoon rainy period. Based on these, the existing and maximum possible estimations of freshwater lens volumes can be derived to have further distinct insight into the present stress level of the aquifers in individual islands.

Additional soil permeability field tests, field investigations for soil profile using core data and steady state pumping tests were carried out at selected representative locations in the islands to gather supplementary aquifer hydraulic conductivity, transmissivity and groundwater yield estimates required to facilitate the procedure aforementioned.

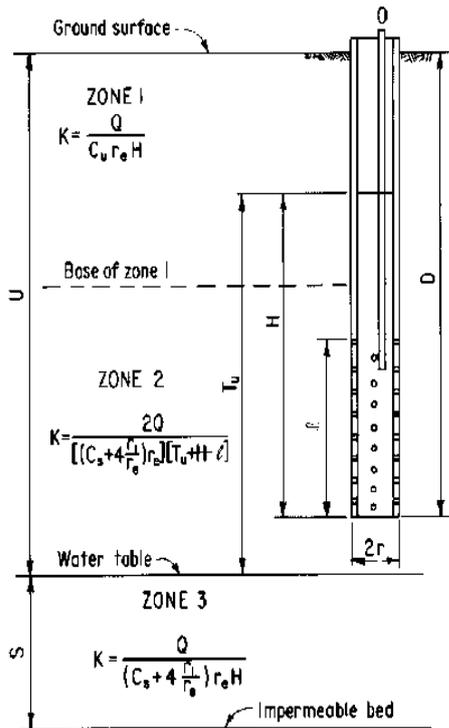
The data on groundwater usage characteristics, existing household/institutional level measures and arrangements for groundwater recharge and the quality of other water sources were collected based on the social/institutional surveys and water quality tests carried out as described in previous sections.

Field permeability testing in the unsaturated zone was carried out by measuring water absorbance at a constant water head in a 4-inch (10 cm) hole dug with a fuel-driven (gas powered) mechanical auger to a depth of ~1.2 m. The permeability test is a measure of the rate of the flow of water through the soil. The methodology for Constant Head Gravity Permeability Tests is shown in Figure 1-9. A minimum of five (5) representative locations were selected in each island depending on the size of the island, land use and hydrogeological and soil overburden characteristics.

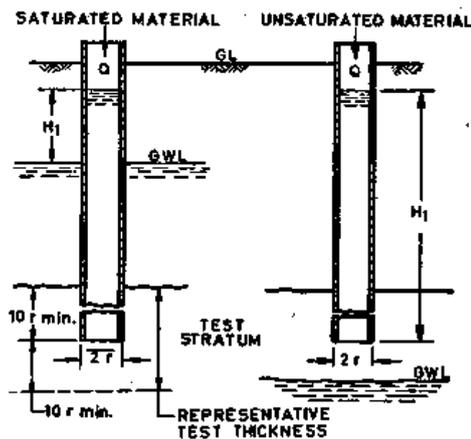
The natural or artificial recharge of groundwater aquifers directly depends on the infiltrated water moving through the impeding upper subsurface soil layers which are largely affected by their permeability, among various other parameters. Permeability tests were carried out at selected representative locations in each island, following Standard Test Method for Field Measurement of Hydraulic Conductivity Using Borehole Infiltration (ASTM D6391-11) and Borehole Infiltration Test (Direct Push Casing Approach) following the Maryland Stormwater Manual (2009).

An average depth of 0.5 m - 1.5 m in the unsaturated zone above the groundwater table was selected to represent the active recharge zone in the islands and manual drilling or petroleum gas-powered hand-operated power auger was used with minimum disturbance to the soil overburden which was mostly either sand, clayey sand or sandy gravel in these atoll based coastal aquifers.

The in-situ soil overburden profile and layering at each well location were determined by the investigation of excavated soil core data and identifying distinct layers and depths by visual inspection of texture, colour and grain sizes. These data were recorded and entered into a GIS database with geo-referenced/geo-tagged photographic information and coordinates, which were subsequently used for generating aquifer profile maps and soil water-bearing volumes for establishing freshwater lens volumes during dry and wet periods, respectively.



K = coefficient of permeability, feet per second under a unit gradient
 Q = steady flow into well, ft³/s
 H = height of water in well, ft
 l = length of perforated section, ft
 r_i = outside radius of casing (radius of hole in consolidated material), ft
 r_o = effective radius of well = r_i (area of perforations) / (outside area of perforated section of casing); $r_i = r_o$ in consolidated material that will stand open and is not cased
 C_u and C_s = conductivity coefficients
 T_u = distance from water level in casing to water table, ft
 a = surface area of test section (area of perforations plus area of bottom), ft²; where clay seal is used at bottom, a = area of perforations
 S = thickness of saturated permeable material above an underlying relatively impermeable stratum, ft
 $X = \frac{t}{T_u} (100)$ = percent of unsaturated stratum
 U = thickness of unsaturated material above water table, ft
 D = distance from ground surface to bottom of test section, ft
 O = observation pipe (1 to 1 1/2 - inch pipe)
 Limitations:
 $S \geq 5l$, $l \geq 10r$, and $\frac{Q}{a} \leq 0.10$
 Notes:
 In zone 3, H is the difference in elevation between the normal water table and the water level in the well. In zones 2 and 3, if a clay seal is placed at the bottom of the casing, the factor $4 \frac{r_i}{r_o}$ is omitted from the equations. Where the test is run with "f" as an open hole, $\frac{r_i}{r_o} = 1$ and $(C_s + 4 \frac{r_i}{r_o}) = (C_s + 4)$.



The permeability by constant head method (open-end test) should be obtained from the following relation determined by electrical analogy experiments:

$$K = \frac{Q}{5.5rH} \quad \dots (1)$$

where

- K = coefficient of permeability;
- Q = constant rate of flow into the hole;
- r = internal radius of casing; and
- H = differential head of water = H_1 (gravity head) - H_f (head loss due to friction).



Figure 1-10: Methodology for Constant Head Gravity Permeability Tests

1.4.5 Soil profiles and sieve analysis

Considering the existing water table height of the particular area, three (03) – five (05) soil profiles were taken for each island covering at least a 50 cm to 110 cm depth. Soil sample drilled out for the permeability test was safely arranged in the form of an undisturbed core sample and measured laterally to verify the geological cross sections generated based on the ER transects. The photographs of the soil profiles of each island taken during field work are annexed under Annex X.

Moreover, four common layers were identified considering the nature of the soil layers during the field works and sieve analysis tests were carried out for those representative soil samples collected at Ha. Muraidhoo Island and the soil laboratory test reports are attached under Annex XI.

Table 1.6: Comparison of sieve analysis test results of representative soil samples

Sample ID	Depth for the Collected Sample from Ground Level (mm)	Uniformity Coefficient (Cu) [D60 / D10]	Remarks
Sample 1	0 – 200	12.22	High permeable
Sample 2	200 – 400	2.78	Moderately permeable
Sample 3	400 - 600	3.43	Moderately permeable
Sample 4	600 - 1000	4.00	Moderately permeable

1.4.5.1 Steady-state pumping tests

A pumping test is a field experiment in which a shallow dug well in the aquifer to be tested is pumped at a controlled rate and water-level response (drawdown) is measured in one or more surrounding observation wells and optionally in the pumped well (control well) itself. The response data from pumping tests in the present study were used to estimate the hydraulic properties of aquifers while they can further be used to evaluate well performance and identify aquifer boundaries.

The typical well configuration for conducting a pumping test in a nonleaky confined aquifer and the procedure for estimation of aquifer properties by matching Theis (1935) type-curve solution to time-drawdown data is presented in Fig. 1-11. However, the bottom layer was a karstic limestone bed and the freshwater lens is limited to the upper soil overburden in the majority of the islands, and thus the well penetration was only limited to the saturated zone below the water table.

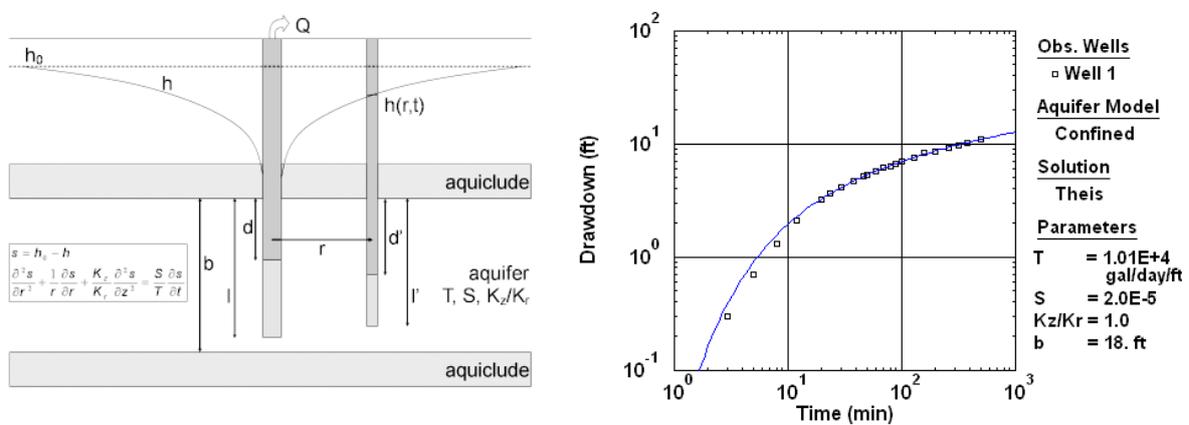


Figure 1-11: Typical well configuration for pumping test in nonleaky confined aquifer and Estimation of aquifer properties by matching Theis (1935) type-curve solution to time-drawdown data

The aquifer properties are estimated from the constant-rate pumping test in the unconfined aquifer by fitting mathematical models (type curves) to drawdown data through the procedure known as curve

matching. In addition to the Constant-rate tests carried out maintaining the pumping at the control well at a constant rate which is the most commonly used pumping test method for obtaining estimates of aquifer properties, recovery tests at selected well locations (almost all) were carried out with water-level (residual drawdown) measurements after the termination of pumping to determine well performance characteristics such as well loss and well efficiency (Fig. 1-12).

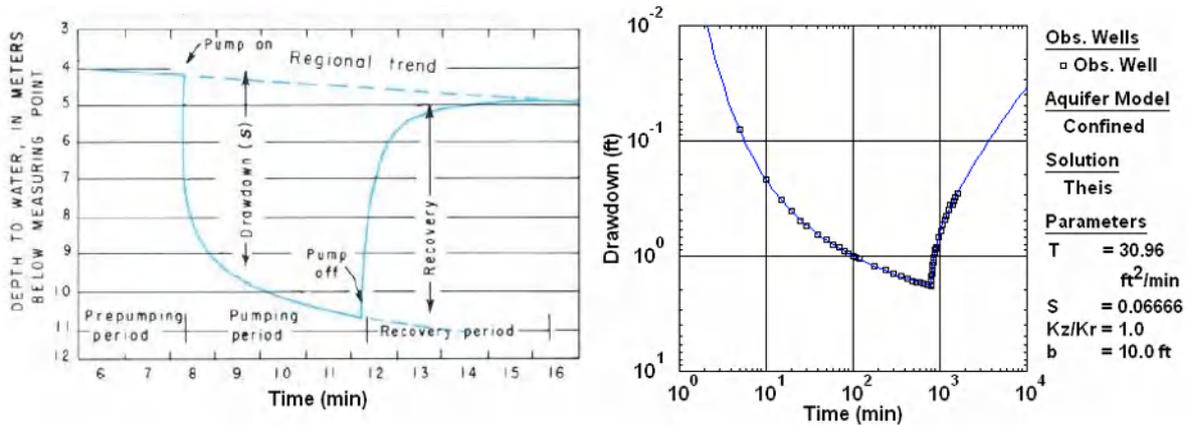


Figure 1-12: Typical well configuration for pumping recovery test in a confined aquifer and Estimation of aquifer properties by matching Theis (1935) type-curve solution to time-drawdown data

1.4.6 Estimation of rates of groundwater recharge and discharge

The groundwater recharge and discharge characteristics of the freshwater lens and associated aquifers in individual islands were estimated based on the findings of the household social surveys, institutional data and results of the water balance modelling approach. The recommendations for the potential groundwater development and artificial recharge is derived based on the above and collected land use, built-up area, local flood extent data and terrain data.

2 GROUNDWATER IN THE MALDIVES

This section briefly outlines the background about 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 Resource Management and Sustainable Sanitation in Maldives (Falkland, 2001), etc.) and recent findings of groundwater surveys.

2.1 Groundwater Occurrence and Freshwater-Saline Interphase

Fresh groundwater occurs in the form of ‘freshwater lenses’ on medium to large sized islands in the Maldives. These freshwater lenses are an important and valuable source of water supply on most of the islands. They are highly susceptible due to saline intrusion as a result of pumping and vulnerable to pollution from the surface and sub-surface waste disposal, particularly from sanitation systems.

The term "freshwater lens" can be misleading as it implies a distinct freshwater aquifer. In reality, there is no distinct boundary between freshwater and seawater but rather a transition zone (refer to the following Figure 2-1). The upper surface of a freshwater lens is the water table. As per the recent findings, two types of groundwater lens are mainly identified in the Maldives islands.

- Freshwater lens that floats over the saline water
- Middle part of the freshwater lens rests on the fresh coral formation and freshwater-saline water interface is observed only at the rim area of the lens

The base of the freshwater zone can be accurately determined by establishing a recognisable salinity limit for freshwater and drilling through the lens to find where the limit occurs. The salinity limit adopted for freshwater (suitable for drinking water) is often taken as the WHO guideline value for chloride ion of 250 mg/L (WHO, 1993). This is approximately equivalent to electrical conductivity (EC) of 1,500 $\mu\text{S}/\text{cm}$. In some islands, a higher value of EC (e.g. 2,500 $\mu\text{S}/\text{cm}$) has been used as an upper limit, noting that the WHO guidelines are based on taste and not health considerations.

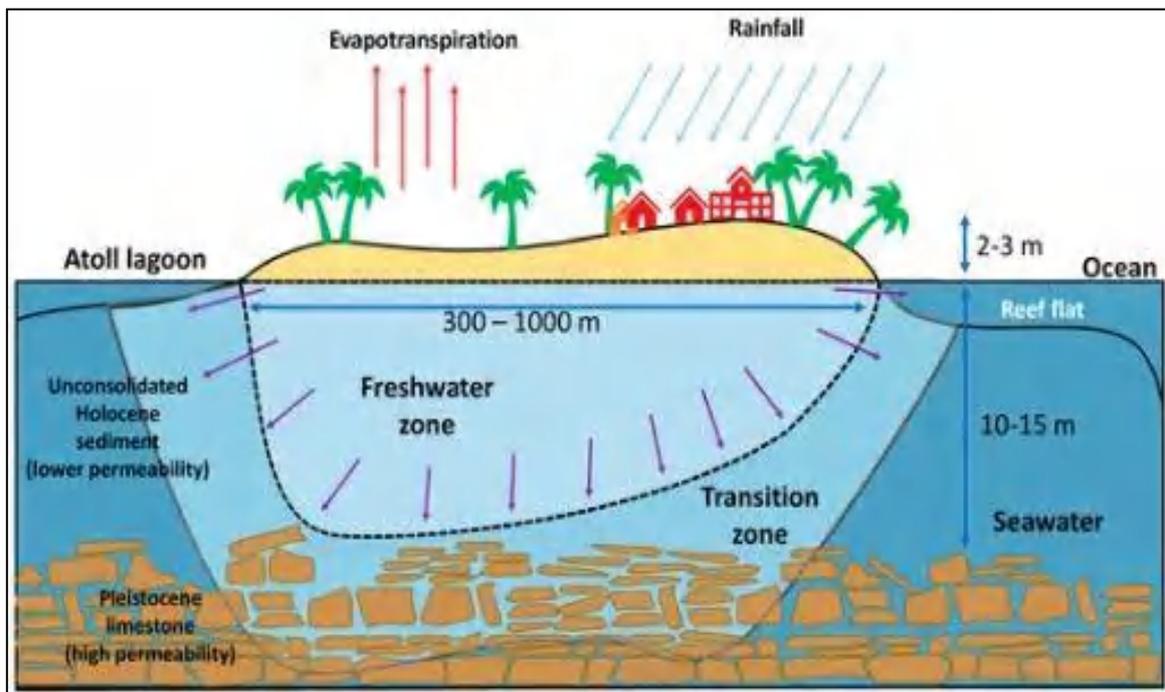


Figure 2-1: Cross section through a small coral island showing main features of a freshwater lens (exaggerated vertical scale) (Source: Jaleel et al., 2020)

Freshwater lens thickness and its geometry on a small coral island are dependent on many factors including:

- Geology of the island
- Topography of the island and changing of island geometry
- Hydrogeological properties, particularly porosity and permeability
- Size of the island, particularly width from coast to coast
- Recharge to groundwater (which is dependent on the magnitude and variability of rainfall and evapotranspiration from the surface of the island and the vegetation)
- Tidal and sea level movements
- Groundwater withdrawal from wells or other systems.

Another potential factor is the height of the groundwater table above sea level and the frequency of seawater inundation in very low-lying parts of islands.

The water balance between rainfall (input of water to the surface of the island) and evapotranspiration (output of water from the surface of the island), as depicted in Figure 2-1, determines the amount of recharge to the groundwater. The amount and variability of recharge is a key determining factor of freshwater lens thickness (amount of freshwater volume stored in the aquifer) and is a key element in determining the sustainable yield of a freshwater lens.

The fresh and seawater dynamics in unconfined aquifers are governed by the Ghyben-Herzberg principle (Falkland, 2000a). If the freshwater level is one meter above the mean sea level, the depth to seawater is 40 m below mean sea level, and vice versa. If sea level was constant and recharge from rainfall was uniform, the saltwater/freshwater interface would remain motionless.

Freshwater lens conditions in selected islands in the south and north of the Maldives have been described in several other reports by Falkland (Falkland; 2000a, 2001). These reports are based on extensive investigations including drilling, geophysics and well surveys to assess the occurrence and behaviour of freshwater lenses. The investigations have revealed that there are considerable variations in thickness, area and volume of freshwater lenses among the islands. Some islands show quite thick and extensive freshwater zones, while others have very small and thin freshwater zones.

It is noted that a relationship was investigated (from the boreholes on Addu atoll) between freshwater lens thickness and width of the island, and it was found that a reasonable relationship did exist (refer Falkland, 2000a).

Detailed studies on other atolls in the Pacific and Indian Oceans, including extensive coring on the Cocos (Keeling) Islands in the Indian Ocean (Woodroffe and Falkland, 1997), have commonly found the existence of two layers of sediments. A geological unconformity, separating these two layers at typical depths of 10-15 m below mean sea level, is one of the main controls to freshwater lens thickness (refer to Figure 2-1). The freshwater zone is mainly or solely contained in the relatively low permeability coral sediments as mixing of freshwater and seawater occurs readily in the high permeability limestone. Based on limited coring on Addu atoll, similar conditions were found on that atoll (Falkland, 2000a). While no cores were obtained from the drilling in 11 islands in Haa Dhaalu and Haa Alifu, there is sufficient evidence from bore logs and permeability tests to suggest that those islands are also similar (Falkland, 2001). Hence, it would be expected that similar conditions apply throughout the islands of the Maldives and that the model shown in Figure 2-1 is a reasonable representation of geological and groundwater conditions. Of course, the thickness of fresh groundwater is however variable, depending on the factors listed above.

In addition to the vertical variation in permeability, there is often an across-island variation in permeability. Often finer sediments with lower permeability accumulate on the more tranquil side of the island while coarser, sediments with higher permeability are found on the more exposed shorelines. In this context, exposed shorelines are those that are most affected by storms and wave

action. Where finer sediments are found, the freshwater lens tends to be thicker due to less mixing of fresh and saline water than in coarser sediments. For this reason, wells at a given distance from the more tranquil shoreline tend to have much lower salinity than wells at the same distance from the more exposed shoreline. This is most noticeable for wells within about 50 m of the coastline.

2.2 Salinity Criteria for ‘Fresh’ and Potable Groundwater

In order to interpret the salinity data for wells and other locations, it is necessary to have an objective means of assessing groundwater as either ‘fresh’ or ‘brackish’. Without such criteria, it is not possible to define the available fresh groundwater resources including the areal extent and thickness of freshwater lenses on islands.

So far, there is no clear definition of ‘fresh’ groundwater for islands in the Maldives.

There are a number of ways to define criteria for ‘fresh’ groundwater. It can be assessed in terms of appropriate guidelines for potable (drinking) water and/or can be assessed for non-potable uses.

In order to assess the salinity of water samples, particularly groundwater samples, in terms of suitability for potable (drinking) purposes, the Guidelines for Drinking-Water Quality published by the World Health Organisation (WHO, 1993) are generally used. There is no specific drinking water guideline provided for electrical conductivity (EC) but guideline values are provided for other measures of salinity, including chloride ion concentration (250 mg/L) and total dissolved solids (1,000 mg/L). Both guidelines are based on taste and not health considerations. From previous comparisons of chloride ion concentrations and EC values on coral islands, including those in the Maldives, a chloride value of 250 mg/L is approximately equivalent to an EC value of 1,200-1,500 $\mu\text{S}/\text{cm}$.

In some other similar coral islands (e.g. Kiribati, and coral islands within the Cook Islands and Tonga), a higher value of EC (e.g. 2,500 $\mu\text{S}/\text{cm}$) has been used as an upper limit for potable water, noting that the WHO guidelines are based on taste and not health considerations. Above an EC value of about 2,500 $\mu\text{S}/\text{cm}$ (approximately equivalent to a chloride concentration of 600 mg/L), the taste of groundwater becomes noticeably saline and the level of corrosion of susceptible metals and scaling (e.g. on heating elements in electric jugs, etc.) becomes greater.

Typical EC values for different types of water are provided in Table 2.1 for comparison with the results obtained from the baseline assessment of the selected islands.

Table 2.1: Typical salinity (EC) values for water

Note: WHO = World Health Organisation Drinking Water Quality Guidelines (1993)

Type of Water	Typical EC range ($\mu\text{S}/\text{cm}$)
Rainwater	50 – 100
Very fresh groundwater	250 – 500
Fresh groundwater	500 – 1,500
Maximum limit for potable water Suggested desirable limit of ‘freshwater’ for non-potable purposes,	1,500 <i>(based on WHO guideline for chloride (250 mg/L))</i>
Suggested maximum limit of freshwater for non-potable purposes	2,500
Mildly brackish water	2,500 – 5,000
Very brackish water	10,000 – 50,000
Seawater	50,000 – 55,000

Hence, for the purposes of this report, the following EC limits are suggested as water quality objectives:

- Potable water 1,500 $\mu\text{S}/\text{cm}$
- Non-potable freshwater (desirable): 1,500 $\mu\text{S}/\text{cm}$
- Non-potable freshwater (maximum): 2,500 $\mu\text{S}/\text{cm}$

Above 2,500 $\mu\text{S}/\text{cm}$, the groundwater can be described as brackish.

It is recognized that groundwater with salinity above the suggested maximum limit for freshwater (2,500 $\mu\text{S}/\text{cm}$) can be used for a number of purposes (e.g. bathing, washing and toilet flushing) without significant impacts, provided that the salinity is not much greater. Water for toilet flushing and cleaning (i.e. floors, yards, etc.) can exceed this limit.

It is noted that of the non-potable water, there are essentially two sub-types with different water quality requirements. Firstly, water used for bathing and washing should be acceptable in terms of both salinity and bacteriological quality. Secondly, water used for toilet flushing could be of a lesser standard in terms of salinity and bacteriological quality. However, even the water used for toilet flushing should not have too high a salinity.

2.3 Recent Literature on Groundwater Resources

The National Strategic Framework to Mobilize International Climate Finance to Address Climate Change in the Maldives 2020- 2024 - Ministry of Environment, Republic of Maldives (MoEnv. 2020b) identifies the key climate risks in Maldives, including 1). Land loss (sea level rise), 2). Coastal floods, 3). The intrusion of saline water into aquifers, 4). Coastal erosion, 5). Ocean acidification, 6). Coral bleaching, 7). Increased frequency of extreme rainfall events (heavy rain, droughts), Increased frequency of cyclones, heat waves, longer dry seasons, shorter rainy seasons, and increased average temperature, where items 2), 3), and 7) are coinciding with the scope of the present project.

Furthermore, the groundwater of small islands is highly susceptible to salinization due to the increase in sea-level rise, higher extraction rates, and inadequate recharge. Over-extraction of groundwater is a commonly reported issue in Small Island Developing States (SIDS). At the same time, the groundwater is increasingly contaminated by activities of the increasing population and urbanization combined with the lack of sewerage infrastructure, both of which are typical characteristics of many SIDS (Jaleel, et al., 2020).

An important reason for the vulnerability of groundwater in coral islands like those of the Maldives is the fact that their bedrock is made of carbonate rock (Pleistocene limestone), which is susceptible to dissolution in rainwater creating karst landforms. These are highly permeable due to the presence of organized networks of open fractures, karst conduits, and caves in the subsurface and facilitate contaminant transport, particularly saltwater intrusion, increasing the fragility of the aquifer. The soil of these islands typically contains Holocene sediments, which comprises a mix of sands, coral fragments, and organic matter. Unaltered Holocene sediments (Coral sands) are moderately permeable but lose permeability due to cementation. Groundwater occurs as a thin “freshwater lens” over seawater in coral island aquifers. This shallow freshwater lens is fed by rainwater recharge through the coral sands and is in a dynamic equilibrium depending on the level of recharge (Jaleel, et al., 2020).

Overextraction especially during extended dry spells causes this freshwater lens to sink, allowing the aquifer to become vulnerable to increased salinity intrusion, and how and to what extent the managed aquifer recharge (MAR) can be used to restore the system back to its original state is the basis of this present project.

The findings of the baseline assessments conducted in individual islands are presented here onwards.

3 HA. FILLADHOO ISLAND

3.1 General Overview of The Island

The island of Filladhoo (Figure 3-1) is located on the southern periphery of Haa Alifu Atoll at coordinates 73°13'45"E, 6°52'31"N. The island has an area of about 2.07 km² and measures about 1.57 km in width and 2.98 km in length. The population of the island was found to be about 1,144 residents as of December 2021. The island has a harbour on the Western side of the island. The following table outlines some basic information about the island and the following map outlines the location of Filladhoo.

Table 3.1: Basic statistical information on Filladhoo island in Haa Alifu Atoll.

Name of the island	Th. Filladhoo
Longitude and Latitude	73°13'45"E, 6°52'31"N
Area	207.08 ha (2.07 km ²)
Population (Dec 2021)	1,144
Distance from Male'	300 km
Harbour	Present
Island sewerage network	No
Water supply network	No
Other infrastructure	No

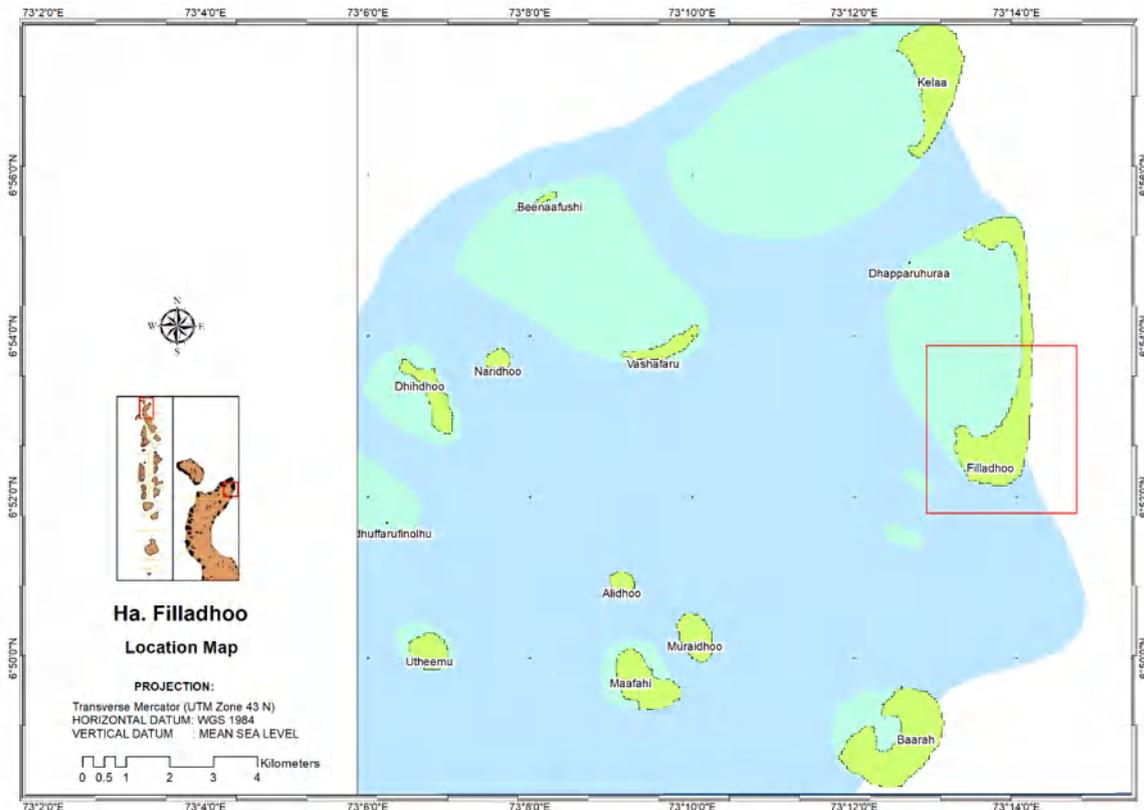


Figure 3-1: Location map for Filladhoo Island, Haa Alifu Atoll.

3.2 Topography and Geology

Filladhoo island is on the East end of the “Haa Alifu Atoll” which is located close to the North end of the chain of Maldives islands. Filladhoo is an island with an elongated shape and extends about 2,500 m (NW-SE) in length and about 750 m (SW-NE) in width. In the elongated island, the northern side is very thin and the southern side is thick may be due to the action of ocean waves and currents. Basic topography and the geological setting are mostly based on the properties of the underground coral beds and the action of ocean waves and currents. The elevation of the island varies from -3.48 m MSL to 3.67 m MSL and is generally a flatland throughout the island. The general geological profile in the island is composed of topsoil and beach coral sand deposits underlain by sandy coral rock (Figure 3-2). The sandy coral rock consists of a weathered coral rock layer and hard fresh coral rock. The cross-section A to B shows it has two segments. The thin area closed to A composed of topsoil and hard coral rock. The wider portion is composed of a topsoil layer (0.2 m) in coastal areas and its thickness in the middle of the island is about 0.5 m. Beach coral sand layer is about 0 to 0.2 m in thickness in the beach area (B) and about 2.0 m in thickness in the middle of the island. In the western side of beach areas, mostly a beach coral sand layer exists as the top layer. However, hard coral rock is exposed in the southern and western sides of the island. The coral sand layer is mostly an unconsolidated and permeable layer. According to the cross-section A - B, the weathered coral rock depth is varying between 0 m (closed to A) to about 4.0 m (closed to B) from MSL and it is a semi permeable layer. Fresh groundwater lens occupies both coral sand layer and weathered coral rock in the wider portion of the island. The hard coral layer is mostly unconsolidated and impermeable and present as a fresh rock. As the compositional and structural differences of coral formation, differential weathering could be observed in the cross-section A-B. Cross section A-B clearly shows two weathered zones. However, the cross-section C-D shows uniform weathering and the general trend is that the central part of the island shows higher weathering compared to the coastal area.

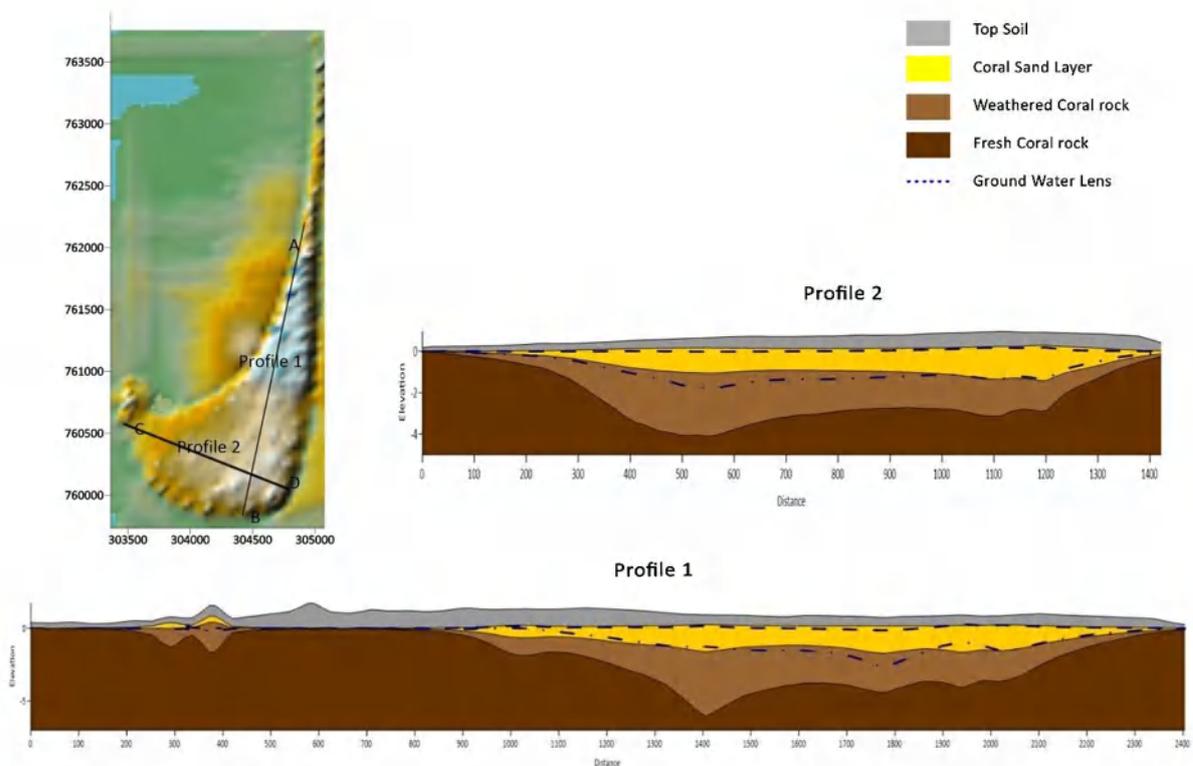


Figure 3-2: Geological sections of the island showing subsurface geological characteristics

3.3 Climate

Filladhoo experiences the typical two monsoons in the Maldives namely, the North-east monsoon from December/January to March/April and the South-west monsoon from Mid-May to November. There are no specific wind and rainfall data available for Filladhoo as there are no weather monitoring stations on the island itself. Based on the rainfall data of the nearest weather monitoring station, it shows a declining trend in rainfall for the past 30 years (Inception Report, 2021).

The historical rainfall data records from Hanimadhoo Island (not included in the 5 selected islands in Lot 1) located in the Haa Alifu atoll (15 km to the south from Filladhoo Island) has an annual average rainfall of 1,747 mm with a standard deviation of 279.1 mm and the trend with the decadal means were shown in the following graph (MEE, 2021).

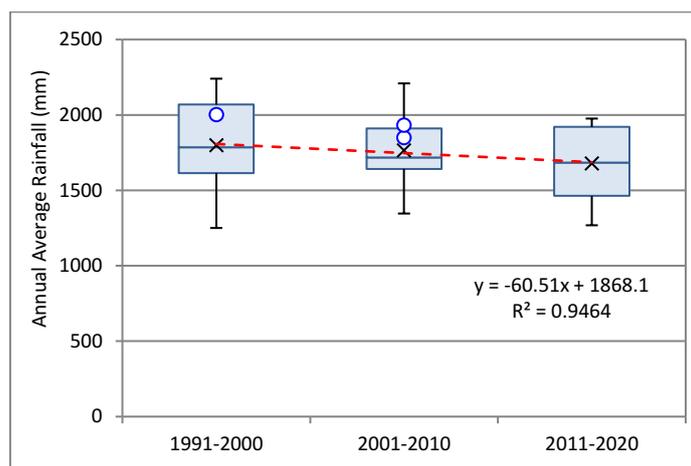


Figure 3-3: Decadal means and trend for rainfall in Hanimadhoo (1990 - 2020).

3.4 Demography

As of December 2021, Filladhoo has a registered population of 1,144 including 575 males and 569 females (Filladhoo Council, 2021). As per the council, an estimate of 565 locals and 40 foreigners currently resides in the island making the residential population 605. Foreigners residing in the island include teachers, medical staff and the labour force working in different infrastructure projects in the island. The island council was not able to provide accurate figures on the residential population by gender. Total number of households in Filladhoo at present is 179. The following table summarises the population breakdown for Filladhoo.

Table 3.2: Demographic Breakdown of Filladhoo Island as of December 2021

Registered population			Resident population		
Both	Male	Female	Total	Maldivians	Foreigners
1144	575	569	605	565	40

Source: Filladhoo Island Council, 2021

3.5 Socio-economic condition

3.5.1 Natural Resources and Land Uses

Filladhoo island is one of the largest islands in the Maldives and is divided into an uninhabited island “Dhapparuu” and an administrative island “Filladhoo”. The administrative island of Filladhoo has an area of 260.9 hectares and the majority of the island is covered with vegetation with only a small area settled by the islanders in the north face of the southern side of the island.

There are three wetland areas in the island where the largest one is on the southwest side of the island, and the other two are in the south of the island. Swell waves are observed near the wetland area at the

southwest side of the island as well as near some residential areas, though the residents have not been affected by swell waves. Soil erosion is also observed across the island and mostly near the same wetland at the southwest side of the island.

In terms of land use and land allocation, the island council now has the authority to allocate land for different purposes with an approved land use plan. The council currently does not have an approved land use plan, however, is in the process of developing the same.

3.5.2 Economic Activities



Figure 3-4: Summary of household and socio-economic activities

The main economic activities carried out by Filladhoo residents include fishing, fish processing (such as drying fish and the production of rihaakuru), agriculture and construction works. Furthermore, a large portion of the youth population is employed in tourist resorts.

Fish processing is mostly done at residential homes or at vacant housing plots as there are no specific land allocated for the activity.

For agriculture, however, the council has allocated 5000sqft plots of land for every household. As of now, there are a total of 143 plots used for agriculture, 50% of which is used for growing bananas while others are used for growing fruits and vegetables. To grow banana plants, farmers usually excavate pits on the ground until it almost touches the water lens (around 1 ft). As per the island council, banana plants do not require much watering or fertilizers. Fertilizers and pesticides are, however, used to grow other types of plants in the island.

There are no tourism establishments or any other industrial activity carried out in Filladhoo.

3.5.3 Accessibility and Transport

The nearest airport to Filladhoo is HDh. Hanimaadhoo International Airport which is around 13 km away. There are three other domestic airports in the region (in Haa Alif Hoarafushi, Haa Dhaalu Kulhudhuffushi and Shaviyani Fonadhoo). The main mode of transport to and from Male' to the island is by flying to Hanimaadhoo and private launch hire from Hanimaadhoo airport to Filladhoo. There are private ferries travelling within the atoll as well as supply boats travelling between the atoll and Male', the capital city.

A harbour with quay walls is built on the west side of the island and is used to access the island. As per the council, since the development of the harbor, soil erosion is observed on the south side of the harbor which is the western side of the island. Furthermore, sand accumulation is also observed within the curved area of the island (northern side beach).

3.5.4 Services and Infrastructures

The island is equipped with the basic services and supporting infrastructures and the details of these are discussed in the following sections.

3.5.4.1 Public Facilities and Amenities

The public facilities available in the island include:

- Health Center
- Pharmacy
- Primary and Secondary School
- Government institutions (Office for Island Council, Island Court)
- Mosques
- Youth Center (with indoor and outdoor sports courts)
- Power house

3.5.4.2 Water supply

Currently, rainwater is used for drinking and cooking when needed, although bottled water sourced from Male' is also used for drinking. Groundwater is used for other purposes such as bathing and washing as well as agriculture and fish processing activities. This is further discussed in Sections 1.3 and 1.4.

3.5.4.3 Energy supply

Filladhoo has electricity for 24 hours, generated from the island powerhouse operated by Fenaka.

3.5.4.4 Waste and Waste water disposal

Solid Waste: Filladhoo currently does not have a waste management plan or a well-equipped waste management center, though the Council reported that they were working on developing a plan at the time of the pre-inception consultations. As per the Council, waste is currently segregated in allocated areas of the island and most of them are burnt. Food waste is mostly thrown to the beach while plastic and metal items remain on the allocated areas. The government currently has a planned and budgeted project to establish a waste management center in Filladhoo.

Sewage Disposal: Main method of sewerage disposal at Filladhoo is by means of septic tanks. Each household has a septic tank within close proximity and the collected effluents are infiltrated into the ground. Filladhoo currently has an ongoing project to establish a water and sewerage system and is scheduled to be complete in April 2022.

3.6 Existing water and sanitation situation

3.6.1 Water

Filladhoo currently does not have a piped drinking water system, however, the establishment of an RO (Reverse Osmosis) Plant with islandwide household connections is ongoing and is expected to be completed and ready to use in 2022.

The locals use groundwater for all uses except for drinking and cooking. For economic activities, such as agriculture and fish processing, the main source of water is groundwater as well. In the pre-inception stakeholder meeting, the Island Council reported that groundwater has been contaminated for almost 18 years, and the residents believe that it may have been affected by the establishment of septic tanks and the increase in the island population. Groundwater contamination is observed through the presence of bad odour across the island and discoloration in some areas. The Council also reported that changes in groundwater levels are observed with the changes in seasons and that a high level of contamination is observed particularly in the dry season, mostly during March and April.

Rainwater is mainly used for drinking and cooking, though bottled water is also used for drinking. Rainwater is harvested at both the household level and island level. At the household level, each household has at least one water tank with a capacity of 2,500 L. Additionally, the Council has

established a rainwater collection system with a total capacity of 30,000 L by using rainwater collection tanks, however, only 6 of which are currently in a usable state thus reducing the capacity by half. Every year during the dry season, the locals have to request for water once or twice a year, mostly during the March-April period.

The general practice of rainwater harvesting at the island level is to clean the roofs thoroughly and let the first flush pass to the nearby roads which would eventually seep into the ground. Excess rainwater is also discharged to the adjacent roads in a similar manner.

3.6.2 Wastewater and Sewage Disposal

Currently, sewage is disposed of by means of septic tanks. Each household has a septic tank within close proximity and is infiltrated into the ground. It was noted that most of the households keep the soakage pits outside the house, away from the groundwater wells although the septic tank is inside the house. According to the household survey that was carried out under this study, about 91% of the households reported keeping the septic tanks 10ft or more away from the ground water well.

The establishment of a proper sewerage system with a household connection is currently ongoing and is expected to be completed in April 2022. Once the new sewerage facility has been established, the existing facility will be abandoned. The septic tank inflows from the pipes will be ceased by disconnecting the inflow pipes. The remaining sludge in the pipes and septic tanks will then be removed by sewer jetting and released to the sea via an outfall pipe.

3.7 Results of the Baseline Surveys: Water Usage

3.7.1 Summary socio-economic surveys

As detailed in the methodology section of this report, a survey was carried out to determine the water usage at households (HHs), commercial entities (cafés/restaurants), institutions and places with industrial uses (agricultural lands, fish processing). This survey was conducted in Filladhoo from 9th August to 11th August 2021 with the help of local enumerators. The following Table 3.3 summarizes samples taken for each sector at a 95% confidence interval, refusals, replacement samples and the total number of completed surveys for each.

Table 3.3: Population and Sample taken for the social survey

Categories	Population	Sample	Sample replacement	Forms Completed	Refusals	Vacant Houses
Households	148	108	9	82	5	10
Registered Farmers	115	88	0	66	-	-
Fishing Vessels	9	8	0	7	-	-
Fish Processing	6	6	0	4	-	-
Institutions	5	5	0	5	-	-
Guest houses	0	-	-	-	-	-
Café/restaurants	3	3	0	0	-	-

Note: A number of mitigation measures were adopted to ensure to achieve the 95% confidence level sample size. The challenges and limitations and the measures undertaken to mitigate the challenges are listed in

The key findings from this survey show that a total of 483.65 liters of groundwater are estimated to be used per capita per day for various domestic uses in Filladhoo. The respective water use situations including domestic, commercial and institutional uses are illustrated in the following sections.

3.7.2 Water usage for domestic purposes

3.7.2.1 Domestic Water Usage

A household (HH) survey was carried out at a 95% confidence interval. A total of 82 HHs were surveyed from Filladhoo. As presented in Table 3.4, 98% of HHs have at least one 2,500 L capacity HDPE rainwater tank at their homes to collect rainwater for daily uses. Among the 82 HHs, 99% uses rainwater for drinking while 100% also uses it for cooking.

Groundwater is mainly used for non-potable use in all the households surveyed.

Table 3.4: Groundwater and rainwater use data for Filladhoo

Rainwater	Per cent (%)
Households with rainwater tanks	98%
Rainwater use for drinking	99%
Rainwater use for cooking	100%
Groundwater	Per cent (%)
Groundwater as a drinking source	0%
Groundwater for cooking	0%
Groundwater for non-potable use	100%
Total number of household wells surveyed	82
Percentage of wells surveyed fitted with pumps	96%

Based on the household survey, the average daily water demand per capita for domestic purposes has been estimated based on the average amount of water used per person for showering, toilet flushing, laundry and gardening, and this data is shown in Section 1.4.3.1

Table 3.5 below shows the total domestic water use estimated to be 483.65 litres per capita per day.

Table 3.5: Domestic Water Usage in Filladhoo

Shower/ Liters per capita per day	Toilet/ Liters per capita per day	Laundry/ Liters per capita per day	Gardening/ Liters per capita per day	Total/ Liters per capita per day
138.7	45	8.7	222.3	414.7

3.7.2.2 Perception on Groundwater

The HHs were also asked about their perception on groundwater, if it is safe to use for daily purposes and whether the quality of groundwater is good or bad.

As can be seen from Figure 3-5, a total of 48% agreed that the groundwater of Filladhoo is safe to use for their daily uses. However, a similar percentage (44%) of people also reported that ground water is not safe for daily usage.

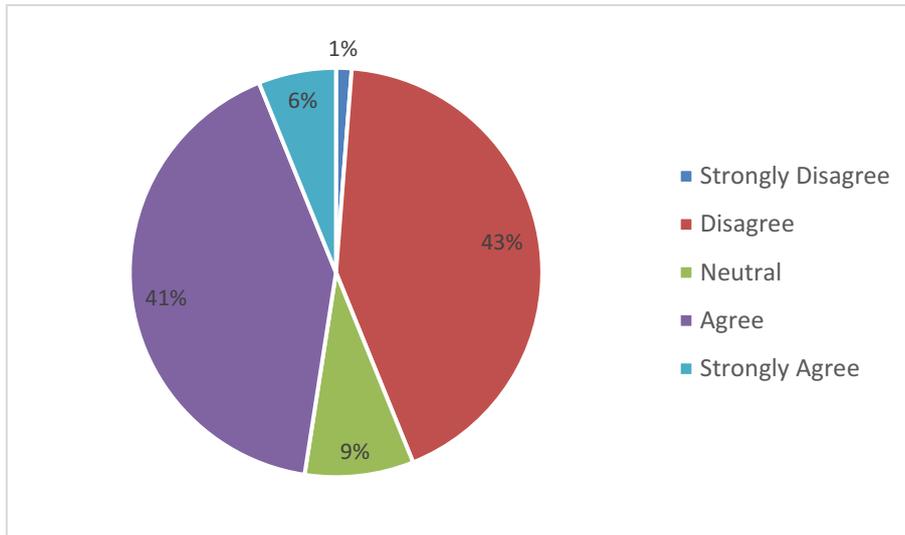


Figure 3-5 Perception of HHs on the safety of groundwater

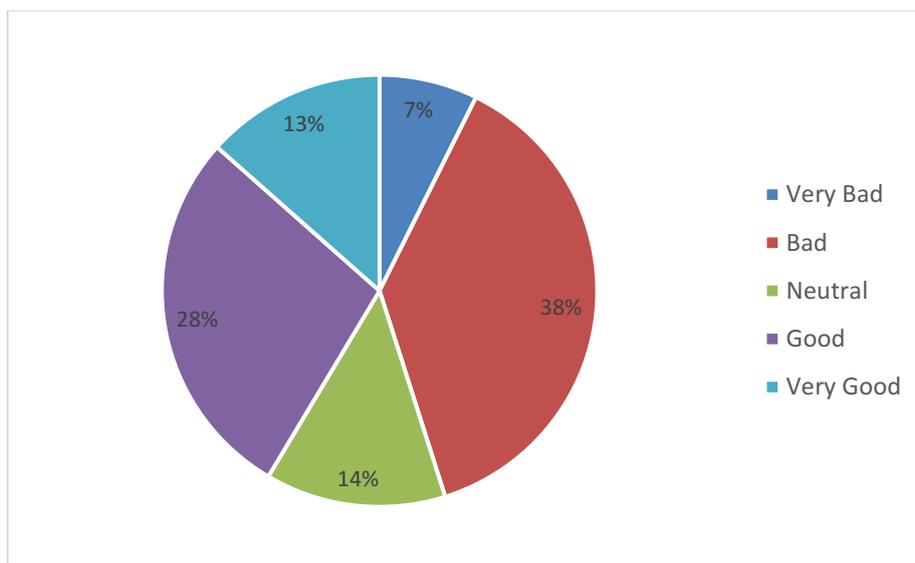


Figure 3-6 Perception of HHs on quality of groundwater

Furthermore, the households were asked about the quality of groundwater with regard to their experience. While 38% said the groundwater quality is bad, 7% said it is very bad. It is, however, important to note that a total of 41% also thought the groundwater quality is good.

The varying opinion on groundwater could be due to differences in the quality of groundwater across different parts of the island. The information received from the island council during the pre- inception stage also supports this claim as the Council noted that groundwater contamination is observed in all parts of the island, though in varied intensity and that the condition worsens during the dry season.

3.7.3 Water Usage by Commercial Activities

Filladhoo has three (3) cafés considered as commercial entities, however, enumerators were not able to collect accurate data on any of the cafés during the survey period. As per the Island Council, there were no registered guesthouses in Filladhoo.

3.7.4 Water Usage by Institutions

In order to estimate water consumption by different institutions in Filladhoo, five different institutions were surveyed including the Island Magistrate Court, Island Council, FENAKA Office, Health Center and School.

Groundwater in the institutions in Filladhoo is mainly used for mopping floors, flushing toilets, washing, and to some extent for gardening. A total of approximately 5,557.5 L of groundwater is estimated to be used per day by these institutions surveyed. As the use of each institution is different, generalizing the water consumption of institutions to an average figure will not be accurate. However, it can be deduced that based on the data, 68.61 L of groundwater is estimated to be used per staff per day at the institutions of Filladhoo (refer to Table 3.6).

Table 3.6: Water Usage by commercial activities in Filladhoo

	Water Flushed (Liters)	Gardening (Liters)	Mopping (Liters)	Sub-Total Water Used (Liters)	Total Water Used (Liters)	Institutional Groundwater Usage (Liters Per Staff Per Day)
Magistrate Court	15	613.5	10	638.5	5,557.5	68.61
Council Office	90	0	10	100		
FENAKA office	65	818	0	883		
Health Centre	80	1,227	10	1,317		
School	155	2,454	10	2,619		

3.7.5 Water Usage for Farming

A total of 66 farmers participated in the survey. This is 57% of the total number of registered farmers in the island. Farmers mainly use groundwater for watering plants. While 100% of the respondents use watering cans to water the plants, 71% collect this water from wells in the farming plots and 29% bring water from the wells in their homes.

According to the total 66 farmers that were surveyed, a total of approximately 5,040.9 L of groundwater are estimated to be used per day for farming.

3.7.6 Water Usage for Fisheries Activities

In Filladhoo, a total of seven (7) fishing boats and five (5) people engaged in fish processing were surveyed. Among the 7 fishing boats, four reported using groundwater for different purposes on the boat while the rest of them reported using rain water. The water is stored in tanks placed in the boats.

Among the 5 individuals engaged in fish processing, 3 were carrying out the work in their homes whilst 2 were in vacant plots of land. All except one of the respondents reported using ground water for the work. Table 3.7 below summarizes water usage for fisheries activities in Filladhoo.

Table 3.7: Water Usage by Fisheries activities in Filladhoo

Fishing Boats/Fish Processing Individuals	Total Volume of water per day (Liters)
1	150.0
2	114.3
3	570.0
4	990.0
5	255.0
6	10,260.0
7	200.0
8	1,250.0
9	285.7
10	333.3
11	1,780.0
12	2.86

As per the table, a total of approximately 19, 111.19 L of groundwater per day is estimated to be used for fishery activities.

3.7.7 Groundwater quality

Groundwater quality measurements were made at selected wells in Filladhoo Island for both physical and microbiological testing.

The following table summarizes the water quality results.

Table 3.8: Summary of groundwater quality tests from Filladhoo Island in 2021

Sample No	EC (µS/cm)	pH	Turbidity (NTU)	DO (ppm)	Temp (°C)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
Samples in Residential Areas											
F2	1157.00	7.60	0.35	2.67	27.98	0.57	1.00	2.50	0.39		
F5	476.00	7.60	0.22	5.48	27.99	0.23	21.00	0.14	0.10		
F6	1013.00	7.70	0.30	6.37	29.49	0.50	43.50	0.83	1.46		
F8	863.00	7.70	0.22	5.79	29.42	0.42	34.10	0.18	0.60	>2420	2
F9	533.00	8.30	0.94	7.60	28.21	0.19	1.50	0.18	0.12		
F10	485.00	8.00	0.38	6.43	27.07	0.23	1.20	0.02	0.11	>2420	
F11	1204.00	7.00	0.28	<1	29.79	0.59	46.60	4.80	0.28		
F12	915.00	7.70	0.22	5.07	28.42	0.45	1.90	0.14	0.22	>2420	>2420
F13	402.00	7.90	0.25	7.47	28.10	0.19	10.50	0.08	0.15		
F14	702.00	8.20	0.35	7.56	29.74	0.34	14.80	0.16	0.19		
F15	372.00	8.20	0.57	7.57	27.80	0.17	4.80	0.10	0.09	>2420	8
F16	609.00	8.10	0.35	5.74	29.60	0.29	19.50	0.20	1.18		

Sample No	EC (µS/cm)	pH	Turbidity (NTU)	DO (ppm)	Temp (°C)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
F17	2024.00	7.50	0.34	5.25	27.54	1.01	1.30	0.16	0.23	>2420	10
F19	563.00	7.80	0.30	5.23	27.70	0.27	8.10	0.30	0.14	>2420	6
F20	1070.00	8.00	0.27	7.59	29.64	0.53	19.20	0.04	0.50		
F21	1141.00	8.30	0.68	7.49	29.78	0.56	1.60	0.18	0.23	1203	8
F23	529.00	7.70	0.28	5.73	28.28	0.24	1.10	0.26	5.10	>2420	
F24	429.00	8.20	0.48	7.55	27.27	0.20	1.40	0.06	0.08		
F26	259.00	8.30	0.42	7.50	28.93	0.12	10.90	0.05	0.12		
F27	413.00	7.60	0.63	4.66	29.32	0.11	1.00	0.22	0.07	>2420	21
F28	513.00	7.90	0.12	6.91	29.74	0.24	1.00	0.10	0.22		
F30	797.00	8.00	0.28	7.50	29.57	0.39	13.00	0.16	0.20	>2420	1203
F32	202.00	7.10	0.43	4.62	26.81	0.09	1.80	0.30	0.55		
F34	1333.00	8.30	0.28	5.73	29.87	0.66	46.90	0.20	0.79	>2420	
F35	723.00	7.90	0.28	7.32	29.86	0.35	33.70	0.12	0.35		
F36	927.00	7.50	0.38	5.21	27.98	0.45	20.20	0.14	0.84	143	
F38	604.00	8.40	0.37	7.62	28.77	0.29	1.70	0.18	0.24	>2420	8
Samples in Agricultural Areas											
F7	752.00	7.60	0.780	7.23	30	0.36	1.30	0.14	0.23		
F25	809.00	7.50	0.260	6.92	29	0.39	1.80	0.20	0.08		
F33	46.74	8.40	1.880	6.75	30	30.22	4.80	0.78	0.25		
F40	873.00	8.30	0.530	5.44	30	0.42	5.90	0.13	0.43		
Samples in Industrial Areas											
F18	587.00	8.00	0.390	7.55	28	0.28	0.70	0.14	0.22		
F29	1200.00	7.10	0.370	3.02	28	0.59	17.50	0.10	1.47	2420	2.00
F37	844.00	8.00	0.440	6.74	30	0.41	18.10	0.20	0.24		
F39	1065.00	6.90	0.470	7.41	30	0.52	5.50	0.69	1.53	2420	
Samples in Other Areas											
F1	941.00	7.40	1.360	7.27	30	0.46	3.70	0.44	0.29		
F3	54.11	7.80	0.240	7.21	30	35.62	5.80	0.63	0.05		
F4	12.99	8.10	0.600	6.97	30	7.41	5.40	1.38	0.19		
F22	12.83	7.80	0.740	7.22	29	7.32	2.70	0.73	0.05		

Based on the full results and the summary shown in above table, the following can be summarized for Filladhoo Island:

- The EC of the groundwater is generally low, with an average of 687.14 µS/cm which is below an acceptable limit for potable water of 1500 µS/cm. The electrical conductivity readings range from 12.83 to 2024µS/cm. 98% of readings fall within the acceptable limit.
- The pH of groundwater ranged from 6.9 to 8.4 with an average of 7.84. The pH values of all samples were within the WHO permissible limits of 6.5-8.5.
- Turbidity ranged from the lowest of 0.12 NTU to 1.88 NTU with an average of 0.45 NTU.
- Dissolved oxygen levels were low to moderate, with values varying from 1 mg/L to 7.62 mg/L with an average of 6.21 mg/L.

- The salinity of groundwater ranged from 0.09 PSU to 35.62 PSU with an average of 2.80 PSU. Salinity is expressed in Practical Salinity Units (PSU) which is equivalent to PPT.
- The average Nitrate concentration was 11.05 mg/L and therefore it does not exceed the WHO guideline limit of 5.09 mg/L. But 21 of the 40 tested water samples exceeded this limit of 5.09 mg/L. The Nitrate concentrations ranged from 0.7 mg/L to 46.9 mg/L.
- Ammonia concentrations were generally low. The average ammonia concentration was 0.78 mg/L. This is within the WHO guideline value of 1.5 mg/L based on aesthetic (taste and odour) considerations. Only 3 tested water samples exceeded this limit (range from 0.02 to 4.8 mg/L). Natural concentration levels of ammonia are generally below 0.2 mg/L (WHO, 1993) and no tests showed concentrations below this level. There is no apparent correlation between increasing levels of ammonia and other nutrients.
- Phosphate concentrations were moderate. All values were within the range 0.05-5.1 mg/L with an average of 0.50 mg/L. There is no WHO drinking water guideline value for phosphate. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater (e.g. effluent from septic tanks and 'greywater' from kitchens and bathrooms). There were 6 samples tested below 0.1 mg/L.
- Total coliform levels were also found to be significant and ranged from the lowest count of 143 MPN/100 mL to the highest count of more than 2420 MPN/100 mL, with an average count of 2187.07 MPN/100 mL. Faecal Coliform levels were found to be less significant and ranged from the lowest count of 2 MPN/100mL to the highest count of 2420 MPN/100mL.

EC values of the selected wells were collected at the start of wet period (September – October) and following table show the summary of all the result collected during dry and wet periods based on the land use distribution.

Table 3.11: Comparison of WQ results based on land usage

Land Use	Number of samples	Results are lined with conditions	Increment of measured parameters
Residential area	39	35	F2, F6, F11, F23
Industrial Areas	7	6	F39
Agricultural area	4	3	F33
Other Areas	21	13	F3, F4, F22, F31, FW1, FW2, FW3, FW14
Total	71	52	14

Considered desirable water quality limits:

- 1) EC < 2500 $\mu\text{s/cm}$ (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 guideline.

Possible reasons for the increment of the measured parameters will be discussed in the feasibility & concept design report.

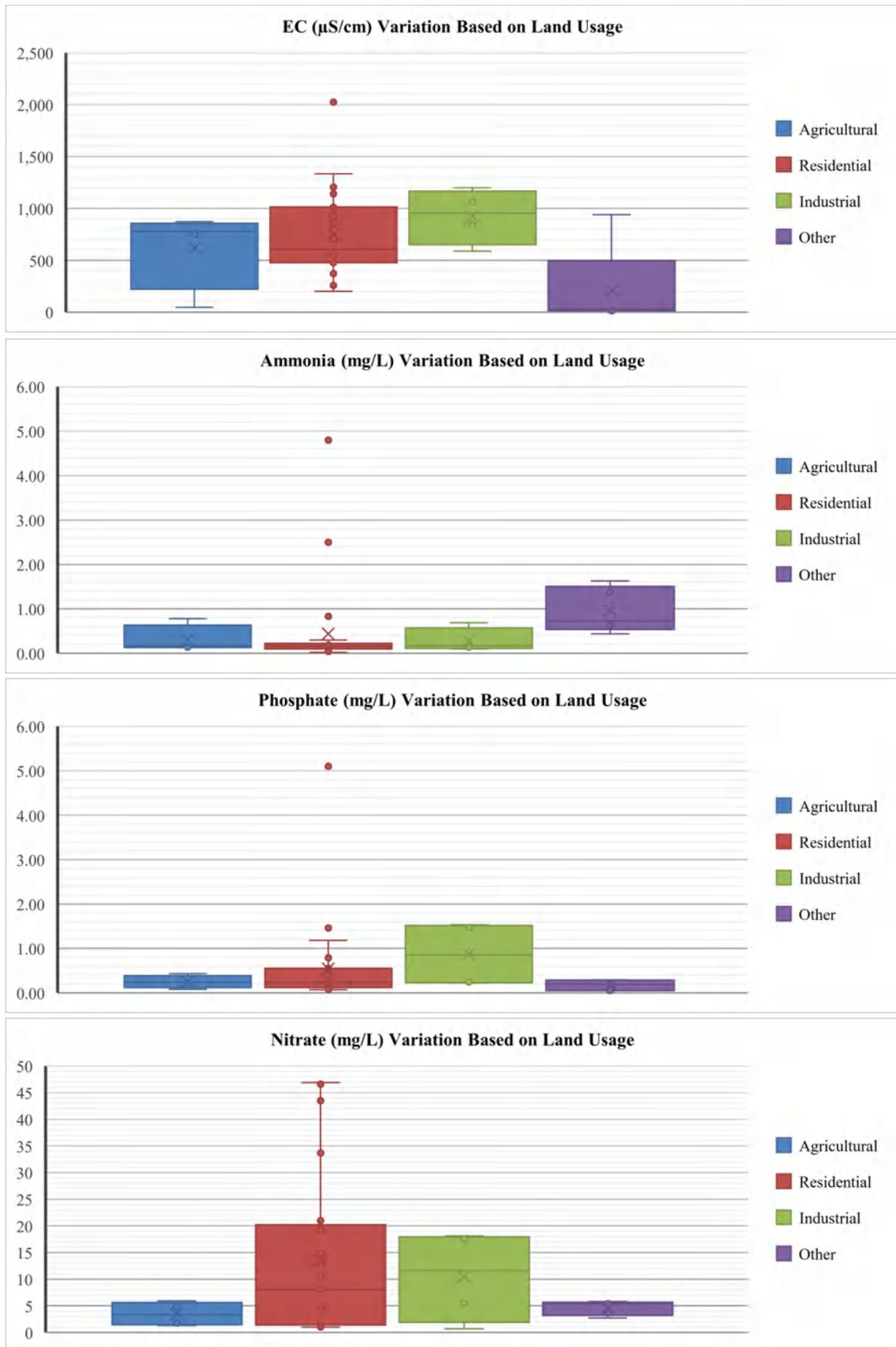


Figure 3-7: Variation of measured WQ parameters in Filladhoo Island



Figure 3-8: Locations of groundwater sampling points in Filladhoo Island

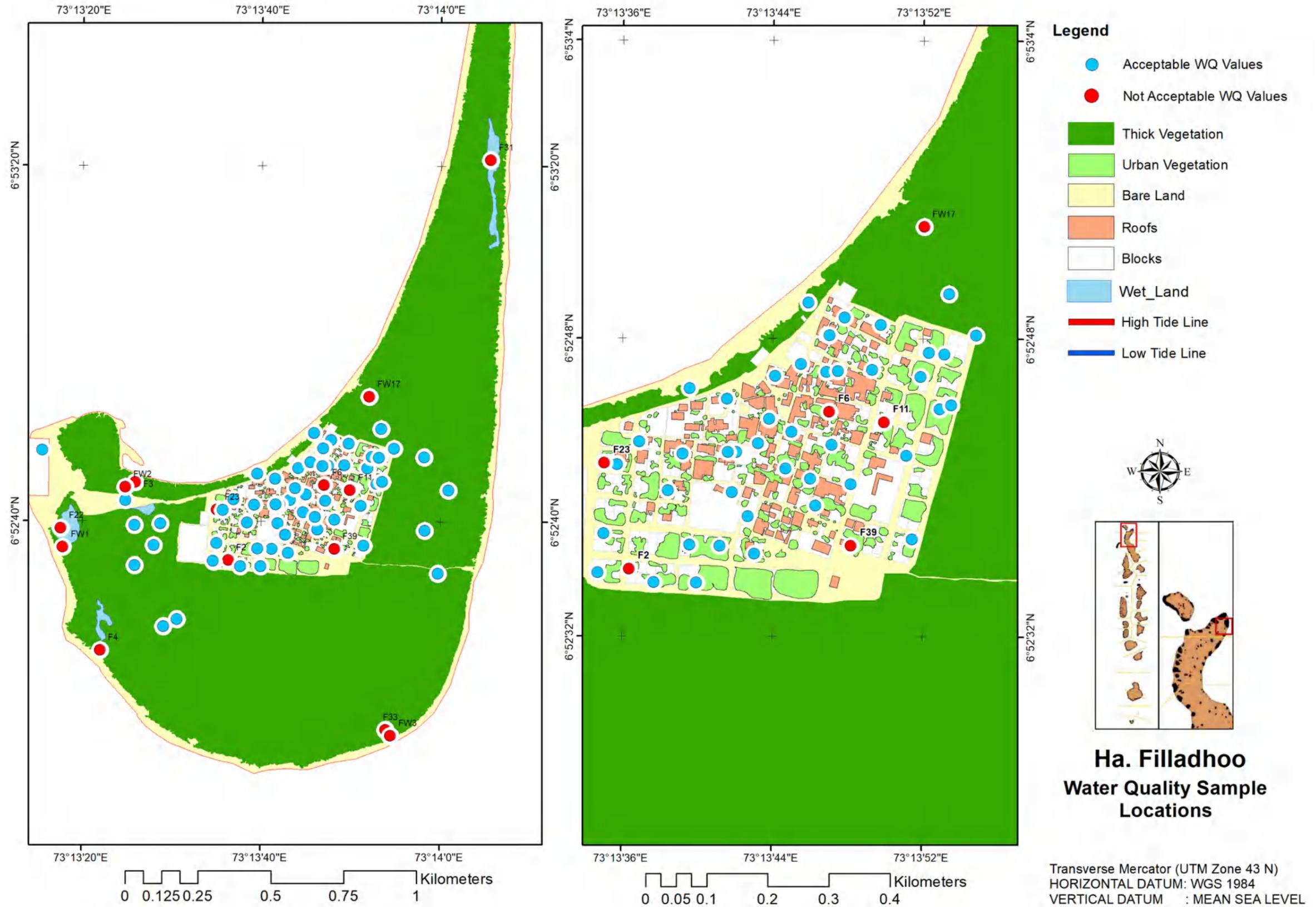


Figure 3-9: Locations of groundwater sampling points with critical WQ values in Filladhoo Island

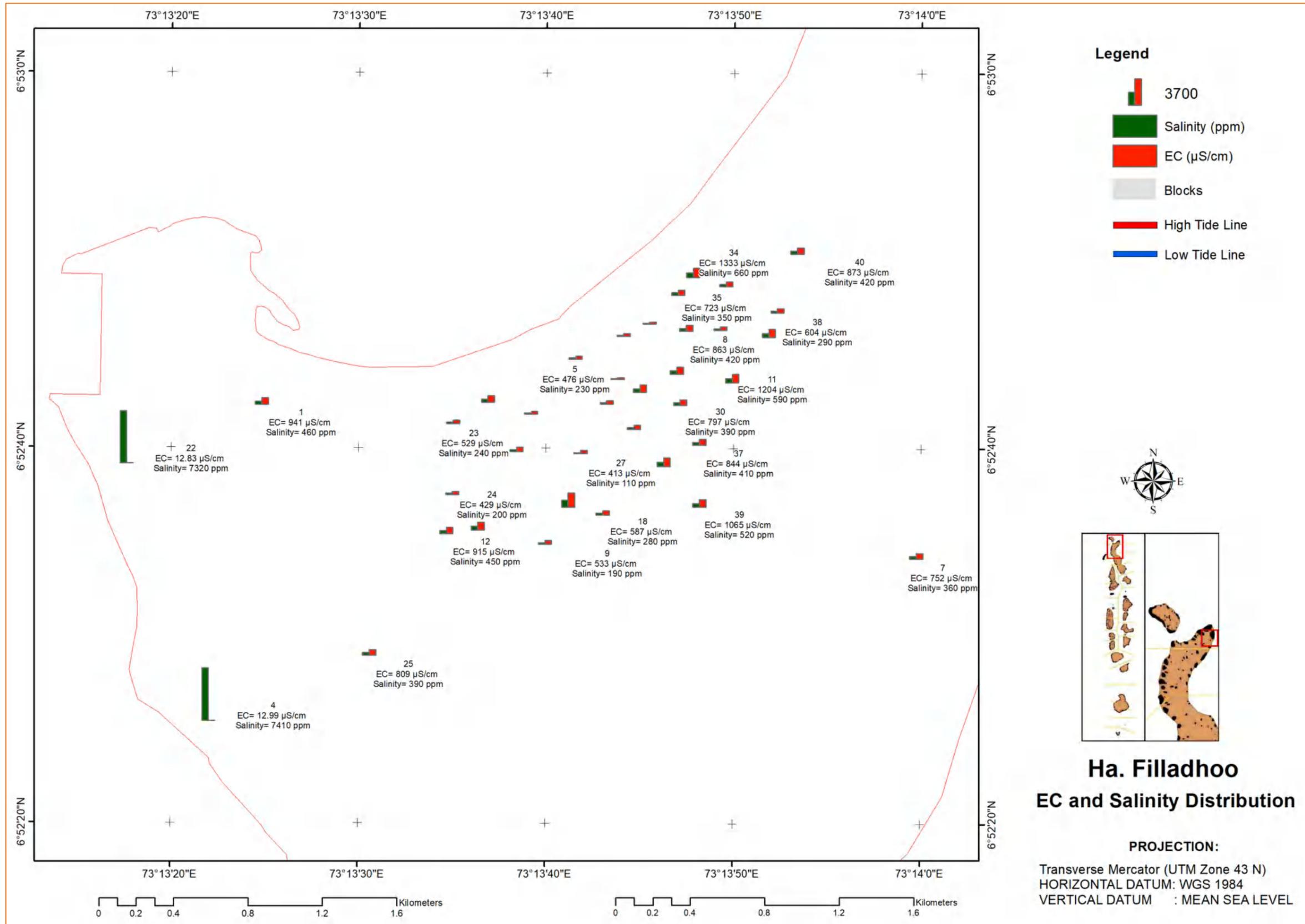


Figure 3-10: EC and Salinity Distribution in Ha. Filladhoo Island

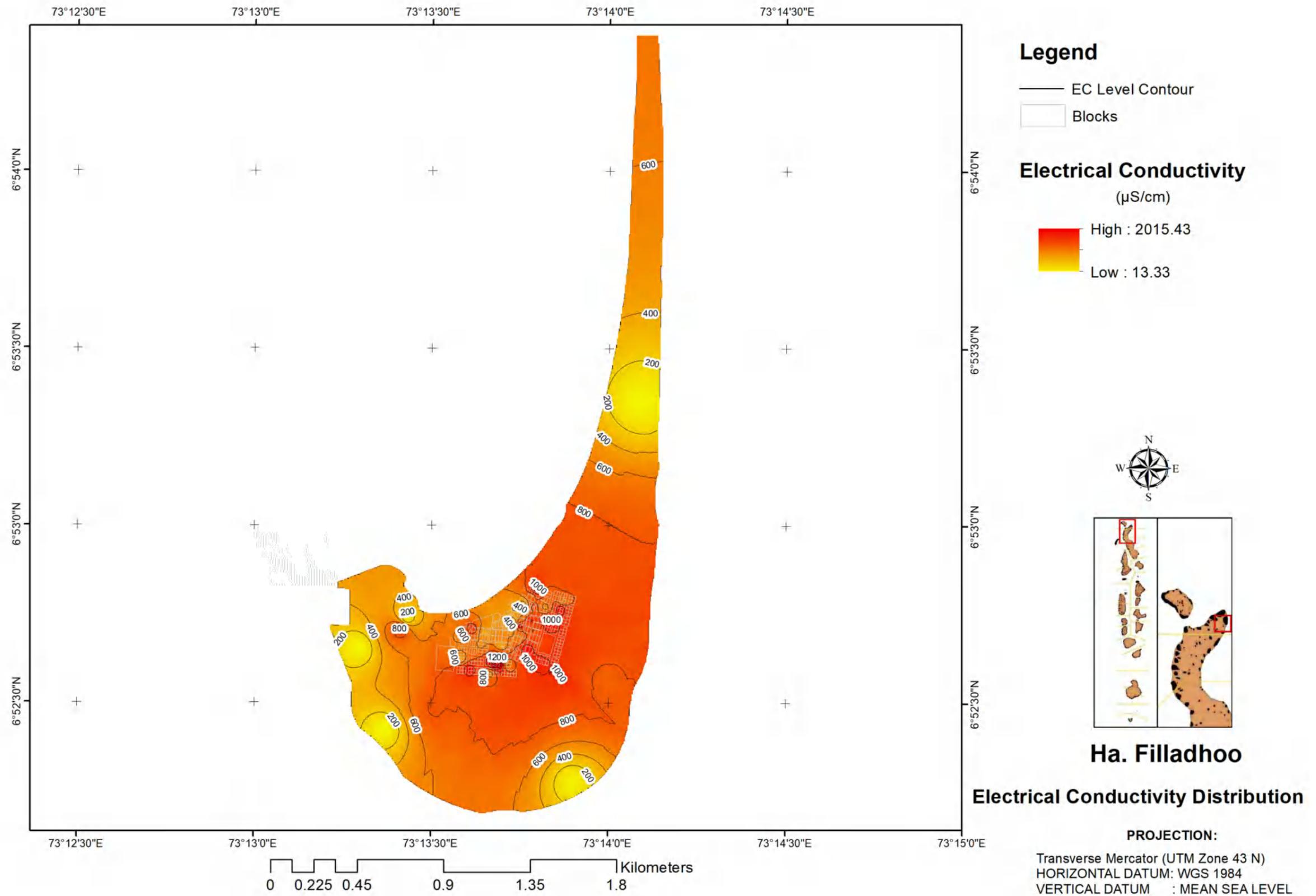


Figure 3-11: EC Distribution in Ha. Filladhoo Island

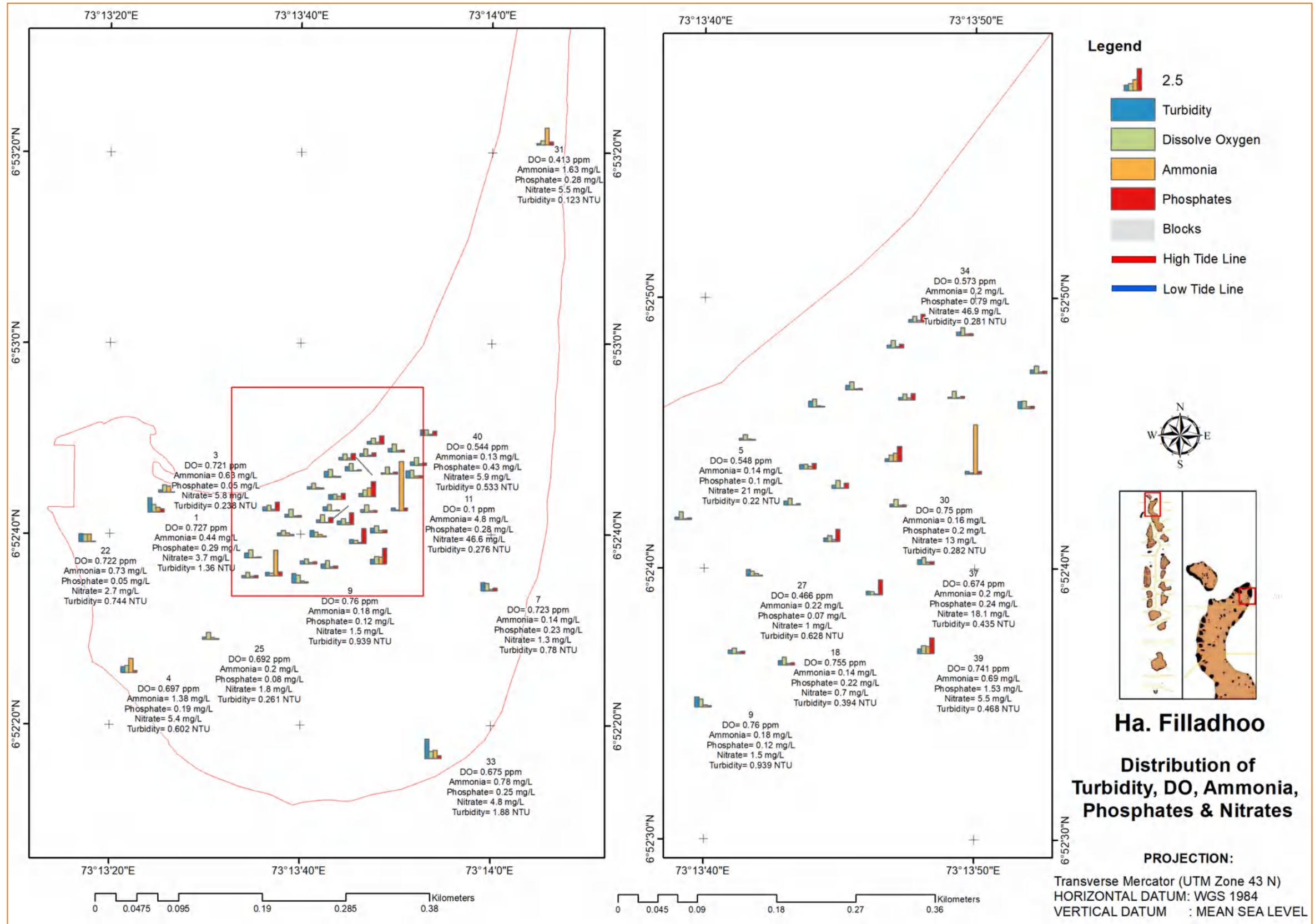


Figure 3-12: Distribution of Turbidity, DO, Ammonia, Phosphates and Nitrates in Ha. Filladhoo Island

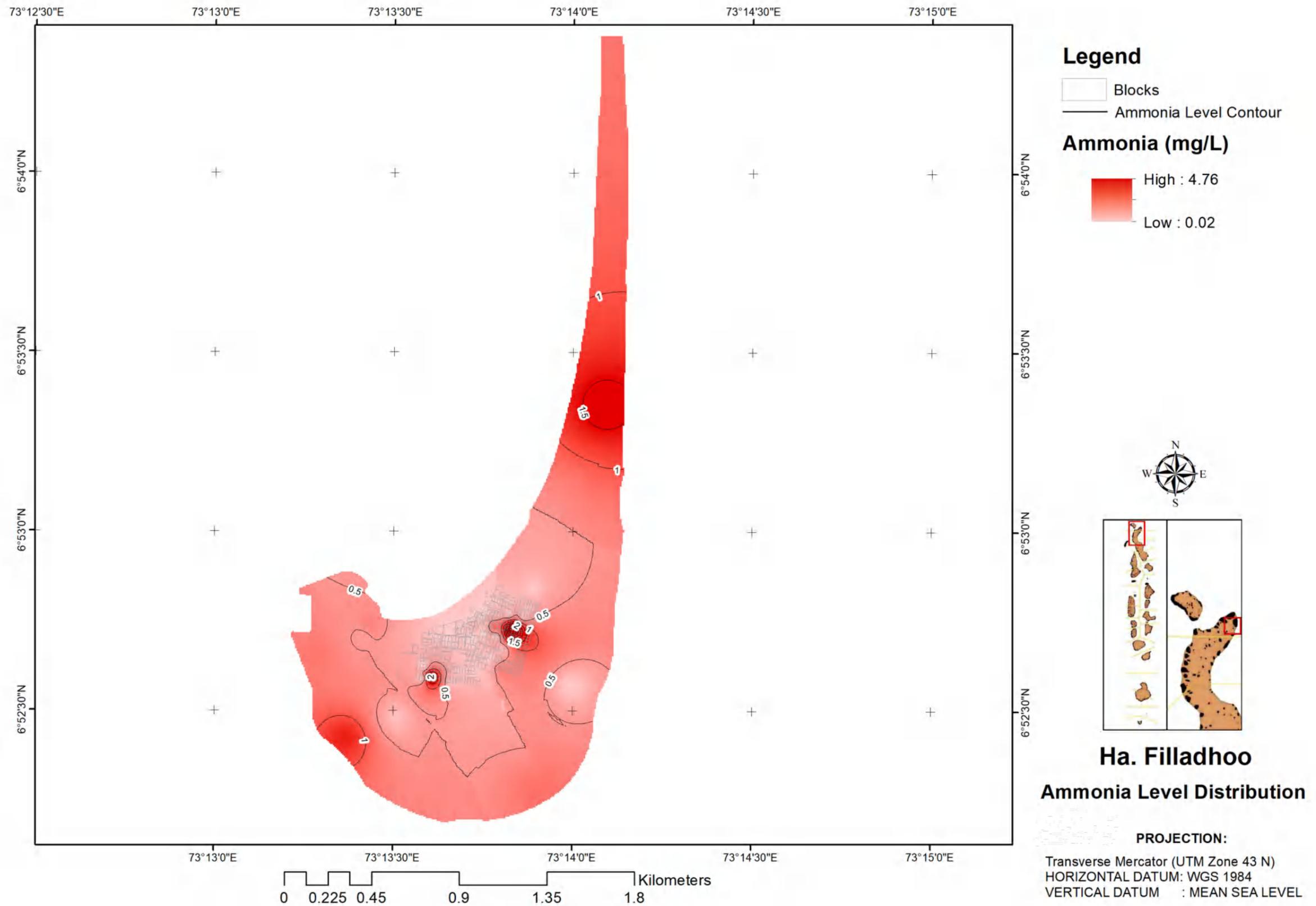


Figure 3-13: Ammonia Level Distribution in Ha. Filladhoo Island

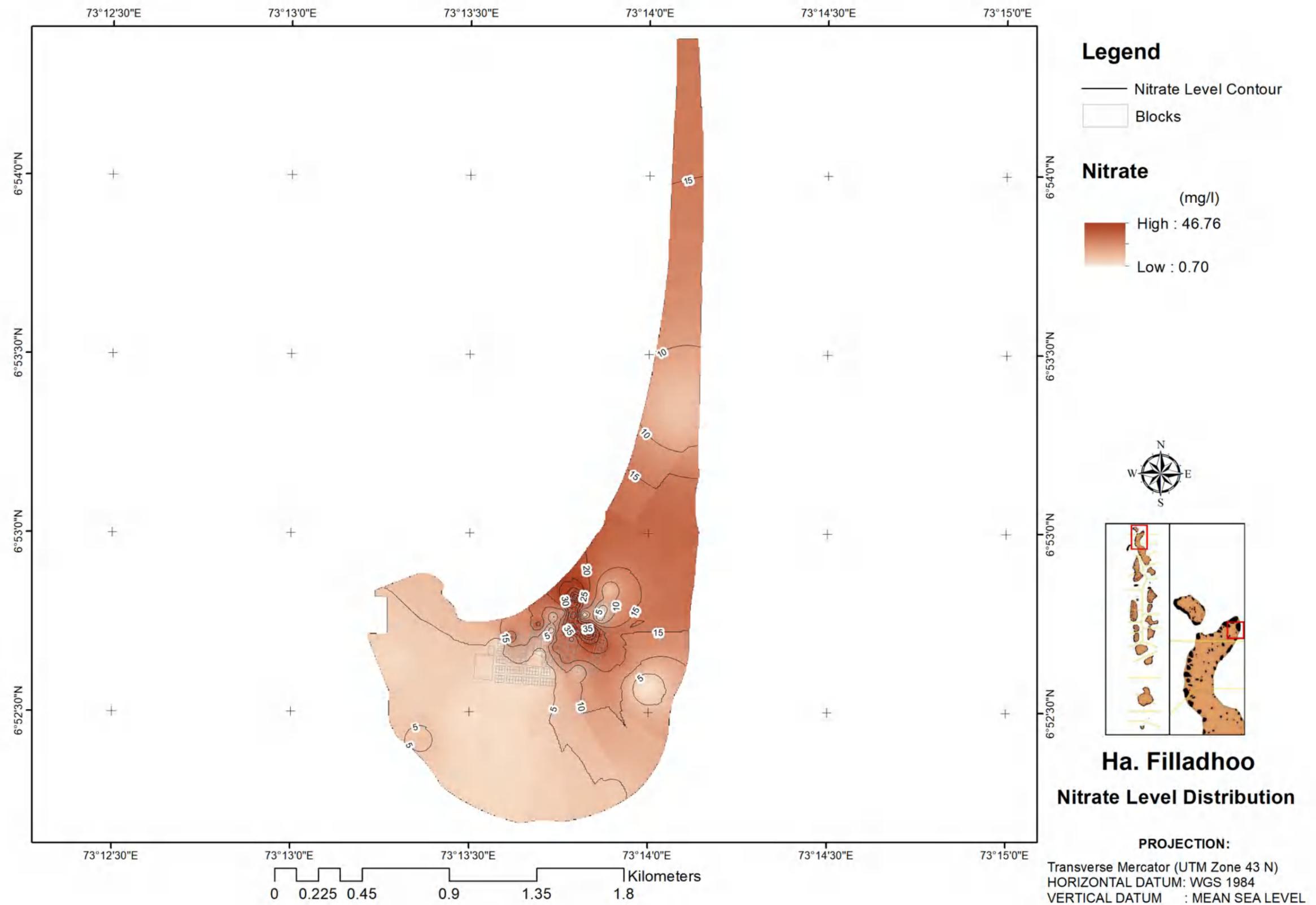


Figure 3-14: Nitrate Level Distribution in Ha. Filladhoo Island

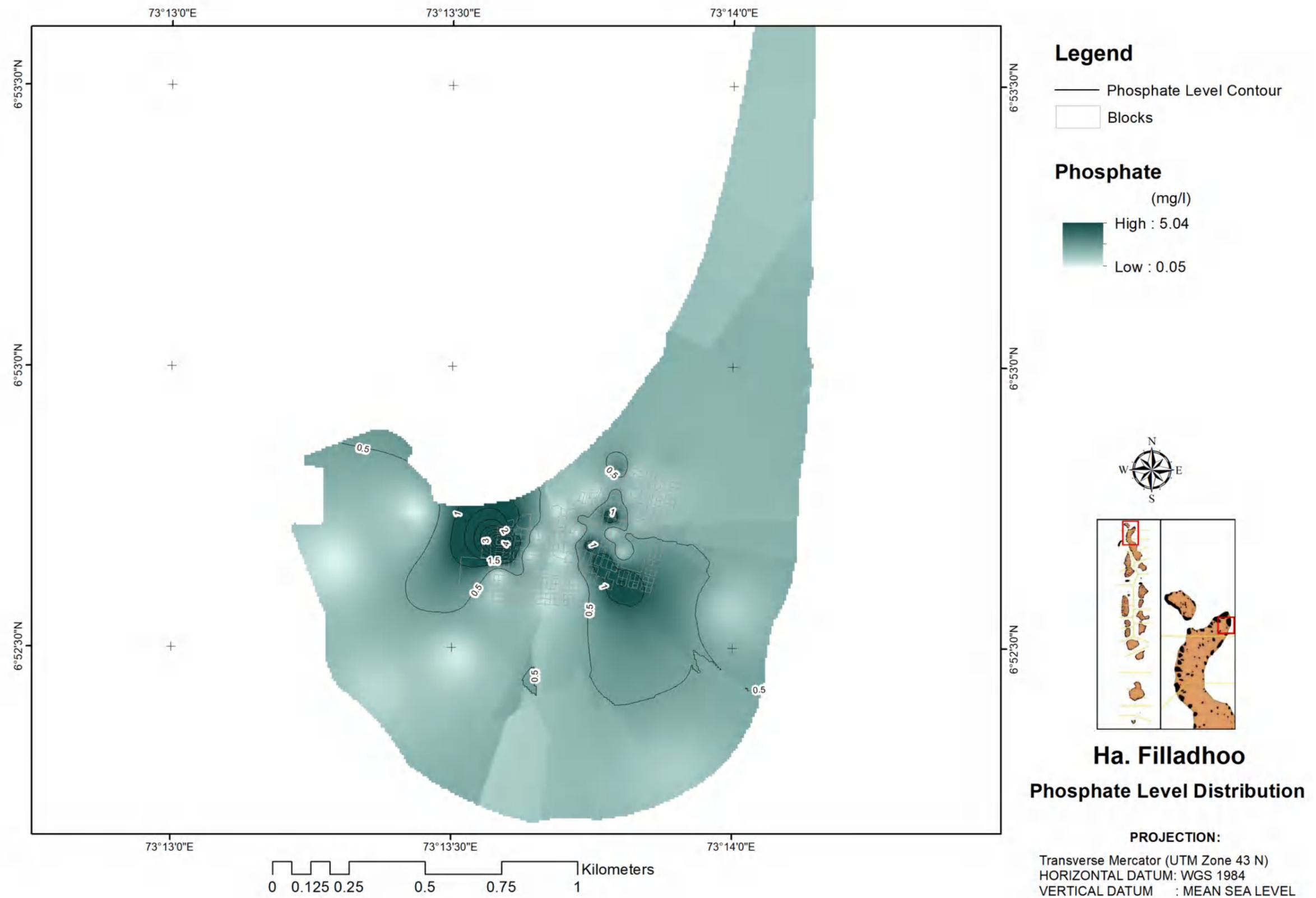


Figure 3-15: Phosphate Level Distribution in Ha. Filladhoo Island

3.7.8 Geophysical survey

The Electrical Resistivity (ER) tests were carried out in the locations as outlined in Figure 3-16 below. The ER survey included test points along 10 transects selected representatively based on reconnaissance surveys to adequately characterise different land uses and island cross-sections. The main transects were aligned along existing roads to maintain consistency and uniformity.

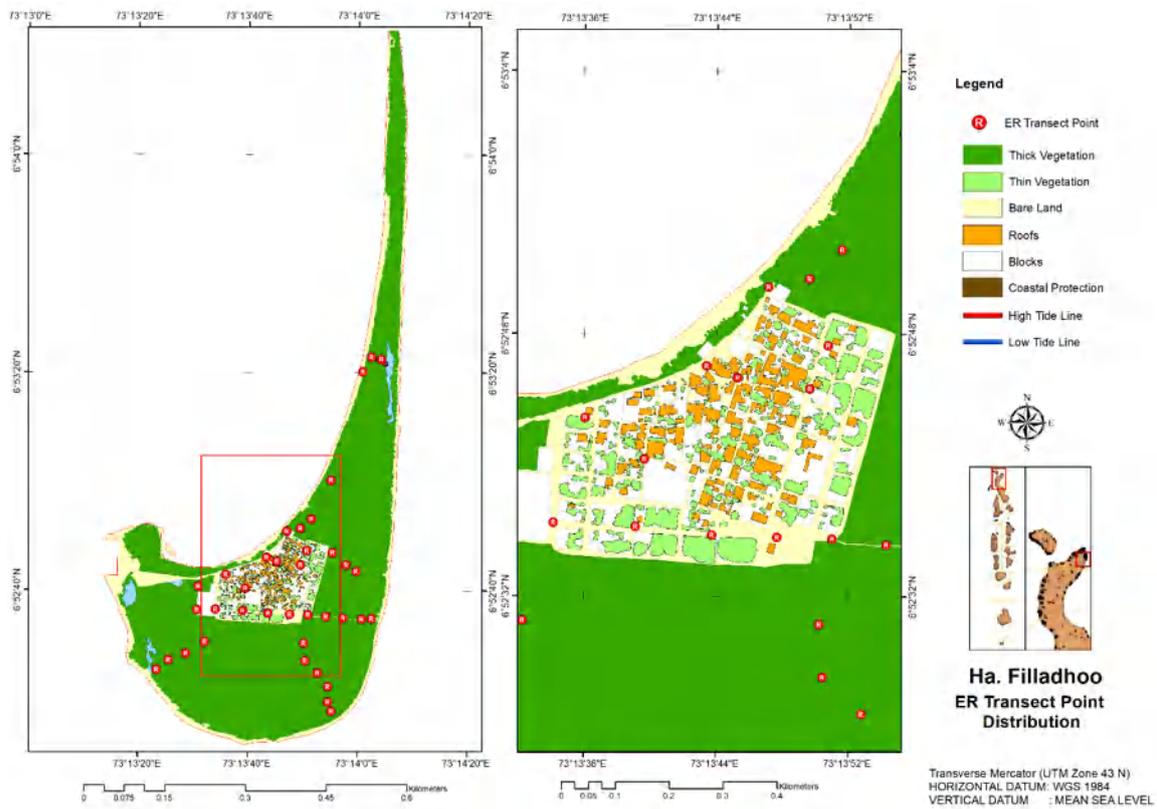


Figure 3-16: Location of ER points in Filladhoo Island

3.7.9 Aerial surveys

Based on the aerial survey, a multiple dataset consisting of buildings, roof cover, land cover, change detection and shoreline were extracted. This data is shown in Figure 3-17. The total roof cover for this island is 32,883 m².

3.7.10 Water demand

The only source of natural water is rainwater collected from the rooftops of households and institutions and groundwater extracted from shallow wells. The runoff water from the domestic yards, road surfaces, etc., is not usable as there is no mechanism for its collection and treatment.

3.7.11 Freshwater lens

Based on the Electrical Resistivity (ER) surveys, the depth to groundwater level and the freshwater-saline water interface were determined for a set of transverse transects as shown in Figure 3-16. Plots in Figure 3-2 show the main two cross-sections of island. The dotted lines in the plots indicate a simple interpolation of levels to mean sea level in the island boundaries.

