Ministry of Environment, Climate Change and Technology
Republic of Maldives

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

FEASIBILITY & CONCEPT DESIGN REPORT

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

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

Funding Agency: Green Climate Fund (GCF)

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Assignment: Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives (Lot 1)

Client: Ministry of Environment, Climate Change and Technology

Consultants: Riyan Pvt. Ltd., Maldives with

Master Hellie's Engineering Consultants Pvt. Ltd, Sri Lanka and

Land and Marine Environmental Resource Group Pvt. Ltd.

Deliverable: Feasibility Concept Design Report

Focus Islands:

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

Table of contents

List of Figures

List of Tables

List of abbreviations and acronyms

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

EXECUTIVE SUMMARY

Background and Methodology

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

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

General Findings from Baseline Surveys

The selected five (05) islands under this package were located in the northernmost 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. Each island shows individual characteristics compared to water usage characteristics, water quality parameters and hydraulic conductivity parameters as discussed in the Baseline Study Report. Based on the variations identified in the groundwater quantity and quality, aquifer hydro-geologic parameters and observations made during the field visits, the identified main reasons for the critical variation on EC, Ammonia, Nitrate and Phosphates are; higher extraction of groundwater, leaching on nitrate based fertilizers, coral stockpiling within the island area, sea water flooding, and contaminants from anthropogenic activities.

Groundwater extraction for daily activities (for domestic, farming, fisheries, industrial and institutional purposes) in selected islands differs from 52,330 ℓ /yr. in Ha. Muraidho to 108,422 ℓ /yr. in Ha. Maarandhoo. Furthermore, the stress level of the aquifer differs from 'Not stressed' (47% of allowable safe yield of Ha. Molhadhoo) to “Very highly stressed’ (232% of allowable safe yield of Ha. Maarandhoo) which could be related to the land usage and population density. Therefore, immediate actions are warranted to avoid further degrading of groundwater quantity and quality issues for the islands with ‘Moderately stressed’ to ‘Very highly stressed’ classification.

Concept of Managed Aquifer Recharge (MAR)

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

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

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

Roof Water Recharging

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

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

Road Runoff Recharging

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

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

Recharging Ponds

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

Contour Drains

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

Application of Aquifer Modifications

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

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. However, based on the considered recharging options, roof recharging was not proposed for the island to shallow groundwater level (<0.75 m) within a residential area and it is suggested to use the existing dug well for roof recharging purposes and roof water after first flushing will be diverted to the existing well.

Road runoff recharging was proposed along selected fifteen (15) roads and the predicted groundwater enhancement is 37,955 m^3/year. Two sites located far from residential zones were selected for implementation of two (02) recharge ponds and it will be connected to the proposed road runoff recharge system. The predicted groundwater enhancement due to the recharging ponds is 24,327 m^3/year. Furthermore, the construction of a barrier wall as an aquifer modification option is considered to prevent seawater flooding and manage groundwater quality.

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. Four (04) recharging options (roof water recharging, road runoff recharging, recharging ponds and aquifer modification) were considered for the islands based on the characteristics identified through the baseline surveys. Two types of recharging wells are identified and the road runoff recharging option is proposed along selected 20 roads. Two sites located far from residential zones are selected for the implementation of two (02) recharge ponds. The predicted groundwater enhancement due to the proposed recharging options of roof water recharging, road runoff recharging and recharging ponds are 35,682 m^3/year, 101,90 m^3/year, and 66,555 m^3/year respectively. Furthermore, the construction of a barrier wall as an aquifer modification option is considered to prevent seawater flooding and manage groundwater quality.

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. Four (04) recharging options (roof water recharging, road runoff recharging, recharging ponds and aquifer modification) were considered for the islands based on the characteristics identified through the baseline surveys. Two types of recharging wells are identified and the road runoff recharging option is proposed along selected 13 roads. A site located far from residential zones is selected for the implementation of a recharge pond. Furthermore, the construction of a barrier wall as an aquifer modification option is considered to prevent seawater flooding and manage groundwater quality. The predicted groundwater enhancement due to the proposed recharging options of roof water recharging, road runoff recharging, recharging ponds and aquifer modification are 53,059 m^3/year, 122,555 m^3/year, 46,512 m^3/year, and 831 m^3/year, respectively.

Ha. Uligan

The land extent of the island is about 109 ha where 80% of the land use can be identified as thick vegetation. Four (04) recharging options (roof water recharging, road runoff recharging, recharging ponds, contour drains and contour drains) were considered for the islands based on the characteristics identified through the baseline surveys. Two types of recharging wells are identified and the road runoff recharging option is proposed along selected 15 roads. Two sites located far from residential zones were selected for the implementation of two (02) recharge ponds. Furthermore, the construction of contour drains is considered with the aim of improving the infiltration capacity of the forest and unused lands. The predicted groundwater enhancement due to the proposed recharging options of roof water recharging, road runoff recharging, contour drains and recharging ponds are 53,160 m^3/year, 155,975 m^3/year, 122,247 m^3/year, and 1,704 m^3/year respectively.

Ha. Molhadhoo

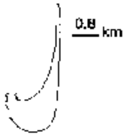
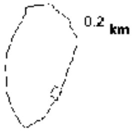
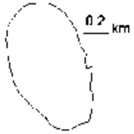
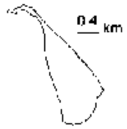
The land extent of the island is about 109 ha where 80% of the land use can be identified as thick vegetation. All three (03) recharging options (roof water recharging, road runoff recharging, recharging ponds and aquifer modification) were considered for the islands based on the characteristics identified through the baseline surveys. One type of recharging well is identified and the road runoff recharging option is proposed along selected 15 roads. Two sites located far from residential zones were selected for the implementation of two (02) recharge ponds. The predicted groundwater enhancement due to the proposed recharging options of roof water recharging, road runoff recharging and recharging ponds are 52,330 m^3/year, 183,759 m^3/year, and 173,808 m^3/year respectively.

Recommendation for Detailed Design

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

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

Summary of feasibility and conceptual design findings for proposed recharge structures

Atoll	Haa Alifu	Haa Alifu	Haa Alifu	Haa Alifu	Haa Alifu
Island	**Filladhoo**	**Maarandhoo**	**Muraidhoo**	**Uligan**	**Molhadhoo**
Shape of the Island					
Proposed Recharge Structures					
Roof Water Recharging	Yes	Yes	Yes	Yes	Yes
Road runoff recharging	Yes	Yes	Yes	Yes	Yes
Recharging pond	Yes	Yes	Yes	Yes	Yes
Aquifer modification/ Barrier wall	Yes	Yes	Yes	No	No
Contour Drain	No	No	No	Yes	No
Yearly Recharging Potential of Recharge Structures					
Roof Water Recharging Structures					
FromType A Recharging Wells	-	6,484	24,975	9,672	52,331
From Type B Recharging Wells	-	29,198	28,084	43,488	-
Total	-	35,682	53,059	53,160	52,331
Road runoff recharging	143,732	26,860	89,465	117,176	102,751
Recharging pond	24,327	66,555	46,512	86,904	173,808
Application Aquifer modification					
Proposed Aquifer Modification Method	Barrier Wall	Barrier Wall	Barrier Wall	-	-
Expected Construction Costing for Recharge Structures					
Roof Water Recharging Structures					
Type A Recharging Wells (MVR)	-	702,000	1,908,000	792,000	2,106,000
Type B Recharging Wells (MVR)	-	1,950,000	1,325,000	2,200,000	-
Road runoff recharging					
Drain (MVR)	37,908,000	33,736,500	29,880,900	39,568,500	22,720,500
Recharging pit (MVR)	3,534,300	3,156,300	2,797,200	3,685,500	2,116,800
Recharging pond (MVR)	1,100,000	1,100,000	550,000	1,100,000	1,100,000
Application Aquifer modification					
Rock and earth (MVR)	4,025,000	1,470,000	969,500	-	-
Estimated construction cost (MVR)	46,567,300	42,114,800	37,430,600	47,346,000	28,043,300
Estimated Operation and Maintenance cost (MVR)	1,397,019	1,263,444	1,122,918	1,420,380	841,299
Validation of The Proposed Recharge Structures					
Catchment Area for Drain Network (m^2)	51,327	49,287	76,967	64,549	48,295
Aggregate runoff coefficient for the catchment area	0.44	0.45	0.47	0.31	0.27
Max. Return Period than Overland Flow Could Managed					
During Normal Rainfall Event (3 Hr. rainfall)	40% of 2 Yr	25 Yr	2 Yr	25 Yr	25 Yr
Extreme Events (30 min rainfall)	7% of 2 Yr	31% of 2 Yr	18% of 2 Yr	36% of 2 Yr	45% of 2 Yr
Extreme Events (1 Hr. rainfall)	15% of 2 Yr	63% of 2 Yr	38% of 2 Yr	91% of 5 Yr	73% of 2 Yr

1 INTRODUCTION

1.1 Background

The Republic of Maldives is a low lying atoll in the Indian Ocean situated about 670 km southwest of Sri Lanka. The 1,196 coral islets of this archipelagic state are administratively grouped into 26 atolls spread over an area of 90,000 km^2 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 km^2. 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

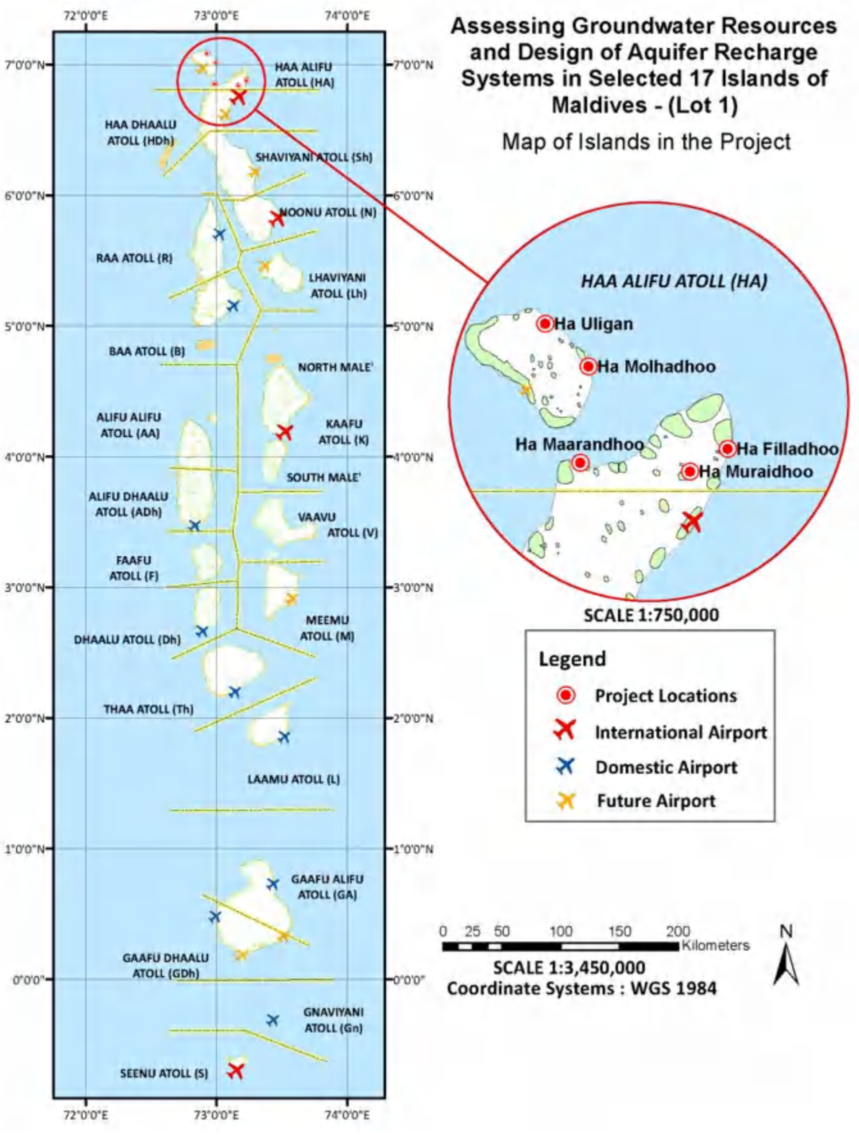


Figure 1-1: Location Map of Selected Six islands in Lot 1

1.3 Structure of the Report

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

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

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

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

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

2 BASIC REQUIREMENTS FOR MANAGED AQUIFER RECHARGE (MAR)

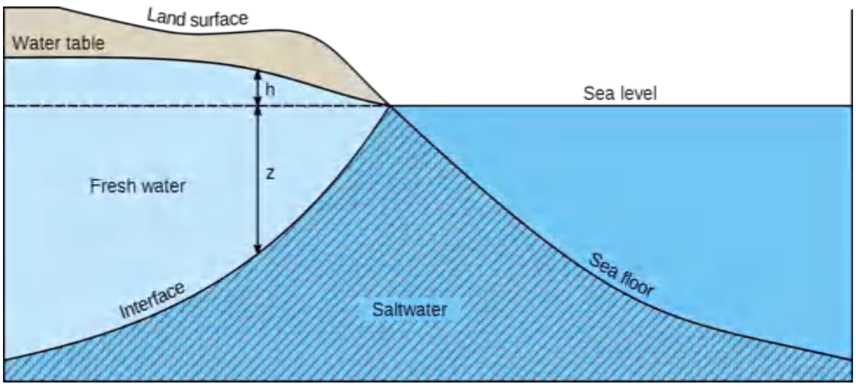
This section briefly outlines the background of groundwater in the Maldives, a vital source of information for the reader in order to understand the broader context of overall water resources management in the island nation. The groundwater occurrence of the islands is discussed based on the available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

2.1 Groundwater Occurrence in the Maldives Islands

2.1.1 Seawater and Freshwater Relationship

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

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



$Z = h \times \rho_f / (\rho_s - \rho_f)$
ρ_s = Density of freshwater
ρ_f = Density of sea water
Z = 40 h

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

2.1.2 Natural Groundwater Recharge and Variation of Groundwater Level

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

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

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

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

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

2.1.2.2 Groundwater level variation due to tidal effect

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

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

2.1.2.3 Addition of wastewater as groundwater

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

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

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

2.2 Managed Aquifer Recharge and Different Options for Groundwater Recharge

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

Compared to surface water storage, the Managed Aquifer Recharge significantly reduces the evaporation loss and needs a smaller land requirement. Managed Aquifer Recharge can also be located close to areas of high demand, can treat water in the aquifer, and can be upscaled to meet the ever-growing water requirements.

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

2.2.1 Source Water Availability

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

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

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

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

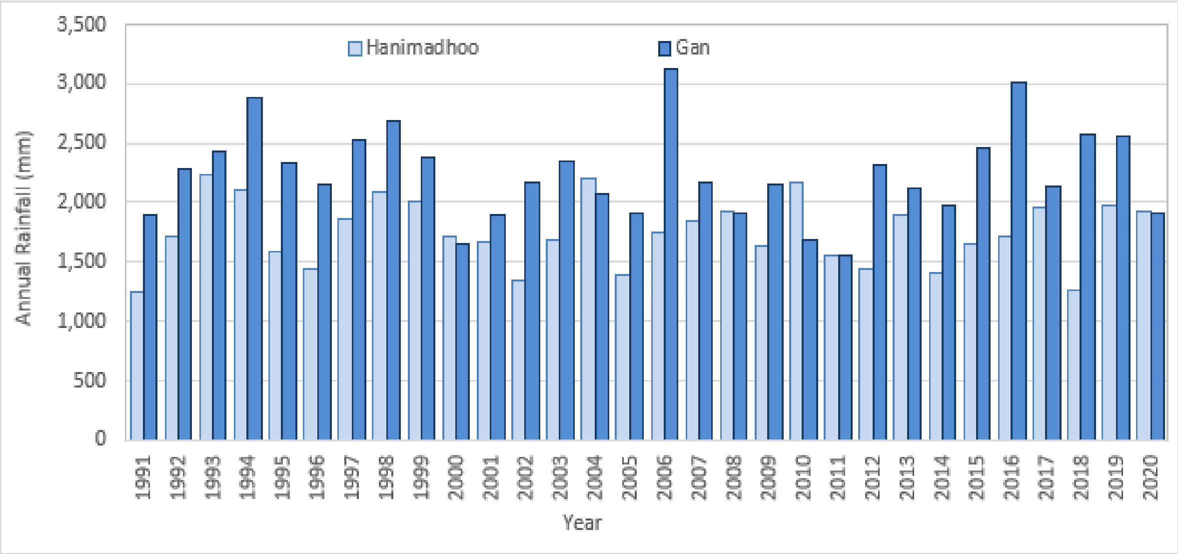


Figure 2-2: Annual rainfall based on past 30 years of data in Hanimaadhoo and Kadhdhoo islands (1991-2020)

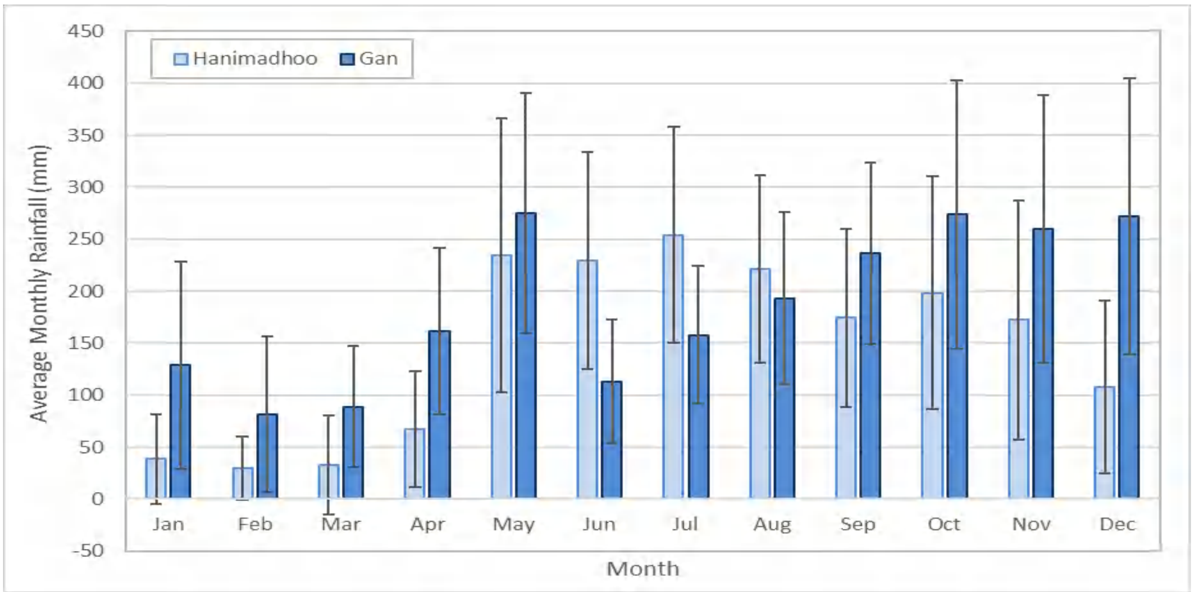


Figure 2-3: Average monthly rainfall and its variation at Hanimaadhoo and Kadhdhoo islands (1991-2020)

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

2.2.2 Different Options for Groundwater Recharge and Management of Overland Flow

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

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

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

2.2.2.1 Roof Water Recharging

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

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

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

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

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

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

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

Table 2.2: Categorization of roof types

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

Table 2.3: Proposed recharging well types

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

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

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

2.2.2.2 Road Runoff Recharging

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

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

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

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

2.2.2.3 Recharging Ponds

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

2.2.2.4 Contour Drains

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

2.2.2.5 Application of Aquifer Modifications

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

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

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

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

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

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

3 HYDROLOGY AND DRAINAGE

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

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

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

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

3.1 General Overview of Climate in the Maldives Islands

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

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

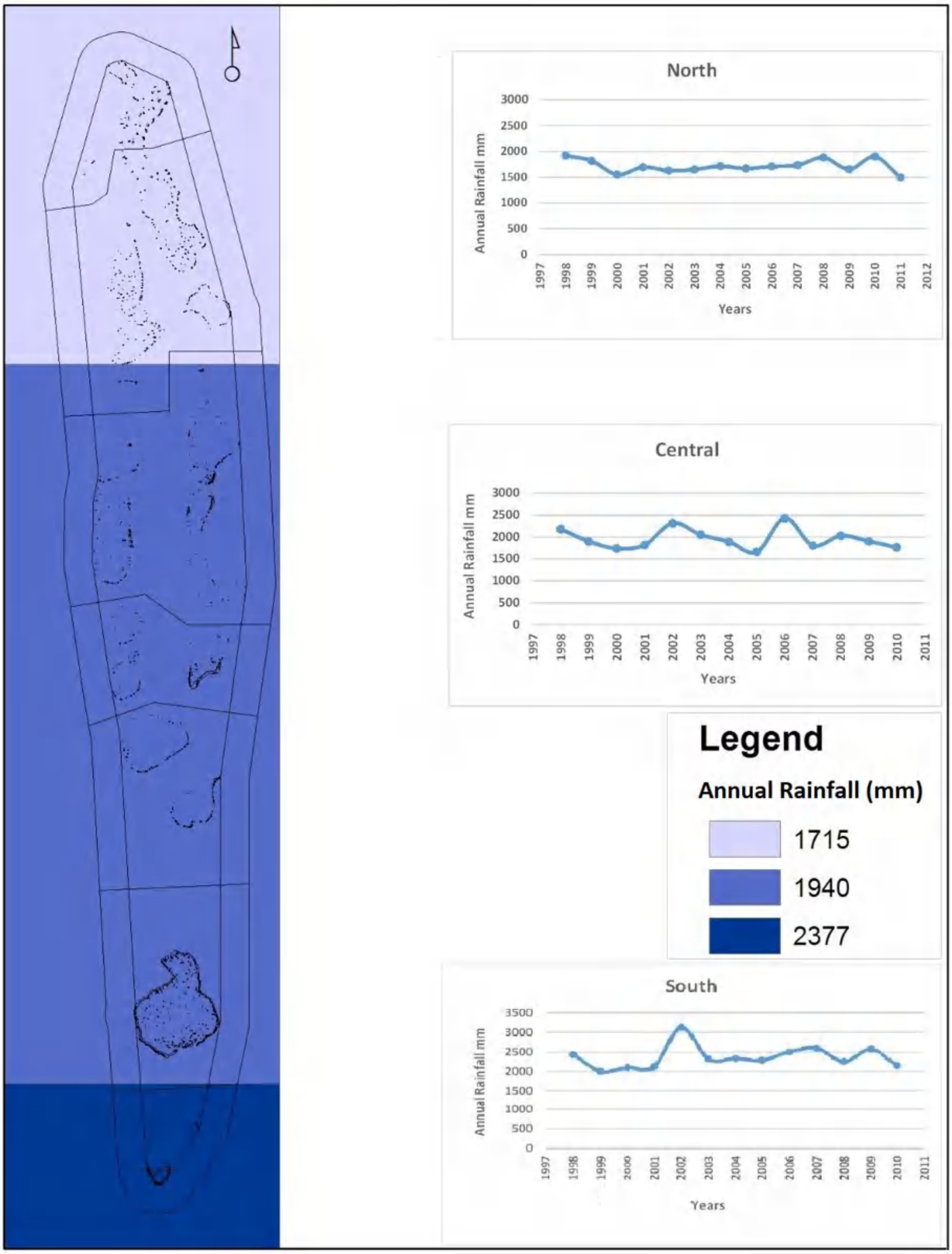


Figure 3-1: Rainfall Variation from South to North in Maldives (Wickramagamage, 2017)