Volume of the lens has been calculated with aid of ArcGIS and Surfer Software.

$$\text{Volume of lens} = 1,385,725 \text{ m}^3$$

$$\text{Groundwater Storage} = \text{Porosity (15\%)} \times \text{Lens volume (m}^3\text{)} = 207,859 \text{ m}^3$$

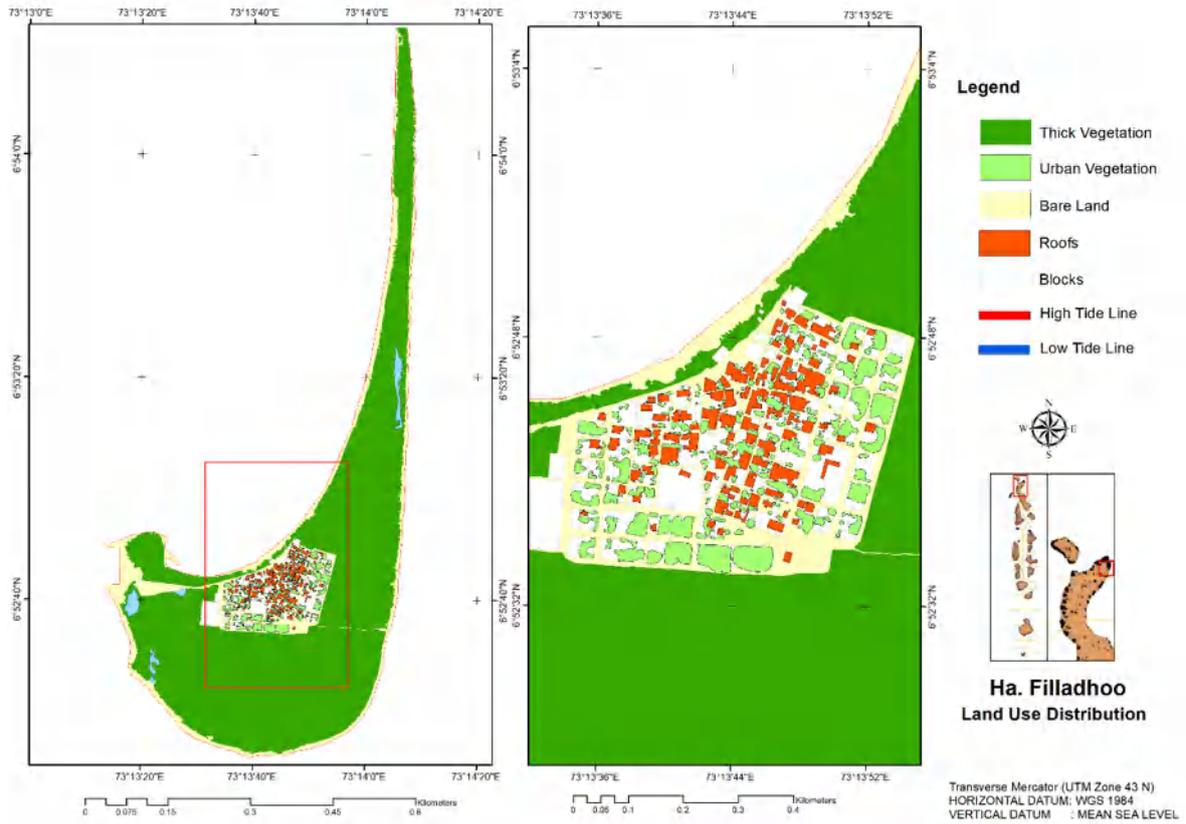


Figure 3-17: Roof Cover in Filladhoo Island based on UAV Survey

The 2-D freshwater lens distribution density maps produced with GIS software for visualization of the spatial and volume extents are also presented below in Figure 3-18 to Figure 3-20.

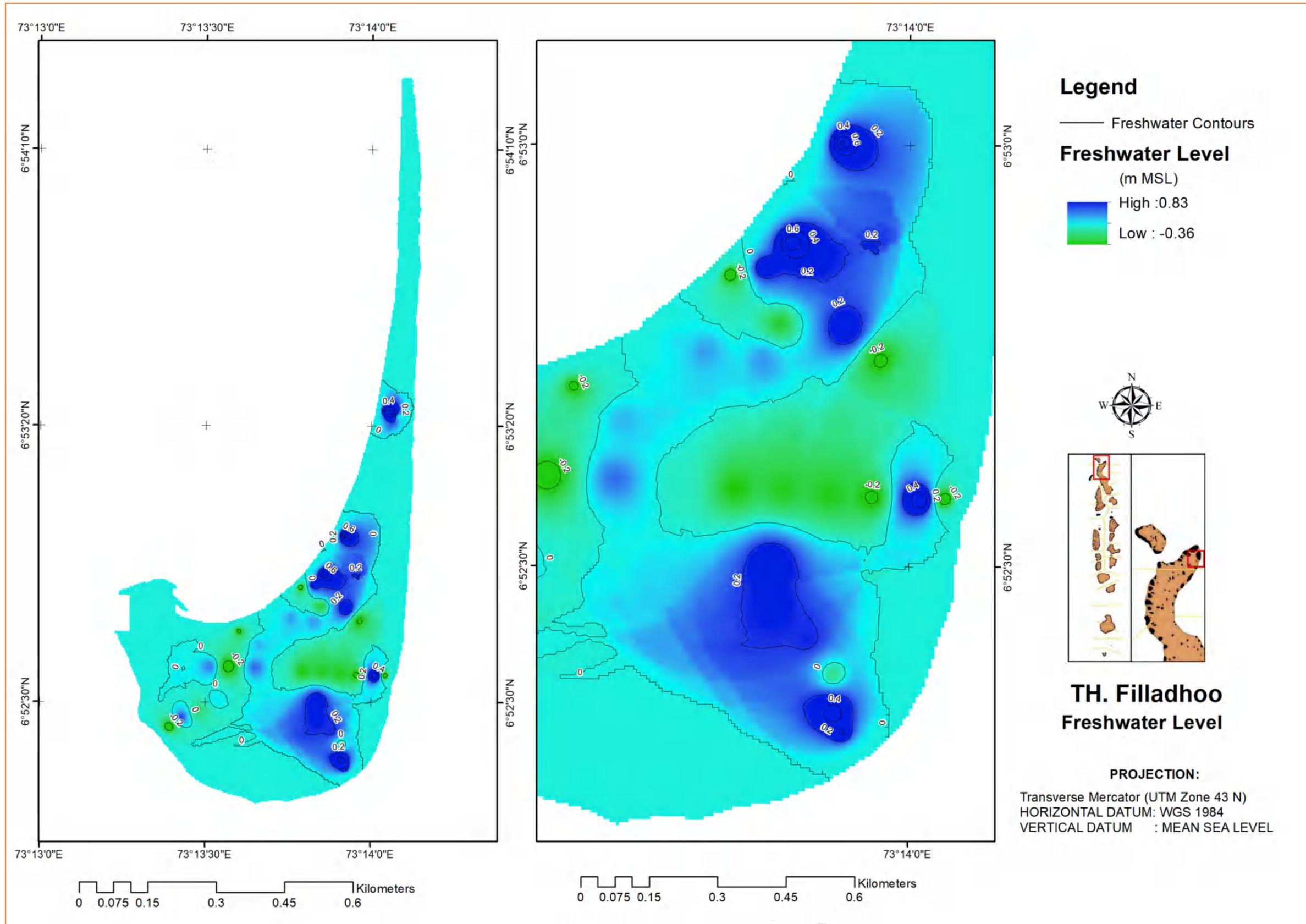


Figure 3-18: Freshwater Level in Filladhoo Island

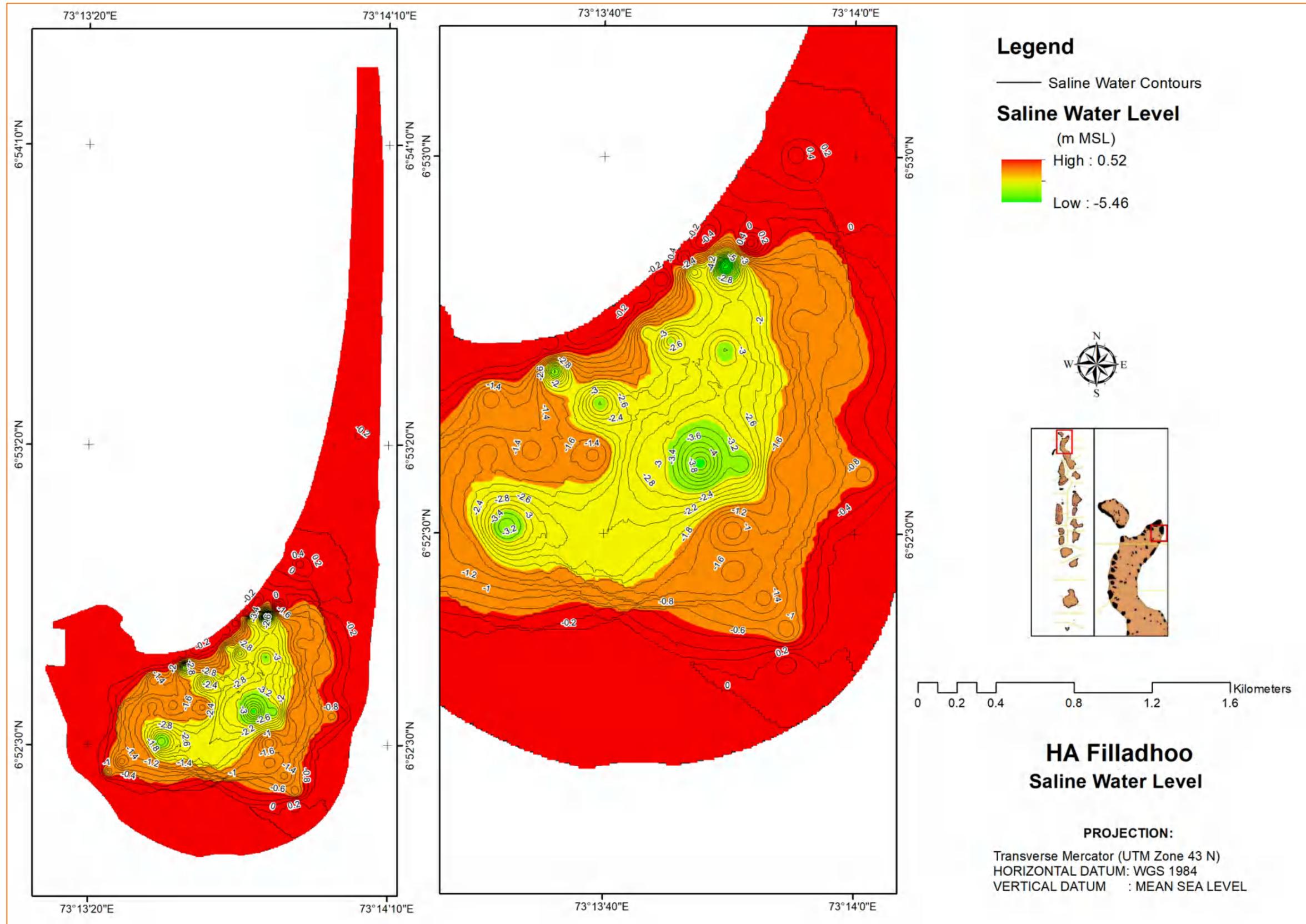


Figure 3-19: Saline water Level in Filladhoo Island

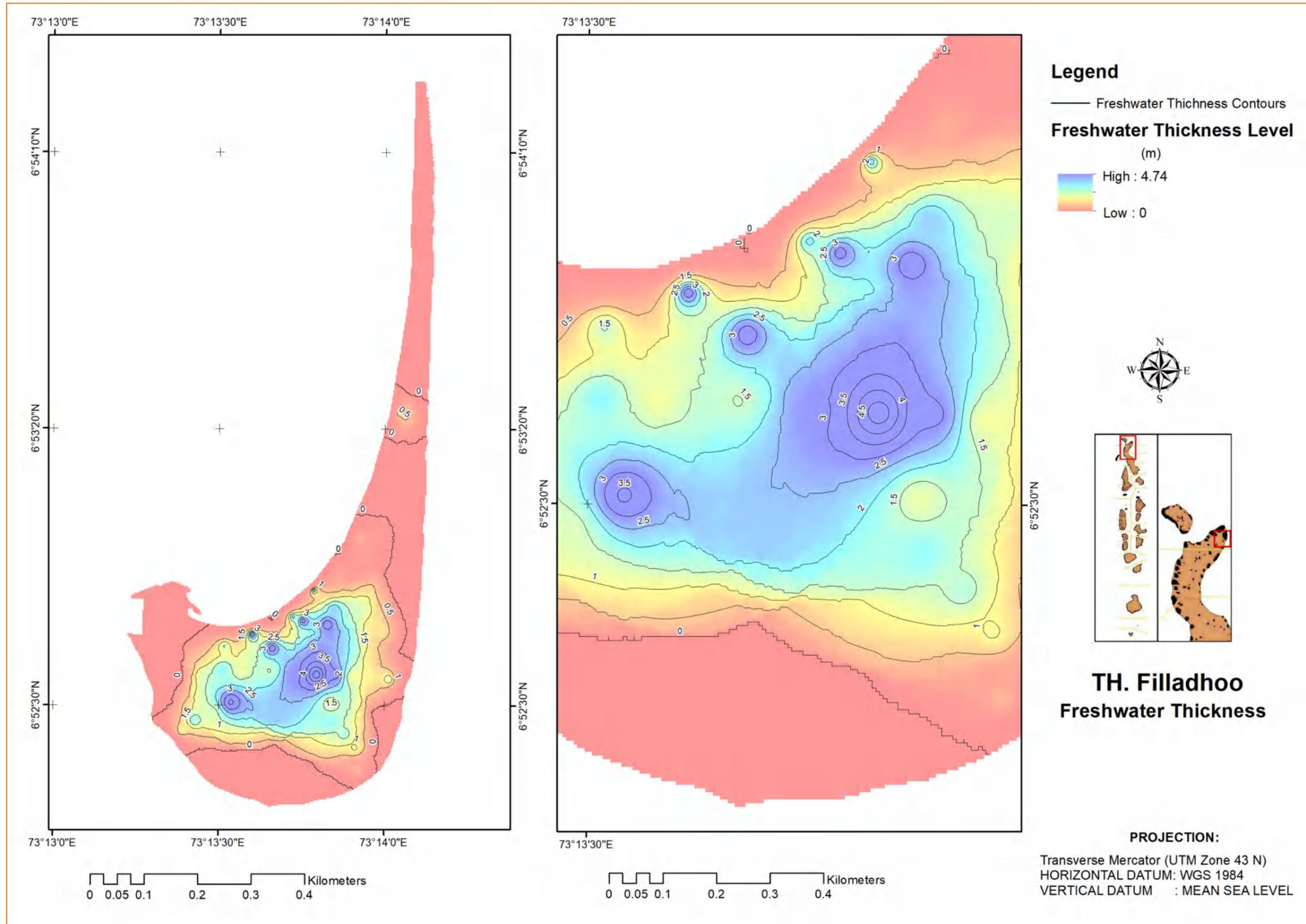


Figure 3-20: Freshwater thickness in Filladhoo Island

The maximum freshwater thickness of the island is 3.99 m (It is noted here that these readings were taken in October, which is the wet season and the with a reasonably higher number of wet days per month of the year).

3.7.12 Water balance and recharge

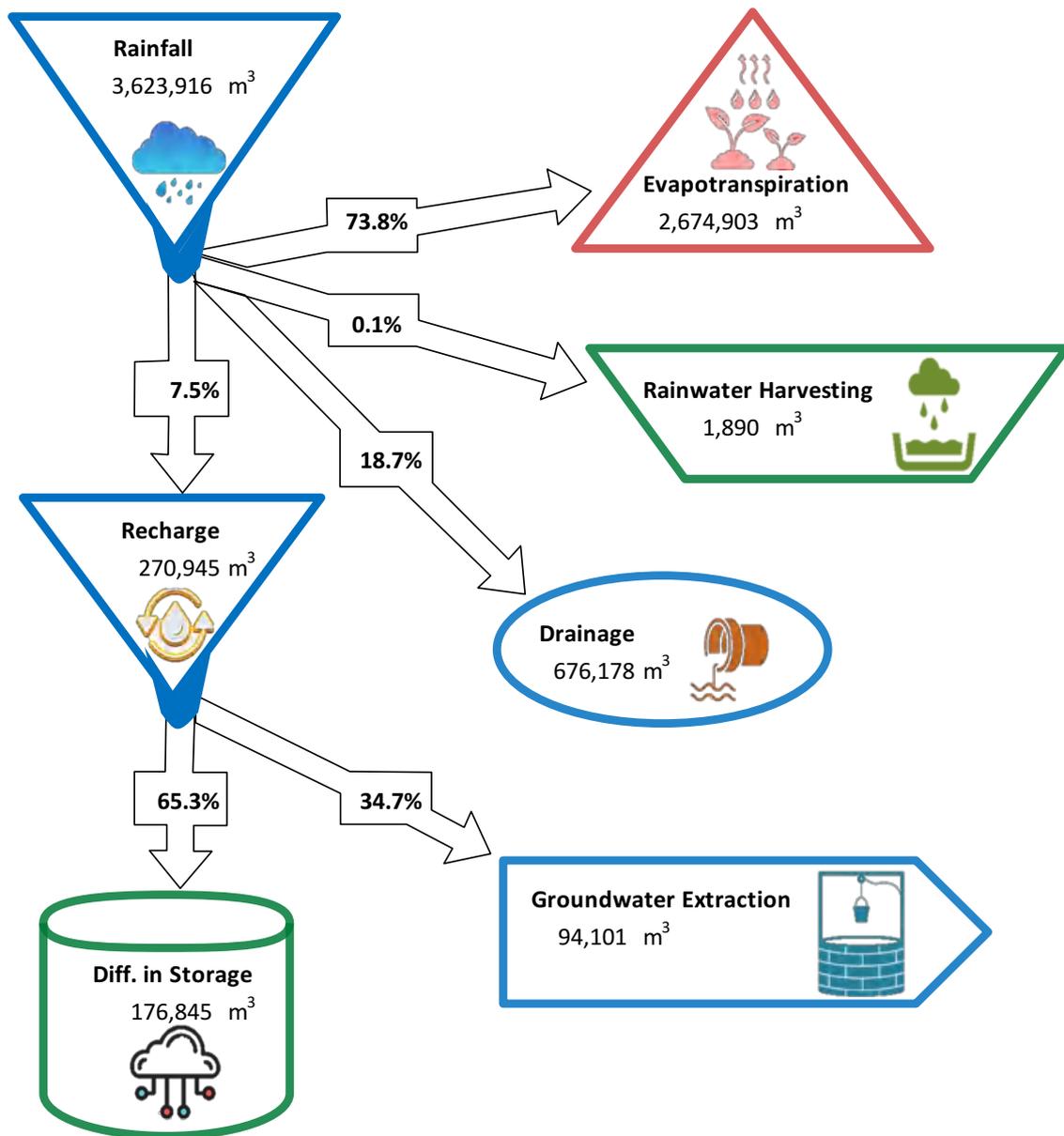


Figure 3-21: Schematic of water balance in Filladhoo Island

An annual estimation is carried out based on the water balance method (Falkland, 2000). Rainwater harvesting is calculated using the number of rainwater harvesting units on the island. According to the spatial mean annual rainfall of the Maldives, the annual average rainfall of Filladhoo Island is reported as 1,750 mm/year. Evapotranspiration was estimated using crop water requirements for different land use. Then, the rainfall was subtracted from rainwater harvesting, evapotranspiration, and drainage to get the recharge volume. Drainage or the surface runoff was calculated by considering an aggregate runoff coefficient for the island based on the land usage (roof cover, bare land, farmland, roads, playgrounds, wetlands). The groundwater extractions were estimated from the amount of water usage in different sectors (residential, resorts, restaurants, agriculture and farming). The difference between recharge and groundwater extraction is taken to estimate the difference in storage.

3.7.13 Sustainable yield of the lens

Sustainable yield of the water lens refers to the safe extraction potential of a given groundwater aquifer without significantly affecting its quality or quantity. This parameter is an important factor in the sustainable development of islands as it allows the planning and design of water and sanitation interventions in islands.

The island has a sustainable yield of 485 m³ per day which was calculated by subtracting groundwater extraction from recharge volume derived from the schematic water balance model in Figure 3-21.

3.7.14 Permeability test

Permeability tests were carried out in the selected locations as outlined in Figure 3-22.

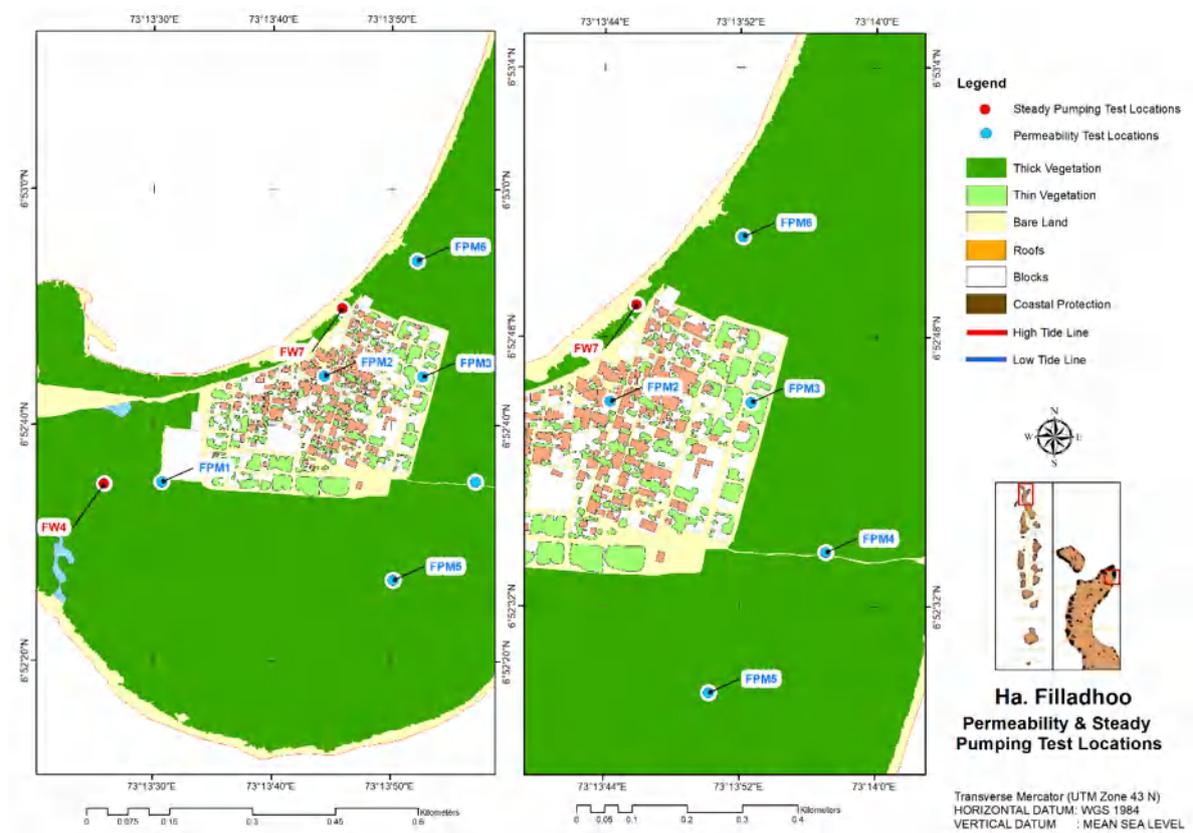


Figure 3-22: Locations of permeability and steady pumping tests in Filladhoo Island

The estimated permeability values for the above test locations are presented below in Table 3.9. The data will be comparatively verified and interpreted when additional data is acquired and calculations for other islands are completed.

The parameters have their usual notations where, K = Coefficient of permeability (m/s under Q unit gradient), Q = Steady flow into well (m³/s), H = Height of water in well (m), l = length of the perforated section (m), U = thickness of saturated permeability material above water table, r_1 = outside radius of the casing (radius of the hole in consolidated material) (m), r_e = effective radius of well = r_1 (area of perforations) / (outside area of perforated section of casing): $r_1 = r_e$ in consolidated material that will stand open and is not cast, C_s = Conductivity Coefficients, and T_u = distance from water level in the casing to water table (m).

Table 3.9: The Estimated Soil Permeability Values in Filladhoo Island

Point	FPM1	FPM2	FPM3	FPM4	FPM5	FPM6
D (m)	0.300	0.500	0.650	0.650	0.650	0.700
H (m)	0.300	0.500	0.650	0.650	0.650	0.700
ℓ (m)	0.300	0.500	0.650	0.650	0.650	0.700
U (m)	0.350	0.600	0.750	0.750	0.750	0.800
T _u (m)	0.350	0.600	0.750	0.750	0.750	0.800
r (m)	0.076	0.076	0.076	0.076	0.076	1.076
Q (m ³ /s)	1.89E-06	1.42E-05	2.78E-06	2.56E-06	1.06E-05	1.06E-05
r ₁ (m)	0.076	0.076	0.076	0.076	0.076	1.076
r _e (m)	0.010	0.010	0.010	0.010	0.010	0.010
T _u /ℓ	1.167	1.200	1.154	1.154	1.154	1.143
X = (H/T _u × 100)	86%	83%	87%	87%	87%	88%
Section	Zone 2	Zone 3				
ℓ/r _e	29	48	63	63	63	67.37
C _s	48	73	92	92	92	100
K (m/s)	1.34E-05	4.46E-05	5.88E-06	5.41E-06	2.23E-05	4.94E-06
K (m/day)	1.16	3.85	0.51	0.47	1.93	0.43

3.7.15 Steady Pumping Test

Pumping tests were conducted in two existing wells to estimate the aquifer properties of unconfined water bearing formation and transmissivity of the water bearing formation was estimated using Muskat's Method, as follows;

$$T = \frac{C'A}{2\pi t'} \ln\left(\frac{S_1}{S_2}\right)$$

where $C' = \ln\frac{r_o}{r_w}$

T - Transmissivity

A - Cross-sectional area

r_o - Distance of which drawdown is negligible at the end of pumping

r_w - Radius of the well

S₁ - Drawdown at the time pumping stops

S₂ - Residual Drawdown at the time of t' after pumping stops.

Table 3.10: Selected Steady State Pumping Test Locations in Filladhoo Island

Well No.	C'	A (m ²)	t' (s)	ln($\frac{S_1}{S_2}$)	T (m ² /s)
FW 1	5.2	1.17	840	4.4	0.0051
FW 4	3.9	5.02	1500	1.83	0.0038

The measured transmissivity (m²/s) values ranged from a minimum of 0.0038 m²/s to a maximum of 0.0051 m²/s, with an average of 0.0044 m²/s. During the testing period, EC (Electrical conductivity) levels of both wells are given below.

- For FW 1, EC has not increased and average EC is about 1190 µs/cm.
- For FW 4, EC has not increased and average EC is about 1150 µs/cm.

3.7.16 Status of groundwater availability in Filladhoo Island

- 1). The selected Filladhoo island has dimensions of width = 1570 m and length = 2890 m, with a total land area of 207.08 ha, a population of 272 persons, and a land use of Roof cover (Built up area) 3.20 ha (1.5%), Vegetation (Thick) 156.37 ha (75.5%), Vegetation (Light) 5.05 ha (2.4%), and Barelands 40.24 ha (19.4%).
- 2). In order to recognize the fluctuation in the groundwater table, freshwater-saline interphase and estimate the volume of freshwater lens (FWL) and its associated recharge-discharge characteristics, 50 number of Electrical Resistivity (ER) location readings along 06 representatively selected transects were collected.
- 3). Soil overburden permeability tests (constant head) were carried out at 05 locations while steady-state pumping tests were conducted at 01 locations. In addition, groundwater level was also recorded at 10 locations where groundwater water quality samples were tested.
- 4). Permeability tests were carried out at representatively selected 05 number of locations. The measured permeability (K m/day) values ranged from a minimum of 5.82 m/day to a maximum of 14.55 m/day, with an average of 10.56 ± 4.41 m/day (Mean \pm Standard Deviation).
- 5). The ground elevation values ranged from a minimum of -3.48 m MSL to a maximum of 3.67 m MSL, with an average of 0.76 ± 0.63 m MSL (Mean \pm Standard Deviation).
- 6). The upper boundary of the freshwater lens (FWL) varied from a minimum of -0.38 m MSL to a maximum of 0.85 m MSL, with an average of 0.02 ± 0.08 m MSL (Mean \pm Standard Deviation).
- 7). The lower boundary of the freshwater lens (FWL) or freshwater-saline interphase ranged from a minimum of -5.46 m MSL to a maximum of 0.52 m MSL, with an average of -0.63 ± 0.92 m MSL (Mean \pm Standard Deviation).
- 8). Accordingly, the freshwater lens (FWL) volumetric values ranged from a minimum of 0.00 m to a maximum of 4.74 m, with an average of 0.64 ± 0.91 m (Mean \pm Standard Deviation).
- 9). The groundwater profile in the island is characterised by a relatively Low (0.05%) Rainwater Harvesting (%) relatively Very Low (18.66%) Drainage (%) relatively Very Low (7.48%) Recharge (%) while the water use shows relatively Low (34.73%) Groundwater extraction (%) leading to relatively Very High (65.27%) Difference in Balance Storage (%).
- 10). The freshwater lens (FWL) volume calculated based on ER transect test data is 207,859 m³ with a maximum FWL thickness of 4.74 m.

3.8 Conclusion

The Safe Yield for the island estimated based on 'Recharge - Extraction' is 485 m³ per day, while it is 993 m³ per day based on 10% of the Average Annual Rainfall Method. The present groundwater extraction rate estimated based on survey data is 258 m³ per day and this is about 53% of the allowable Safe Yield in the island (not stressed). At present, there exists no island wide sewerage network or water supply network.

Relative hydraulic conductivity of the island lies in the 'Semi-pervious' state while the present aquifer condition remains at 'Poor' state based on the hydraulic conductivity estimation carried out as per Bear (1972) and transmissivity of the formation was compared as per Kranj (1993). Moreover, general status based on transmissivity is ranked as 'High' and the potential for groundwater recharge remains 'Low' – 'Moderate' as per the estimations.

4 HA. MAARANDHOO ISLAND

4.1 General Overview of The Island

The island of Maarandhoo (Figure 4-1) is located on the southern periphery of Haa Alifu Atoll at coordinates 72°59'3" E, 6°51'7" N. The island has an area of about 0.4 km² and measures about 0.53 km in width and 1.09 km in length. The population of the island was found to be about 700 residents as of December 2021. The island has a harbour on the South Eastern side of the island. The following table outlines some basic information about the island and the following map outlines the location of Maarandhoo.

Table 4.1: Basic statistical information on Maarandhoo island in Haa Alifu Atoll.

Name of the island	Th. Maarandhoo
Longitude and Latitude	72°59'3"E, 6°51'7" N
Area	41.1 ha (0.4 km ²)
Population (Dec 2021)	1079
Distance from Male'	302 km
Harbour	Present
Island sewerage network	Under construction
Water supply network	Under construction
Other infrastructure	No

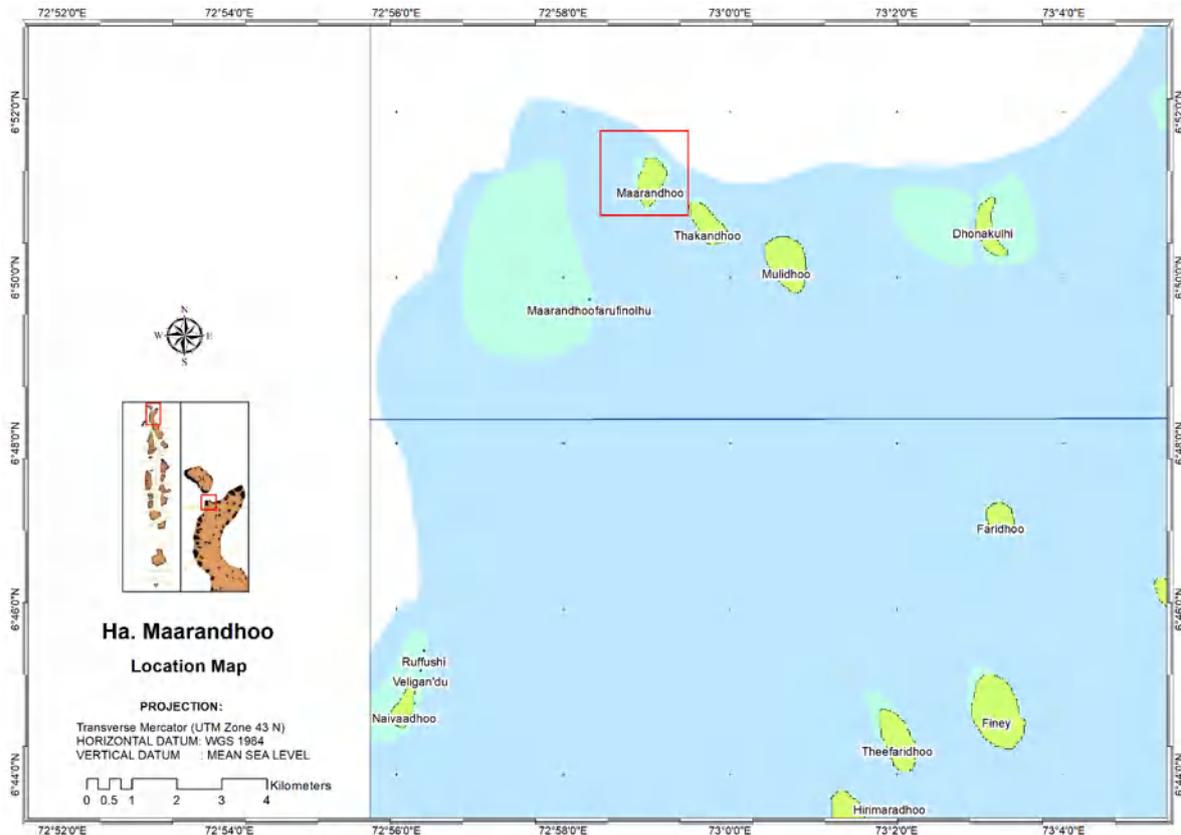


Figure 4-1: Location map for Maarandhoo Island, Haa Alifu Atoll.

4.2 Topography and Geology

Maarandhoo island is on the middle of the “Ha. Alifu Atoll” which is located close to the North end of the chain of Maldives islands. Maarandhoo is an island with an ellipsoid shape and extends about 1,000 m (NE-SW) in length (AB) and about 550 m (NW-SE) in width (CD). Basic topography and the geological setting are mostly based on the properties of the underground coral beds and the actions of ocean waves and currents. The elevation of the island varies from -0.16 m MSL to 3.45 m MSL and generally flatland through the island with few elevated peaks. The general geological profile in the island is composed of topsoil and beach coral sand deposits underlain by sandy coral rock (Figure 4-2). The sandy coral rock consists of a weathered coral rock layer and hard fresh coral rock. According to the cross-section AB, the topsoil layer ranges from 0 to 0.5 m. The beach coral sand layer is about 0.2 m thickness in beach areas (AB) and about 1.5 m thickness in the middle of the island. In western beach areas mostly beach coral sand exists as the top layer. Coral sand layer is mostly unconsolidated and permeable layer. According to the cross-section A-B weathered coral rock depth is varying between 0.2 m (coastal areas) to about 4.0 m (middle of island) from MSL, and it is a semi permeable layer. Fresh groundwater lens occupies both coral sand layer and weathered coral rock. The hard coral layer is mostly unconsolidated and impermeable and present as a fresh rock. As the compositional and structural differences of coral formation, differential weathering could be observed in the cross-section A-B. The cross-section A-B clearly shows few deep weathered zones. However, the cross-section C-D shows uniform weathering and general trend is central part of the island shows higher weathering compared to the coastal area.

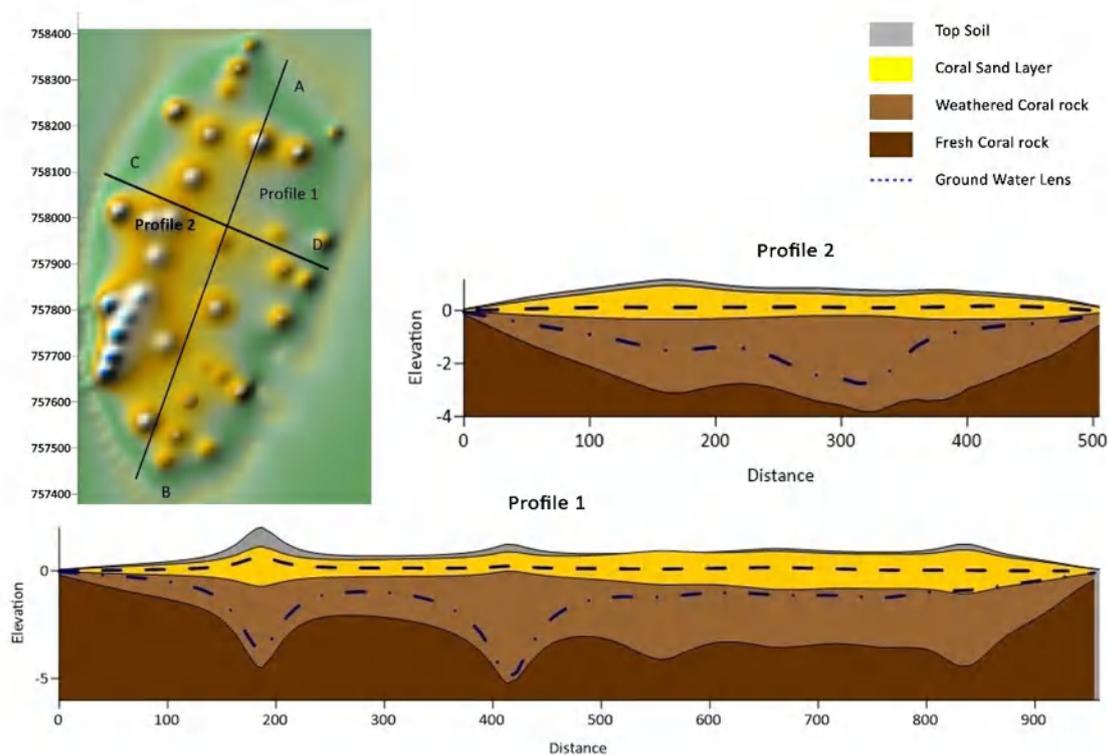


Figure 4-2: Geological sections of the island showing subsurface geological characteristics

4.3 Climate

Maarandhoo experiences the typical two monsoons in the Maldives namely, the North-east monsoon from December/January to March/April and the South-west monsoon from Mid-May to November. There are no specific wind and rainfall data available for Maarandhoo as there are no weather monitoring stations on the island itself. Based on the rainfall data of the nearest weather monitoring station, it shows a declining trend in rainfall for the past 30 years (Inception Report, 2021).

The historical rainfall data records from Hanimadhoo Island (not included in the 5 selected islands in Lot 1) located in the Haa Alifu atoll (23 km to the south east from Maarandhoo Island) has an annual average rainfall of 1,747 mm with a standard deviation of 279.1 mm and the trend with the decadal means were shown in the following graph (MEE, 2021).

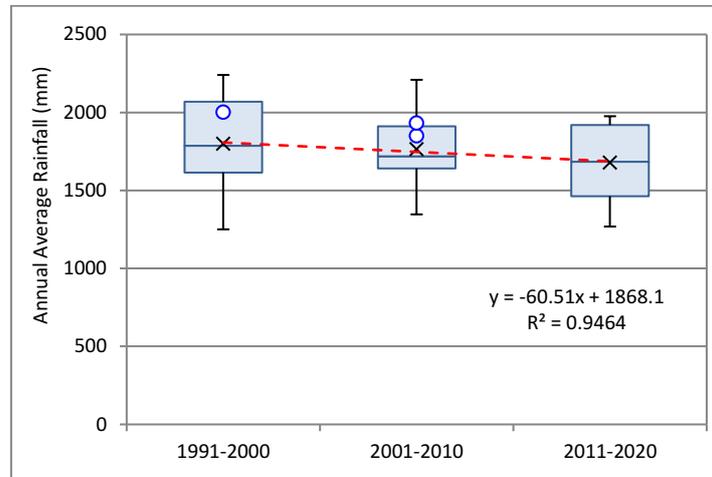


Figure 4-3: Decadal means and trend for rainfall in Hanimadhoo (1990 - 2020).

4.4 Demography

As of December 2021, Maarandhoo has a registered population of 1079 including 563 males and 516 females (Maarandhoo Council 2021). As per the council, an estimate of 665 locals and 35 foreigners currently resides in the island making the residential population 700. Foreigners includes teachers, medical staff and labour force working in different projects that are being undertaken in the island.

Total number of households in Maarandhoo at present is 144. The following table summarises the population breakdown for Maarandhoo.

Table 4.2: Demographic Breakdown of Maarandhoo Island as of December 2021

Registered Population			Resident population								
			Total			Maldivians			Foreigners		
Both	Male	Female	Both	Male	Female	Both	Male	Female	Both	Male	Female
1079	563	516	700	691	384	665	290	375	35	26	9

Source: Maarandhoo Island Council 2021

4.5 Socio-economic condition

4.5.1 Natural Resources and Land Uses

Maarandhoo has an area of 43.6 hectares with the majority of the western side of the island settled by the islanders.

There is one wetland areas on the north east side of the island. According to the island council, there area is not managed well and is mainly used to bury coconut husk. See appendix xx for google image with wetlands marked as per the island councils during pre-inception meeting

As per the island council, flooding is not a big issue that affects most of the population, however is observed in southeastern side of the island where around 12 houses are located. The topographic level of the island is lower at the eastern side, especially in the southeastern side. The same side also have a shallow groundwater lens and along with the uneven ground level with natural slope towards the inland causes water to get collected and subsequently flooded.

In terms of land use and land allocation, the island council now has the authority to allocate lands for different purposes with an approved land use plan. The council currently does not have an approved land use plan, however, is in the process of developing the same.

4.5.2 Economic Activities



Figure 4-4: Summary of household and socio-economic activities

Most people in the island are employed in tourist resorts and in different ongoing infrastructure projects in the island. According to the Council members who attended the pre-inception meeting, 90% of the workers in the ongoing infrastructure projects in the islands are locals. Fishing (mostly reef fishing) and construction work is also done to some extent. Reef fish is often sold to nearby islands and resorts.

4.5.3 Accessibility and Transport

The nearest airport to Maarandhoo is HA. Hoarafushi Airport which is around 17 Km away. There are three other airports in the region (in Haa Dhaalu Hanimaadhoo, Haa Dhaalu Kulhudhuffushi and Shaviyani Fonadhoo). The main mode of transport to and from Male' and the island is by flying to Hoarafushi and private launch hire from Hoarafushi airport to Maarandhoo. There are private ferries travelling within the atoll as well as supply boats travelling between the atoll and Male', the capital city.

A harbour with quay walls is built on the west side of the island and is used to access the island. As per the council, swell waves and soil erosion is observed on the north side of the harbor. Since the construction of harbor in 2008, soil erosion has also increased around the entire (mostly in south, north and north east) island.

4.5.4 Services and Infrastructures

The island is equipped with the basic services and supporting infrastructures and the details of these are discussed in the following sections.

4.5.4.1 Public Facilities and Amenities

The public facilities available in the island includes:

- Health Center
- Pharmacy
- Primary and Secondary School
- Government institutions (Office for Island Council, Island Court)
- Mosques
- Social Center (with indoor and outdoor sports courts)
- Power house
- MWSC office for ongoing infrastructure projects
- FENAKA office

4.5.4.2 Water supply

Currently rainwater is used for drinking and cooking when needed, although bottled water sourced from Male' is also used for drinking. Groundwater is used for other purposes such as bathing and washing. This is further discussed in section 1.3 and 1.4.

4.5.4.3 Energy supply

Maarandhoo has electricity for 24 hours generated from island powerhouse operated by FENAKA.

4.5.4.4 Waste and Waste water disposal

Solid Waste: Maarandhoo currently does not have a waste management plan or a well-equipped waste management center. As per the council, at the moment waste is segregated in allocated areas at the two ends of the island and most are burnt. Food waste is mostly thrown to the beach while plastic and metal items remain on the allocated areas.

Sewage Disposal: Main method of sewerage disposal at Maarandhoo is by means of septic tanks. Each household has a septic tank within close proximity and are infiltrated into the ground. The island currently has an ongoing project to establish a water and sewerage system and is scheduled to be complete in 2022.

4.6 Existing water and sanitation situation

4.6.1 Water

Maaramdhoo currently does not have a piped drinking water system, however, establishment of an RO Plant with household connection is ongoing and is expected to be completed and ready to use in 2022.

The locals use groundwater for all uses except for drinking and cooking. In the pre-inception meeting, the Island Council reported that groundwater is contaminated in the eastern side of the island with bad smell and discolouration. According to the council members present in the meeting, the ground water lens is shallow in this side of the island

Rainwater is mainly used for drinking and cooking. Rainwater is harvested at both household level and island level by using water tanks in individual households as well by water tanks placed in public spaces by the council. Each household has at least one water tank with a capacity of 2,500L and the council collectively has the capacity to collect and store 100,000L of water. However, as per the island council, 7 of the community water tanks are currently not in usable condition due to lack of maintenance. During the pre-inception meeting, the council also reported having to request for water from outside at least once a year during dry season for the last 7 years.

The general practice of rainwater harvesting at island level is to clean the roofs thoroughly and letting the first flush pass to the roads which would eventually seep into the ground. Excess rainwater is also discharged to the roads in a similar manner.

4.6.2 Wastewater and Sewage Disposal

Currently sewage is deposited by means of septic tanks. Each household has a septic tank within close proximity and are infiltrated into the ground. It was noted that most of the households keep the soakage pits outside the house, away from the groundwater wells although the septic tank is inside the house. According to the social survey that was carried out under this study, about 95% of the households reported keeping the septic tanks 10ft or more away from the well.

Establishment of a proper sewerage system with household connection is currently ongoing and is expected to be completed in 2022. Once the new sewerage facility has been established, the existing

facility will be abandoned. The septic tank inflows from the pipes will be ceased by disconnecting the inflow pipes. The remaining sludge in the pipes and septic tanks will then be removed by sewer jetting and released to the sea via outfall pipe.

4.7 Results of the Baseline Surveys: Water Usage

4.7.1 Summary socio-economic surveys

As detailed in the methodology section of this report (Section 1.4.3), a survey was carried out to determine the water usage at households (HHs), commercial entities (cafés/restaurants), institutions and places with industrial uses (agricultural lands, fish processing). The survey was conducted in Maarandhoo from 12th August to 14th August 2021 with the help of local enumerators. The following Table 4.3 summarizes samples taken for each sector at 95% confidence interval, refusals, replacement samples and total number of completed surveys for each.

Table 4.3: Population and Sample taken for the social survey

Categories	Population	Sample	Sample replacement	Forms Completed	Refusals	Vacant Houses
Households	144	105	12	96	1	8
Registered Farmers	2	1	0	2	-	-
Fishing Vessels	1	1	0	1	-	-
Fish Processing	1	1	0	1	-	-
Institutions	5	5	0	3	-	-
Guest houses	0	-	-	-	-	-
Café/restaurants	0	-	-	-	-	-

Note: A number of mitigation measures were adopted to ensure to achieve the 95% confidence level sample size. The challenges and limitations and the measures undertaken to mitigate the challenges are listed in Section 1.4.3.1.

The key findings from this survey show that a total of 429.61 liters of groundwater are estimated to be used per capita per day for various domestic uses in Maarandhoo. The respective water use situations including domestic, commercial and institutional uses are illustrated in the following sections.

4.7.2 Water usage for domestic purposes

4.7.2.1 Domestic Water Usage

The water usage estimates are calculated based on internationally applied flow rates. A household survey was carried out at 95% confidence interval. A total of 96 HHs were surveyed from Maarandhoo. As presented in Table 4.4, 100% of HHs have at least one of 2,500L capacity HDPE rainwater tanks at their homes to collect rainwater for daily uses. Among the 82 HHs, 84% uses rainwater for drinking while 88% also uses it for cooking.

Groundwater is mainly used for non-potable use in all the households surveyed.

Table 4.4: Groundwater and rainwater use data for Maarandhoo

Rainwater	Per cent (%)
Households with rainwater tanks	100%
Rainwater use for drinking	84%
Rainwater use for cooking	88%
Groundwater	Per cent (%)
Groundwater as drinking source	1%
Groundwater for cooking	7%
Groundwater for non-potable use	98%
Total number of household wells surveyed	96
Percentage of wells surveyed fitted with pumps	99%

Based on the survey carried out, average daily water demand per capita for domestic purposes has been estimated based on the average amount of water used per person for showering, toilet flushing, laundry and gardening, this data is shown in Table 4.5. The total domestic water use is estimated to be 429.1 litres per capita per day.

Table 4.5 Domestic Water Usage in Maarandhoo

Shower/ Liters per capita per day	Toilet/ Liters per capita per day	Laundry/ Liters per capita per day	Gardening/ Liters per capita per day	Total/ Liters per capita per day
105.0	45.0	17.3	246.9	414.1

4.7.2.2 Perception on Groundwater

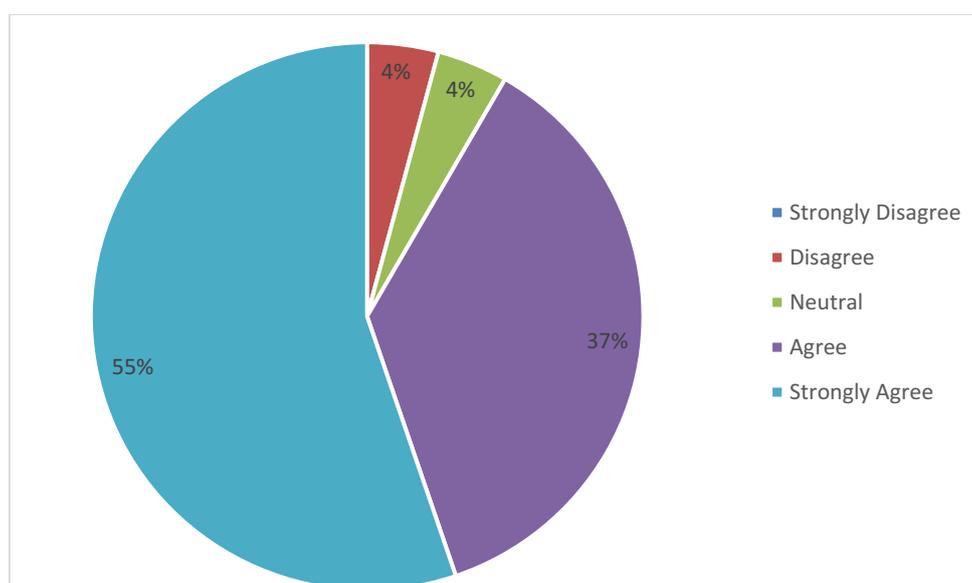


Figure 4-5: Perception of HHs on safety of Groundwater

The HHs were also asked about their perception on groundwater, if it is safe to use for daily purposes and whether the quality of groundwater is good or bad.

As can be seen from Figure 4-5, a total of 92% agreed that groundwater of Maarandhoo is safe to use for their daily uses.

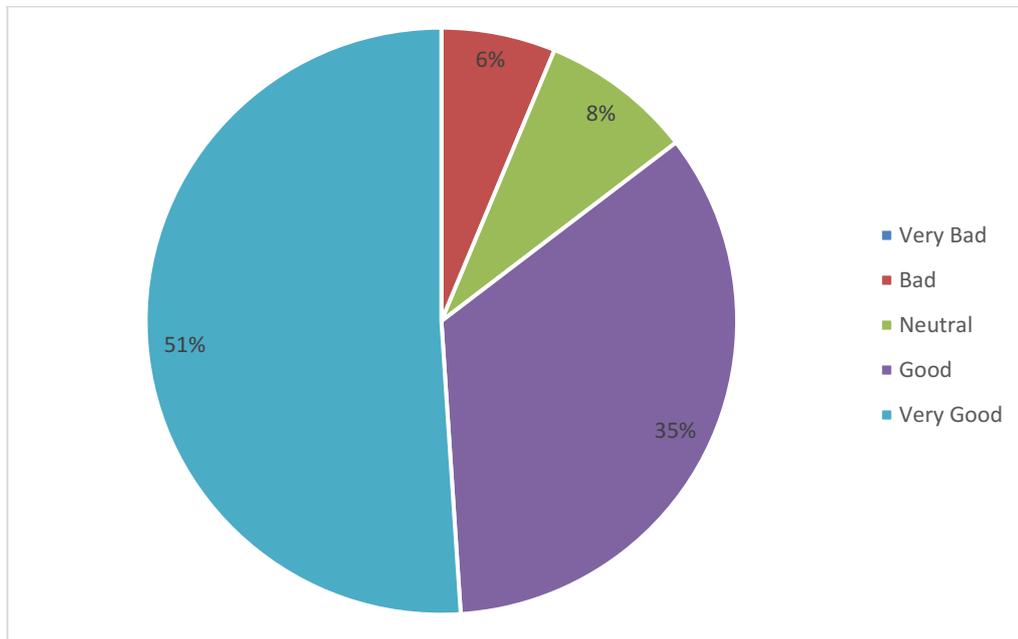


Figure 4-6: Perception of HHs on quality of groundwater

Furthermore, the households were asked about the quality of groundwater with regards to their experience and 85% of the respondents reported that they thought the groundwater quality in Maarandhoo is good. A little over half (51%) of the respondents thought that groundwater quality is very good indicating that the islands' groundwater may not be as bad as most of the other islands in this project.

4.7.3 Water Usage by Commercial Activities

No commercial activities such as café/restaurants were reported by the council, hence no data was collected for this area.

4.7.4 Water Usage by Institutions

In order to estimate water consumption by different institutions in Maarandhoo, three institutions were surveyed including the island magistrate court, island council and FENAKA office

Groundwater in the institutions in Maarandhoo are mainly used for mopping floors, flushing toilets, and to some extent gardening. A total of approximately 6995 liters of groundwater are estimated to be used per day by these institutions. As the use of each institution is different, to generalize water consumption of institutions to an average figure will not be accurate. However, it can be deduced that based on the data, 169.10 liters of groundwater are estimated to be used per staff per day by the institutions of Maarandhoo (Table 4.6).

Table 4.6: Water Usage by commercial activities in Maarandhoo

	Water Flushed (Liters)	Gardening (Liters)	Mopping (Liters)	Sub-Total Water Used (Liters)	Total Water Used (Liters)	Institutional Groundwater Usage (Liters Per Staff Per Day)
Power House	50	1,227	50	1,327	6,595	169.10
Court	160	10	75	245		
School	90	4,908	25	5,023		
Health Centre	50	1,227	50	1,327		

4.7.5 Water Usage for Farming

As per the island council, there are two registered farmers in the island, however, the survey team only managed to interview one of them. As per this interview, farmers mainly use groundwater for watering the plants. The Table 4.7 below summarizes water usage by the farmer participated in the survey. Further data on water usage for farming in the households are presented under domestic water usage in Table 4.5.

Table 4.7: Water Usage by Farmers in Maarandhoo

Farmlands	Area of farmland	Volume of water used per day (Liters)	Total volume of water used per day (Liters) per sqft
1	50 sqft	190.9	190.9
Total		190.9	190.9

4.7.6 Water Usage for Fisheries Activities

In Maarandhoo, the survey team was able to survey 1 fishing boat and 1 individual involved in fish processing. The fishing vessel reported using rain water stored on the boat for their daily uses while the individual working in fish processing reported using ground water for the work. The table below summarizes water usage by the two respondents

Table 4.8: Water Usage by Fisheries activities in Maarandhoo

Fishing Boats/Fish Processing Individuals	Total Volume of water per day (Liters)
1	1,780
2	2.86

4.7.7 Groundwater quality

Groundwater quality measurements were made at selected wells in Maarandhoo Island for both physical and microbiological testing.

The following Table 4.9 summarizes the water quality results.

Table 4.9: Summary of groundwater quality tests from Maarandhoo Island in 2021

Sample No	EC ($\mu\text{S}/\text{cm}$)	pH	Turbidity (NTU)	DO (ppm)	Temp ($^{\circ}\text{C}$)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
MA1	1217	8.4	0.24	7.47	29	0.6	12	0.16	<0.05		
MA2	613	8.2	0.38	7.31	29	0.29	2.3	0.14	0.16	>2420	308
MA3	1632	7.9	0.35	7.36	29	0.82	34.8	0.12	0.12	276	2
MA4	1216	8.2	0.36	7.58	28	0.6	14.4	0.07	0.07		
MA5	2439	7	0.25	4.39	29	1.25	118.2	0.2	0.19		
MA6	610	8.4	0.38	7.54	29	0.29	1.1	0.05	0.15	345	
MA7	1485	7.9	0.63	6.76	30	0.97	18.8	0.11	<0.05	161	1
MA8	660	7.8	0.44	7.67	28	0.32	84.2	0.17	<0.05	214	
MA9	2051	7.8	0.34	7.67	29	1.04	15.8	0.18	0.14		
MA10	2656	7.8	0.37	7.24	29	1.36	20.8	0.09	0.21	770	6
MA11	580	7.7	0.44	7.56	29	0.28	5.9	0.2	<0.05		
MA12	2090	7.1	0.42	1.5	29	1.06	83.2	0.11	0.19	120	
MA13	1660	8.1	0.36	7.69	29	0.83	1	0.11	0.23	187	2
MA14	1231	7.9	0.37	7.69	29	0.61	22	0.1	0.36		
MA15	1603	7.5	0.39	6.84	29	0.8	8.7	0.1	0.09	308	5
MA16	2012	7.7	0.44	7.03	29	1.02	5.9	0.2	<0.05		
MA17	1555	7.8	0.38	7.18	29	0.78	115.9	0.14	0.71		
MA18	872	8.1	0.22	7.17	29	0.42	30.5	0.1	0.19		
MA19	1016	7.7	0.36	7.46	29	0.5	8.1	0.11	0.16	>2420	
MA20	898	8.1	0.44	6.96	29	0.44	57.5	0.15	<0.05		
MA21	2481	7.2	0.16	6.19	30	1.27	20.6	0.2	1.12		
MA22	1055	7.6	0.39	7.37	29	0.52	33.1	0.17	0.09		
MA23	1082	7.4	0.29	6.82	29	0.53	23.2	0.16	0.09		
MA24	1650	8.2	0.69	7.54	29	0.83	37.1	0.1	0.14		
MA25	1110	8	0.55	7.49	29	0.55	3.2	0.14	0.16		
MA26	1680	7.6	0.48	7.49	29	0.84	14.3	0.16	0.11		
MA27	2998	7.9	0.29	7.76	28	1.55	44.2	0.24	1.8		
MA28	1661	8.3	0.65	7.16	28	0.83	23.2	0.16	0.19	235	
MA29	2100	7	0.40	7.46	29	1.06	3.4	0.12	0.3		
MA30	3115	7.8	0.57	6.7	29	1.61	26	0.08	0.09		
MA31	4065	7.4	0.38	6.77	29	2.13	45	0.2	0.18	>2420	26
MA32	2150	8.9	0.47	7.59	28	1.02	5	0.08	0.15		
MA33	2753	7.2	0.31	6.53	28	1.42	5.8	0.18	0.21	1553	100
MA34	261	7.9	0.55	7.64	29	0.12	1.8	0.07	0.69		
MA35	1584	8	0.37	7.62	29	0.79	59.2	0.14	0.09	2420	308
MA36	1300	7.5	0.40	5.38	29	0.64	158.2	2.49	0.36		
MA37	872	8.1	0.38	7.74	29	0.42	14.5	0.24	0.3	>2420	59
MA38	1702	7.3	0.28	6.71	29	0.85	31.4	0.12	0.41		
MA39	1388	7.4	0.22	7.32	29	0.69	50.1	0.12	0.31		
MA40	1900	7.5	0.28	7.29	29	0.96	4.9	0.08	0.13		

Based on the full results and the summary shown in Table 4.9, the following can be summarized for Maarandhoo Island;

- The EC of the groundwater is generally low, with an average of 1625.08 $\mu\text{S}/\text{cm}$ which is below an acceptable limit for potable water of 1500 $\mu\text{S}/\text{cm}$. The electrical conductivity readings range from 261 to 4065 $\mu\text{S}/\text{cm}$. 45% of readings fall within the acceptable limit.
- The pH of groundwater ranged from 7 to 8.9 with an average of 7.78. The pH values of all samples were within the WHO permissible limits of 6.5-8.5.
- Turbidity ranged from the lowest of 0.16 NTU to 0.69 NTU with an average of 0.39 NTU.
- Dissolved oxygen levels were low to moderate, with values varying from 1.5 mg/L to 7.76 mg/L with an average of 7.02 mg/L.
- The salinity of groundwater ranged from 0.12 PSU to 2.13 PSU with an average of 0.82 PSU. Salinity is expressed in Practical Salinity Units (PSU) which is equivalent to PPT.
- The average Nitrate concentration was 31.63 mg/L and therefore it does not exceed the WHO guideline limit of 5.09 mg/L. But 32 of the 40 tested water samples exceeded this limit of 5.09 mg/L. The Nitrate concentrations ranged from 1 mg/L to 158.2 mg/L.
- Ammonia concentrations were generally low. The average ammonia concentration was 0.78 mg/L. This is within the WHO guideline value of 1.5 mg/L based on aesthetic (taste and odour) considerations. Only 1 tested water samples exceeded this limit (range from 0.05 to 2.49 mg/L). Natural concentration levels of ammonia are generally below 0.2 mg/L (WHO, 1993) and no tests showed concentrations below this level. There is no apparent correlation between increasing levels of ammonia and other nutrients.
- Phosphate concentrations were moderate. All values were within the range 0.05 - 1.8 mg/L with an average of 0.25 mg/L. There is no WHO drinking water guideline value for phosphate. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater (e.g. effluent from septic tanks and 'greywater' from kitchens and bathrooms). There were 12 samples tested below 0.1 mg/L.
- Total coliform levels were also found to be significant and ranged from the lowest count of 120 MPN/100 mL to the highest count of more than 2420 MPN/100 mL, with an average count of 1084.60 MPN/100 mL. Faecal Coliform levels were found to be less significant and ranged from the lowest count of 1 MPN/100mL to the highest count of 308 MPN/100mL.

EC values of the selected wells were collected at the start of wet period (September – October) and following table show the summary of all the result collected during dry and wet periods based on the land use distribution.

Land Use	Number of samples	Results are lined with conditions	Increment of measured parameters
Residential area	36	30	MA27, MA12, MW13, MA17, MA30, MA10
Other area	25	15	MW1, MW10, MA31, MA5, MA20, MA33, MA39, MA8, MA36, MA35
Industrial areas	1	0	MW19
Total	62	45	17

Considered desirable water quality limits:

- 1) $\text{EC} < 2500 \mu\text{S}/\text{cm}$ (water could be used for potable and non-potable use depending of EC.
- 2) Nitrate ($< 50 \text{ mg/l}$), Phosphate ($< 5 \text{ mg/l}$), and ammonia ($< 0.5 \text{ mg/l}$) as per WHO guideline.

Possible reasons for the increment of the measured parameters will be discussed in the feasibility & concept design report.

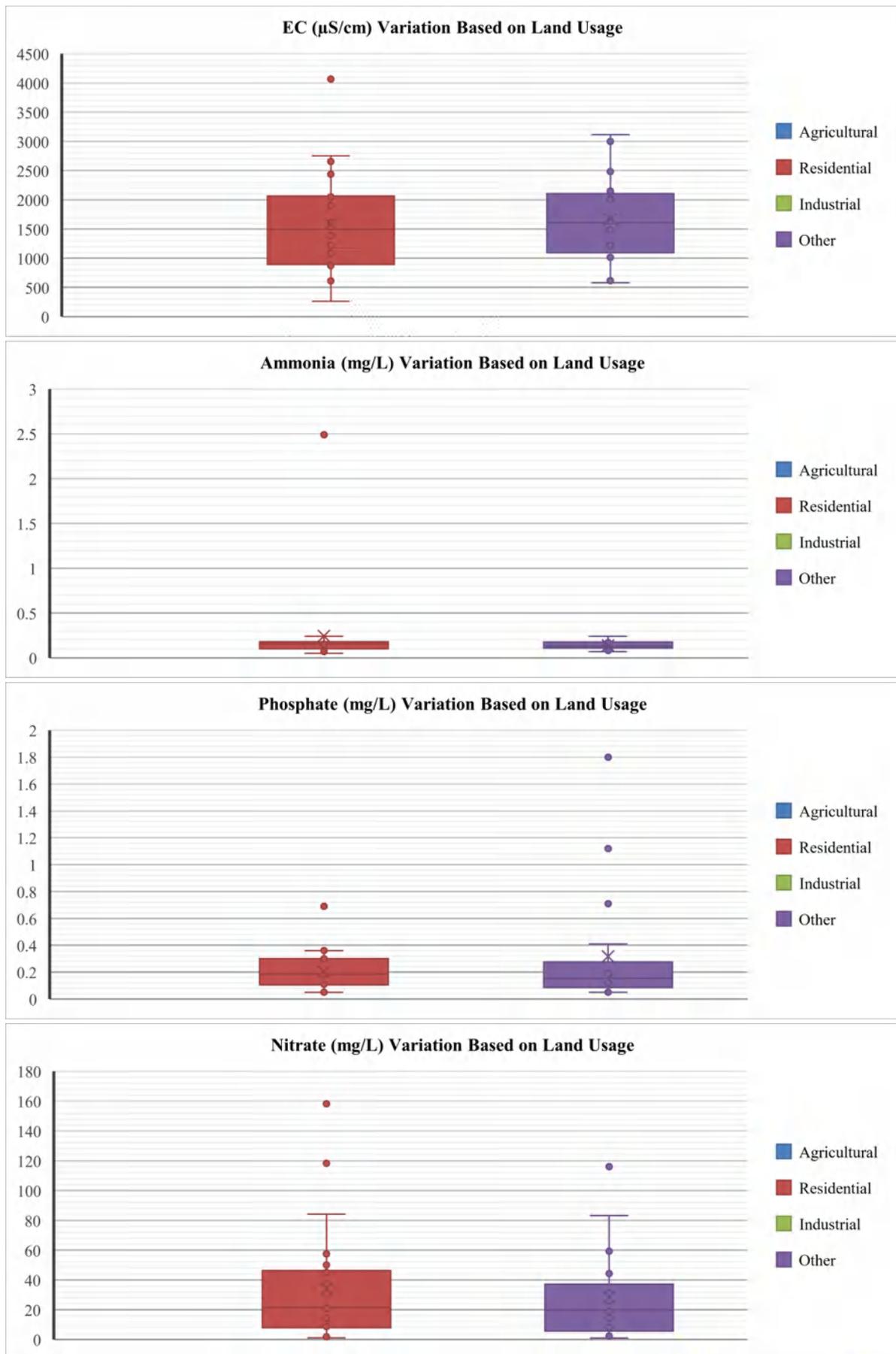


Figure 4-7: Variation of measured WQ parameters in Maarandhoo Island

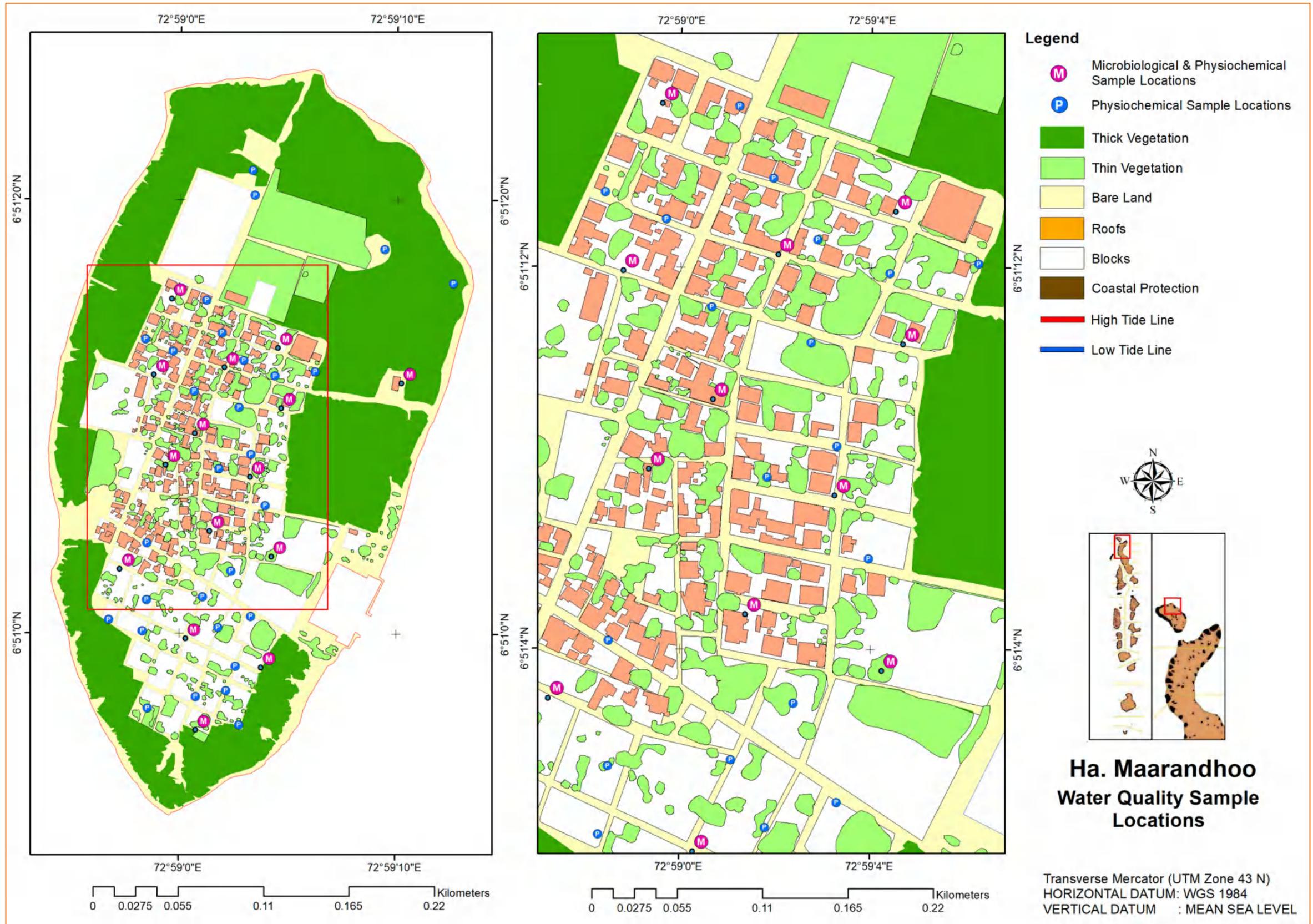


Figure 4-8: Location of groundwater sampling points in Maarandhoo Island

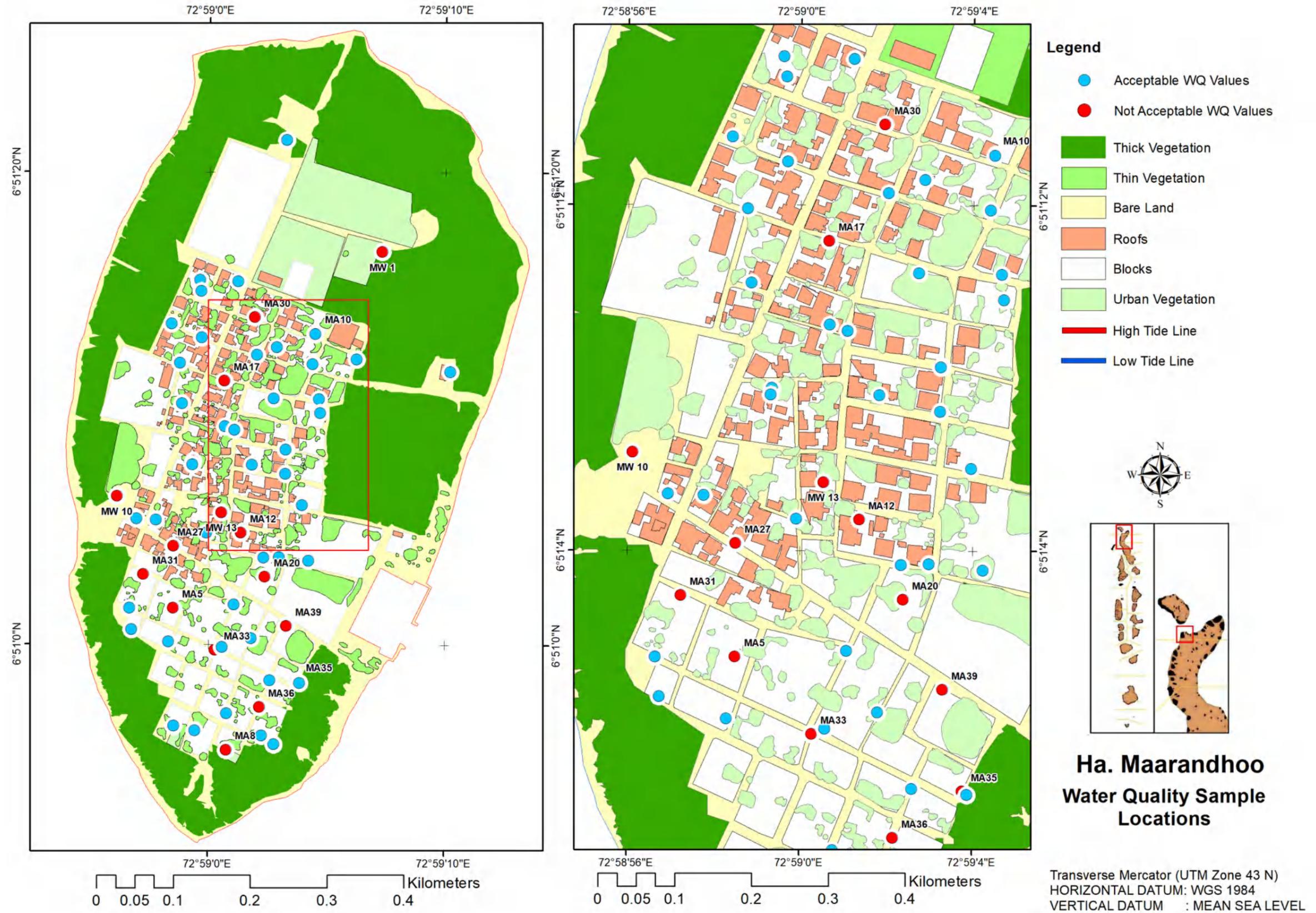


Figure 4-9: Location of groundwater sampling points with critical WQ values in Maarandhoo Island

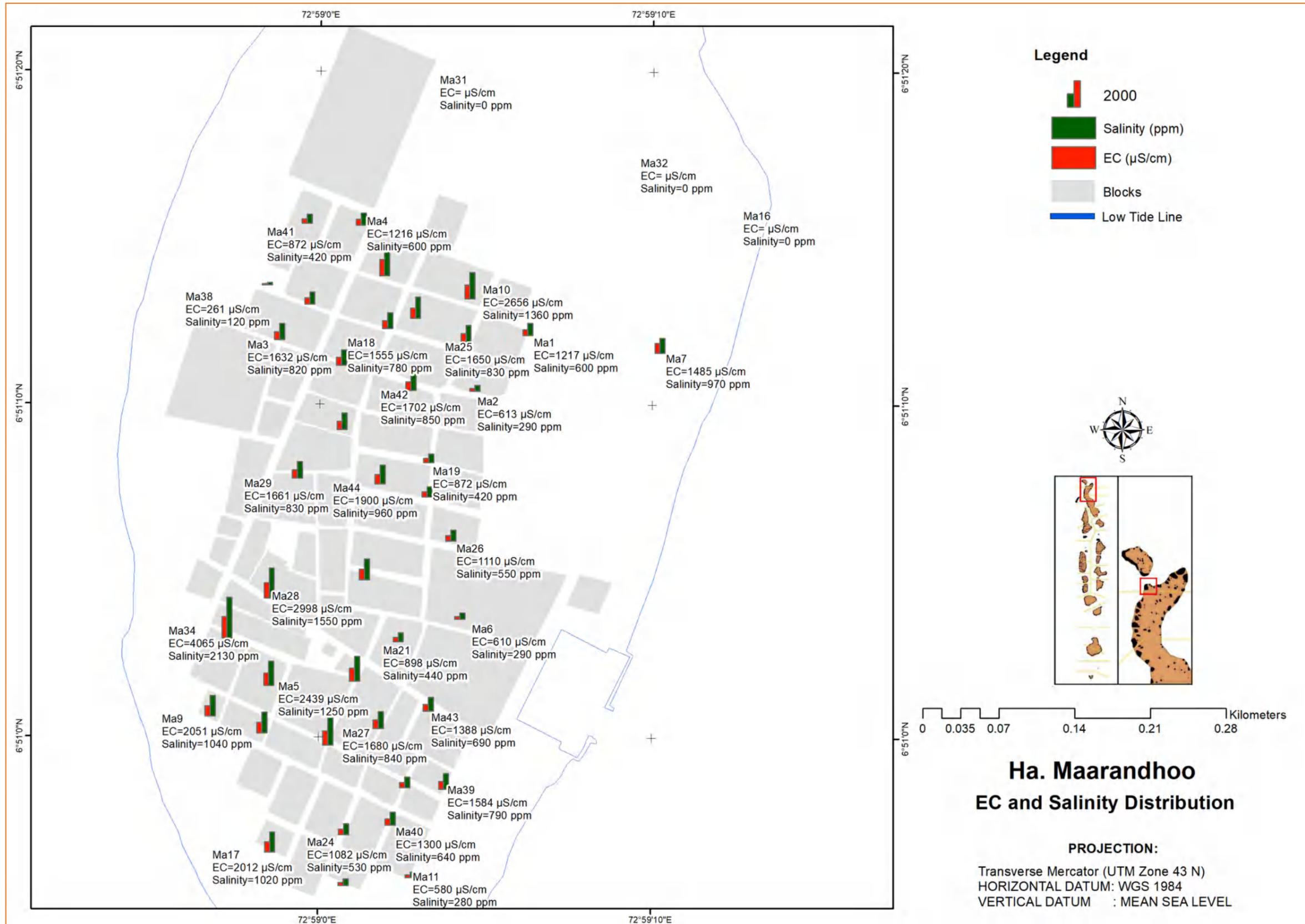


Figure 4-10: EC and Salinity Distribution in Ha. Maarandhoo Island

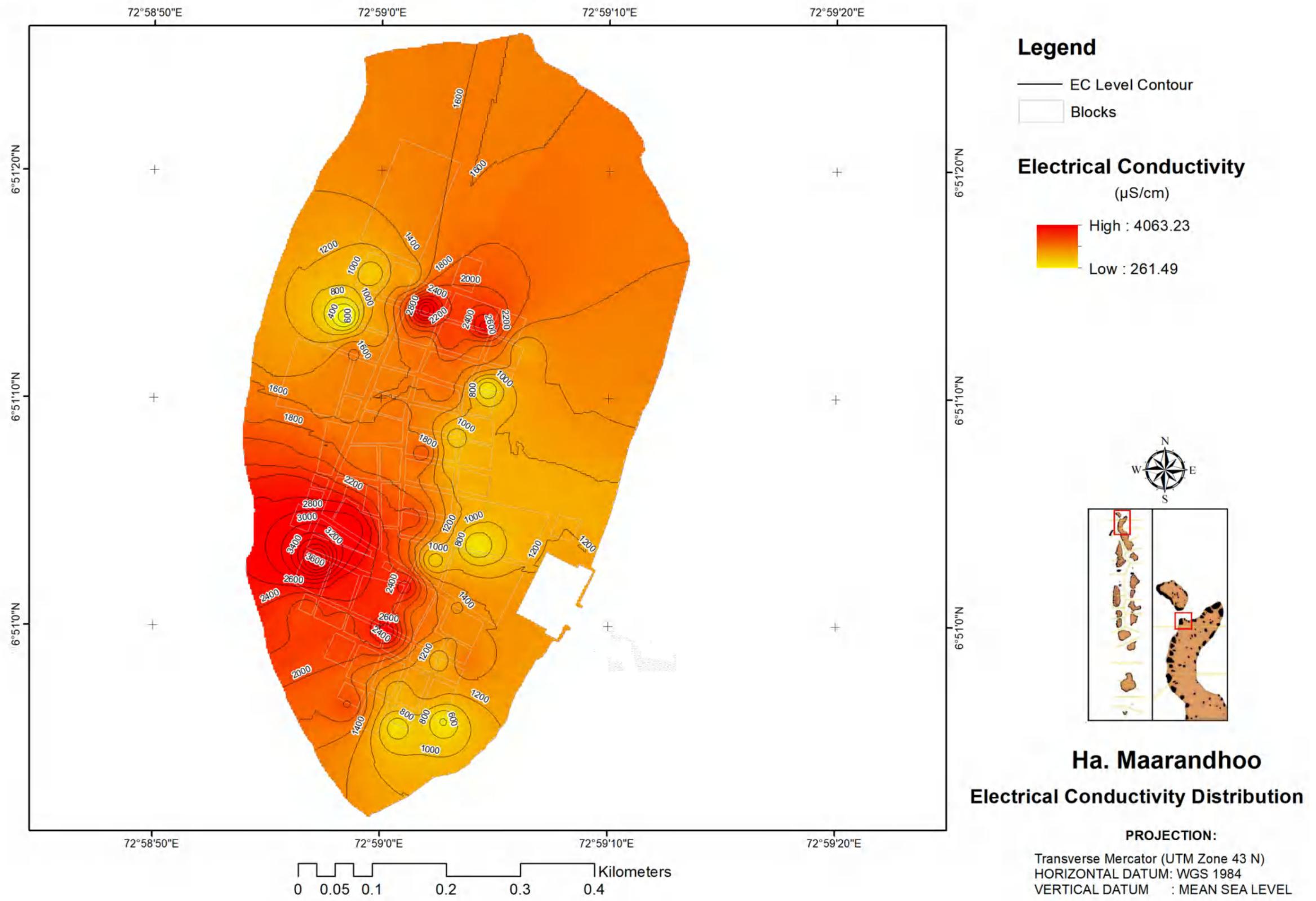


Figure 4-11: EC Distribution in Ha. Maarandhoo Island

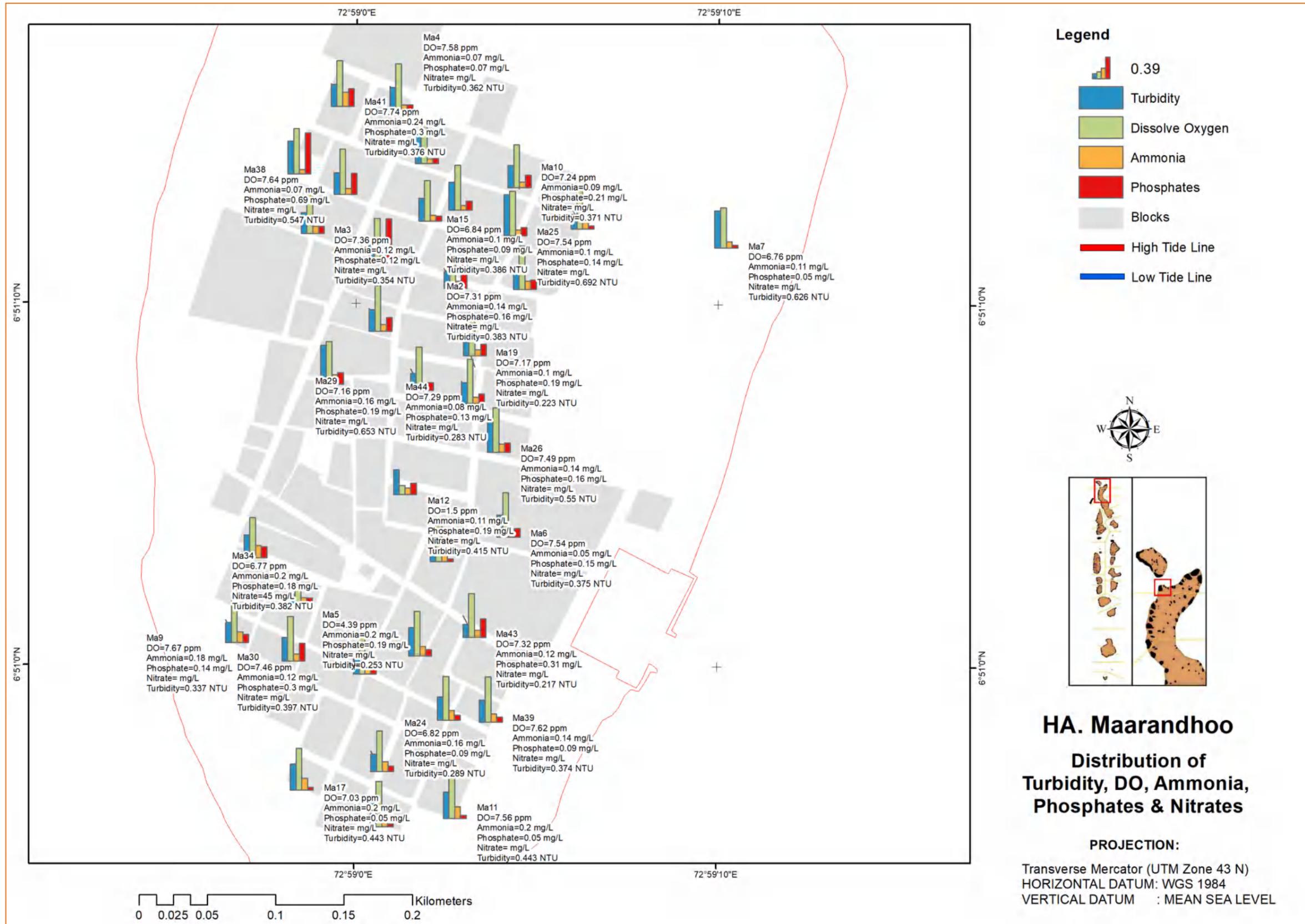


Figure 4-12: Distribution of Turbidity, DO, Ammonia, Phosphates and Nitrates in Ha. Maarandhoo Island

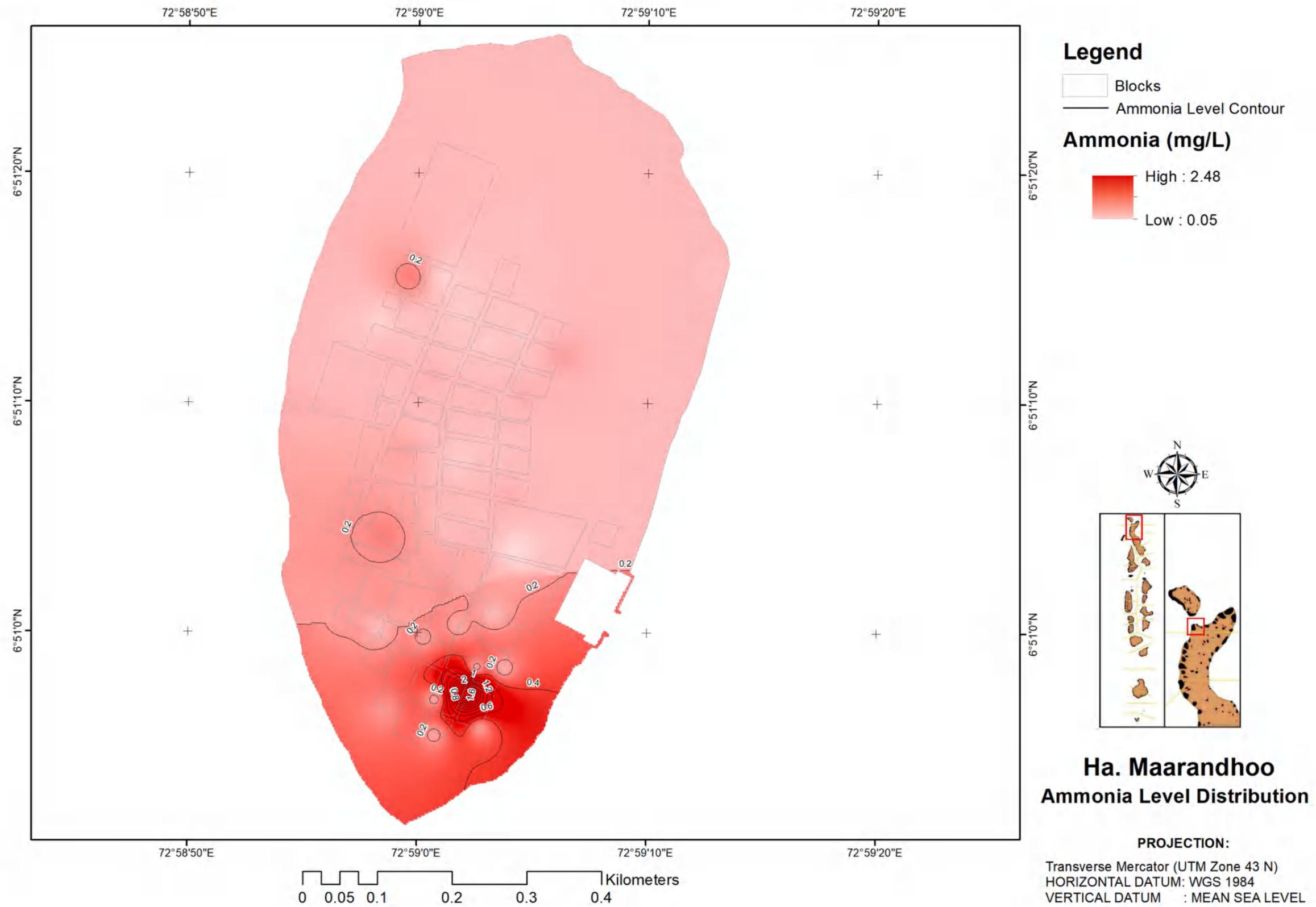


Figure 4-13: Ammonia Level Distribution in Ha. Maarandhoo Island

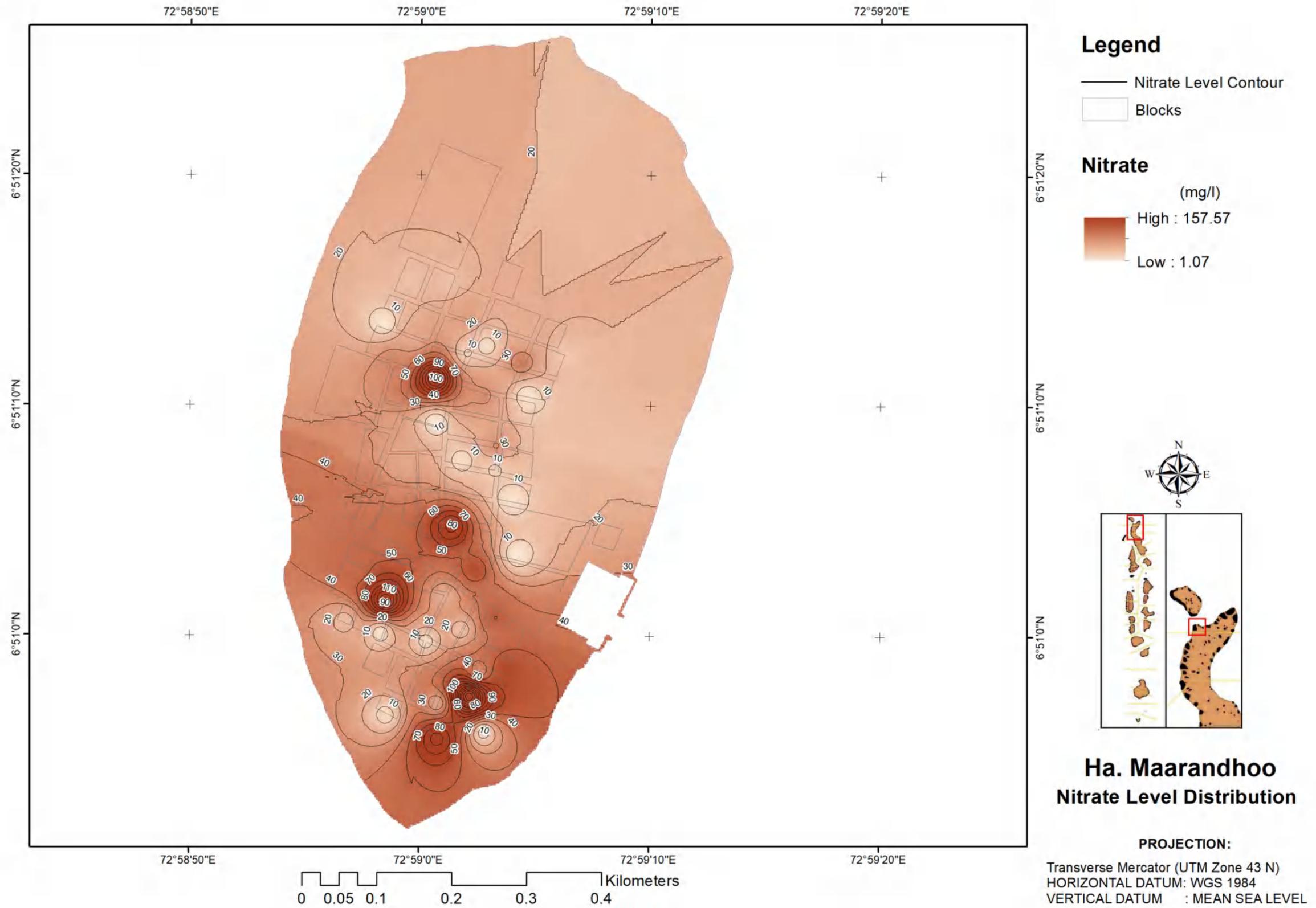


Figure 4-14: Nitrate Level Distribution in Ha. Maarandhoo Island

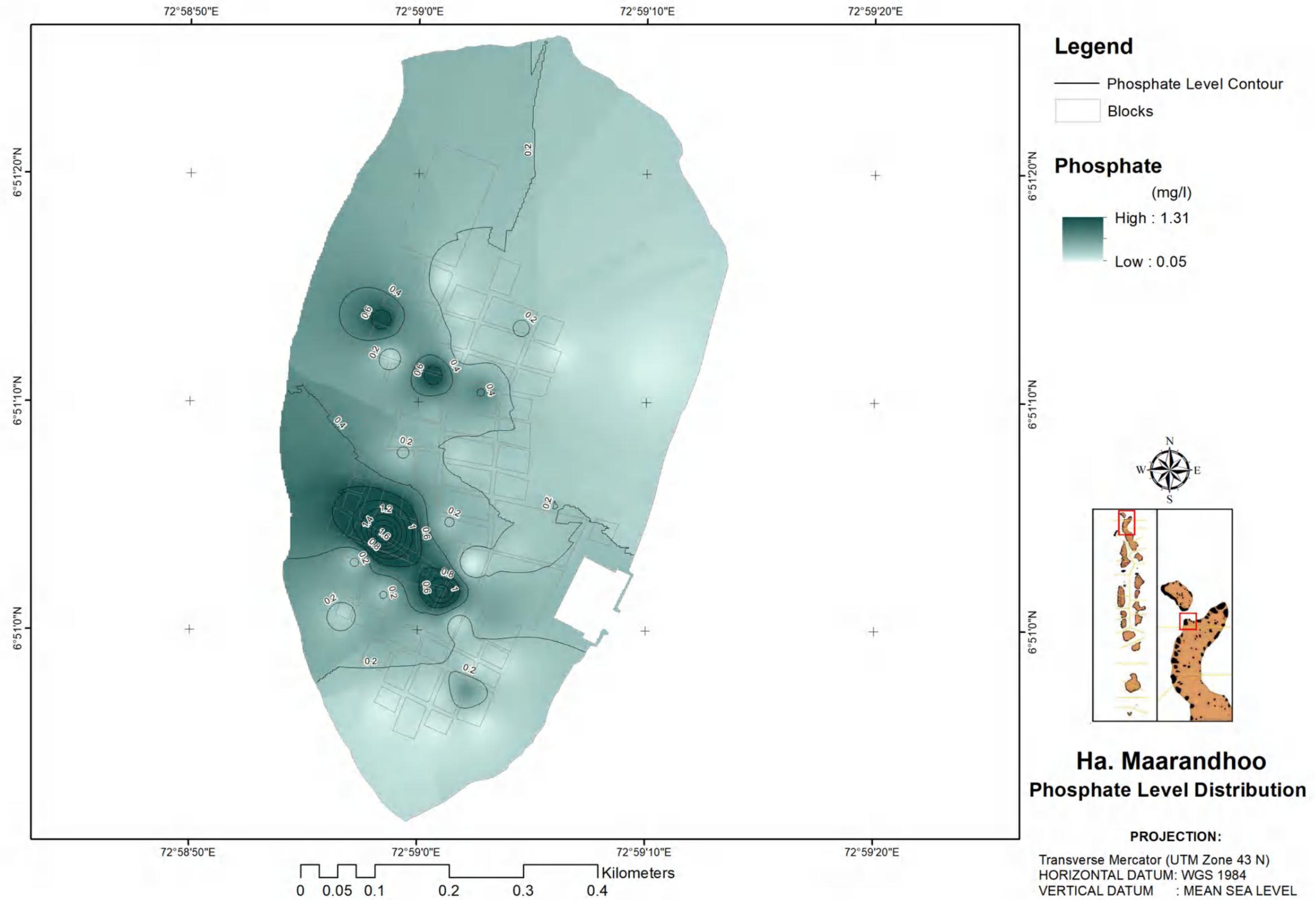


Figure 4-15: Phosphate Level Distribution in Ha. Maarandhoo Island

4.7.8 Geophysical survey

The Electrical Resistivity (ER) tests were carried out in the locations as outlined in Figure 4-16 below. The ER survey included test points along 8 transects selected representatively based on reconnaissance surveys to adequately characterise different land uses and island cross-sections. The main transects were aligned along existing roads to maintain consistency and uniformity.



Figure 4-16: Location of ER points in Maarandhoo Island

4.7.9 Aerial surveys

Based on the aerial survey, a multiple dataset consisting of buildings, roof cover, land cover, change detection and shoreline were extracted. This data is shown in Figure 4-17. The total roof cover for this island is 21,831 m².

4.7.10 Water demand

The only source of natural water is rainwater collected from the rooftops of households and institutions and groundwater extracted from shallow wells. The runoff water from the domestic yards, road surfaces, etc., is not usable as there is no mechanism for its collection and treatment.

4.7.11 Freshwater lens

Based on the Electrical Resistivity (ER) surveys, the depth to groundwater level and the freshwater-saline water interface were determined for a set of transverse transects as shown in Figure 4-16. Plots in Figure 4-2 show the main two cross-sections of island. The dotted lines in the plots indicate a simple interpolation of levels to mean sea level in the island boundaries.

Volume of the lens has been calculated with aid of ArcGIS and Surfer Software.

$$\text{Volume of lens} = 388,411 \text{ m}^3$$

$$\text{Groundwater Storage} = \text{Porosity (15\%)} \times \text{Lens volume (m}^3\text{)} = 58,262 \text{ m}^3$$

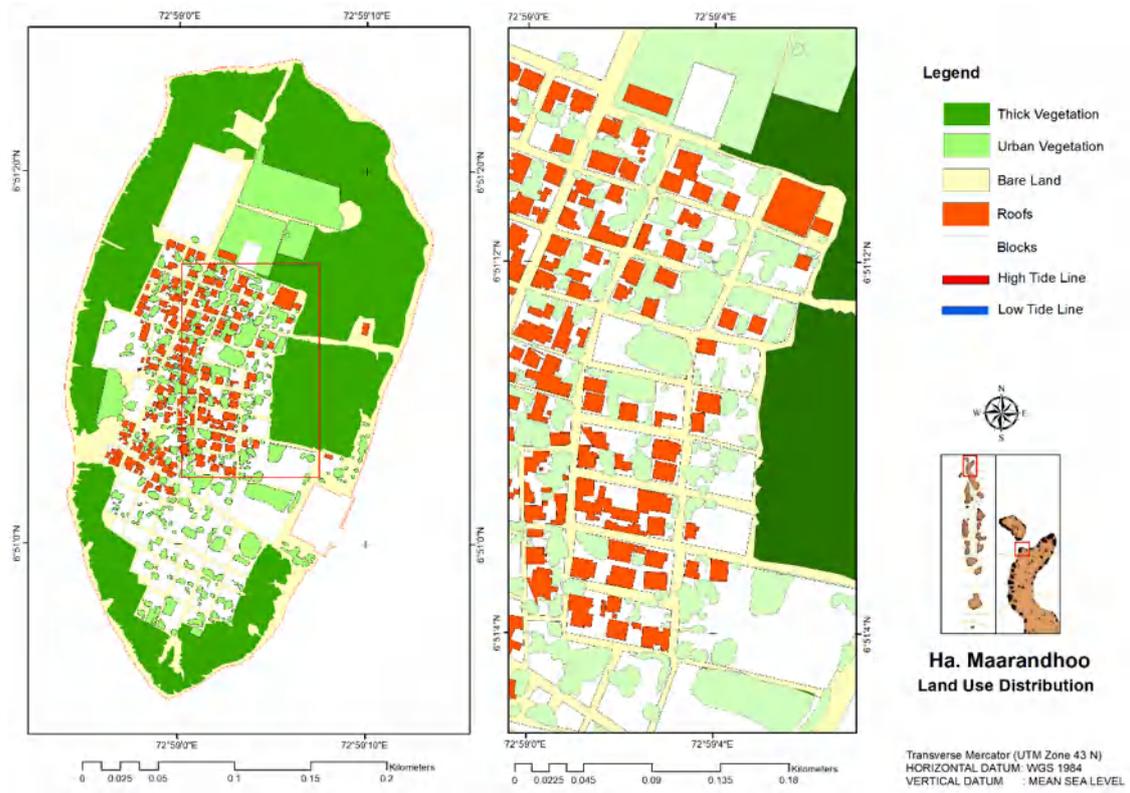


Figure 4-17: Roof Cover in Maarandhoo Island based on UAV Survey

The 2-D freshwater lens distribution density maps produced with GIS software for visualization of the spatial and volume extents are also presented below in Figure 4-18 to Figure 4-20.

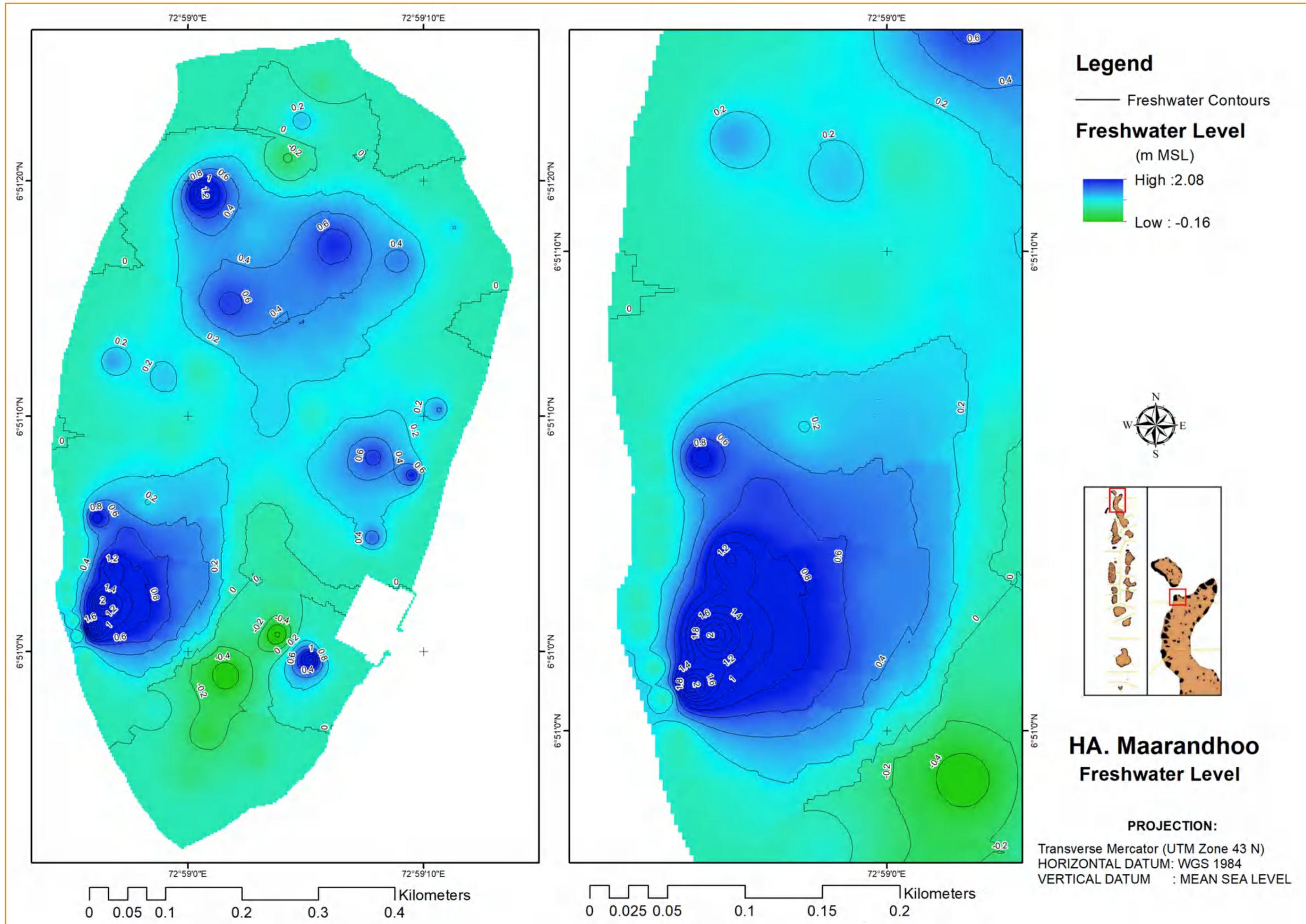


Figure 4-18: Freshwater Level in Maarandhoo Island

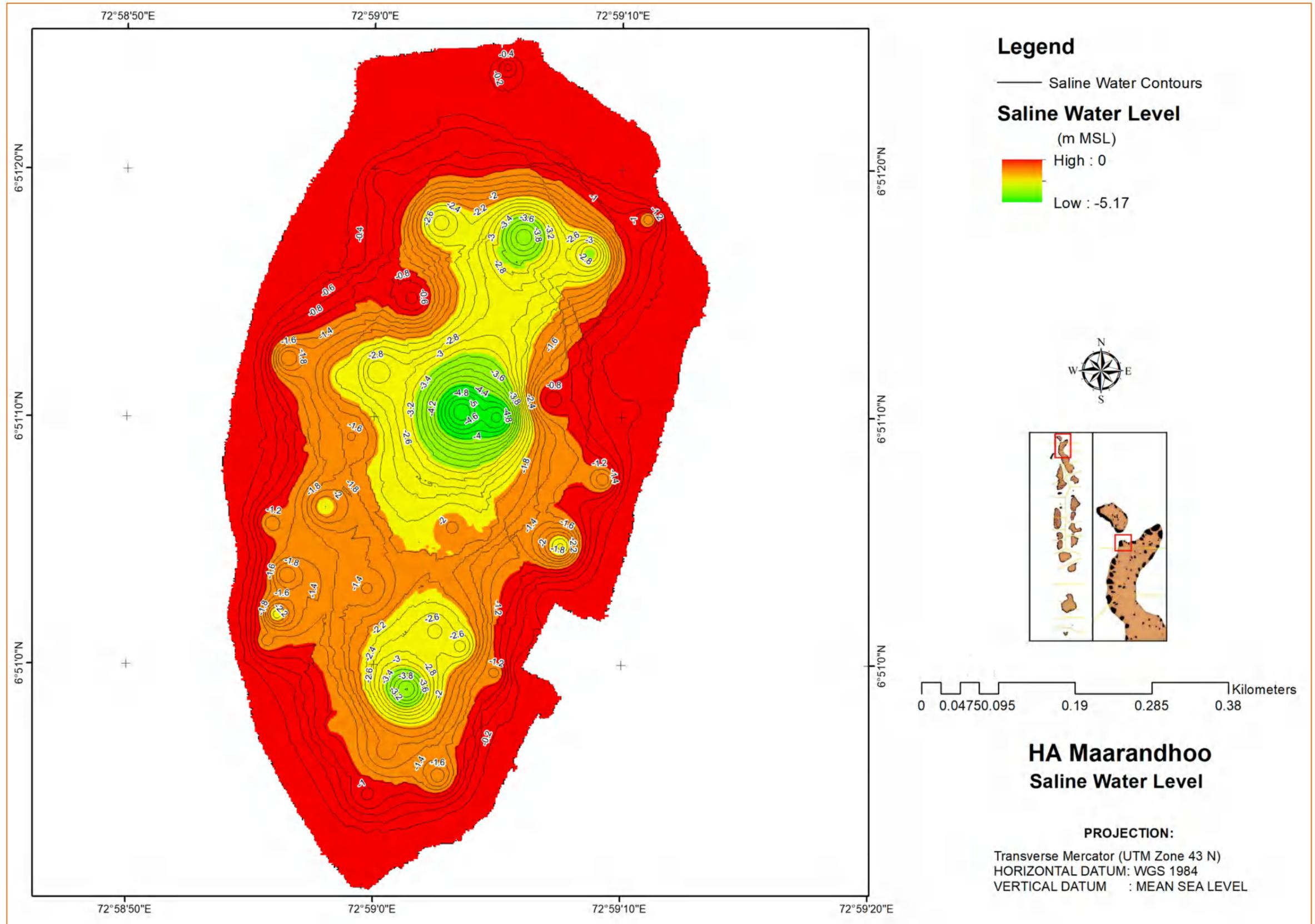


Figure 4-19: Saline water Level in Maarandhoo Island

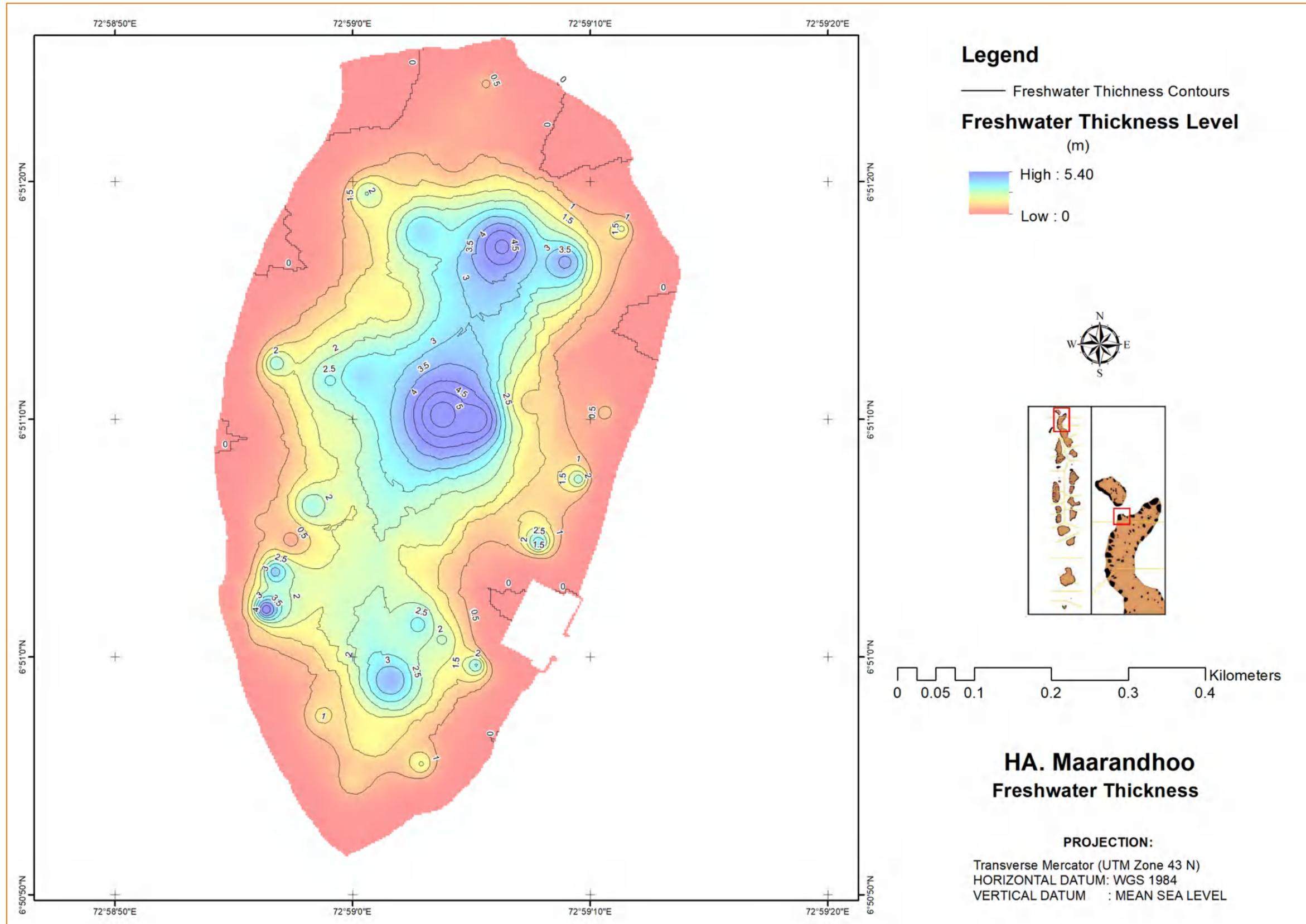


Figure 4-20: Freshwater thickness in Maarandhoo Island

The maximum freshwater thickness of the island is 3.39 m (It is noted here that these readings were taken in October, which is the wet season and the with a reasonably higher number of wet days per month of the year).

4.7.12 Water balance and recharge

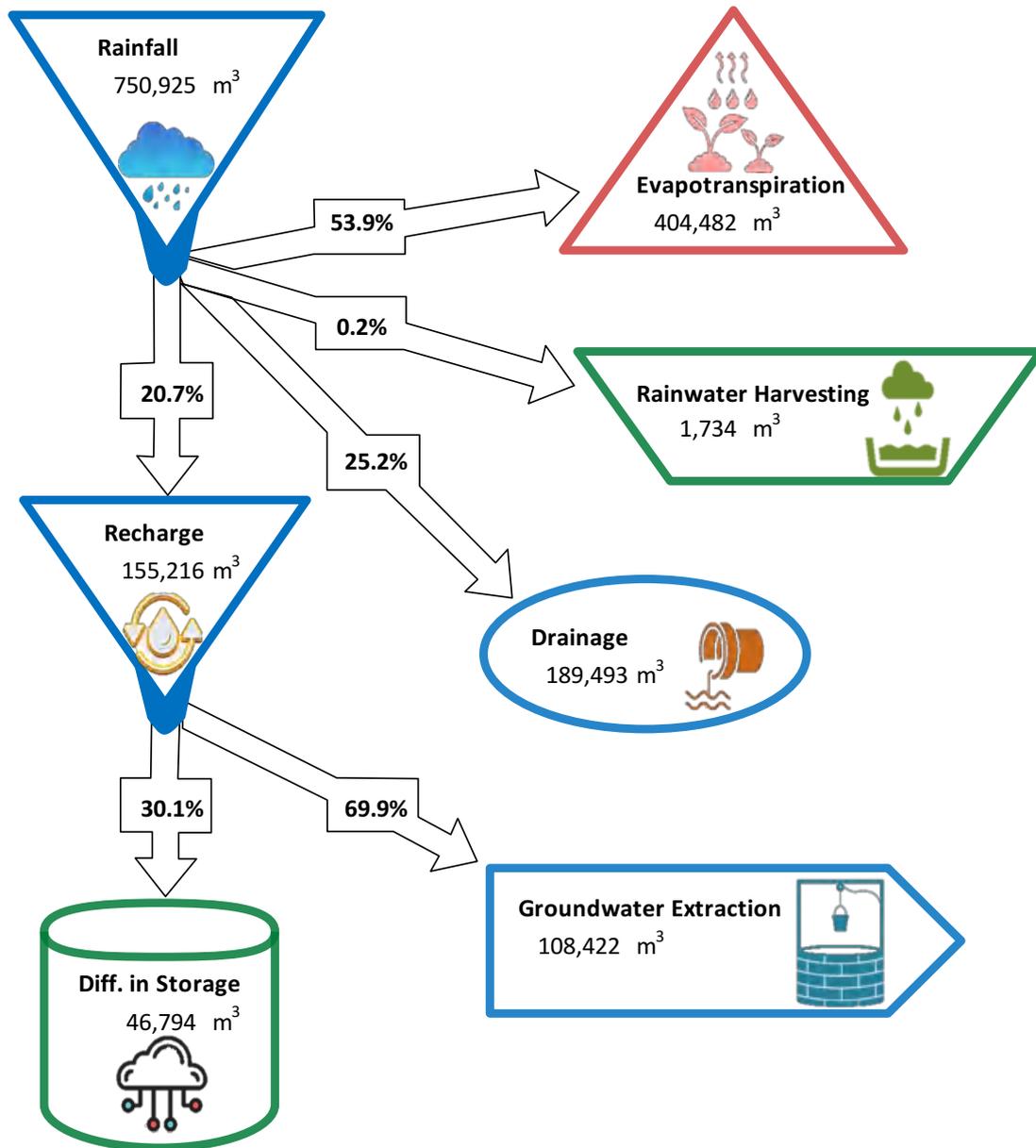


Figure 4-21: Schematic of water balance in Maarandhoo Island

An annual estimation is carried out based on the water balance method (Falkland, 2000). Rainwater harvesting is calculated using the number of rainwater harvesting units on the island. According to the spatial mean annual rainfall of the Maldives, the annual average rainfall of Maarandhoo Island is reported as 1,750 mm/year. Evapotranspiration was estimated using crop water requirements for different land use. Then, the rainfall was subtracted from rainwater harvesting, evapotranspiration, drainage to get the recharge volume. Drainage or the surface runoff was calculated by considering an aggregate runoff coefficient for the island based on the land usage (roof cover, bare land, farmland, roads, playgrounds, wetlands). The groundwater extractions were estimated from the amount of water usage in different sectors (residential, resorts, restaurants, agriculture and farming). The difference between recharge and groundwater extraction is taken to estimate the difference in storage.

4.7.13 Sustainable yield of the lens

Sustainable yield of the water lens refers to the safe extraction potential of a given groundwater aquifer without significantly affecting its quality or quantity. This parameter is an important factor in the sustainable development of islands as it allows planning and design of water and sanitation intervention in islands.

The island has a sustainable yield of 128 m³ per day which was calculated by subtracting groundwater extraction from recharge volume derived from the schematic water balance model in Figure 4-21.

4.7.14 Permeability test

Permeability tests were carried out in the selected locations as outlined in Figure 4-22.

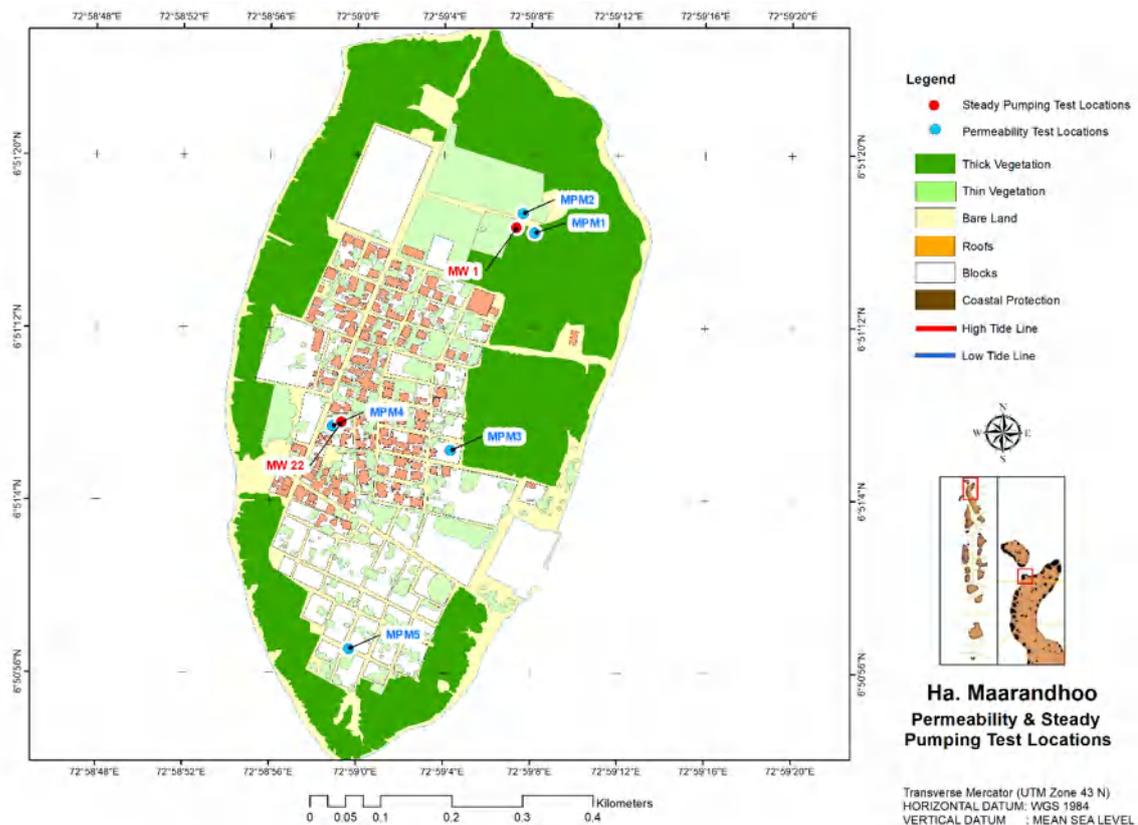


Figure 4-22: Locations of permeability and steady pumping tests in Maarandhoo Island

The estimated permeability values for the above test locations are presented below in Table 4.10. The data will be comparatively verified and interpreted when additional data is acquired and calculations for other islands are completed.

The parameters have their usual notations where, K = Coefficient of permeability (m/s under Q unit gradient), Q = Steady flow into well (m³/s), H = Height of water in well (m), l = length of the perforated section (m), U = thickness of saturated permeability material above water table, r_1 = outside radius of the casing (radius of the hole in consolidated material) (m), r_e = effective radius of well = r_1 (area of perforations) / (outside area of perforated section of casing): $r_1 = r_e$ in consolidated material that will stand open and is not cast, C_s = Conductivity Coefficients, and T_u = distance from water level in the casing to water table (m).

Table 4.10: The Estimated Soil Permeability Values in Maarandhoo Island

Point	MPM1	MPM2	MPM3	MPM4	MPM5
D (m)	0.800	1.000	1.100	0.650	0.600
H (m)	0.800	1.000	1.100	0.650	0.600
ℓ (m)	0.800	1.000	1.100	0.650	0.600
U (m)	1.200	1.200	1.800	0.750	0.700
T _u (m)	1.200	1.200	1.800	0.750	0.700
r (m)	0.076	0.076	0.076	0.076	0.076
Q (m ³ /s)	5.06E-05	6.89E-05	8.22E-05	1.63E-05	1.39E-05
r ₁ (m)	0.076	0.076	0.076	0.076	0.076
r _e (m)	0.010	0.010	0.010	0.010	0.010
T _u /ℓ	1.500	1.200	1.636	1.154	1.167
X = (H/T _u × 100)	67%	83%	61%	87%	86%
Section	Zone 2				
ℓ/r _e	77	96	106	63	58
C _s	120	135	145	92	85
K (m/s)	5.43E-05	6.72E-05	5.04E-05	3.45E-05	3.34E-05
K (m/day)	4.69	5.81	4.36	2.98	2.89

4.7.15 Steady Pumping Test

Pumping tests were conducted in two existing wells to estimate the aquifer properties of unconfined water bearing formation.

Table 4.11: Selected Steady State Pumping Test Locations in Maarandhoo Island

Well No.	C'	A (m ²)	t' (s)	ln ($\frac{s_1}{s_2}$)	T (m ² /s)
MW 1	4.8	2.21	960	5.05	0.0089
MW 22	4.6	2.98	2100	5.63	0.0059

The measured transmissivity (m²/s) values ranged from a minimum of 0.0059 m²/s to a maximum of 0.0089 m²/s., with an average of 0.0074 m²/s. During the testing period, EC (Electrical conductivity) level of both wells were increased as below.

- For MW 1, EC increases from 2600 μs/cm to 4100 μs/cm.
- For MW 22, EC increases from 1490 μs/cm to 2400 μs/cm.

4.7.16 Status of groundwater availability in Maarandhoo Island

- 1). The selected Maarandhoo island has dimensions of width = 530 m and length = 1090 m, with a total land area of 42.91 ha, a population of 700 persons, and a land use of Roof cover (Built up area) 2.94 ha (6.9%), Vegetation (Thick) 25.39 ha (59.2%), Vegetation (Light) 8.61 ha (20.1%), and Wetlands (Inland) 5.96 ha (13.9%).
- 2). In order to recognize the fluctuation in the groundwater table, freshwater-saline interphase and estimate the volume of freshwater lens (FWL) and its associated recharge-discharge characteristics, 60 number of Electrical Resistivity (ER) location readings along 12 representatively selected transects were collected.
- 3). Soil overburden permeability tests (constant head) were carried out at 05 locations while steady-state pumping tests were conducted at 03 locations. In addition, groundwater level was also recorded at 40 locations where groundwater water quality samples were tested.
- 4). Permeability tests were carried out at representatively selected 05 number of locations. The measured permeability (K m/day) values ranged from a minimum of 2.77 m/day to a maximum of 15.00 m/day, with an average of 8.32 ± 4.92 m/day (Mean \pm Standard Deviation).
- 5). The ground elevation values ranged from a minimum of -0.16 m MSL to a maximum of 3.45 m MSL, with an average of 1.62 ± 0.62 m MSL (Mean \pm Standard Deviation).
- 6). The upper boundary of the freshwater lens (FWL) varied from a minimum of -0.62 m MSL to a maximum of 2.08 m MSL, with an average of 0.15 ± 0.24 m MSL (Mean \pm Standard Deviation).
- 7). The lower boundary of the freshwater lens (FWL) or freshwater-saline interphase ranged from a minimum of -5.17 m MSL to a maximum of 0.00 m MSL, with an average of -1.18 ± 1.05 m MSL (Mean \pm Standard Deviation).
- 8). Accordingly, the freshwater lens (FWL) volumetric values ranged from a minimum of 0.00 m to a maximum of 5.40 m, with an average of 1.13 ± 1.13 m (Mean \pm Standard Deviation).
- 9). The groundwater profile in the island is characterised by a relatively Very High (0.23%) Rainwater Harvesting (%) relatively Very High (25.23%) Drainage (%) relatively Very High (20.67%) Recharge (%) while the water use shows relatively Very High (69.85%) Groundwater extraction (%) leading to relatively Very Low (30.15%) Difference in Balance Storage (%) .
- 10). The freshwater lens (FWL) volume calculated based on ER transect test data is 58,262 m³ with a maximum FWL thickness of 5.40 m.

4.8 Conclusion

The Safe Yield for the island estimated based on 'Recharge - Extraction' is 128 m³ per day, while it is 206 m³ per day based on 10% of Average Annual Rainfall Method. The present groundwater extraction rate estimated based on survey data is 297 m³ per day and this exceeds the allowable Safe Yield in the island by 232% (Very highly stressed). At present, there exists no island wide sewerage network or water supply network.

Relative hydraulic conductivity of the island lies in 'Semi-pervious' state while present aquifer condition remains at 'Poor' state based on the hydraulic conductivity estimation carried out as per Bear (1972) and transmissivity of the formation was compared as per Krany (1993). Moreover, general status based on transmissivity ranged 'High' and potential for groundwater recharge remains 'Low' – 'Moderate' as per the estimations.

5 TH. MURAIIDHOO ISLAND

5.1 General Overview of The Island

The island of Muraidhoo (Figure 5-1) is located on the southern periphery of Haa Alifu Atoll at coordinates 73°10'0"E, 6°50'16"N . The island has an area of about 0.5 km² and measures about 0.6 km in width and 1.01 km in length. The population of the island was found to be about 909 residents as of December 2021. The island has a harbour on the Eastern side of the island. The following table outlines some basic information about the island and the following map outlines the location of Muraidhoo.

Table 5.1: Basic statistical information on Muraidhoo Island in Haa Alifu Atoll.

Name of the island	Th. Muraidhoo
Longitude and Latitude	73°10'0"E, 6°50'16"N
Area	44.65 ha (0.5 km ²)
Population (Dec 2021)	909
Distance from Male'	297 km
Harbour	Present
Island sewerage network	Yes
Water supply network	Under construction
Other infrastructure	No

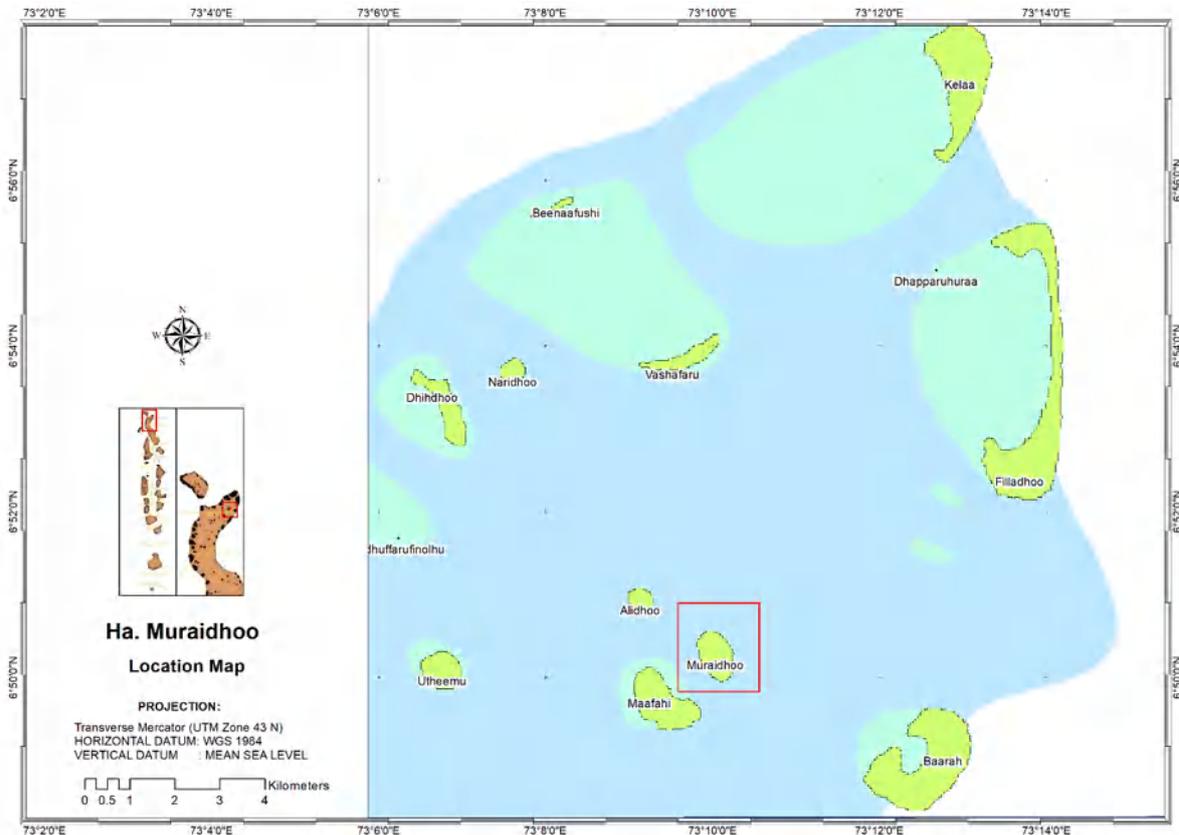


Figure 5-1: Location map for Muraidhoo Island, Haa Alifu Atoll.

5.2 Topography and Geology

Muraidhoo island is on the Eastern end of the “Haa Alifu Atoll” which is located close to the North end of the chain of Maldives islands. Muraidhoo is an island with ellipsoid shape and extends about 980 m (NW-SE) in length (AB) and about 750 m (NE-SW) in width (CD). The basic topography and the geological setting are mostly based on the properties of the underground coral beds and the actions of ocean waves and currents. The elevation of the island varies from -0.22 m MSL to 2.65 m MSL and generally flatland through the island with rim of elevated areas. The general geological profile in the island is composed of topsoil and beach coral sand deposits underlain by sandy coral rock (Figure 5-2). The sandy coral rock consists of a weathered coral rock layer and a hard fresh coral rock. According to the cross-section A-B, the topsoil layer is thick (1.0 m) in coastal areas and in the middle of the island is thin (0.5 m). Beach coral sand layer is range from 0 to 0.2 m in thickness in beach areas (A-B) and about 1m thickness in middle of the island. In the beach areas, beach coral sand layer exists mostly as the top layer. The coral sand layer is mostly unconsolidated and permeable layer. According to the cross-section A-B, the depth of weathered coral rock is varying from 0.2 m (coastal areas) to about 5m (middle of the island) from MSL, and it is a semi permeable layer. The fresh groundwater lens occupies both coral sand layer and weathered coral rock. The hard coral layer is mostly unconsolidated and impermeable and present as a fresh rock. As the compositional and structural differences of coral formation, differential weathering could be observed in cross section A-B. The cross section A-B clearly shows few deep weathered zones. However, in the cross-section C-D in the island shows uniform weathering and general trend is central part of the island show higher weathering compared to the coastal area.

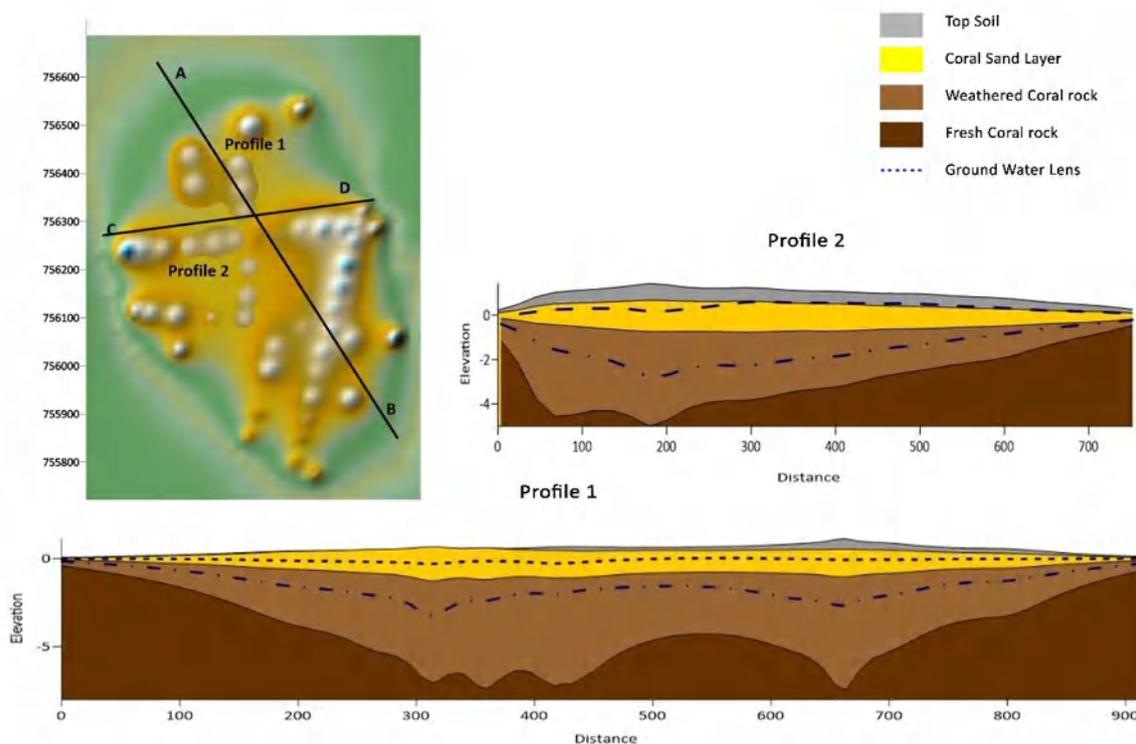


Figure 5-2: Geological sections of the island showing subsurface geological characteristics

5.3 Climate

Muraidhoo experiences the typical two monsoons in the Maldives namely, the North-east monsoon from December/January to March/April and the South-west monsoon from Mid-May to November. There are no specific wind and rainfall data available for Muraidhoo as there are no weather

monitoring stations on the island itself. Based on the rainfall data of the nearest weather monitoring station, it shows a declining trend in rainfall for the past 30 years (Inception Report, 2021).

The historical rainfall data records from Hanimadhoo Island (not included in the 5 selected islands in Lot 1) located in the Haa Alifu atoll (9 km to the south from Muraidhoo Island) has an annual average rainfall of 1,747 mm with a standard deviation of 279.1 mm and the trend with the decadal means were shown in the following graph (MEE, 2021).

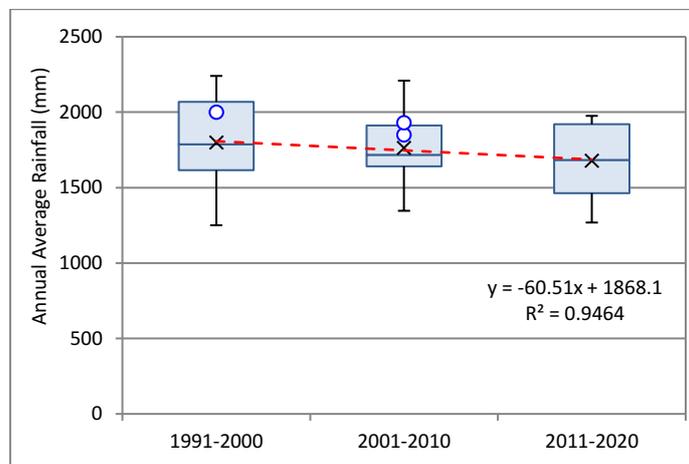


Figure 5-3: Decadal means and trend for rainfall in Hanimadhoo (1990 - 2020).

5.4 Demography

As of December 2021, Muraidhoo has a registered population of 909 people with 454 Males and 455 Females (Muraidhoo Council, 2021). As per the Island Council, an estimate of 620 locals and 14 foreigners currently resides in the island making the total residential population to 634 people. Foreigners include teachers, medical professionals, and laborers working in different infrastructure projects in the island. Total number of residential households in Muraidhoo at present is 98. The island council was not able provide accurate figures on the residential population by gender.

Table 5.2, below summarizes the demographic breakdown of the Muraidhoo registered and residential population.

Table 5.2: Demographic Breakdown of Muraidhoo Island as of December 2021

Registered Population			Resident population		
Both	Male	Female	Total	Maldivians	Foreigners
909	454	455	634	620	14

Source: Muraidhoo Council 2021

5.5 Socio-economic condition

5.5.1 Natural Resources and Land Uses

Muraidhoo has an area of 47.4 hectares and the majority of the island is covered with vegetation with only a small area settled by the islanders in the center of the island. There are two mangroves/wetland areas in the island, one in the south tip of the island and the other in the southeast side of the island. The area in the south tip of the island however, has been destroyed due to soil erosion and currently the area is used for waste collection.

The island council now has the authority to allocate land for different purposes with an approved land use plan. The most recent land use plan prepared by the council was in 2015.

5.5.2 Economic Activities

Economic activities carried out by the island population include employment in tourist resorts and government institutions, construction, agriculture (specializing in different varieties of banana) and a few home businesses such as tailoring among women. According to the council, 90% of jobs created through the ongoing infrastructure projects are currently occupied by locals as well.

Though there are no registered farmers or allocated farming lots in the island, the islanders grow a variety of banana plants across the forest area. To grow banana plants, farmers usually excavate pits on the ground until it almost touches the water lens. As per the island population, banana plants do not require much watering or fertilizers.

5.5.3 Accessibility and Transport

The nearest airport to Muraidhoo is HDh. Hanimaadhoo International Airport which is around 7.2 Kms away. There are three other domestic airports in the region (in Haa Alif Hoarafushi, Haa Dhaalu Kulhudhuffushi and Shaviyani Fonadhoo). The main mode of transport to and from the island is by flying to Hanimaadhoo and private launch hire from airport to Muraidhoo. There are private ferries travelling within the atoll as well as supply boats travelling between the atoll and Male', the capital city.

A harbor with quay walls is located at the eastern side of the island and is used to access the island. During the pre-inception meeting with the island council, it was noted that server erosion is observed around the whole island, particularly worse on the south of the harbor. Furthermore, as per the council, due to sediment filling up the entrance of channel, wave shoaling and flooding is observed around the area.

5.5.4 Services and Infrastructures

The island is equipped with the basic services and supporting infrastructures and the details of these are discussed in the following sections.

5.5.4.1 Public Facilities and Amenities

The public facilities available in the island include:

- Health Center
- Preschool
- Primary and Secondary School
- Government institutions (Office for Island Council, Island Court)
- Mosques
- Powerhouse
- Fenaka office (in construction)

5.5.4.2 Water supply

The main source of water used by the locals is rainwater for drinking and cooking and groundwater for other household tasks as well as agricultural purposes.

This is further discussed in section 1.3 and 1.4.

5.5.4.3 Energy supply

Muraidhoo has electricity for 24 hours generated from island powerhouse operated by FENAKA.

5.5.4.4 Waste and waste water disposal

Solid Waste: The island council has a written waste management guideline and is responsible for overseeing the waste management in the island. Under the waste management guideline, laborers and other resources are hired/allocated to manage the waste within the island. A total of 5 laborers engages in collecting waste from households and other areas of the island. The collected waste is then segregated and where possible, burned in the open air. Materials such as metal and some plastics are segregated but there is no mechanism to manage these.

Sewage Disposal: A sewerage system with household connections was commissioned in Muraidhoo in 2021. The system has a sea outfall pipe.

5.6 Existing water and sanitation situation

5.6.1 Water

The island currently does not have a piped drinking water system, however, a project to establish a piped water system is currently on going and is targeted to be completed in 2023.

Groundwater is the main source of water for all uses except drinking and cooking. During the consultation meeting with the council at the pre-inception stage in June 2021, it was reported that the groundwater quality was good in the past, however, in the last 10 years, noticeable changes have occurred including changes to the odor, color and taste (particularly on the west side of the island). It was also reported that after the recent establishment of the sewerage system, groundwater quality seems to have improved compared to past.

Rainwater is mainly used for drinking and cooking and is harvested at both household and island level. Rainwater is harvested from roofs and stored in water tanks in individual households as well as water tanks placed in public areas by the Council. Each household has at least one water tank with a capacity of 2,500L and the Council collectively has the capacity to collect and store 45,000L of water.

The general practice of rainwater harvesting at island level is to clean the roofs thoroughly and letting the first flush pass to the roads which would eventually seep into the ground. Excess rainwater is also discharged to the roads in a similar manner.

5.6.2 Wastewater and Sewage Disposal

A sewerage system with household connections was commissioned in Muraidhoo in 2021. The system has a sea outfall pipe.

5.7 Results of the Baseline Surveys: Water Usage

5.7.1 Summary socio-economic surveys

As detailed in the methodology section of this report (Section 1.4.3), a survey was carried out to determine the water usage at households (HHs), commercial entities (cafés/restaurants), institutions and places with industrial uses (agricultural lands, fish processing). The survey was conducted in Muraidhoo from 14th August to 17th August 2021. The following Table 5.3 summarizes samples taken for each sector at 95% confidence interval, refusals, replacement samples and total number of completed surveys for each.

Table 5.3: Population and Sample taken for the social survey

Categories	Population	Sample	Sample replacement	Forms Completed	Refusals	Vacant Houses
Households	98	79	5	78	2	7
Registered Farmers	0	-	-	-	-	-
Fishing Vessels	0	-	-	-	-	-
Fish Processing	0	-	-	-	-	-
Institutions	6	6	0	3	-	-
Guest houses	0	-	-	-	-	-
Café/restaurants	2	2	-	1	-	-

Note: A number of mitigation measures were adopted to ensure to achieve the 95% confidence level sample size. The challenges and limitations and the measures undertaken to mitigate the challenges are listed in Section 1.4.3.1.

The key findings from this survey show that a total of 503.45 liters of groundwater are estimated to be used per capita per day for various domestic uses. The respective water use situations including domestic, commercial and institutional uses are illustrated in the following sections.

5.7.2 Water usage for domestic purposes

5.7.2.1 Domestic Water Usage

A household survey was carried out at 95% confidence interval. A total of 78 HHs were surveyed. As presented in Table 5.4, 99% of HHs have at least one of 2,500L capacity HDPE rainwater tanks at their homes to collect rainwater for daily uses. Among the 78 HHs, 97% uses rainwater for drinking while 100% of the HHs also uses it for cooking. Groundwater is mainly used for non-potable use in all the households surveyed.

Table 5.4: Groundwater and rainwater use data for Muraidhoo

Rainwater	Per cent (%)
Households with rainwater tanks	99%
Rainwater use for drinking	97%
Rainwater use for cooking	100%
Groundwater	Per cent (%)
Groundwater as drinking source	0%
Groundwater for cooking	0%
Groundwater for non-potable use	96%
Total number of household wells surveyed	78
Percentage of wells surveyed fitted with pumps	99%

Based on the survey carried out, average daily water demand per capita for domestic purposes has been estimated based on the average amount of water used per person for showering, toilet flushing, laundry and gardening, this data is shown in Table 5.5. The total domestic water use is estimated to be 503.45 litres per capita per day.

Table 5.5: Domestic Water Usage in Muraidhoo

Shower/ Liters per capita per day	Toilet/ Liters per capita per day	Laundry/ Liters per capita per day	Gardening/ Liters per capita per day	Total/ Liters per capita per day
150.9	45	17.8	157.8	371.5

5.7.2.2 Perception on Groundwater

The households were also asked about their perception on groundwater, if it is safe to use for daily purposes and whether the quality of groundwater is good or bad.

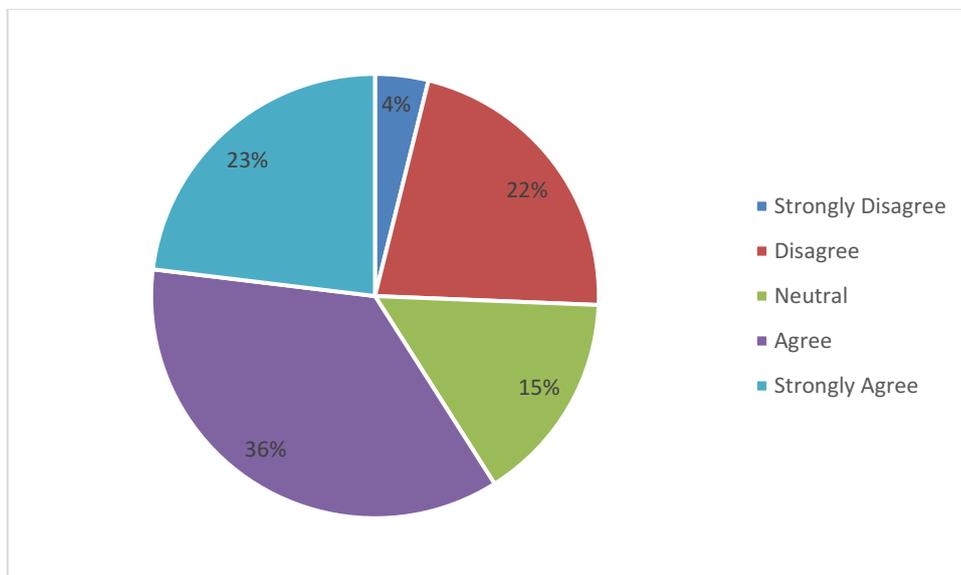


Figure 5-4: Perception of HHs on safety of Groundwater

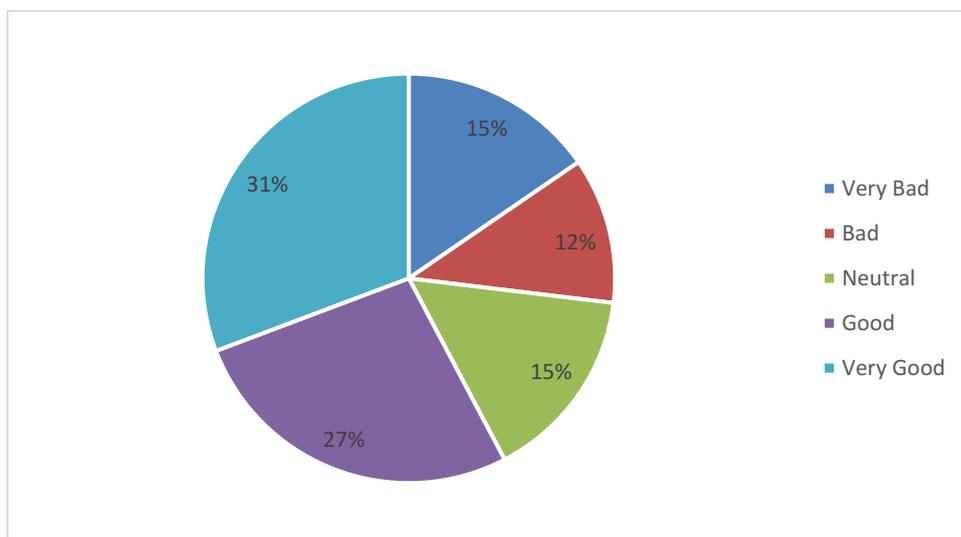


Figure 5-5 Perception of HHs on quality of Groundwater

As it can be seen from Figure 5-4, more than half of the respondents (59%), agreed that groundwater of Muraidhoo is safe to use for daily uses. Among this 59%, 23% respondents strongly agreed that its safe for daily uses. This indicates that the groundwater condition in Muraidhoo is not as bad as in some other islands under this project.

Furthermore, the HHs were asked about the quality of groundwater with regards to their experience. While 27% said the quality is good, 31% said it is very good. However, it is important to note that a total of 27% thought the groundwater quality is not good. The varying opinion on groundwater quality could be, as mentioned earlier, due to the water quality of the island been different in different parts of the island.

5.7.3 Water Usage by Commercial Activities

In terms of commercial water usage, only 2 cafés were identified as commercial entities present in the island and the survey team managed to collect data from one of them.

The Table 5.6 below presents a summary of water usage by the café.

Table 5.6: Water Usage by commercial activities in Muraidhoo

Cafés	Total Volume of water per day (Liters)
1	2127

The main use of groundwater for the café is for dishwashing. The total groundwater consumption for the café is estimated to be 2127 litres. It is important to note here that the average figure cannot be generalised for every café' in the island as the capacity of each café' and its level of operation would be different.

5.7.4 Water Usage by Institutions

In order to estimate water consumption by different institutions in Muraidhoo, three different institutions were surveyed including, Muraidhoo council office, pre-school and health center.

Groundwater in the institutions in Muraidhoo are mainly used for mopping floors, flushing toilets, showering, laundry and to some extent, for gardening. A total of approximately 3752.5liters of groundwater are estimated to be used per day by the institutions surveyed. As the use of each institution is different, to generalize water consumption of institutions to an average figure will not be accurate. However, it can be deduced that based on the data, 150.1 liters of groundwater are estimated to be used per staff per day at the institutions of Muraidhoo (Refer to Table 5.7)

Table 5.7: Water Usage by commercial activities in Muraidhoo

	Water Flushed (Liters)	Gardening (Liters)	Mopping (Liters)	Sub-Total Water Used (Liters)	Total Water Used (Liters)	Institutional Groundwater Usage (Liters Per Staff Per Day)
Council Office	125.4	1,227	50	1,402.4	3,752.5	150.1
Preschool	34.2	1,227	200	1,461.2		
Health Center	125.4	613.5	150	888.9		

5.7.5 Water Usage for Farming

As per the island council, there are no officially registered farmers in the island, though a lot of people grow banana in various parts of the island. As a result, the survey team was not able to obtain a sample frame to collect data on farming in the Muraidhoo. Furthermore, discussions with the island council revealed that not much watering is required for the banana plants.

5.7.6 Water Usage for Fisheries Activities

Since there were no farmers reported in Muraidhoo, data was not collected for this activity.

5.7.7 Groundwater quality

Groundwater quality measurements were made at selected wells in Muraidhoo Island for both physical and microbiological testing.

The following Table 5.8 summarizes the water quality results.

Table 5.8: Summary of groundwater quality tests from Muraidhoo Island in 2021

Sample No	EC ($\mu\text{S}/\text{cm}$)	pH	Turbidity (NTU)	DO (ppm)	Temp ($^{\circ}\text{C}$)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
MU1	770.00	7.57	0.00	1.09	28.09	0.37	1.30	0.07	0.23		
MU2	1652.00	7.30	0.00	13.40	28.06	0.84	104.80	0.26	0.36		
MU3	594.00	7.67	0.00	2.80	27.28	0.29	8.20	0.08	0.37		
MU4	1702.00	7.95	0.00	4.49	28.57	0.85	0.70	0.15	0.56		
MU5	1374.00	7.82	0.00	2.76	27.42	0.68	14.10	0.05	0.29		
MU6	1651.00	7.26	0.00	1.05	29.22	0.83	16.70	0.11	0.13	>2420	980
MU7	1796.00	7.33	0.00	1.31	29.13	0.91	1.30	0.08	0.24	>2420	236
MU8	1526.00	7.22	33.20	1.10	28.29	0.76	0.80	12.25	0.35		
MU9	1546.00	7.51	0.00	0.36	28.63	0.77	0.90	0.13	1.02	326	79
MU10	1022.00	7.74	0.00	3.65	28.83	0.50	2.70	0.09	0.87		
MU11	1033.00	7.63	0.00	3.27	27.51	0.51	0.70	5.06	0.54	>2420	205
MU12	1151.00	7.32	0.00	0.14	28.41	0.57	25.10	2.25	0.37		
MU13	1033.00	8.25	0.60	7.66	27.38	0.51	9.50	0.23	0.59		
MU14	736.00	7.49	2.70	5.99	27.20	0.36	2.60	0.05	0.26	>2420	290
MU15	972.00	7.48	0.00	1.79	28.55	0.47	2.10	0.09	0.23		
MU16	1284.00	7.63	0.00	0.40	27.81	0.64	17.50	0.71	0.27		
MU17	1629.00	7.43	0.00	1.70	28.48	0.82	12.20	1.64	0.57		
MU18	184.00	7.49	0.00	5.79	26.51	8.56	17.20	0.74	0.24		
MU19	1035.00	8.00	0.40	5.10	28.42	0.51	3.60	0.06	0.13	816	93
MU20	1048.00	7.45	0.00	0.80	29.07	0.51	16.50	0.10	0.31	>2420	65
MU21	789.00	7.88	0.00	3.19	28.48	0.38	7.10	5.19	0.35		
MU22	975.00	7.51	0.00	2.25	28.79	0.48	14.80	0.06	0.20	>2420	411
MU23	1800.00	7.95	0.00	5.28	28.50	0.91	2.30	0.06	0.27	1553	19

Sample No	EC (µS/cm)	pH	Turbidity (NTU)	DO (ppm)	Temp (°C)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
MU24	1670.00	7.35	0.10	1.30	28.24	0.83	0.70	0.14	0.10		
MU25	723.00	8.14	0.00	4.58	29.45	0.35	5.40	0.10	0.54	43	22
MU26	1014.00	7.49	0.00	0.55	28.57	0.50	11.90	0.10	0.42	866	179
MU27	6528.00	8.10	10.20	2.81	28.51	3.54	2.10	0.12	0.15		
MU28	1180.00	7.51	0.00	0.71	29.07	0.58	6.30	0.06	0.56		
MU29	1285.00	7.57	0.00	3.20	28.24	0.64	10.40	0.39	0.19		
MU30	1216.00	7.39	3.80	1.39	29.48	0.60	3.60	0.05	0.40		
MU31	1466.00	7.26	5.80	2.52	28.36	0.73	6.20	0.12	0.29	980	649
MU32	1038.00	7.64	0.00	2.72	27.92	0.51	6.60	0.13	0.75		
MU33	762.00	7.70	0.00	1.45	28.07	0.37	4.80	0.08	0.21	>2420	61
MU34	1035.00	7.70	0.50	4.69	29.03	0.51	20.30	0.15	0.21	>2420	291
MU35	1978.00	7.24	9.60	2.57	28.40	1.00	0.50	0.09	0.23	>2420	291
MU36	50826.00	7.35	8.90	4.35	28.83	33.23	3.70	0.62	0.17		
MU37	2924.00	7.49	0.20	3.54	28.80	1.51	1.00	0.13	0.41		
MU38	503.00	8.70	86.50	10.84	30.39	0.32	4.60	0.03	0.39		
MU39	1327.00	7.60	0.00	3.09	27.83	0.66	1.90	0.09	0.29		
MU40	6420.00	7.41	52.60	3.68	30.92	3.45	42.80	0.59	0.27		

Based on the full results and the summary shown in Table 5.8, the following can be summarized for Muraidhoo Island;

- The EC of the groundwater is generally low, with an average of 1496.69 µS/cm which is below an acceptable limit for potable water of 1500 µS/cm. The electrical conductivity readings range from 184 to 6528µS/cm. 67% of readings fall within the acceptable limit.
- The pH of groundwater ranged from 7.22 to 8.7 with an average of 7.61. The pH values of all samples were within the WHO permissible limits of 6.5-8.5.
- Turbidity ranged from the lowest of 0 NTU to 86.50 NTU with an average of 5.38 NTU.
- Dissolved oxygen levels were low to moderate, with values varying from 0.14 mg/L to 13.4 mg/L with an average of 3.23 mg/L.
- The salinity of groundwater ranged from 0.29 PSU to 33.23 PSU with an average of 1.78 PSU. Salinity is expressed in Practical Salinity Units (PSU) which is equivalent to PPT.
- The average Nitrate concentration was 10.39 mg/L and therefore it does not exceed the WHO guideline limit of 5.09 mg/L. But 20 of the 40 tested water samples exceeded this limit of 5.09 mg/L. The Nitrate concentrations ranged from 0.5 mg/L to 104.8 mg/L.
- Ammonia concentrations were generally low. The average ammonia concentration was 0.78 mg/L. This is within the WHO guideline value of 1.5 mg/L based on aesthetic (taste and odour) considerations. Only 5 tested water samples exceeded this limit (range from 0.03 to 12.25 mg/L). Natural concentration levels of ammonia are generally below 0.2 mg/L (WHO, 1993) and no tests showed concentrations below this level. There is no apparent correlation between increasing levels of ammonia and other nutrients.
- Phosphate concentrations were moderate. All values were within the range 0.1-1.02 mg/L with an average of 0.36 mg/L. There is no WHO drinking water guideline value for phosphate. However,

it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater (e.g. effluent from septic tanks and ‘greywater’ from kitchens and bathrooms). There were 0 samples tested below 0.1 mg/L.

- Total coliform levels were also found to be significant and ranged from the lowest count of 43 MPN/100 mL to the highest count of more than 2420 MPN/100 mL, with an average count of 1757.60 MPN/100 mL. Faecal Coliform levels were found to be less significant and ranged from the lowest count of 19 MPN/100mL to the highest count of 980 MPN/100mL.

EC values of the selected wells were collected at the start of wet period (September – October) and following table show the summary of all the result collected during dry and wet periods based on the land use distribution.

Table 3.11: Comparison of WQ results based on land usage

Land Use	Number of samples	Results are lined with conditions	Increment of measured parameters
Residential area	58	48	MU11, MU12, MU8, MU21, MU15, MU16, MU17, MU18, MU2, MU37
Agricultural area	5	4	MU27
Industrial areas	2	2	
Other areas	3	1	MU36, MU40
Total	68	55	13

Considered desirable water quality limits:

- 1) EC < 2500 $\mu\text{s/cm}$ (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 guideline.

Possible reasons for the increment of the measured parameters will be discussed in the feasibility & concept design report.

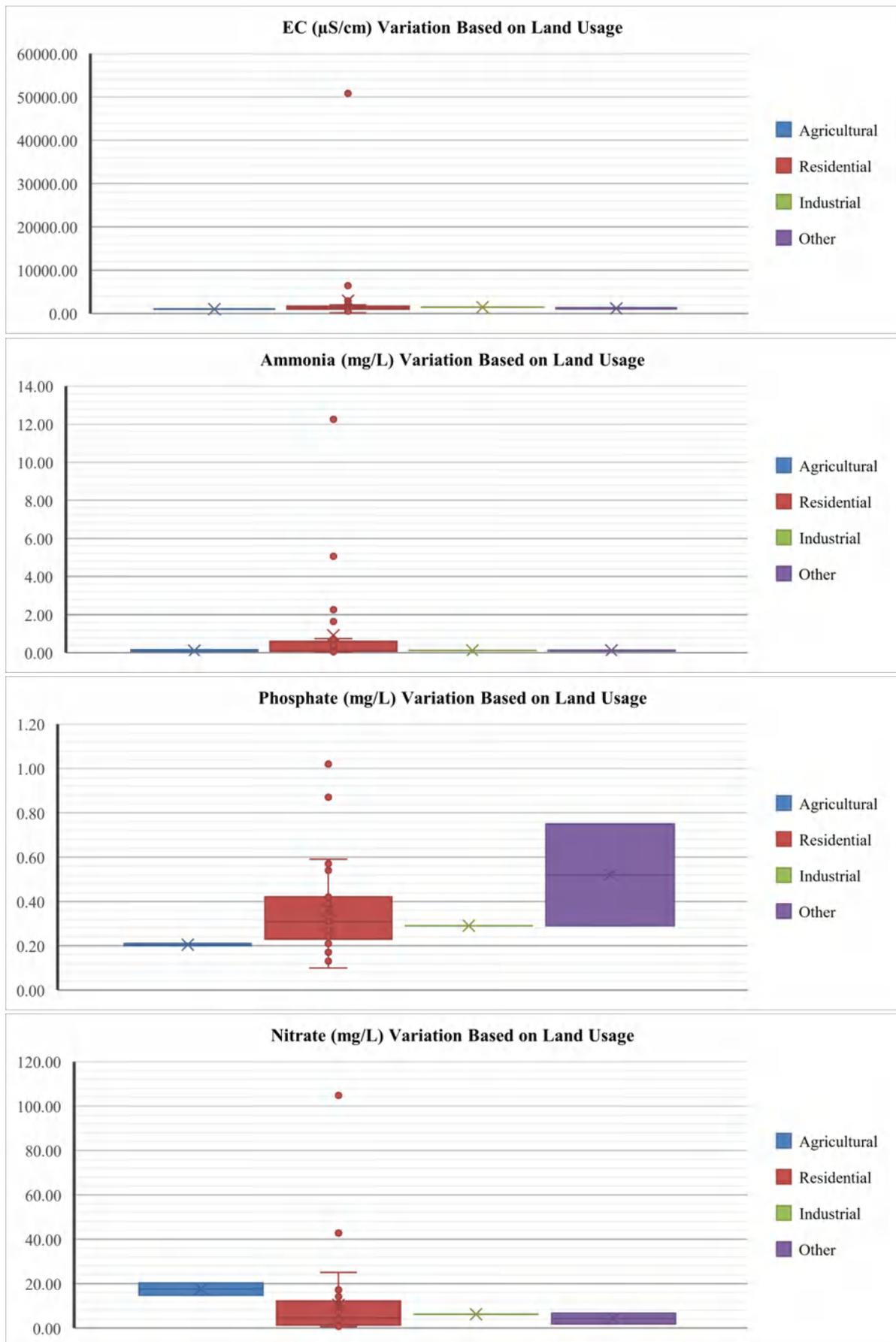


Figure 5-6: Variation of measured WQ parameters in Muraidhoo Island

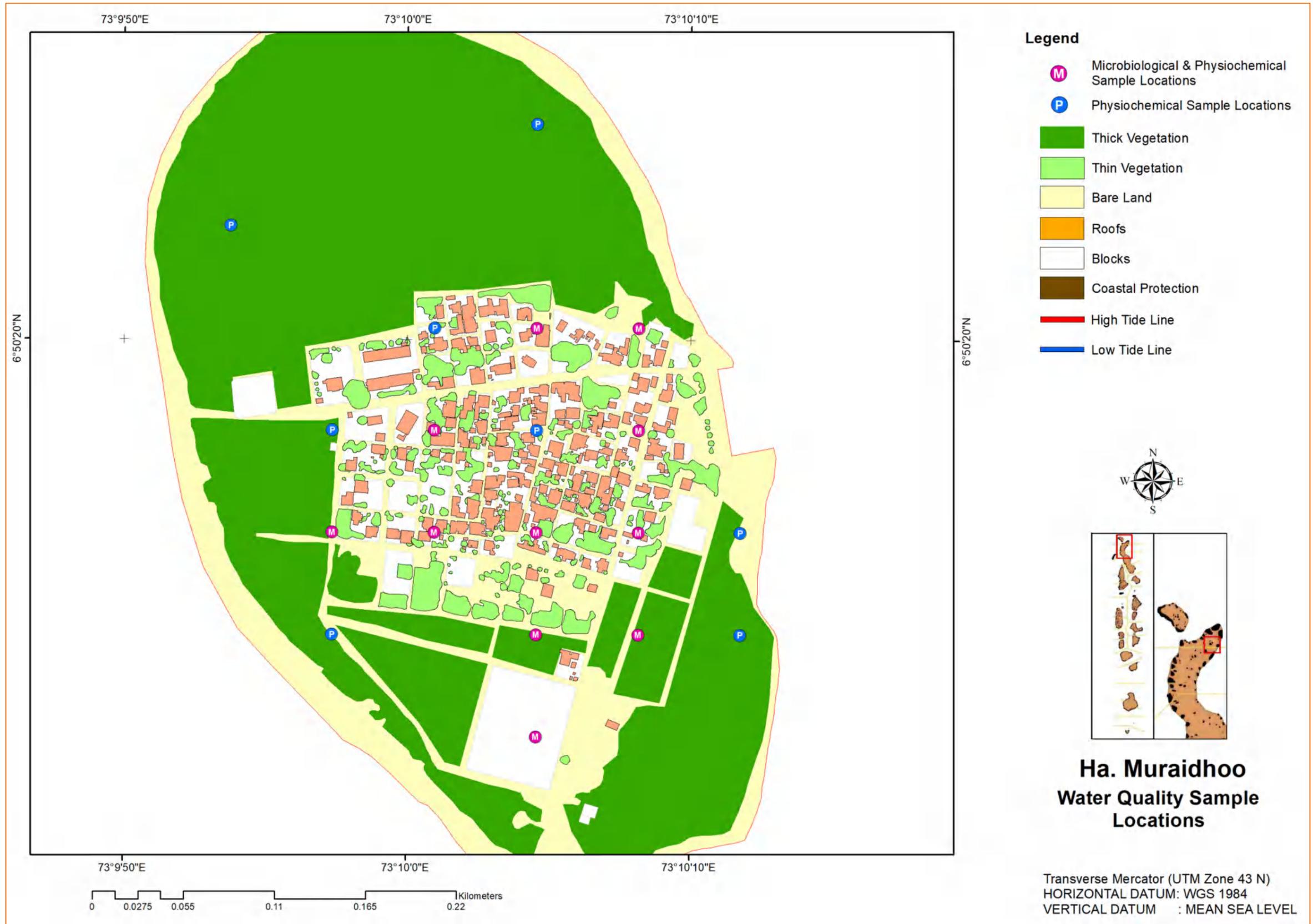


Figure 5-7: Location of groundwater sampling points in Muraidhoo Island

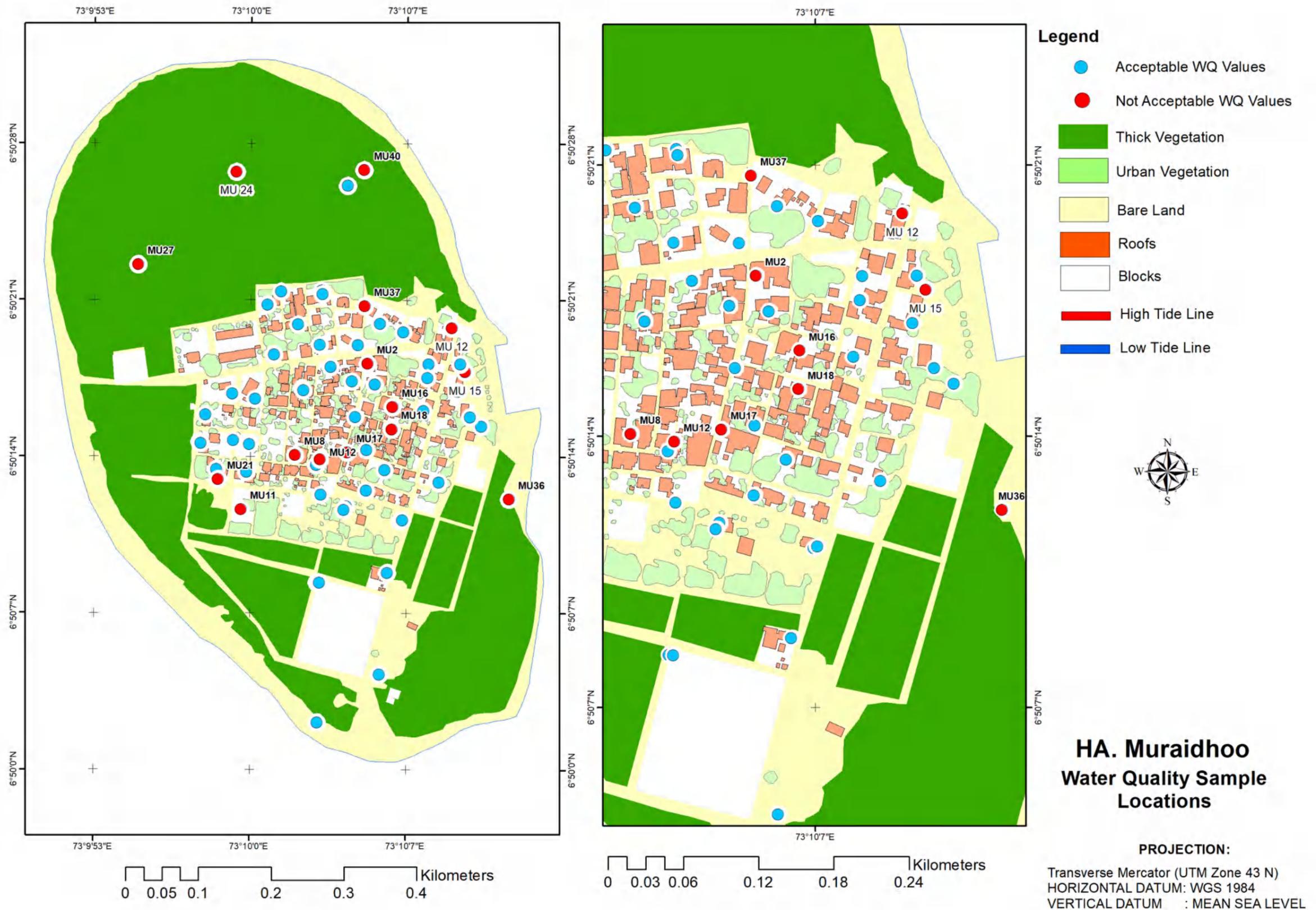


Figure 5-8: Location of groundwater sampling points with critical WQ values in Muraidhoo Island



Figure 5-9: EC and Salinity Distribution in Ha. Muraidhoo Island

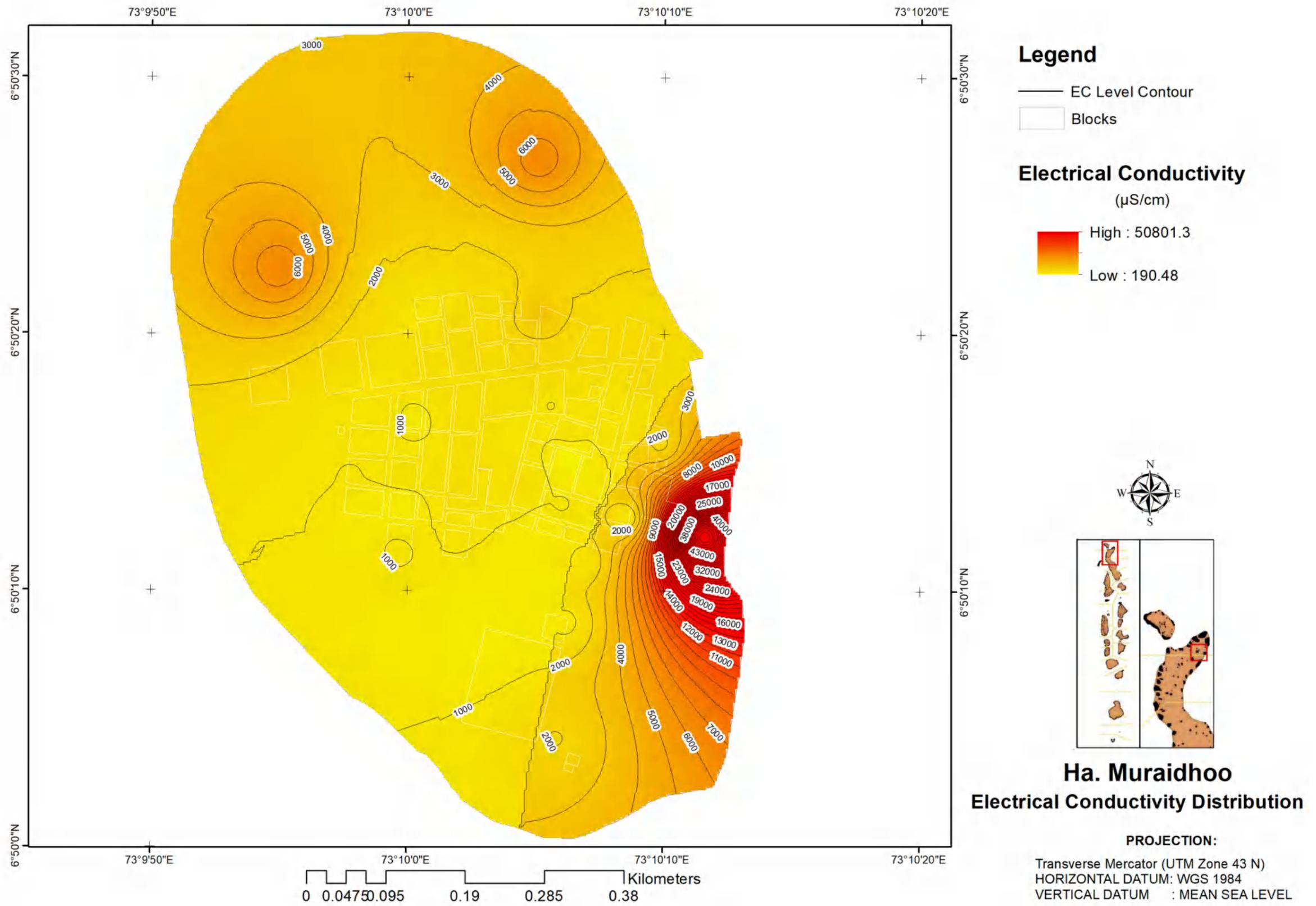


Figure 5-10: EC Distribution in Ha. Muraidhoo Island

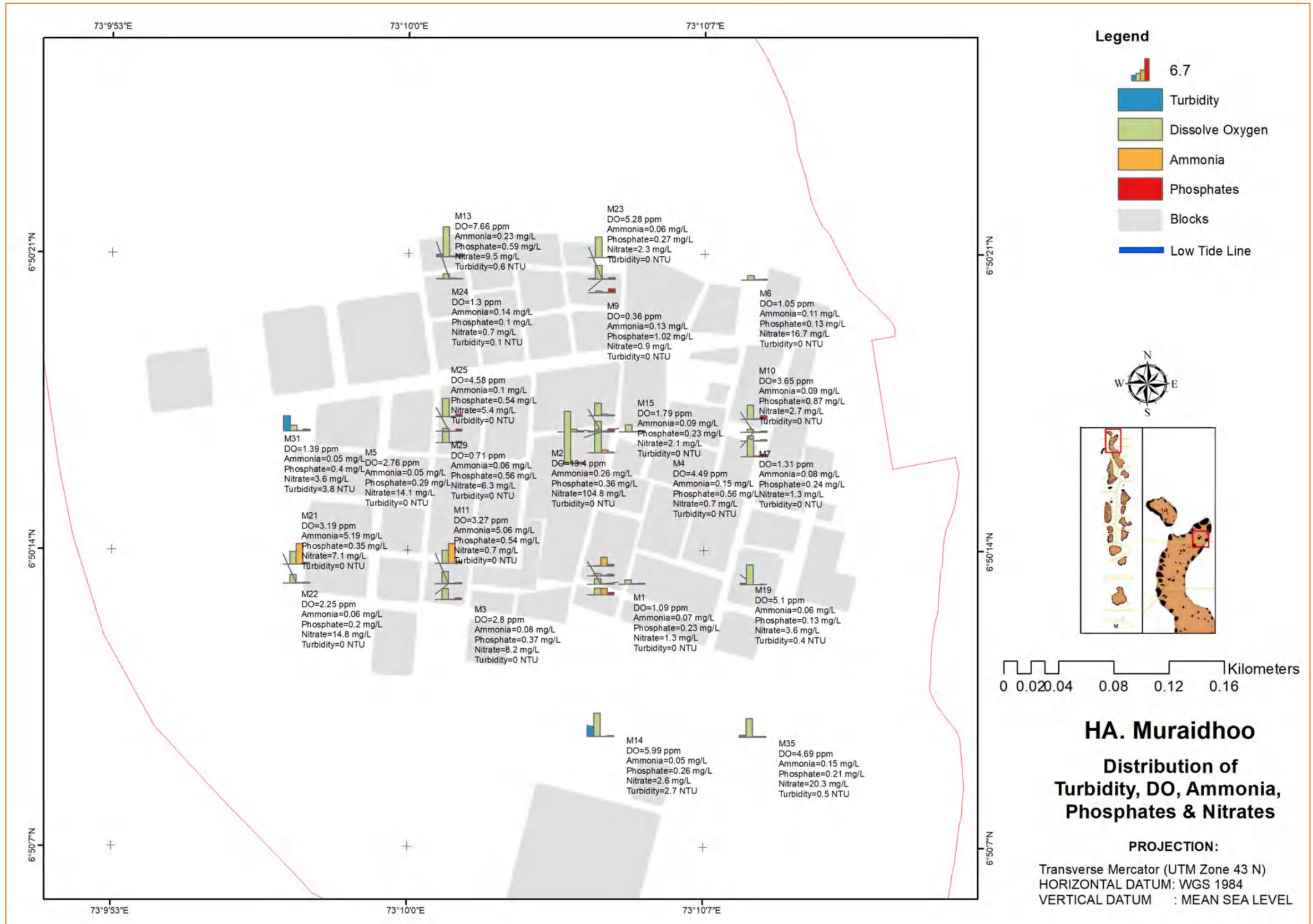


Figure 5-11: Distribution of Turbidity, DO, Ammonia, Phosphates and Nitrates in Ha. Muraidhoo Island

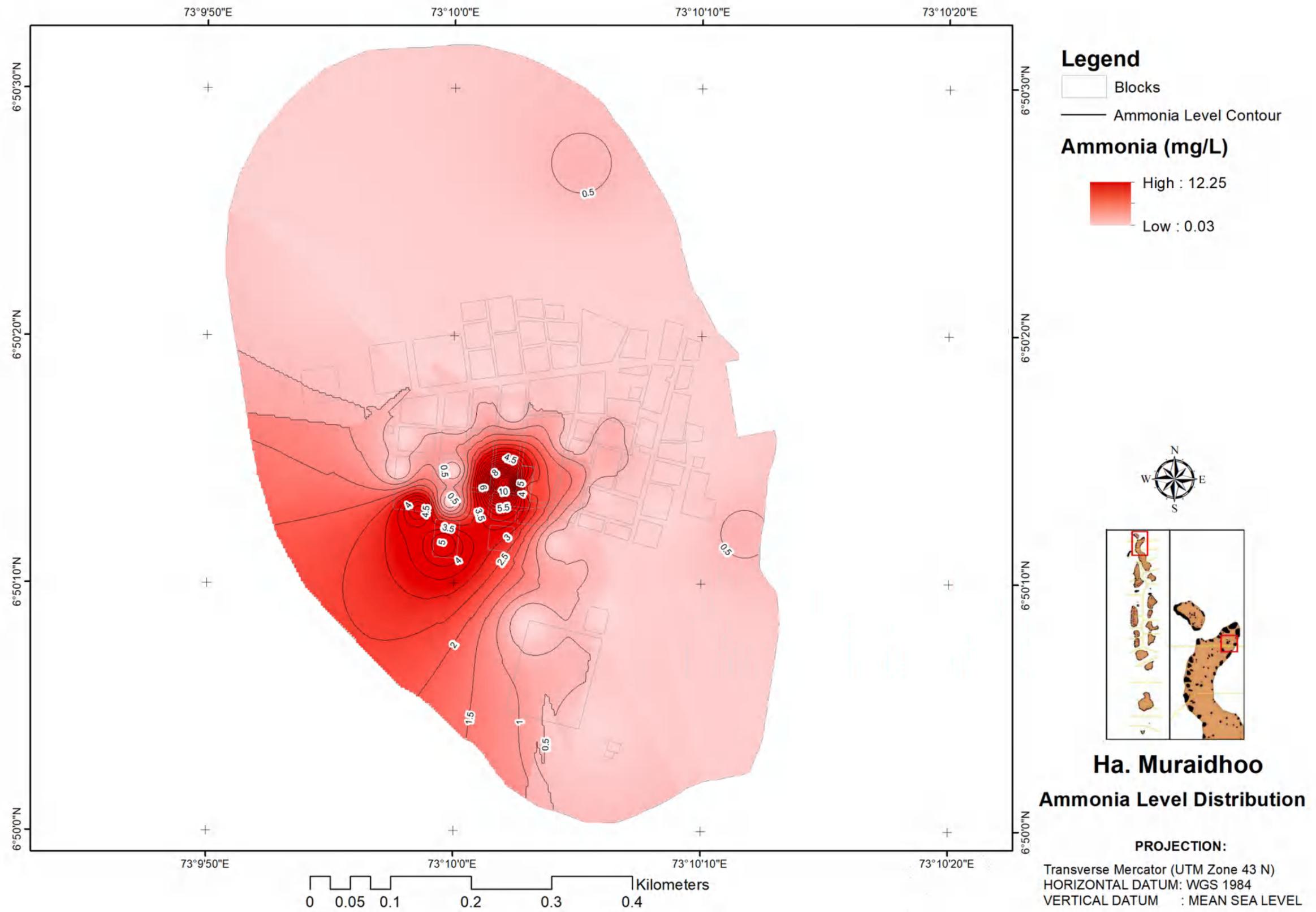


Figure 5-12: Ammonia Level Distribution in Ha. Muraidhoo Island

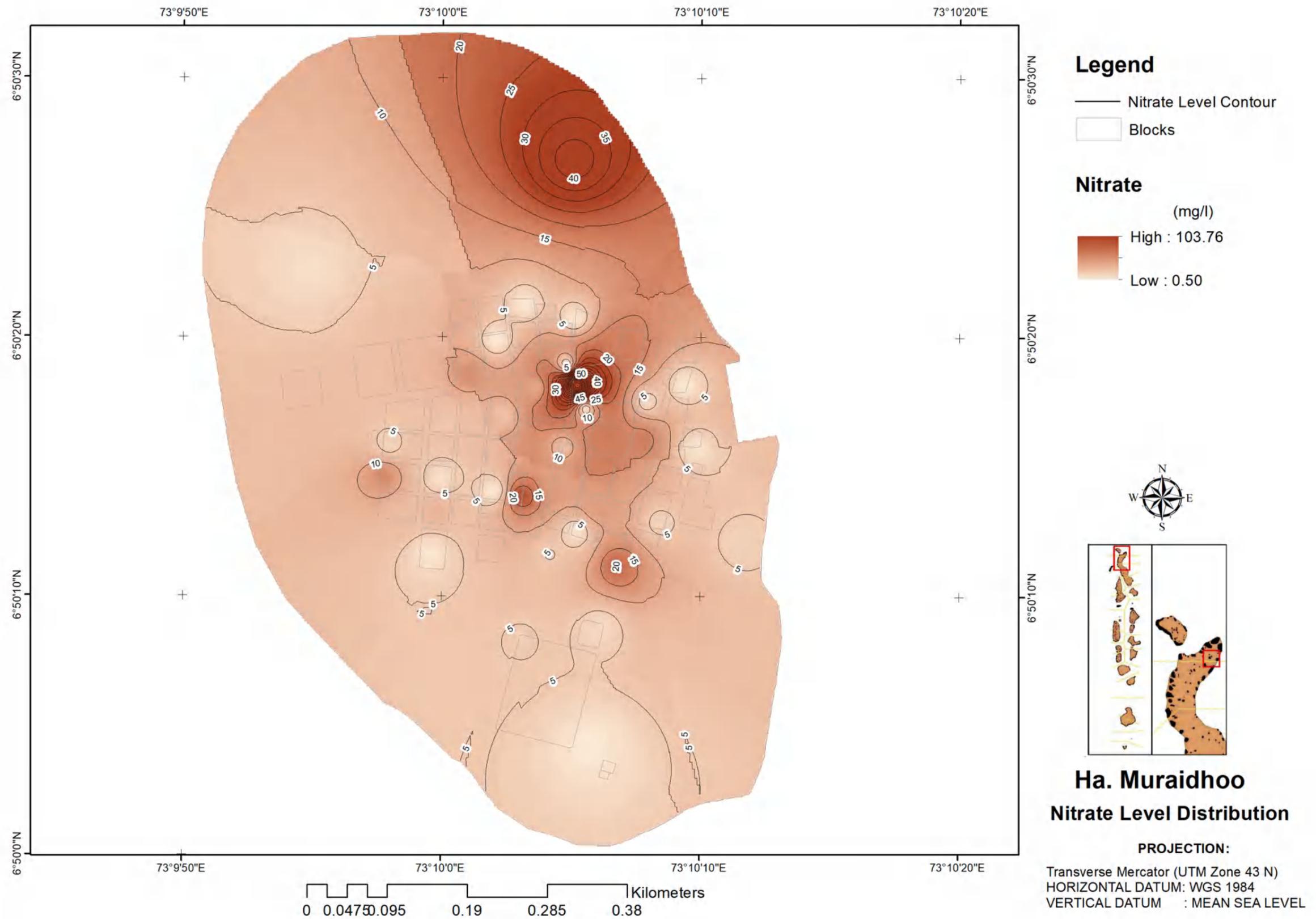


Figure 5-13: Nitrate Level Distribution in Ha. Muraidhoo Island

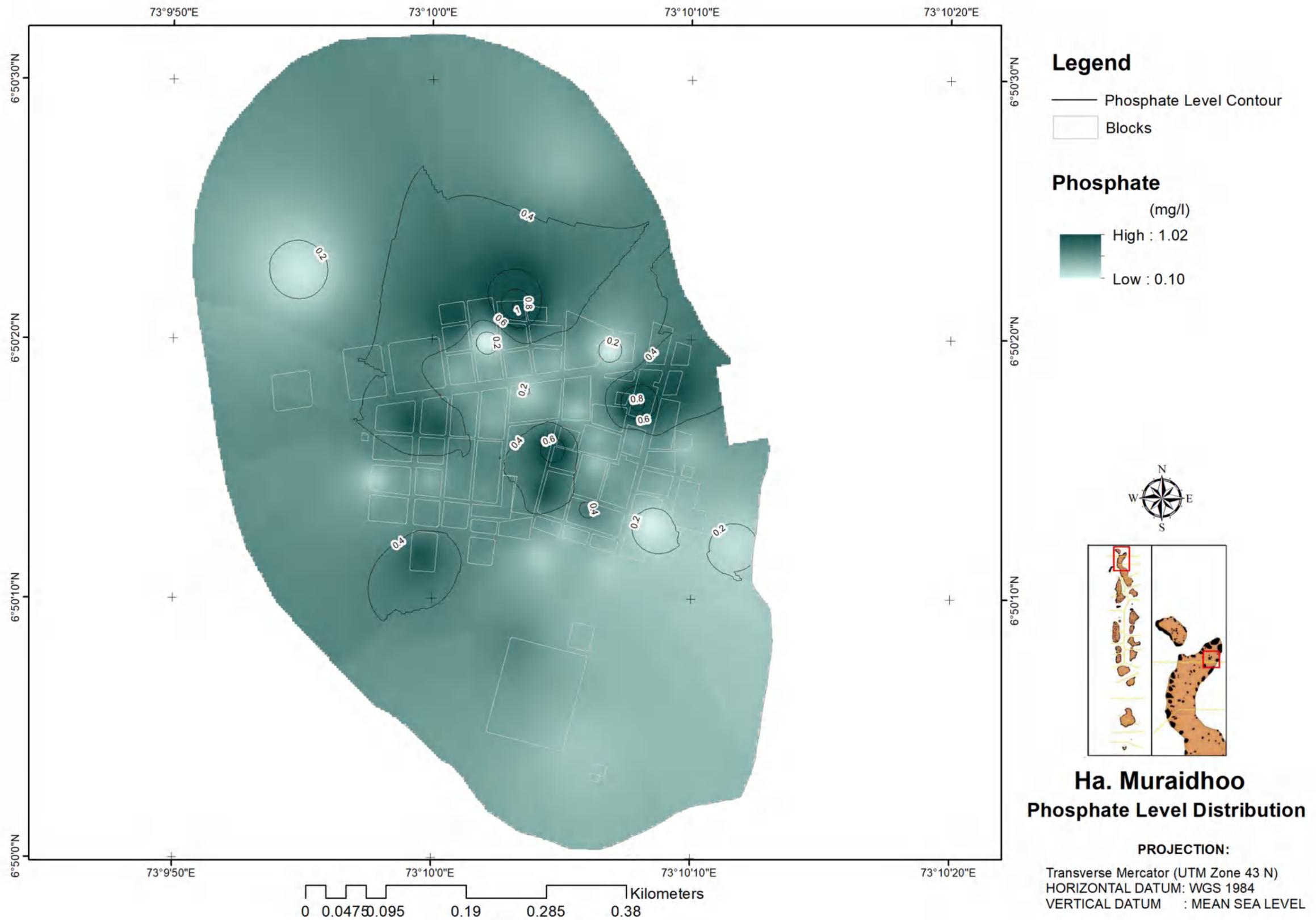


Figure 5-14: Phosphate Level Distribution in Ha. Muraidhoo Island

5.7.8 Geophysical survey

The Electrical Resistivity (ER) tests were carried out in the locations as outlined in Figure 5-15 below. The ER survey included test points along 8 transects selected representatively based on reconnaissance surveys to adequately characterise different land uses and island cross-sections. The main transects were aligned along existing roads to maintain consistency and uniformity.