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

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

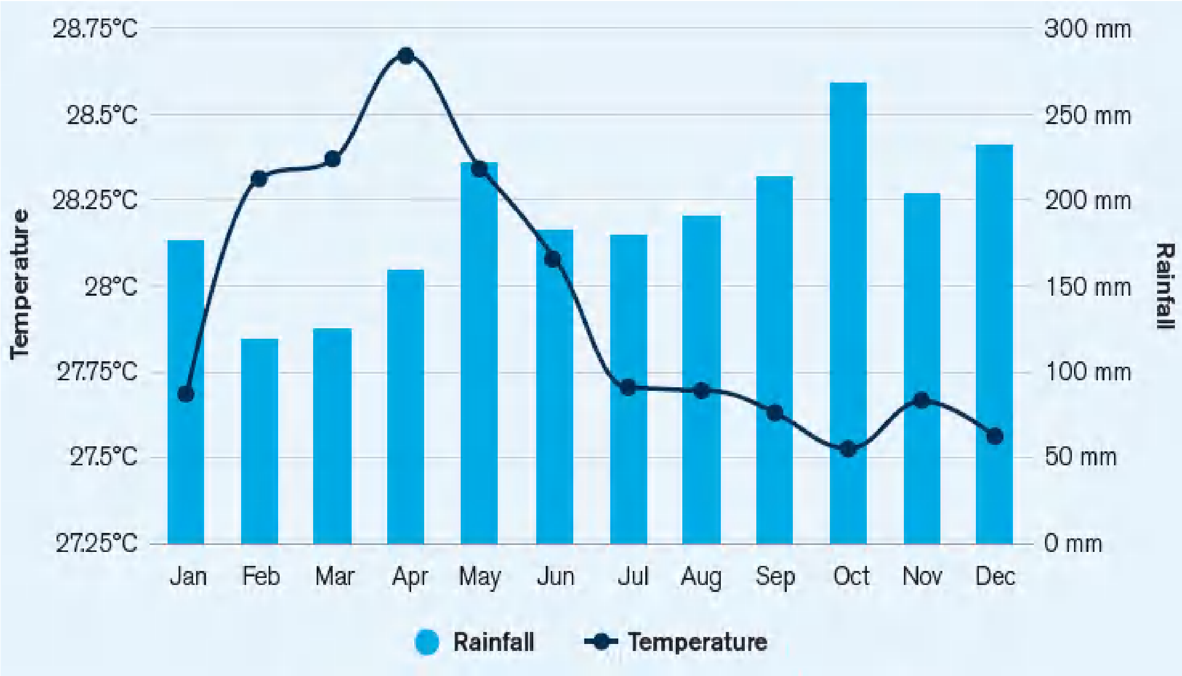


Figure 3-2: Average monthly temperature and rainfall in the Maldives, 1991–2019 (CCKP, 2020)

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

Trend in Temperature

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

Trend in Precipitation

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

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

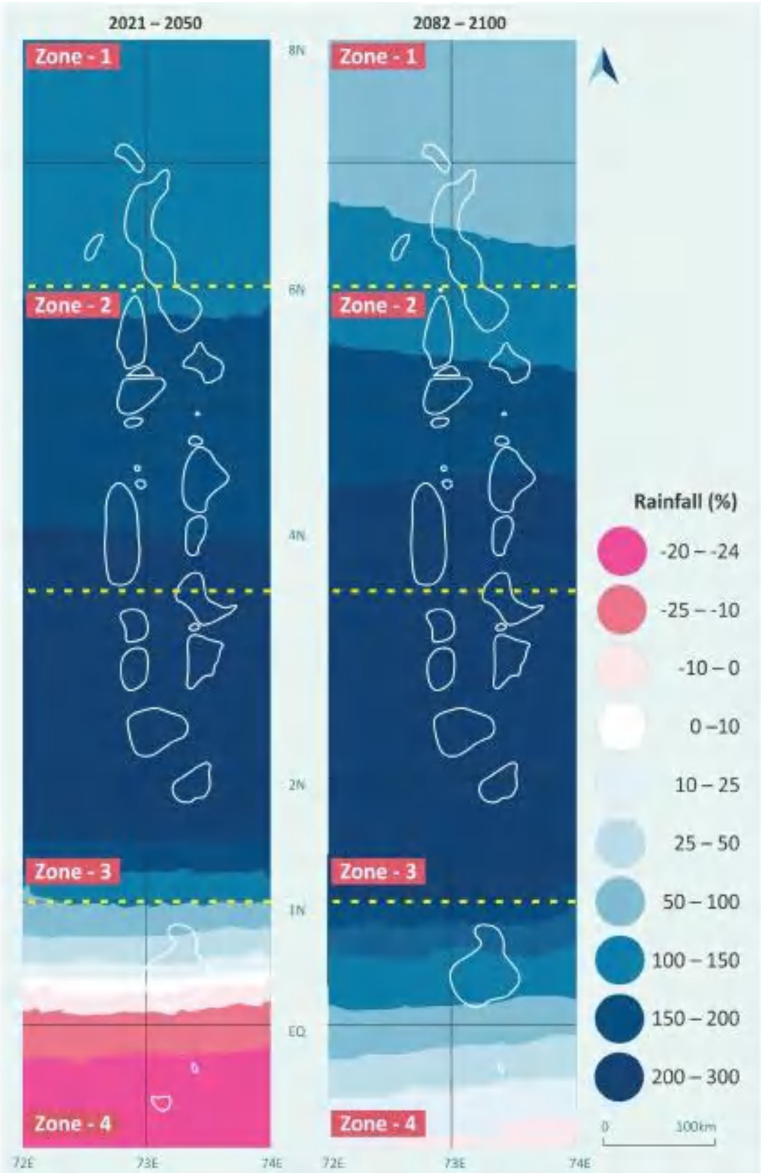


Figure 3-3: Average changes in monsoonal rainfall from IPRC RegCM scenario for time slices (2021-2050) and (2082-2100) from baseline (1980-2000)

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

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

3.2 Recent Rainfall Trends in the Maldives Islands

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

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

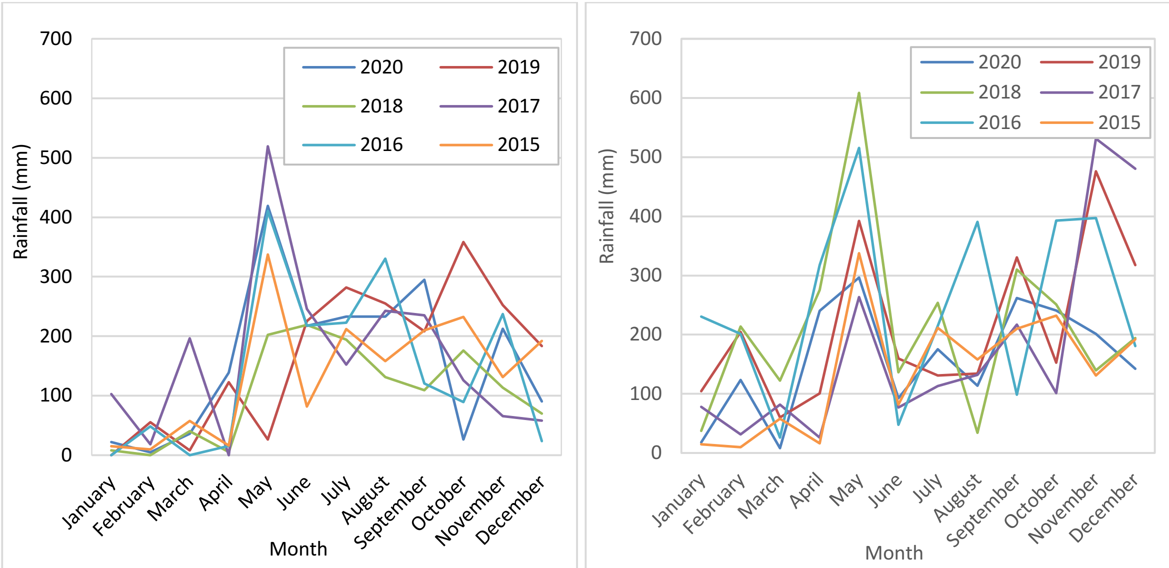


Figure 3-4: Monthly rainfall variation in Hanimaadhoo (Left) and Kadhdhoo (Right) from 2015-2020

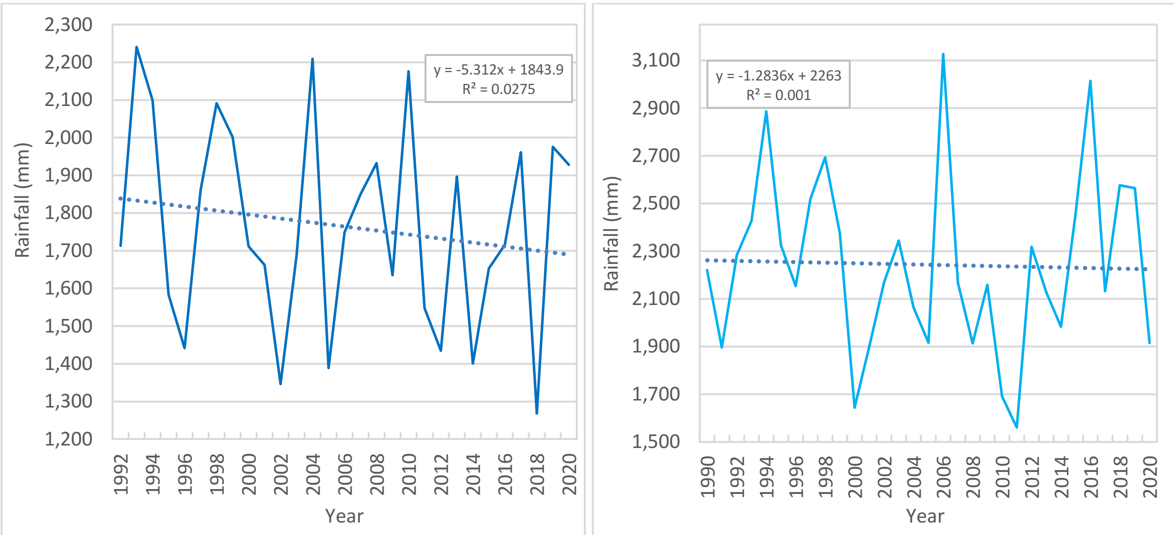


Figure 3-5: Annual rainfall variation in Hanimaadhoo (Left) and Kadhdhoo (Right) from 1990 - 2020

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

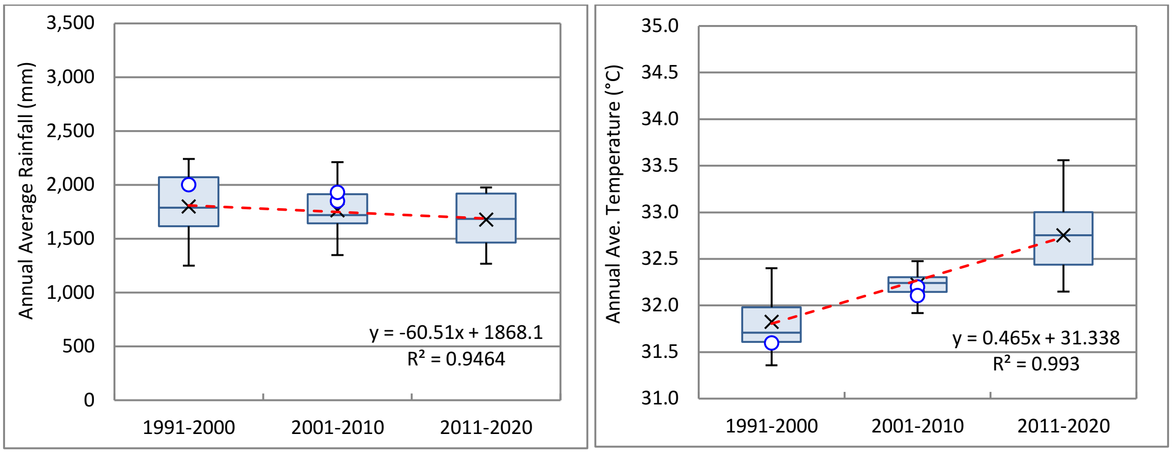


Figure 3-6: Decadal means and trend for rainfall and temperature in Hanimaadhoo (1990 - 2020)

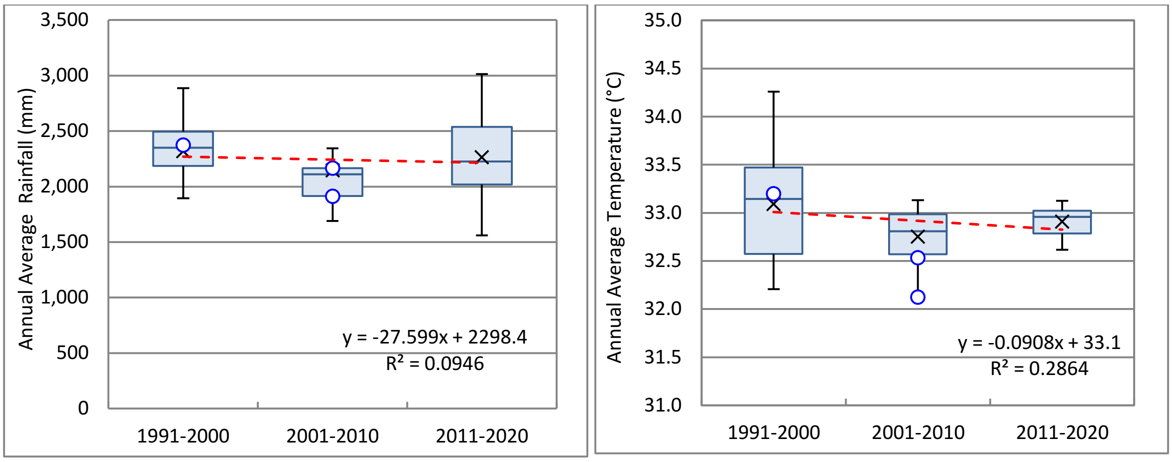


Figure 3-7: Decadal means and trend for rainfall and temperature in Kadhdhoo (1990 - 2020)

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

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

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

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

3.3 Rainfall Characteristics Data for Recharge Estimation in the Selected Islands

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

3.3.1 Distinct Characteristics in Annual Rainfall Series

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

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

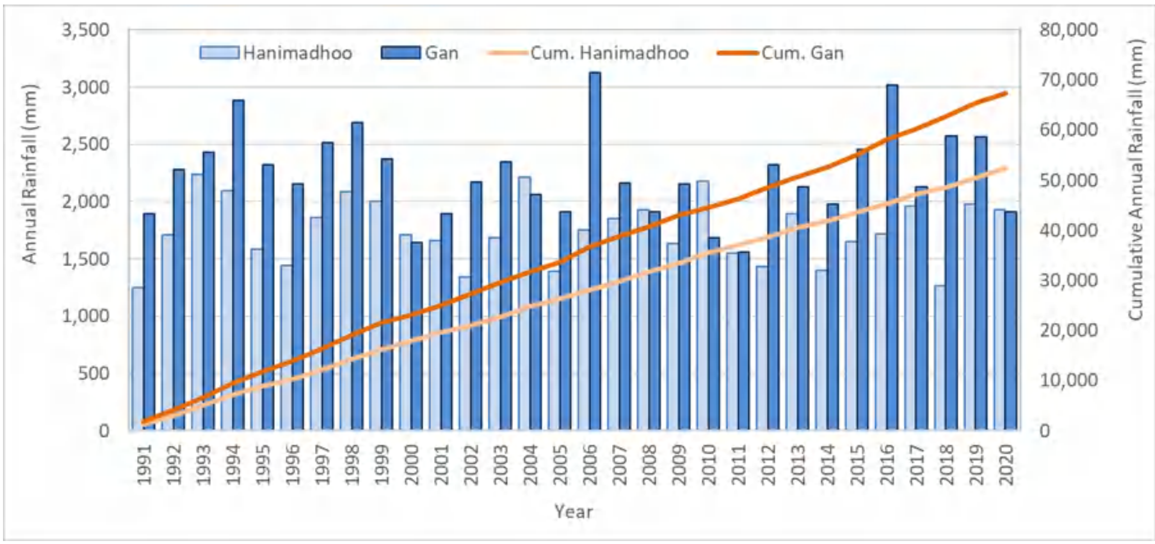


Figure 3-8: Annual rainfall based on past 30 years of data in Hanimaadhoo and Kadhdhoo islands

3.3.2 Monthly Rainfall Variations in Northern and Southern Islands

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

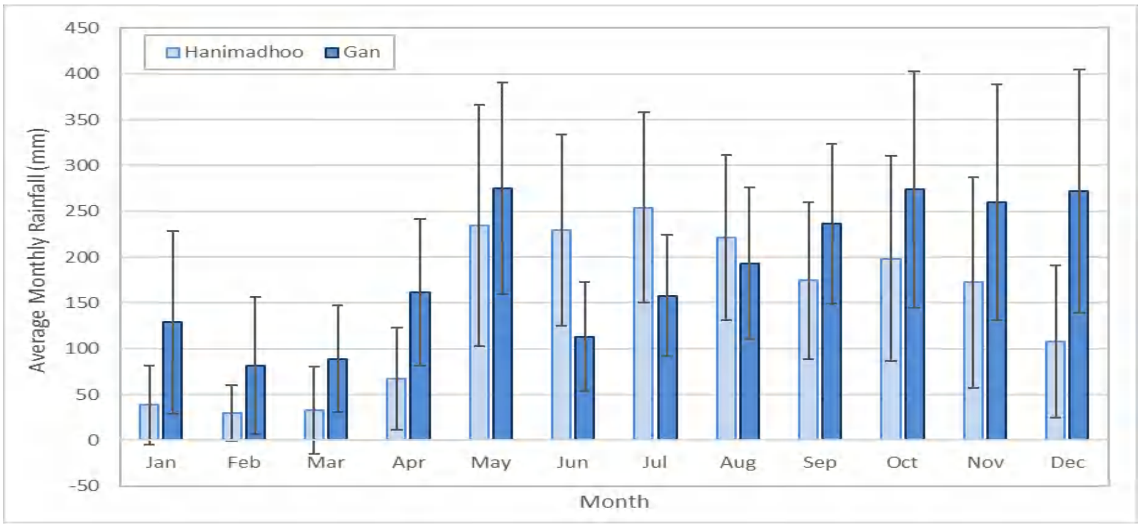


Figure 3-9: Monthly average rainfall based on past 30 years in Hanimaadhoo and Kadhdhoo islands

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

3.3.3 Rainfall Intensity for Recharge Estimation

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

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

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

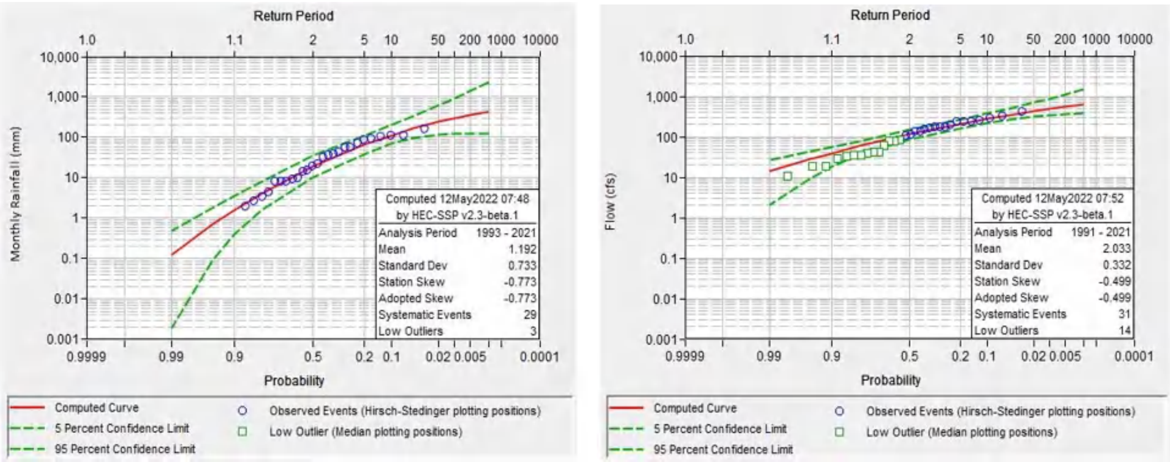


Figure 3-10: Probabilistic plot of Monthly rainfall in Hanimaadhoo (Left) and Kadhdhoo islands (Right) for the Month of January (Dry Period)

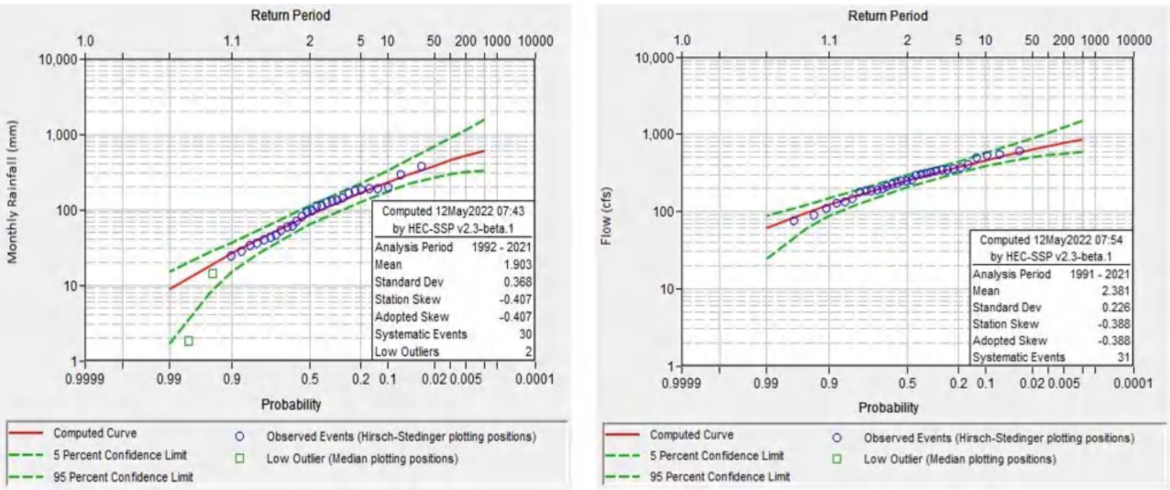


Figure 3-11: Probabilistic plot of Monthly rainfall in Hanimaadhoo (Left) and Kadhdhoo islands (Right) for the Month of December (Wet Period)

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

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

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

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

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

3.4 Runoff Coefficients for Roof Runoff and Overland Flow Estimation

The roof runoff and direct overland flow, equivalent to the resultant excess rainfall used to estimate the accumulation of potential recharge volume over an impervious or partially impervious area, are calculated based on the above 50% probabilistic rainfall incidence (in mm) falling on top of a particular area of concern (in m^2) and by applying the concept of runoff coefficient.