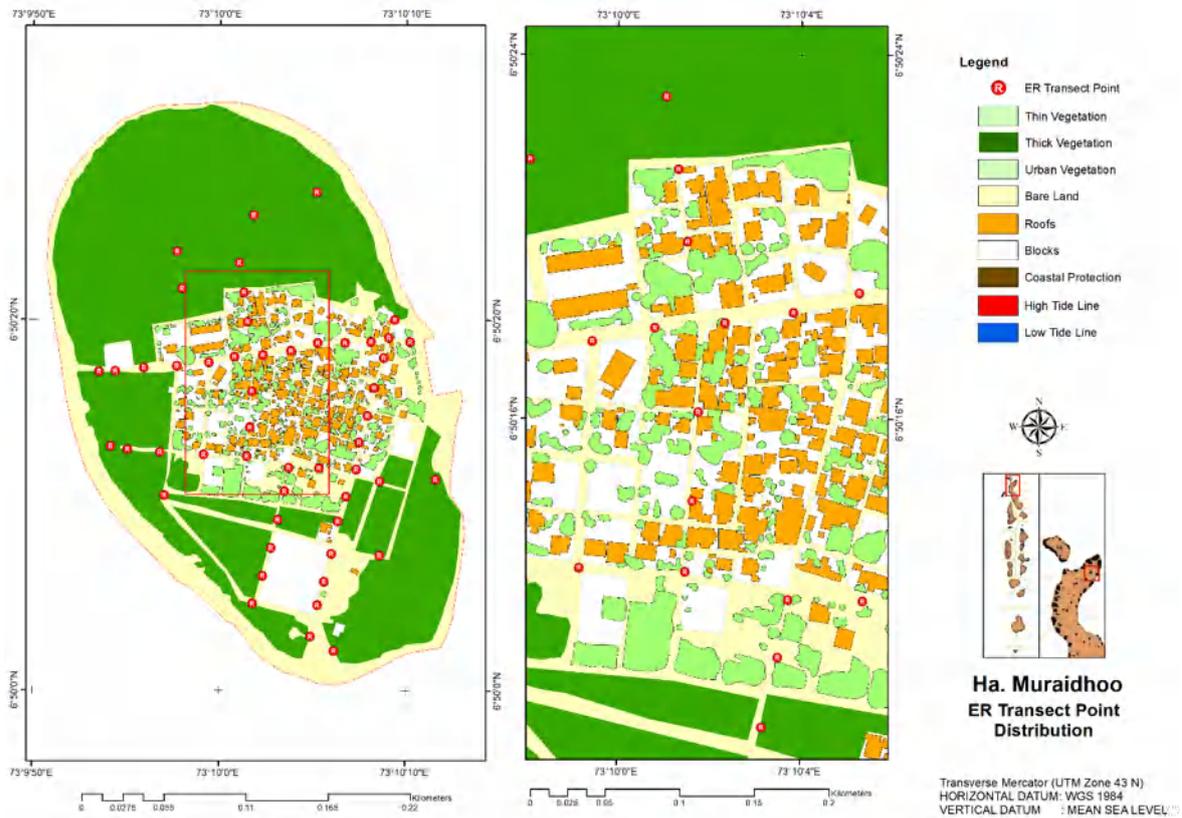


Figure 5-15: Location of ER points in Muraidhoo Island

5.7.9 Aerial surveys

Based on the aerial survey, a multiple dataset consisting of buildings, roof cover, land cover, change detection and shoreline were extracted. This data is shown in Figure 5-16. The total roof cover for this island is 26,015 m².

5.7.10 Water demand

The only source of natural water is rainwater collected from the rooftops of households and institutions and groundwater extracted from shallow wells. The runoff water from the domestic yards, road surfaces, etc., is not usable as there is no mechanism for its collection and treatment.

5.7.11 Freshwater lens

Based on the Electrical Resistivity (ER) surveys, the depth to groundwater level and the freshwater-saline water interface were determined for a set of transverse transects as shown in Figure 5-15. Plots in Figure 5-2 show the main two cross-sections of island. The dotted lines in the plots indicate a simple interpolation of levels to mean sea level in the island boundaries.

Volume of the lens has been calculated with aid of ArcGIS and Surfer Software.

$$\text{Volume of lens} = 454,349 \text{ m}^3$$

$$\text{Groundwater Storage} = \text{Porosity (15\%)} \times \text{Lens volume (m}^3\text{)} = 68,152 \text{ m}^3$$

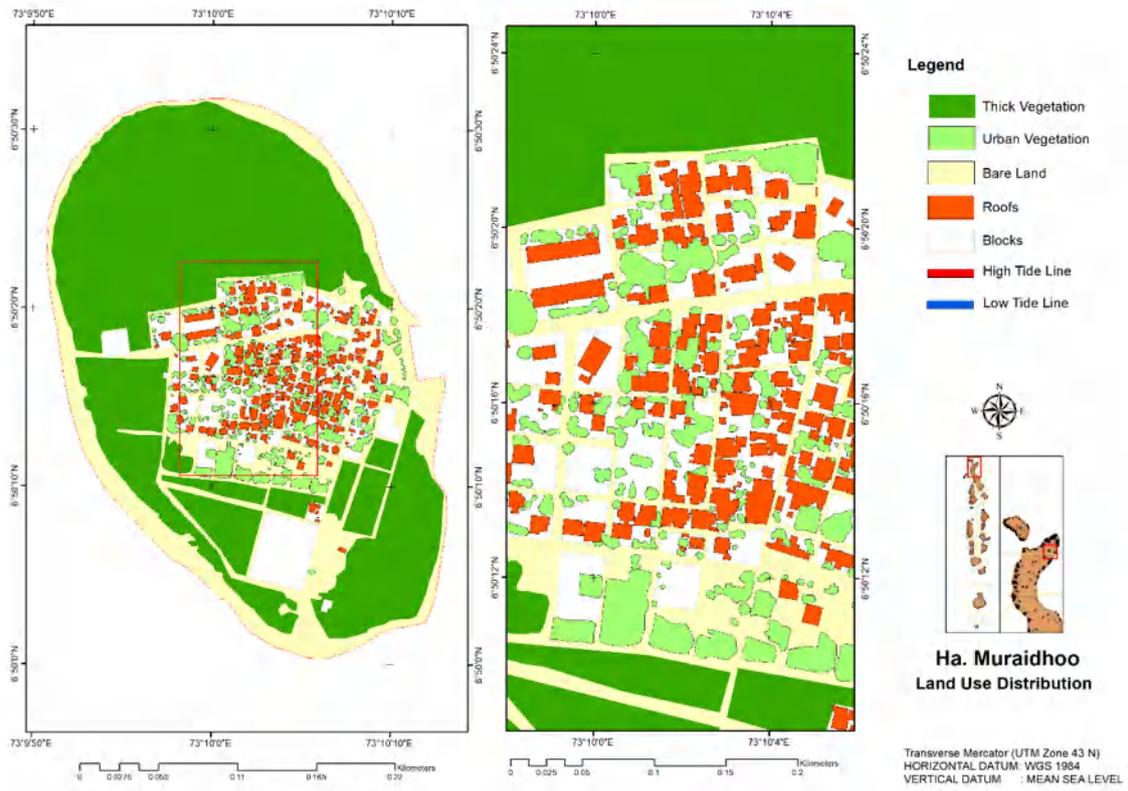


Figure 5-16: Roof Cover in Muraidhoo Island based on UAV Survey

The 2-D freshwater lens distribution density maps produced with GIS software for visualization of the spatial and volume extents are also presented below in Figure 5-17 to Figure 5-19.

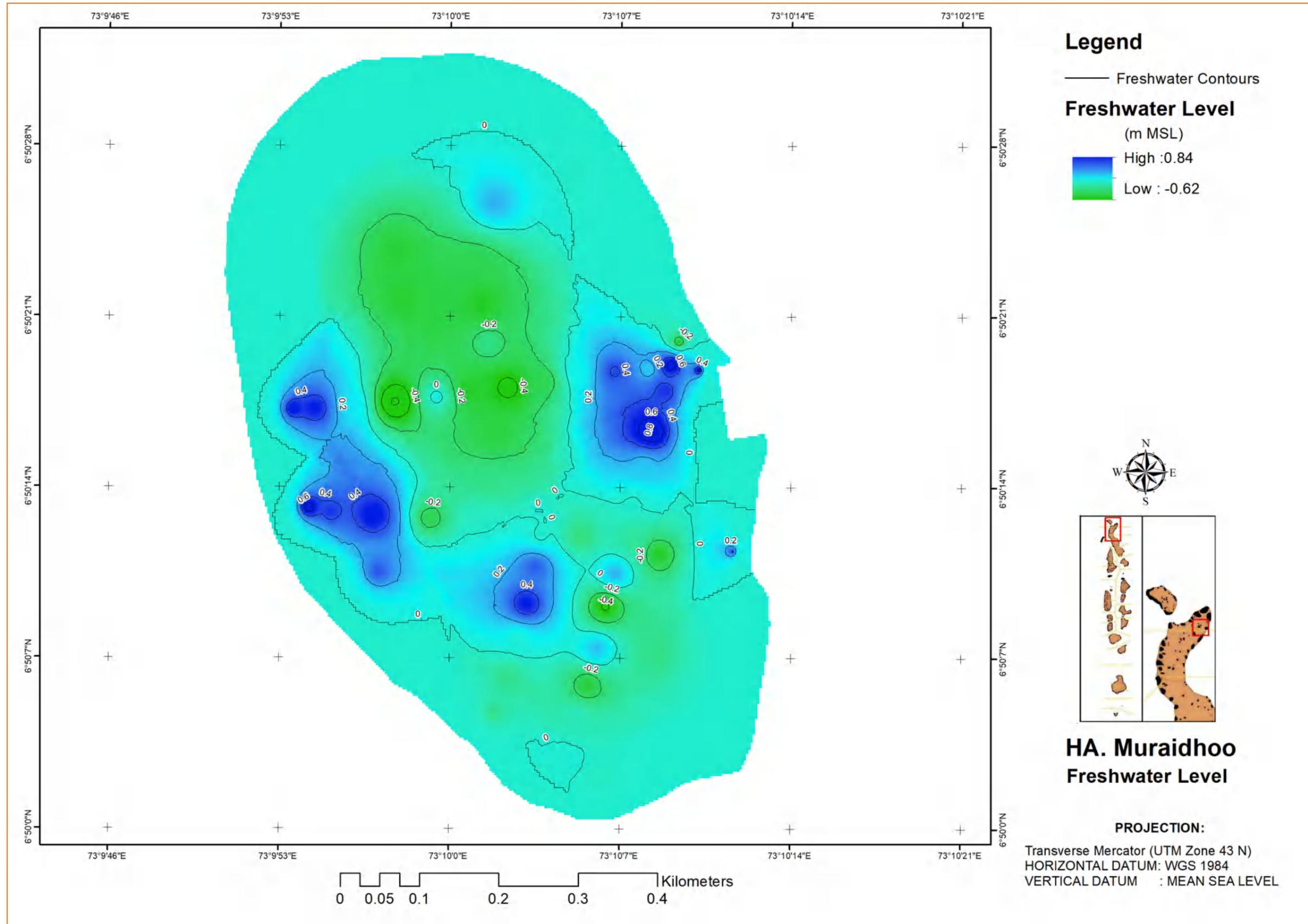


Figure 5-17: Freshwater Level in Muraidhoo Island

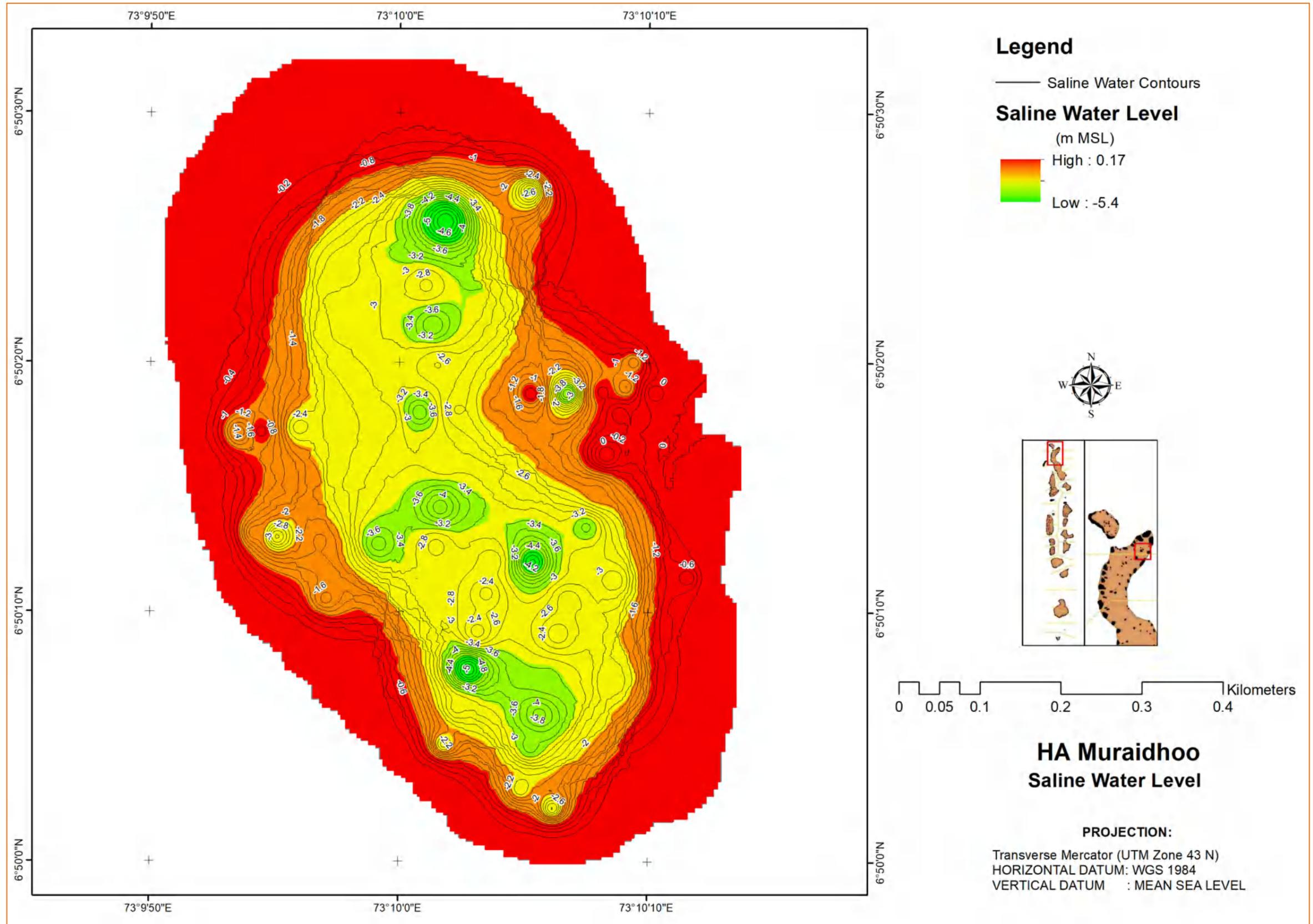


Figure 5-18: Saline water Level in Muraidhoo Island

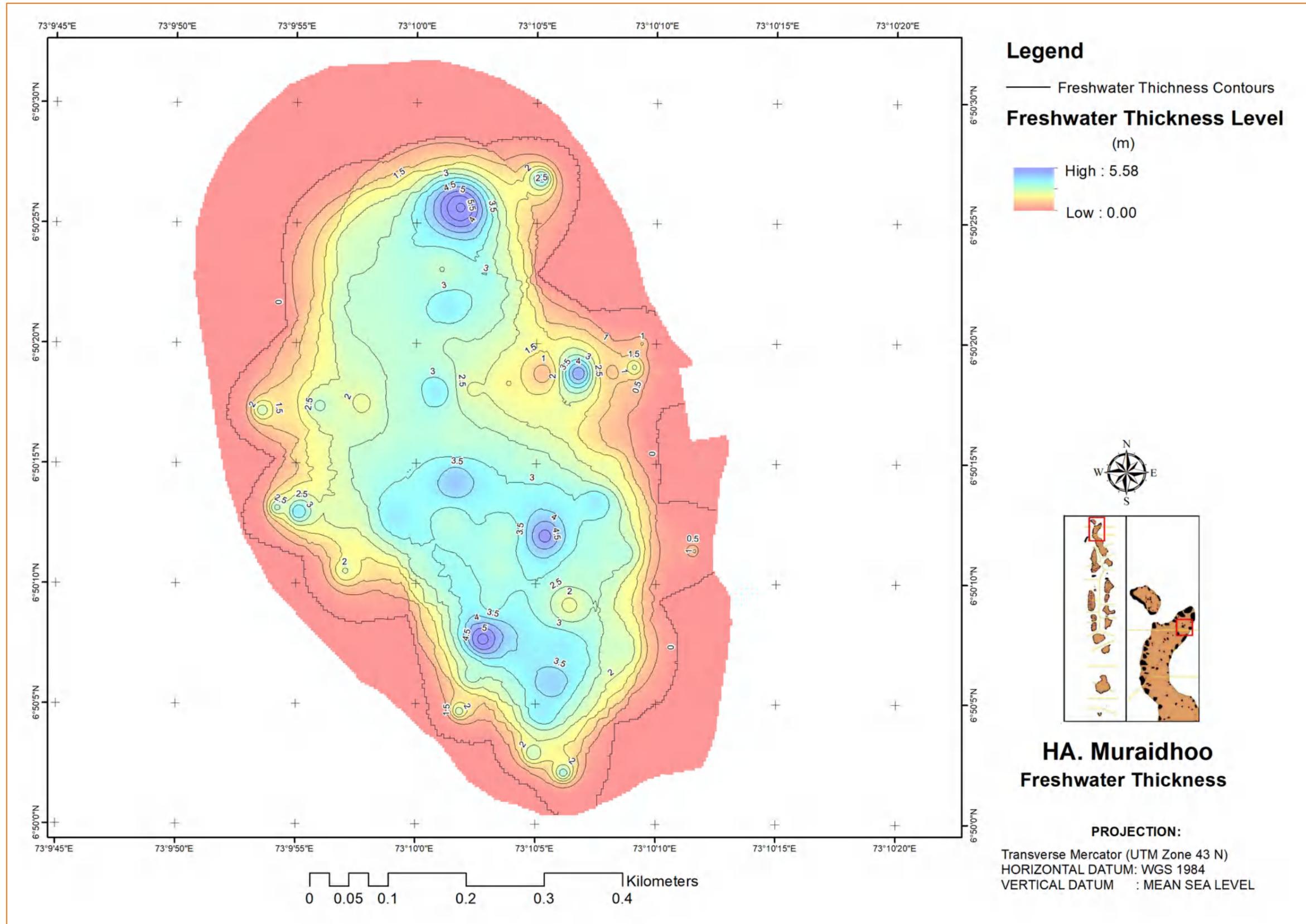


Figure 5-19: Freshwater thickness in Muraidhoo Island

The maximum freshwater thickness of the island is 3.19 m (It is noted here that these readings were taken in October, which is the wet season and the with a reasonably higher number of wet days per month of the year).

5.7.12 Water balance and recharge

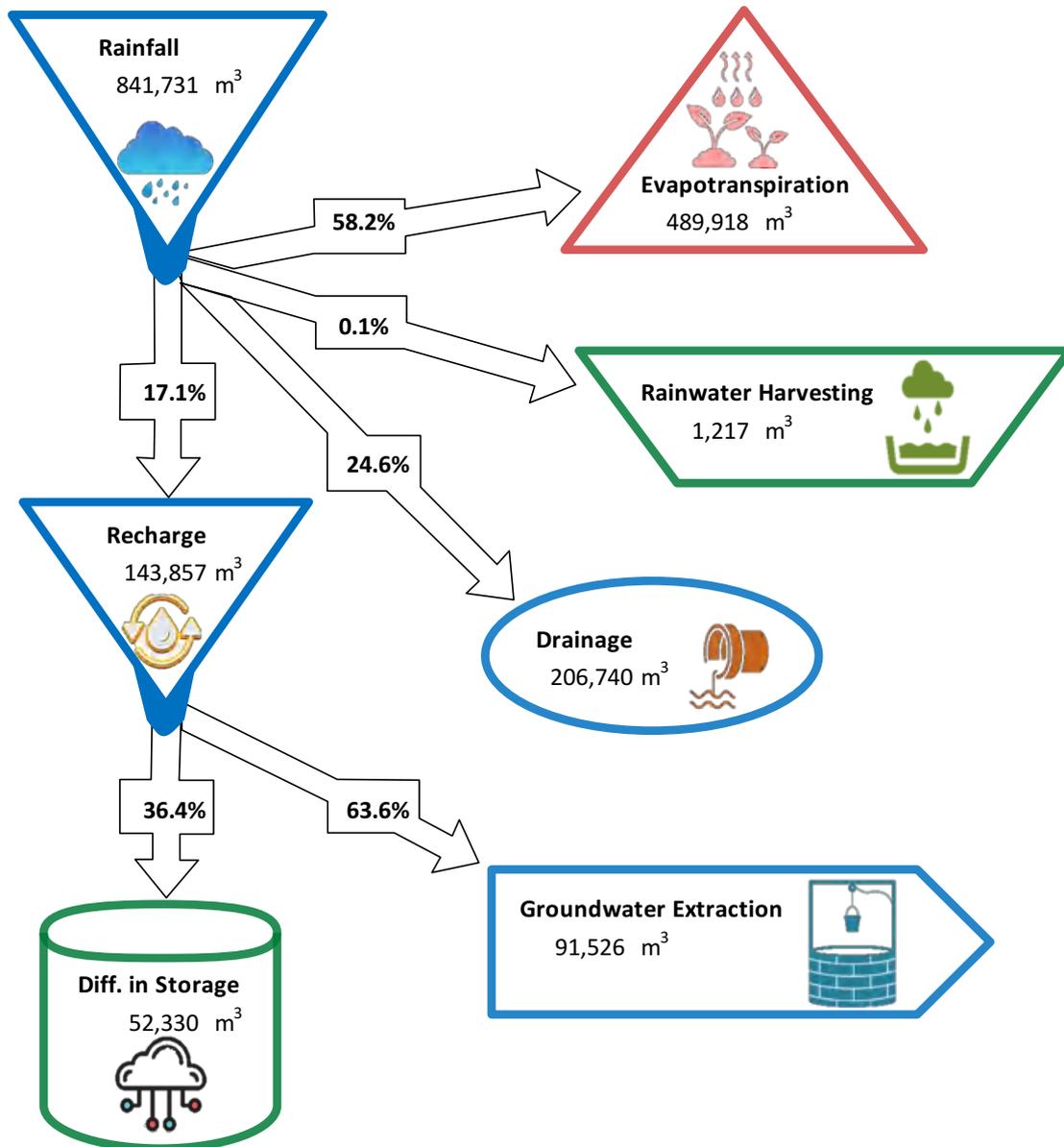


Figure 5-20: Schematic of water balance in Muraidhoo Island

An annual estimation is carried out based on the water balance method (Falkland, 2000). Rainwater harvesting is calculated using the number of rainwater harvesting units on the island. According to the spatial mean annual rainfall of the Maldives, the annual average rainfall of Muraidhoo Island is reported as 1,750 mm/year. Evapotranspiration was estimated using crop water requirements for different land use. Then, the rainfall was subtracted from rainwater harvesting, evapotranspiration, drainage to get the recharge volume. Drainage or the surface runoff was calculated by considering an aggregate runoff coefficient for the island based on the land usage (roof cover, bare land, farmland, roads, playgrounds, wetlands). The groundwater extractions were estimated from the amount of water usage in different sectors (residential, resorts, restaurants, agriculture and farming). The difference between recharge and groundwater extraction is taken to estimate the difference in storage.

5.7.13 Sustainable yield of the lens

Sustainable yield of the water lens refers to the safe extraction potential of a given groundwater aquifer without significantly affecting its quality or quantity. This parameter is an important factor in the sustainable development of islands as it allows planning and design of water and sanitation intervention in islands.

The island has a sustainable yield of 143 m³ per day which was calculated by subtracting groundwater extraction from recharge volume derived from the schematic water balance model in Figure 5-20.

5.7.14 Permeability test

Permeability tests were carried out in the selected locations as outlined in Figure 5-21.



Figure 5-21: Locations of permeability and steady pumping tests in Muraidhoo Island

The estimated permeability values for the above test locations are presented below in Table 5.9. The data will be comparatively verified and interpreted when additional data is acquired and calculations for other islands are completed.

The parameters have their usual notations where, K = Coefficient of permeability (m/s under Q unit gradient), Q = Steady flow into well (m³/s), H = Height of water in well (m), l = length of the perforated section (m), U = thickness of saturated permeability material above water table, r_1 = outside radius of the casing (radius of the hole in consolidated material) (m), r_e = effective radius of well = r_1 (area of perforations) / (outside area of perforated section of casing): $r_1 = r_e$ in consolidated material that will stand open and is not cast, C_s = Conductivity Coefficients, and T_u = distance from water level in the casing to water table (m).

Table 5.9: The Estimated Soil Permeability Values in Muraidhoo Island

Point	MUPM1	MUPM2	MUPM3	MUPM4	MUPM5
D (m)	0.450	0.750	0.800	0.500	0.700
H (m)	0.450	0.750	0.800	0.500	0.700
l (m)	0.450	0.750	0.800	0.500	0.700
U (m)	0.500	0.800	0.850	0.550	0.750
T_u (m)	0.500	0.800	0.850	0.550	0.750
r (m)	0.076	0.076	0.076	0.076	0.076
Q (m ³ /s)	5.06E-06	2.56E-05	1.14E-04	1.50E-06	4.75E-05
r_1 (m)	0.076	0.076	0.076	0.076	0.076
r_e (m)	0.010	0.010	0.010	0.010	0.010
T_u/l	1.111	1.067	1.063	1.100	1.071
$X = (H/T_u \times 100)$	90%	94%	94%	91%	93%
Section	Zone 2				
l/r_e	43	72	77	48	67
C_s	67	110	120	73	100
K (m/s)	2.02E-05	4.41E-05	1.74E-04	5.13E-06	9.43E-05
K (m/day)	1.75	3.81	14.99	0.44	8.14

5.7.15 Steady Pumping Test

Pumping tests were conducted in two existing wells to estimate the aquifer properties of unconfined water bearing formation.

Table 5.10: Selected Steady State Pumping Test Locations in Muraidhoo Island

Well No.	C'	A (m ²)	t' (s)	$\ln \left(\frac{s_1}{s_2} \right)$	T (m ² /s)
MUW 21	4.42	4.44	960	3.83	0.012
MUW 22	5.29	1.09	480	2.89	0.005

The measured transmissivity (m²/s) values ranged from a minimum of 0.005 m²/s to a maximum of 0.012 m²/s., with an average of 0.009 m²/s. During the testing period, EC (Electrical conductivity) level of both wells are given below.

- For MUW 21, EC (Electrical conductivity) has not increased and average EC is 1090 μ s/cm.
- For MUW 22, EC (Electrical conductivity) increases from 3880 μ s/cm to 4480 μ s/cm.

5.7.16 Status of groundwater availability in Muraidhoo Island

- 1). The selected Muraidhoo island has dimensions of width = 600 m and length = 1010 m, with a total land area of 48.10 ha, a population of 737 persons, and a land use of Roof cover (Built up area) 3.01 ha (6.3%), Vegetation (Thick) 29.93 ha (62.2%), Vegetation (Light) 3.24 ha (6.7%), and Barelands 11.93 ha (24.8%).
- 2). In order to recognize the fluctuation in the groundwater table, freshwater-saline interphase and estimate the volume of freshwater lens (FWL) and its associated recharge-discharge characteristics, 55 number of Electrical Resistivity (ER) location readings along 09 representatively selected transects were collected.
- 3). Soil overburden permeability tests (constant head) were carried out at 05 locations while steady-state pumping tests were conducted at 02 locations. In addition, groundwater level was also recorded at 09 locations where groundwater water quality samples were tested.
- 4). Permeability tests were carried out at representatively selected 05 number of locations. The measured permeability (K m/day) values ranged from a minimum of 0.94 m/day to a maximum of 16.36 m/day, with an average of 7.62 ± 7.92 m/day (Mean \pm Standard Deviation).
- 5). The ground elevation values ranged from a minimum of -0.22 m MSL to a maximum of 2.65 m MSL, with an average of 0.00 ± 0.00 m MSL (Mean \pm Standard Deviation).
- 6). The upper boundary of the freshwater lens (FWL) varied from a minimum of -0.62 m MSL to a maximum of 0.84 m MSL, with an average of -0.01 ± 0.15 m MSL (Mean \pm Standard Deviation).
- 7). The lower boundary of the freshwater lens (FWL) or freshwater-saline interphase ranged from a minimum of -5.40 m MSL to a maximum of 0.17 m MSL, with an average of -1.39 ± 1.28 m MSL (Mean \pm Standard Deviation).
- 8). Accordingly, the freshwater lens (FWL) volumetric values ranged from a minimum of 0.00 m to a maximum of 5.58 m, with an average of 1.33 ± 1.27 m (Mean \pm Standard Deviation).
- 9). The groundwater profile in the island is characterised by a relatively Low (0.14%) Rainwater Harvesting (%) relatively Very High (24.56%) Drainage (%) relatively Very High (17.09%) Recharge (%) while the water use shows relatively Very High (63.62%) Groundwater extraction (%) leading to relatively Low (36.38%) Difference in Balance Storage (%).
- 10). The freshwater lens (FWL) volume calculated based on ER transect test data is 68,152 m³ with a maximum FWL thickness of 5.58 m.

5.8 Conclusion

The Safe Yield for the island estimated based on 'Recharge - Extraction' is 143 m³ per day, while it is 231 m³ per day based on 10% of Average Annual Rainfall Method. The present groundwater extraction rate estimated based on survey data is 251 m³ per day and this exceeds the allowable Safe Yield in the island by 175% (Highly stressed). At present, there exists no island wide sewerage network or water supply network.

Relative hydraulic conductivity of the island lies in 'Semi-pervious' state while present aquifer condition remains at 'Poor' state based on the hydraulic conductivity estimation carried out as per Bear (1972) and transmissivity of the formation was compared as per Krany (1993). Moreover, general status based on transmissivity ranged "Very High" to 'High' and potential for groundwater recharge remains 'Low' – 'Moderate' as per the estimations.

6 HA. ULIGAN ISLAND

6.1 General Overview of The Island

The island of Uligan (Figure 6-1) is located on the southern periphery of Haa Alifu Atoll at coordinates 72°55'36"E, 7° 5'N. The island has an area of about 1.04 km² and measures about 0.78 km in width and 2.42 km in length. The population of the island was found to be about 547 residents as of December 2021. The island has a harbour on the Western side of the island. The following table outlines some basic information about the island and the following map outlines the location of Uligan.

Table 6.1: Basic statistical information on Uligan island in Haa Alifu Atoll.

Name of the island	Th. Uligan
Longitude and Latitude	72°55'36"E, 7° 5'N
Area	103.98 ha (1.04 km ²)
Population (Dec 2021)	547
Distance from Male'	328 km
Harbour	Present
Island sewerage network	Under Construction
Water supply network	Under Construction
Other infrastructure	No

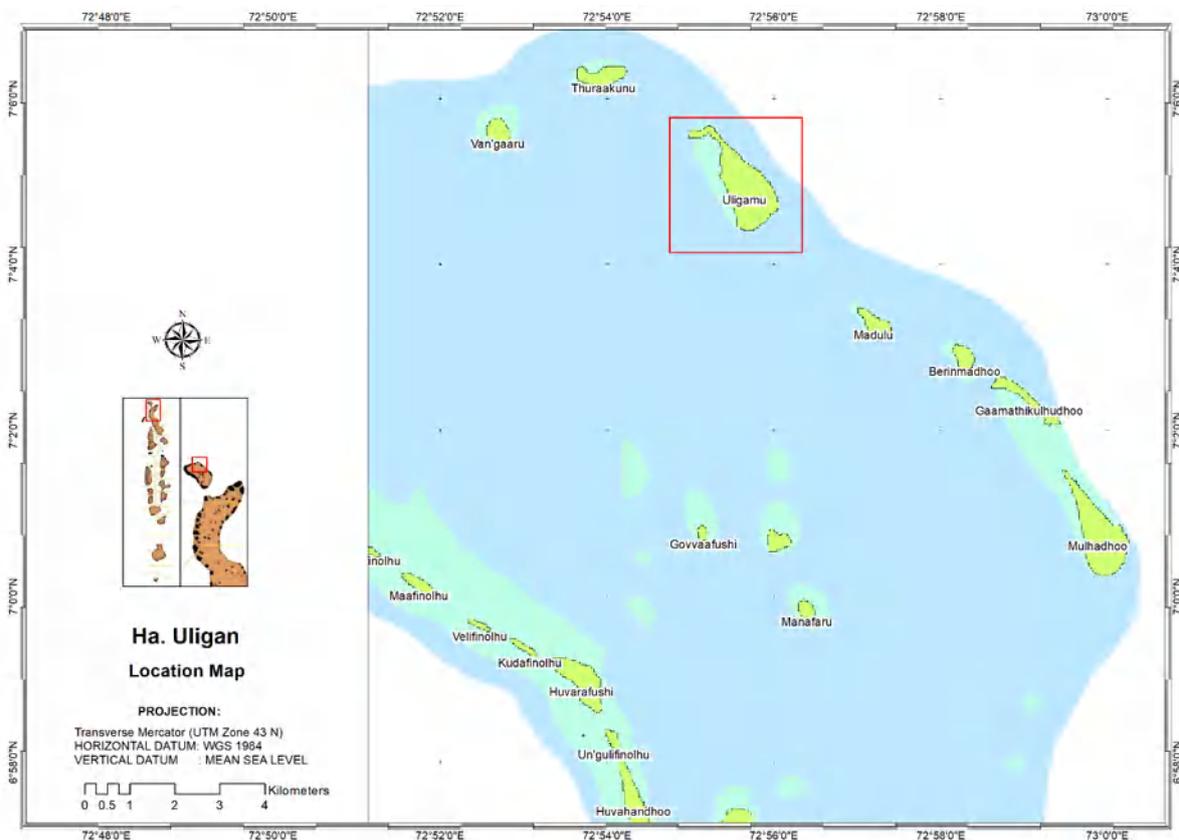


Figure 6-1: Location map for Uligan Island, Haa Alifu Atoll.

6.2 Topography and Geology

Uligan island is on the Northern most part of the “Haa Alifu Atoll” which is located North end of Maldives. The Uligan island located long NW – SE trending submerge coral reef which is extending about 16km. Uligan is an island with elongated shape and extends about 2,400 m (NW-SE) in length and about 780 m (SW-NE) in width. In the elongated island northern side is thin and the southern side is thick may be due to the actions of ocean waves and currents. Basic topography and the geological setting are mostly based on the properties of the underground coral beds and the actions of ocean waves and currents. The elevation of the island varies from -0.36 m MSL to 2.57 m MSL and is generally flatland through the island. The general geological profile in the island is composed of topsoil and beach coral sand deposits underlain by sandy coral rock (Figure 6-2). The sandy coral rock consists of a weathered coral rock layer and a hard fresh coral rock. According to the cross-section A-B, the topsoil layer varies from 0 to 1.0 m. Beach coral sand layer is about 1.0 m thickness in beach areas (B) and about 1.5 m thickness in middle of the island and ending with about 200m from A. In the southern beach areas, the beach coral sand exists mostly as the top layer. The coral sand layer is mostly unconsolidated and permeable layer. According to cross-section A-B, the weathered coral rock depth is varying between 0 m MSL (closed to A) to about 5.0 m MSL (middle of island), and it is a semi permeable layer. The fresh groundwater lens occupied both coral sand layer and weathered coral rock. The hard coral layer is mostly unconsolidated and impermeable and present as a fresh rock. As the compositional and structural differences of coral formation, differential weathering could be observed in cross section A-B. Cross section A-B clearly shows several deep weathered zones. In the cross-section C-D, it shows uniform weathering and general trend in western part of the island (C) show higher weathering compared to the Eastern part of the island (D).

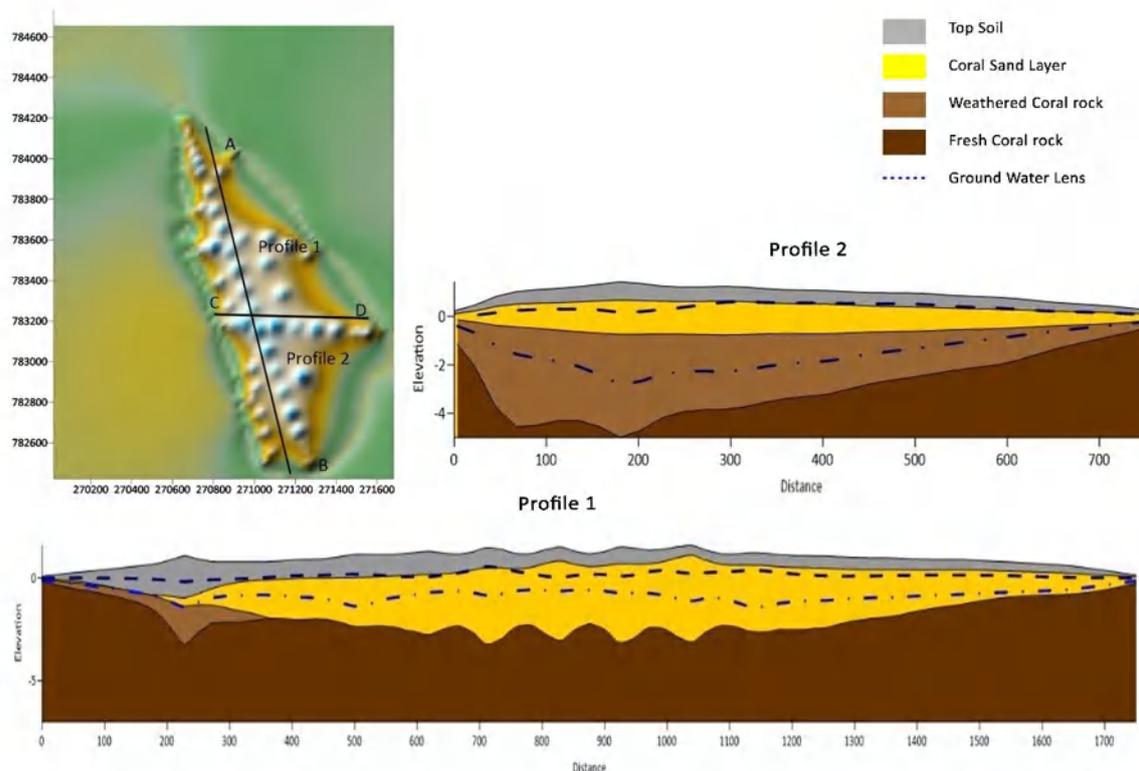


Figure 6-2: Geological sections of the island showing subsurface geological characteristics

6.3 Climate

Uligan experiences the typical two monsoons in the Maldives namely, the North-east monsoon from December/January to March/April and the South-west monsoon from Mid-May to November. There

are no specific wind and rainfall data available for Uligan as there are no weather monitoring stations on the island itself. Based on the rainfall data of the nearest weather monitoring station, it shows a declining trend in rainfall for the past 30 years (Inception Report, 2021).

The historical rainfall data records from Hanimadhoo Island (not included in the 5 selected islands in Lot 1) located in the Haa Alifu atoll (45 km to the south east from Uligan Island) has an annual average rainfall of 1,747 mm with a standard deviation of 279.1 mm and the trend with the decadal means were shown in the following graph (MEE, 2021).

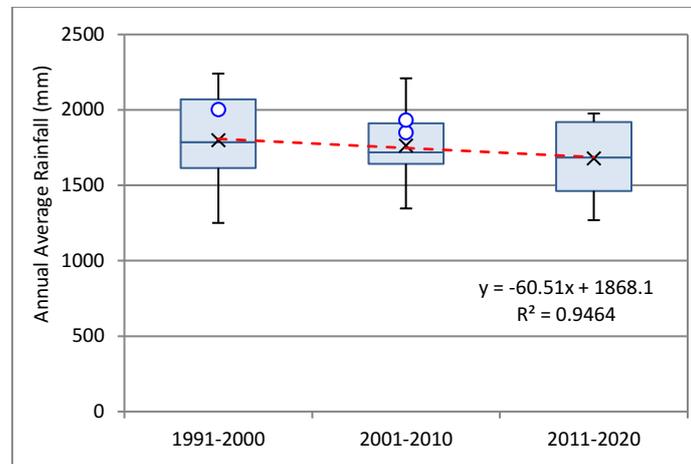


Figure 6-3: Decadal means and trend for rainfall in Hanimadhoo (1990 - 2020).

6.4 Demography

As of December 2021, Uligan has a registered population of 547 people including 278 males and 269 females (Uligan Council, 2021). As per the council, an estimate of 37 foreigners including 33 males and 4 females currently resides in the island. Foreigners includes teachers, medical staff and labour force working in different projects that are being undertaken in the island. The island council was not able provide accurate figures on the residential population by gender.

Total number of households in Uligan at present is 72.

Table 6.2: Demographic Breakdown of Uligan Island as of December 2021

Registered Population			Foreigners		
Both	Male	Female	Both	Male	Female
547	278	269	37	33	4

Source: Filladhoo Island Council 2021

6.5 Socio-economic condition

6.5.1 Natural Resources and Land Uses

Uligan is located in the northernmost region of Haa Alif Atoll and therefore is one of the islands located in the topmost region of the country. Similar to most of the other islands in the atoll, majority of Uligan is also covered with vegetation with only a small area settled by the residents on the west side of the island. The island size is 112 hectares.

There are two wetland areas and a “marsh” land area in the island. The wetland areas are located on the southeastern side of the island. See appendix xx for google image with wetlands marked as per the island councils during pre-inception meeting.

While the island has never had to face any problems regarding swell waves, soil erosion is observed in different parts of the island. The issue is severe in the northern part of the island, with a recent storm causing a lot of trees to come off the roots and the plants now gone. Soil erosion is also observed in the southeast side of the island, and depending on the season, ‘thundi’ (i.e. the broad sandy beach) of the island may shift from southwest.

As per the Island Council, Uligan also faces flooding issues due to the nature of the surface level of the island and a few hours of rain can cause flooding in some areas. The Council reported that flooding mainly occurs near the harbour area, the current powerhouse area and in some residential areas. There are 4 areas in particular where some households have to face severe flooding. In some areas of flooding, a very high level of groundwater pollution is also observed. The Council believes that this may be due to issues in rainwater not draining well into the ground.

In terms of land use and allocation, the island council now has the authority to allocate lands for different purposes with an approved land use plan. The island currently does not have an approved land use plan; however, the council is in the process of developing the same. The council, however, does have a zone planning chart, approved by the MNPHI.

6.5.2 Economic Activities



Figure 6-4: Summary of household and socio-economic activities

The main economic activities carried out in Uligan include agriculture, hospitality and tourism, and employment in government sectors.



Figure 6-5: Agricultural Lands allocated in Uligan

Main agricultural crops grown in the island include pumpkin, watermelon, cucumber, tomato and bananas. Residents usually practice farming in their households/backyards, though the council has allocated 21 land agricultural plots to those who had expressed interest for farming. The general practices of farming in Uligan as similar to most islands of the Maldives include planting trees straight in the ground or in large containers such as empty oil barrels. For bananas they excavate pits on the ground until it almost touches the water lens whereas for other plants, it is usually by making beds or planting in pots or barrels. Use of fertilisers and chemicals are practiced in most islands of Maldives and is the case in Uligan as well.

While there are no tourist accommodations and guest houses in the island, Uligan is considered as a stop-over island for big vessels such as tourist yachts passing by, due to its convenient geographic location. Reportedly, around 130 yachts might stopover a year, particularly during peak season during the months between September and April. As per the island council, a total of 33 yachts stopped over in the first half of 2021, bringing around 170 tourists to the island. The island mainly provides different amenities and hospitality services such as laundry and food for the tourists. The council also informed that 36 hectares of land has been allocated for tourism establishment in the island, the works of which are now continuing after being halted for some time. A considerable percentage of the youth population currently works in tourist resorts.

6.5.3 Accessibility and Transport

The nearest airport to Uligan is HA. Hoarafushi Airport which is around 12 Km away. There are three other airports in the region (in HDh. Hanimaadhoo, Haa Dhaalu Kulhudhuffushi and Shaviyani Fonadhoo). The main mode of transport to and from Male' to the island is by flying to Hoarafushi and private launch hire from Hoarafushi airport to Uligan. There are private ferries travelling within the atoll as well as supply boats travelling between the atoll and Male', the capital city.

A harbor with quay walls is built on the west side of the island and is used to access the island. As per the council, soil erosion is observed on the north side of the harbor since the development of the harbor.

6.5.4 Services and Infrastructures

The island is equipped with the basic services and supporting infrastructures and the details of these are discussed in the following sections.

6.5.4.1 Public Facilities and Amenities

The public facilities available in the island includes:

- Health Center
- Pharmacy
- Primary and Secondary School
- Government institutions (Office for Island Council, Island Court)
- Mosques
- FENAKA office
- MNDF rescue coordination center
- Immigration desk (at MNDF office)
- Custom office
- Ports health desk (established in the island health center)
- Police desk (established in the island council office)

6.5.4.2 Water supply

The main sources of water for the island are rainwater and groundwater. Locals use rainwater mainly for drinking and cooking while groundwater is used for agriculture and other household purposes. This is further discussed in section 1.3 and 1.4.

6.5.4.3 Energy supply

Uligan has electricity for 24 hours generated from island powerhouse operated by FENAKA.

6.5.4.4 Waste and Waste water disposal

Solid Waste: The island council has prepared a waste management plan/guideline for the island; however, is not properly implements and waste is left in different non-residential areas.

Sewage Disposal: Main method of sewerage disposal at Uligan is by means of septic tanks. Most of the household has a septic tank within close proximity and are infiltrated into the ground. The island currently has an ongoing project to establish a water and sewerage system. Household connections for the sewerage system is currently ongoing, though the system is not commissioned yet. The project is scheduled to be complete in 2023.

6.6 Existing water and sanitation situation

6.6.1 Water

The island currently does not have a piped drinking water system, however, establishment of an RO Plant with household connection is ongoing and is expected to be completed and ready to use in 2023.

The locals use groundwater for all purposes except of drinking and cooking. Ground water is also used agriculture. In the pre-inception meeting, the island council reported that even though ground water is not used for cooking and drinking, the quality of ground of water remains quite good in the island. However, the council also reported that some groundwater contamination such as bad odor and discoloration is observed in areas where the first septic tanks were established in the island.

Locals use rainwater mainly for drinking and cooking. Rainwater is harvested using water tanks in individual households. Each household has at least one water tank with a capacity of 2,500 L. The council also collectively has the capacity to collect and store 25,000L of water. During the pre-inception meeting, the council reported that they have had to request water from external sources once and that community tanks has been established since then.

The general practice of rainwater harvesting at island level is to clean the roofs thoroughly and letting the first flush pass to the roads which would eventually seep into the ground. Excess rainwater is also discharged to the roads in a similar manner.

6.6.2 Wastewater and Sewage Disposal

Currently sewage is deposed by means of septic tanks. Most household has a septic tank within close proximity and are infiltrated into the ground. It was noted that most of the households keep the soakage pits outside the house, away from the groundwater wells although the septic tank is inside the house.

According to the household survey that was carried out under this study, 74% of the households reported having septic tanks, 10% reported having local outfall pipes and 16% reported having connected to the island sewerage network. As per the island council, though household connections are completed for some households, the system has not been commissioned yet.

Among the households reported having septic tanks, about 97% reported having the septic tanks 10ft or more away from the well.

Establishment of a proper sewerage system with household connection is currently ongoing and is expected to be completed in 2023. Once the new sewerage facility has been established, the existing facility will be abandoned. The septic tank inflows from the pipes will be ceased by disconnecting the inflow pipes. The remaining sludge in the pipes and septic tanks will then be removed by sewer jetting and released to the sea via outfall pipe.

6.7 Results of the Baseline Surveys: Water Usage

6.7.1 Summary socio-economic surveys

As detailed in the methodology section of this report (Section 1.4.3), a survey was carried out to determine the water usage at households (HHs), commercial entities (cafés/restaurants), institutions and places with industrial uses (agricultural lands, fish processing). The survey was conducted in Uligan from 15th August to 16th August 2021 with the help of local enumerators. The following Table 6.3 summarizes samples taken for each sector at 95% confidence interval, refusals, replacement samples and total number of completed surveys for each.

Table 6.3: Population and Sample taken for the social survey

Population		Sample	Sample replacement	Forms Completed	Refusals	Vacant Houses
Households	72	62	4	62	0	4
Registered Farmers	10	0	0	10	-	-
Fishing Vessels	0	-	-	-	-	-
Fish Processing	0	-	-	-	-	-
Institutions	6	6	-	4	-	-
Guest houses	0	-	-	-	-	-
Café/restaurants	1	1	1	-	-	-

Note: A number of mitigation measures were adopted to ensure to achieve the 95% confidence level sample size. The challenges and limitations and the measures undertaken to mitigate the challenges are listed in Section 1.4.3.1.

The key findings from this survey show that a total of 811.76 liters of groundwater are estimated to be used per capita per day for various domestic uses. The respective water use situations including domestic, commercial and institutional uses are illustrated in the following sections.

6.7.2 Water usage for domestic purposes

6.7.2.1 Domestic Water Usage

The water usage estimates are calculated based on internationally applied flow rates. A total of 62 HHs were surveyed from Uligan. As presented in Table 6.4, 97% of HHs have at least one of 2,500L capacity HDPE rainwater tanks at their homes to collect rainwater for daily uses. Among the 62 HHs, 98% uses rainwater for drinking while 100% also uses it for cooking.

Groundwater is mainly used for non-potable use in all the households surveyed.

Table 6.4: Groundwater and rainwater use data for Uligan

Rainwater	Per cent (%)
Households with rainwater tanks	97%
Rainwater use for drinking	98%
Rainwater use for cooking	100%
Groundwater	Per cent (%)
Groundwater as drinking source	0%
Groundwater for cooking	0%
Groundwater for non-potable use	100%
Total number of household wells surveyed	62
Percentage of wells surveyed fitted with pumps	98%

Based on the survey carried out, average daily water demand per capita for domestic purposes has been estimated based on the average amount of water used per person for showering, toilet flushing, laundry and gardening, this data is shown in Table 6.5, The total domestic water use is estimated to be 811.76 litres per capita per day.

Table 6.5: Domestic Water Usage in Uligan

Shower/ Liters per capita per day	Toilet/ Liters per capita per day	Laundry/ Liters per capita per day	Gardening/ Liters per capita per day	Total/ Liters per capita per day
190.0	45	14.1	229.0	478.0

6.7.2.2 Perception on Groundwater

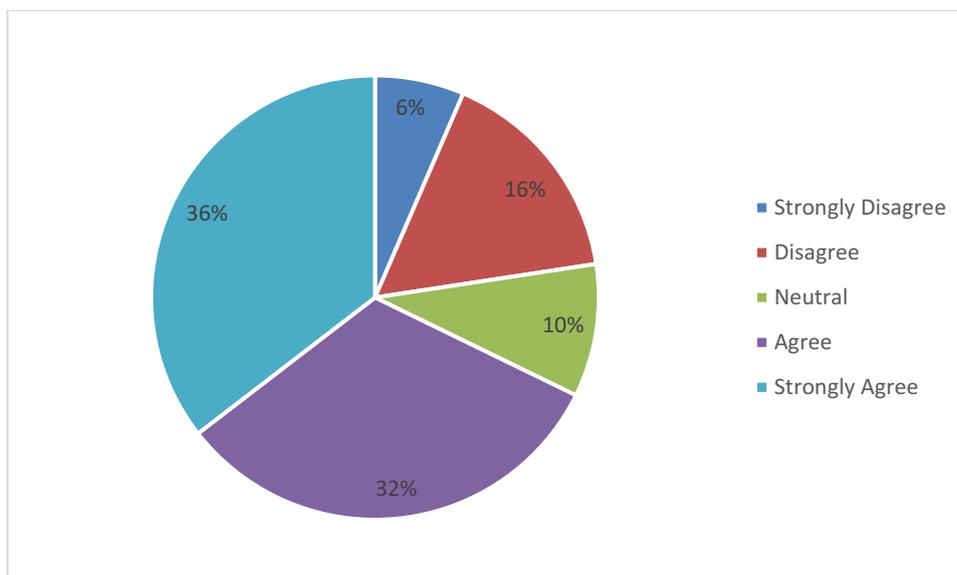


Figure 6-6: Perception of HHs on safety of Groundwater

The households were also asked about their perception on groundwater, if it is safe to use for daily purposes and whether the quality of groundwater is good or bad.

As it can be seen from Figure 6-6, a total of 68% agreed that groundwater of Uligan is safe to use for their daily uses. Among this 68% household, 36% strongly agreed that that the ground water in the island is safe for their daily purposes.

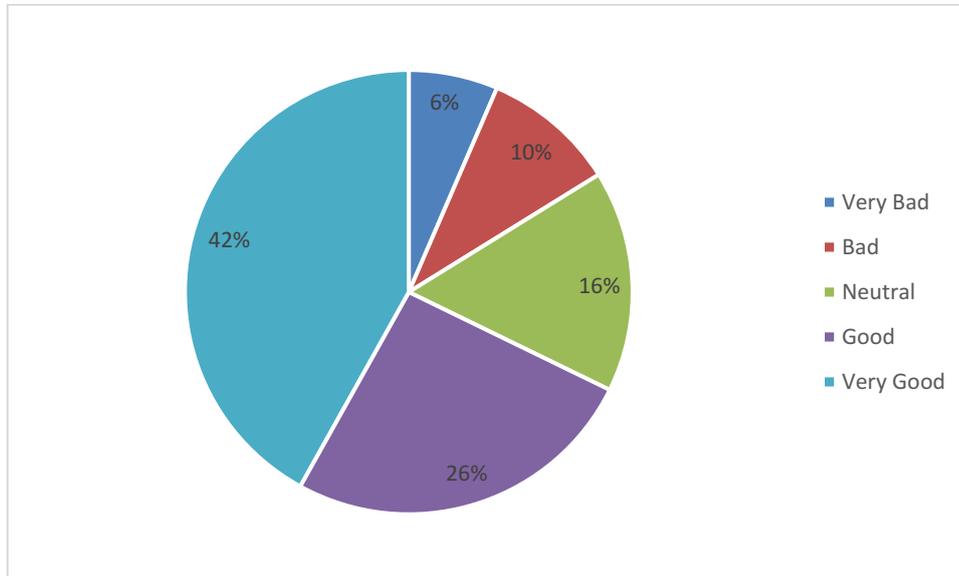


Figure 6.7.2.2 Perception of HHs on quality of groundwater

Furthermore, the households were asked about the quality of groundwater with regards to their experience. As it can be seen from Figure 6.7.2., a total of 68% agreed that groundwater quality in the island is good. Among this 68% households, 42% reported that the ground water quality is very good. This data is in line with the information received from the council as the generally, the quality of ground water is good in Uligan.

6.7.3 Water Usage by Commercial Activities

In terms of commercial water usage, only 1 café were identified as commercial entities present in the island and data was collected from the café’.

The Table 6.6 below presents a summary of water usage by the café.

Table 6.6: Water Usage by commercial activities in Uligan

Cafés	Total Volume of water per day (Liters)
1	1,227

The main use of groundwater usage reported from the café’ was for dishwashing. The total daily groundwater consumption for this Cafés is estimated to be 1227 liters. It is important to note here that the figure for this café’ cannot be generalised for every café’ in the island as the capacity of each café’ and its level of operation would be different.

6.7.4 Water Usage by Institutions

In order to estimate water consumption by different institutions in Uligan, four institutions were surveyed including the island magistrate court, FENAKA office, school and customs office.

Groundwater in the institutions in Uligan are mainly used for mopping floors, flushing toilets, washing, and to some extent gardening. A total of approximately 6032.8 liters of groundwater are

estimated to be used per day by the institutions. As the use of each institution is different, to generalize water consumption of institutions to an average figure will not be accurate. However, it can be deduced that based on the data, 84.97 liters of groundwater are estimated to be used per staff per day at the institutions of Uligan (Table 6.7: Water Usage by commercial activities in).

Table 6.7: Water Usage by commercial activities in Uligan

	Water Flushed (Liters)	Gardening (Liters)	Mopping (Liters)	Sub-Total Water Used (Liters)	Total Water Used (Liters)	Institutional Groundwater Usage (Liters Per Staff Per Day)
Magistrate Court	620	1,227	500	2,347	6,032.8	84.97
FENAKA office	80	2,454	25	2,559		
School	100	81.8	75	256.8		
Customs office	320	200	50	570		

6.7.5 Water Usage for Farming

Though the council reported having 10 registered farmers in the island, a total of 11 farmers participated in the survey. According to the survey findings, farmers mainly use groundwater for watering the plants. When asked about how they water the plants, 7/11 farmers (64%) reported using a pipe connected to a pump, 3/11 (27%) reported using watering cans, and one (9%) reported using a sprinkler system. The Table 6.8 below summarizes the water usage by farmers every day.

Table 6.8: Water Usage by Farmers in Uligan

Farmlands	Area of farmland (sqft)	Volume of water used per day (Liters)	Total volume of water used per day (Liters) per sqft
1	40,000	40.9	0.00
2	20,000	300	0.02
3	1,000	NA	NA
4	1,600	1000	0.63
5	20,000	9000	0.45
6	8,000	40.9	0.01
7	40,000	40.9	0.00
8	5,000	81.8	0.02
9	15,000	12.27	0.00
10	10,000	163.6	0.02
11	10,000	163.6	0.02
Total		10,843.97	

From the total 11 farmers that were surveyed, total of approximately 10,843.97 liters of groundwater are estimated to be used per day. Therefore, an average of approximately 0.115 liters of groundwater are estimated to be used per day per sqft by the farmers of Uligan.

6.7.6 Groundwater quality

Groundwater quality measurements were made at selected wells in Uligan Island for both physical and microbiological testing.

The following Table 6.9 summarizes the water quality results.

Table 6.9: Summary of groundwater quality tests from Uligan Island in 2021

Sample No	EC (µS/cm)	pH	Turbidity (NTU)	DO (ppm)	Temp (°C)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
U1	661.00	7.60	0.36	7.31	29	0.32	15.30	<0.02	0.30	>2420	435
U2	587.00	7.70	0.25	6.58	28	0.28	40.00	0.05	0.16	>2420	
U3	532.00	8.00	0.68	7.49	32	0.28	2.50	0.22	0.22		
U4	57.00	7.80	0.24	6.79	26	0.03	30.30	0.19	0.31		
U5	1013.00	8.20	0.47	7.61	28	0.49	42.40	0.30	1.10		
U6	526.00	8.20	0.16	7.76	30	0.25	29.90	0.04	0.07		
U7	867.00	7.20	0.28	5.37	29	0.42	24.80	0.13	0.18		
U8	680.00	8.30	5.05	7.69	24	0.33	1.40	0.18	<0.05		
U9	152.00	7.70	0.29	6.74	27	0.04	11.80	0.16	0.19		
U10	700.00	7.70	0.26	7.53	29	0.34	39.70	0.17	0.18	>2420	
U11	533.00	7.80	0.24	7.14	29	0.25	15.40	0.05	0.54		
U12	404.00	7.90	0.50	7.56	28	0.19	15.50	0.10	0.11		
U13	533.00	7.50	0.35	7.14	28	0.25	0.40	0.16	0.14	187	
U14	615.00	7.60	0.25	6.79	28	0.30	15.30	0.04	0.12		
U15	1585.00	7.10	0.29	5.32	29	0.79	44.30	0.04	0.16		
U16	799.00	7.80	0.33	7.39	29	0.39	47.20	0.21	0.06	>2420	
U17	535.00	7.80	0.24	6.79	29	0.26	33.90	0.11	<0.05		
U18	280.00	8.20	2.61	7.61	23	0.13	0.50	0.19	<0.05		
U19	612.00	7.50	0.33	7.09	29	0.29	33.70	0.16	0.80		
U20	636.00	8.20	0.53	7.70	28	0.31	12.60	0.15	0.09		
U21	528.00	8.20	0.19	7.67	28	0.25	24.60	0.27	0.67		
U22	489.00	8.10	0.32	7.71	28	0.25	16.20	<0.02	0.13		
U23	51.09	7.80	0.48	7.45	36	0.25	40.60	0.49	0.15		
U24	636.00	8.20	0.31	7.80	28	0.25	29.20	0.09	0.10	921	
U25	619.00	8.10	0.27	7.58	29	0.25	7.60	0.14	0.20		
U26	423.00	8.30	0.39	7.67	29	0.25	12.10	0.11	0.11	>2420	
U27	421.00	8.10	0.82	7.73	28	0.25	20.10	0.24	0.13	>2420	
U28	636.00	8.30	0.44	7.69	29	0.25	46.70	0.14	0.09	>2420	
U29	472.00	7.80	0.26	7.37	28	0.25	35.50	0.22	0.09		
U30	204.00	8.00	0.96	7.21	27	0.25	2.20	0.03	0.13		
U31	268.00	7.90	0.32	7.18	27	0.25	9.00	0.14	0.26	1986	
U32	525.00	8.30	0.51	7.73	28	0.25	31.40	0.18	0.24		

Sample No	EC (µS/cm)	pH	Turbidity (NTU)	DO (ppm)	Temp (°C)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
U33	333.00	8.10	0.17	7.68	27	0.25	15.70	0.10	0.11		
U34	574.00	7.70	0.29	7.41	29	0.25	13.90	0.07	0.18	>2420	
U35	402.00	7.80	1.59	7.63	24	0.25	1.30	0.17	<0.05		
U36	331.00	7.70	0.47	6.77	29	0.25	5.20	0.14	0.15	387	
U37	2201.00	9.30	1.01	7.81	31	0.25	20.20	0.20	0.19	>2420	
U38	590.00	7.70	0.21	6.63	28	0.25	17.80	0.12	0.19		
U39	561.00	7.40	0.52	5.97	29	0.25	0.60	<0.02	0.27	165	
U40		8.30	0.37	7.73			23.20	0.11	0.17		
U41	335.00	8.20	0.45	7.59	29	0.16	27.20	0.12	0.1		

Based on the full results and the summary shown in Table 6.9, the following can be summarized for Uligan Island;

- The EC of the groundwater is generally low, with an average of 572.65 µS/cm which is below an acceptable limit for potable water of 1500 µS/cm. The electrical conductivity readings range from 51.09 to 2201µS/cm. 95% of readings fall within the acceptable limit.
- The pH of groundwater ranged from 7.1 to 9.3 with an average of 7.93. The pH values of all samples were within the WHO permissible limits of 6.5-8.5.
- Turbidity ranged from the lowest of 0.16 NTU to 5.05 NTU with an average of 0.59 NTU.
- Dissolved oxygen levels were low to moderate, with values varying from 5.32 mg/L to 7.81 mg/L with an average of 7.25 mg/L.
- The salinity of groundwater ranged from 0.03 PSU to 0.79 PSU with an average of 0.27 PSU. Salinity is expressed in Practical Salinity Units (PSU) which is equivalent to PPT.
- The average Nitrate concentration was 20.91 mg/L and therefore it does not exceed the WHO guideline limit of 5.09 mg/L. But 34 of the 41 tested water samples exceeded this limit of 5.09 mg/L. The Nitrate concentrations ranged from 0.4 mg/L to 47.2 mg/L.
- Ammonia concentrations were generally low. The average ammonia concentration was 0.78 mg/L. This is within the WHO guideline value of 1.5 mg/L based on aesthetic (taste and odour) considerations. Only 0 tested water samples exceeded this limit (range from 0.02 to 0.49 mg/L). Natural concentration levels of ammonia are generally below 0.2 mg/L (WHO, 1993) and no tests showed concentrations below this level. There is no apparent correlation between increasing levels of ammonia and other nutrients.
- Phosphate concentrations were moderate. All values were within the range 0.05-1.1 mg/L with an average of 0.21 mg/L. There is no WHO drinking water guideline value for phosphate. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater (e.g. effluent from septic tanks and 'greywater' from kitchens and bathrooms). There were 9 samples tested below 0.1 mg/L.
- Total coliform levels were also found to be significant and ranged from the lowest count of 165 MPN/100 mL to the highest count of more than 2420 MPN/100 mL, with an average count of 1816.14 MPN/100 mL. Faecal Coliform levels were found to be less significant and ranged from the lowest count of 435 MPN/100mL to the highest count of 435 MPN/100mL.

EC values of the selected wells were collected at the start of wet period (September – October) and following table show the summary of all the result collected during dry and wet periods based on the land use distribution.

Table 3.11: Comparison of WQ results based on land usage

Land Use	Number of samples	Results are lined with conditions
Residential area	46	46
Agricultural area	4	4
Industrial area	2	2
Other areas	10	10
Total	62	62

Considered desirable water quality limits:

- 1) EC < 2500 $\mu\text{s/cm}$ (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 guideline.

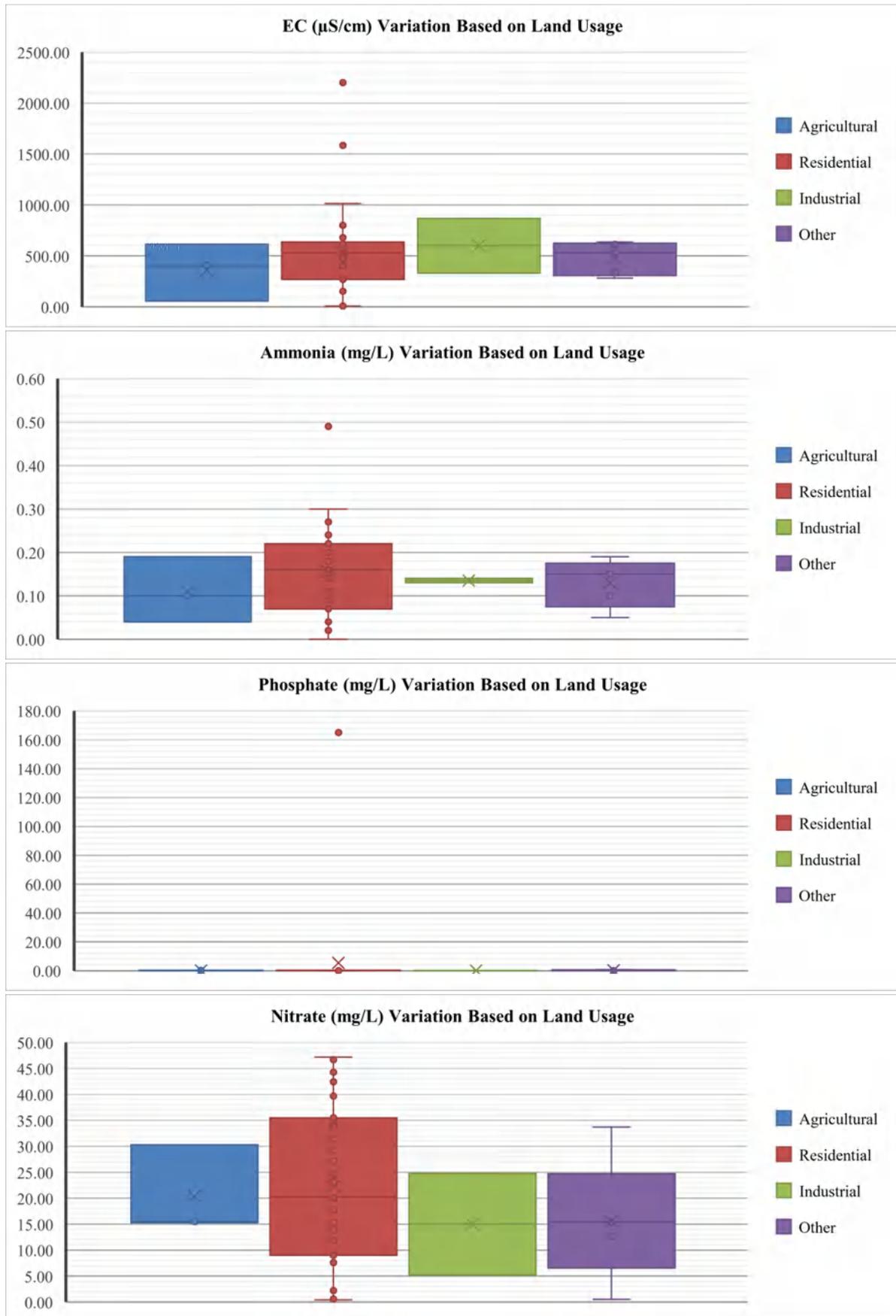


Figure 6-7: Variation of measured WQ parameters in Filladhoo Island

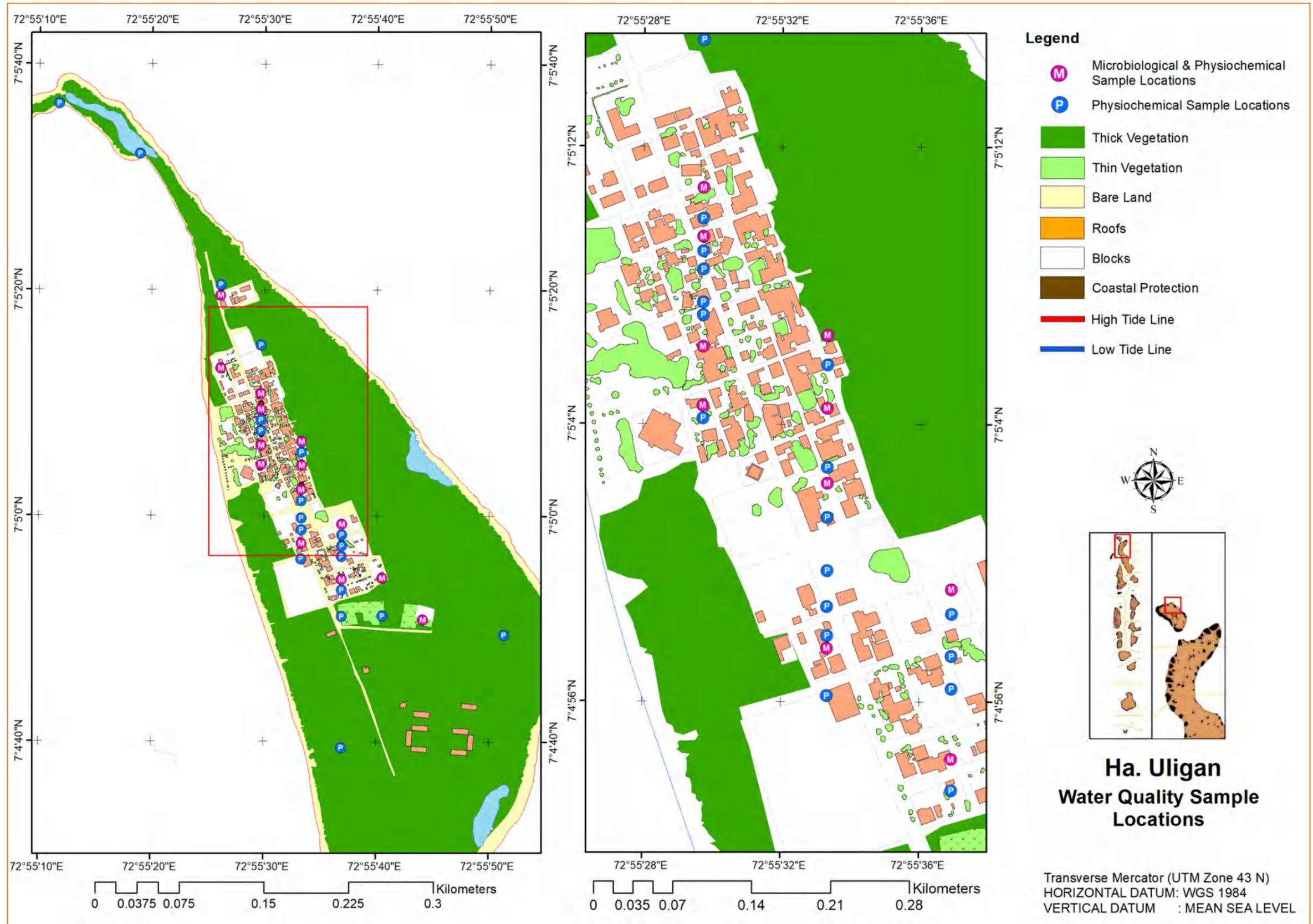


Figure 6-8: Location of groundwater sampling points in Uligan Island

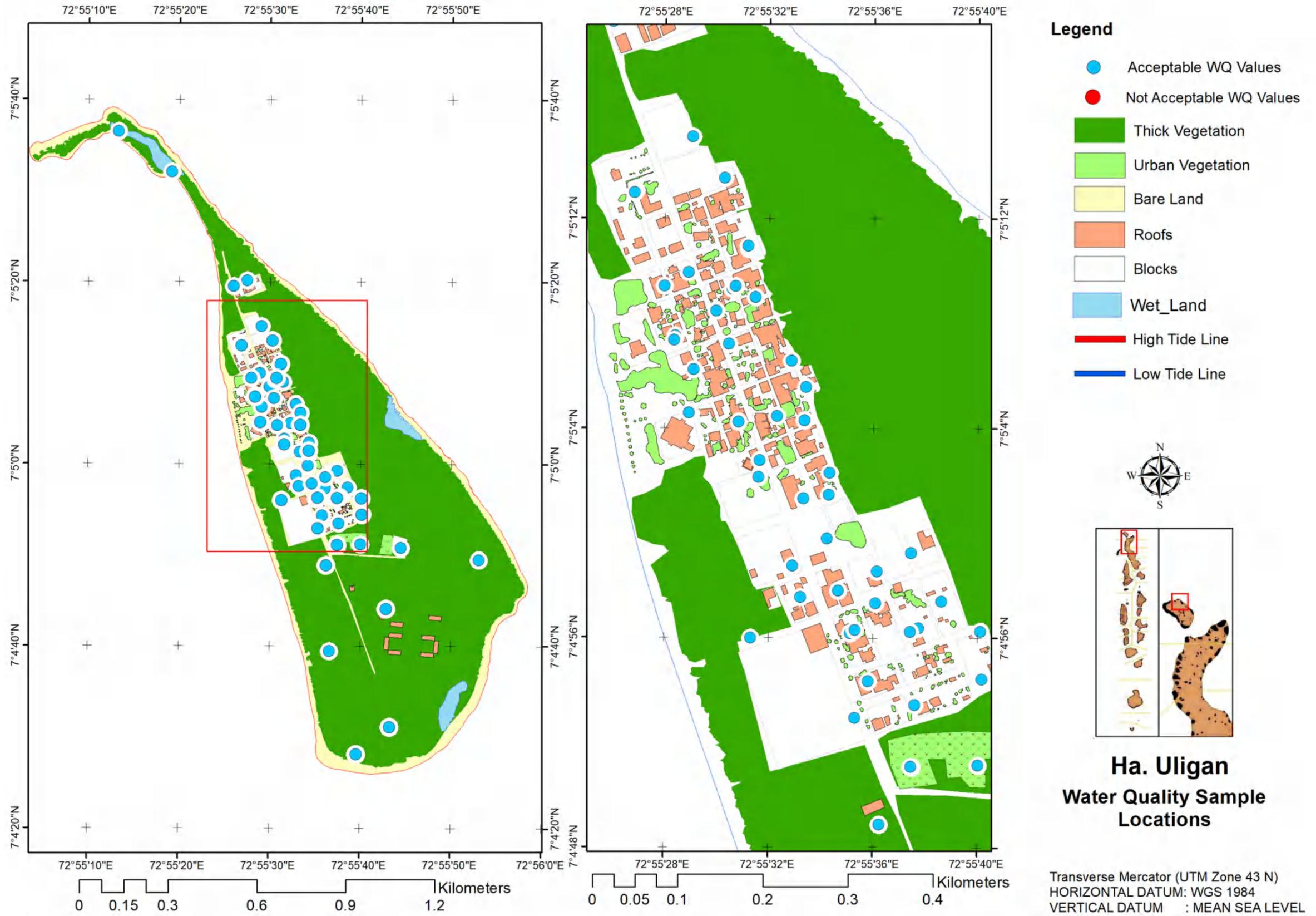


Figure 6-9: Location of groundwater sampling points with critical WQ values in Uligan Island

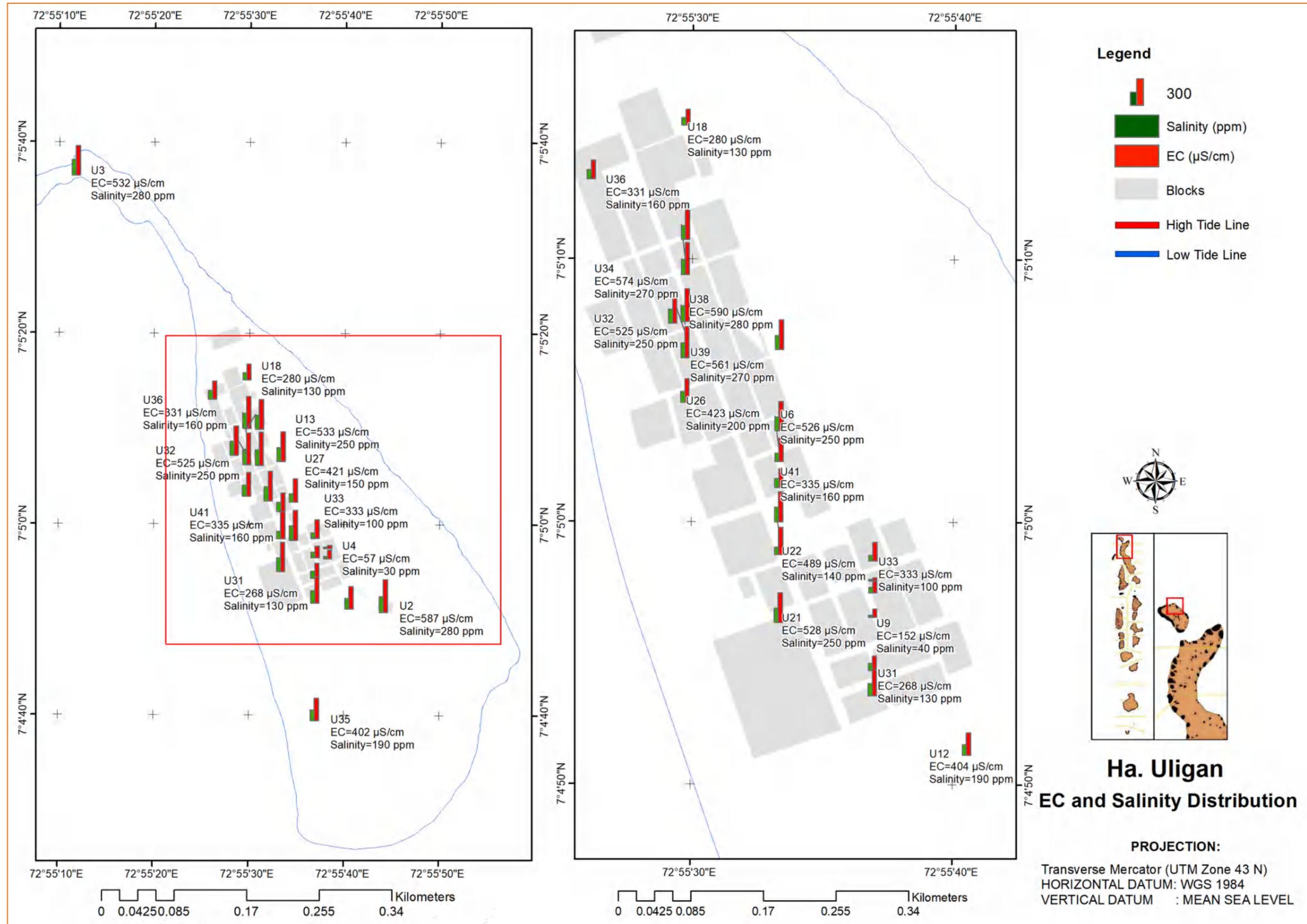


Figure 6-10: EC and Salinity Distribution in Ha. Uligan Island

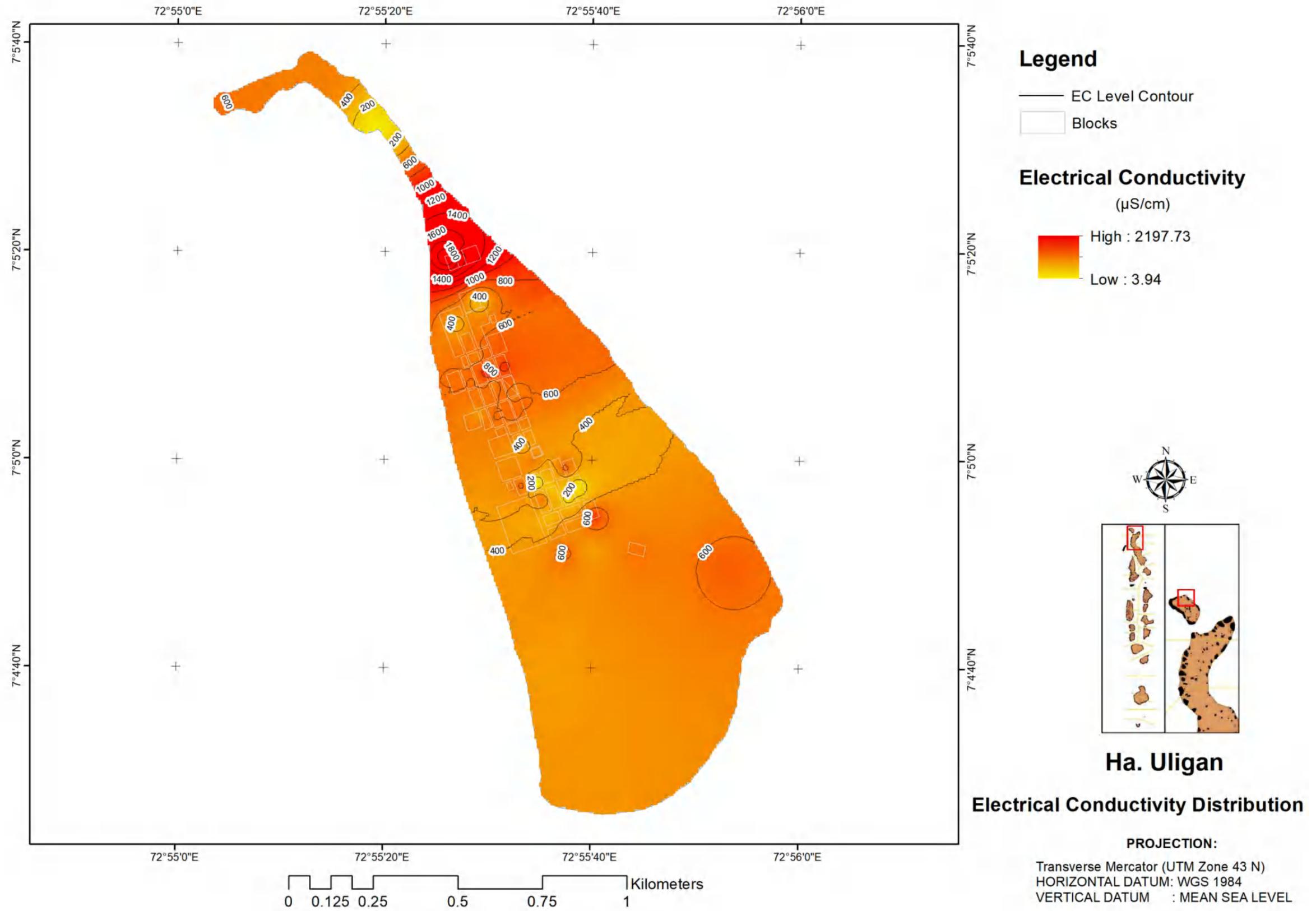


Figure 6-11: EC Distribution in Ha. Uligan Island

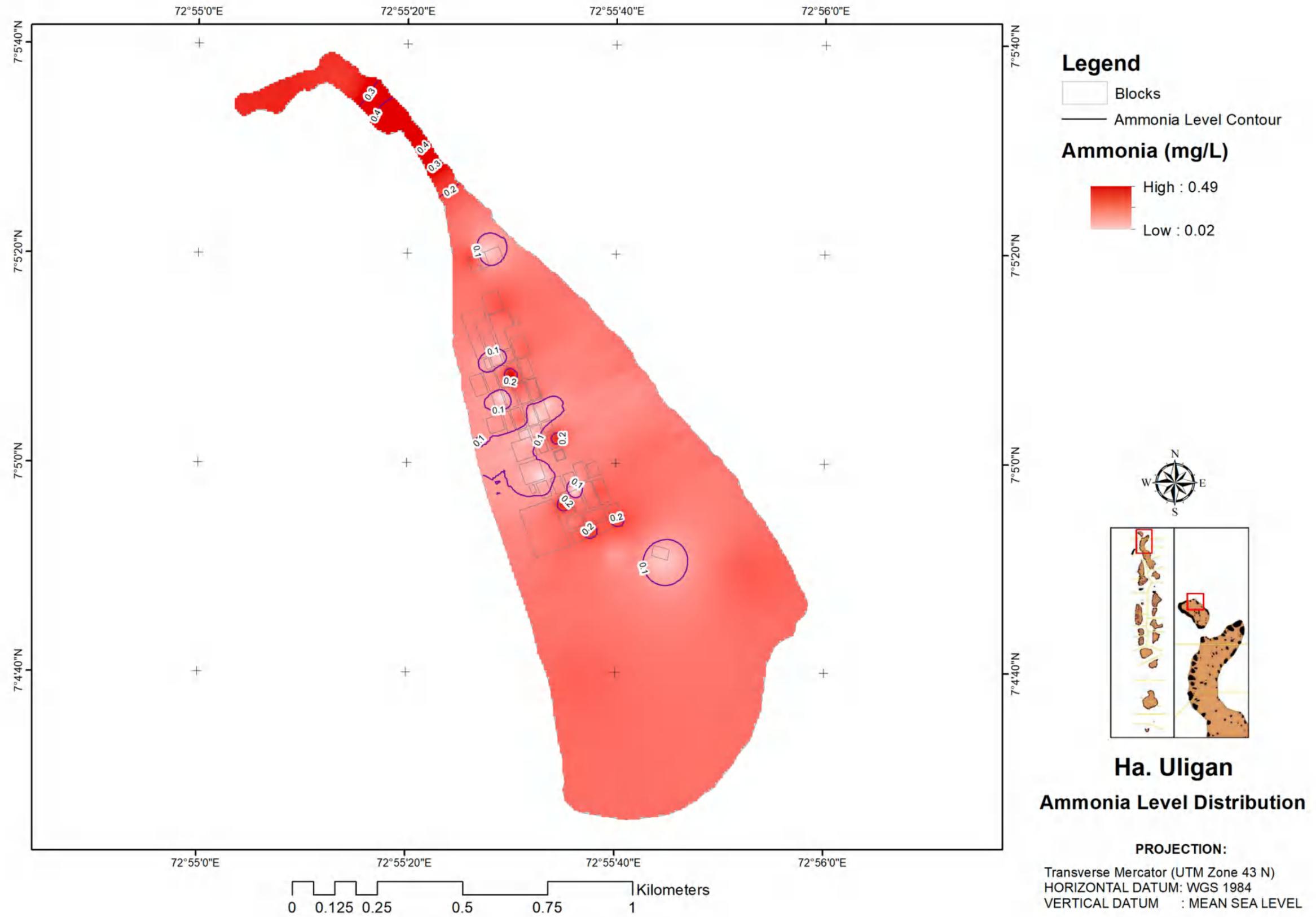


Figure 6-13: Ammonia Level Distribution in Ha. Uligan Island

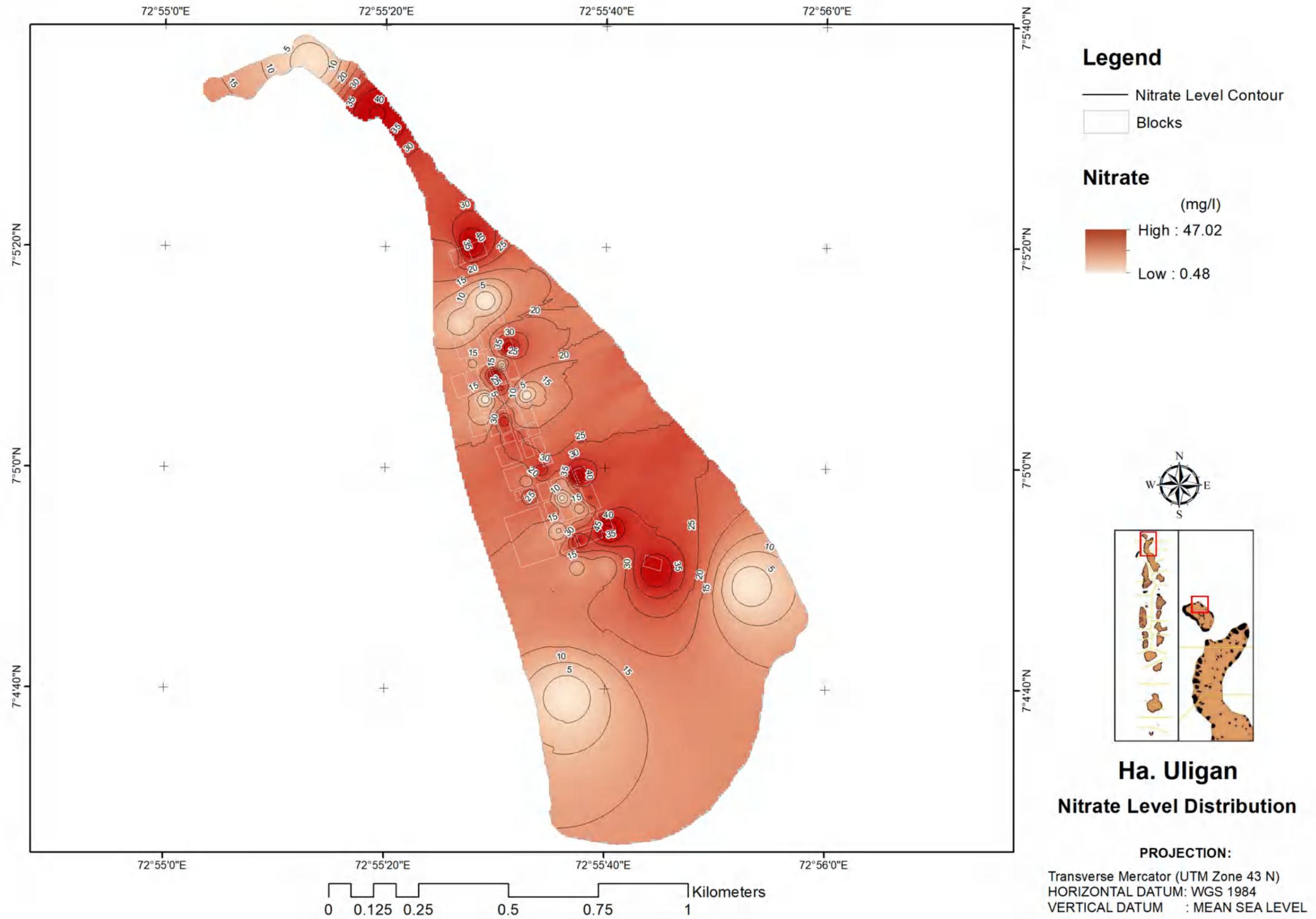


Figure 6-14: Nitrate Level Distribution in Ha. Uligan Island

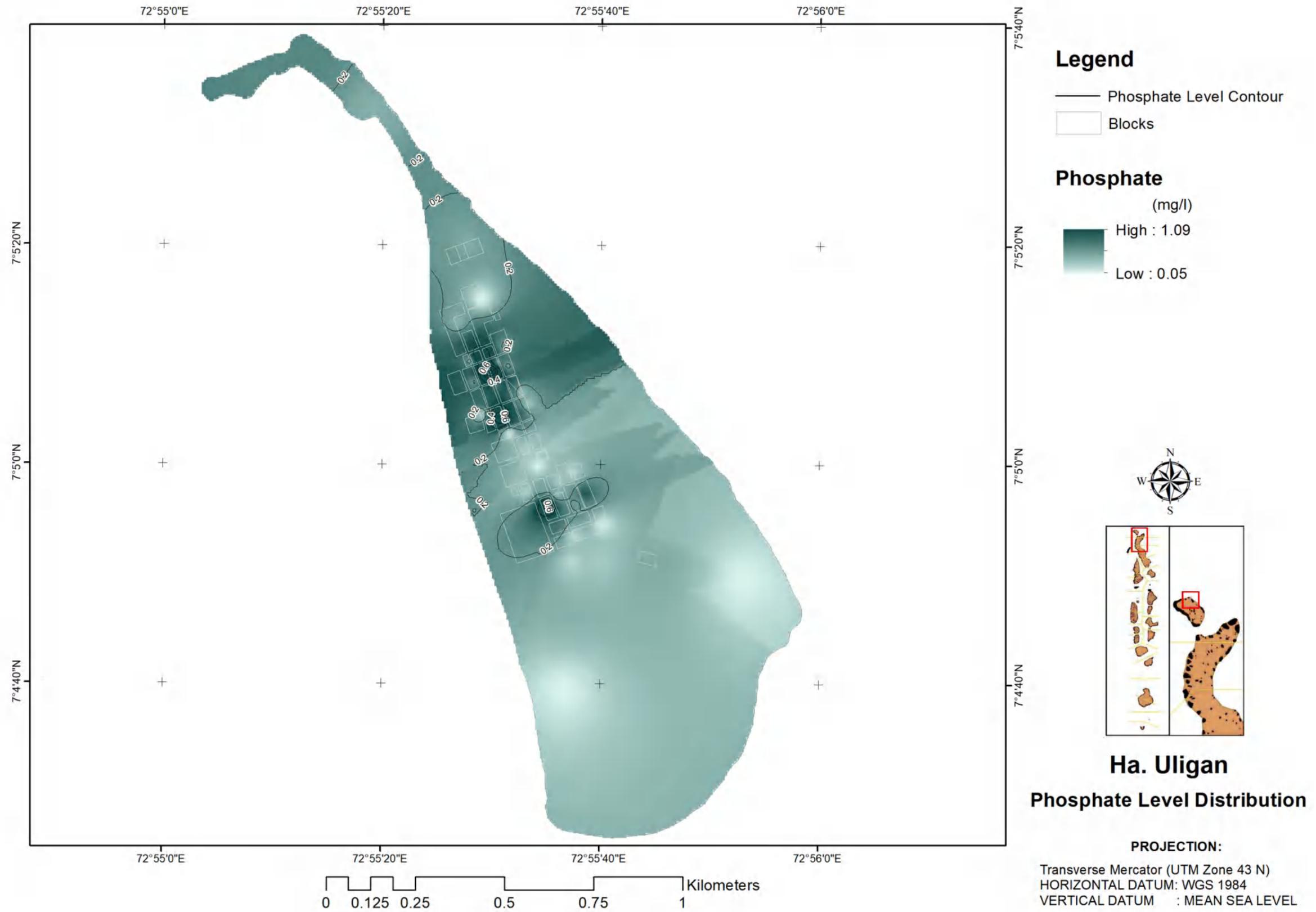


Figure 6-15: Phosphate Level Distribution in Ha. Uligan Island

6.7.7 Geophysical survey

The Electrical Resistivity (ER) tests were carried out in the locations as outlined in Figure 6-16 below. The ER survey included test points along 9 transects selected representatively based on reconnaissance surveys to adequately characterise different land uses and island cross-sections. The main transects were aligned along existing roads to maintain consistency and uniformity.