The distinct runoff coefficients used for different roof materials (Thomas and Martinson, 2007) and different land use types (Tsutsumi et al.,2009) for estimating runoff volume calculations are presented in Table 3.2 to Table 3.4.

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

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

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

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

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

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

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

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

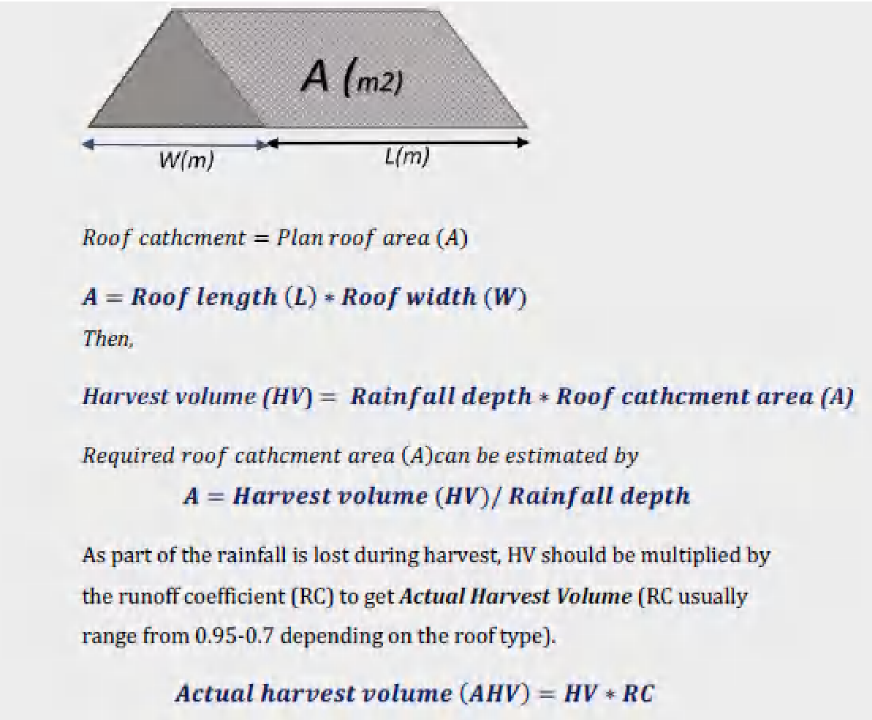


Figure 3-12: Methodology and equations for obtaining the Plan roof area (Source: NBRO, 2021)

The same procedure may be applied for any surface drainage flow or volume estimates as necessary by referring to Table 3.3 and Table 3.4.

4 METHODOLOGY AND CALCULATIONS FOR CONCEPTUAL DESIGNS

Summary of the Methodology Carried out for the Baseline Assessment

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

4.1 Geological and Hydrogeological Aspects for Feasibility and Concept Design

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

4.2 Conceptual Designs of Proposed MAR System (MAR)

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

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

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

4.3 Assumptions and Major Considerations in Conceptual Designs

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

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

Northern islands

Table 4.1: Average rainfall data used for the northern island

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

Note: Daily maximum for year = 39.08 mm.

4.4 Calculations for Conceptual Designs of Proposed MAR system for HA Maarandhoo

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

4.4.1 Assessment of Unsaturated Area

The selected zone for groundwater recharging is the upper part of the geological profile depending on the groundwater level of the particular area. The distribution of thickness of the unsaturated zone of the Maarandhoo island is given in Figure 4–1 and Table 4.2.

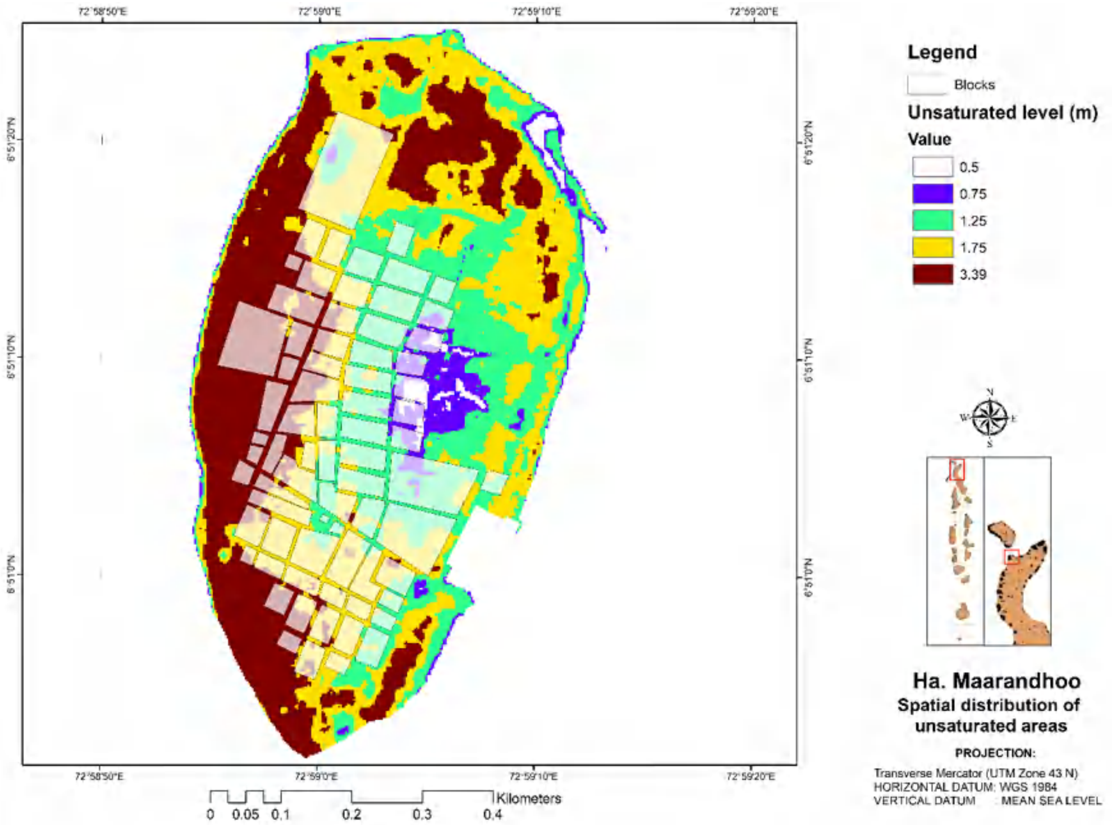


Figure 4–1: Spatial distribution of unsaturated areas in Maarandhoo

Table 4.2: Distribution of unsaturated areas within Maarandhoo

Thickness of the Unsaturated Zone(m)	Area(m^2) and Percentages (%)
Less than 0.5	11,215 (3.32%)
0.5-0.75	17,608 (5.22%)
0.75-1.25	91,817 (27.20%)
1.25-1.75	112,979 (33.46%)
More than 1.75	103,982 (30.80%)

About 91.46% of land area (thickness of unsaturated zone > 0.75 m) in the island is available for groundwater recharging activities through roof water recharging, road runoff recharging, recharging ponds, and aquifer modification. The unsaturated thickness in the middle part of the land mainly in the forest areas is less than o.75 m and these areas are only suitable for recharging ponds.

4.4.2 Recharging Using Roof Water

The residential plots are located in the mainly southwestern part of the island. Some rainwater is currently used (rainwater harvesting) for domestic purposes and the balance amount is either diverted to the free space of the land block or to the adjoining roads.

4.4.2.1 Distribution of roof areas and design volume of recharging well

The roof sizes of the island vary from 3 m^2 to 959 m^2 and three different roof sizes (Type 1: 59 m^2, Type 2: 118 m^2, and Type 3: 167 m^2 have been selected for the conceptual design using probability exceedance (75%, 50%, and 25%) curves (Figure 4–2).

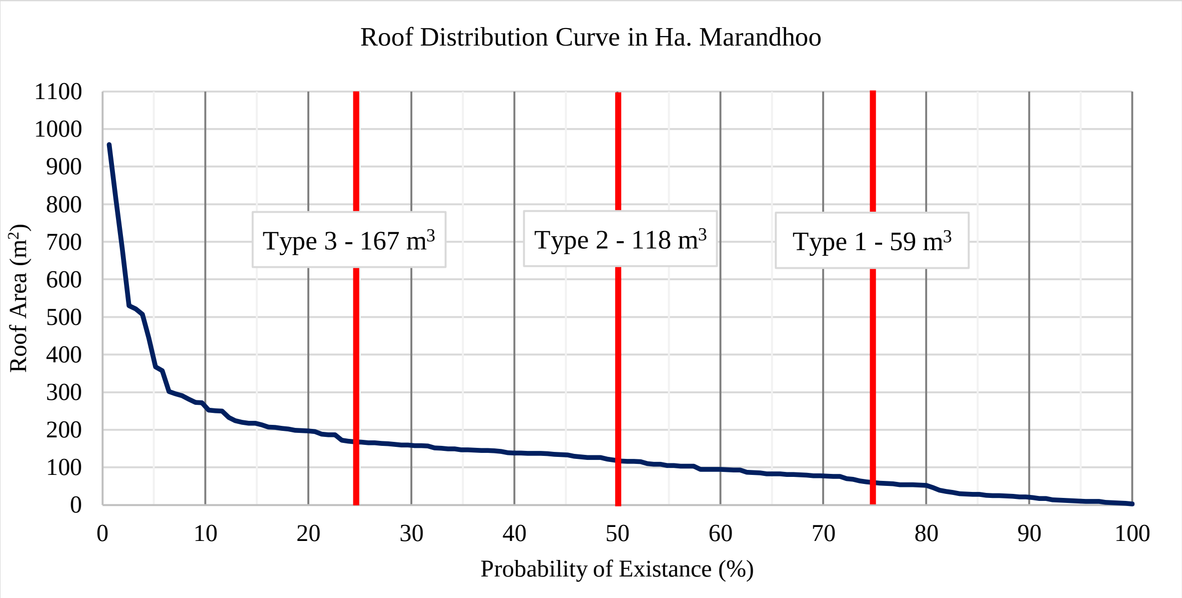


Figure 4–2: Distribution curve for roof areas in Maarandhoo

As per the roof runoff estimation, Type 1, Type 2, and Type 3 roofs generate volumes of about 2.07 m^3, 4.15 m^3, and 5.87 m^3 respectively per day event (rainfall= 39.08 mm). The design volume of recharging wells is given in Table 4.3.

Table 4.3: Design of recharging volume

Type	Roof Area(m^2)	Design Volume(m^3/d)
Type 1 (75 % of roof area)	59	2.07
Type 2 (50% of roof area)	118	4.15
Type 3 (25% of roof area)	167	5.87

4.4.2.2 Conceptual design of recharging well

The average hydraulic conductivity (4.15 m/d) was considered to estimate the potential recharging volume of the proposed size of the recharging well and the number of recharging wells for the island. The potential recharging volumes of proposed structures are given in Table 4.4.

Table 4.4: Potential recharging volume of proposed structures

Type	Roof Area (m^2)	Proposed Recharging Well				Total Storage of the pit (m^3)	Total Daily Recharge Volume(m^3/d)
		Well Type	Depth (m -bgl)	Diameter (m)	Number of Recharging Well		
Type 1	59	A	1.5	1.0	1	0.78	3.26
Type 2	118	B	1.5	1.5	1	1.76	7.34
Type 3	167	B	1.5	1.5	1	1.76	7.34

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

The predicted monthly and yearly groundwater recharging volumes through two well types are given in Table 4.5 and Table 4.6.