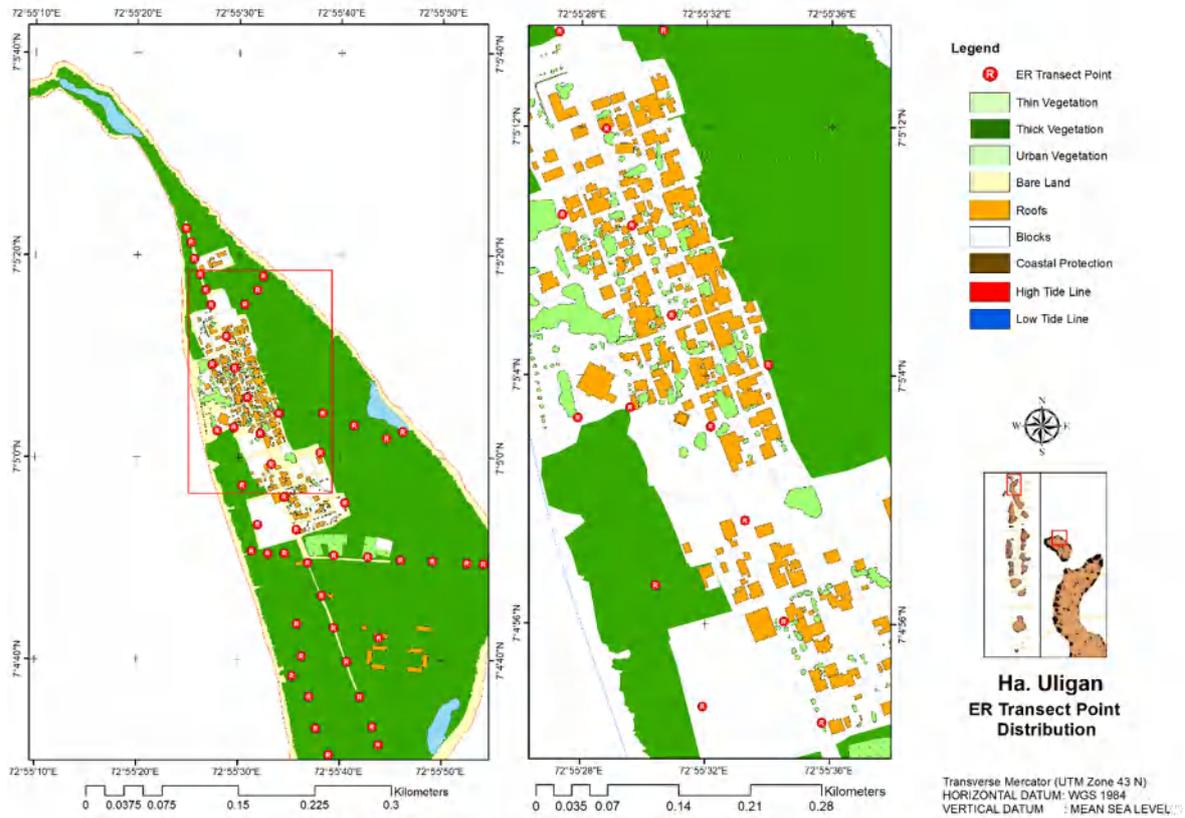


Figure 6-16: Location of ER points in Uligan Island

6.7.8 Aerial surveys

Based on the aerial survey, a multiple dataset consisting of buildings, roof cover, land cover, change detection and shoreline were extracted. This data is shown in Figure 6-17. The total roof cover for this island is 32,512 m².

6.7.9 Water demand

The only source of natural water is rainwater collected from the rooftops of households and institutions and groundwater extracted from shallow wells. The runoff water from the domestic yards, road surfaces, etc., is not usable as there is no mechanism for its collection and treatment.

6.7.10 Freshwater lens

Based on the Electrical Resistivity (ER) surveys, the depth to groundwater level and the freshwater-saline water interface were determined for a set of transverse transects as shown in Figure 6-16. Plots in Figure 6-2 show the main two cross-sections of island. The dotted lines in the plots indicate a simple interpolation of levels to mean sea level in the island boundaries.

Volume of the lens has been calculated with aid of ArcGIS and Surfer Software.

$$\text{Volume of lens} = 996,988 \text{ m}^3$$

$$\text{Groundwater Storage} = \text{Porosity (15\%)} \times \text{Lens volume (m}^3\text{)} = 149,548 \text{ m}^3$$

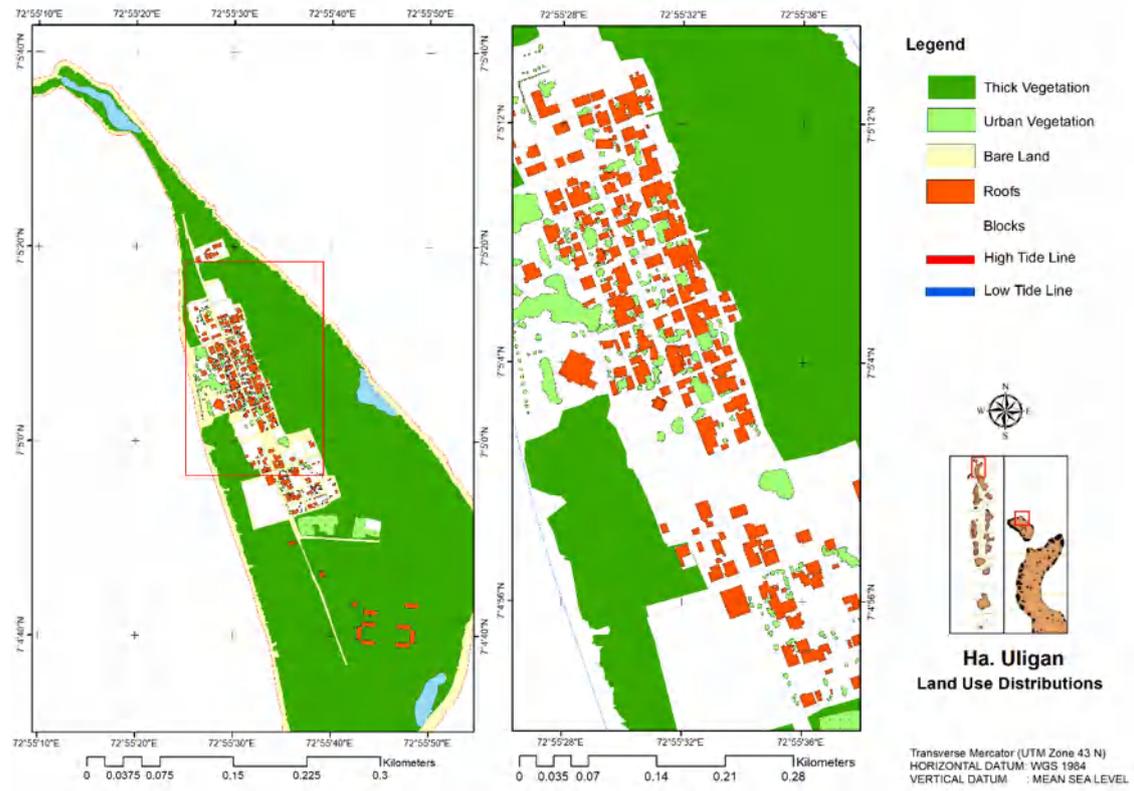


Figure 6-17: Roof Cover in Uligan Island based on UAV Survey

The 2-D freshwater lens distribution density maps produced with GIS software for visualization of the spatial and volume extents are also presented below in Figure 6-18 to Figure 6-20.

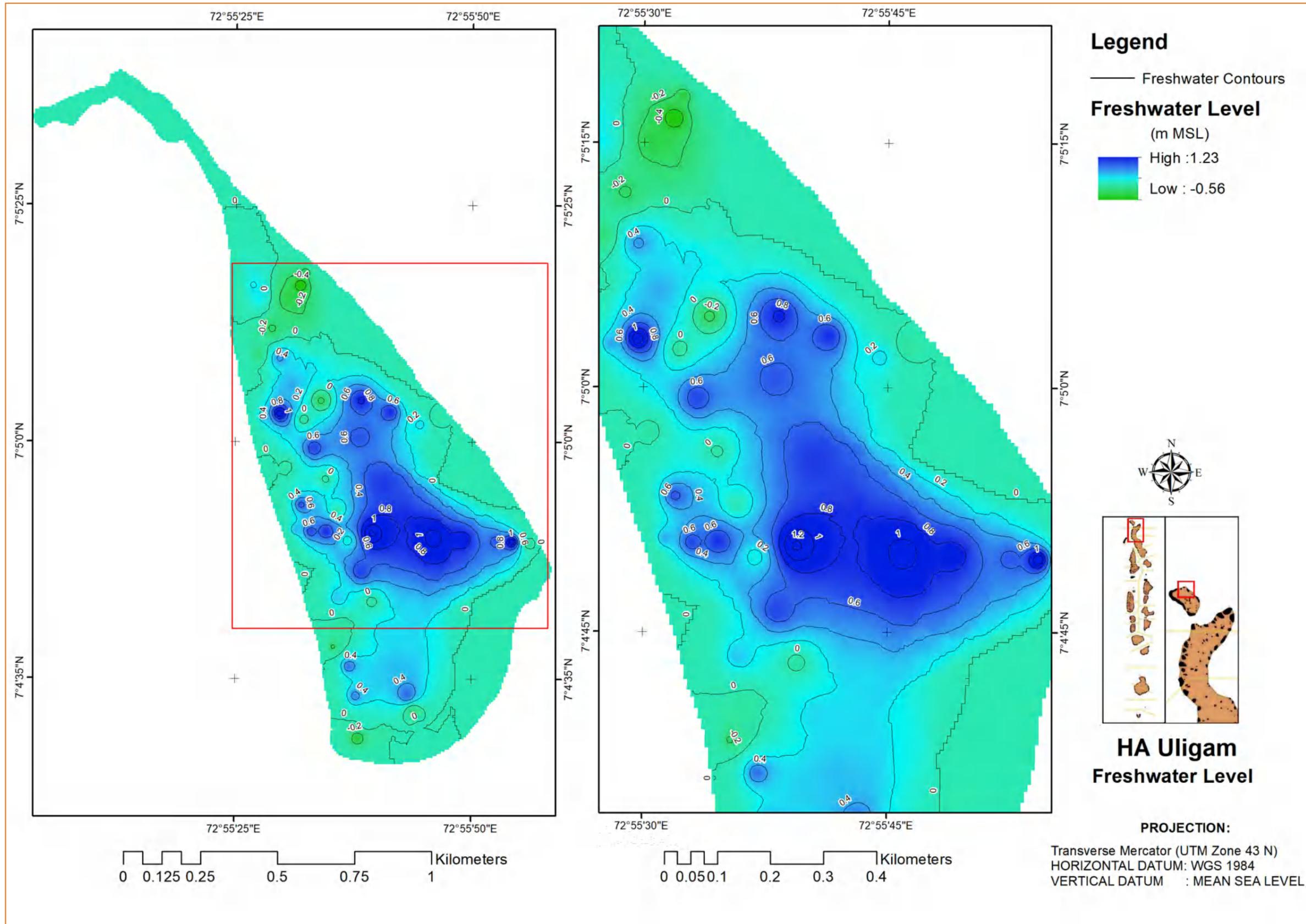


Figure 6-18: Freshwater Level in Uligam Island

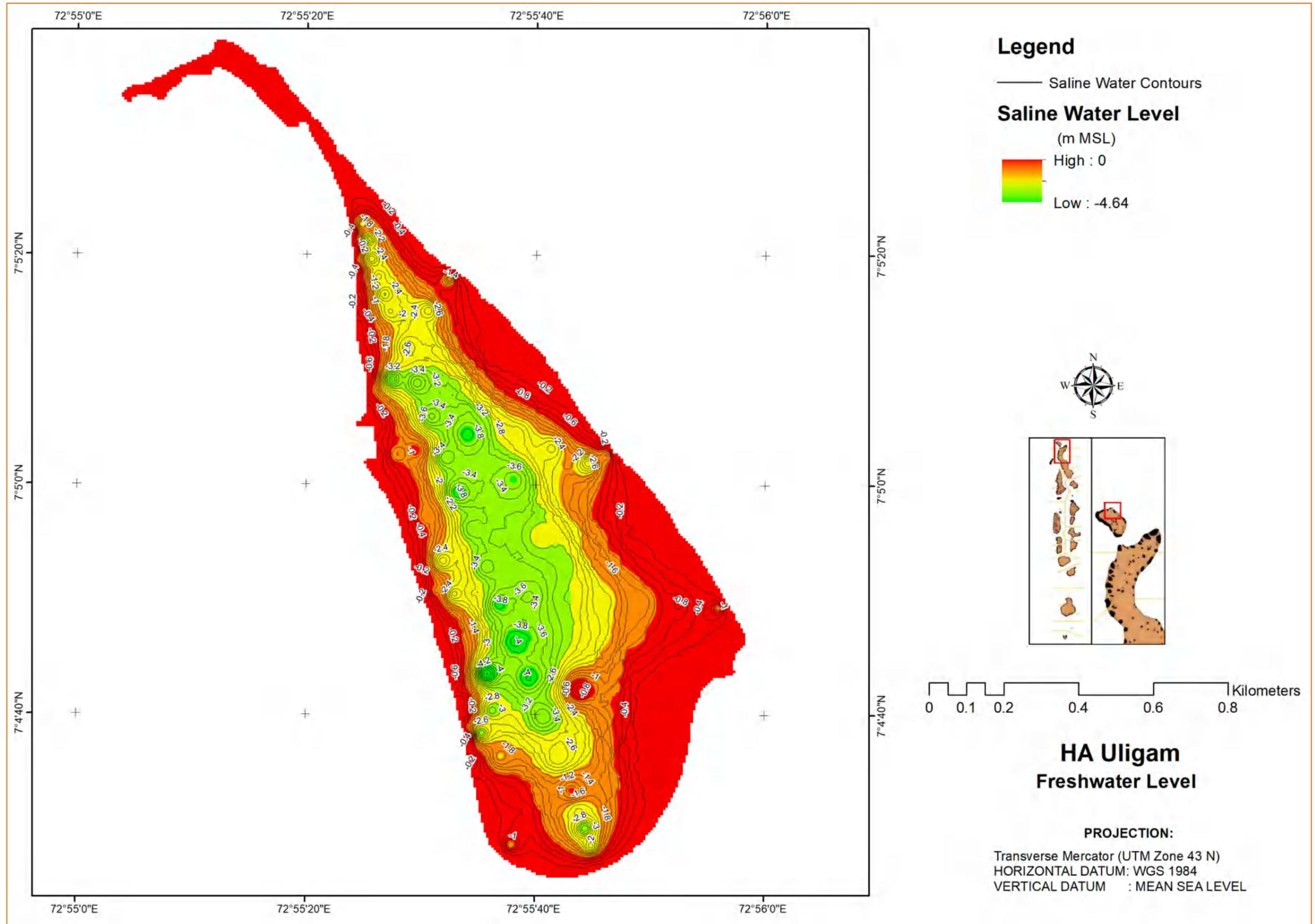


Figure 6-19: Saline water Level in Uligam Island

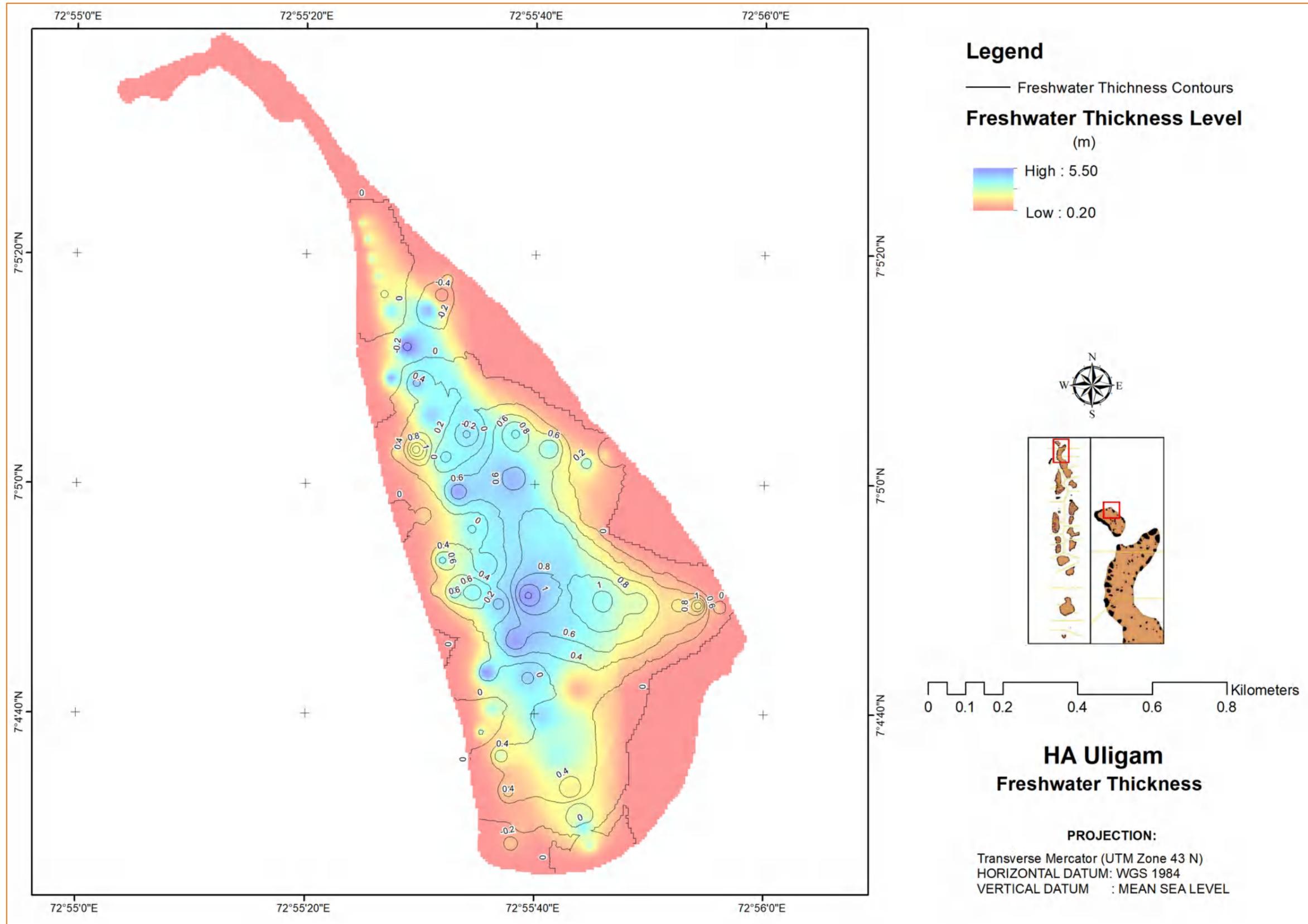


Figure 6-20: Freshwater thickness in Uligam Island

The maximum freshwater thickness of the island is 4.27 m (It is noted here that these readings were taken in October, which is the wet season and the with a reasonably higher number of wet days per month of the year).

6.7.11 Water balance and recharge

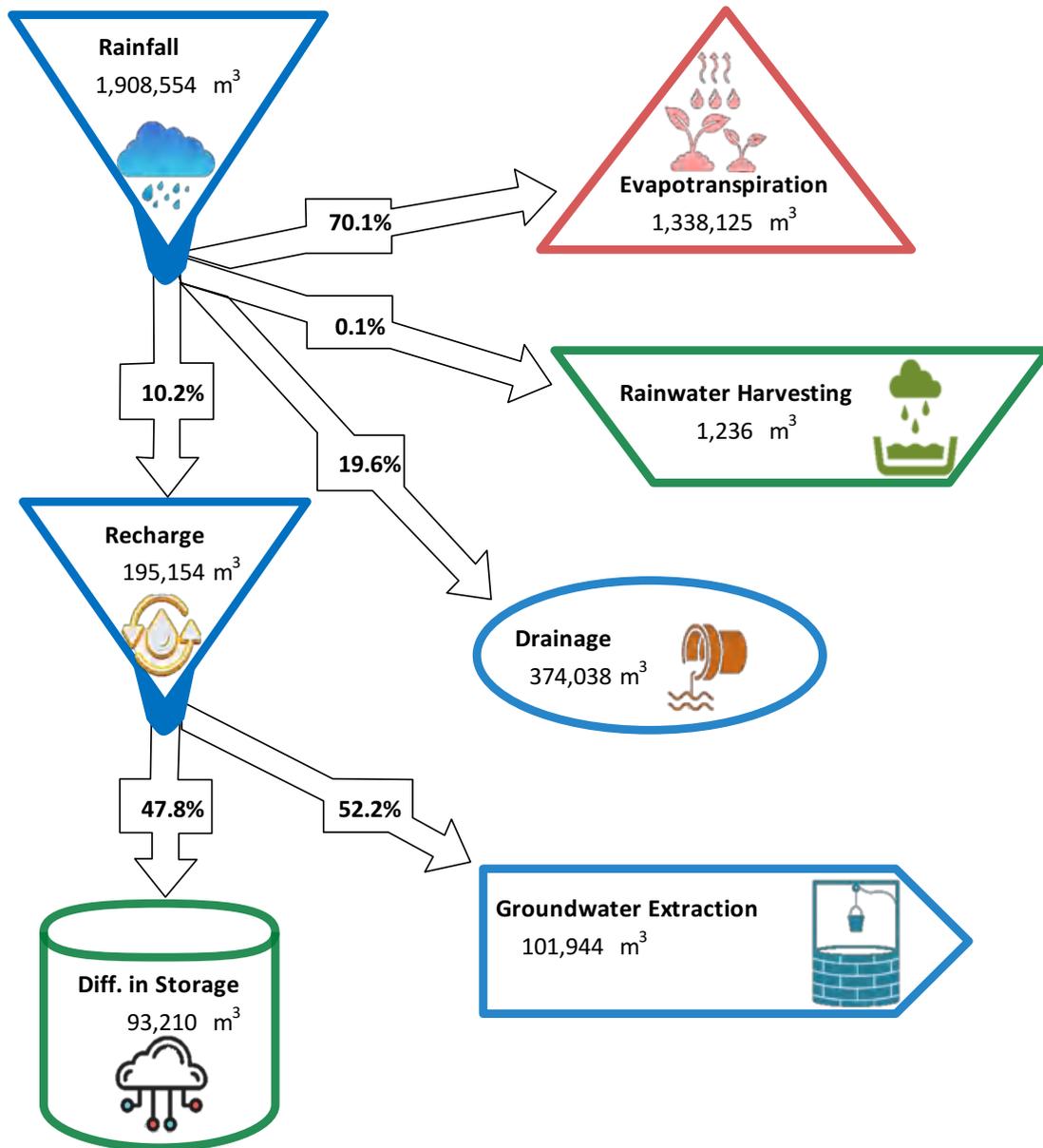


Figure 6-21: Schematic of water balance in Uligan Island

An annual estimation is carried out based on the water balance method (Falkland, 2000). Rainwater harvesting is calculated using the number of rainwater harvesting units on the island. According to the spatial mean annual rainfall of the Maldives, the annual average rainfall of Uligan Island is reported as 1,750 mm/year. Evapotranspiration was estimated using crop water requirements for different land use. Then, the rainfall was subtracted from rainwater harvesting, evapotranspiration, drainage to get the recharge volume. Drainage or the surface runoff was calculated by considering an aggregate runoff coefficient for the island based on the land usage (roof cover, bare land, farmland, roads, playgrounds, wetlands). The groundwater extractions were estimated from the amount of water usage in different sectors (residential, resorts, restaurants, agriculture and farming). The difference between recharge and groundwater extraction is taken to estimate the difference in storage.

6.7.12 Sustainable yield of the lens

Sustainable yield of the water lens refers to the safe extraction potential of a given groundwater aquifer without significantly affecting its quality or quantity. This parameter is an important factor in the sustainable development of islands as it allows planning and design of water and sanitation intervention in islands.

The island has a sustainable yield of 255 m³ per day which was calculated by subtracting groundwater extraction from recharge volume derived from the schematic water balance model in Figure 6-21.

6.7.13 Permeability test

Permeability tests were carried out in the selected locations as outlined in Figure 6-22.

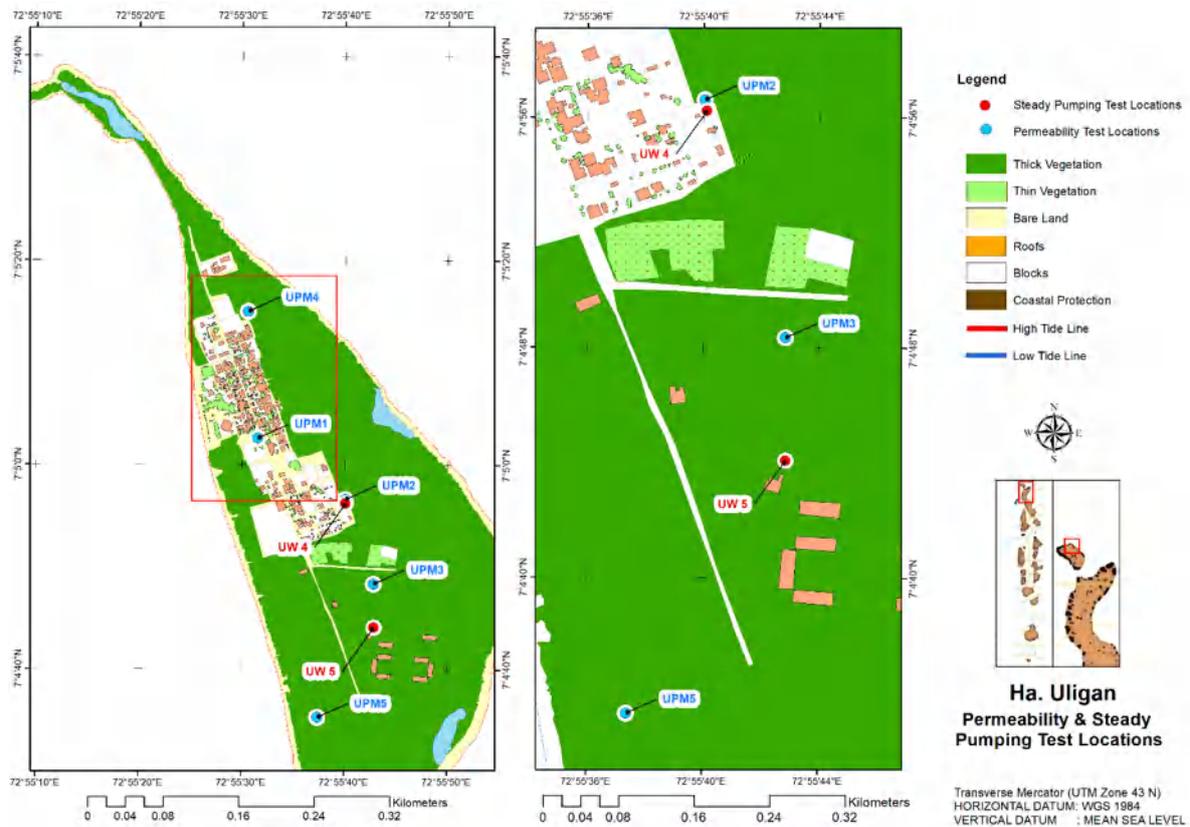


Figure 6-22: Locations of permeability and steady pumping tests in Uligan Island

The estimated permeability values for the above test locations are presented below in Table 6.10. The data will be comparatively verified and interpreted when additional data is acquired and calculations for other islands are completed.

The parameters have their usual notations where, K = Coefficient of permeability (m/s under Q unit gradient), Q = Steady flow into well (m³/s), H = Height of water in well (m), l = length of the perforated section (m), U = thickness of saturated permeability material above water table, r_1 = outside radius of the casing (radius of the hole in consolidated material) (m), r_e = effective radius of well = r_1 (area of perforations) / (outside area of perforated section of casing): $r_1 = r_e$ in consolidated material that will stand open and is not cast, C_s = Conductivity Coefficients, and T_u = distance from water level in the casing to water table (m).

Table 6.10: The Estimated Soil Permeability Values in Uligan Island

Point	UPM1	UPM2	UPM3	UPM4	UPM5
D (m)	0.800	0.800	0.850	1.000	1.100
H (m)	0.800	0.800	0.850	1.000	1.100
ℓ (m)	0.800	0.800	0.850	1.000	1.100
U (m)	1.300	1.340	1.300	1.200	1.200
T_u (m)	1.300	1.340	1.300	1.200	1.200
r (m)	0.076	0.076	0.076	0.076	0.076
Q (m ³ /s)	3.61E-05	4.67E-05	3.96E-05	1.08E-04	1.00E-04
r_1 (m)	0.076	0.076	0.076	0.076	0.076
r_e (m)	0.010	0.010	0.010	0.010	0.010
T_u/ℓ	1.625	1.675	1.529	1.200	1.091
X = (H/ T_u x 100)	62%	60%	65%	83%	92%
Section	Zone 2				
ℓ/r_e	77	77	82	96	106
C_s	120	120	122	135	145
K (m/s)	3.58E-05	4.49E-05	3.87E-05	1.06E-04	9.20E-05
K (m/day)	3.09	3.88	3.34	9.14	7.95

6.7.14 Steady Pumping Test

Pumping tests were conducted in two existing wells to estimate the aquifer properties of unconfined water bearing formation.

Table 6.11: Selected Steady State Pumping Test Locations in Uligan Island

Well No.	C'	A (m ²)	t' (s)	$\ln \left(\frac{s_1}{s_2} \right)$	T (m ² /s)
UW 4	4.5	3.97	2100	3.67	0.0051
UW 5	4.7	4.14	1800	5.24	0.0091

The measured transmissivity (m²/s) values ranged from a minimum of 0.0051 m²/s to a maximum of 0.0091 m²/s., with an average of 0.0071 m²/s. During the testing period, EC (Electrical conductivity) level of both wells are given as below.

- For UW 4, EC has not increased and average EC is about 650 μ s/cm.
- For UW 5, EC has not increased and average EC is about 1370 μ s/cm.

6.7.15 Status of groundwater availability in Uligan Island

- 1). The selected Uligan island has dimensions of width = 500 m and length = 670 m, with a total land area of 109.06 ha, a population of 610 persons, and a land use of Roof cover (Built up area) 3.48 ha (3.2%), Vegetation (Thick) 88.21 ha (80.9%), Vegetation (Light) 1.35 ha (1.2%), and Wetlands (Inland) 12.36 ha (11.3%).
- 2). In order to recognize the fluctuation in the groundwater table, freshwater-saline interphase and estimate the volume of freshwater lens (FWL) and its associated recharge-discharge characteristics, 28 number of Electrical Resistivity (ER) location readings along 06 representatively selected transects were collected.
- 3). Soil overburden permeability tests (constant head) were carried out at 05 locations while steady-state pumping tests were conducted at 02 locations. In addition, groundwater level was also recorded at 05 locations where groundwater water quality samples were tested.
- 4). Permeability tests were carried out at representatively selected 05 number of locations. The measured permeability (K m/day) values ranged from a minimum of 1.02 m/day to a maximum of 50.92 m/day, with an average of 25.35 ± 18.71 m/day (Mean \pm Standard Deviation).
- 5). The ground elevation values ranged from a minimum of -0.36 m MSL to a maximum of 2.57 m MSL, with an average of 1.47 ± 0.46 m MSL (Mean \pm Standard Deviation).
- 6). The upper boundary of the freshwater lens (FWL) varied from a minimum of -0.56 m MSL to a maximum of 1.23 m MSL, with an average of 0.19 ± 0.26 m MSL (Mean \pm Standard Deviation).
- 7). The lower boundary of the freshwater lens (FWL) or freshwater-saline interphase ranged from a minimum of -4.64 m MSL to a maximum of 0.00 m MSL, with an average of -1.43 ± 1.20 m MSL (Mean \pm Standard Deviation).
- 8). Accordingly, the freshwater lens (FWL) volumetric values ranged from a minimum of 0.21 m to a maximum of 5.52 m, with an average of 2.90 ± 0.83 m (Mean \pm Standard Deviation).
- 9). The groundwater profile in the island is characterised by a relatively Low (0.06%) Rainwater Harvesting (%) relatively High (19.60%) Drainage (%) relatively High (10.23%) Recharge (%) while the water use shows relatively High (52.24%) Groundwater extraction (%) leading to relatively High (47.76%) Difference in Balance Storage (%).
- 10). The freshwater lens (FWL) volume calculated based on ER transect test data is 149,548 m³ with a maximum FWL thickness of 5.52 m.

6.8 Conclusion

The Safe Yield for the island estimated based on 'Recharge - Extraction' is 255 m³ per day, while it is 523 m³ per day based on 10% of Average Annual Rainfall Method. The present groundwater extraction rate estimated based on survey data is 279 m³ per day and this exceeded the allowable safe yield by 109% (Moderately stressed). At present, there exists no island wide sewerage network or water supply network.

Relative hydraulic conductivity of the island lies in 'Semi-pervious' state while present aquifer condition range from 'Poor' – 'Good' state based on the hydraulic conductivity estimation carried out as per Bear (1972) and transmissivity of the formation was compared as per Krany (1993). Moreover, general status based on transmissivity ranged 'High' and potential for groundwater recharge remains 'Low' – 'Moderate' as per the estimations.

7 HA. MOLHADHOO ISLAND

7.1 General Overview of The Island

The island of Molhadhoo (Figure 7-1) is located on the southern periphery of Haa Alifu Atoll at coordinates 72°59'52" E, 7° 00'42" N. The island has an area of about 2.4 km² and measures about 0.89 km in width and 2.7 km in length. The population of the island was found to be about 401 residents as of December 2021. The island has a harbour on the Western side of the island. The following table outlines some basic information about the island and the following map outlines the location of Molhadhoo.

Table 7.1: Basic statistical information on Molhadhoo island in Haa Alifu Atoll.

Name of the island	Ha. Molhadhoo
Longitude and Latitude	72°59'52" E, 7° 00'42" N
Area	240 ha (2.4 km ²)
Population (Dec 2021)	401
Distance from Male'	318 km
Harbour	Present
Island sewerage network	Under Construction
Water supply network	No
Other infrastructure	No

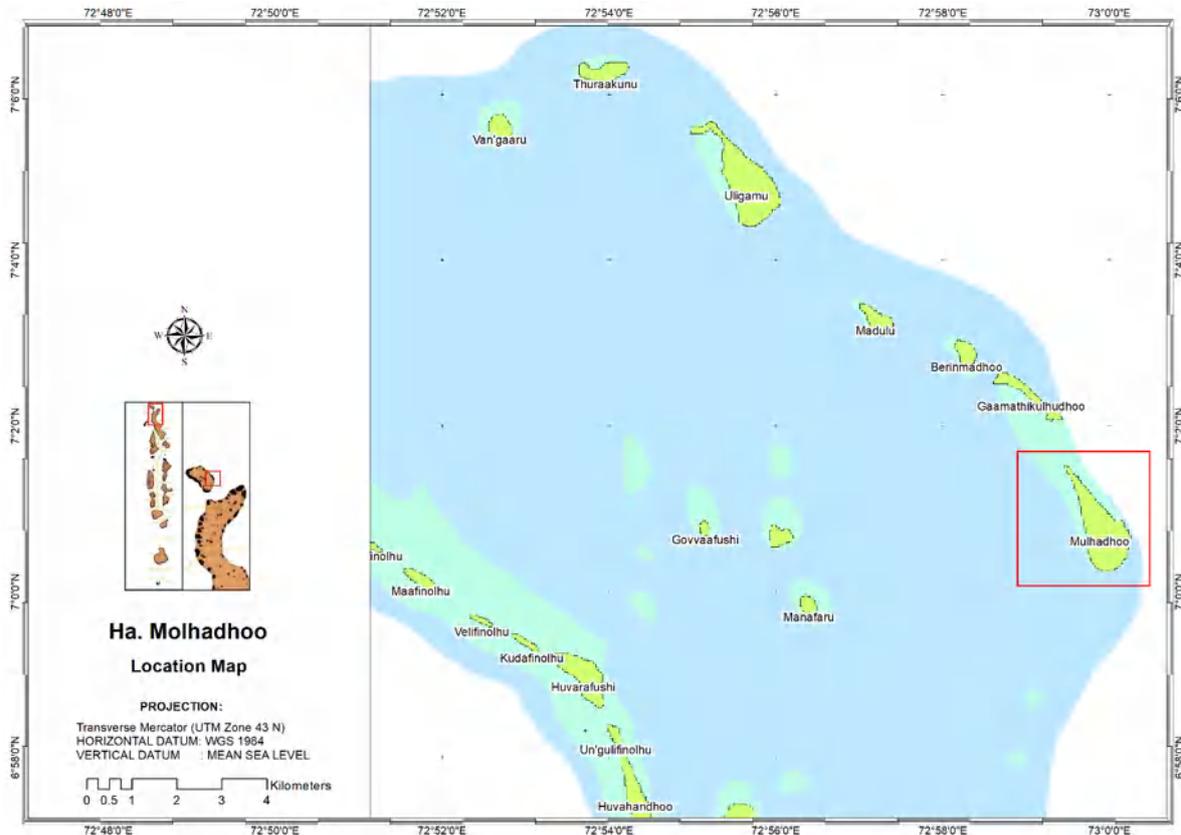


Figure 7-1: Location map for Molhadhoo Island, Haa Alifu Atoll.

7.2 Topography and Geology

Molhadhoo island is on the Northern side of the “Haa Alifu Atoll” which is located North end of the chain of Maldives islands. The Molhadhoo island located SE end of the long NW – SE trending submerge coral reef which is extending about 16km. Molhadhoo is a island with elongated shape and extend about 2,700 m (NW-SE) in length and about 880 m (SW-NE) in width. In the elongated island the northern side is very thin and the southern side is thick may be due to the actions of ocean waves and currents. Basic topography and the geological setting are mostly based on the properties of the underground coral beds and the actions of ocean waves and currents. The elevation of the island varies from -0.4 m MSL to 2.34 m MSL and is generally flatland through the island. The general geological profile in the island is composed of topsoil and the beach coral sand deposits underlain by sandy coral rock (Figure 7-2). The sandy coral rock consists of a weathered coral rock layer and a hard fresh coral rock. Considering the cross-section A-B, topsoil layer varies from 0 to 0.5 m. Thickness of the beach coral sand layer is about 0.3 m in beach areas (A & B) and it’s about 2 m in middle of the island. In the southern beach areas mostly beach coral sand exists as the top layer. The coral sand layer is mostly unconsolidated and permeable layer. According to cross section A-B, weathered coral rock depth is varying between 0.2 m (coastal areas) to about 4 m (middle of island) from MSL, and it is a semi-permeable layer. The fresh groundwater lens occupies both coral sand layer and a weathered coral rock. The hard coral layer is mostly unconsolidated and impermeable and present as a fresh rock. As the compositional and structural differences of coral formation, differential weathering could be observed in cross section A-B. The cross section A-B clearly shows two deep weathered zones. In the cross-section C-D in the island also shows two deep weathered zones.

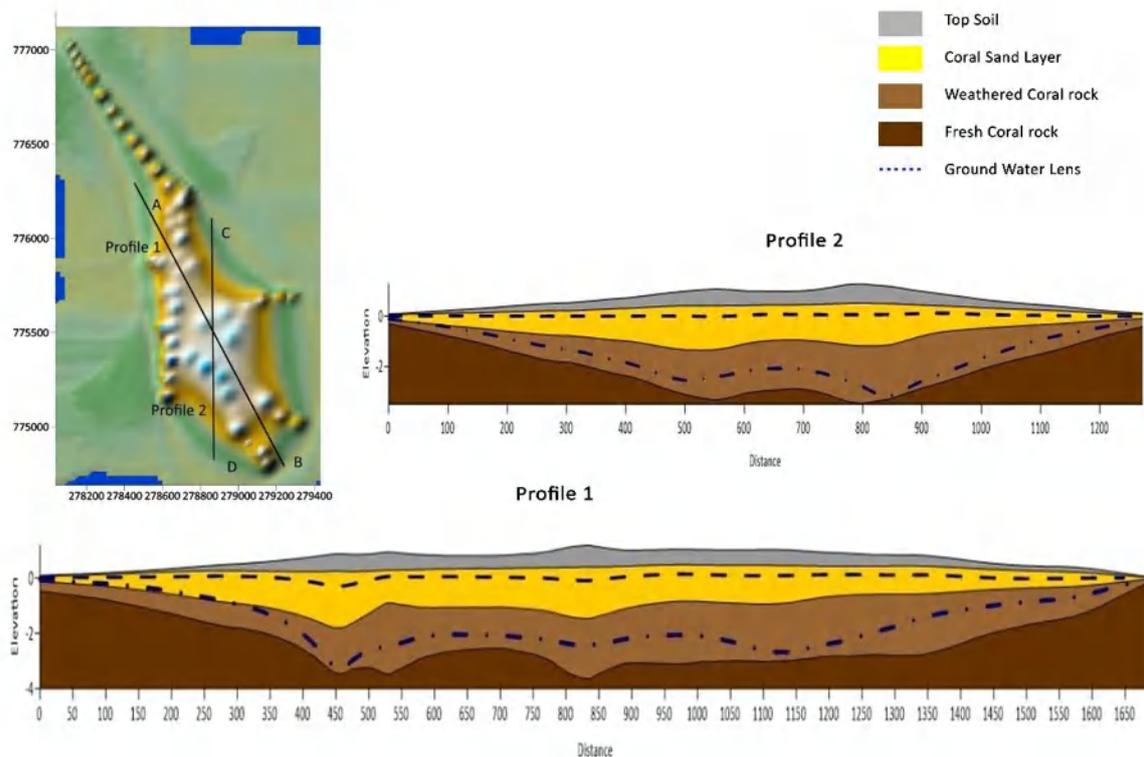


Figure 7-2: Geological sections of the island showing subsurface geological characteristics

7.3 Climate

Molhadhoo experiences the typical two monsoons in the Maldives namely, the North-east monsoon from December/January to March/April and the South-west monsoon from Mid-May to November. There are no specific wind and rainfall data available for Molhadhoo as there are no weather

monitoring stations on the island itself. Based on the rainfall data of the nearest weather monitoring station, it shows a declining trend in rainfall for the past 30 years (Inception Report, 2021).

The historical rainfall data records from Hanimadhoo Island (not included in the 5 selected islands in Lot 1) located in the Haa Alifu atoll (35 km to the south east from Molhadhoo Island) has an annual average rainfall of 1,747 mm with a standard deviation of 279.1 mm and the trend with the decadal means were shown in the following graph (MEE, 2021).

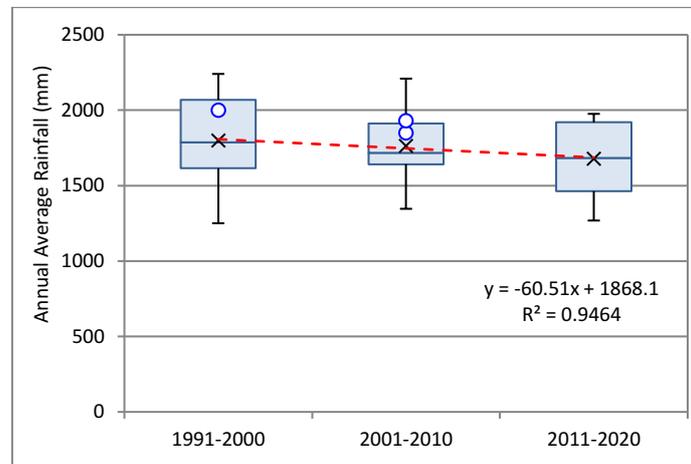


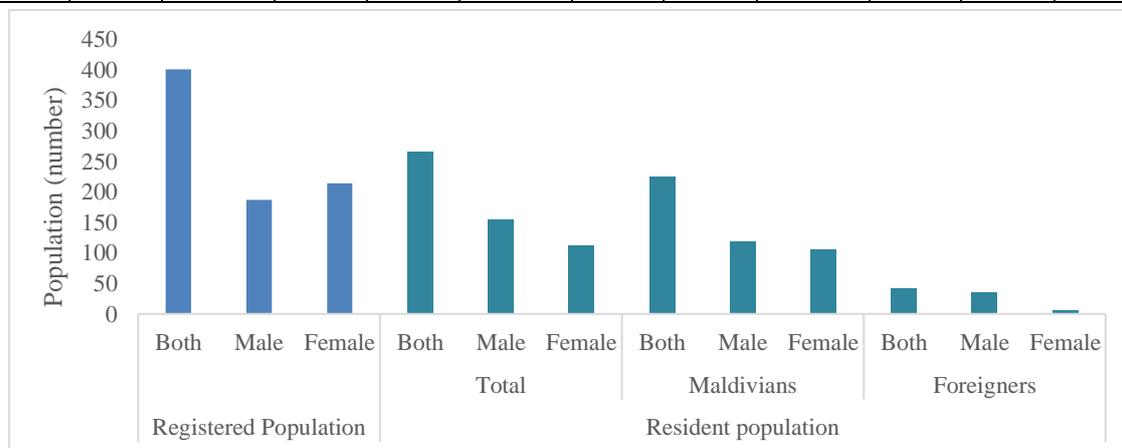
Figure 7-3: Decadal means and trend for rainfall in Hanimadhoo (1990 - 2020).

7.4 Demography

Molhadhoo has a smallest population in the atoll with a registered population of 401 people including 187 men and 214 women (Molhadhoo Council, 2021). As per the island council, the resident population is even smaller and estimated as 266 with 225 locals and 41 foreigners. Foreigners includes teachers, medical staff and labour force working in different projects that are currently ongoing in the island. The majority of foreigners are males (35 males out of total 41). At present, there are 68 residential households in the island. The following Table 7.2 and Figure 7-4 illustrates the population breakdown for Molhadhoo.

Table 7.2: Demographic Breakdown of Molhadhoo Island as of December 2021

Registered Population			Resident population								
			Total			Maldivians			Foreigners		
Both	Male	Female	Both	Male	Female	Both	Male	Female	Both	Male	Female
401	187	214	266	154	112	225	119	106	41	35	6



Source: Molhadhoo Council, 2021

Figure 7-4: Population breakdown of Molhadhoo (Maldivians & Foreigners)

Note: Registered population represents the total number of people registered in Molhadhoo as of December 2021 and the Resident population shows the number of locals and foreigners living in Molhadhoo as of December 2021. The total represents the total number of locals and foreigners residing in the Molhadhoo as of December 2021

7.5 Socio-economic Condition

7.5.1 Natural Resources and Land Uses

Molhadhoo is located at the northern side of the atoll with an area of 118 hectares. Similar to most of the other islands in the atoll, majority of Molhadhoo is covered with vegetation with only a small area settled by the residents on the southwest side of the island.

A significantly large wetland area is present on the westside of the island and there are few other areas with smaller wetlands. See appendix xx for google image with wetlands marked as per the island councils during pre-inception meeting.

In terms of land use and land allocation, the island council now has the authority to allocate lands for different purposes with an approved land use plan. The council currently does not have an approved land use plan, however, is in the process of developing the land use plan.

7.5.2 Economic Activities

The main economic activities of the island include agriculture, construction, thatch weaving and other business establishments.

As per the island council, there are no registered farmers in the island, though agriculture is one of the main economic activities in the island. During the pre-inception meeting with the island council, it was also noted that the council has recently allocated 3,000 sqft plots of land to every household in the island for 2 years for free to do farming. However, none of the farming plots are currently used to grow products. This can be explained by the fact that agricultural products in the island are mostly, if not all, grown in the backyards of their homes (home gardening).

The general practices of farming in Molhadhoo as similar to most islands of the Maldives include planting trees straight in the ground or in large containers such as empty oil barrels. Chemical fertilizers are somewhat used, mostly to treat pesticides when needed.

Most of the business establishments on the island include small shops, also built on plots allocated by the Council. While there is some small-scale fishing on the island, fish is not sold to other islands nor done commercially on a large scale. Instead, the catch is mainly sold within the island.

7.5.3 Accessibility and Transport

The nearest airport to Molhadhoo is HA. Hoarafushi Airport which is around 12 Kms away. There are three other airports in the region (in Haa Dhaalu Hanimaadhoo, Haa Dhaalu Kulhudhuffushi and Shaviyani Fonadhoo). The main mode of transport to and from the island is by flying to Hoarafushi and private launch hire from airport to Molhadhoo. There are private ferries travelling within the atoll as well as supply boats travelling between the atoll and Male', the capital city.

Molhadhoo currently has a jetty to access the island. Construction of a harbor with quay walls are currently ongoing and is planned to be completed in 2021. As per the island council and elderly in the island, soil erosion in the island has worsened since the start of the harbor project.

7.5.4 Services and Infrastructures

The island is equipped with the basic services and supporting infrastructures and the details of these are discussed in the following sections.

7.5.4.1 Public facilities and amenities

The public facilities available in the island includes:

- Health Center
- Primary/Secondary School
- Government institutions (Office for Island Council, Island Court)
- Mosques
- FENAKA office (power house located inside the office building)

7.5.4.2 Water supply

The main source of water for Ha. Molhadhoo is rainwater and groundwater. Locals use mostly bottled water or rain water for drinking purposes and rainwater for cooking. Groundwater however is used for other household uses and for agriculture. This is further discussed in section 1.3 and 1.4.

7.5.4.3 Energy supply

Molhadhoo has electricity for 24 hours generated from island powerhouse operated by FENAKA.

7.5.4.4 Waste and Waste water disposal

Solid Waste: Molhadhoo has an approved waste management plan and in 2011, a designated area of the island was allocated to collect and manage waste. However, the council currently do not have any equipment for waste management and waste segregation is not practiced as per the island waste management plan. Recently, a new waste management area has been identified and the council is currently in the process of transitioning the locations.

Sewage Disposal: Main method of sewerage disposal at Molhadhoo is by means of septic tanks. Each household has a septic tank within close proximity and are infiltrated into the ground. This is further discussed in section 1.3.

7.6 Existing water and sanitation situation

7.6.1 Water

The island currently does not have a piped drinking water system, however, establishment of an RO Plant with household connection is ongoing and is expected to be completed and ready to use in 2023.

The locals use groundwater for all purposes except for drinking and cooking. While there has not been any noticeable groundwater contamination such as bad smell or discoloration the council believes that some level of contamination must be present due to the septic tanks being connected to the ground.

Rainwater is mainly used for drinking and cooking in the island. Rainwater is harvested using water tanks in individual households as well as by water tanks placed in public spaces by the council. Each household has at least one water tank with a capacity of 2,500L and the council collectively has the capacity to collect and store a total of 25,000L of water.

However, it was reported by the island council that most household use bottled water for drinking and rainwater harvesting is not practiced in some of the households. The council also reported that there are a lot of fluctuations in weather and that dry season can last particularly long in some years causing water shortage in the island. As a result, the council has had to request for water from outside a few times in the past.

The general practice of rainwater harvesting at island level is to clean the roofs thoroughly and letting the first flush pass to the roads which would eventually seep into the ground. Excess rainwater is also discharged to the roads in a similar manner.

7.6.2 Wastewater and sewage disposal

Currently sewage is disposed by means of septic tanks. Each household has a septic tank within close proximity and are infiltrated into the ground. It was noted that most of the households keep the soakage pits outside the house, away from the groundwater wells although the septic tank is inside the house. According to the household survey that was carried out under this study, about 91% of the respondents kept the septic tanks 15ft or more away from the well.

Establishment of a proper sewerage system with household connection is currently ongoing in the island and is expected to be completed in 2023. Once the new sewerage facility has been established, the existing facility will be abandoned. The septic tank inflows from the pipes will be ceased by disconnecting the inflow pipes. The remaining sludge in the pipes and septic tanks will then be removed by sewer jetting and released to the sea via outfall pipe.

7.7 Results of the Baseline Surveys: Water Usage

7.7.1 Summary socio-economic surveys

As detailed in the methodology section of this report (Section 1.4.3), a survey was carried out to determine the water usage at households (HHs), commercial entities (cafés/restaurants), institutions and places with industrial uses (agricultural lands, fish processing). The survey was conducted in Molhadhoo from 9th August to 10th August 2021 with the help of local enumerators. The following Table 7.3 Table 3.3 summarizes samples taken for each sector at 95% confidence interval, refusals, replacement samples and total number of completed surveys for each.

Table 7.3: Population and Sample taken for the social survey

Categories	Population	Sample	Sample replacement	Forms Completed	Refusals	Vacant Houses
Households	68	58	4	58	0	4
Registered Farmers	0	-	-	-	-	-
Fishing Vessels	0	-	-	-	-	-
Fish Processing	0	-	-	-	-	-
Institutions	5	5	0	4	-	-
Guest houses	0	-	-	-	-	-
Café/restaurants	0	-	-	-	-	-

Note: A number of mitigation measures were adopted to ensure to achieve the 95% confidence level sample size. The challenges and limitations and the measures undertaken to mitigate the challenges are listed in 1.4.3.1.

The key findings from this survey show that a total of 581.71 liters of groundwater are estimated to be used per capita per day for various domestic uses. The respective water use situations including domestic, commercial and institutional uses are illustrated in the following sections.

7.7.2 Water usage for domestic purposes

7.7.2.1 Domestic Water Usage

The water usage estimates are calculated based on internationally applied flow rates. A total of 58 HHs were surveyed from Molhadhoo. As presented in Table 7.4, 95% of households have at least one

of 2,500L capacity HDPE rainwater tanks at their homes to collect rainwater for daily uses. Among the 58 HHs, 74% uses rainwater for drinking while 98% also uses it for cooking.

Groundwater is mainly used for non-potable use in all the households surveyed.

Table 7.4: Groundwater and rainwater use data for Molhadhoo

Rainwater	Per cent (%)
Households with rainwater tanks	95%
Rainwater use for drinking	74%
Rainwater use for cooking	98%
Groundwater	Per cent (%)
Groundwater as drinking source	0%
Groundwater for cooking	0%
Groundwater for non-potable use	98%
Total number of household wells surveyed	58
Percentage of wells surveyed fitted with pumps	97%

Based on the survey findings, average daily water demand per capita for domestic purposes has been estimated based on the average amount of water used per person for showering, toilet flushing, laundry and gardening, as shown in Table 7.5. The total domestic water use is estimated to be 581.71 litres per capita per day.

Table 7.5: Domestic Water Usage in Molhadhoo

Shower/ Liters per capita per day	Toilet/ Liters per capita per day	Laundry/ Liters per capita per day	Gardening/ Liters per capita per day	Total/ Liters per capita per day
146.3	45	13.0	269.2	473.5

7.7.2.2 Perception on Groundwater

The households were also asked about their perception on groundwater, if it is safe to use for daily purposes and whether the quality of groundwater is good or bad.

As can be seen from Figure 7-5, the majority of the respondents agreed that groundwater of Molhadhoo is safe to use for the daily uses (97%). Over half of the respondents (57%) also strongly agreed that the islands' ground water is safe for daily use. This indicates that the groundwater condition in Molhadhoo is quite good compared to the other islands in the project.

Furthermore, the households were asked about the quality of groundwater with regards to their experience. As can be seen from Figure 7-6, the majority of respondents 98% reported that in their opinion, the quality of ground water in the island is good. Out of this 98%, 44% reported that the islands' ground water is very good. While in general it was noted even by the island council that groundwater quality is not bad in the island.

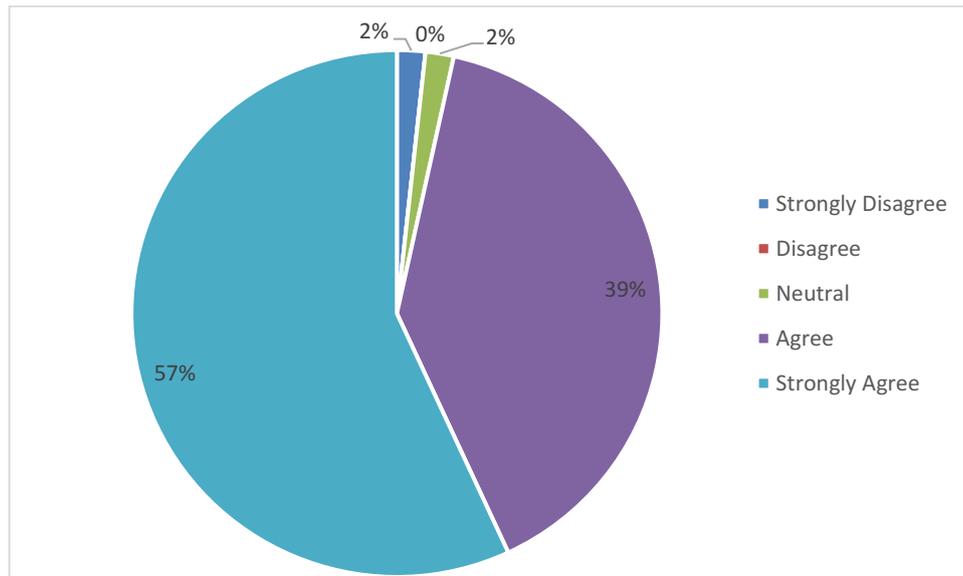


Figure 7-5: Perception of HHs on safety of Groundwater

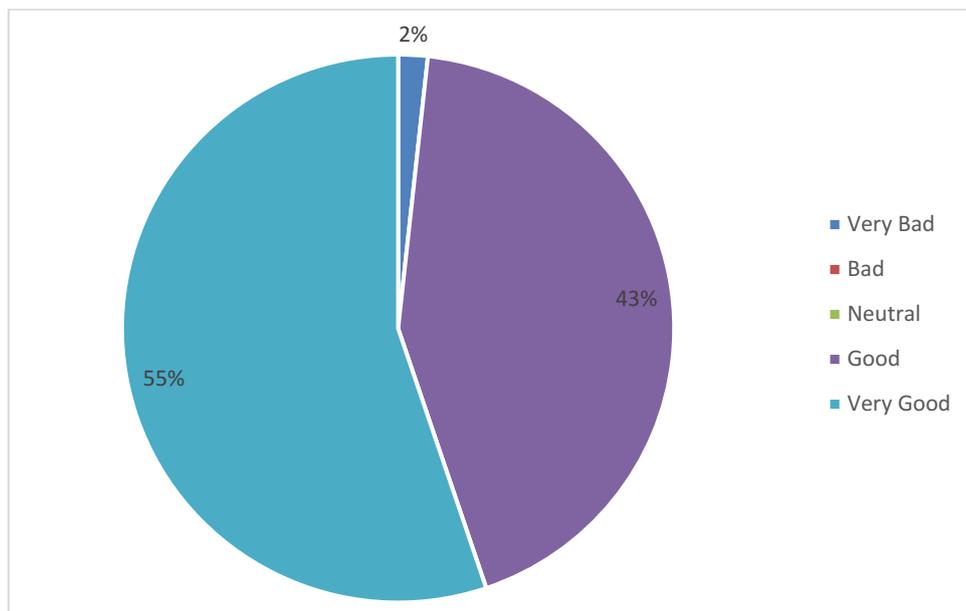


Figure 7-6: Perception of HHs on quality of groundwater

7.7.3 Water Usage by Commercial Activities

Since Molhadhoo council did not report any commercial activities such as café restaurants in the island, there were not data collected on this area.

7.7.4 Water Usage by Institutions

In order to estimate water consumption by different institutions in Molhadhoo, four institutions were surveyed including the island council office, FENAKA office, island court, and school.

Groundwater in the institutions in Molhadhoo are mainly used for mopping floors, flushing toilets, showering, laundry and to some extent gardening. A total of approximately 1802.8 liters of groundwater are estimated to be used per day by the institutions. As the use of each institution is different, to generalize water consumption of institutions to an average figure will not be accurate. However, it can be deduced that based on the data, 31.63 liters of groundwater are estimated to be used per staff per day at the institutions of Molhadhoo.

Table 7.6: Water Usage by commercial activities in molhadhoo

	Water Flushed(Liters)	Gardening(Liters)	Mopping(Liters)	Sub-Total Water Used (Liters)	Total Water Used (Liters)	Institutional Groundwater Usage (Liters Per Staff Per Day)
Council Office	160	613.5	40	813.5	1,802.8	31.63
FENAKA office	224	0	60	284		
Island Court	48	175.28	0	225.28		
School	480	0	2	480		

7.7.5 Water Usage for Farming

Since Molhadhoo council did not report registered farmers in the island and due to the lack of a sample frame, there were no data collected on this area. Furthermore, as discussed previously, farming in Molhadhoo is mostly carried out in the backyards of their homes. Hence, the data on water usage for home gardening is presented under domestic water usage in Table 7.5.

7.7.6 Water Usage for Fisheries Activities

Since there is no fishing activity on Molhadhoo, no data were collected on this area.

7.7.7 Groundwater quality

Groundwater quality measurements were made at selected wells in Molhadhoo Island for both physical and microbiological testing.

The following Table 7.7 summarizes the water quality results.

Table 7.7: Summary of groundwater quality tests from Molhadhoo Island in 2021

Sample No	EC (µS/cm)	pH	Turbidity (NTU)	DO (ppm)	Temp (°C)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
ML1	512.00	8.10	0.31	7.56	28	0.24	23.70	0.20	0.12	236	6
ML2	1252.00	8.10	0.27	7.39	28	0.62	14.80	0.08	0.19	2420	2
ML3	802.00	7.90	0.36	7.49	28	0.39	27.40	0.17	0.17	238	196
ML4	555.00	7.80	0.27	6.53	30	0.27	30.30	0.09	0.13		
ML5	699.00	8.00	1.33	7.36	27	0.34	0.70	0.12	0.08		
ML6	299.00	8.40	0.70	7.64	27	0.14	5.20	0.20	<0.05		
ML7	308.00	7.80	0.21	6.43	27	0.04	1.20	0.11	0.09		
ML8	318.00	8.10	0.16	7.53	28	0.36	1.00	0.18	0.27		
ML9	583.00	8.00	0.13	7.41	28	0.28	47.80	0.16	1.12		
ML10	243.00	7.70	0.55	7.55	29	0.11	17.80	0.16	0.26	1553	93
ML11	565.00	10.00	2.84	7.28	28	0.27	5.80	0.16	0.17		
ML12	480.00	8.20	0.34	7.41	28	0.24	15.80	0.11	0.25		
ML13	600.00	8.00	0.21	7.37	28	0.29	1.00	0.12	0.22		

Sample No	EC (µS/cm)	pH	Turbidity (NTU)	DO (ppm)	Temp (°C)	Salinity (PSU)	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)	Total Coliform (MPN/100ml)	Faecal Coliform (MPN/100ml)
ML14	637.00	8.20	0.35	7.40	28	0.31	10.10	0.20	0.23		
ML15	1669.00	7.80	0.60	7.61	28	0.84	18.10	0.18	0.17		
ML16	186.00	7.70	0.27	6.13	28	0.09	32.40	0.11	0.32	99	3
ML17	583.00	7.70	0.24	6.22	28	0.28	4.40	0.20	0.13	173	6
ML18	592.00	7.70	0.31	6.25	28	0.28	11.20	0.10	0.15		
ML19	20.41	7.20	0.84	4.25	26	12.17	3.20	0.14	<0.05		
ML20	1647.00	7.40	0.26	5.49	28	0.83	5.60	0.08	0.09		
ML21	749.00	7.80	0.23	6.05	28	0.36	9.20	0.18	1.23	15	8
ML22	704.00	8	0.22	7.39	29	0.34	28.1	0.08	0.09	2420	2
ML23	677.00	8.20	0.22	7.28	28	0.33	2.30	0.28	0.18		
ML24	816.00	7.40	0.40	5.73	28	0.40	16.60	0.08	0.10	1986	2
ML25	293.00	7.60	0.52	5.90	30	0.14	21.20	0.28	0.37	1203	2
ML26	354.00	8.20	0.18	7.48	28	0.17	15.80	0.16	0.21	17	6
ML27	198.00	8.30	0.46	7.65	28	0.09	23.50	0.10	0.40		
ML28	203.00	8.10	0.27	7.39	29	0.09	14.80	0.08	0.19		
ML29	287.00	7.90	0.33	7.08	29	0.13	24.60	0.20	1.01	2420	19
ML30	640.00	7.90	0.41	7.09	28	0.31	27.40	0.18	0.25		
ML31	834.00	7.60	0.56	7.36	28	0.41	14.70	0.14	0.14		
ML32	446.00	8.20	0.22	7.48	28	0.21	2.10	0.18	0.24		
ML33	609.00	8.20	0.35	5.34	28	0.29	2.50	0.20	0.08	548	1
ML34	529.00	7.90	0.53	6.21	28	0.25	32.10	0.10	0.16	1414	3
ML35	799.00	8.20	0.18	7.42	28	0.39	20.20	0.14	0.35		
ML36	106.00	7.20	0.33	7.55	28	0.05	38.30	0.25	1.09	2420	5
ML37	587.00	7.80	0.27	6.11	28	0.28	43.40	0.08	0.24		
ML38	320.00	8.00	0.36	7.56	28	0.15	18.60	0.33	0.33		
ML39	398.00	7.80	0.26	6.54	28	0.19	4.50	0.11	0.11		
ML40	824.00	8.10	0.29	7.24	28	0.40	15.40	0.14	0.19		
ML41	531	8	0.307	7.04	28	0.25	6.6	0.22	1.14		

Based on the full results and the summary shown in Table 7.7, the following can be summarized for Molhadhoo Island;

- The EC of the groundwater is generally low, with an average of 572.06 µS/cm which is below an acceptable limit for potable water of 1500 µS/cm. The electrical conductivity readings range from 20.41 to 1669µS/cm. 95% of readings fall within the acceptable limit.
- The pH of groundwater ranged from 7.2 to 10 with an average of 7.96. The pH values of all samples were within the WHO permissible limits of 6.5-8.5.
- Turbidity ranged from the lowest of 0.129 NTU to 2.84 NTU with an average of 0.42 NTU.
- Dissolved oxygen levels were low to moderate, with values varying from 4.25 mg/L to 7.65 mg/L with an average of 6.91 mg/L.
- The salinity of groundwater ranged from 0.04 PSU to 12.17 PSU with an average of 0.58 PSU. Salinity is expressed in Practical Salinity Units (PSU) which is equivalent to PPT.

- The average Nitrate concentration was 16.08 mg/L and therefore it does not exceed the WHO guideline limit of 5.09 mg/L. But 31 of the 41 tested water samples exceeded this limit of 5.09 mg/L. The Nitrate concentrations ranged from 0.7 mg/L to 47.8 mg/L.
- Ammonia concentrations were generally low. The average ammonia concentration was 0.78 mg/L. This is within the WHO guideline value of 1.5 mg/L based on aesthetic (taste and odour) considerations. Only 0 tested water samples exceeded this limit (range from 0.08 to 0.33 mg/L). Natural concentration levels of ammonia are generally below 0.2 mg/L (WHO, 1993) and no tests showed concentrations below this level. There is no apparent correlation between increasing levels of ammonia and other nutrients.
- Phosphate concentrations were moderate. All values were within the range 0.05-1.23 mg/L with an average of 0.30 mg/L. There is no WHO drinking water guideline value for phosphate. However, it would normally be expected that phosphate concentrations in groundwater are less than 0.1 mg/L, where there are no impacts from human wastewater (e.g. effluent from septic tanks and ‘greywater’ from kitchens and bathrooms). There were 7 samples tested below 0.1 mg/L.
- Total coliform levels were also found to be significant and ranged from the lowest count of 15 MPN/100 mL to the highest count of more than 2420 MPN/100 mL, with an average count of 1144.13 MPN/100 mL. Faecal Coliform levels were found to be less significant and ranged from the lowest count of 1 MPN/100mL to the highest count of 196 MPN/100mL.

EC values of the selected wells were collected at the start of wet period (September – October) and following table show the summary of all the result collected during dry and wet periods based on the land use distribution.

Table 3.11: Comparison of WQ results based on land usage

Land Use	Number of samples	Results are lined with conditions
Residential area	36	36
Agricultural area	9	9
Industrial area	4	4
Other areas	15	15
Total	64	64

Considered desirable water quality limits:

- 1) EC < 2500 $\mu\text{s}/\text{cm}$ (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 guideline.

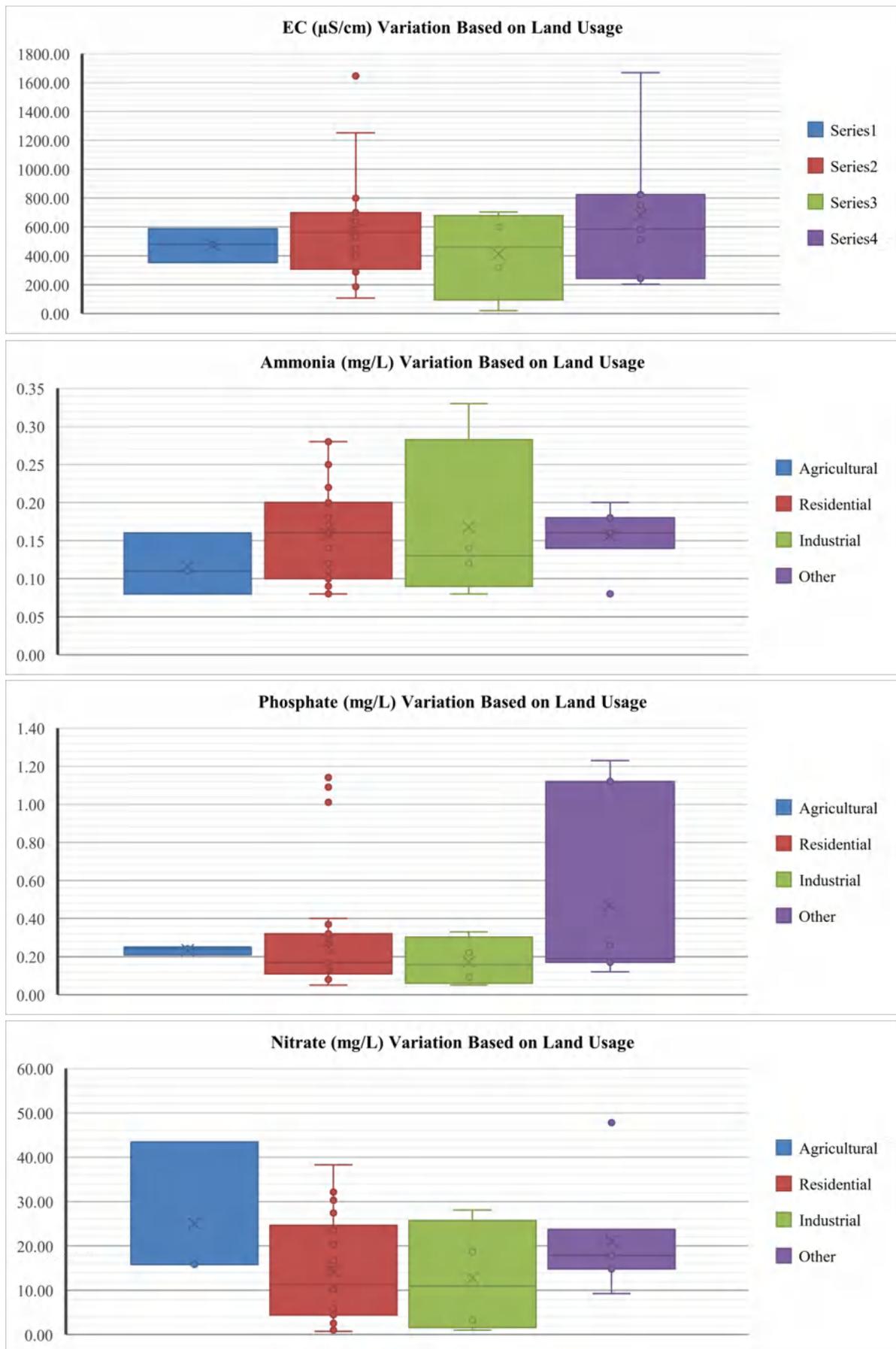


Figure 7-7: Variation of measured WQ parameters in Molhadhoo Island



Figure 7-8: Location of groundwater sampling points in Molhadhoo Island

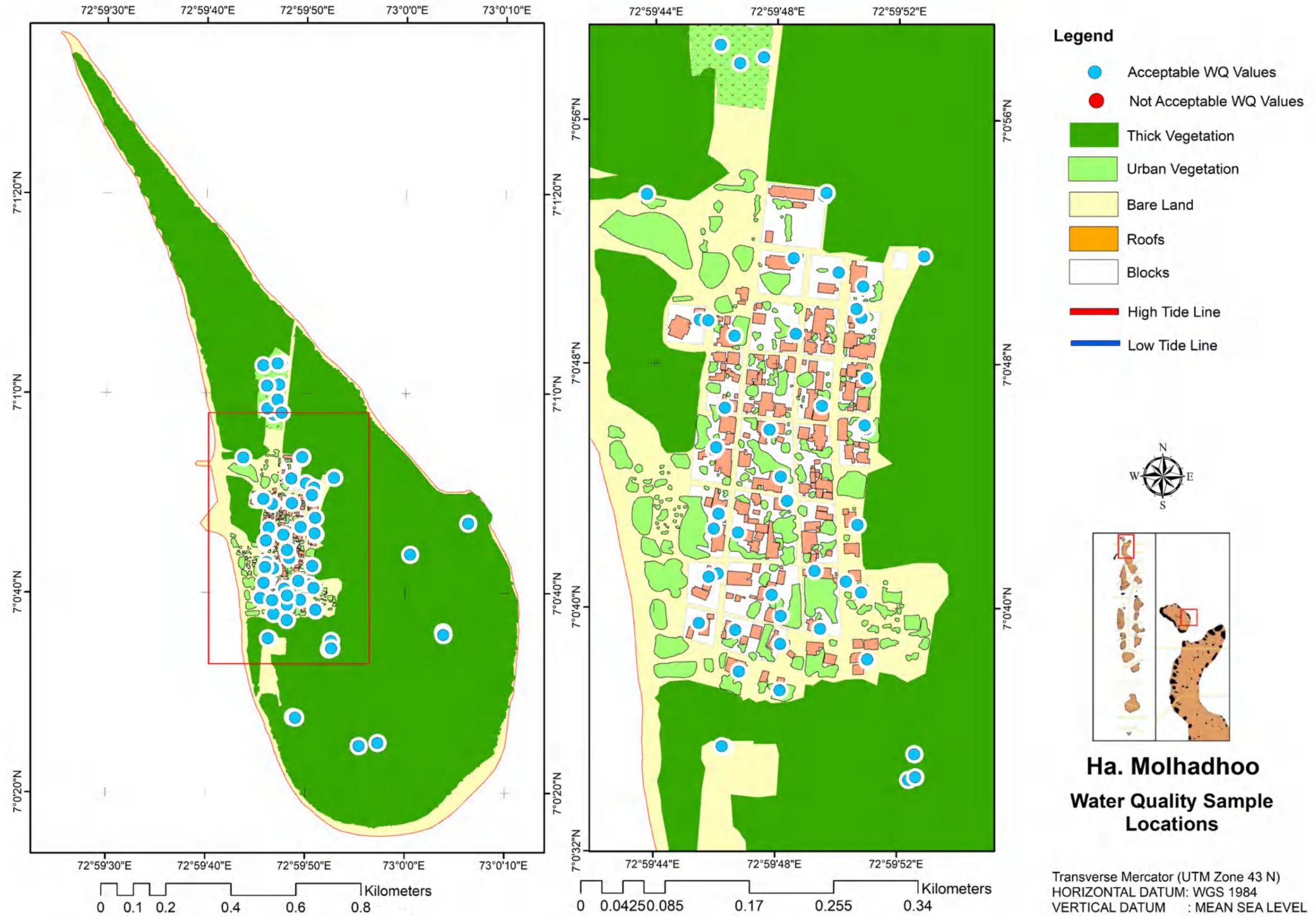


Figure 7-9: Location of groundwater sampling points with critical WQ values in Molhadhoo Island

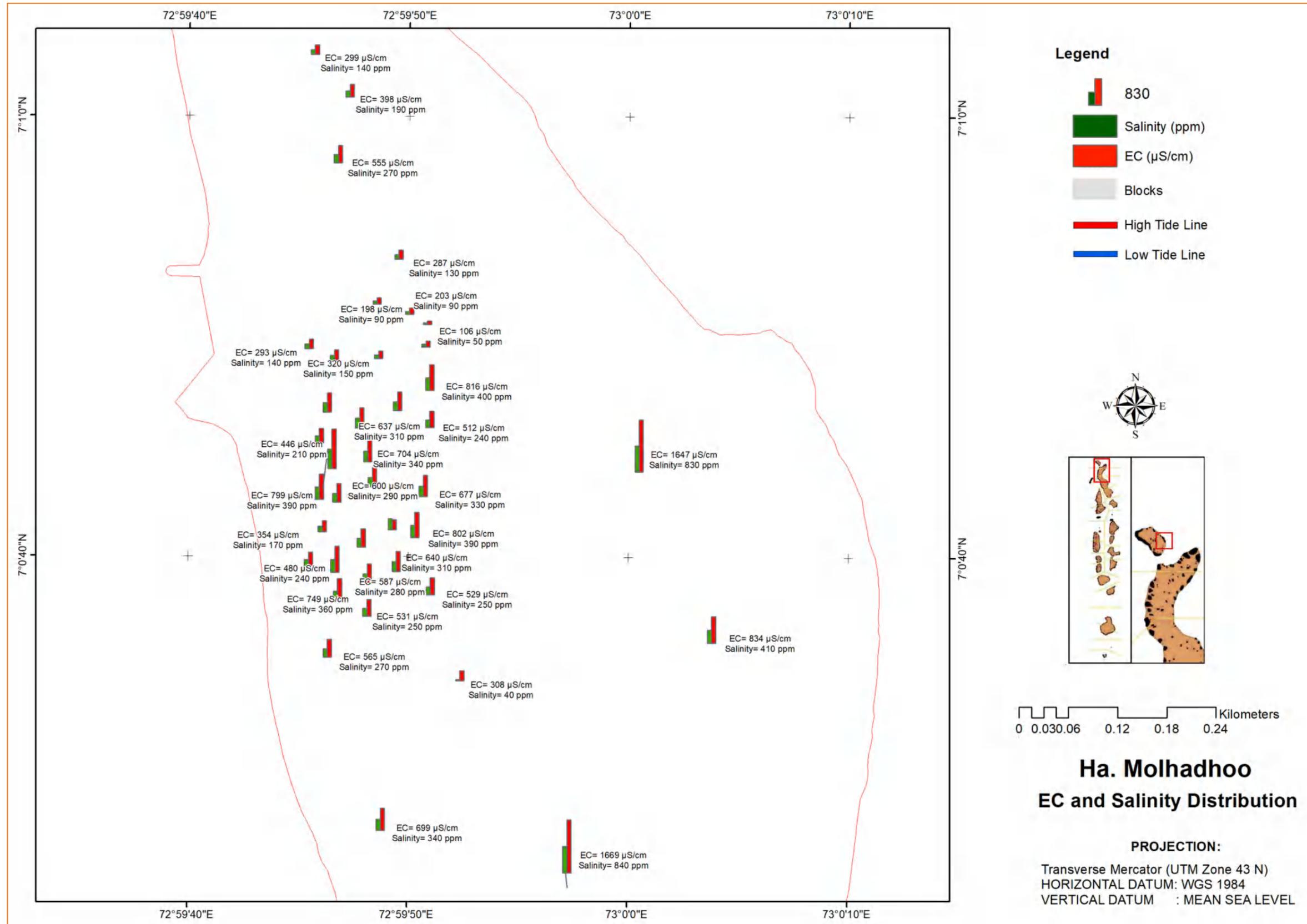


Figure 7-10: EC and Salinity Distribution in Ha. Molhadhoo Island

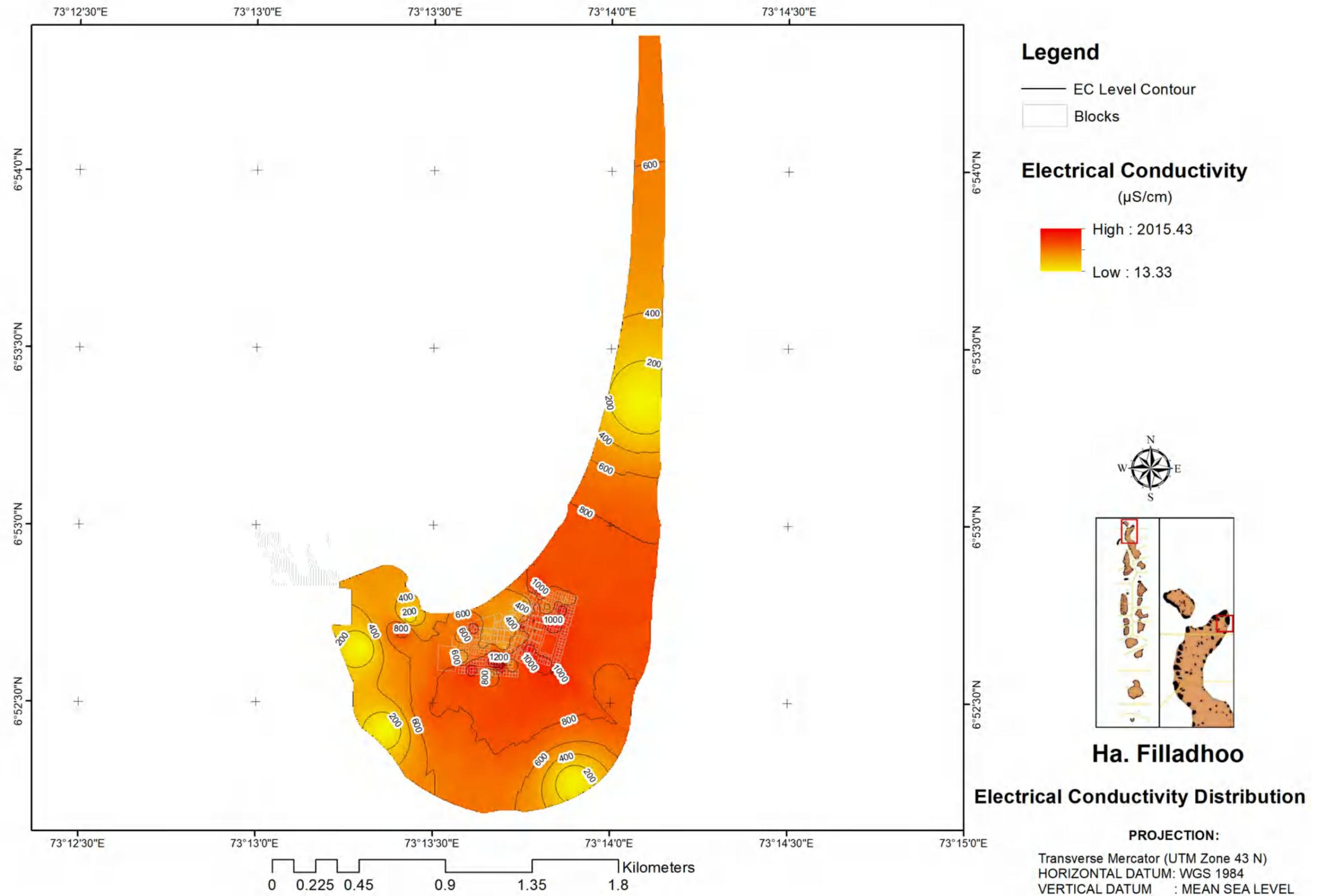


Figure 7-11: EC Distribution in Ha. Molhadhoo Island

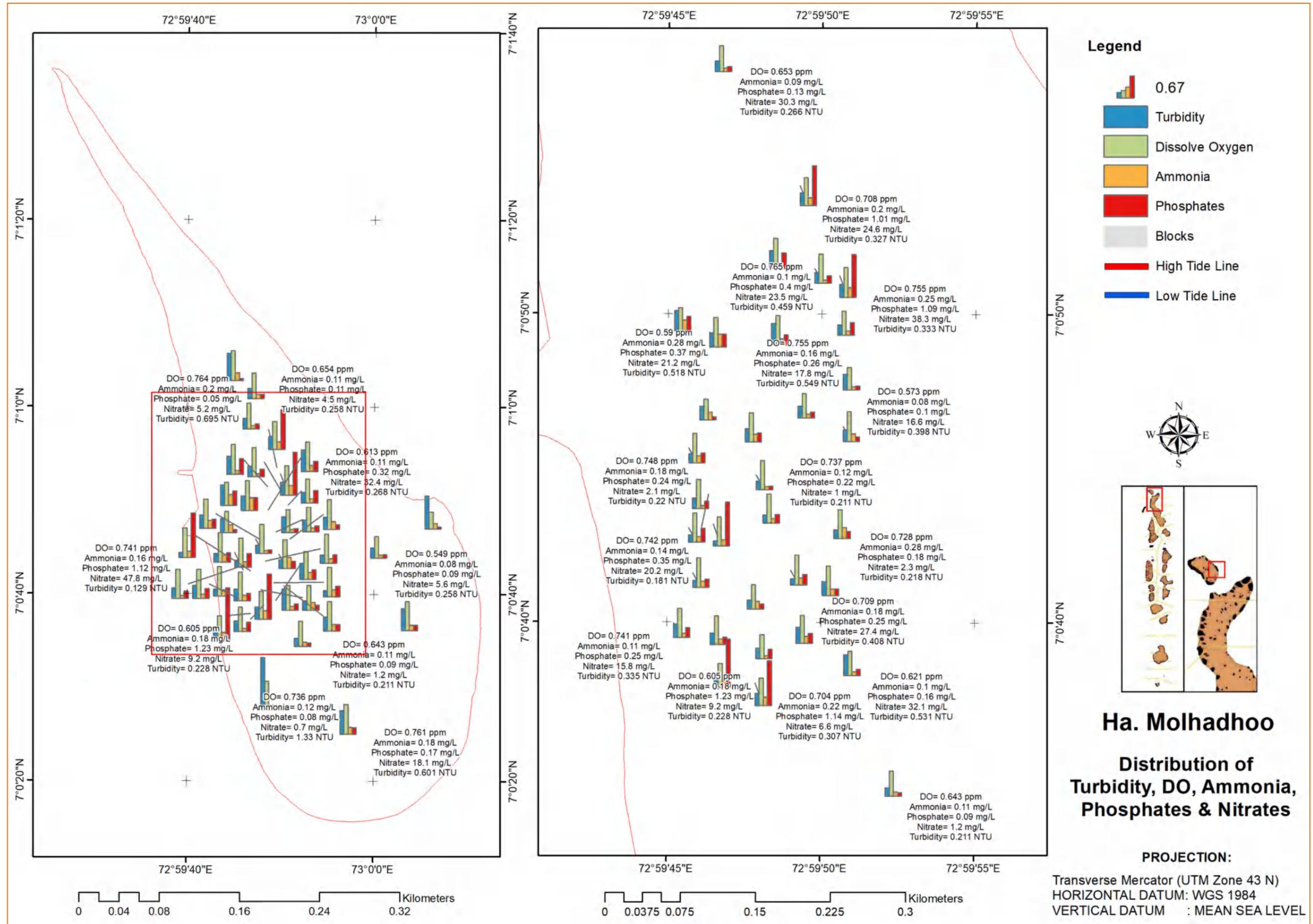


Figure 7-12: Distribution of Turbidity, DO, Ammonia, Phosphates and Nitrates in Ha. Molhadhoo Island

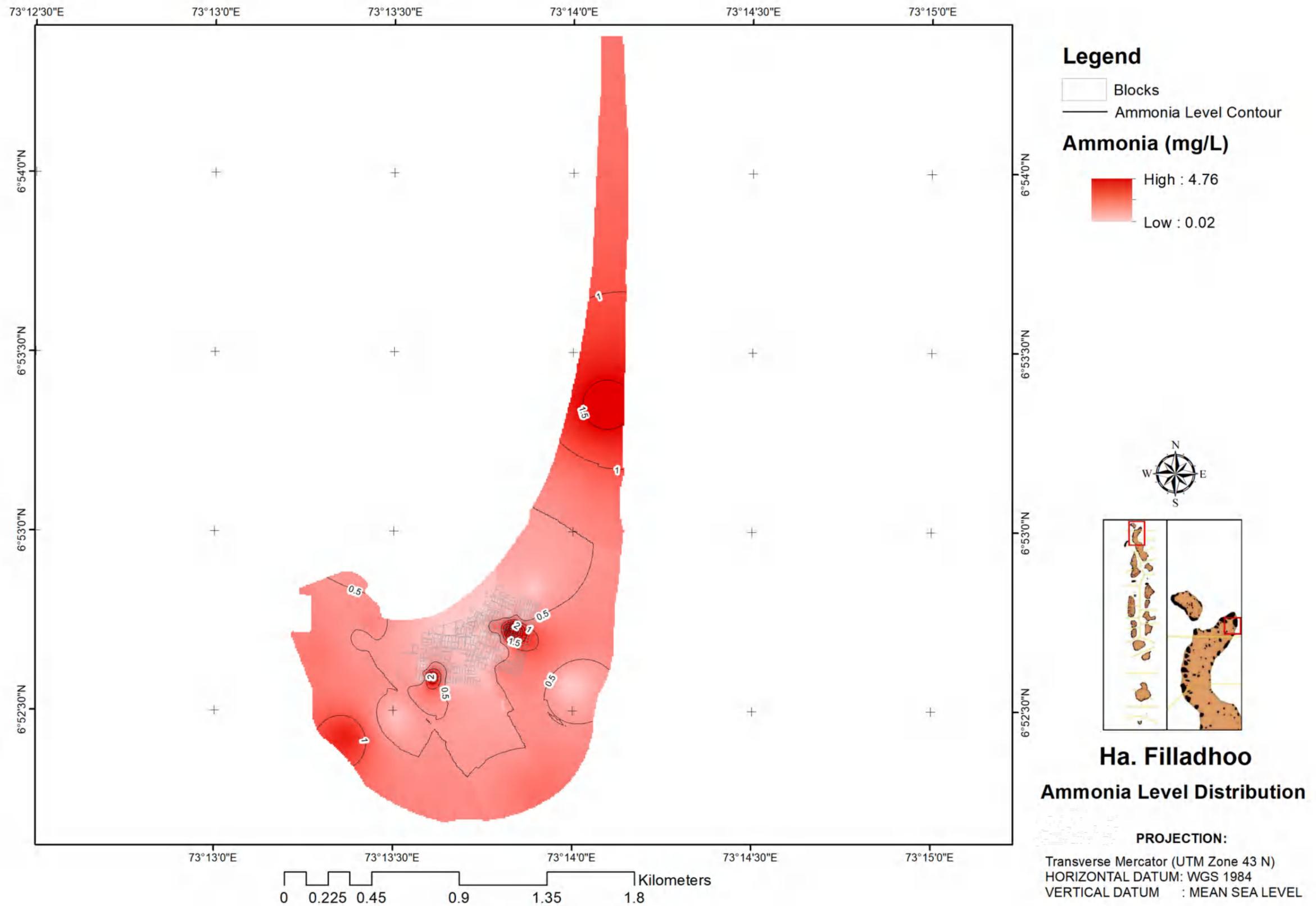


Figure 7-13: Ammonia Level Distribution in Ha. Molhadhoo Island

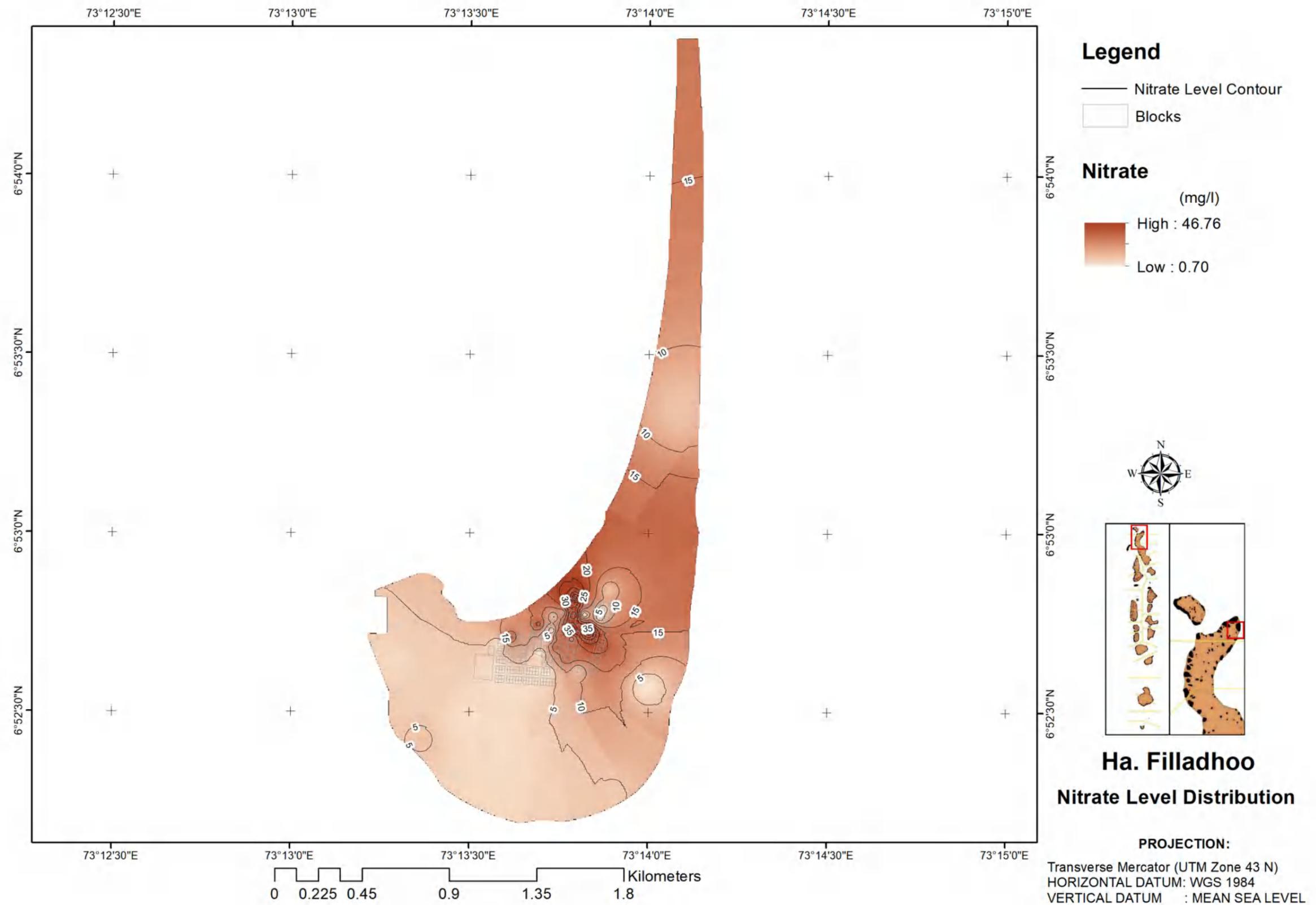


Figure 7-14: Nitrate Level Distribution in Ha. Molhadhoo Island

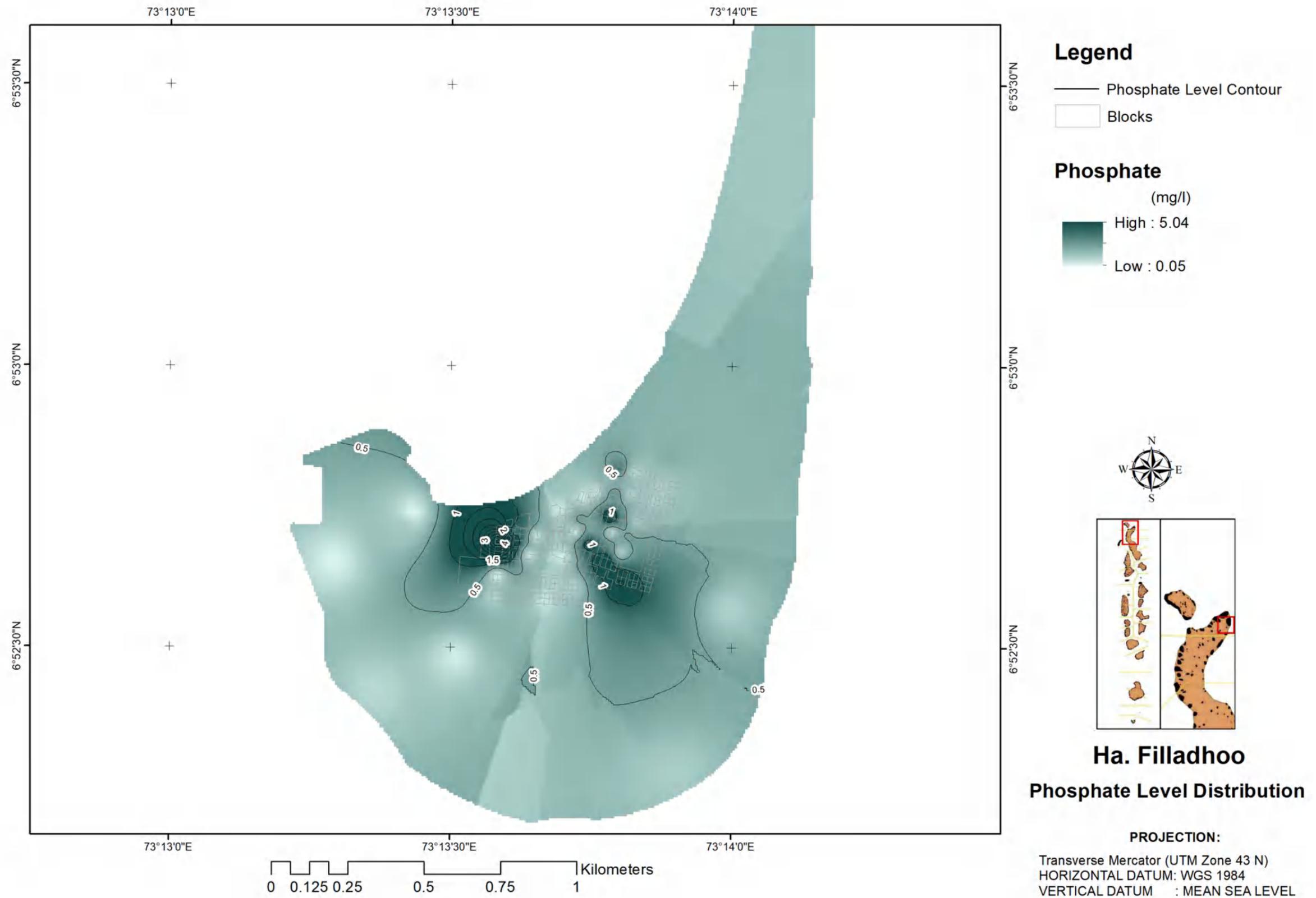


Figure 7-15: Phosphate Level Distribution in Ha. Molhadhoo Island

7.7.8 Geophysical survey

The Electrical Resistivity (ER) tests were carried out in the locations as outlined in Figure 7-16 below. The ER survey included test points along 9 transects selected representatively based on reconnaissance surveys to adequately characterise different land uses and island cross-sections. The main transects were aligned along existing roads to maintain consistency and uniformity.