Table 4.5: Monthly predicted recharging volume through proposed recharging wells.

Month	Recharging Volume for Type A (m^3)	Type B (m^3)
January	39 x 1 x 3.26=127.14	78 x 1 x 7.34= 572.52
February	39 x 1 x 3.26=127.14	78 x 1 x 7.34= 572.52
March	39 x 1 x 3.26=127.14	78 x 1 x 7.34= 572.52
April	39 x 2 x 3.26=254.28	78 x 2 x 7.34= 1145.04
May	39 x 6 x 3.26=762.84	78 x 6 x 7.34= 3435.12
June	39 x 7 x 3.26=889.98	78 x 7 x 7.34= 4007.64
July	39 x 7 x 3.26=889.98	78 x 7 x 7.34= 4007.64
August	39 x 7 x 3.26=889.98	78 x 7 x 7.34= 4007.64
September	39 x 5 x 3.26=635.70	78 x 5 x 7.34= 2862.60
October	39 x 6 x 3.26=762.84	78 x 6 x 7.34= 3435.12
November	39 x 5 x 3.26=635.70	78 x 5 x 7.34= 2862.60
December	39 x 3 x 3.26=381.42	78 x 3 x 7.34= 1717.56
Total	6,484.14	29,198.52

Table 4.6: Total potential of the yearly roof recharging volume

Category of Recharging Well	No of Recharging Structures Proposed	Total Recharging Volume per year (m^3)
Type A	39	6,484.14
Type B	78	29,198.52
Total	**117**	**35,683**

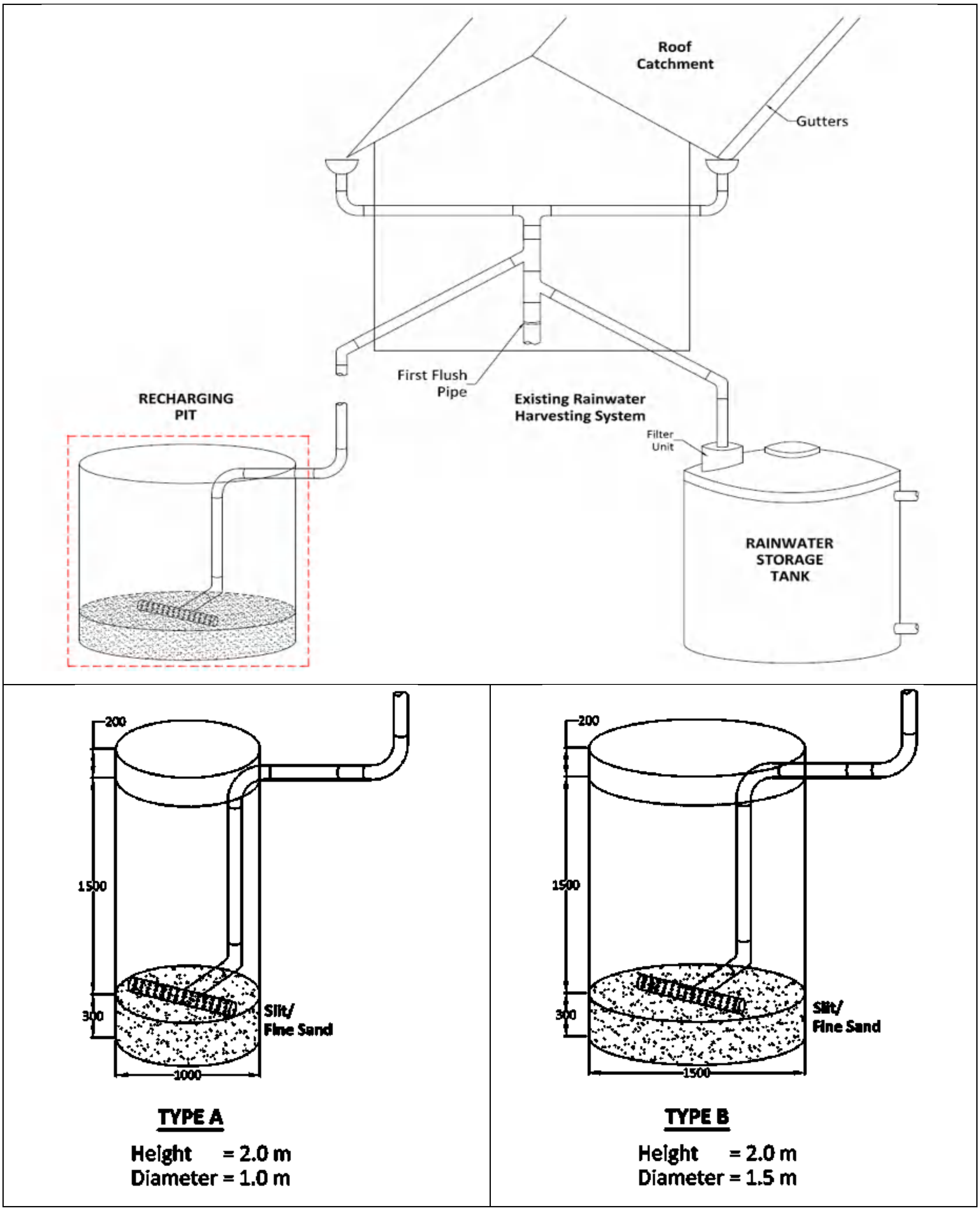


Figure 4–3: Conceptual drawing for the recharging well

4.4.3 Road Runoff Recharging

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

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

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

The runoff volume along the selected road is calculated by considering the runoff coefficient (0.6) and daily maximum average rainfall per month (39.08 mm). The estimated total runoff along each road is given in following Table 4.7.

Table 4.7: Estimated runoff along the selected roads

Road	Road Area (m^2)	Length of the Road (m)	Width of the Road (m)	Estimated Runoff in the Road (m^3/d)
Road 1	6,250	625	10	6,250 x 0.6 x 0.03908 =146.55
Road-2	2,880	480	6	2,880 x 0.6 x 0.03908 =67.53

Road	Road Area (m^2)	Length of the Road (m)	Width of the Road (m)	Estimated Runoff in the Road (m^3/d)
Road-3	2,244	374	6	2,244 x 0.6 x 0.03908 =52.62
Road-4	1,260	210	6	1,260 x 0.6 x 0.03908 =29.54
Road-5	1,260	210	6	1,260 x 0.6 x 0.03908 =29.54
Road-6	1,110	185	6	1,110 x 0.6 x 0.03908 =26.03
Road-7	930	155	6	930 x 0.6 x 0.03908 =21.81
Road-8	960	160	6	960 x 0.6 x 0.03908 =22.51
Road-9	228	38	6	228 x 0.6 x 0.03908 =5.35
Road-10	522	87	6	522 x 0.6 x 0.03908 =12.24
Road-11	1,008	168	6	1,008 x 0.6 x 0.03908 =23.63
Road-12	1,158	193	6	1,158 x 0.6 x 0.03908 =27.15
Road-13	1,038	173	6	1,038 x 0.6 x 0.03908 =24.34
Road-14	510	85	6	510 x 0.6 x 0.03908 =11.96
Road-15	570	95	6	570 x 0.6 x 0.03908 =13.36
Road-16	552	92	6	552 x 0.6 x 0.03908 =12.94
Road-17	2,320	290	8	2,320 x 0.6 x 0.03908 =54.40
Road-18	1,458	243	6	1,458 x 0.6 x 0.03908 =34.19
Road-19	1,200	200	6	1,200 x 0.6 x 0.03908 =28.14
Road-20	612	102	6	612 x 0.6 x 0.03908 =14.35
Total	26,810	4,165		657.88

The runoff contribution from the residential area covered with drains (Figure 4–5) is estimated by considering the runoff coefficient (0.5) and daily maximum average rainfall per month (39.08 mm).

Runoff contribution from residential area = Total area -(roof area + drain area)

Runoff contribution from residential area = (161,000 m^2) - (21,831x 90% +26810 x 80%)

= 161,000 m^2- 41,000 m^2 = 120,000 m^2

The estimated runoff volume = 120,000 x 0.03908 x 0.5= 2,344.8 m^3/d

The estimated runoff volume from drains and residential area= 2,344.8 m^3/d +657.88 m^3/d

The estimated runoff volume from drains and residential area = 3,002.68 m^3/d

Figure 4–5: Residential vacant area considered for calculation of runoff

4.4.3.1 Conceptual design of roadside drains and recharging pits

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

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

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

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

Proposed drain

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

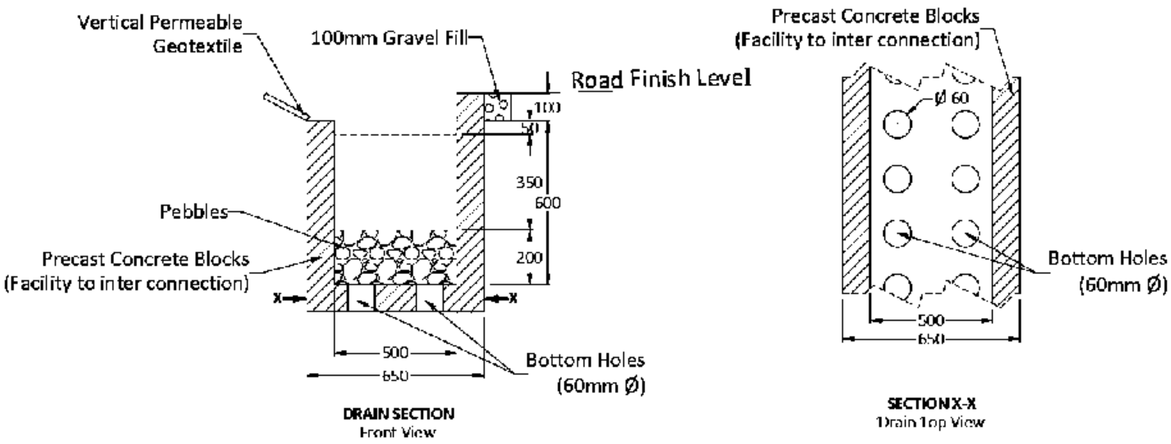


Figure 4–6: Cross section of the recharging drain

Proposed recharging pit

Width (m)	1
Length (m)	1
Depth (m)	1.5
Remark	The recharging pit will be filled with layers of pebble, sand, and silt to filter the stormwater before it is added to groundwater. Once the recharging pit is filled, excess water will flow to the adjoining pit through the open drain. The top of the recharging pit is 20 cm above the ground level and a concrete cover will be used for the recharging pit. The cross section of the recharging drain is given in Figure 4–7.