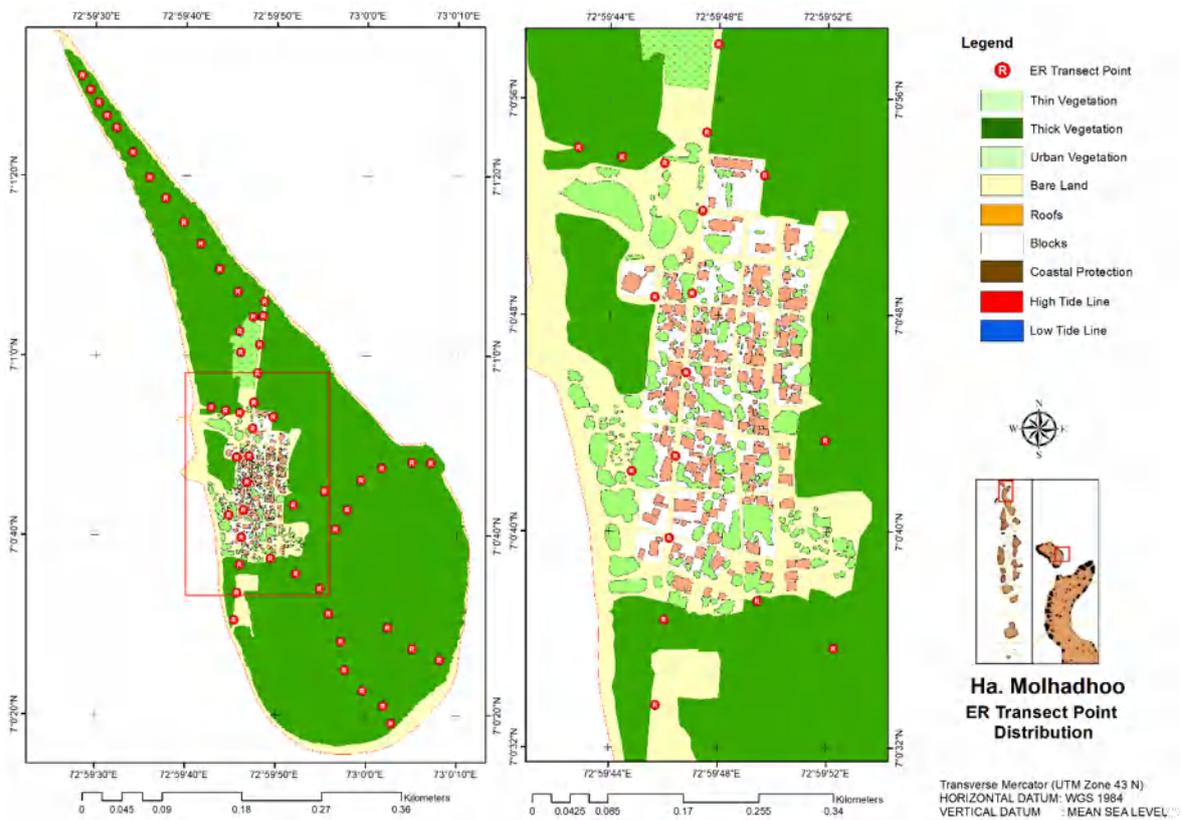


Figure 7-16: Location of ER points in Molhadhoo Island

7.7.9 Aerial surveys

Based on the aerial survey, a multiple dataset consisting of buildings, roof cover, land cover, change detection and shoreline were extracted. This data is shown in Figure 7-17. The total roof cover for this island is 17,764 m².

7.7.10 Water demand

The only source of natural water is rainwater collected from the rooftops of households and institutions and groundwater extracted from shallow wells. The runoff water from the domestic yards, road surfaces, etc., is not usable as there is no mechanism for its collection and treatment.

7.7.11 Freshwater lens

Based on the Electrical Resistivity (ER) surveys, the depth to groundwater level and the freshwater-saline water interface were determined for a set of transverse transects as shown in Figure 7-16. Plots in Figure 7-2 show the main two cross-sections of island. The dotted lines in the plots indicate a simple interpolation of levels to mean sea level in the island boundaries.

Volume of the lens has been calculated with aid of ArcGIS and Surfer Software.

$$\text{Volume of lens} = 1,409,913 \text{ m}^3$$

$$\text{Groundwater Storage} = \text{Porosity (15\%)} \times \text{Lens volume (m}^3\text{)} = 211,487 \text{ m}^3$$

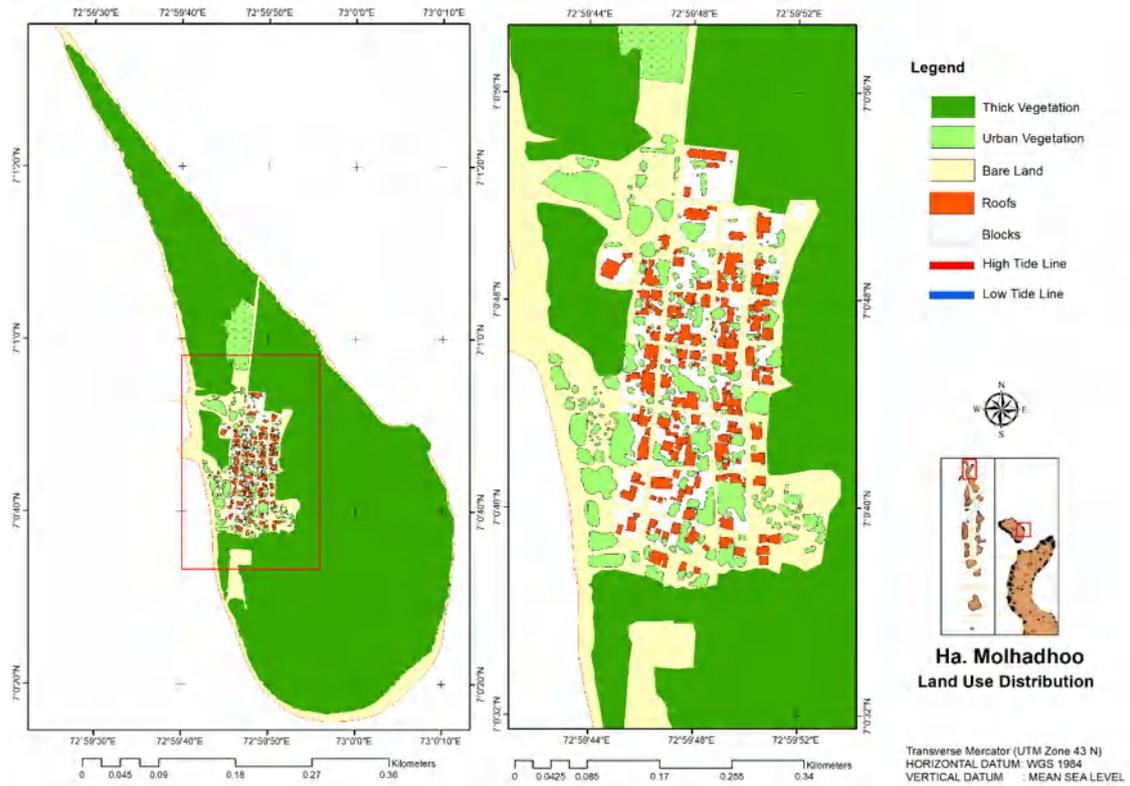


Figure 7-17: Roof Cover in Molhadhoo Island based on UAV Survey

The 2-D freshwater lens distribution density maps produced with GIS software for visualization of the spatial and volume extents are also presented below in Figure 7-18 to Figure 7-20.

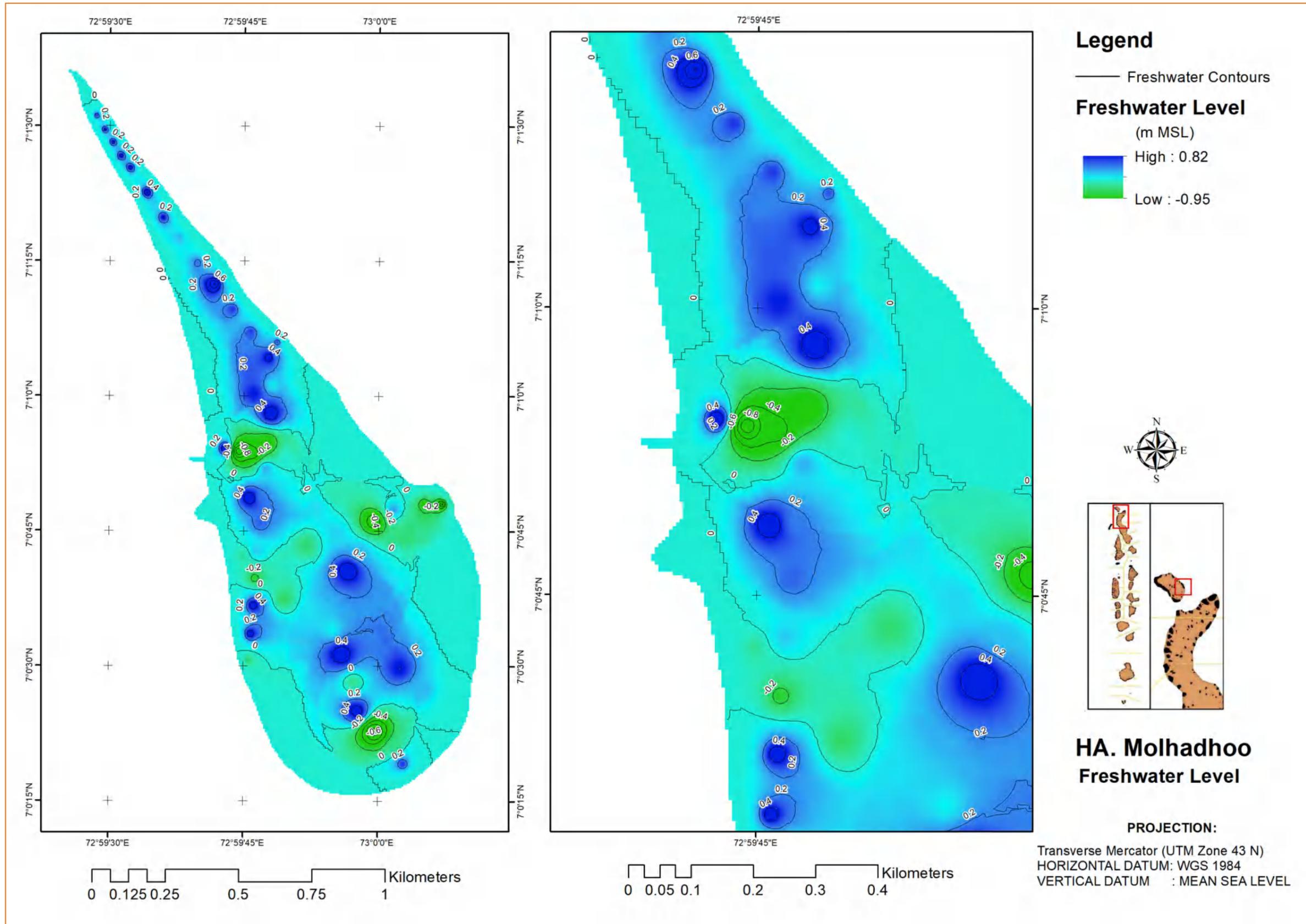


Figure 7-18: Freshwater Level in Molhadhoo Island

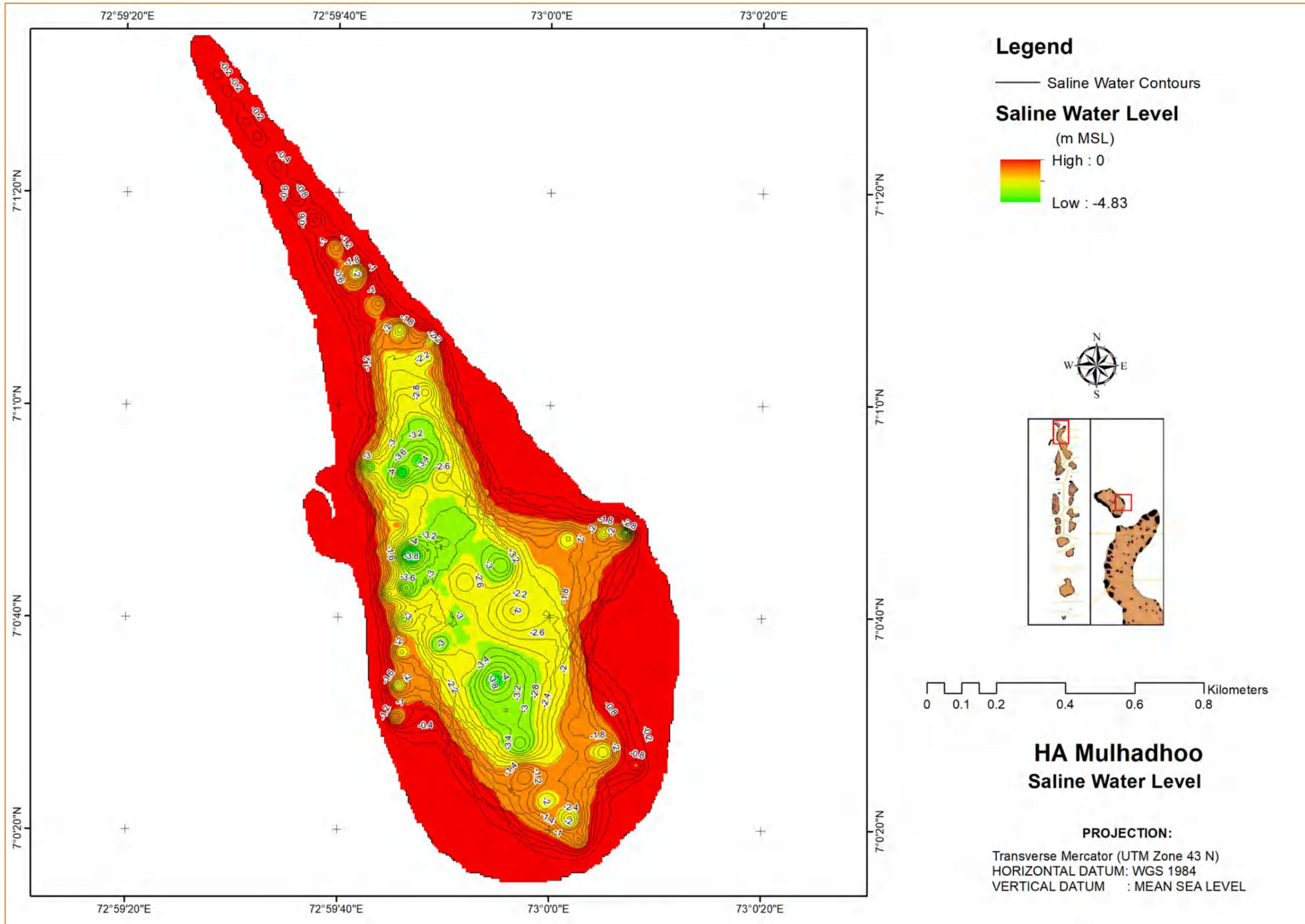


Figure 7-19: Saline water Level in Molhadhoo Island

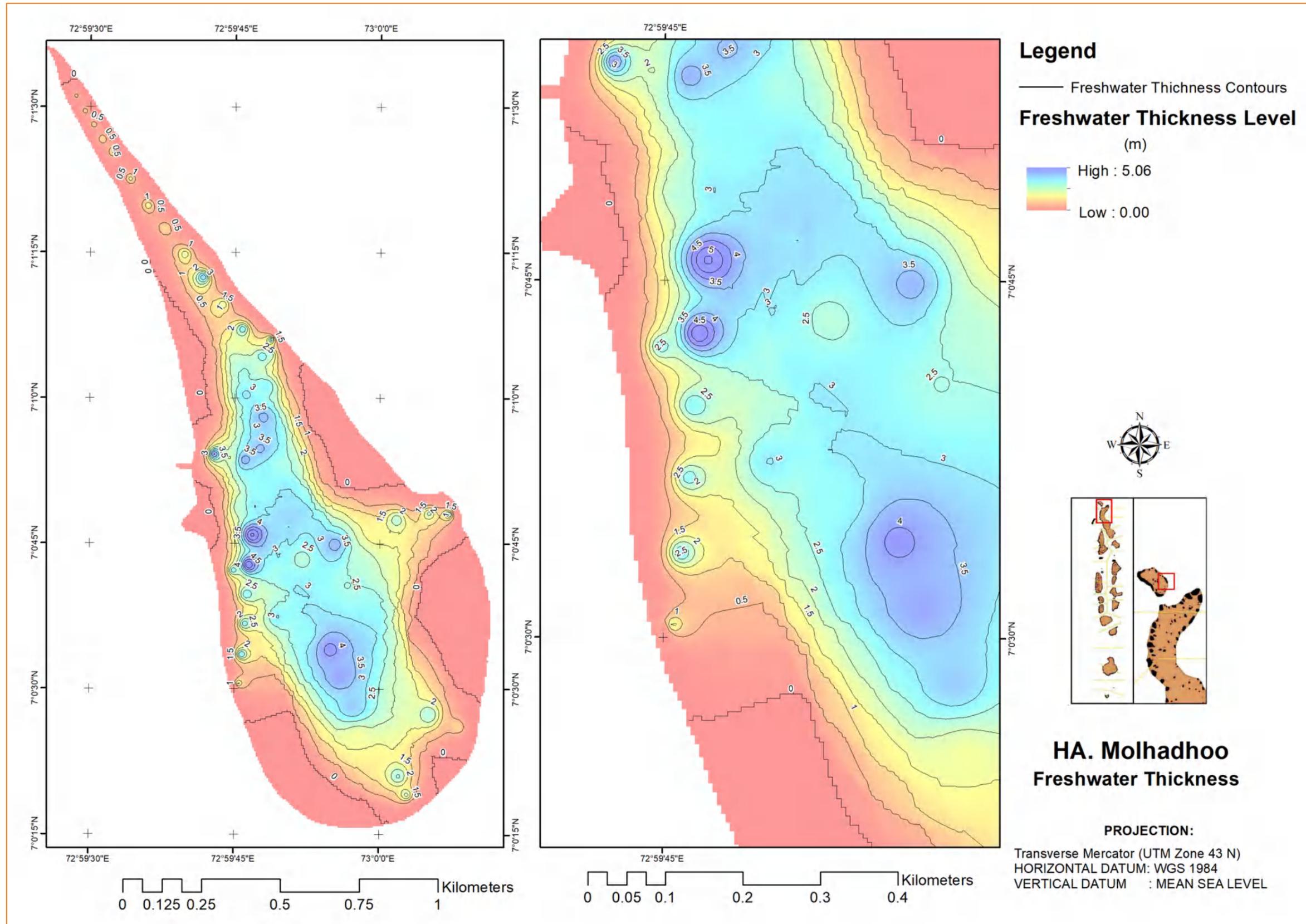


Figure 7-20: Freshwater thickness in Molhadhoo Island

The maximum freshwater thickness of the island is 1.85 m (It is noted here that these readings were taken in October, which is the wet season and the with a reasonably higher number of wet days per month of the year).

7.7.12 Water balance and recharge

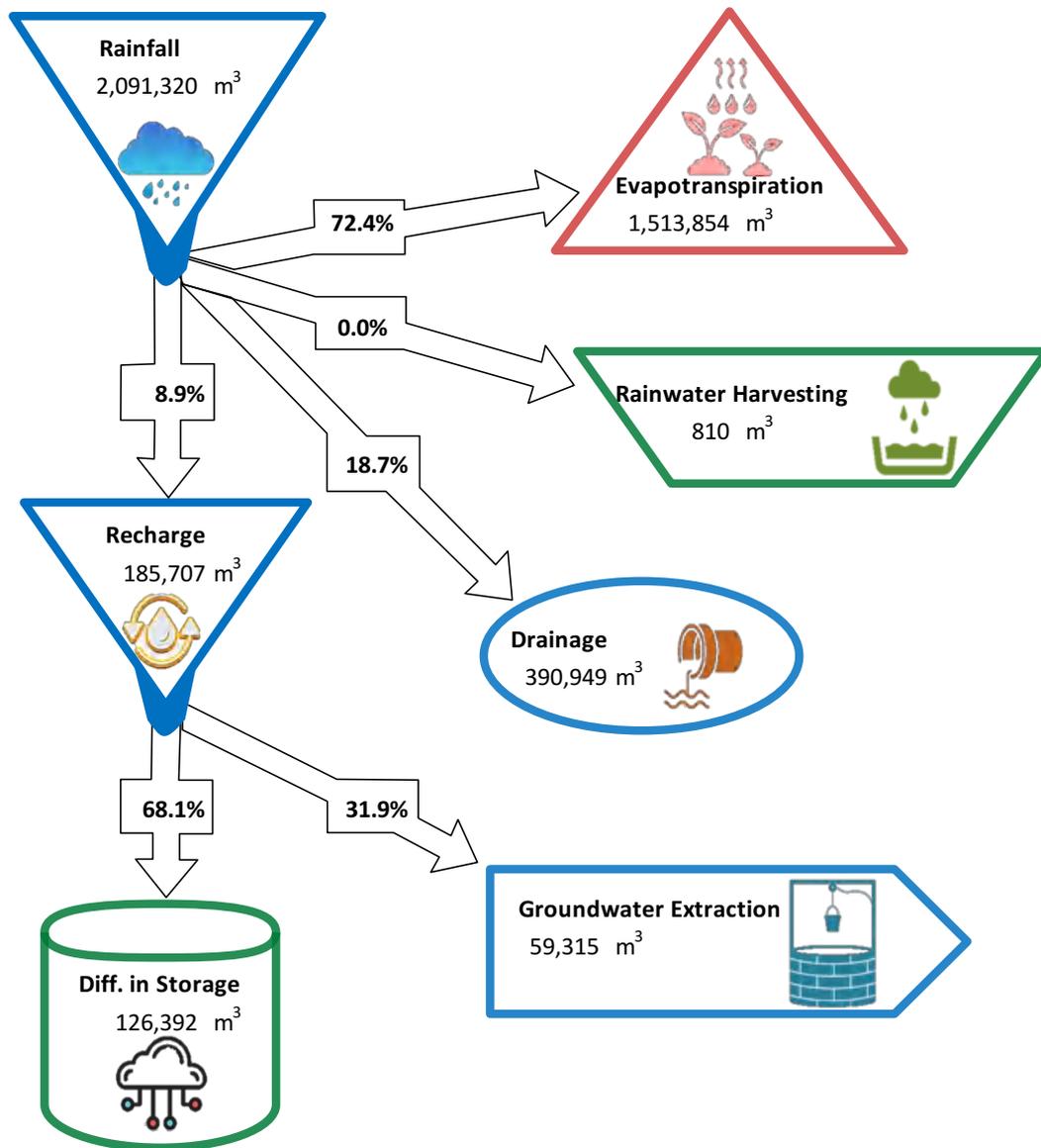


Figure 7-21: Schematic of water balance in Molhadhoo Island

An annual estimation is carried out based on the water balance method (Falkland, 2000). Rainwater harvesting is calculated using the number of rainwater harvesting units on the island. According to the spatial mean annual rainfall of the Maldives, the annual average rainfall of Molhadhoo Island is reported as 1,750 mm/year. Evapotranspiration was estimated using crop water requirements for different land use. Then, the rainfall was subtracted from rainwater harvesting, evapotranspiration, drainage to get the recharge volume. Drainage or the surface runoff was calculated by considering an aggregate runoff coefficient for the island based on the land usage (roof cover, bare land, farmland, roads, playgrounds, wetlands). The groundwater extractions were estimated from the amount of water usage in different sectors (residential, resorts, restaurants, agriculture and farming). The difference between recharge and groundwater extraction is taken to estimate the difference in storage.

7.7.13 Sustainable yield of the lens

Sustainable yield of the water lens refers to the safe extraction potential of a given groundwater aquifer without significantly affecting its quality or quantity. This parameter is an important factor in the sustainable development of islands as it allows planning and design of water and sanitation intervention in islands.

The island has a sustainable yield of 346 m³ per day which was calculated by subtracting groundwater extraction from recharge volume derived from the schematic water balance model in Figure 7-21.

7.7.14 Permeability test

Permeability tests were carried out in the selected locations as outlined in Figure 7-22.

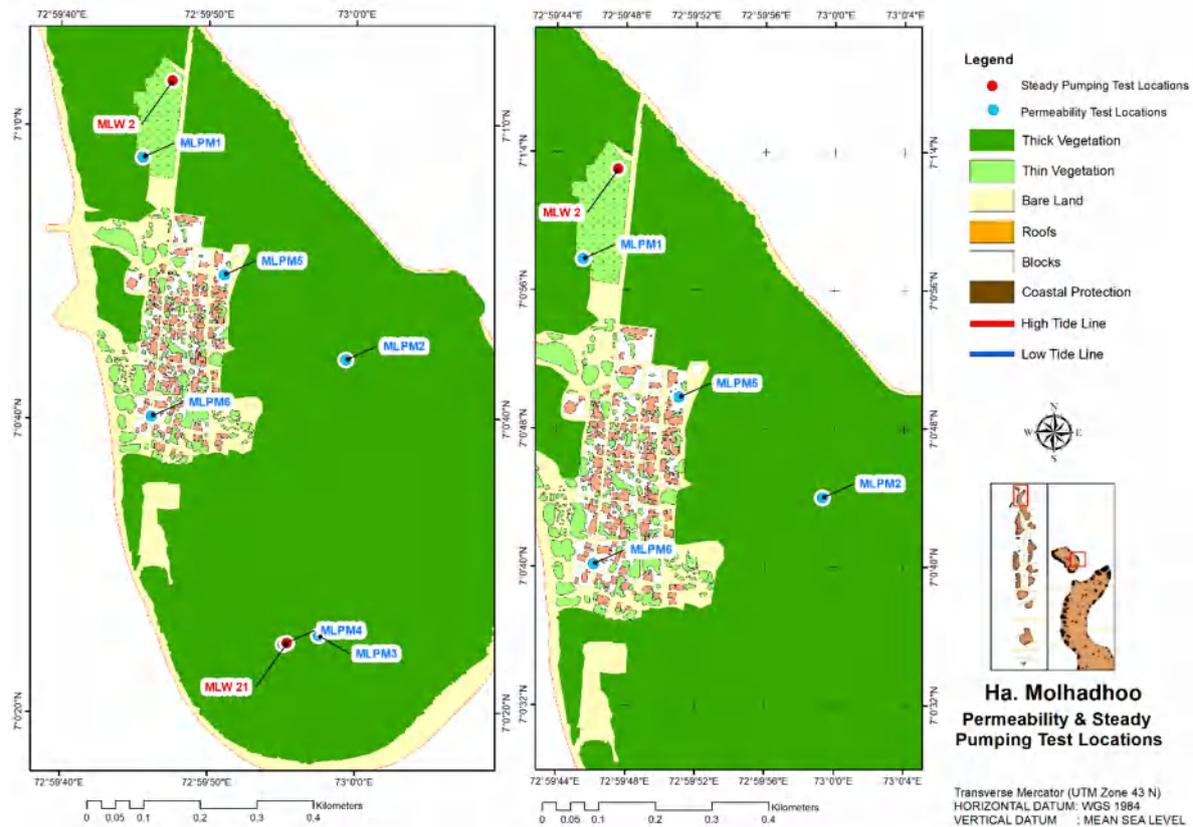


Figure 7-22: Locations of permeability and steady pumping tests in Molhadhoo Island

The estimated permeability values for the above test locations are presented below in Table 7.8. The data will be comparatively verified and interpreted when additional data is acquired and calculations for other islands are completed.

The parameters have their usual notations where, K = Coefficient of permeability (m/s under Q unit gradient), Q = Steady flow into well (m³/s), H = Height of water in well (m), l = length of the perforated section (m), U = thickness of saturated permeability material above water table, r_1 = outside radius of the casing (radius of the hole in consolidated material) (m), r_e = effective radius of well = r_1 (area of perforations) / (outside area of perforated section of casing): $r_1 = r_e$ in consolidated material that will stand open and is not cast, C_s = Conductivity Coefficients, and T_u = distance from water level in the casing to water table (m).

Table 7.8: The Estimated Soil Permeability Values in Molhadoo Island

Point	MLPM1	MLPM2	MLPM3	MLPM4	MLPM5	MLPM6
D (m)	0.750	0.600	1.100	1.100	0.900	1.100
H (m)	0.750	0.600	1.100	1.100	0.900	1.100
ℓ (m)	0.750	0.600	1.100	1.100	0.900	1.100
U (m)	0.850	0.700	1.350	1.350	1.100	1.400
T _u (m)	0.850	0.700	1.350	1.350	1.100	1.400
r (m)	0.076	0.076	0.076	0.076	0.076	1.076
Q (m ³ /s)	5.50E-05	1.08E-04	1.60E-04	1.50E-04	1.50E-04	5.72E-05
r ₁ (m)	0.076	0.076	0.076	0.076	0.076	1.076
r _e (m)	0.010	0.010	0.010	0.010	0.010	0.010
T _u /ℓ	1.133	1.167	1.227	1.227	1.222	1.273
X = (H/T _u × 100)	88%	86%	81%	81%	82%	79%
Section	Zone 2	Zone 3				
ℓ/r _e	72	58	106	106	87	106
C _s	110	90	145	145	125	145
K (m/s)	8.94E-05	2.48E-04	1.31E-04	1.23E-04	1.70E-04	1.41E-05
K (m/day)	7.72	21.40	11.31	10.60	14.69	1.22

7.7.15 Steady Pumping Test

Pumping tests were conducted in two existing wells to estimate the aquifer properties of unconfined water bearing formation.

Table 7.9 : Selected Steady State Pumping Test Locations in Molhadoo Island

Well No.	C'	A (m ²)	t' (s)	ln ($\frac{s_1}{s_2}$)	T (m ² /s)
MLW 2	5.25	0.865	420	4.65	0.008
MLW 21	4.5	4.63	300	5	0.055

The measured transmissivity (m²/s) values ranged from a minimum of 0.008 m²/s to a maximum of 0.055 m²/s., with an average of 0.032 m²/s. During the testing period, EC (Electrical conductivity) level of both wells were increased as below.

- For MLW 2, EC (Electrical conductivity) increases from 700 µs/cm to 790 µs/cm.
- For MLW 21, EC (Electrical conductivity) increases from 1580 µs/cm to 1620 µs/cm.

7.7.16 Status of groundwater availability in Molhadhoo Island

- 1). The selected Molhadhoo island has dimensions of width = 890 m and length = 2700 m, with a total land area of 119.50 ha, a population of 929 persons, and a land use of Roof cover (Built up area) 1.75 ha (1.5%), Vegetation (Thick) 93.64 ha (78.4%), Vegetation (Light) 2.71 ha (2.3%), and Barelands 19.66 ha (16.4%).
- 2). In order to recognize the fluctuation in the groundwater table, freshwater-saline interphase and estimate the volume of freshwater lens (FWL) and its associated recharge-discharge characteristics, 31 number of Electrical Resistivity (ER) location readings along 09 representatively selected transects were collected.
- 3). Soil overburden permeability tests (constant head) were carried out at 05 locations while steady-state pumping tests were conducted at 02 locations. In addition, groundwater level was also recorded at 06 locations where groundwater water quality samples were tested.
- 4). Permeability tests were carried out at representatively selected 05 number of locations. The measured permeability (K m/day) values ranged from a minimum of 1.27 m/day to a maximum of 50.92 m/day, with an average of 25.83 ± 18.23 m/day (Mean \pm Standard Deviation).
- 5). The ground elevation values ranged from a minimum of -0.40 m MSL to a maximum of 2.34 m MSL, with an average of 1.13 ± 0.52 m MSL (Mean \pm Standard Deviation).
- 6). The upper boundary of the freshwater lens (FWL) varied from a minimum of -0.95 m MSL to a maximum of 0.82 m MSL, with an average of 0.04 ± 0.13 m MSL (Mean \pm Standard Deviation).
- 7). The lower boundary of the freshwater lens (FWL) or freshwater-saline interphase ranged from a minimum of -4.83 m MSL to a maximum of 0.00 m MSL, with an average of -1.19 ± 1.16 m MSL (Mean \pm Standard Deviation).
- 8). Accordingly, the freshwater lens (FWL) volumetric values ranged from a minimum of 0.00 m to a maximum of 5.06 m, with an average of 1.18 ± 1.19 m (Mean \pm Standard Deviation).
- 9). The groundwater profile in the island is characterised by a relatively Very Low (0.04%) Rainwater Harvesting (%) relatively Low (18.69%) Drainage (%) relatively Low (8.88%) Recharge (%) while the water use shows relatively Very Low (31.94%) Groundwater extraction (%) leading to relatively Very High (68.06%) Difference in Balance Storage (%) .
- 10). The freshwater lens (FWL) volume calculated based on ER transect test data is 211,487 m³ with a maximum FWL thickness of 5.06 m.

7.8 Conclusion

The Safe Yield for the island estimated based on 'Recharge - Extraction' is 346 m³ per day, while it is 573 m³ per day based on 10% of Average Annual Rainfall Method. The present groundwater extraction rate estimated based on survey data is 163 m³ per day and this is about 47% of the allowable Safe Yield in the island. At present, there exists no island wide sewerage network or water supply network.

Relative hydraulic conductivity of the island lies in 'Semi-pervious' state while present aquifer condition range from 'Poor' – 'Good' state based on the hydraulic conductivity estimation carried out as per Bear (1972) and transmissivity of the formation was compared as per Krany (1993). Moreover, general status based on transmissivity ranged 'Very High' to 'High' and potential for groundwater recharge remains 'Low' – 'Moderate' as per the estimations.

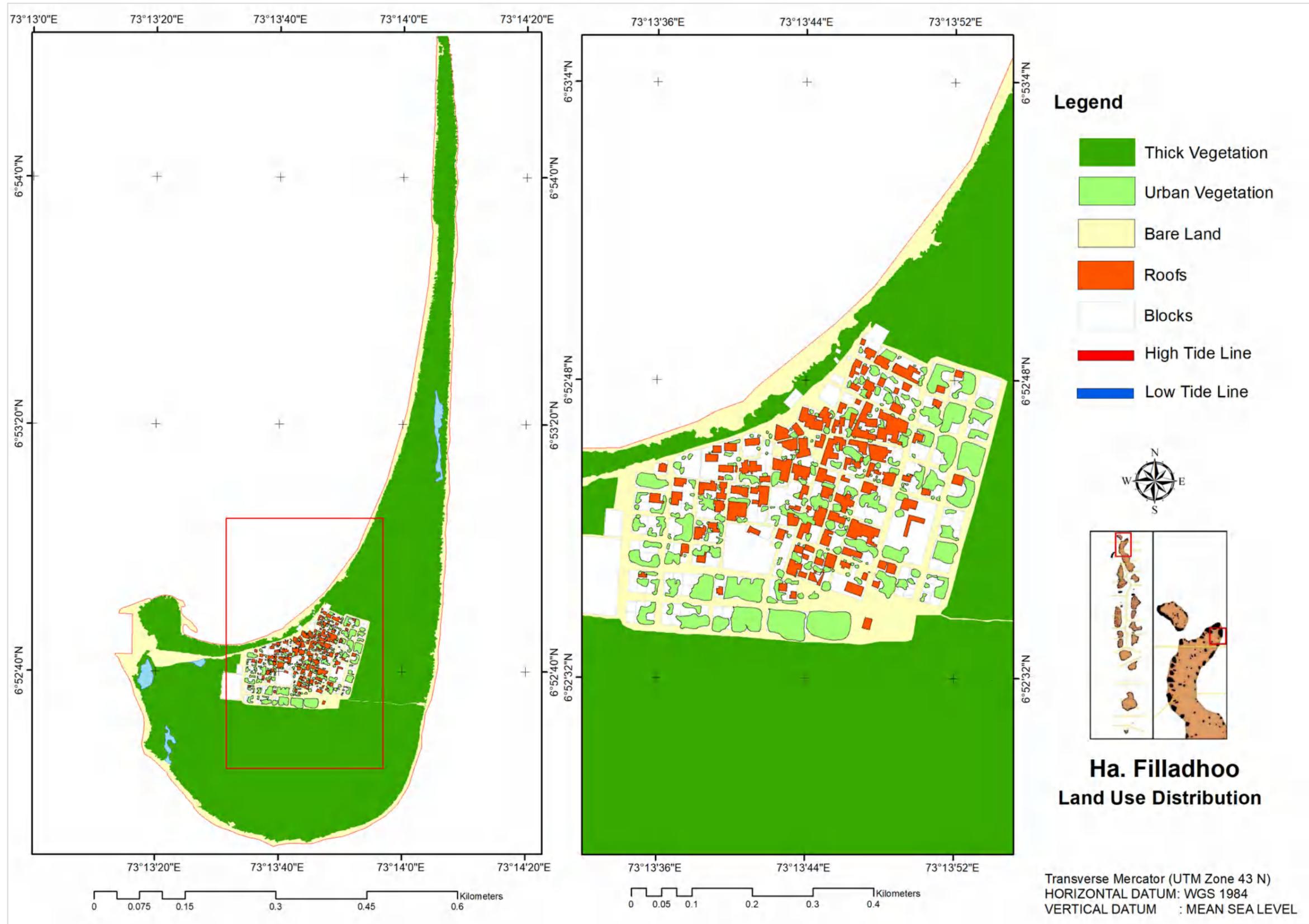
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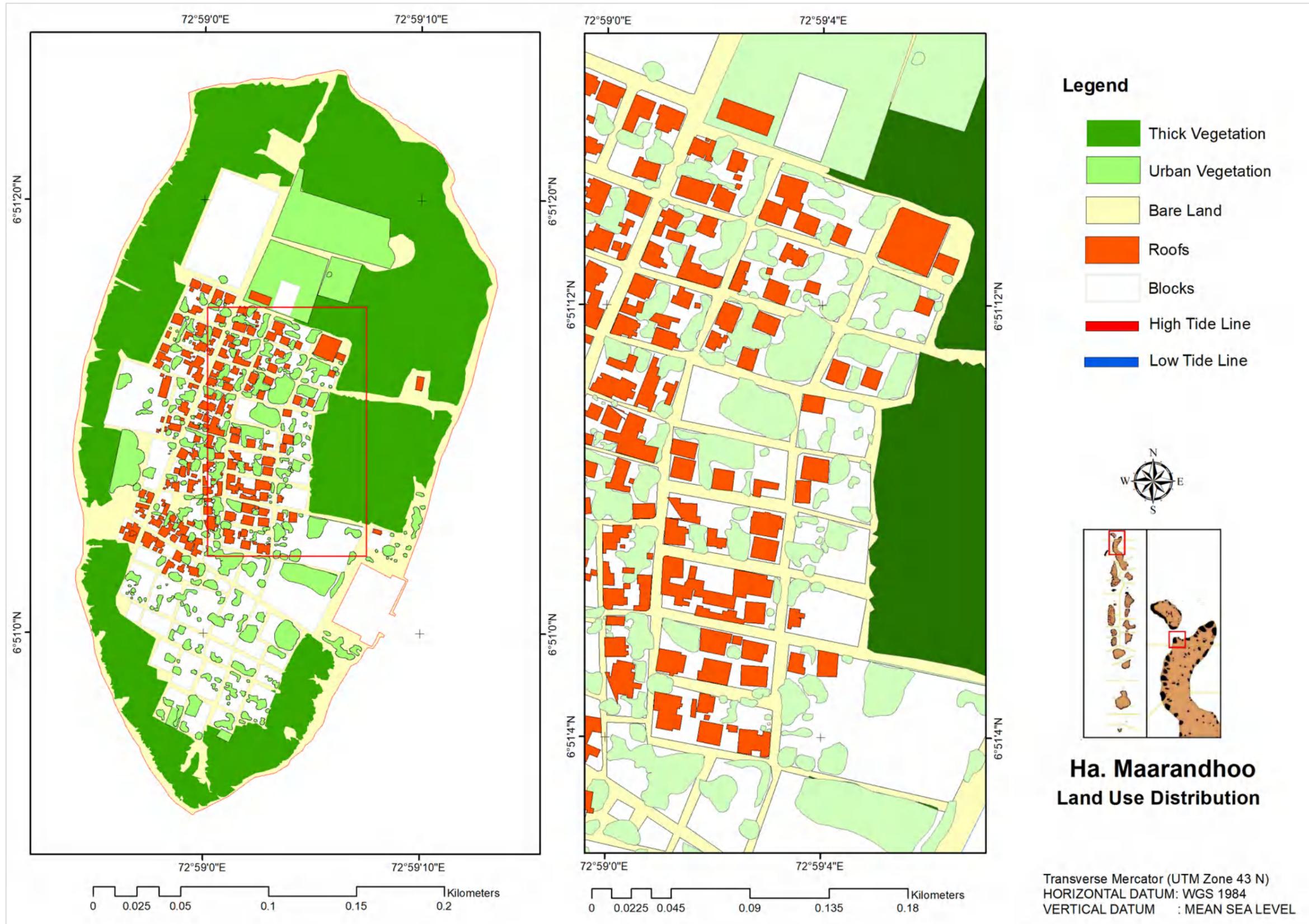
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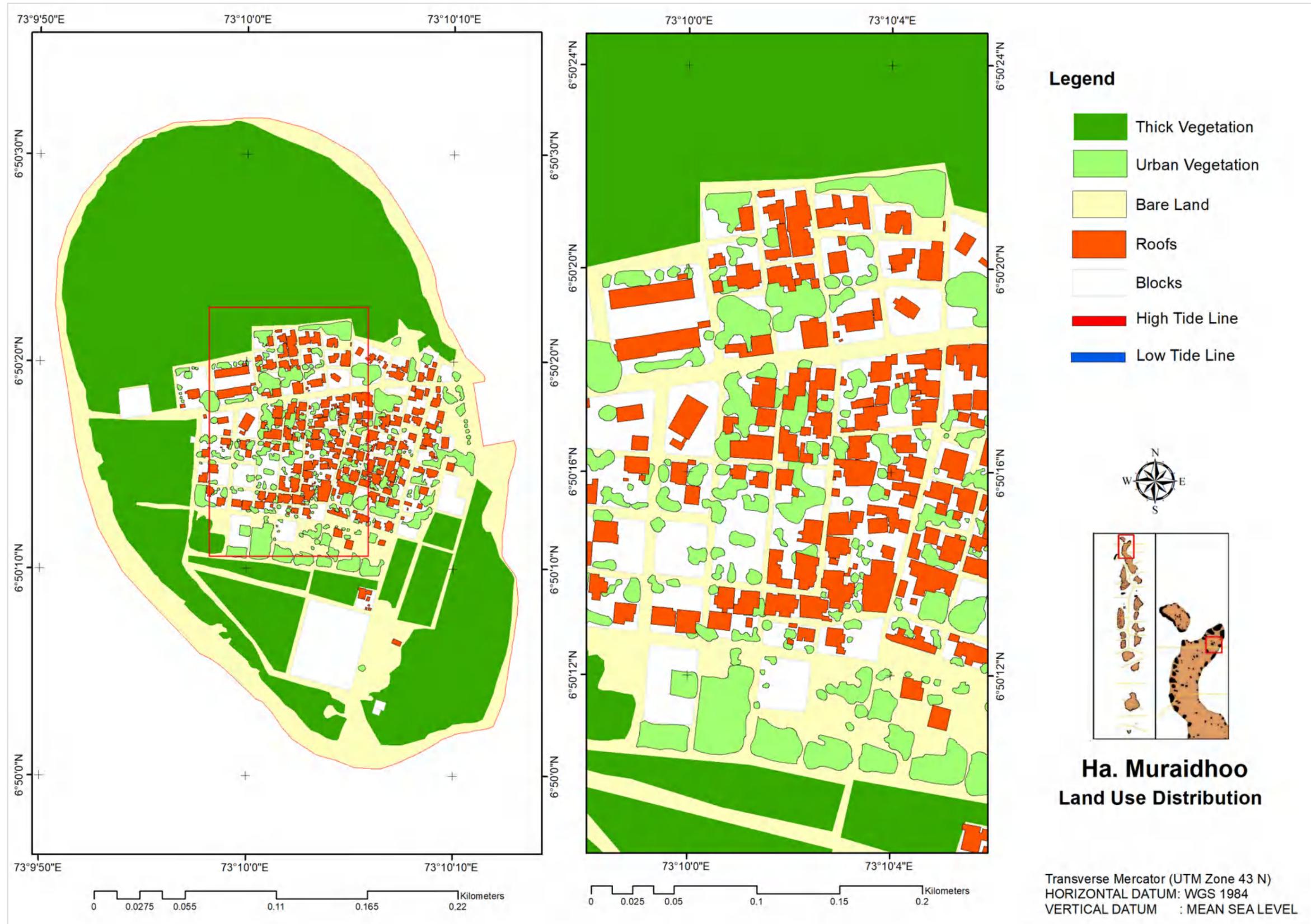
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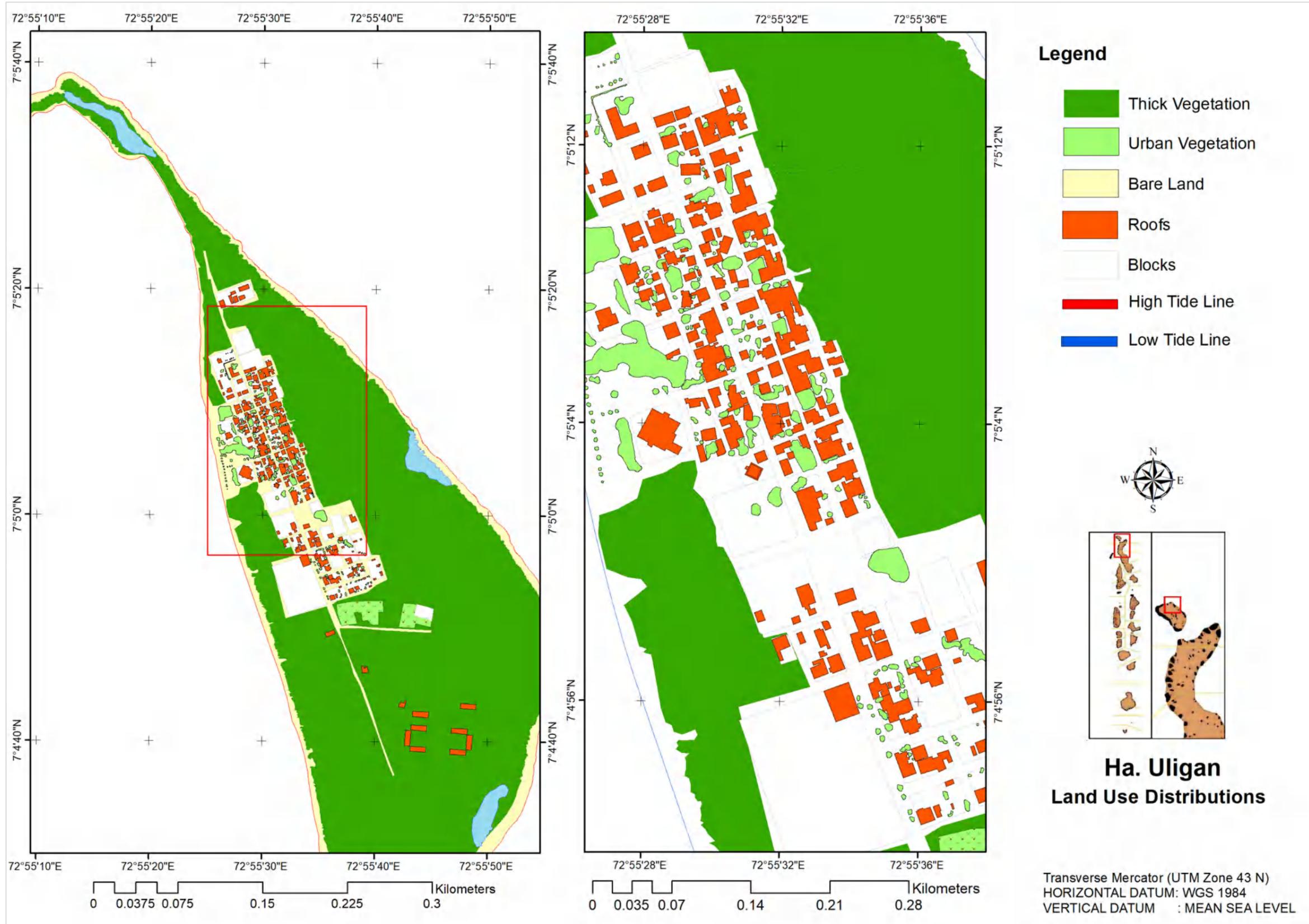
Annex I: Location Map of the Islands

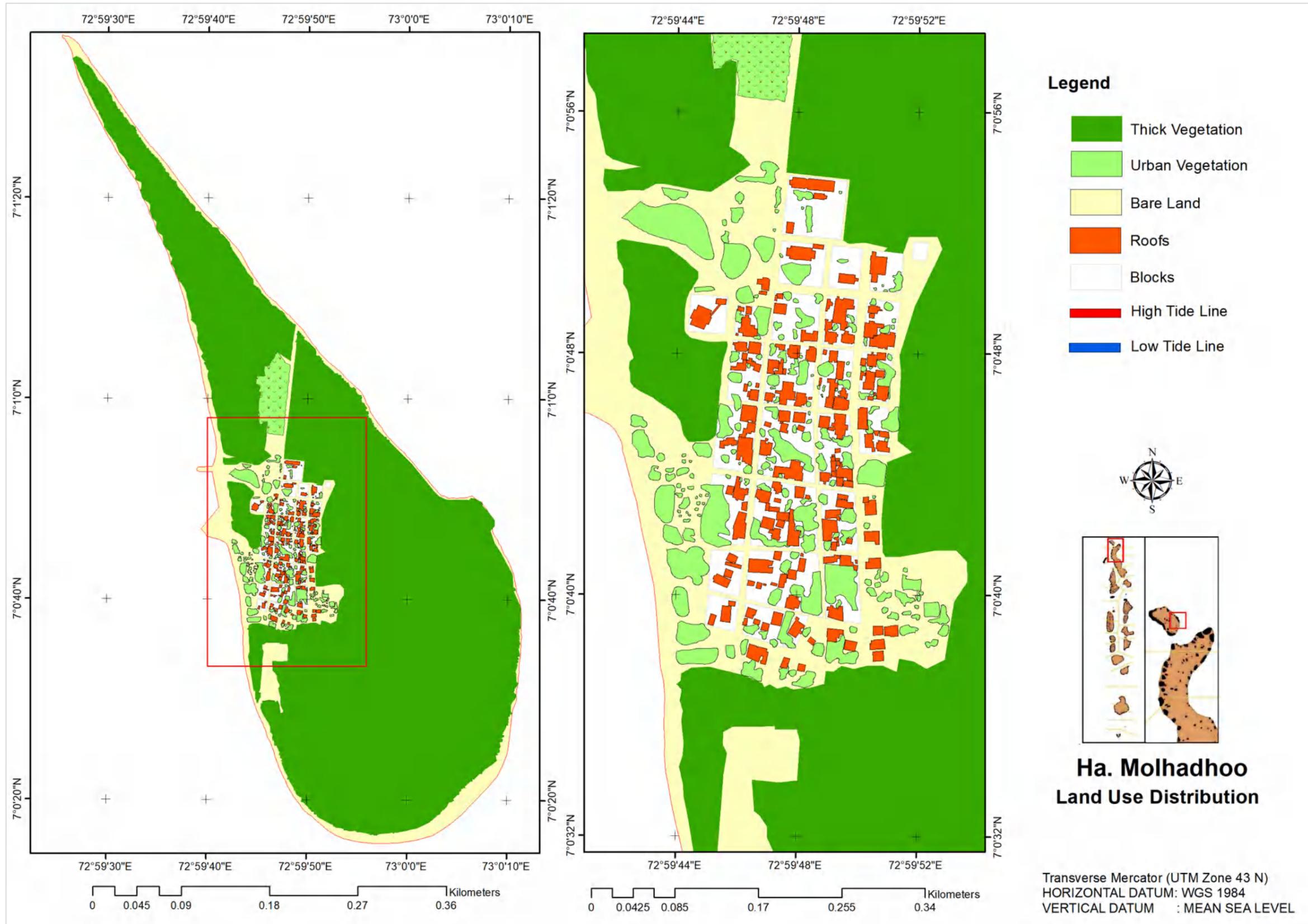
Annex II: Land Use Distribution of Islands



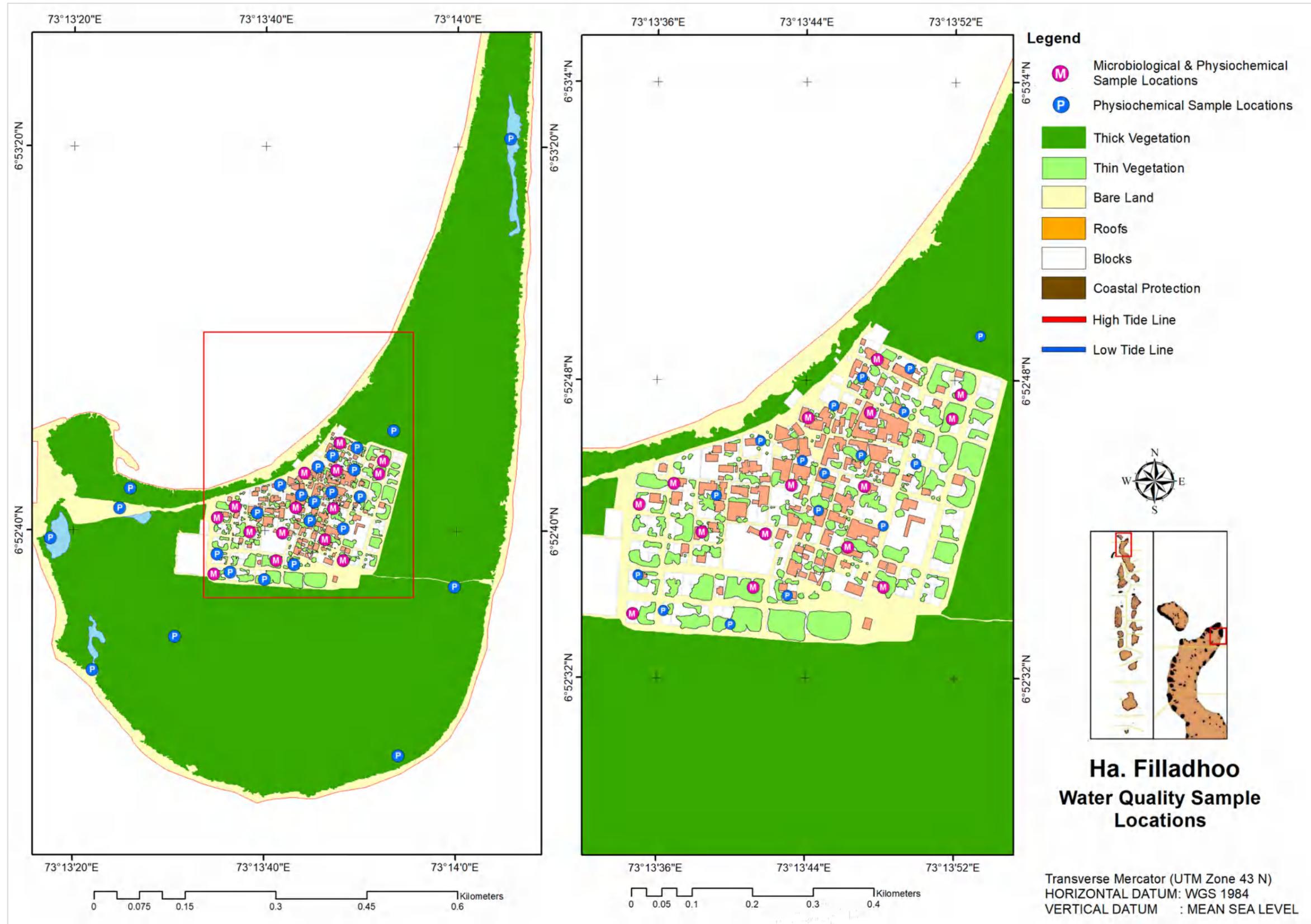


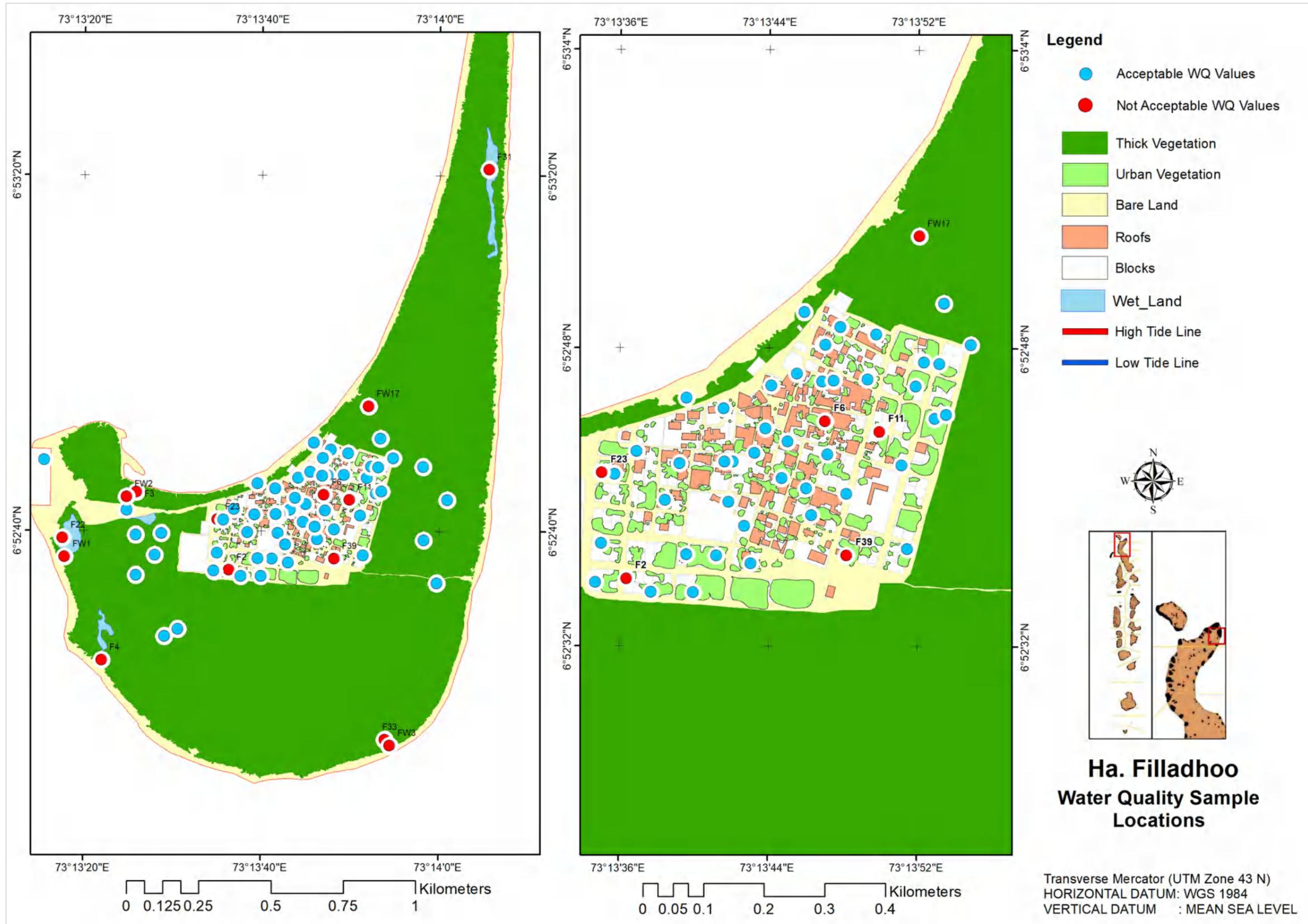


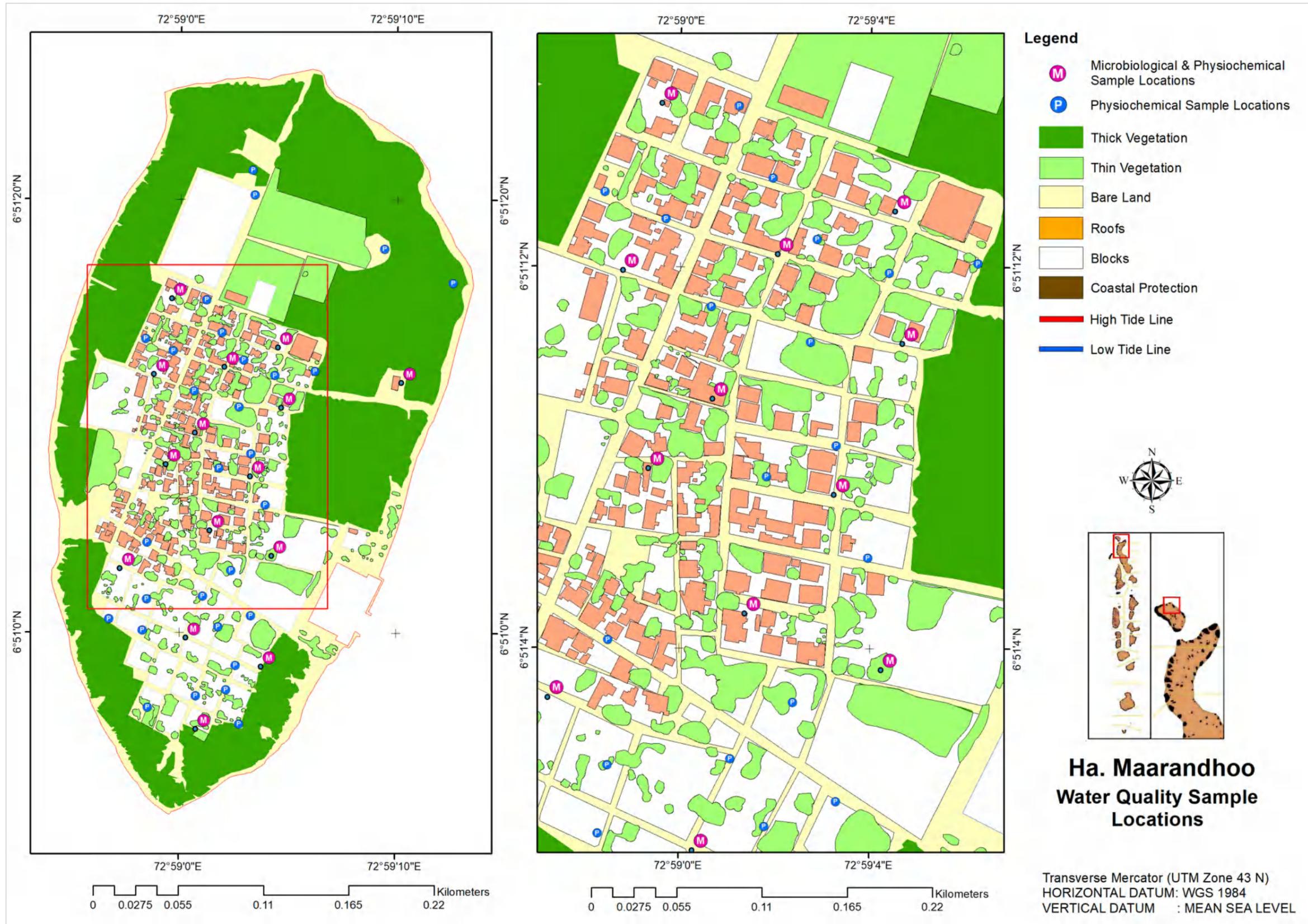


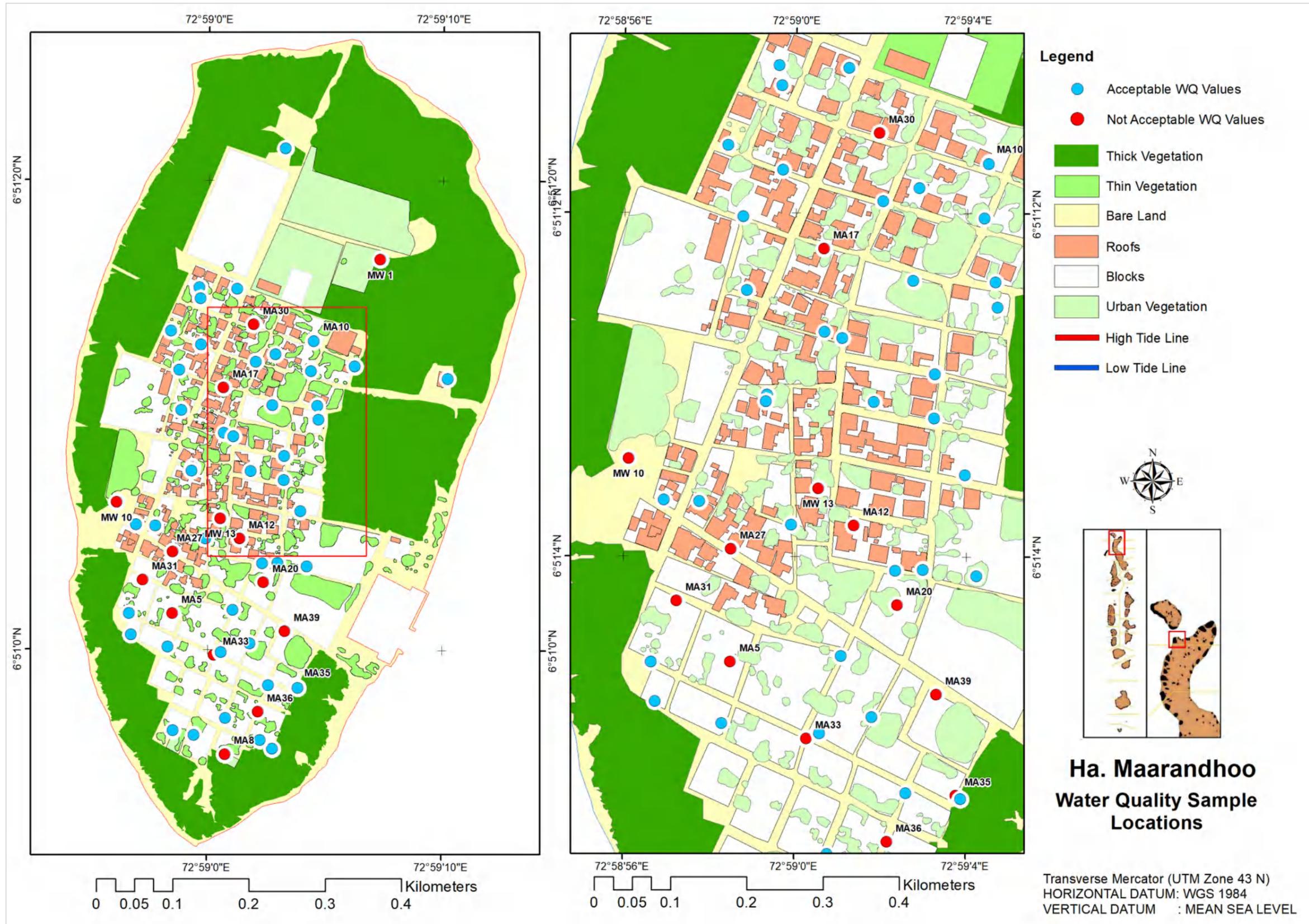


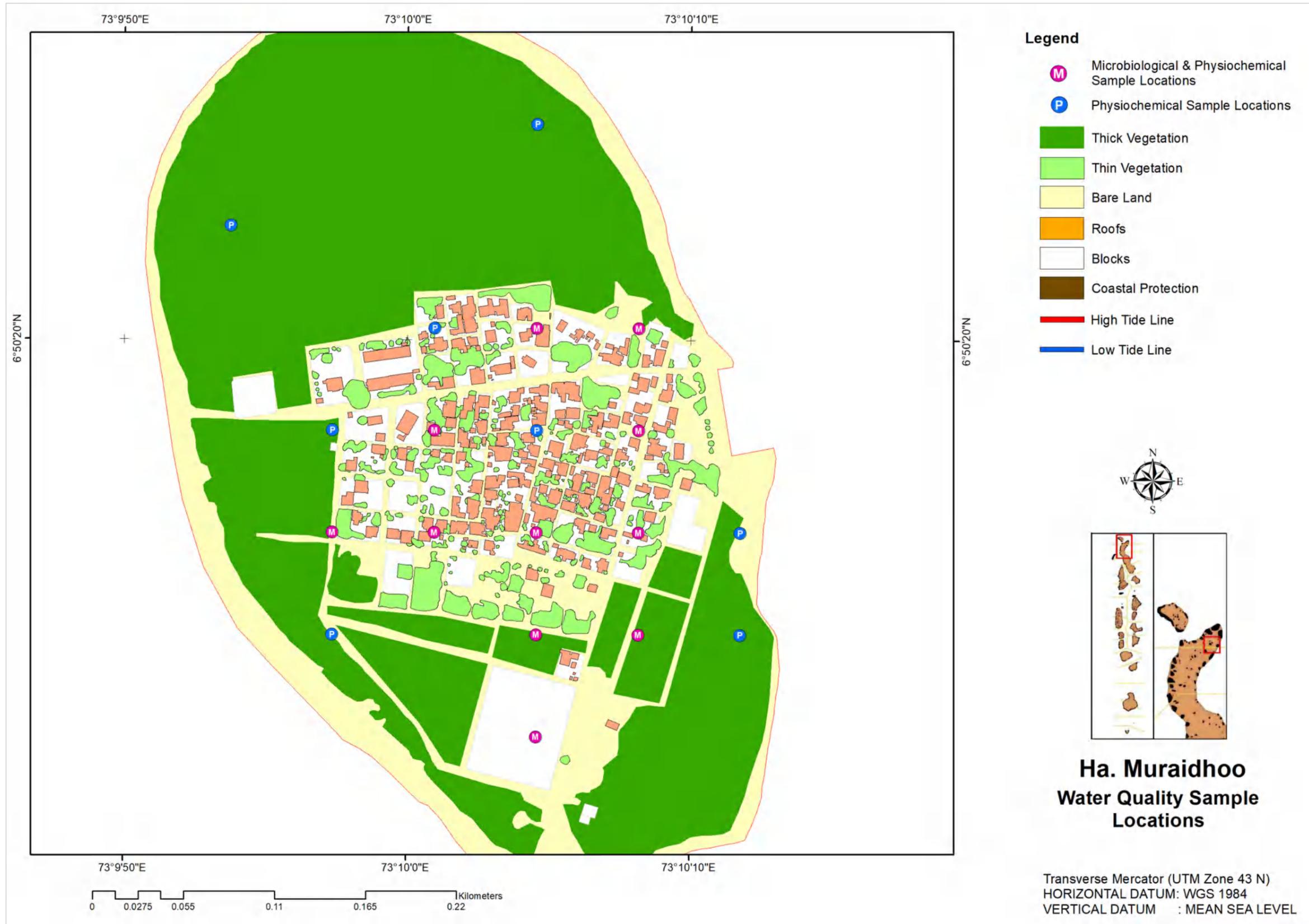
Annex III: Water Quality Sample Locations of the Islands

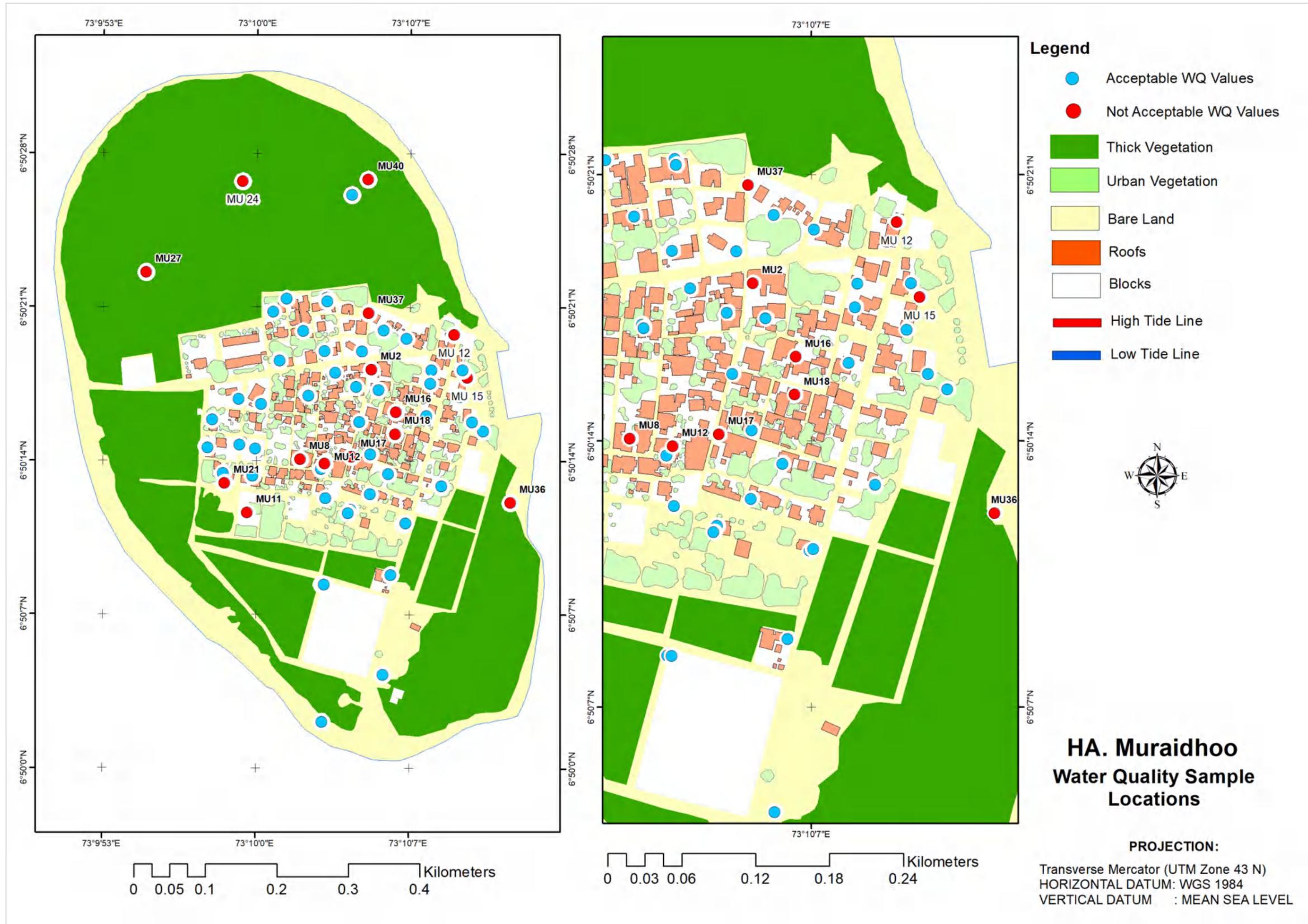


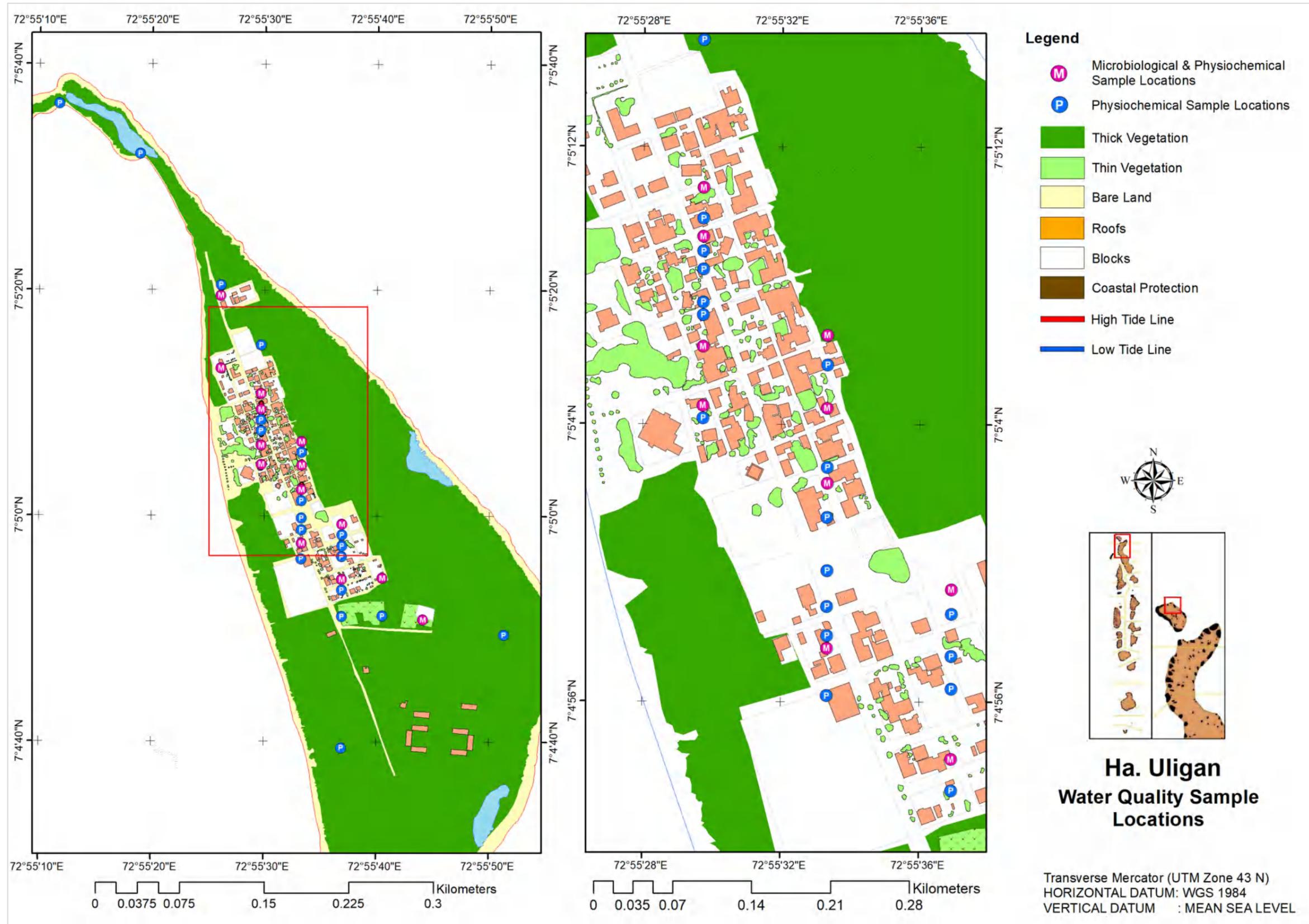


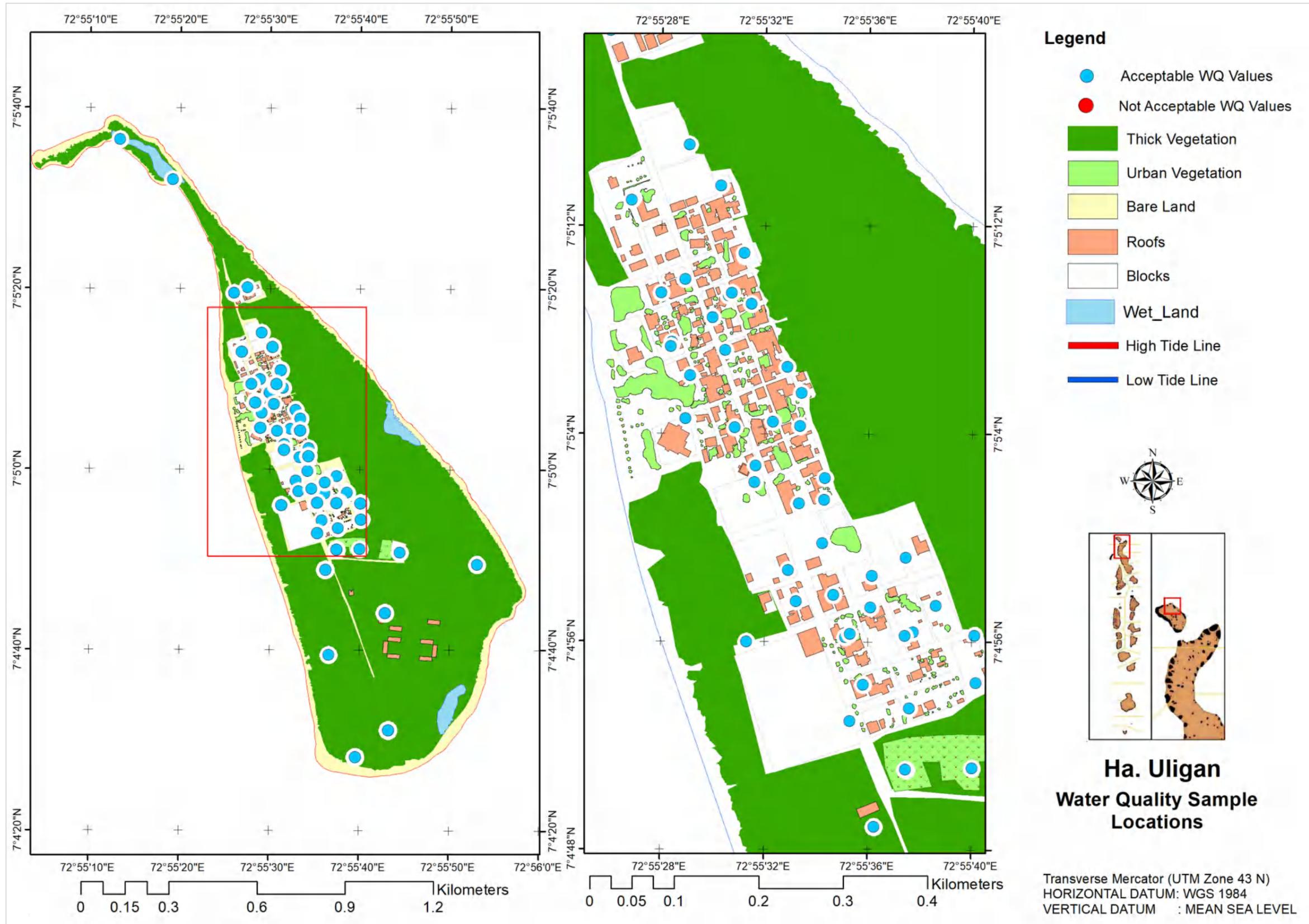




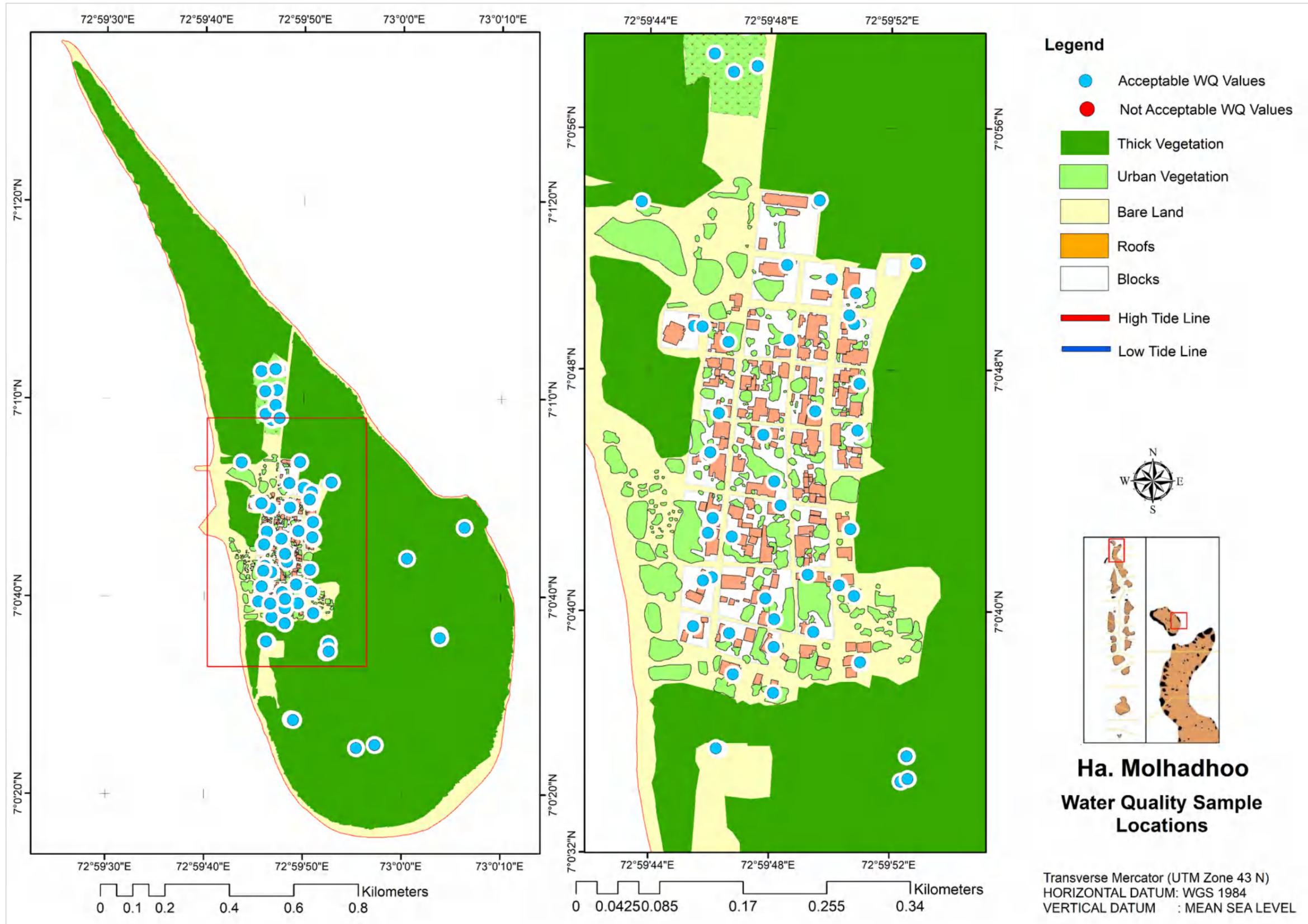




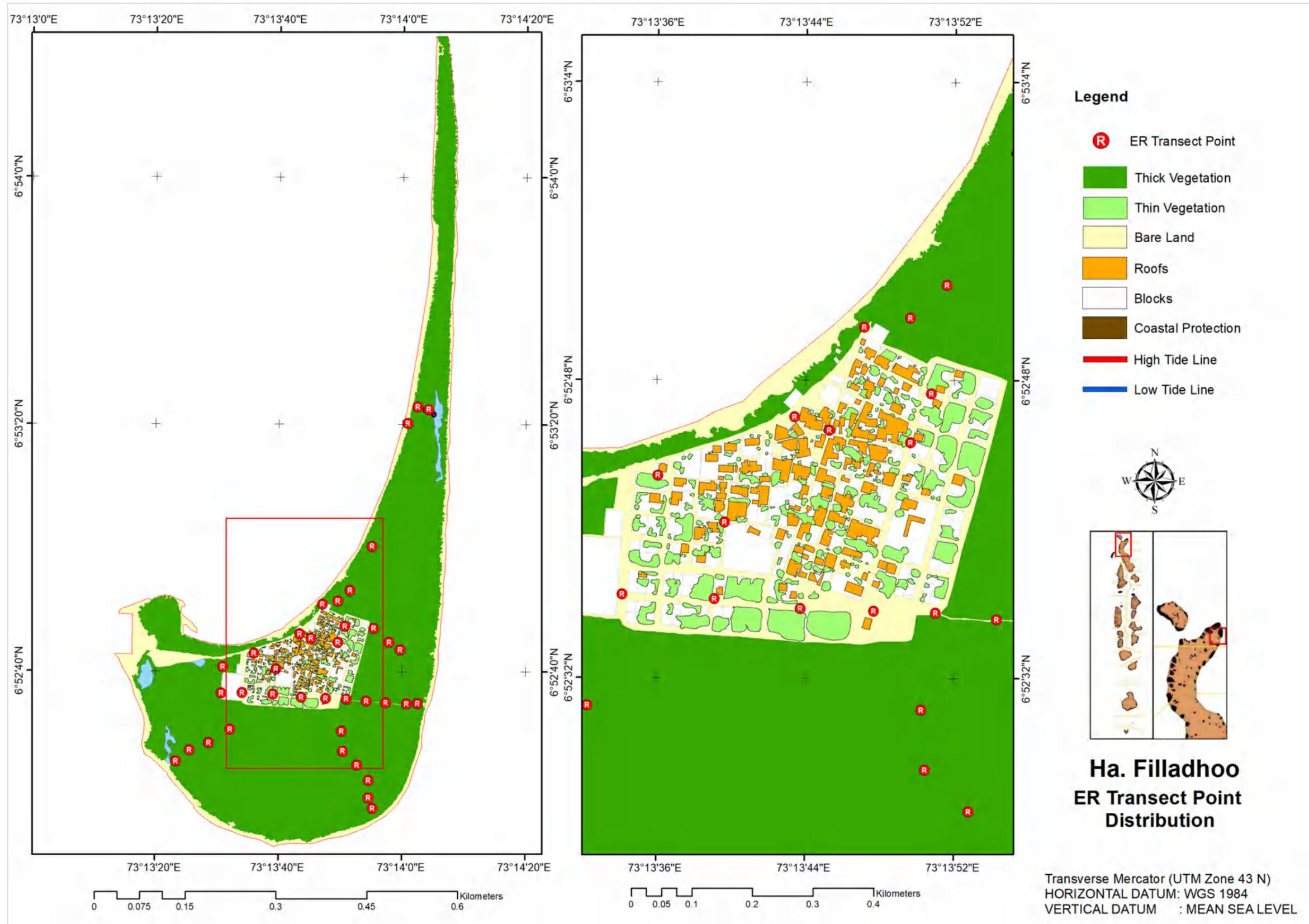


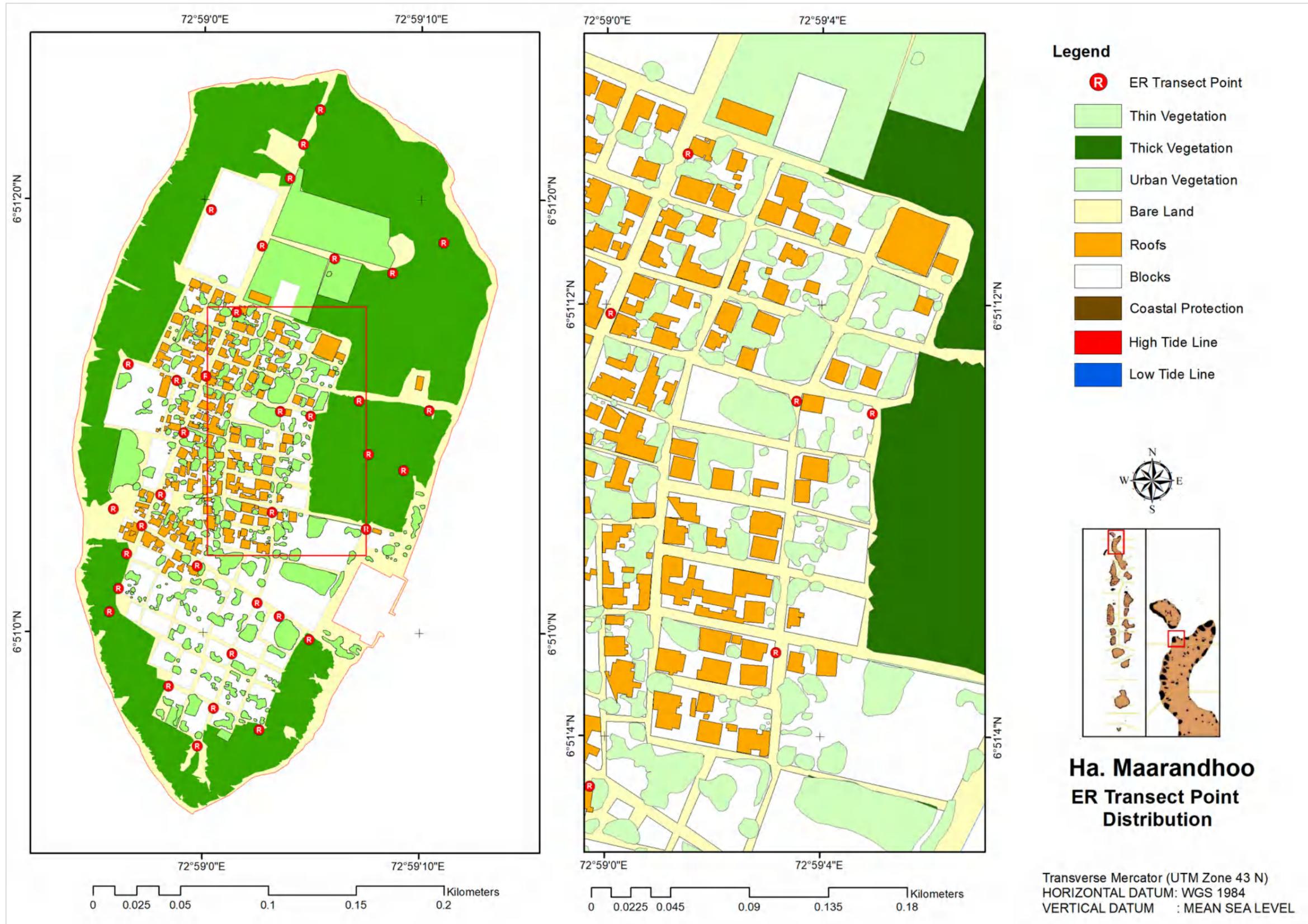


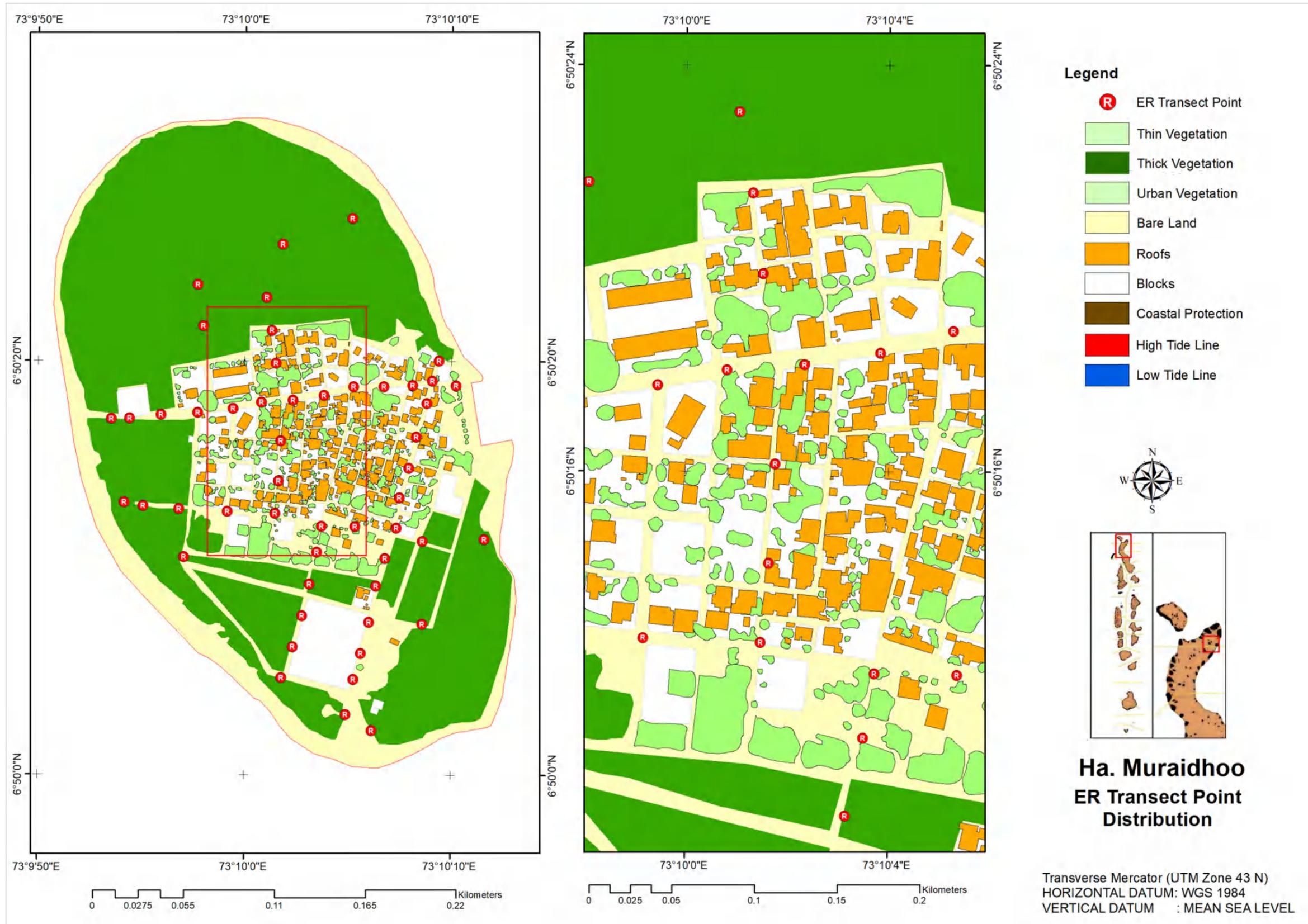




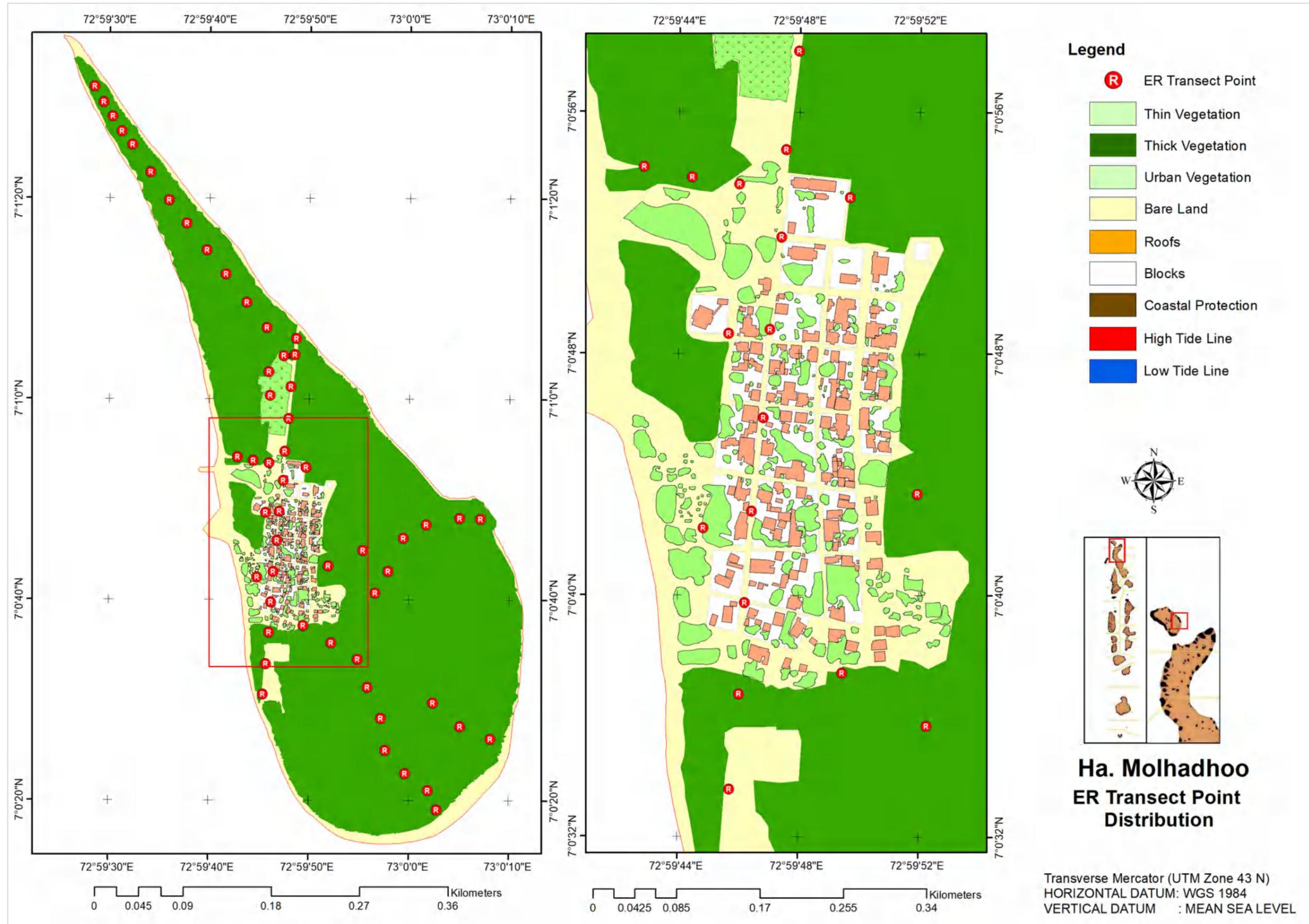
Annex IV: ER Transect Point Locations of the Islands