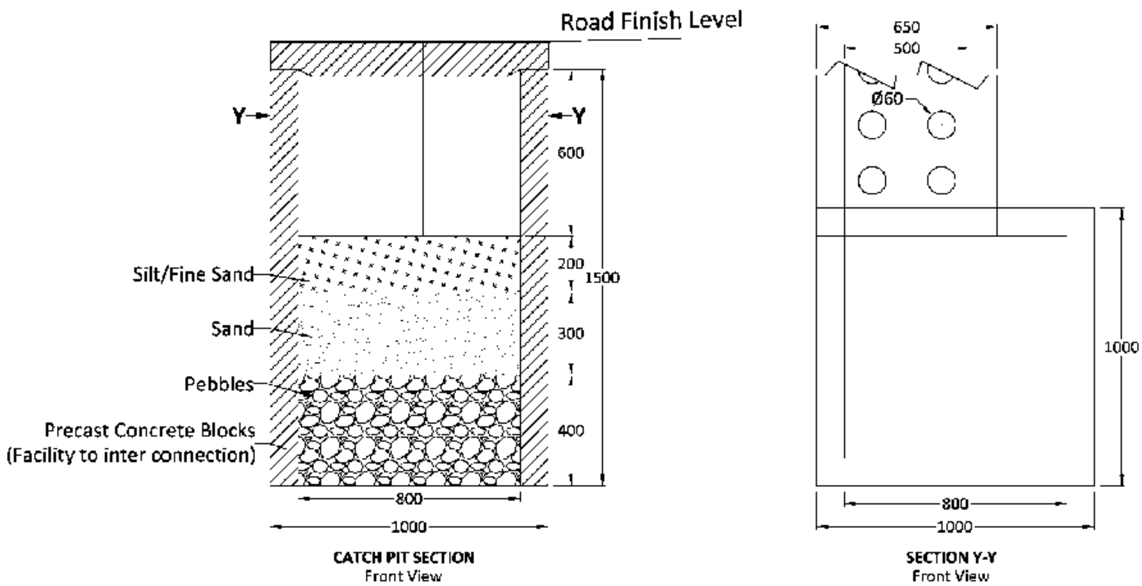


Figure 4–7: Cross section of the recharging pit

The required recharging pits and drains for the selected roads are given in Table 4.8.

Table 4.8: The potential recharge through drains and recharging pits

Selected Road and Length (m)	No. of Rechar. Pits	Rechar. Holes along the Drain (60 mm Ø)	Daily Recharging Volume (m^3)		Total Retention Volume (m^3) in Drains and Recharging pits	Total Managed Potential Daily Volume (m^3)
			Drains	Rechar. Pits		
Road 1(625 m)	25	10,800	127	103.75	(42.33+20.75) = 63.08	293.83
Road 2(480 m)	20	8,280	97	83.00	(32.33+16.6) = 48.93	228.93
Road 3(374 m)	15	6,462	76	62.25	(25.33+12.45) = 37.78	176.03
Road 4(210 m)	9	3,618	42	37.35	(14+7.47) = 21.47	100.82
Road 5(210 m)	9	3,618	42	37.35	(14+7.47) = 21.47	100.82
Road 6(185 m)	8	3,186	37	33.20	(12.33+6.64) = 18.97	89.17
Road 7(155 m)	7	2,664	31	29.05	(10.33+5.81) = 16.14	76.19
Road 8 (160 m)	7	2,754	32	29.05	(10.66+5.81) = 16.47	77.52
Road 9 (38 m)	2	648	7	8.3	(2.33+1.66) = 16.96	32.26
Road 10 (87 m)	4	1,494	17	16.6	(5.66+3.32) = 8.98	42.58
Road 11 (168 m)	7	2,898	34	29.05	(11.33+5.81) = 17.14	80.19
Road 12 (193 m)	8	3,330	39	33.20	(13+6.64) = 19.64	91.84
Road 13 (173 m)	7	2,988	35	29.05	(11.66+5.81) = 17.47	81.52
Road 14 (85 m)	4	1,458	17	16.6	(5.66+3.32) = 8.98	42.58
Road 15 (95 m)	4	1,638	19	16.6	(6.33+3.32) = 9.65	45.25
Road 16 (92 m)	4	1,584	18	16.6	(6+3.32) = 9.32	43.92
Road 17 (290 m)	12	5,004	59	49.80	(19.66+9.96) = 29.62	138.42
Road 18 (243 m)	10	4,194	49	41.5	(16.33+8.3) = 24.63	115.13
Road 19 (200 m)	8	3,456	40	33.20	(13.33+6.64) = 19.97	93.17
Road 20 (102 m)	4	1,764	21	16.6	(7+3.32) = 10.32	47.92
Total	174	71,838	839	722.9	437	1,998

The proposed drains, recharging pond, and recharging pits are capable of handling more volume than the predicted water accumulation along the roads and runoff contribution from residential areas covered by drains.

The Predicted monthly and yearly recharging volume through proposed drains and recharging pits are given in Table 4.9.

Table 4.9: Monthly predicted recharging volume through proposed recharging pits and drains

Month	Recharging Volume from Drains and Recharging Pits (m^3)
January	1,998.09 x 1 = 1,998.09
February	1,998.09 x 1 = 1,998.09
March	1,998.09 x 1 = 1,998.09
April	1,998.09 x 2 = 3,996.18
May	1,998.09 x 6 = 11,988.54
June	1,998.09 x 7 = 13,986.63
July	1,998.09 x 7 = 13,986.63
August	1,998.09 x 7 = 13,986.63
September	1,998.09 x 5 = 9,990.45
October	1,998.09 x 6 = 11,988.54
November	1,998.09 x 5 = 9,990.45
December	1,998.09 x 3 = 5,994.27
Yearly Total	101,903

4.4.4 Recharging pond

The overland flow water in the area around the recharging pond and excess water in the roadside drains will be diverted to the proposed recharging pond (Figure 4–8). Two recharging ponds are proposed for the island. The details of the recharging pond are given below.

Width (m)	10.0
Length (m)	15.0
Depth (m)	1.0 below ground level
Height of the Gabion Wall	1.5 m (0.5 m above the ground level)
Remark	Gabion wall will be constructed for the recharging pond to avoid the direct mixing of the surface water to the recharging pond. About 0.25 m thick sand layer will be laid to filter stormwater before it is added to groundwater.
Retention Volume of the Pond (m^3)	60 m^3 from two ponds
Daily Recharging Volume (m^3)	1245 m^3 from two ponds
Total (m^3)	1305 m^3 from two ponds

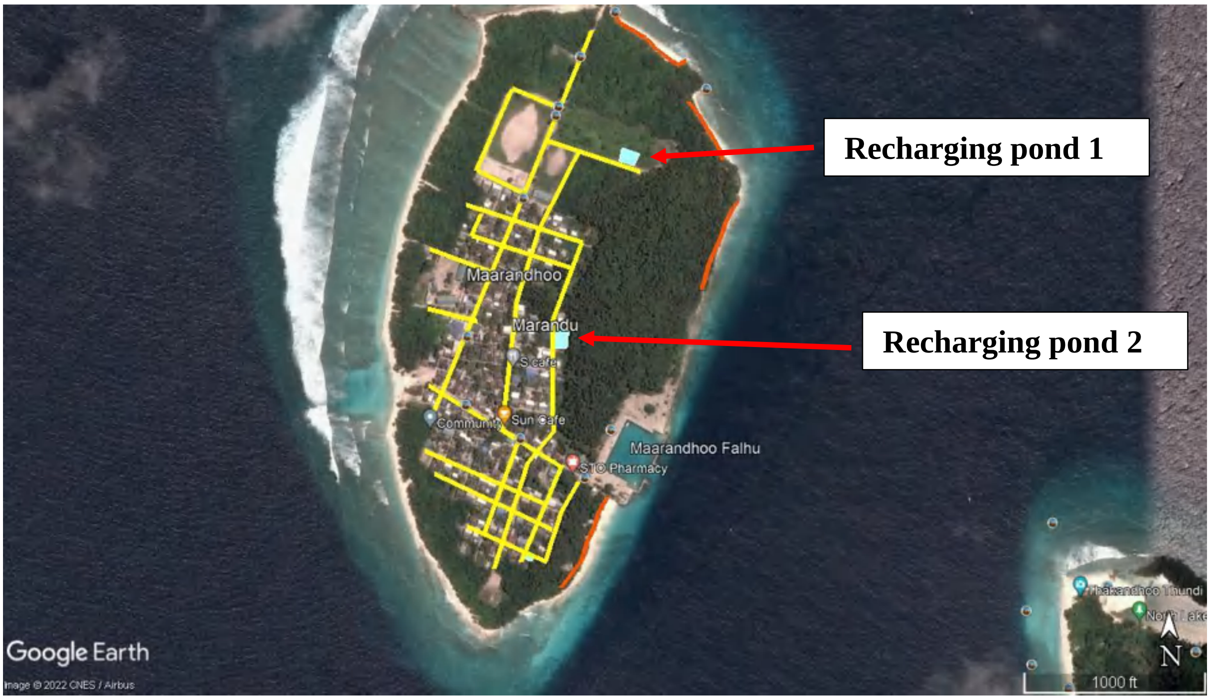


Figure 4–8: Location of recharging ponds

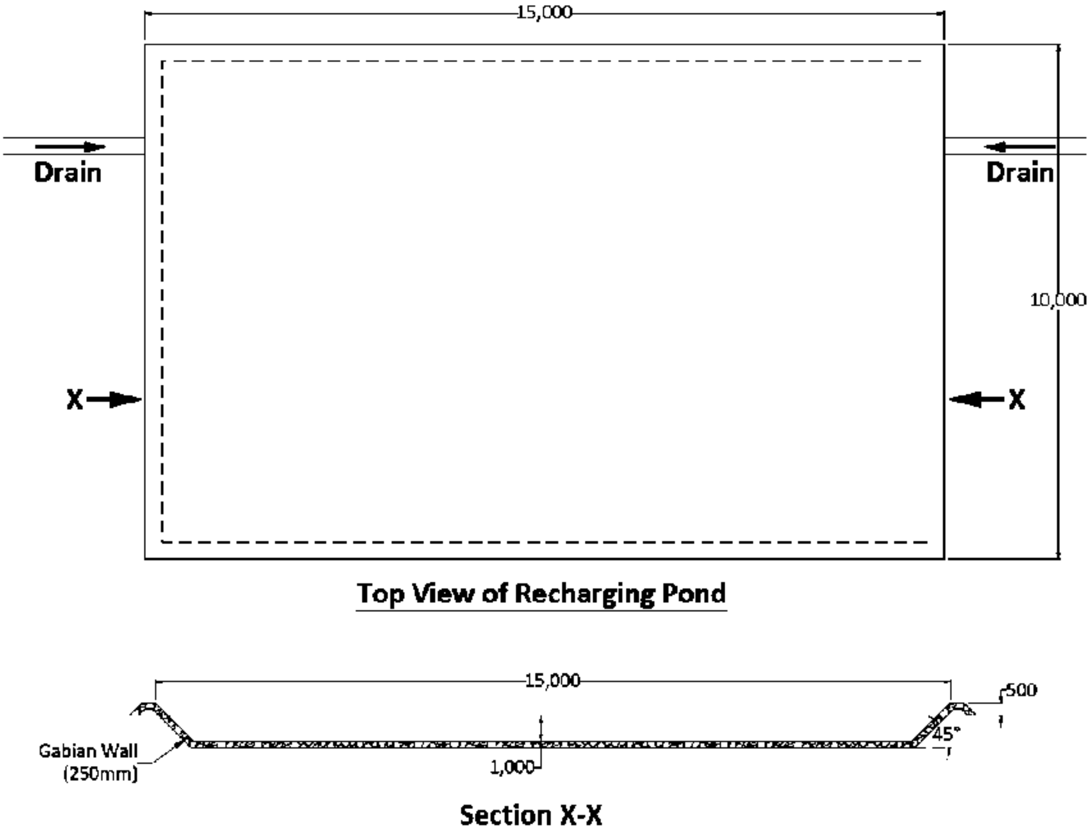


Figure 4-9: Proposed recharging pond

The Predicted yearly and monthly recharging volumes through the proposed recharging ponds are given in Table 4.10.

Table 4.10: Predicted yearly and monthly recharging volume through proposed two ponds

Month	Recharging Volume (m^3)
January	(1305) x 1=1,305
February	(1305) x 1=1,305
March	(1305) x 1=1,305
April	(1305) x 2=2,610
May	(1305) x 6=7,830
June	(1305) x 7=9,135
July	(1305) x 7=9,135
August	(1305) x 7=9,135
September	(1305) x 5=6,525
October	(1305) x 6=7,830
November	(1305) x 5=6,525
December	(1305) x 3=3,915
Yearly total	66,555

4.4.5 Aquifer Modification (construction of barrier walls)

It is noted that several seawater flooding areas along the northeastern and eastern coastal lines are observed. Also, flooded sea water is mixed with freshwater and deteriorates the fresh groundwater. Therefore, it is proposed to construct a barrier wall (Figure 4–10) along the marked areas to prevent seawater flooding in the northeastern and eastern parts of the island for managing the groundwater quality.

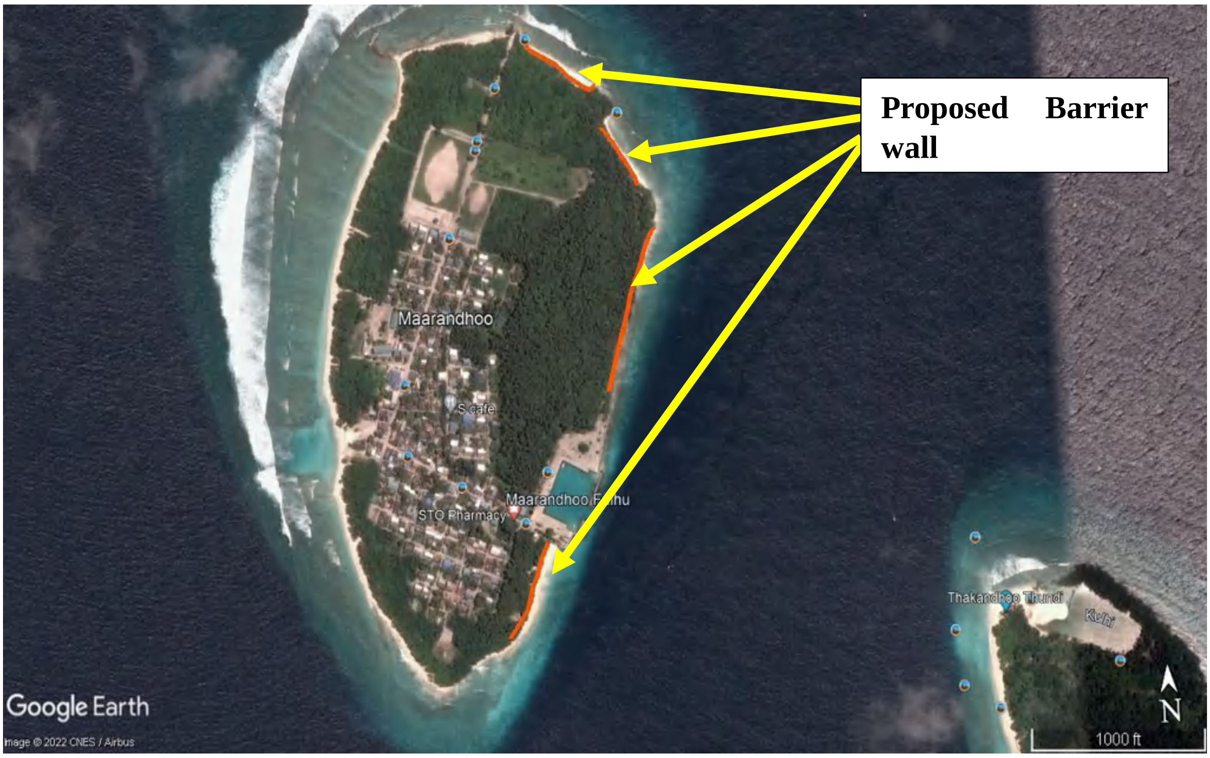


Figure 4–10: Proposed barrier wall for controlling the seawater flooding

As per the initial information, no freshwater is available along the coastal stretch and the groundwater level is close to the mean sea level. The expected outcome from the barrier is limited to the eastern part of the island and water level enhancement could not be expected. The groundwater quality in the eastern part will be improved gradually and freshwater lenses will be developed. The quantification of predicted groundwater quality enhancement could not be done due to a lack of baseline data along the northeastern and eastern coastal stretch.

The details of the liner and road are given below.

Height of the barrier	- 1.5 m above coastal line
Length of liner	- 840 m(four segments)
Width of barrier	- 4-5 m
Barrier material	- Rock and earth

4.4.6 Predicted Groundwater Enhancement In The Island

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

Table 4.11: Predicted groundwater enhancing quantities of Maarandhoo

Recharging Method	Predicted Groundwater Enhancing Quantity (m^3/year)
Roof recharging system	35,682
Road runoff recharging system	101,902
Recharging pond	66,555
Aquifer modification (barrier wall)	-
Total	204,139

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

Table 4.12: Comparison of available groundwater amount vs predicted additional recharge from MAR

Approaches	Predicted Groundwater Quantity(m^3/year)
Natural Recharge	
Water balance method	46,791
Indirect investigation through the resistivity method	58,262
MAR Schemes	
Predicted additional recharge from the roof, road runoff, and recharging pond	204,139

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

4.5 Social and Environmental Feasibility and Impact of Proposed MAR Systems

4.5.1 Ha. Maarandhoo

Table 4.13: Impact and Social and Environmental Feasibility of Proposed MAR Systems

Proposed Recharging Structure	Details of MAR System	Feasibility and Other Remarks
Recharging well for house units. Recharging well (Depth: -1.5 m, Maximum diameter: -2.0 m).	Diameter will be selected based on the roof size. Condition of the roof and height of the roof to be assessed.	• Are there lands available for these structures? ○ Some houses have land issues • Can there be any safety issues specially for children? ○ If lid is incorporated then deem safe • Will they use these structures for waste water diversion? ○ Cannot believe that its possible unless accidentally • Can these wells be maintained properly? ○ Can be done. Most houses collect rainwater and excess is discharged • Any other impacts? ○ No
Road runoff recharging structures- 1)Installation of "U" shaped precast concreate drains along the one side of the road. 2) Series of recharging wells will be connected to drains. 3) Size of the recharging structure (Depth: -1.5 m, Width: -1.0 m, Length: -1.0 m).	1)Drain is open and the depth is 0.6 m. 2) Cover slab will be provided for drains for road crossings. 3)Cover slab will be provided to cover the recharging pit. 4) Top level of the recharging pit is 0.3 m above the ground level. 5) Excess water in the drain will be diverted to recharging ponds or the sea..	• Will Road authorities give permission to build these structures along the roads? ○ Council permits but will require excavation locations/drawings and also the designs • Can there be any safety issues, especially for children/cyclists/ pedestrians? ○ If kept level with ground catch pits are fine. And open drains are fine as long as it is filled. Narrow streets would make it difficult • Will they use these structures for wastewater diversion and solid waste disposal? ○ Won't do deliberately. Currently roads are well maintained • Impact on existing services including electricity, water, cable TV, telecommunication, etc. ? ○ The current buried services are very old and installed 3ft away from the

Proposed Recharging Structure	Details of MAR System	Feasibility and Other Remarks
		boundary wall. Currently planning to change service construction standard by using a road width ratio. Drain design should incorporate this • Can they be well maintained? ○ Can be maintained well • Who will maintain them? ○ Say, if ministry assigns to council. Then council will hire people to do the maintenance • Any other impacts? ○ No
Aquifer modification- **(controlling sea water flowing)**. Earth bunt(1.5 m height) will be proposed along the beach in red areas.		• Land ownership issues of council/private lands? ○ No issues • Will there be any impact on agricultural practices? ○ Not at the moment. No agricultural activities at the zones identified • Will there be any negative impact due to the rise in groundwater table (this is common to all) ? ○ No issues • Any other impacts? ○ Council would suggest to install an earth bund at the northern area marked Council believes the southern bund near jetty would cause worries for the people as they currently use it as a beach/fishing Also the blue region is very shallow water table currently

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

4.6 Quantification and Cost Estimation of Proposed Conceptual Designs

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

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

Table 4.14: Estimates of costs

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

4.6.1 Roof recharging structures

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

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

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

Table 4-15: Proposed recharging well types

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

The required quantities of roof recharging structures are given in island-wise in Table 4-16 to Table 4-19.

Table 4-16: Required quantities of roof recharging structures in Maarandhoo

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type A	39	1	39	15.9 %
Type B	78	1	78	80.7 %
Total	117		117	96.6 %

Note: Roof area <59 m^2 is not covered with recharging structures. About 96.7% of roof areas are covered with proposed recharging structures.

Table 4-17: Required quantities of roof recharging structures in Muraidhoo

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type A	106	1	106	41.7 %
Type B	53	1	53	55.3 %
Total	159		159	97.0 %

Note: Roof area <32m 2 is not covered with recharging structures. About 97% of roof areas are covered with proposed recharging structures.

Table 4-18: Required quantities of roof recharging structures in Uligan

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type A	44	1	44	10.4 %
Type B	88	1	88	86.6 %
Total	132		132	97.0 %

Note: Roof area <40 m 2 is not covered with recharging structures. About 97% roof of the areas are covered with proposed recharging structures.

Table 4-19: Required quantities of roof recharging structures in Molhadhoo

Recharging well type	Selected number of Houses	Number of unit per house	Selected number of recharging units	Total roof coverage (%)
Type A	117	1	117	95.4
Total	117		117	95.4

Note: Roof area <35 m 2 is not covered with recharging structures. About 95% roof of the areas are covered with proposed recharging structures.

4.6.2 Road runoff recharging.

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

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

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

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

Table 4-20: Required length of the drains and recharging pits

Number of selected roads	Total length of selected road(m)	Required Pre-cast concrete structures		Required recharging pits with cover slabs
		If length is 1 m	If length is 2 m	
Maarandhoo				
20	4,165	3,998	1,999	167
Muraidhoo				
13	3,689	3,541	1,771	148
Uligan				
15	4,885	4,690	2,345	195
Molhadhoo				
15	2,805	2,693	1,346	112
Filladhoo				
15	4,680	4,493	2.246	187

4.6.3 Recharging pond

The proposed recharging ponds are connected with recharging drains to increase the recharging amounts.

Table 4-21: No. of proposed recharging ponds

Island	Number of ponds proposed
Maarandhoo	2
Muraidhoo	1
Uligan	2
Molhadhoo	2
Filladhoo	2

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

4.6.4 Application of Aquifer Modifications

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

Table 4-22: Proposed aquifer modifications of the islands

Island	Details
Maarandhoo	Barrier Wall
Muraidhoo	Barrier Wall
Filladhoo	Barrier Wall

4.7 Validation of the Proposed Recharge Structures

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

Rational Formula; $Q = CIA$

Where;
Q = Design Discharge (m^3/s)
C = Runoff Coefficient
I = Rainfall Intensity (m/s)
A = Catchment Area (m^2)

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

General Condition;

Pe(inch) = $(P-0.2S)^2/(P+0.8S)$

Fa = P-Pe-Ia.

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

For dry condition: CN (dry) =4.2 CN(normal)/(10-0.58 CN(normal))

For wet condition: CN(wet) = 23 CN(normal)/(10 + 0.13 CN(normal))

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

4.7.1 Rational Formula Method

The following table illustrates the summary of the rainfall intensity values for the Northern Islands taken from the developed IDF curves. IDF curves developed for the Southern and Northern Islands with the use of 30-year rainfall data of Kadhdhoo Island and Hanimadhoo island are attached under Annex IX.

Table 4.23: Rainfall Intensities taken from developed IDF curves for Northern Islands

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	56	63.5	71	86
1	38	42.5	49	62
3	22	27.3	31.3	36.7
6	12.7	15.3	17.3	19.9