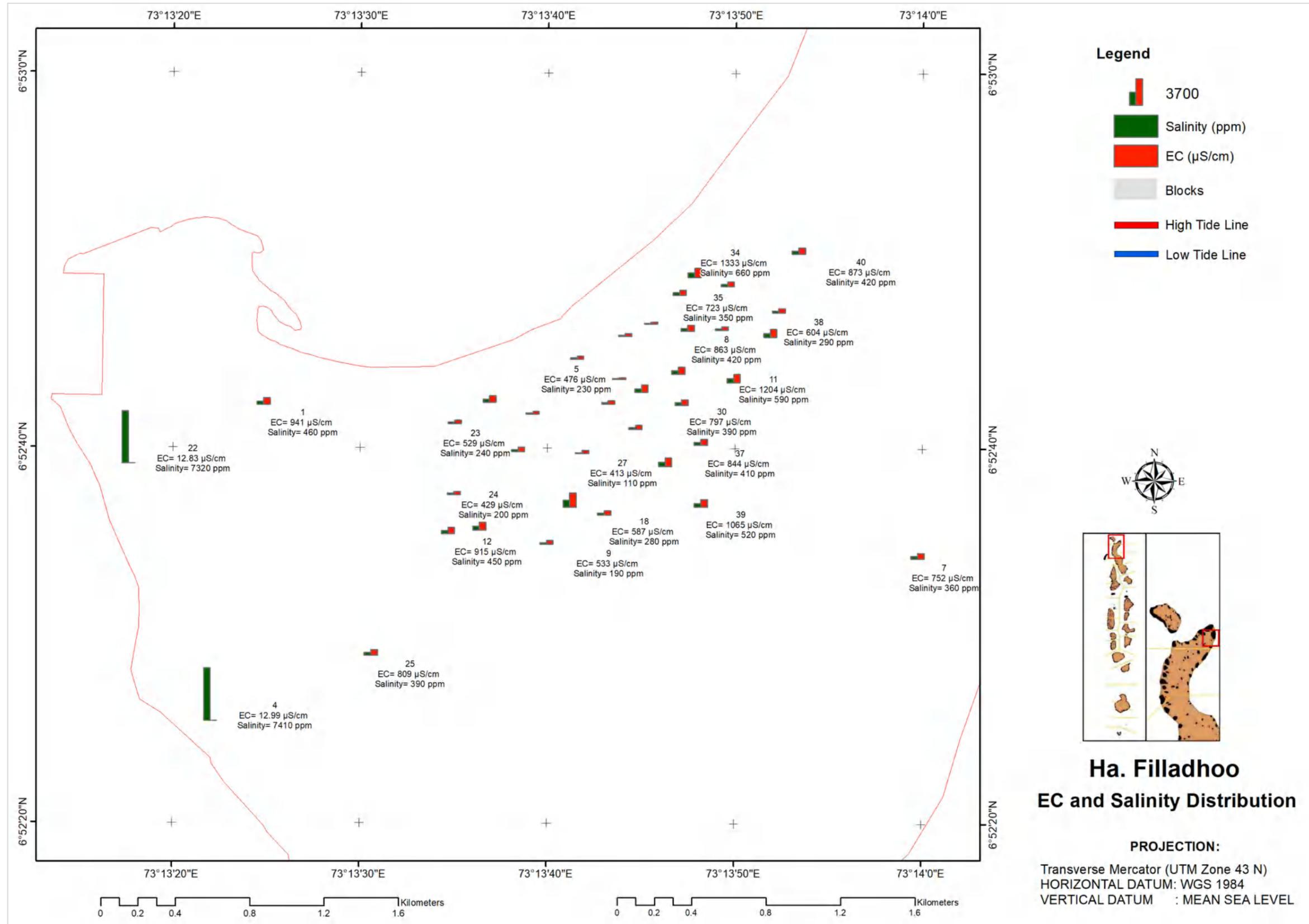


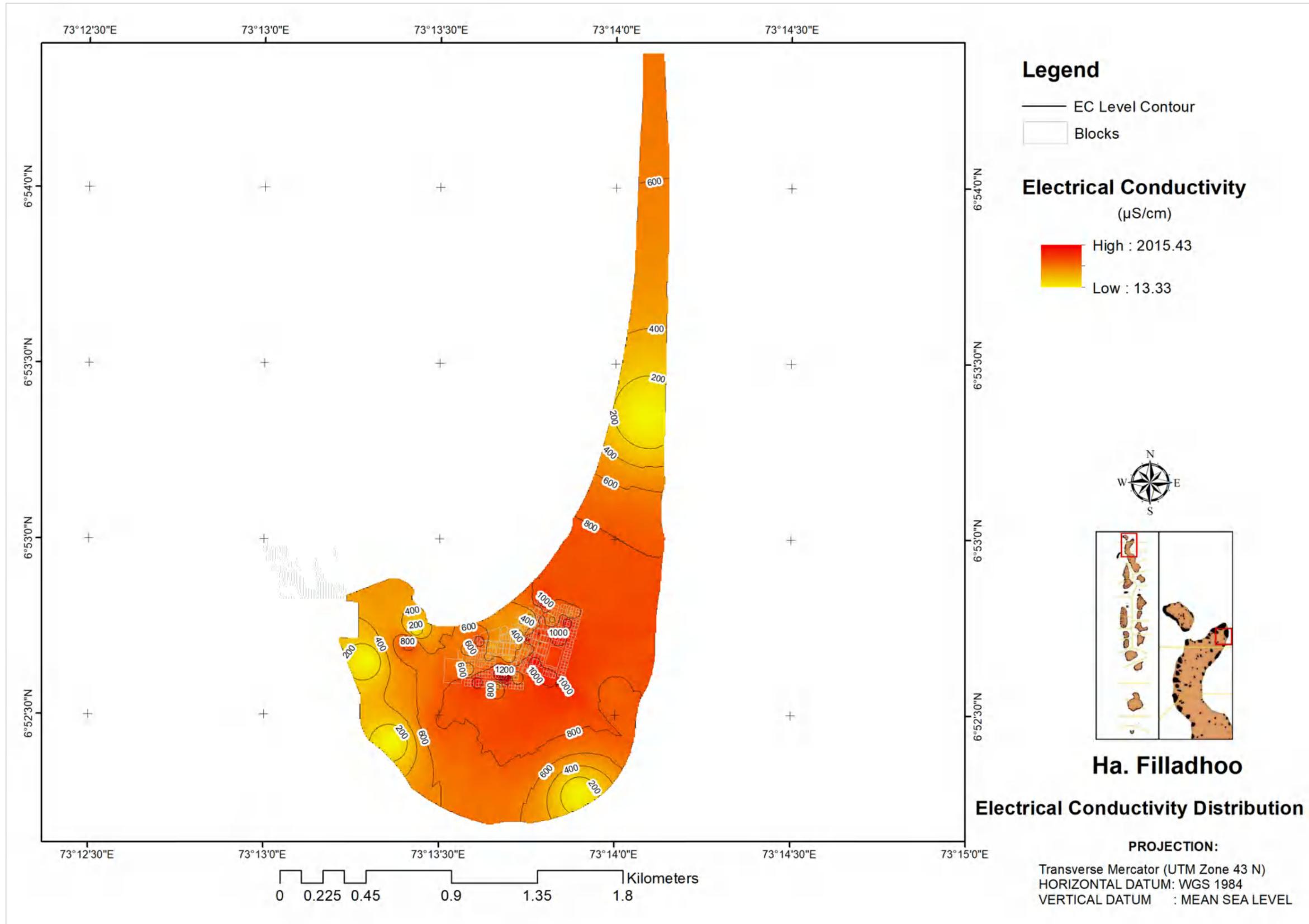


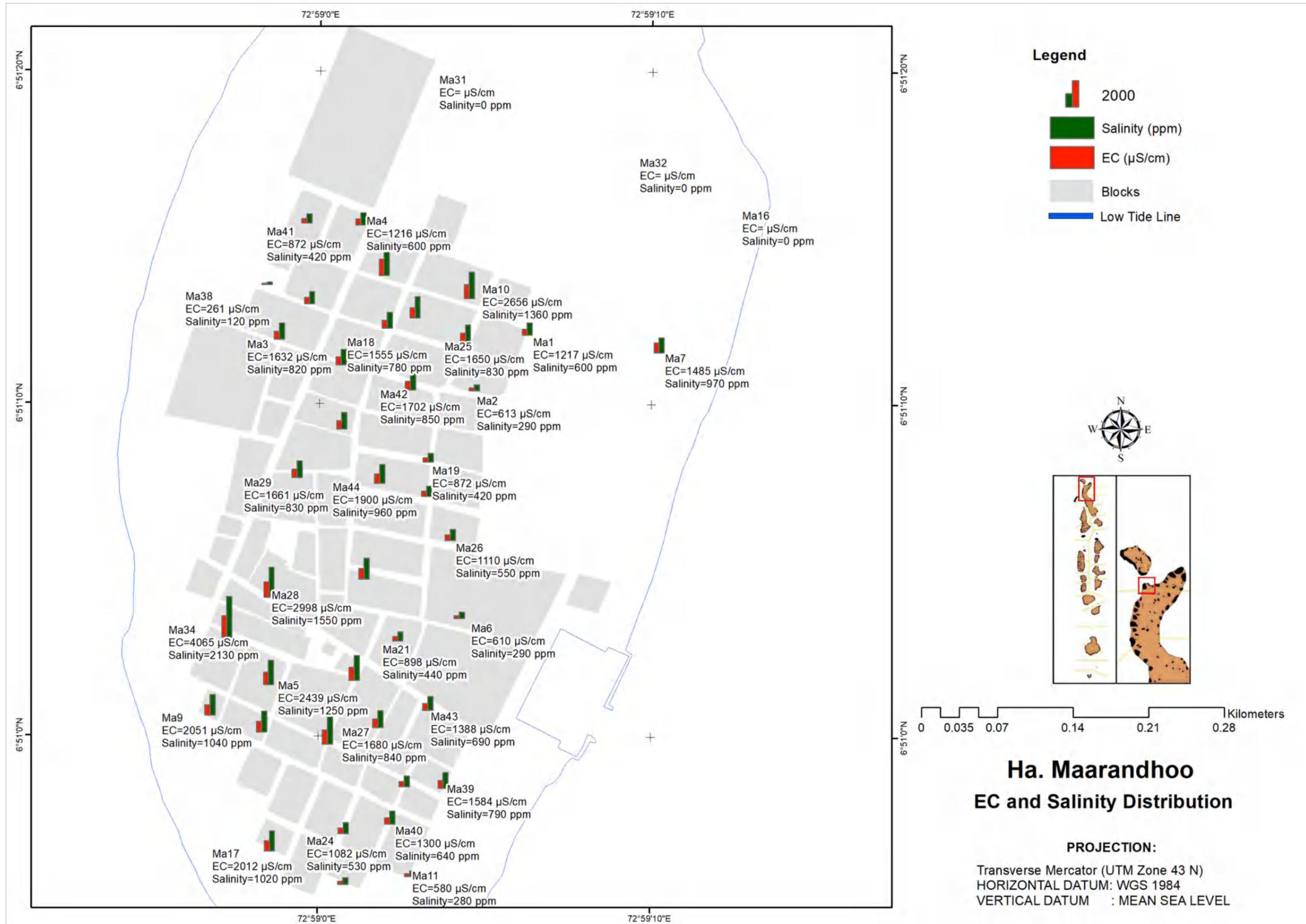


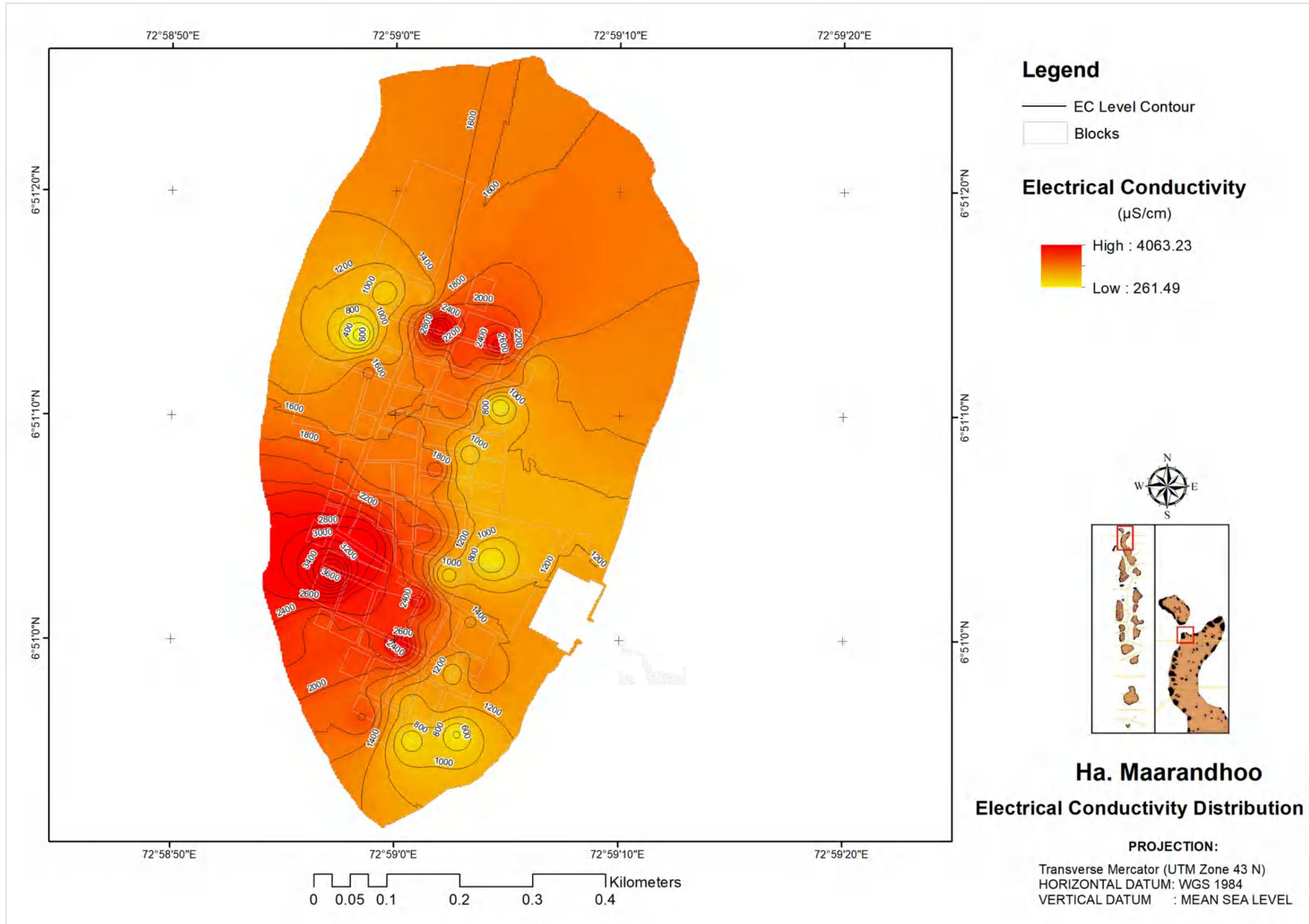


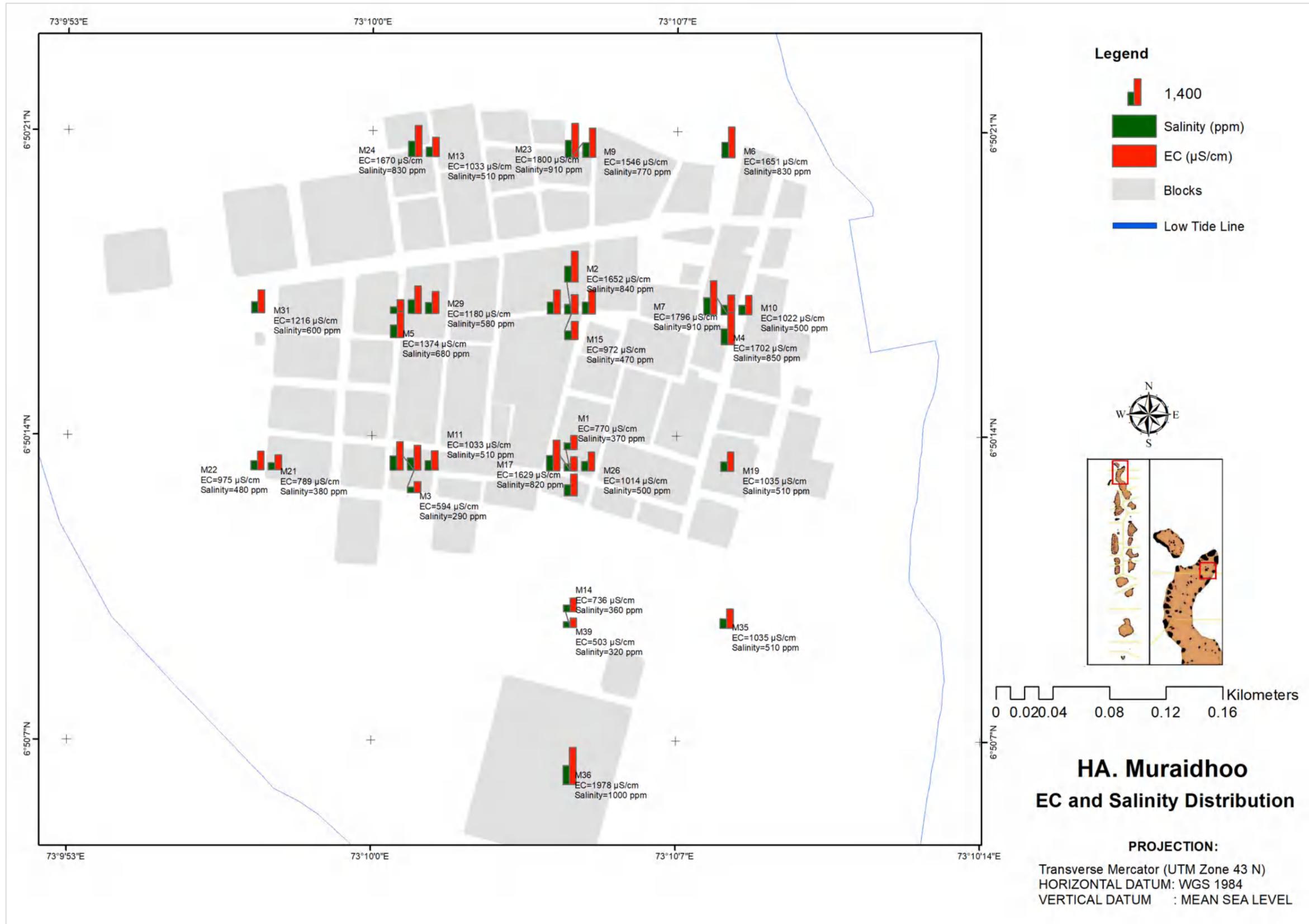
Annex V: EC and Salinity Distribution of the Islands

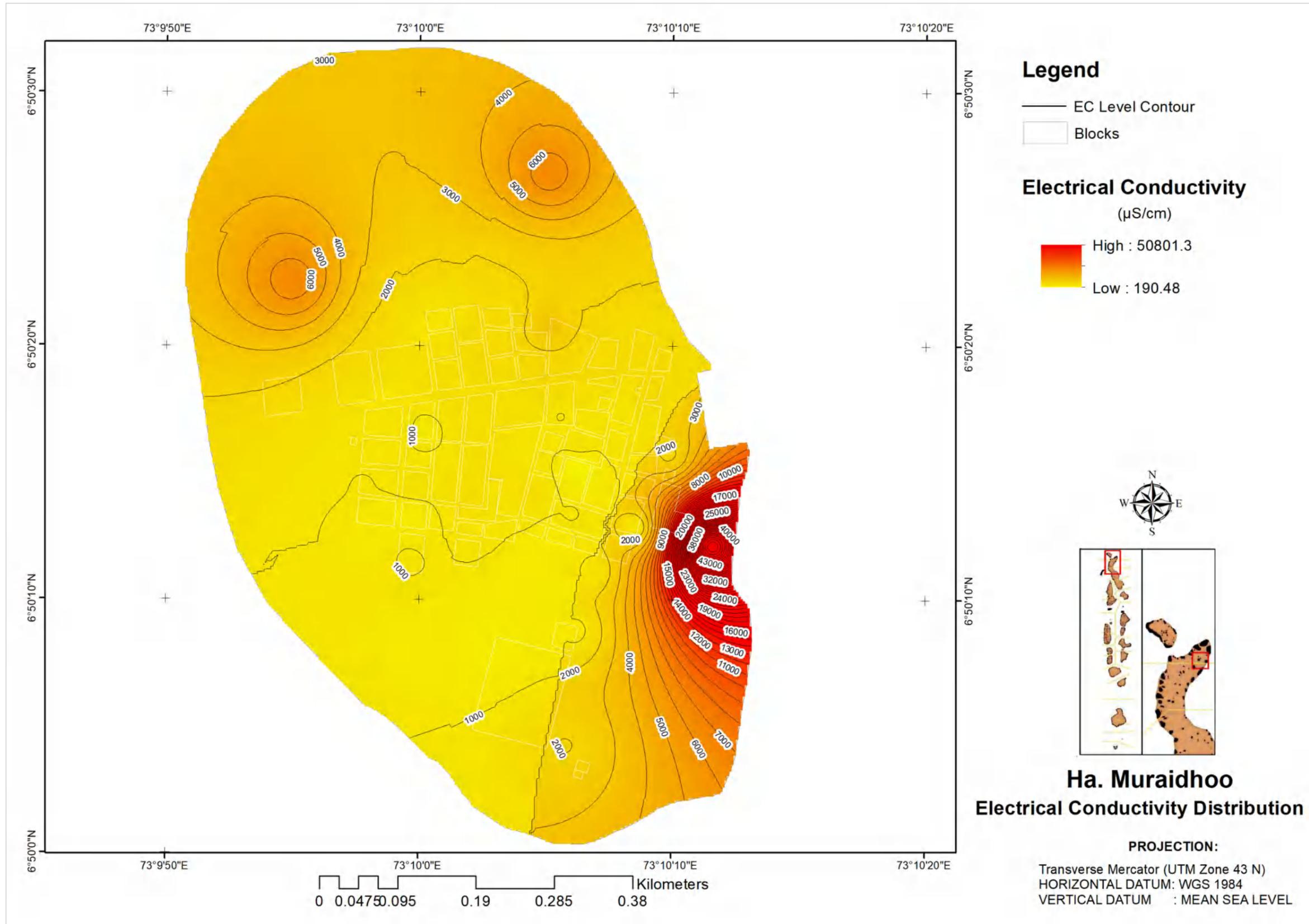


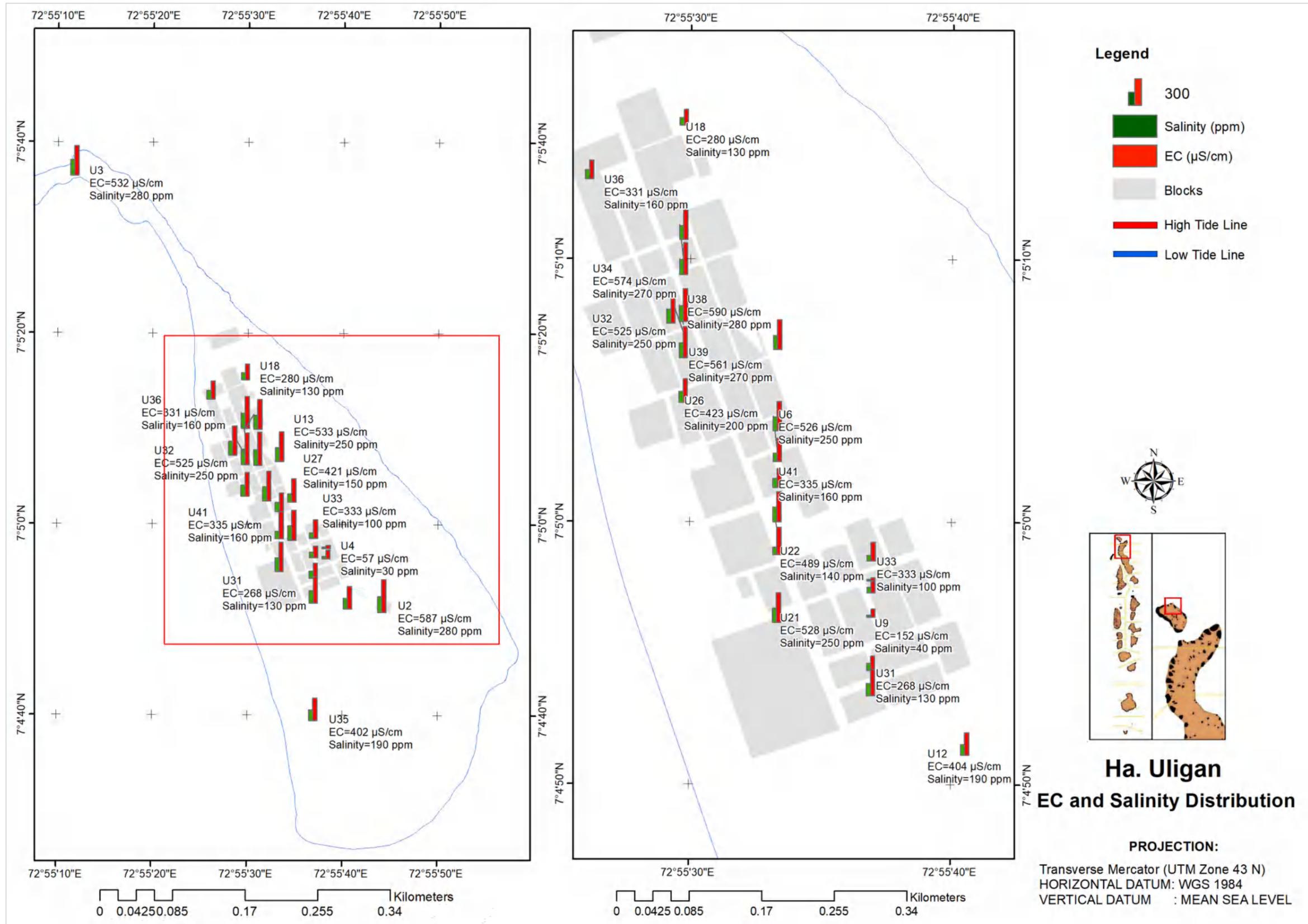


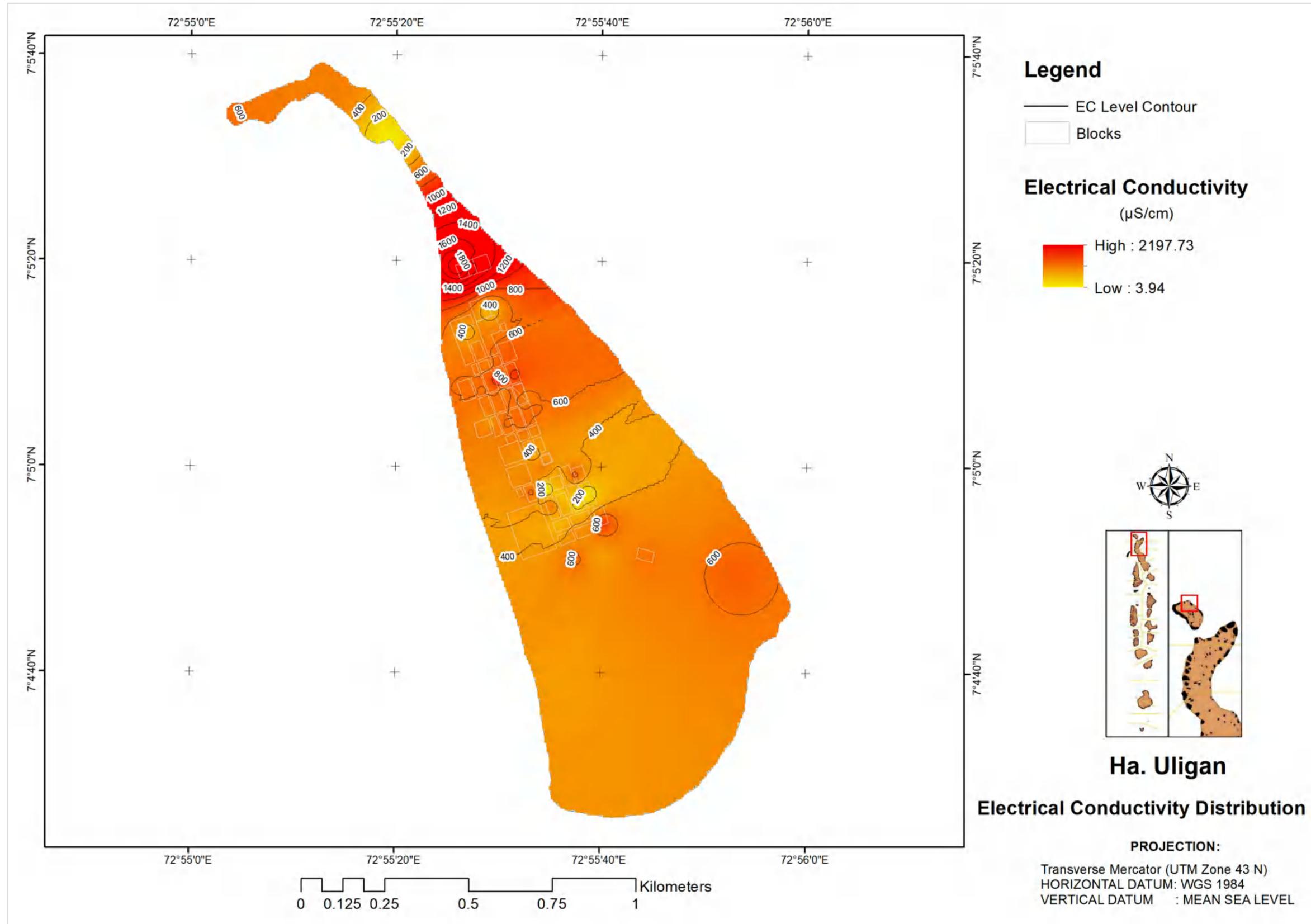


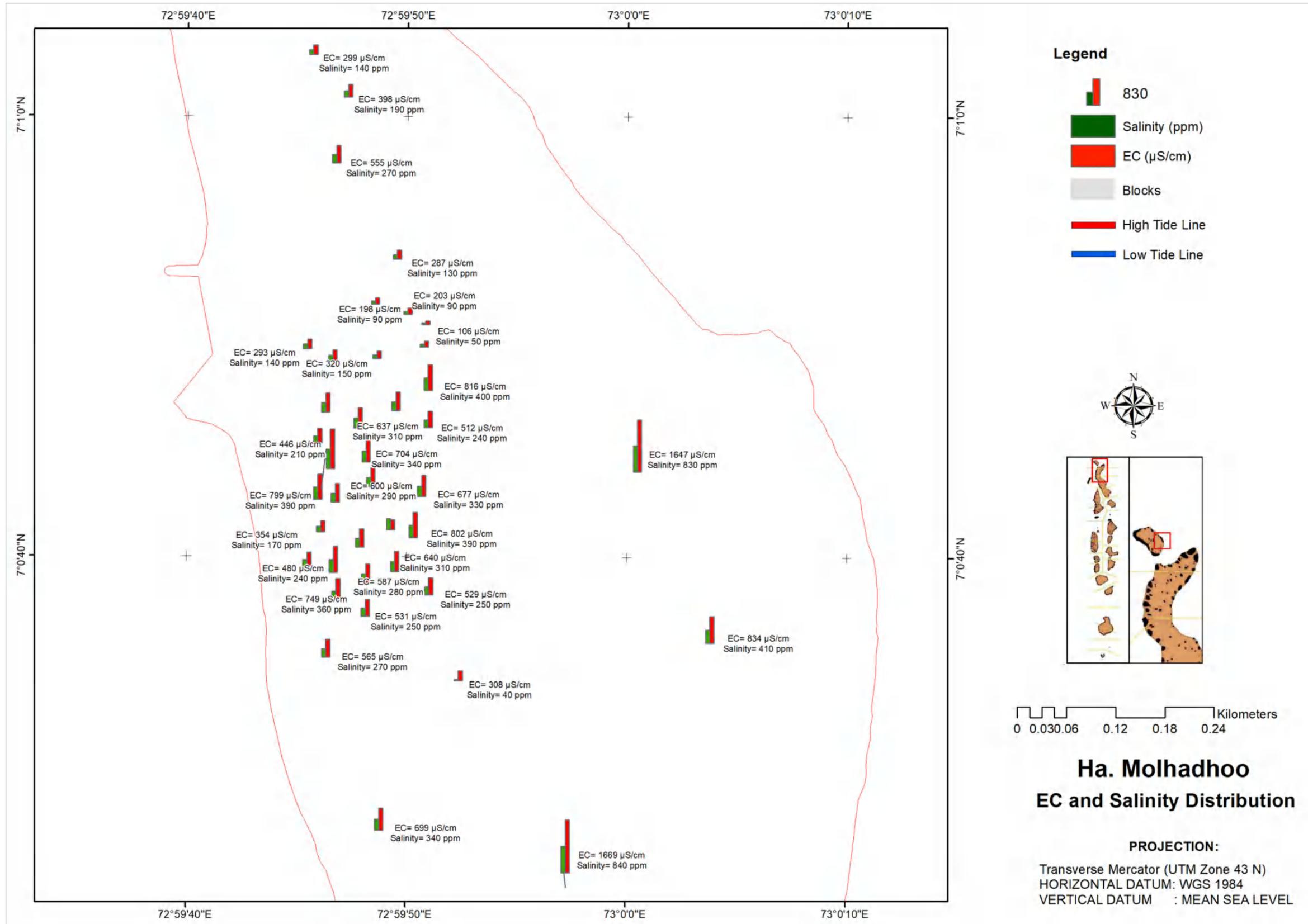


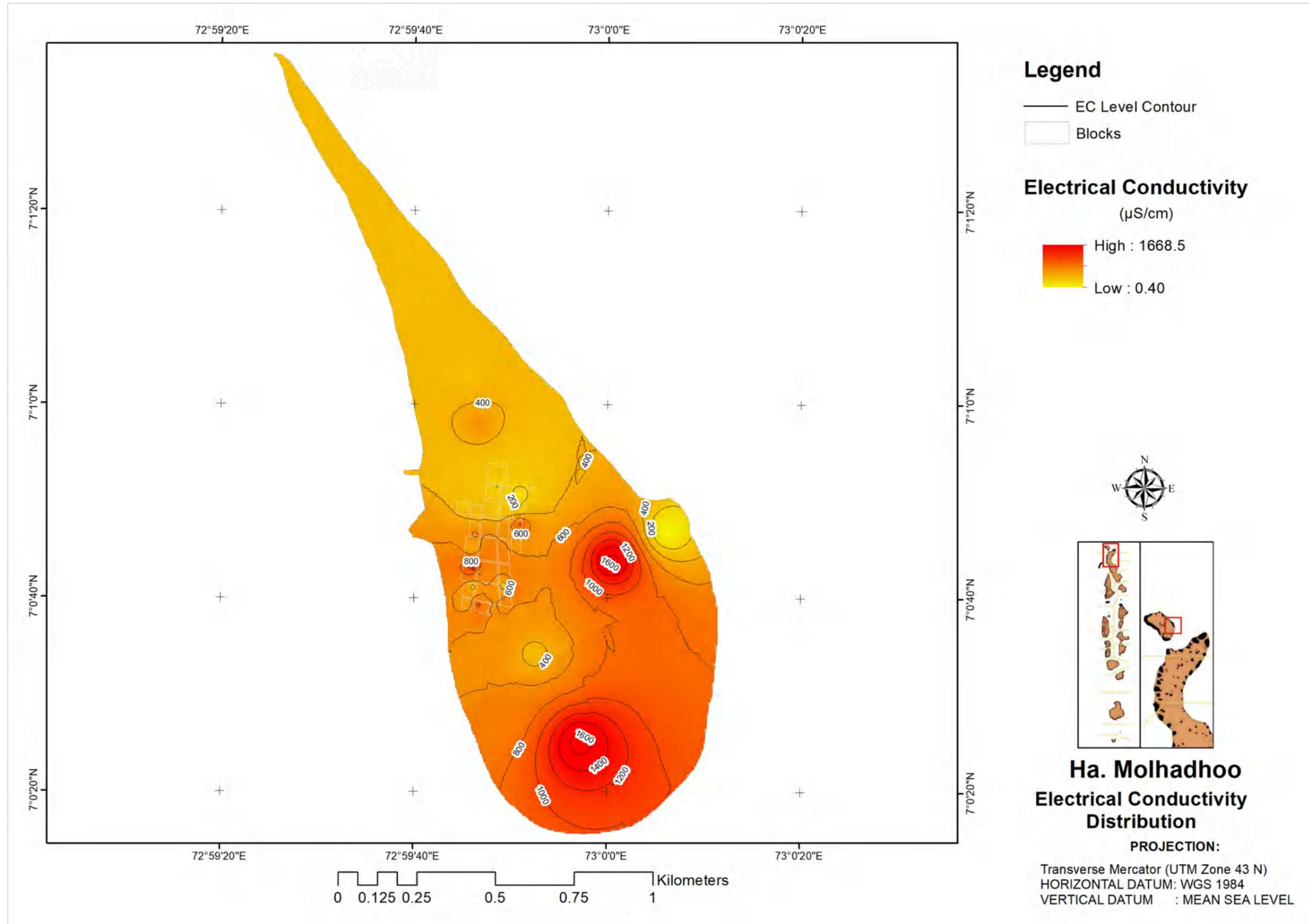




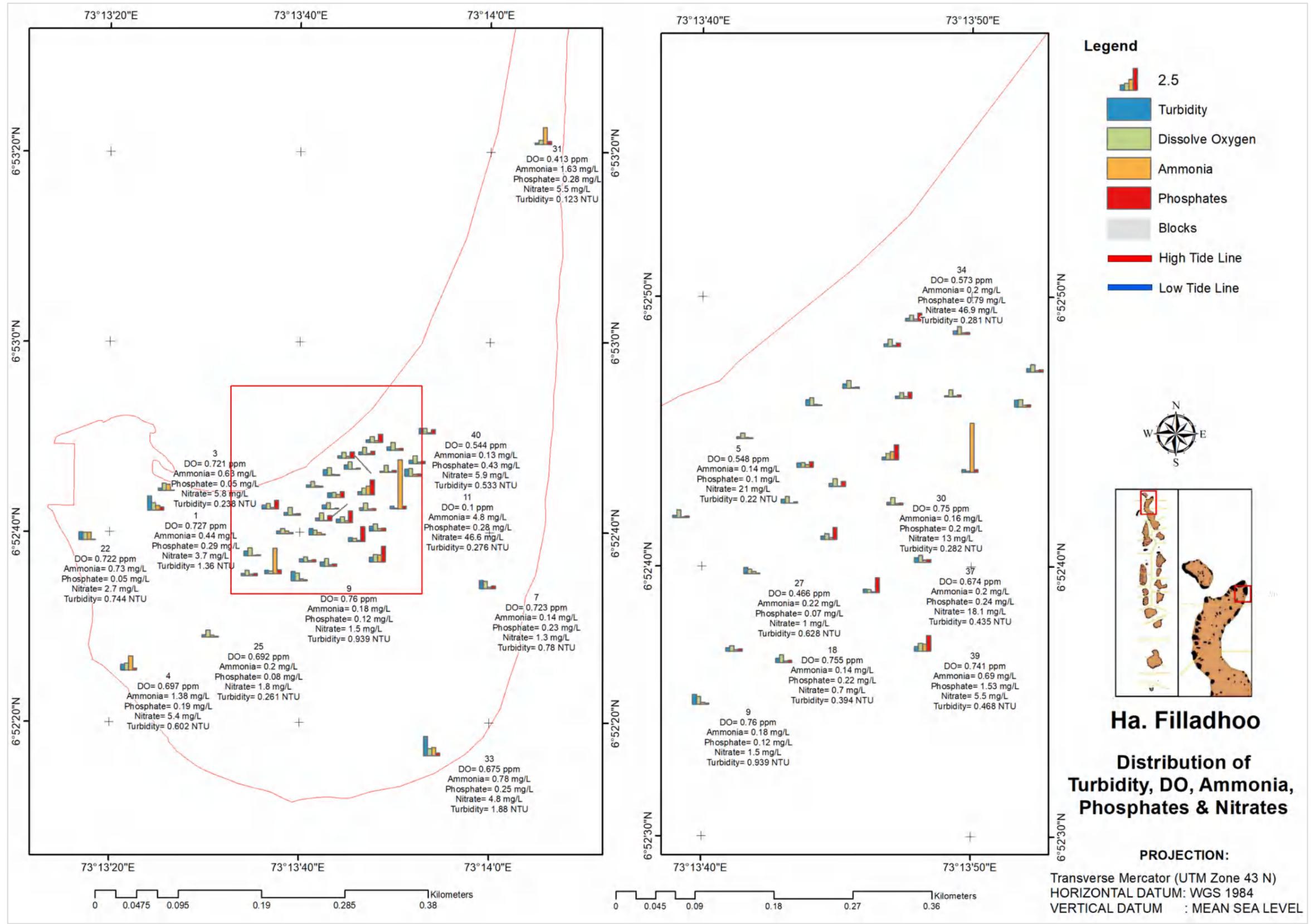


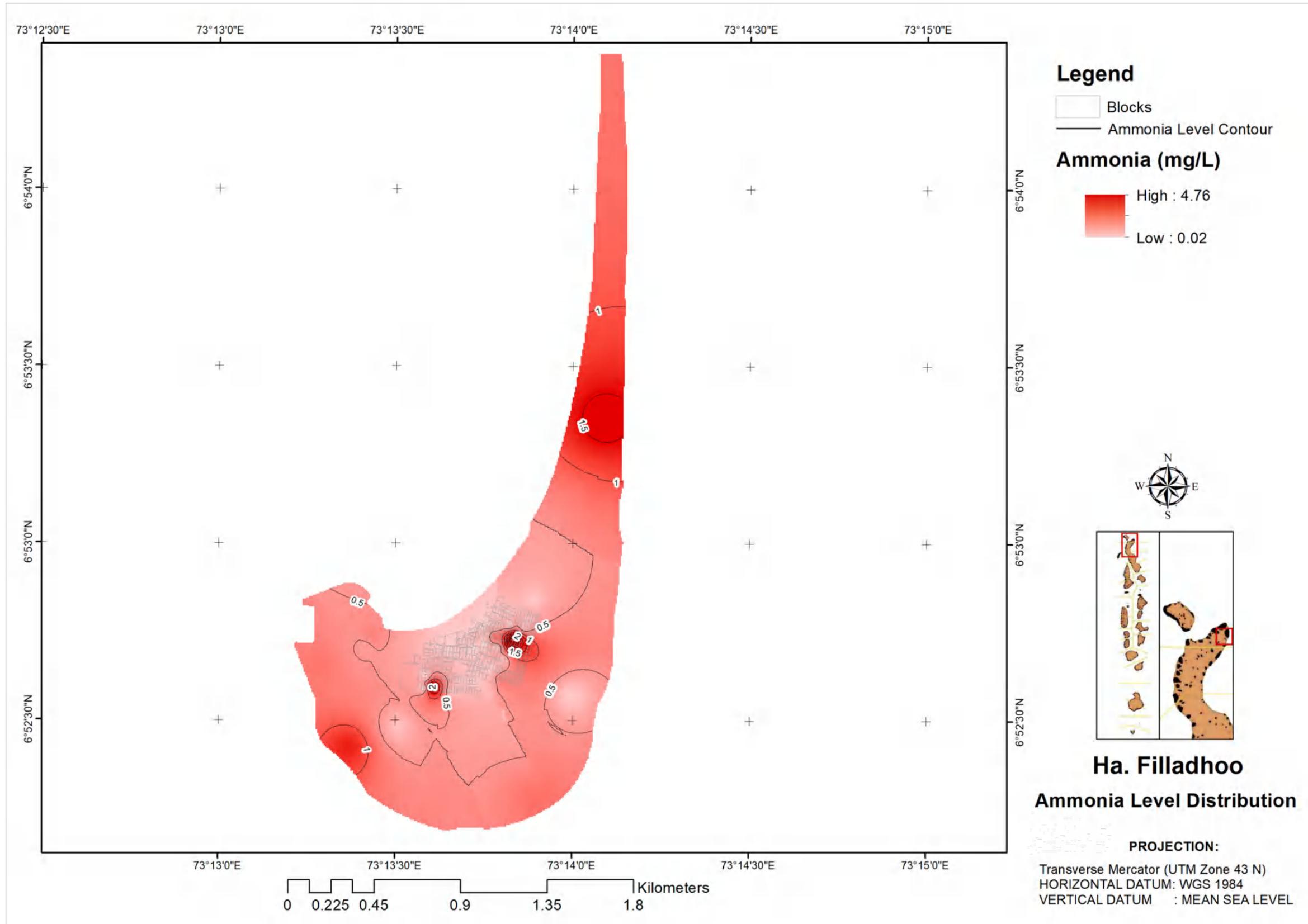


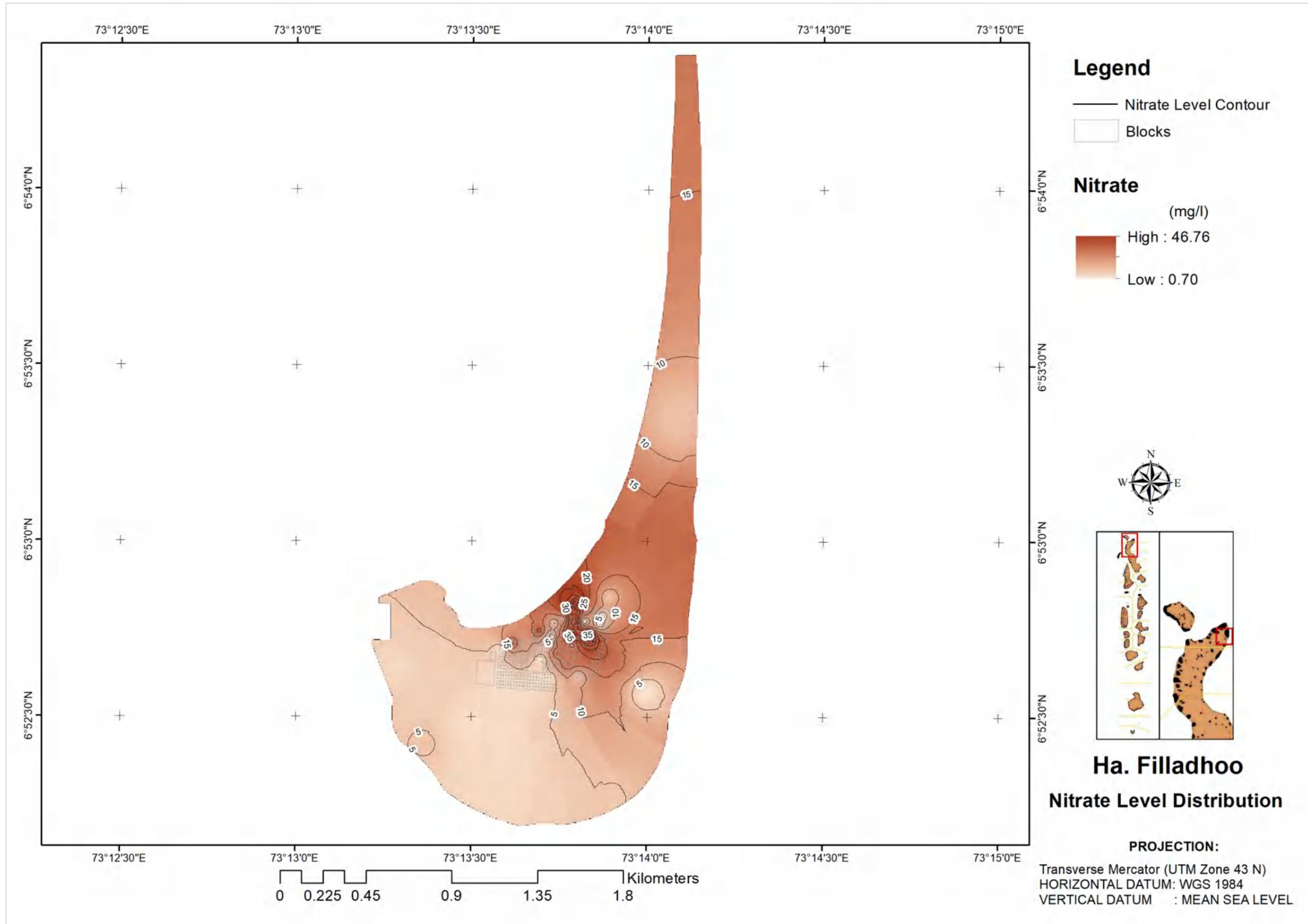


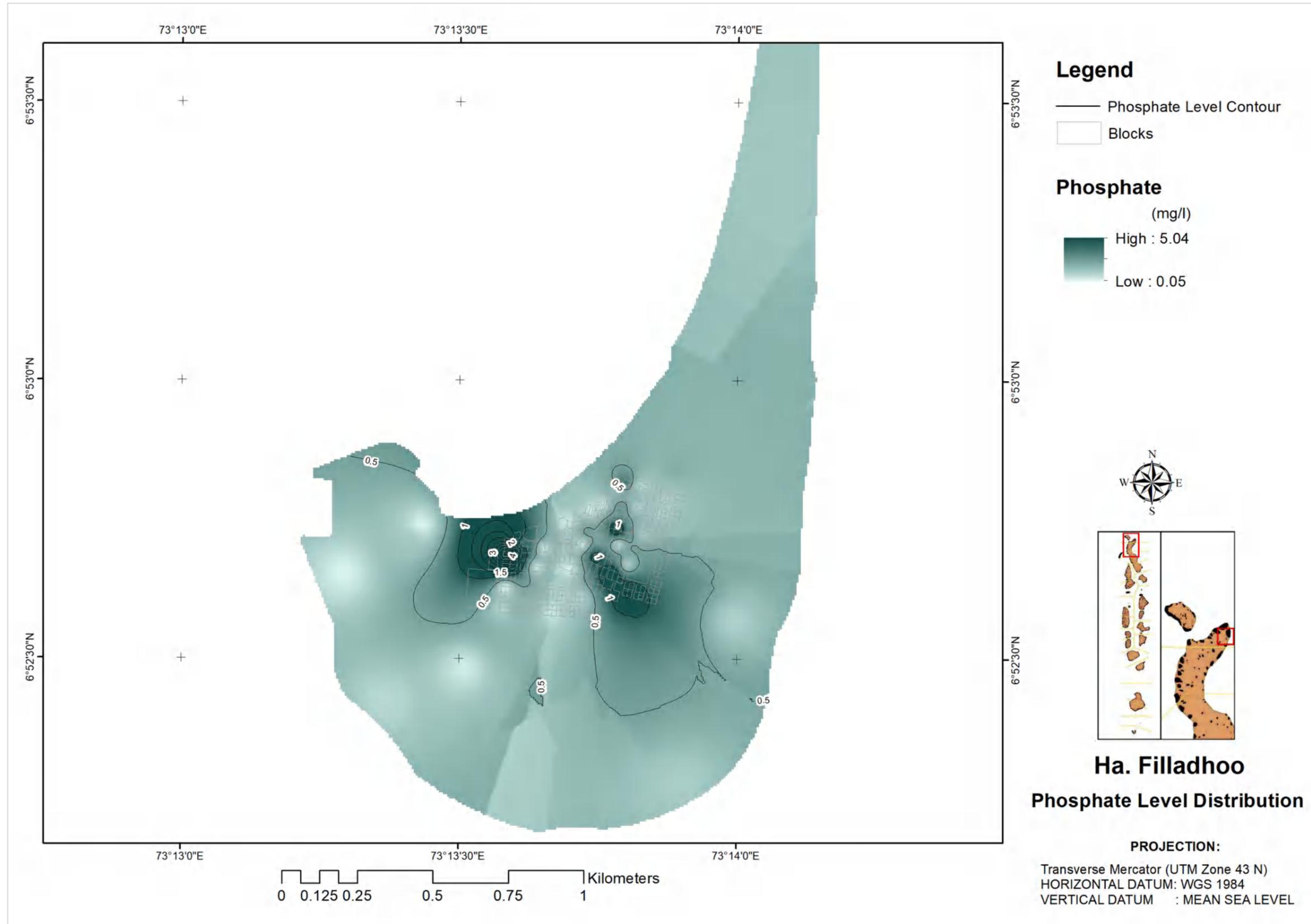


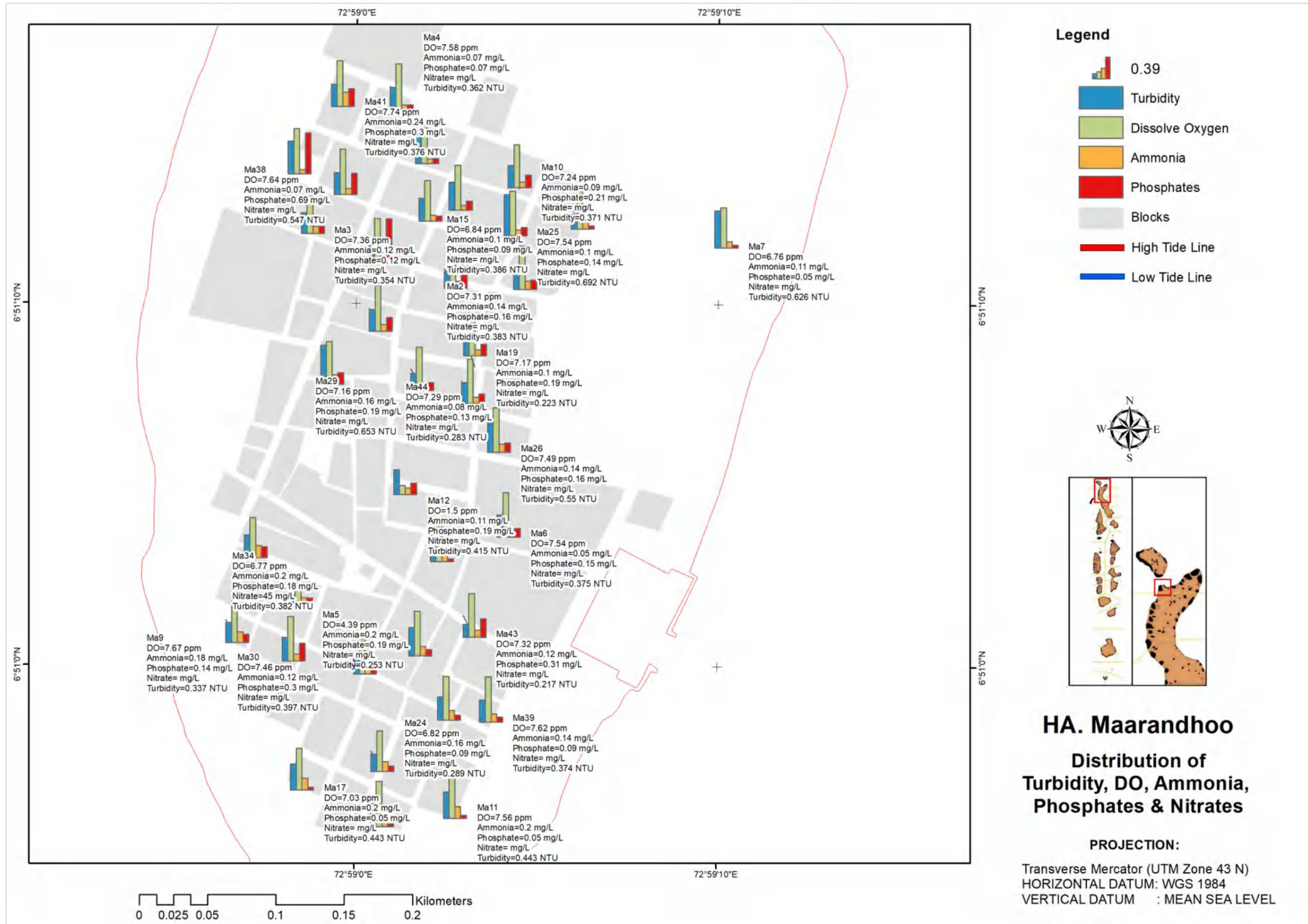
Annex VI: Distribution of Turbidity, DO, Ammonia, Phosphates & Nitrates in the Islands

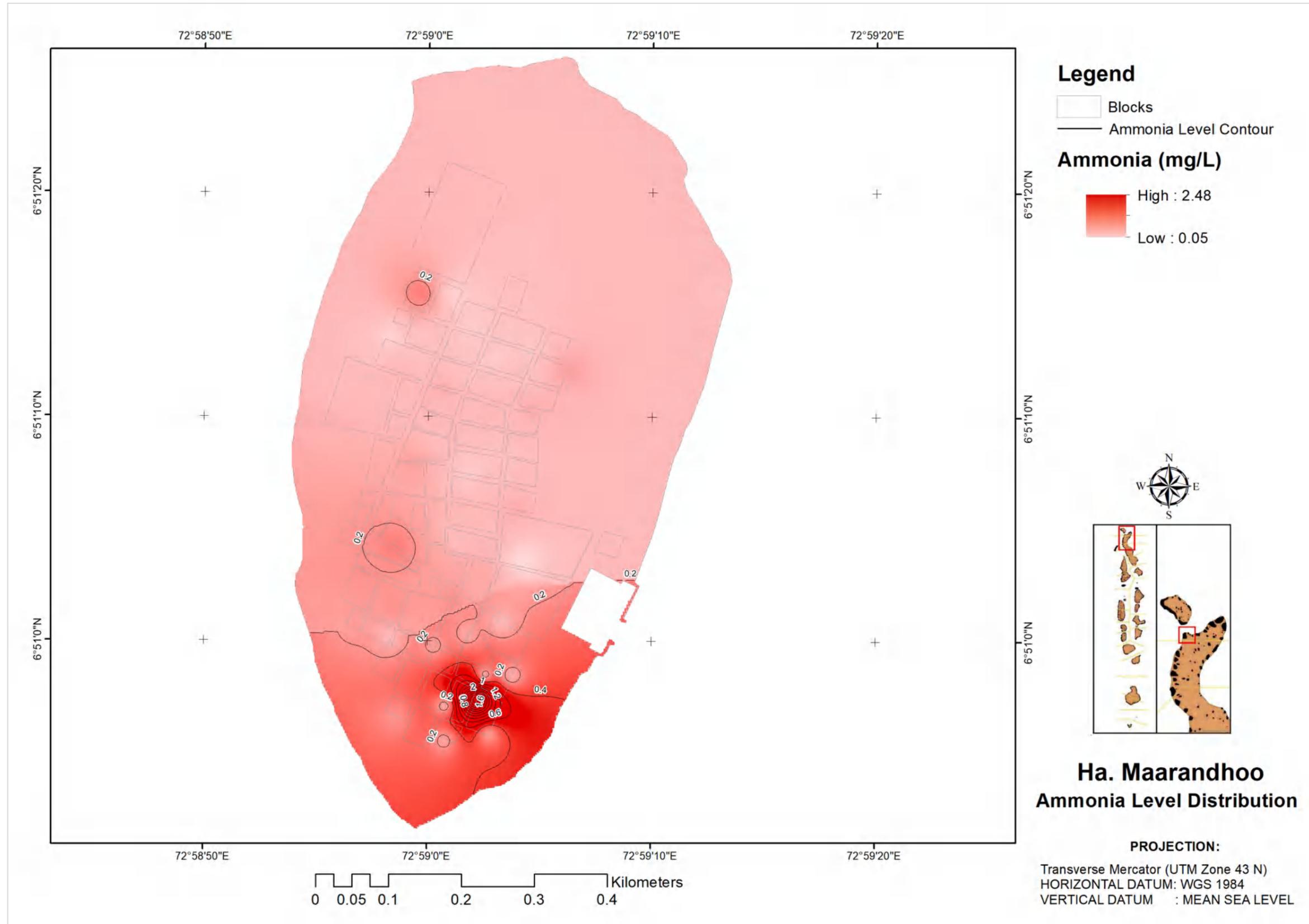


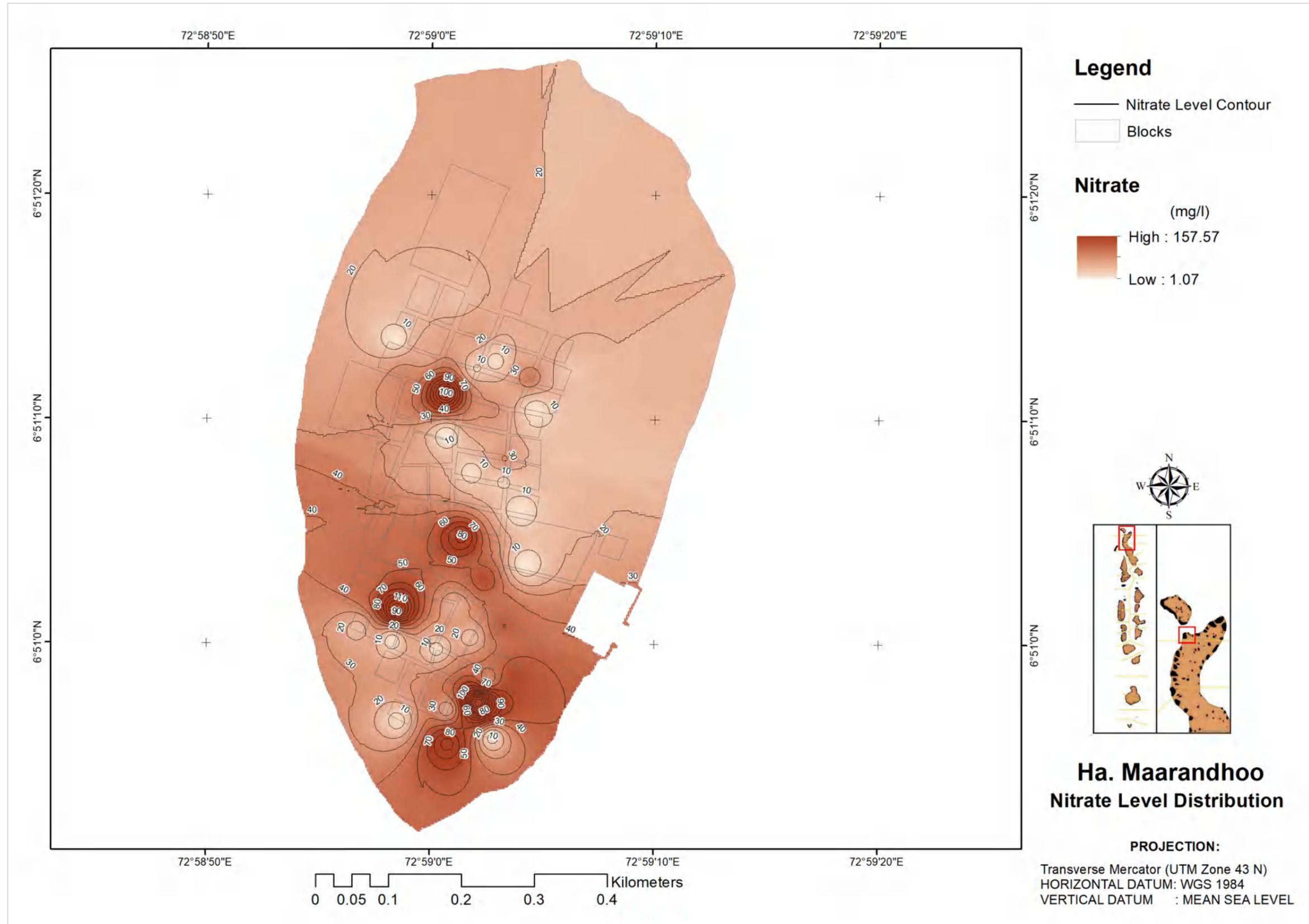


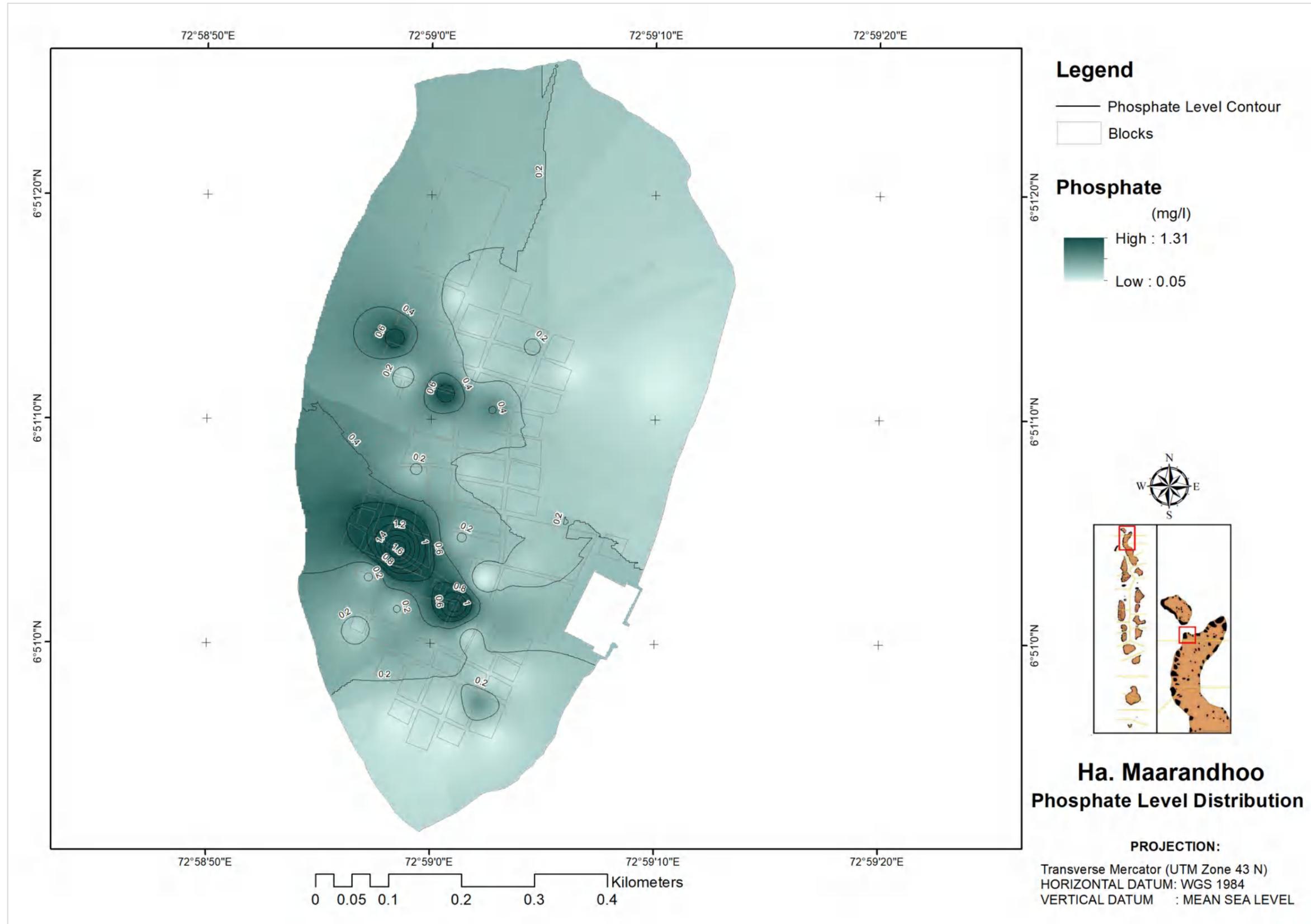


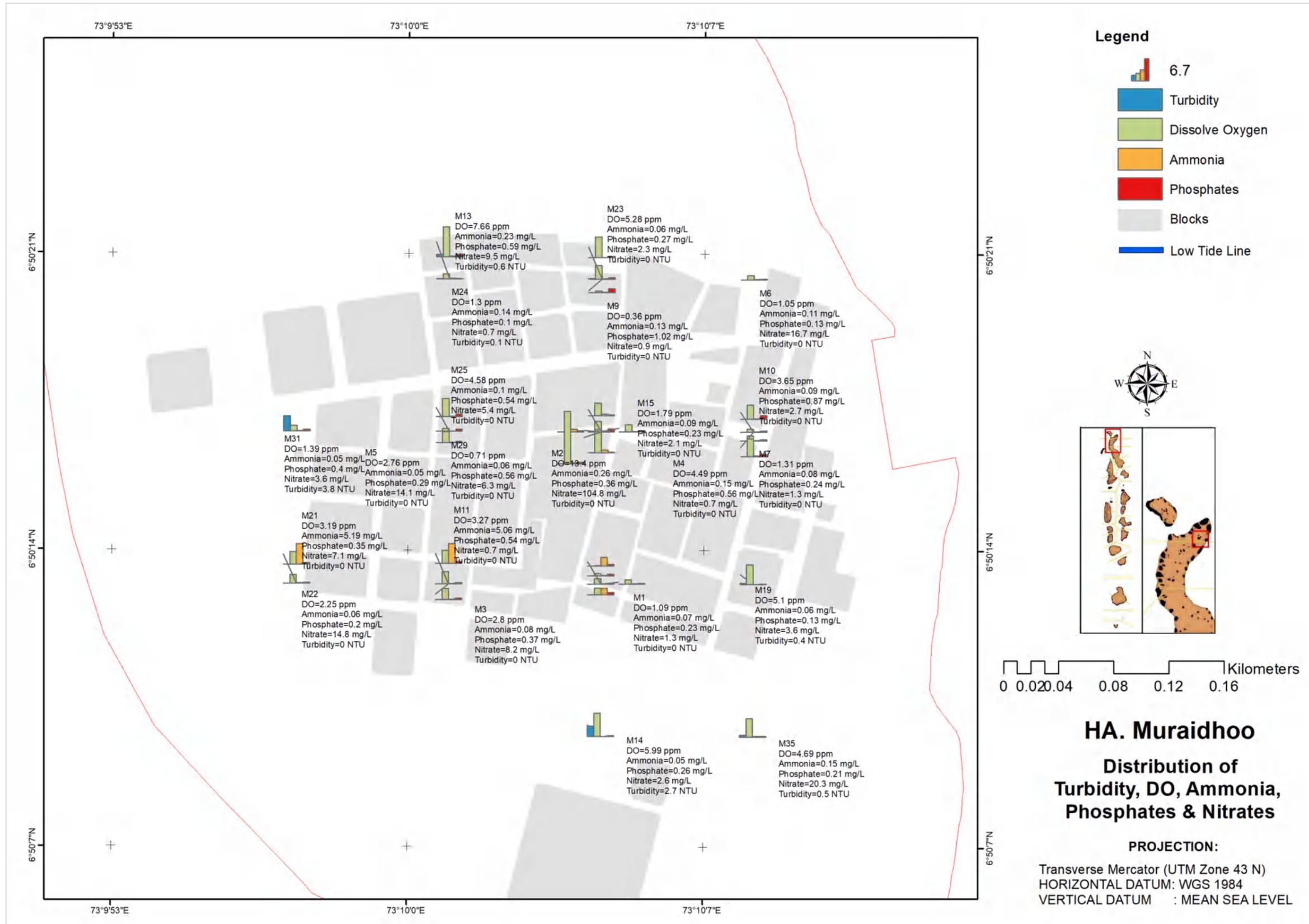


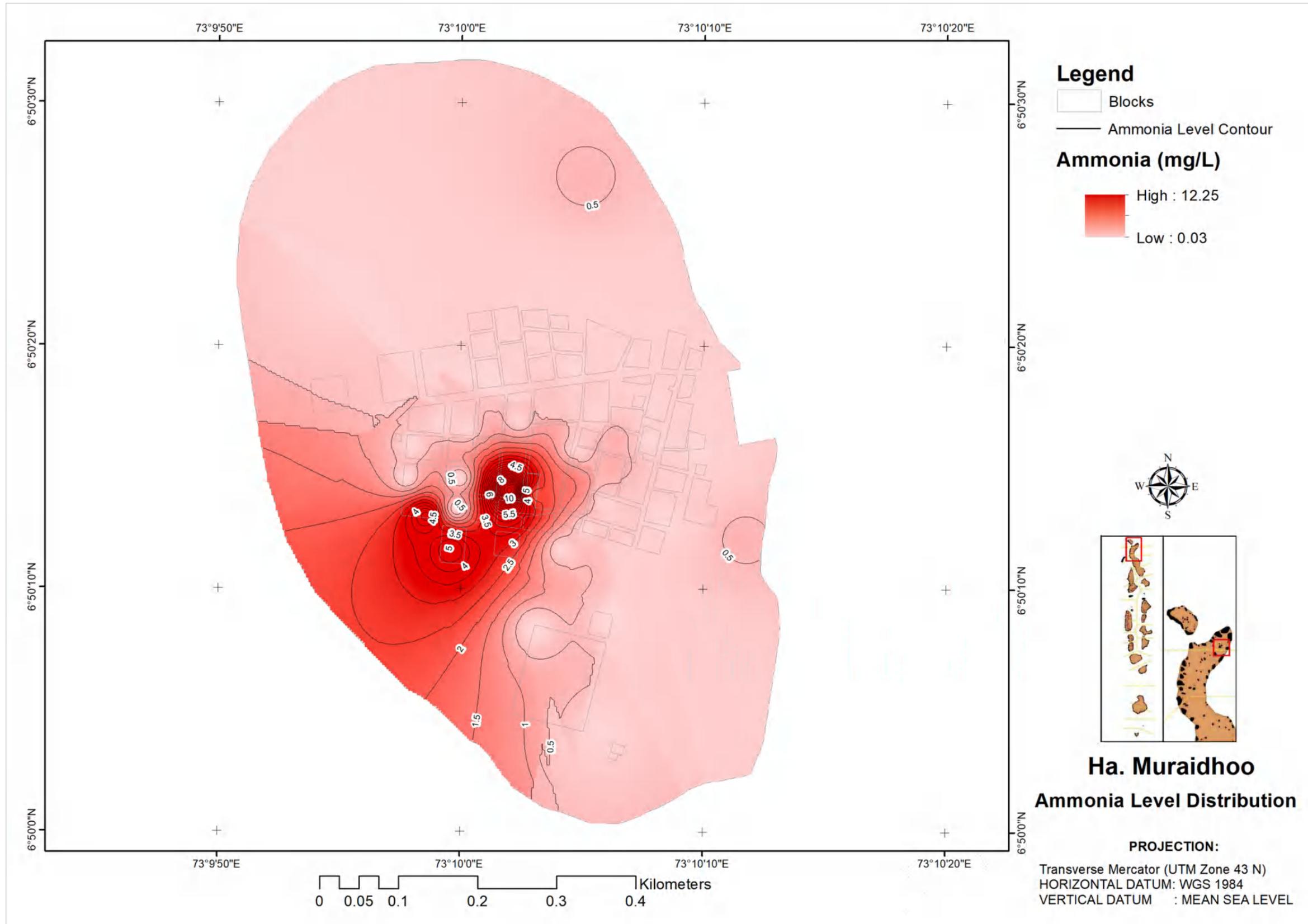


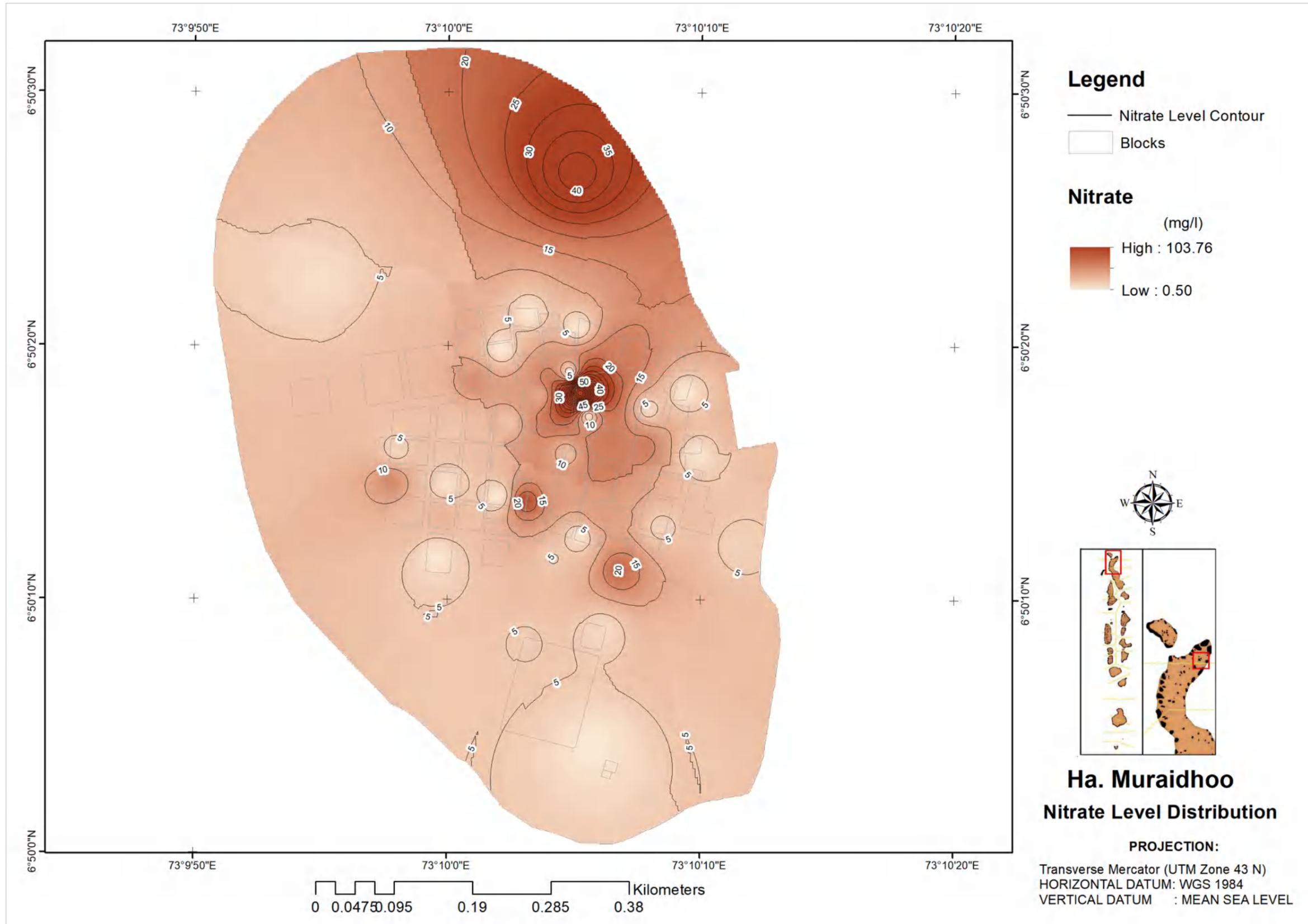


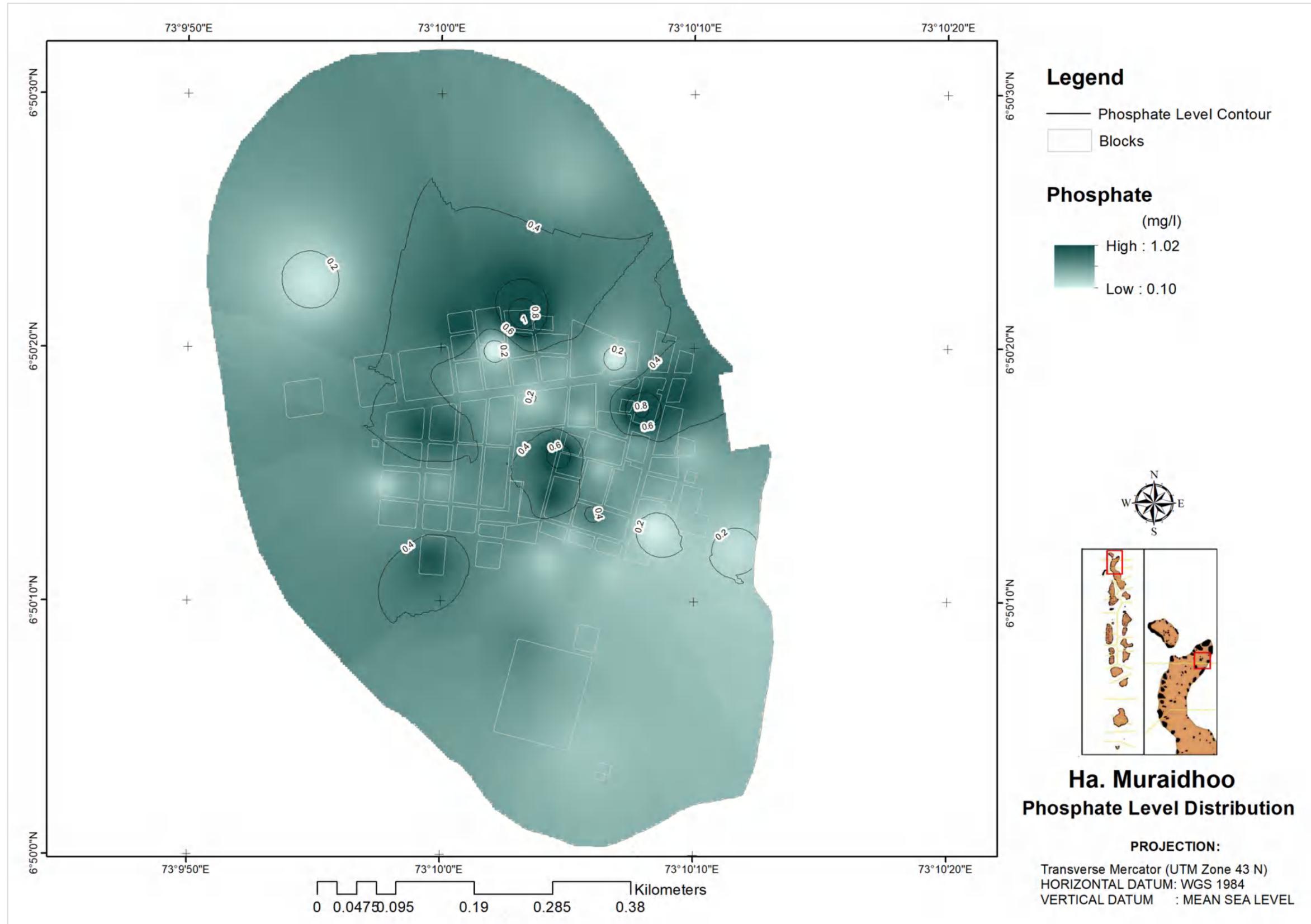


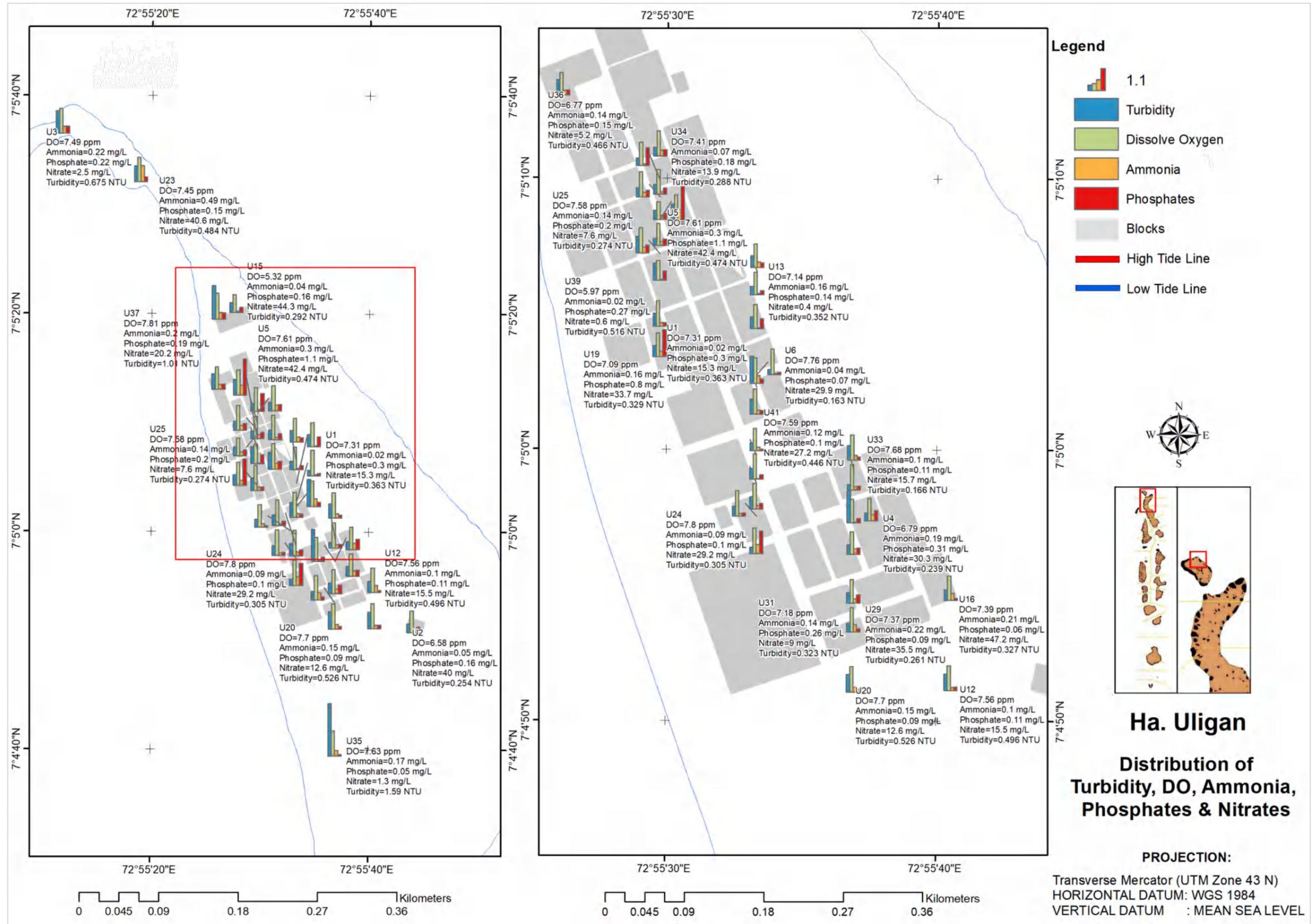


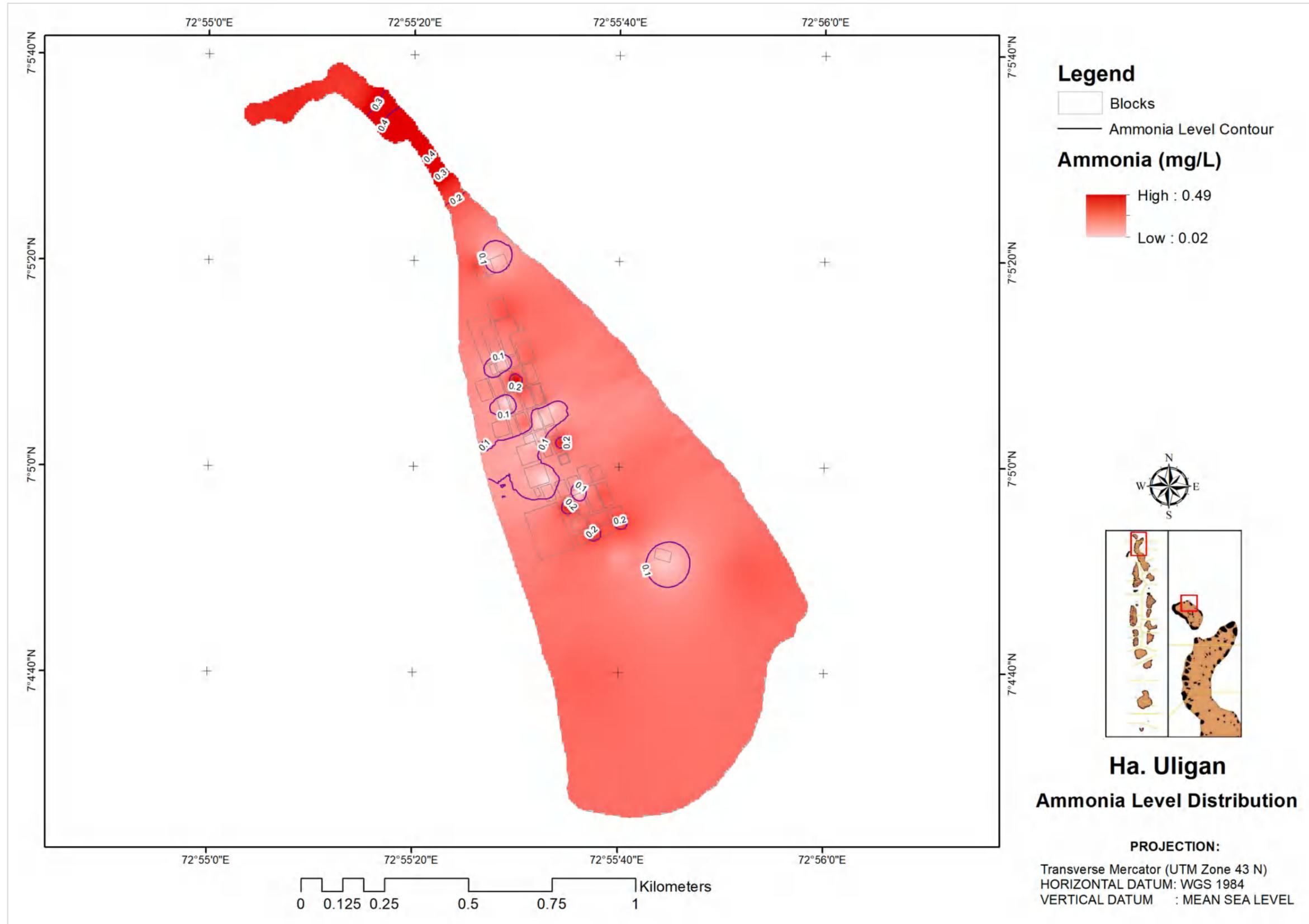


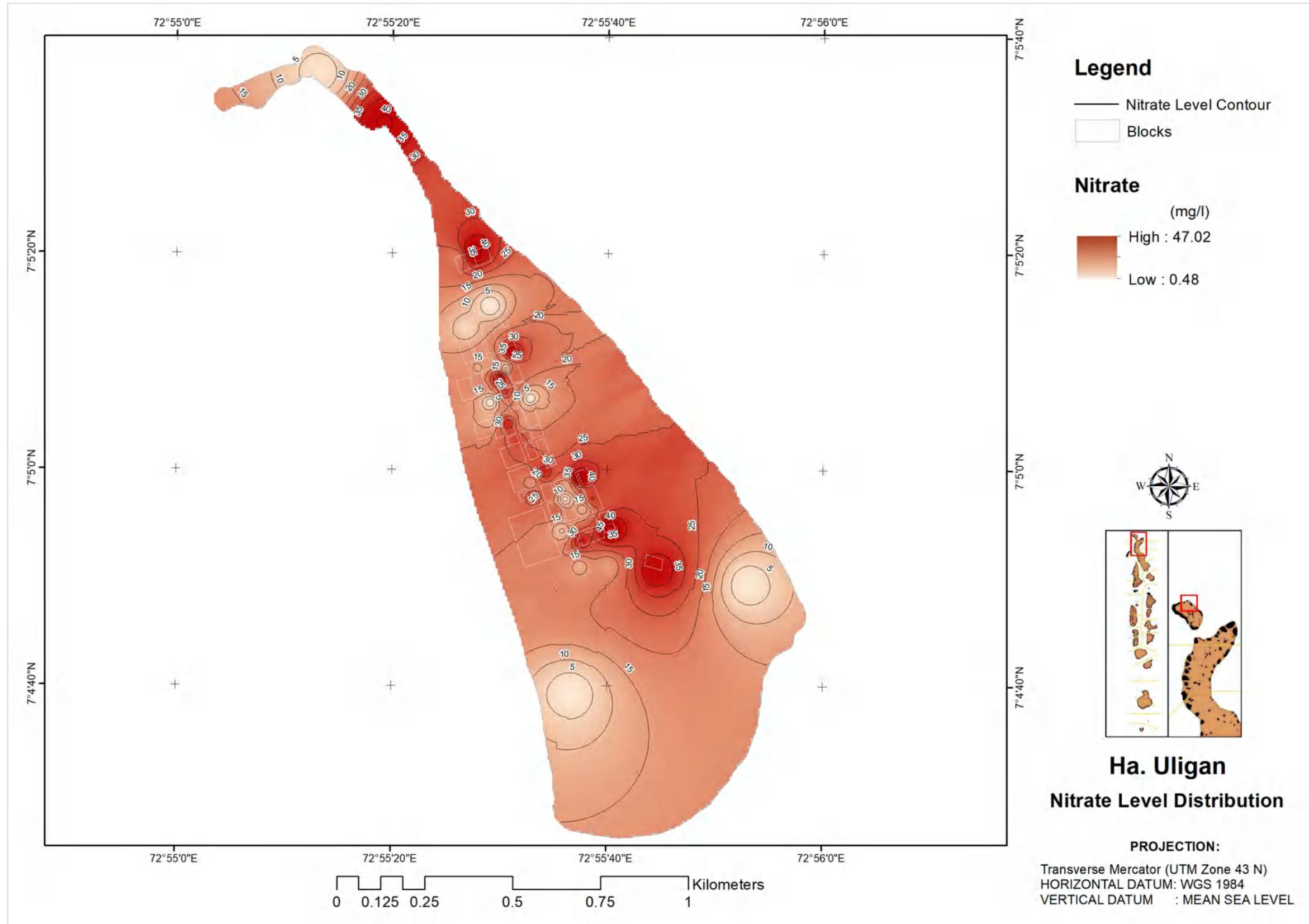


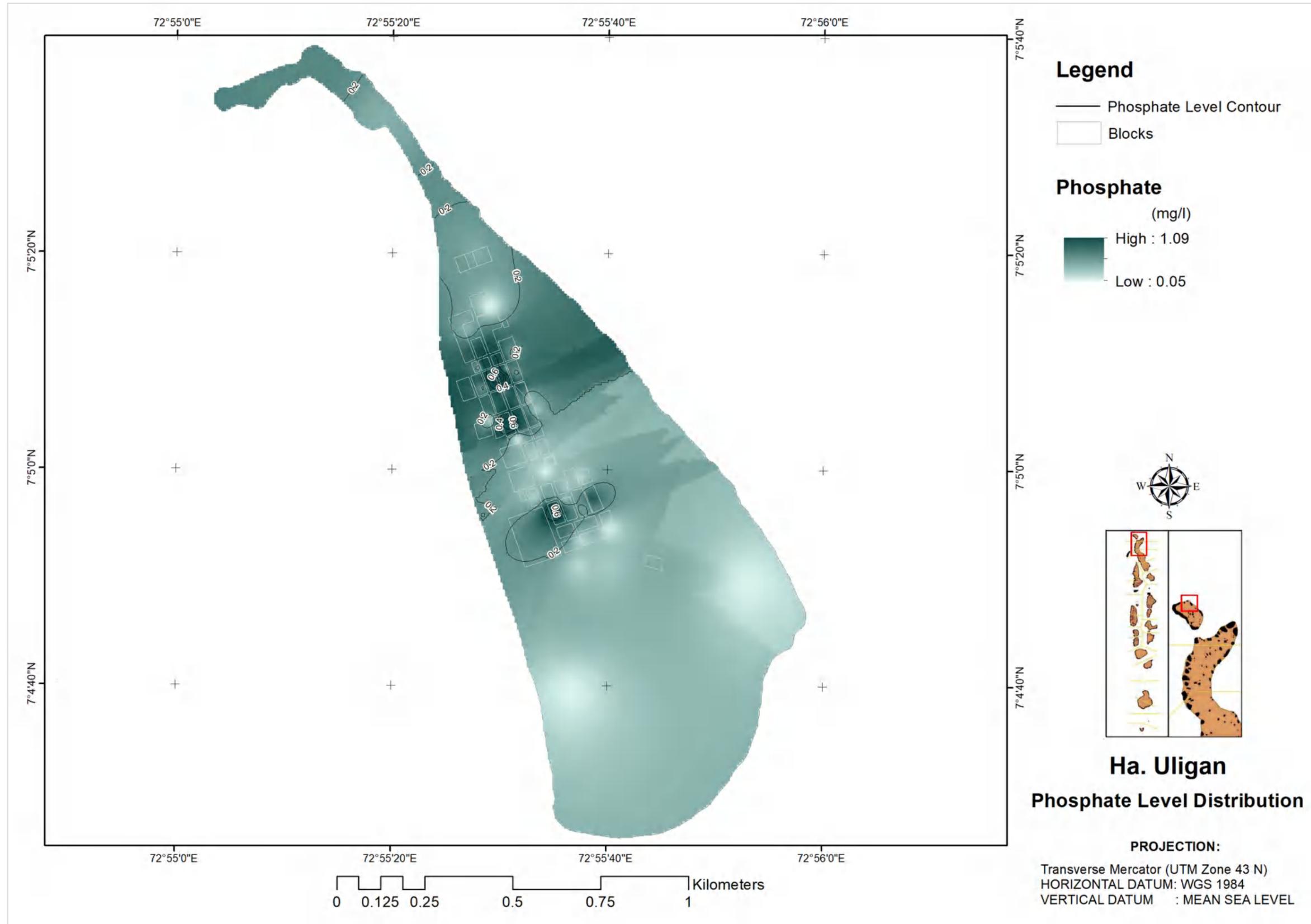


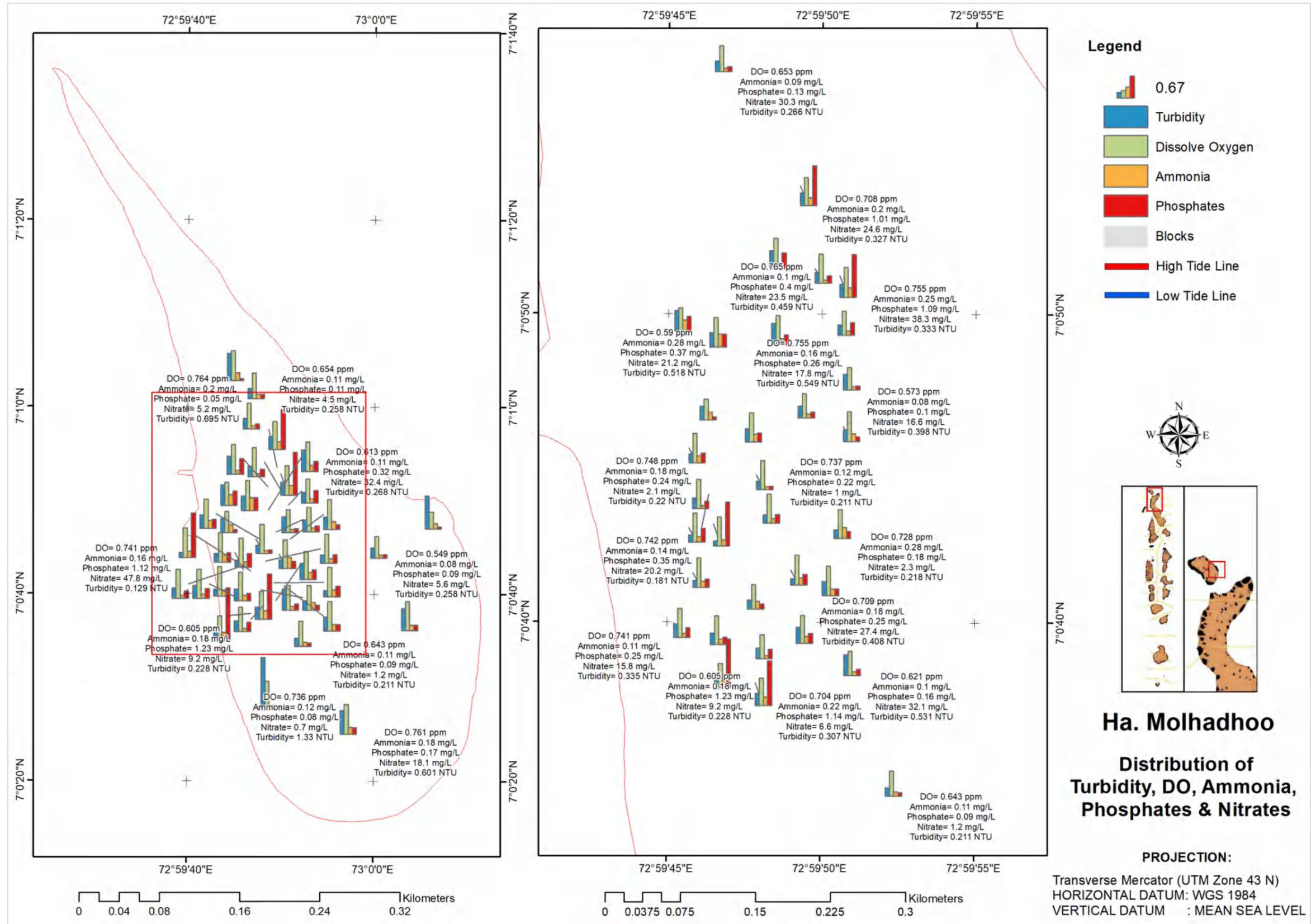


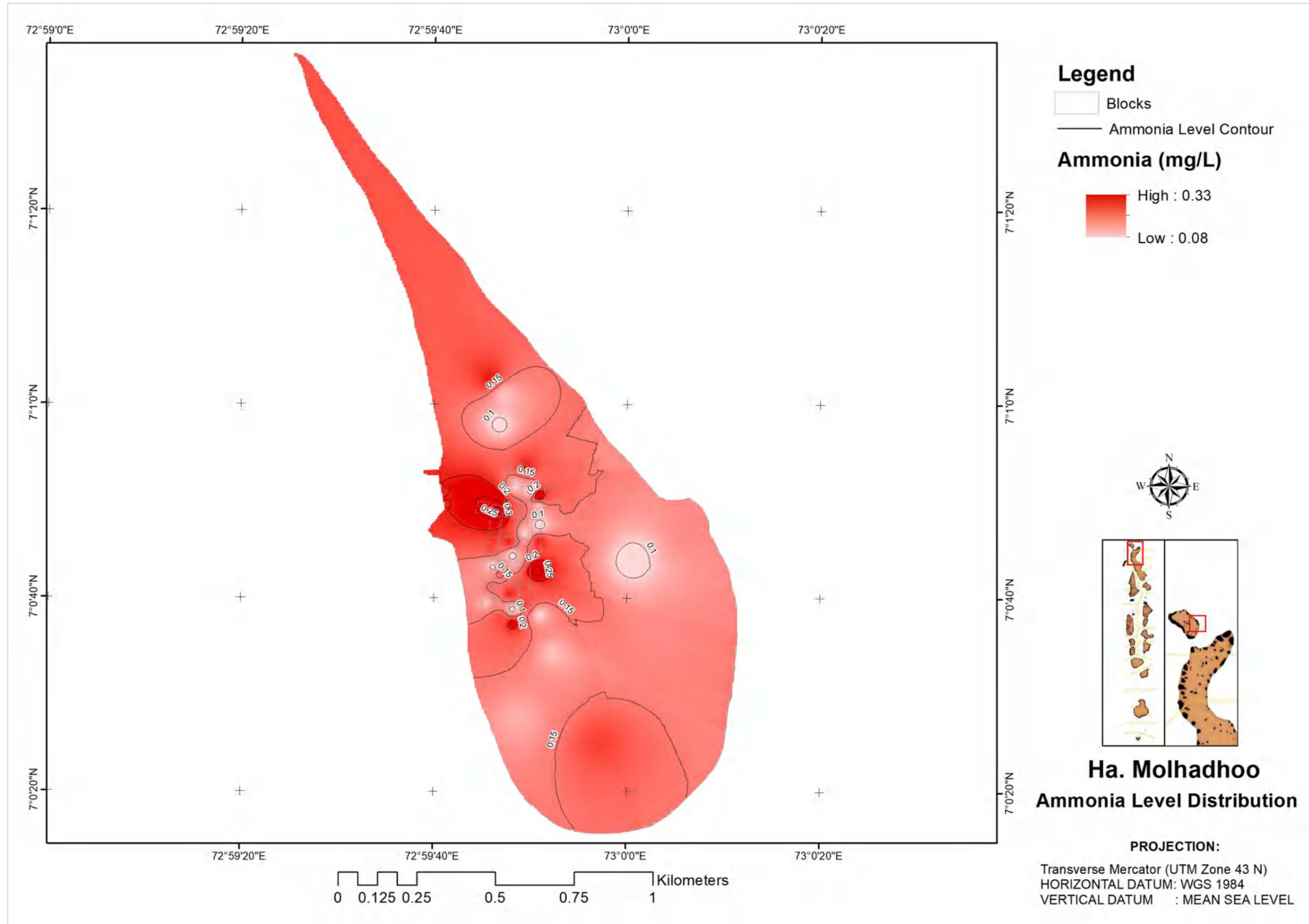


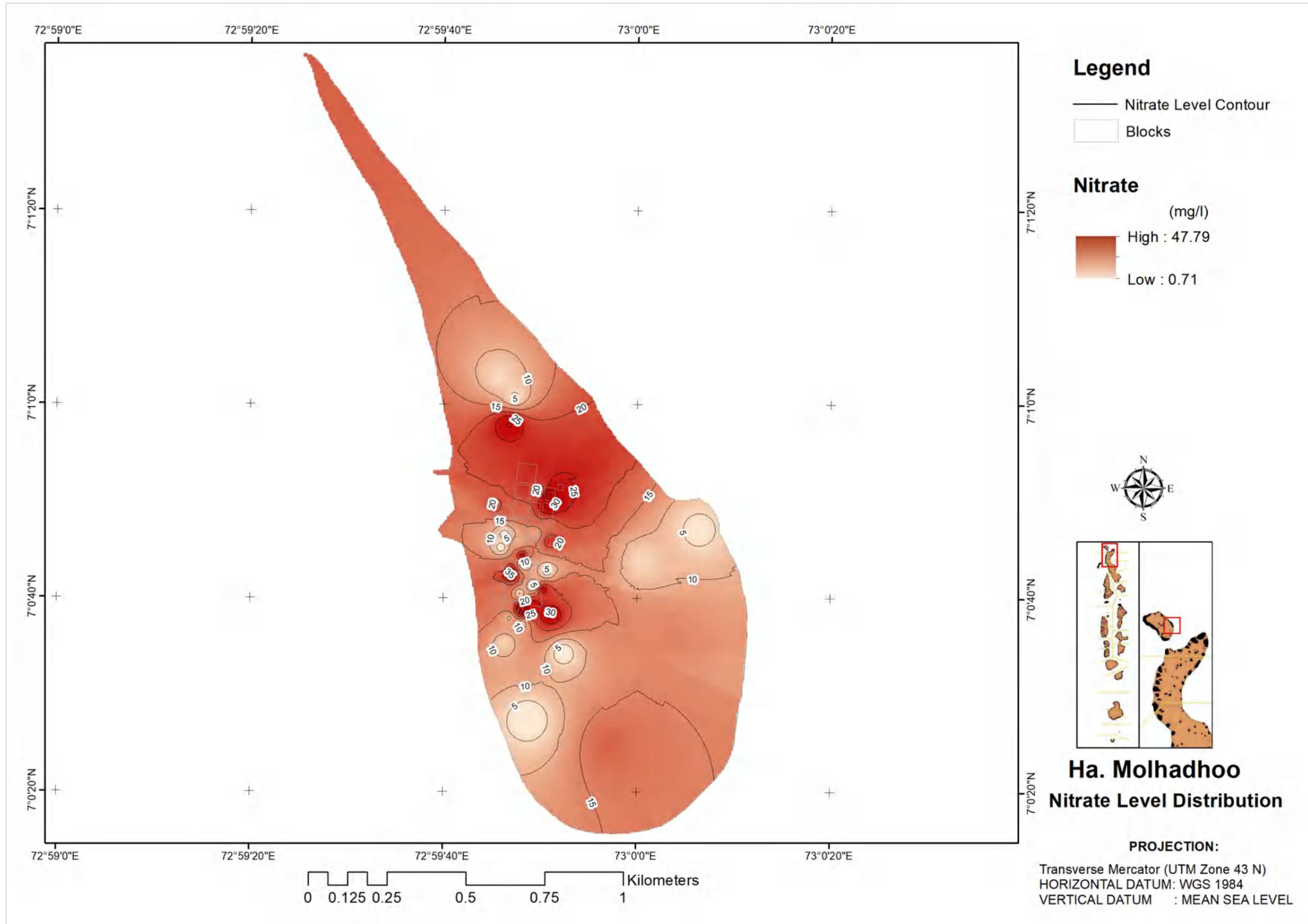


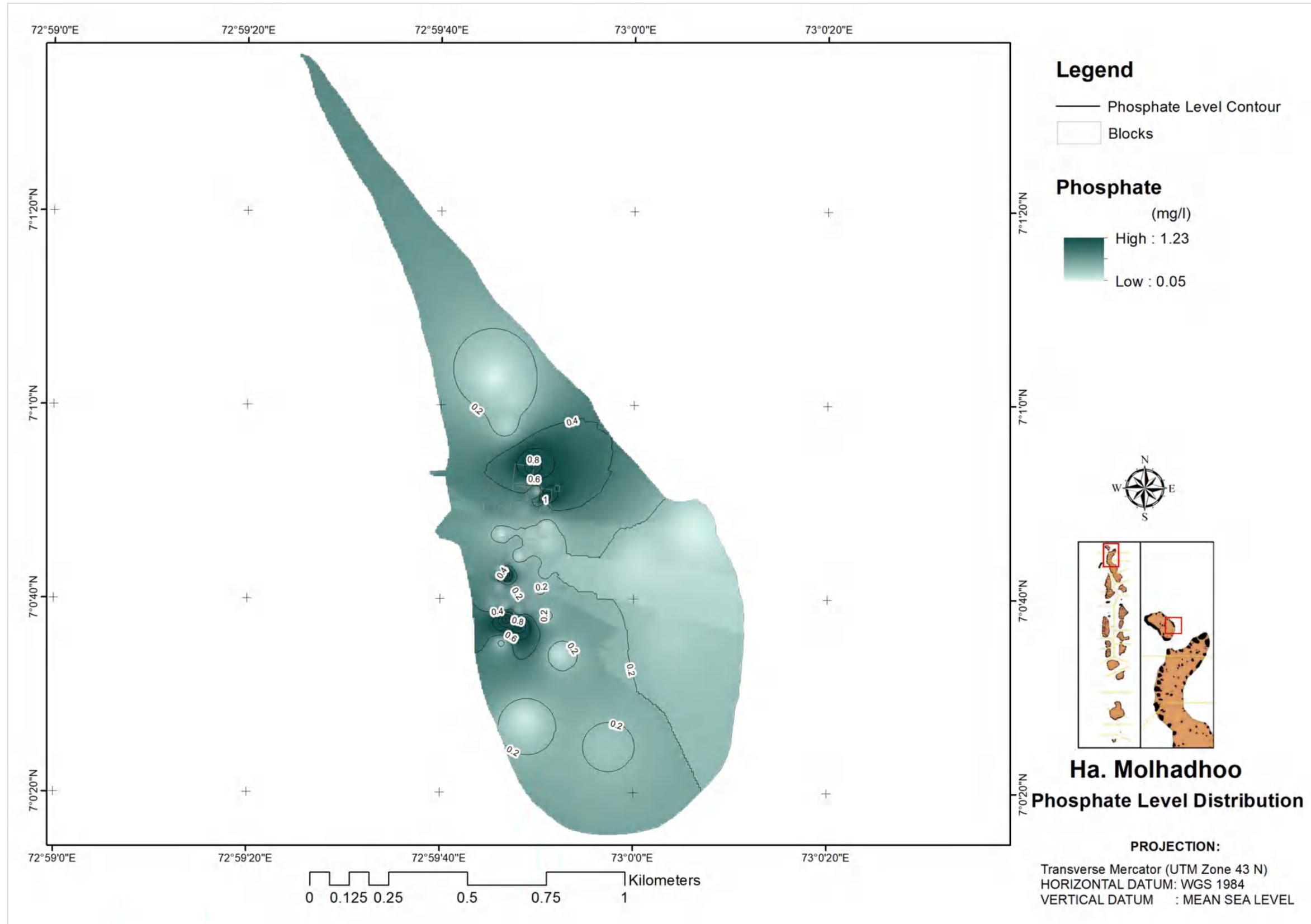




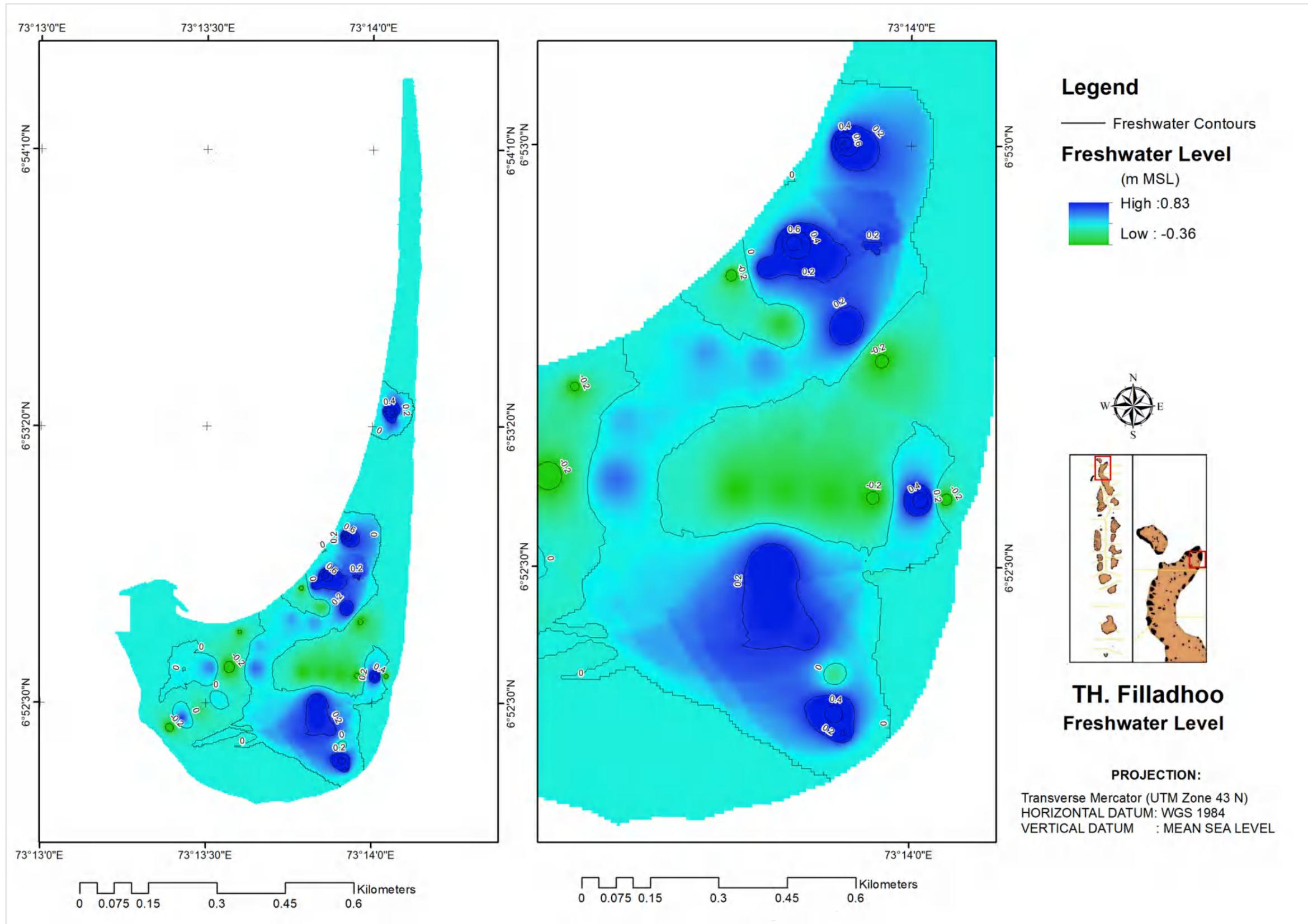


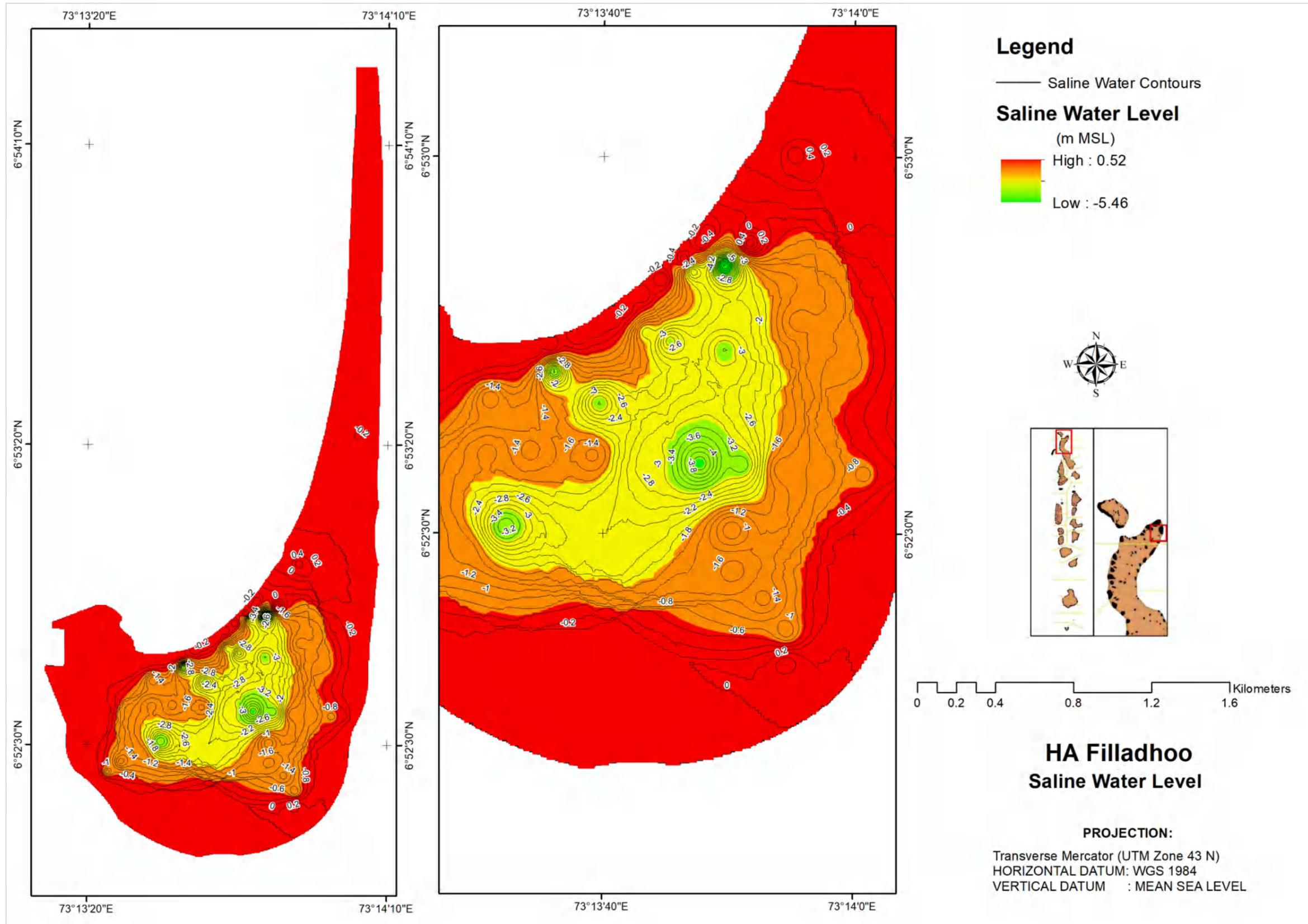


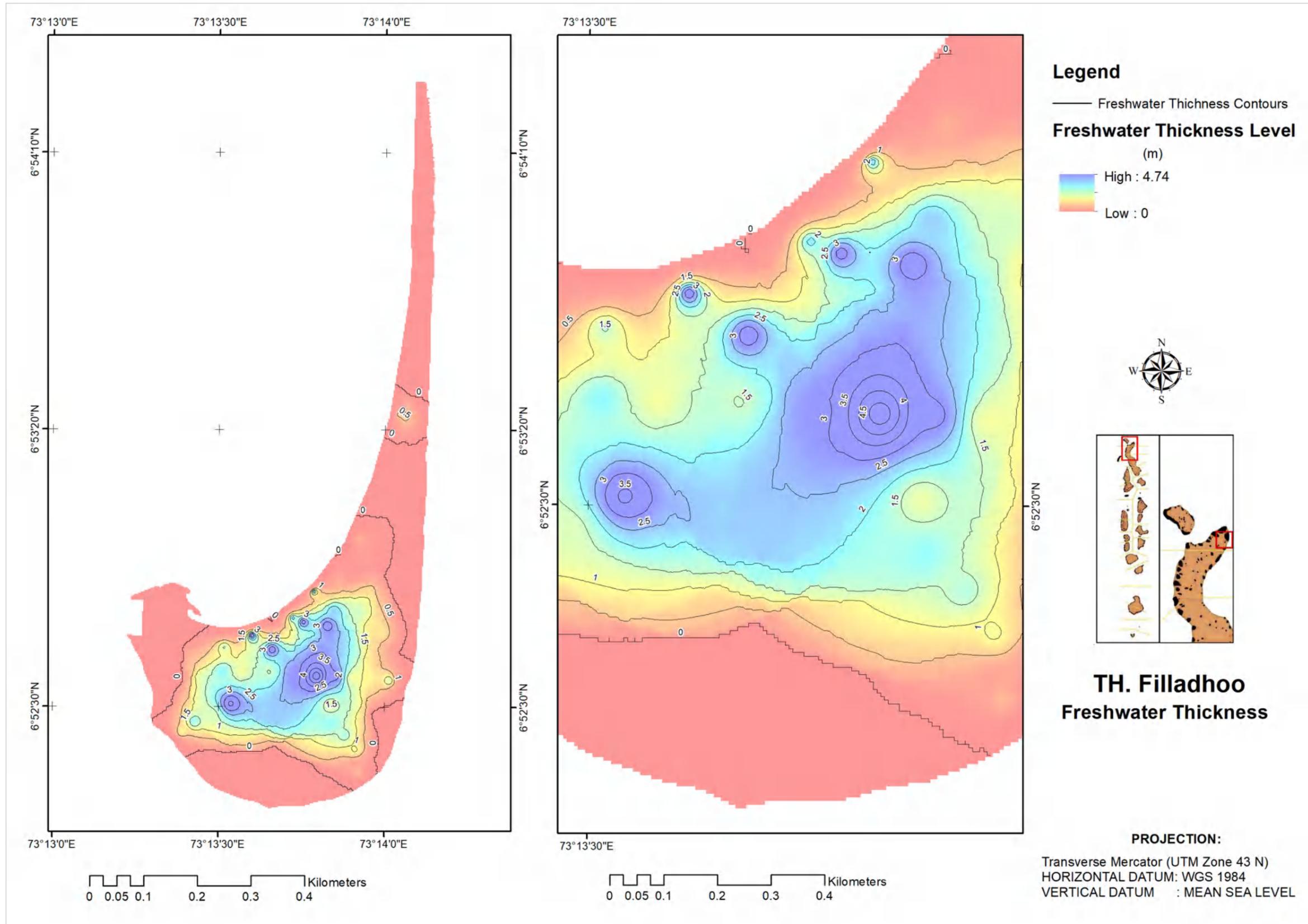


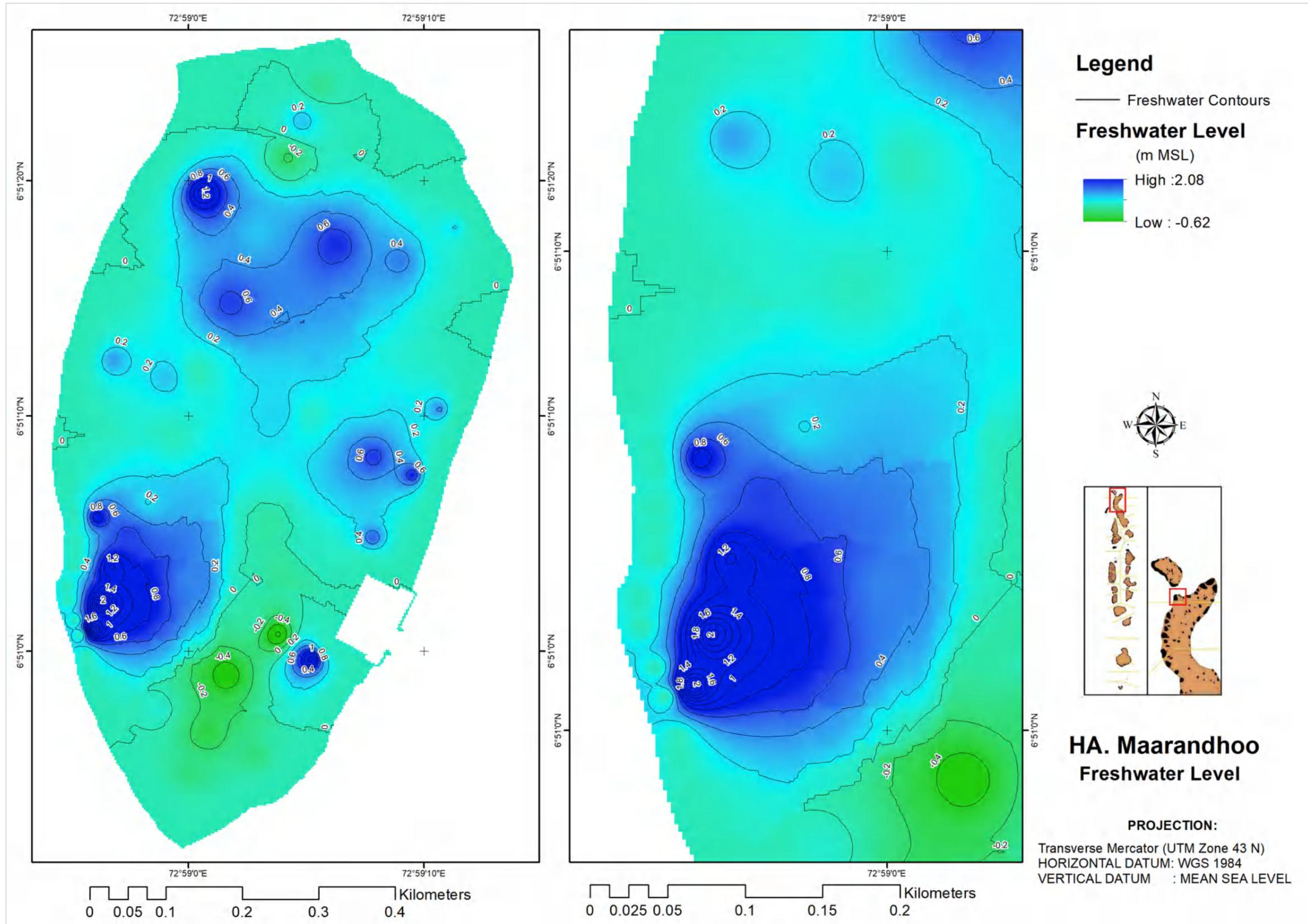


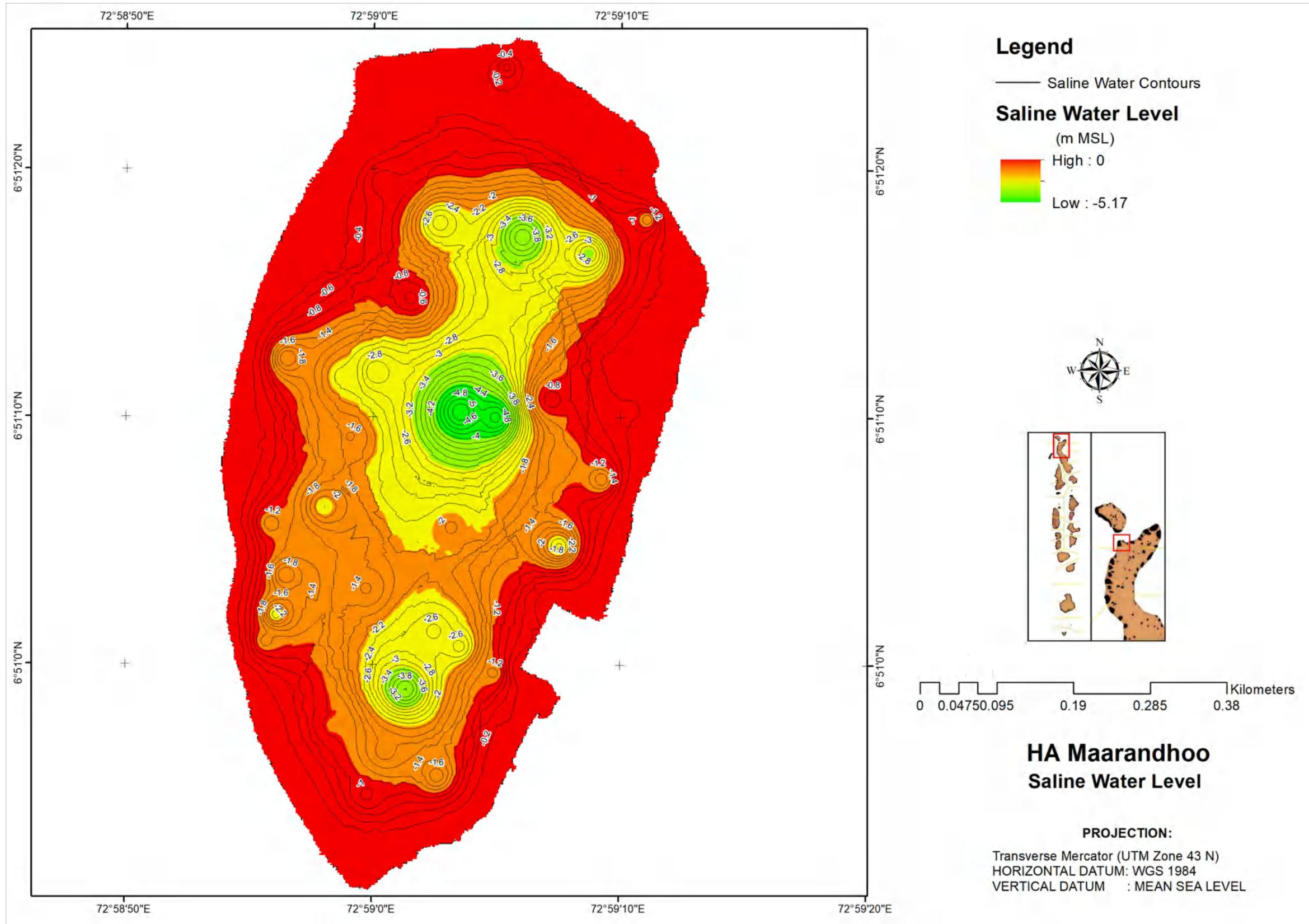
Annex VIII: Freshwater level, Saline Water Level and Freshwater thickness of the Islands

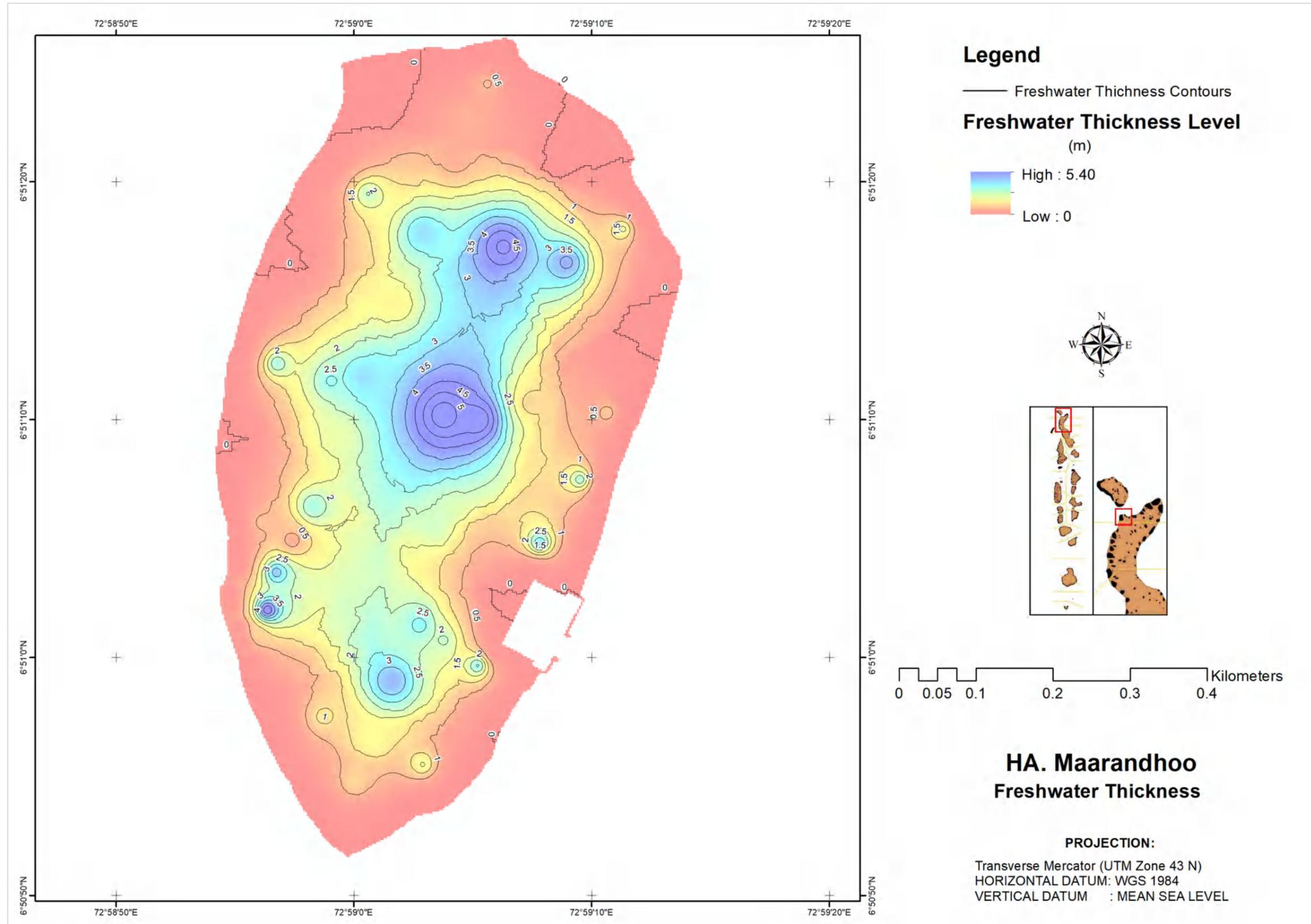


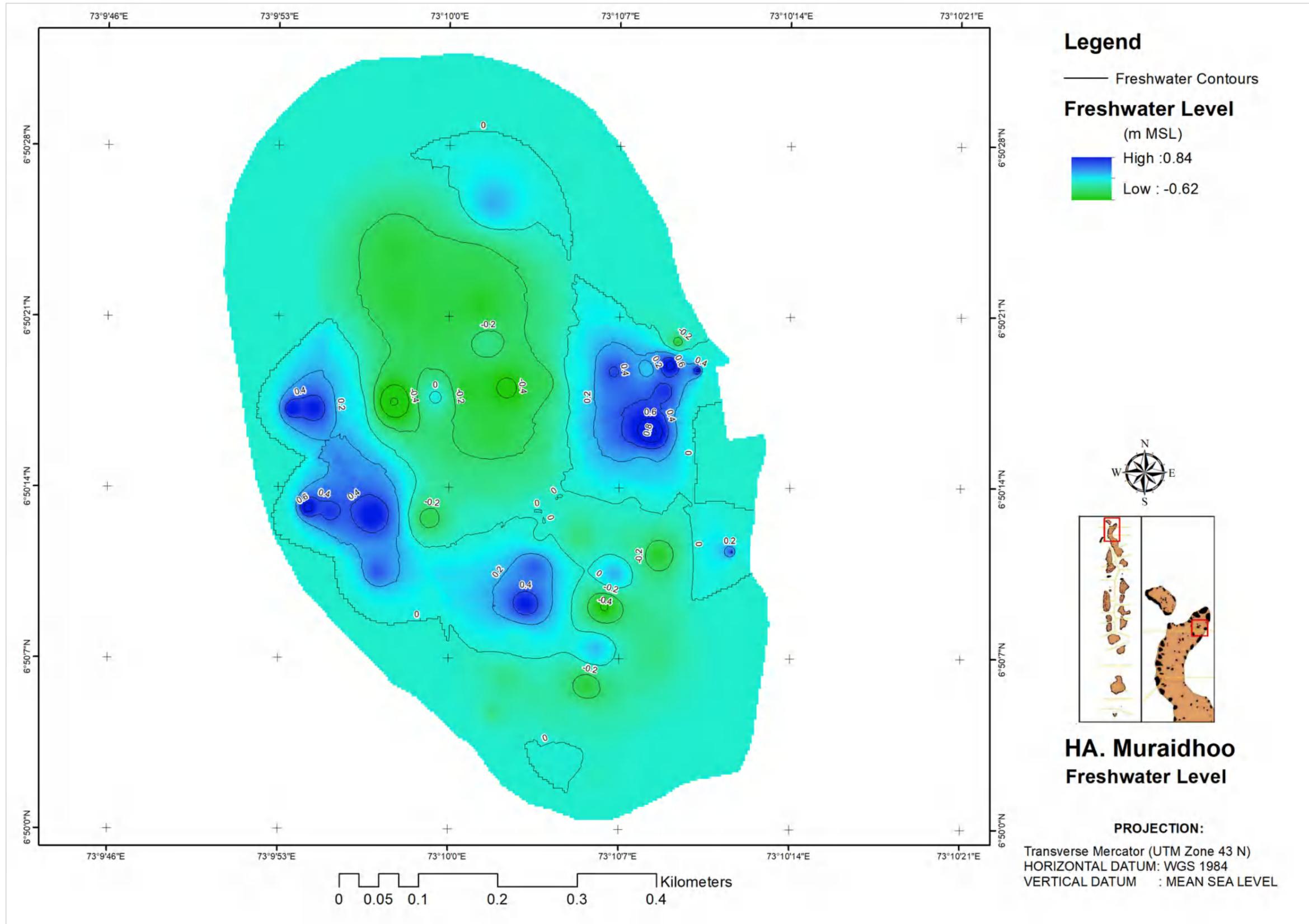


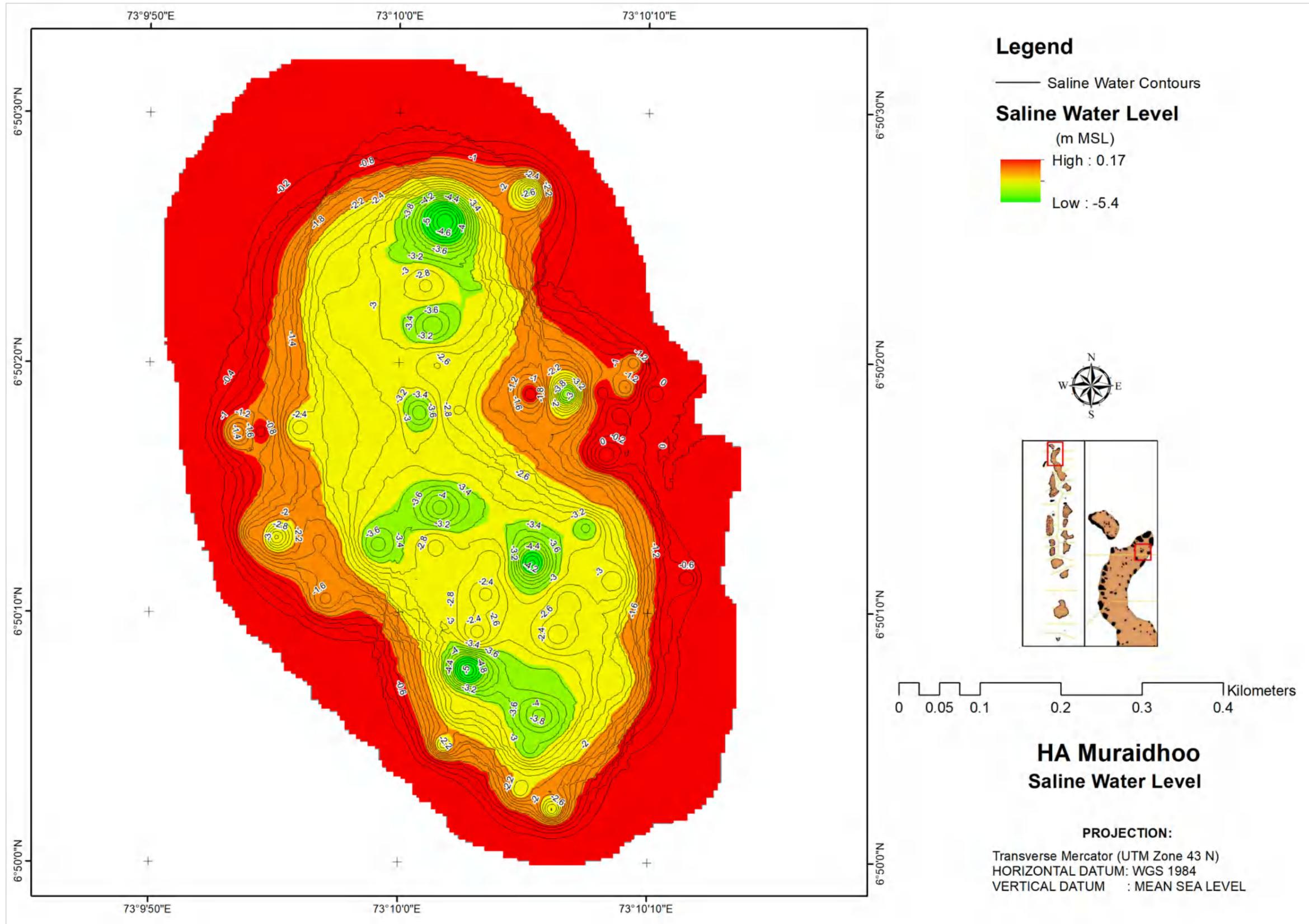


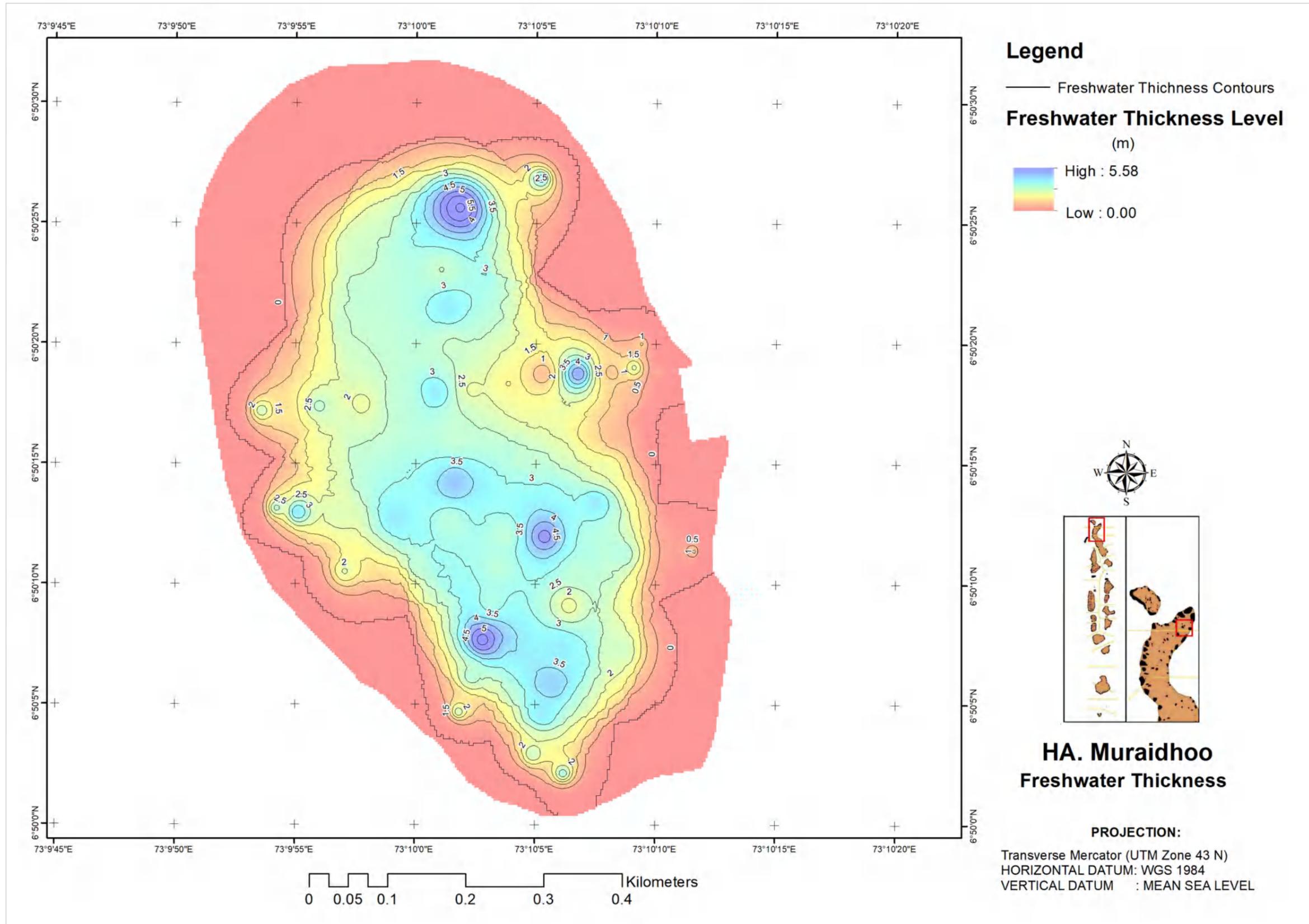


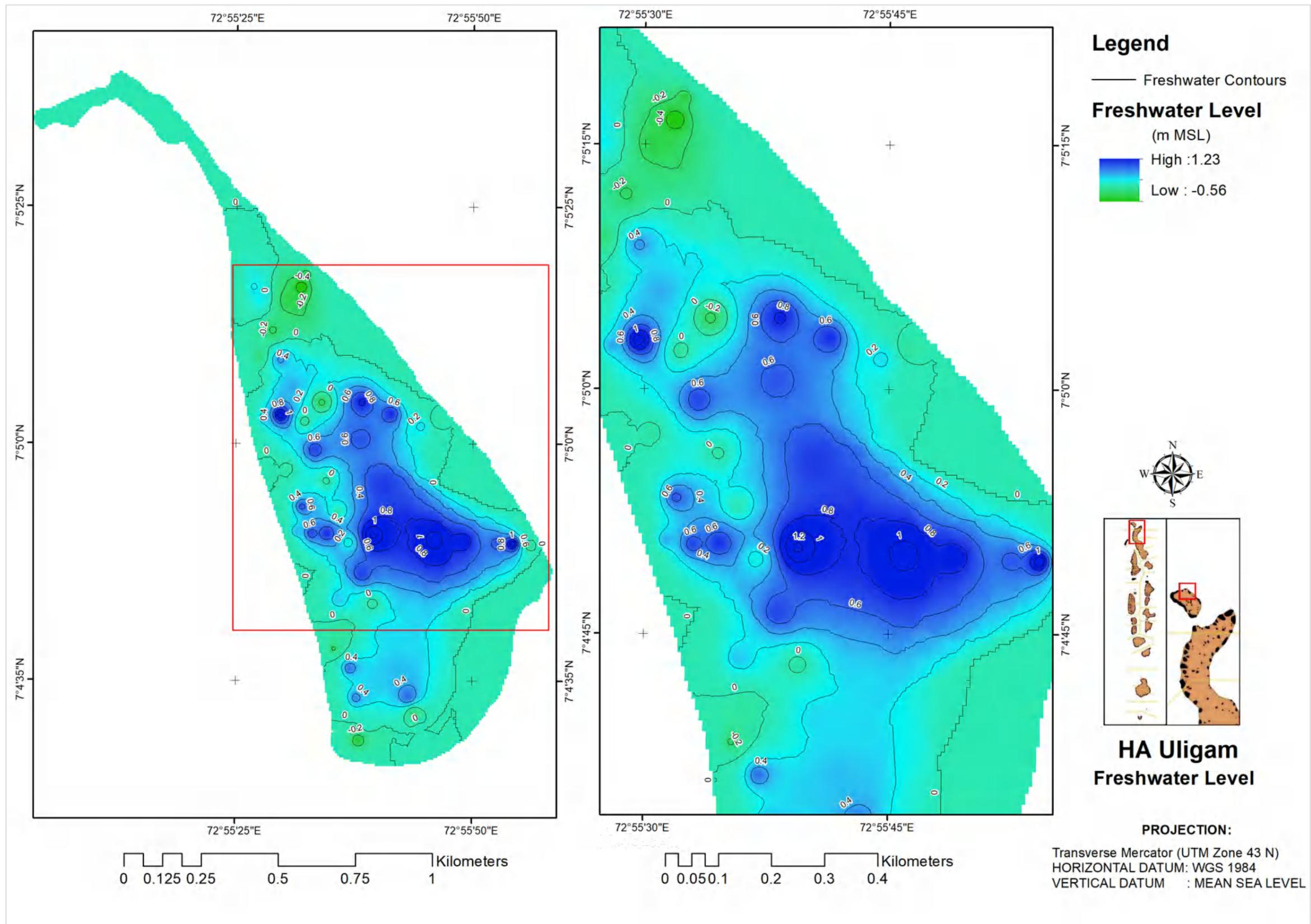


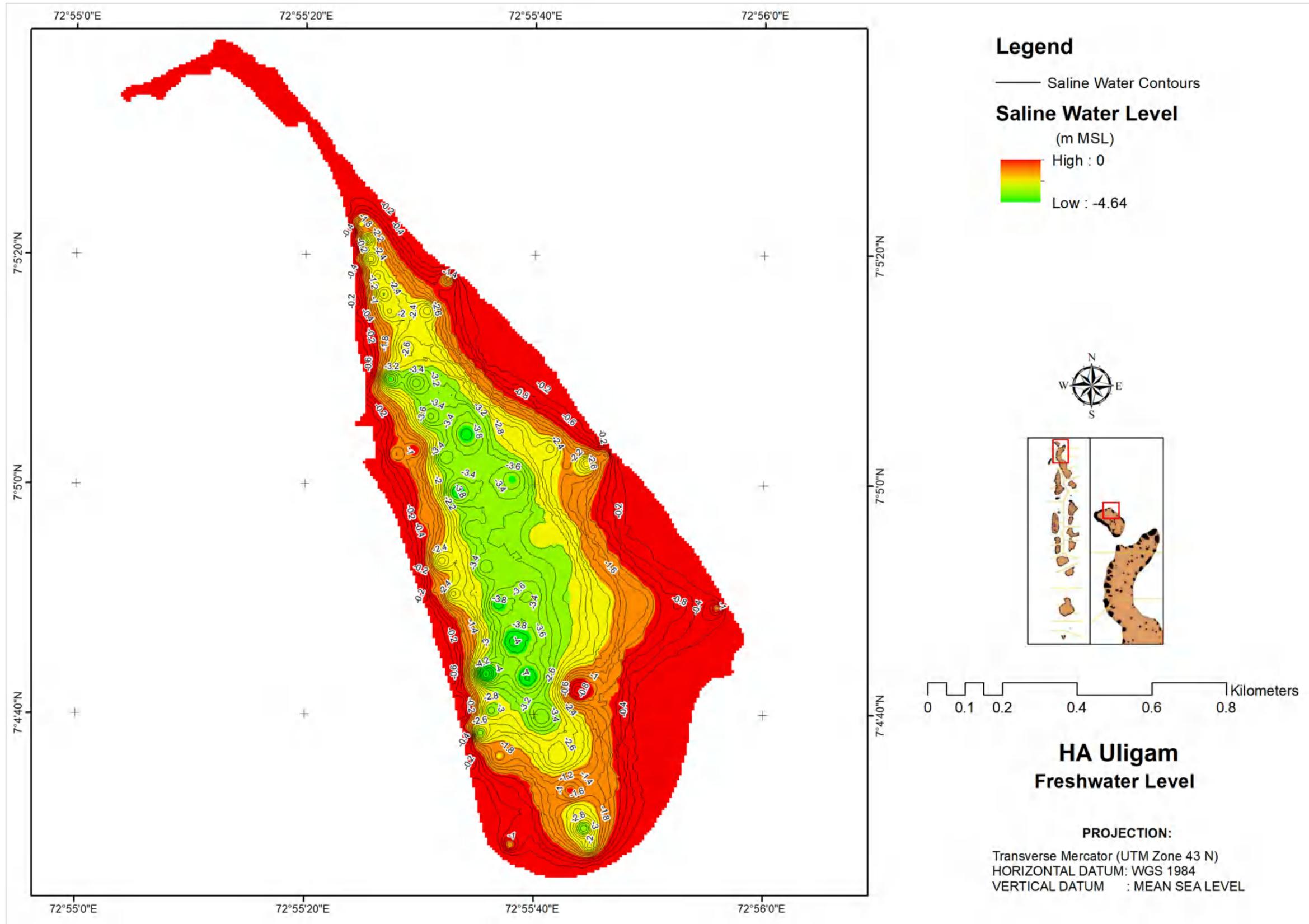


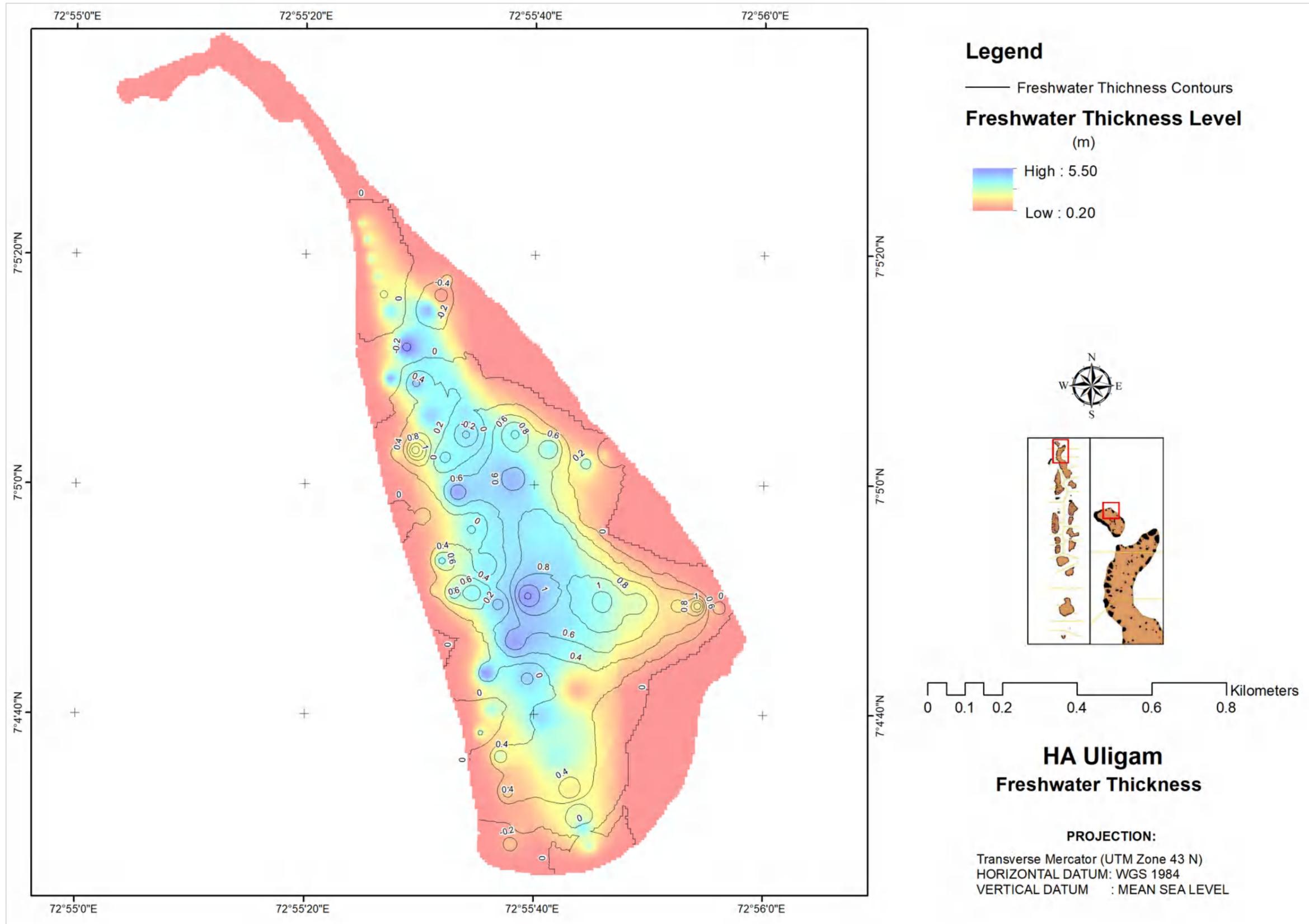


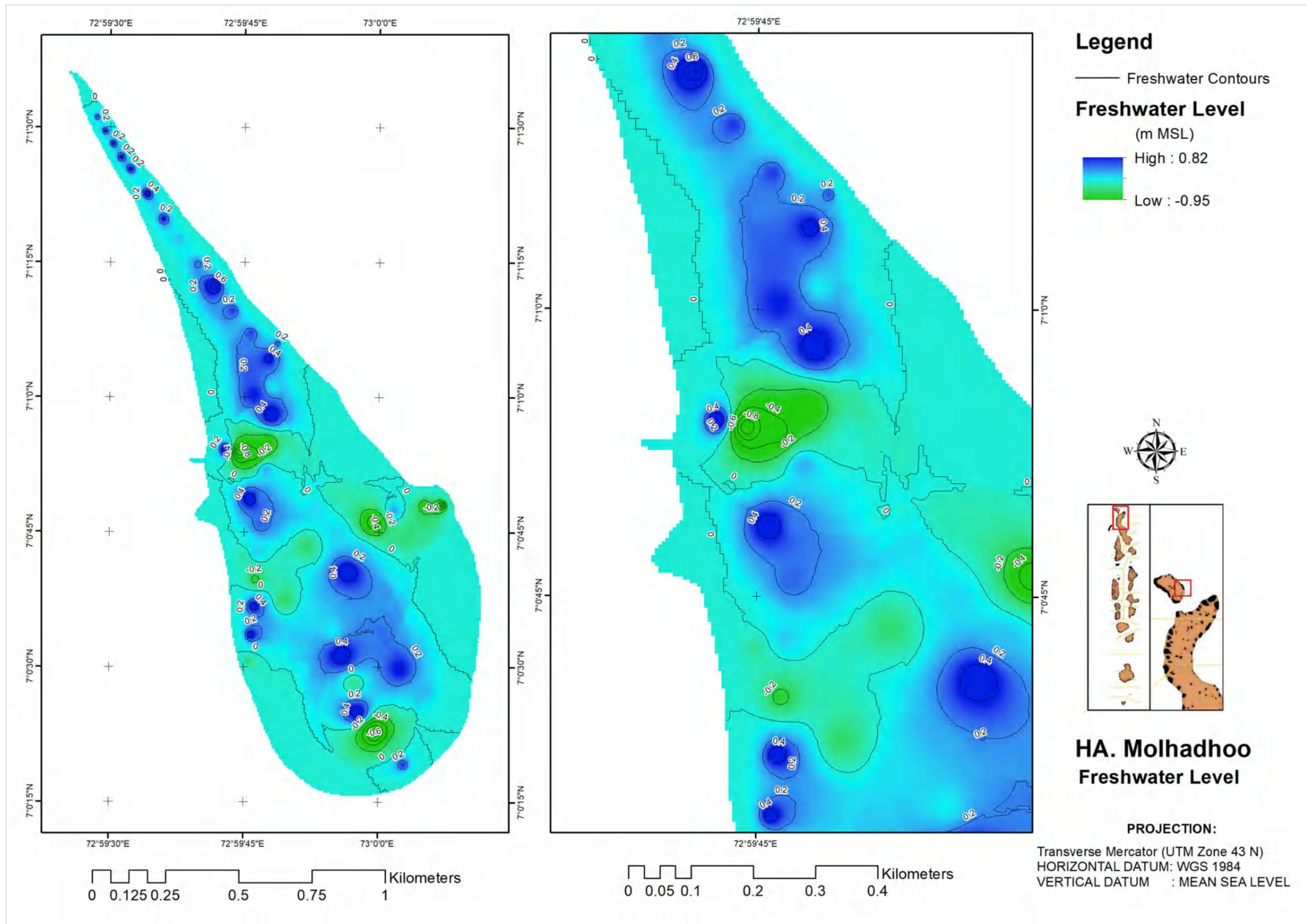


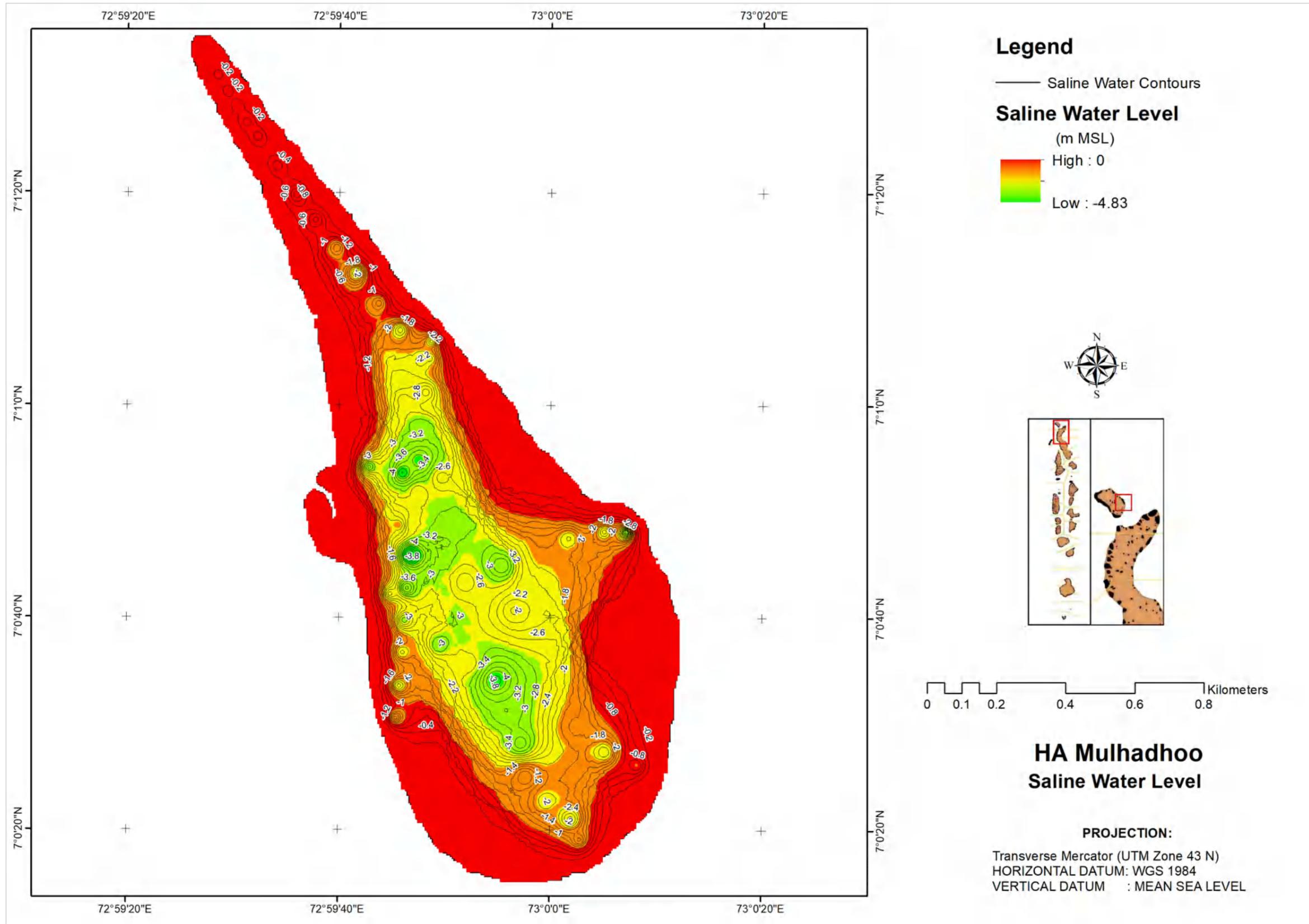


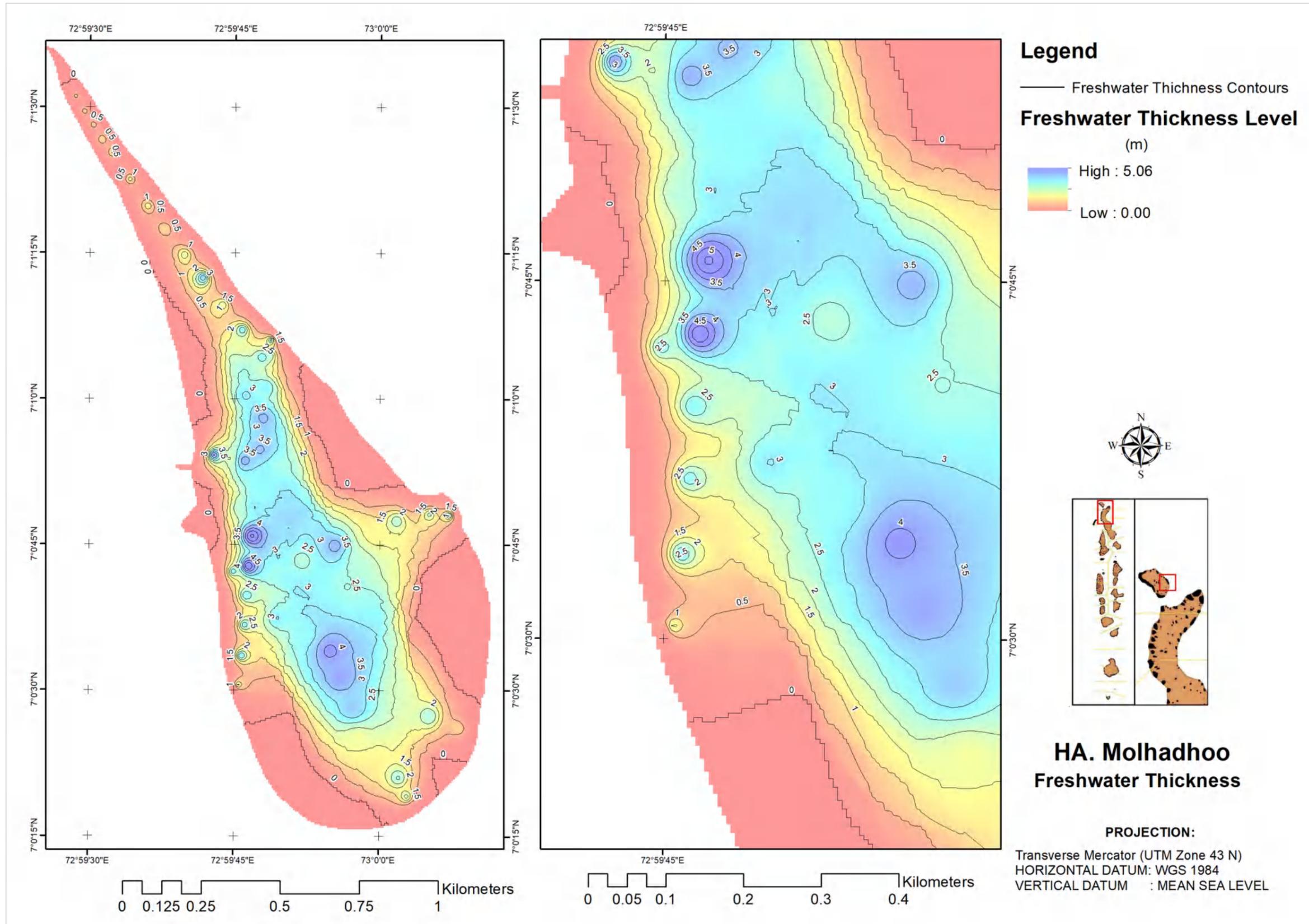












Annex IX: Stakeholder Meeting Details and Meeting Minutes

Consultancy Service to Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives – Lot 1
 RIYAN in JV with MHEC & LAMER



MINUTES OF MEETINGS:

MEETING WITH FILLADHOO ISLAND COUNCIL (18/OCT/2021)

Introduction	Field team made the introducing remarks of the meeting with a brief introduction of the project
	Field team explained that the purpose of the trip is to collect data of the current status of the island's ground water (aquifer) and design a ground water recharging mechanism which can be used throughout the year. The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
	The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
Water quality	Water quality is bad, with prominent smell. Sewerage system not yet available, leading to smell.
	The ground water is salty. The water table is very high.
Flooding Zones	When raining and floods, when locals flush the waste water it doesn't drain all the way. They assume that it is due to the higher water table during the rainy period
Other remarks	There was a resort construction project but was discontinued.
	Locals started noticing water quality drop around 2005
	There is no RO and sewerage system in the island. However, the government is planning to install this system in the island soon.

Consultancy Service to Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives – Lot 1

RIYAN in JV with MHEC & LAMER



MINUTES OF MEETINGS:

MEETING WITH MAARANDHOO ISLAND COUNCIL (11/OCT/2021)

Introduction	Field team made the introducing remarks of the meeting with a brief introduction of the project
	Field team explained that the purpose of the trip is to collect data of the current status of the island's ground water (aquifer) and design a ground water recharging mechanism which can be used throughout the year. The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
	The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
Water quality	There is no change in water quality between wet and dry seasons
	The taste of water has changed in the last 10 years. Water cannot be used for any drinking purpose anymore. Where new population grows, the quality of water reduces. The Island Council noted that RO water used for all purposes in the island
Other remarks	RO water have started for all purposes
	There is no agricultural land - however, it is under planning but not specified Traditionally each house offsets their well to prevent contamination from neighbors sanitary waste disposal

Consultancy Service to Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives – Lot 1

RIYAN in JV with MHEC & LAMER



MINUTES OF MEETINGS:

MEETING WITH MOLHADHOO ISLAND COUNCIL (14/OCT/2021)

Introduction	Field team made the introducing remarks of the meeting with a brief introduction of the project
	Field team explained that the purpose of the trip is to collect data of the current status of the island's ground water (aquifer) and design a ground water recharging mechanism which can be used throughout the year. The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
	The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
Water quality	The construction of harbour reduced water quality
	When there is no rain for 2-3 months, then smell accumulates.
Concerns of the Council	Council wanted to know the possibility of diverting water to the picnic area. They had already dug a well at the area to get fresh water, however, it also became saline very quickly.

Consultancy Service to Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives – Lot 1

RIYAN in JV with MHEC & LAMER



MINUTES OF MEETINGS:

MEETING WITH MURAI DHOO ISLAND COUNCIL (22/OCT/2021)

Introduction	Field team made the introducing remarks of the meeting with a brief introduction of the project
	Field team explained that the purpose of the trip is to collect data of the current status of the island's ground water (aquifer) and design a ground water recharging mechanism which can be used throughout the year. The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
	The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
Water quality	At the island west side there is smell in water. During the last 2 to 3 years, after the sewerage system was established, the water became salty.
	No changes in water quality was observed from harbour construction. Lots of banana trees grew in the last 5 years. These areas have a strong-smelling water.
Flooding Zones	Flooding due to rain reduces after 2-3 days. Almost all areas are prone to flooding. Waste burning area is prone to udha.
Water scarcity	The Island Council noted that ground water used for all purposes in the island
Other remarks	Island west side has a higher elevation.
	The locals have already emptied sanitation tanks and filled them with black soil

Consultancy Service to Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives – Lot 1

RIYAN in JV with MHEC & LAMER



MINUTES OF MEETINGS:

MEETING WITH ULIGAN ISLAND COUNCIL (12/OCT/2021)

Introduction	Field team made the introducing remarks of the meeting with a brief introduction of the project
	Field team explained that the purpose of the trip is to collect data of the current status of the island's ground water (aquifer) and design a ground water recharging mechanism which can be used throughout the year. The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
	The data collected will be used to design an ground water recharging system that captures the water during the monsoon season and makes the best use of it for later when the water table level gets depleted. Further, after the implementation of the system, it will help to maintain the ground water with better properties such as the smell, taste, color and etc.
Water quality	Water quality is bad in populated areas. Water has both smell and colour. It is not used for drinking. The smell is most prominent during wet season
	Ground water is used only for showering, not for drinking
Flooding Zones	When raining and floods, when locals flush the waste water it doesn't drain all the way. They assume that it is due to the higher water table during the rainy period
Other remarks	There was a resort construction project but was discontinued. Locals started noticing water quality drop around 2005 There is no RO and sewerage system in the island. However, the government is planning to install this system in the island soon.

Annex X: Photographs of the Soil Profiles

	Soil Profile 1	Soil Profile 2	Soil Profile 3	Soil Profile 4	Soil Profile 5
Ha. Filladhoo					
Ha. Maarandhoo					
Ha. Muraidhoo					
Ha. Uligan					
Ha. Molhadhoo					

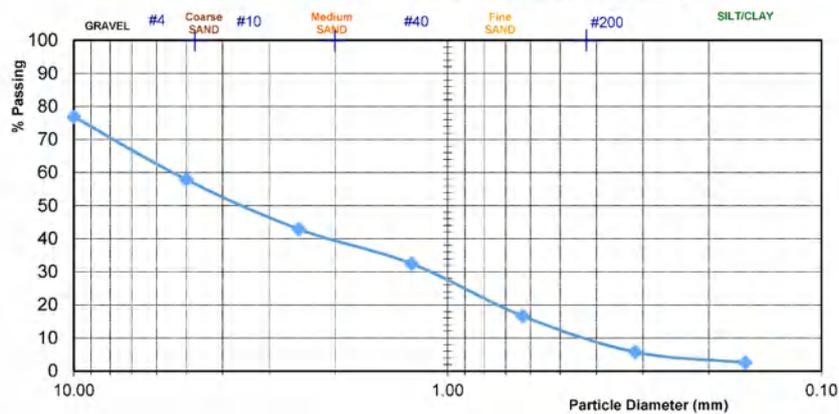
Annex XI: Sieve Analysis Test Results



Sieve Analysis Data

Project Name: N/A	Tested By: Shunaif
Source: MHEC (SL)	Checked By: Naushad
Sample No: 1	Test #: 1
Sample Depth: Varies 0-2m	Tested on: 14.11.2021

Sieve Number	Diameter (mm)	Mass of Sieve (g)	Mass of Sieve & Soil (g)	Soil Retained (g)	Soil Retained (%)	Soil Passing (%)
#	10.00	690	945	255.0	23.1	76.9
#	5.00	705	915	210.0	19.0	57.8
#	2.50	685	850	165.0	15.0	42.9
#	1.25	585	700	115.0	10.4	32.5
#	0.63	545	720	175.0	15.9	16.6
#	0.32	570	690	120.0	10.9	5.7
#	0.160	540	575	35.0	3.2	2.5
Pan		470	498	28.0	2.5	0.0
TOTAL:				1103.0	100.0	



Weight of Sample **1090 g**
 Percentage Loss **-1.19%**
 Fineness modulus **5.7**

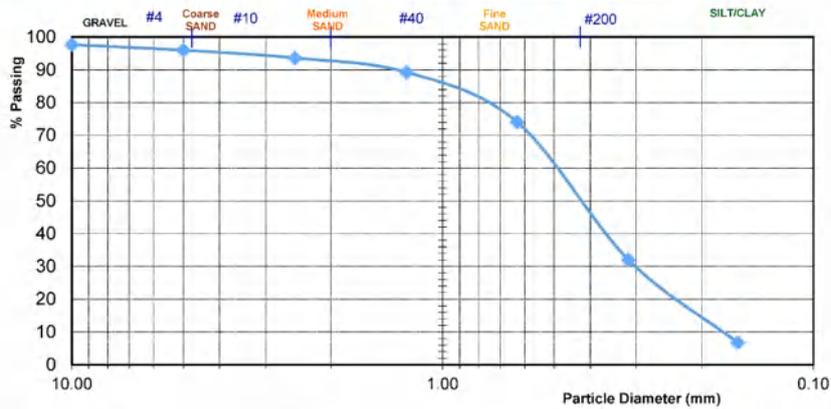
Notes:
 Sample with roots and organic matter



Sieve Analysis Data

Project Name: N/A	Tested By: Shunaif
Source: MHEC (SL)	Checked By: Naushad
Sample No: 2	Test #: 1
Sample Depth: Varies 0-2m	Tested on: 14.11.2021

Sieve Number	Diameter (mm)	Mass of Sieve (g)	Mass of Sieve & Soil (g)	Soil Retained (g)	Soil Retained (%)	Soil Passing (%)
#	10.00	690	725	35.0	2.4	97.6
#	5.00	705	730	25.0	1.7	96.0
#	2.50	685	720	35.0	2.4	93.6
#	1.25	585	650	65.0	4.4	89.2
#	0.63	545	770	225.0	15.2	74.1
#	0.32	570	1195	625.0	42.1	32.0
#	0.160	540	915	375.0	25.3	6.7
Pan		470	570	100.0	6.7	0.0
TOTAL:				1485.0	100.0	



Weight of Sample **1485 g**
 Percentage Loss **0.00%**
 Fineness modulus **3.1**

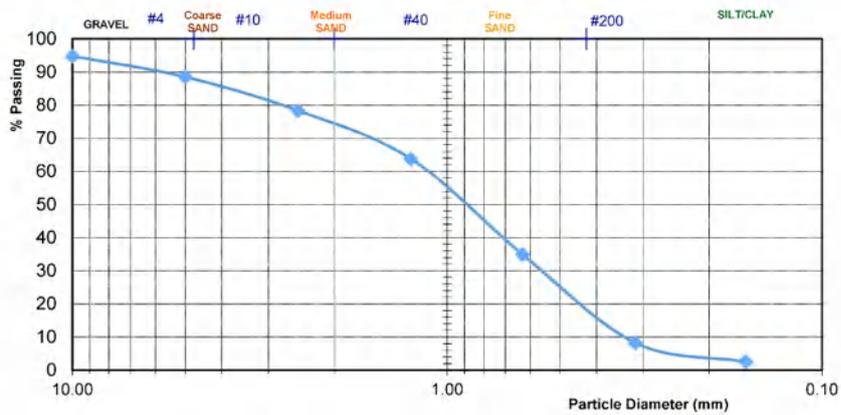
Notes:



Sieve Analysis Data

Project Name: N/A	Tested By: Shunaif
Source: MHEC (SL)	Checked By: Naushad
Sample No: 3	Test #: 1
Sample Depth: Varies 0-2m	Tested on: 14.11.2021

Sieve Number	Diameter (mm)	Mass of Sieve (g)	Mass of Sieve & Soil (g)	Soil Retained (g)	Soil Retained (%)	Soil Passing (%)
#	10.00	690	785	95.0	5.2	94.8
#	5.00	705	820	115.0	6.3	88.5
#	2.50	685	870	185.0	10.2	78.3
#	1.25	585	850	265.0	14.6	63.7
#	0.63	545	1070	525.0	28.8	34.9
#	0.32	570	1055	485.0	26.6	8.2
#	0.160	540	645	105.0	5.8	2.5
Pan		470	515	45.0	2.5	0.0
TOTAL:				1820.0	100.0	



Weight of Sample **1820 g**
 Percentage Loss **0.00%**
 Fineness modulus **4.3**

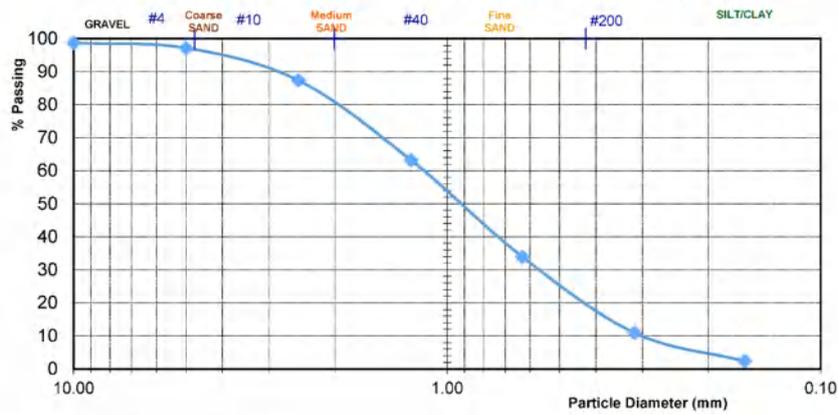
Notes:



Sieve Analysis Data

Project Name: N/A	Tested By: Shunaif
Source: MHEC (SL)	Checked By: Naushad
Sample No: 4	Test #: 1
Sample Depth: Varies 0-2m	Tested on: 14.11.2021

Sieve Number	Diameter (mm)	Mass of Sieve (g)	Mass of Sieve & Soil (g)	Soil Retained (g)	Soil Retained (%)	Soil Passing (%)
#	10.00	690	715	25.0	1.3	98.7
#	5.00	705	735	30.0	1.6	97.2
#	2.50	685	875	190.0	9.8	87.3
#	1.25	585	1050	465.0	24.1	63.2
#	0.63	545	1110	565.0	29.3	33.9
#	0.32	570	1015	445.0	23.1	10.9
#	0.160	540	705	165.0	8.5	2.3
Pan		470	515	45.0	2.3	0.0
TOTAL:				1930.0	100.0	



Weight of Sample **1930 g**
 Percentage Loss **0.00%**
 Fineness modulus **4.1**

Notes: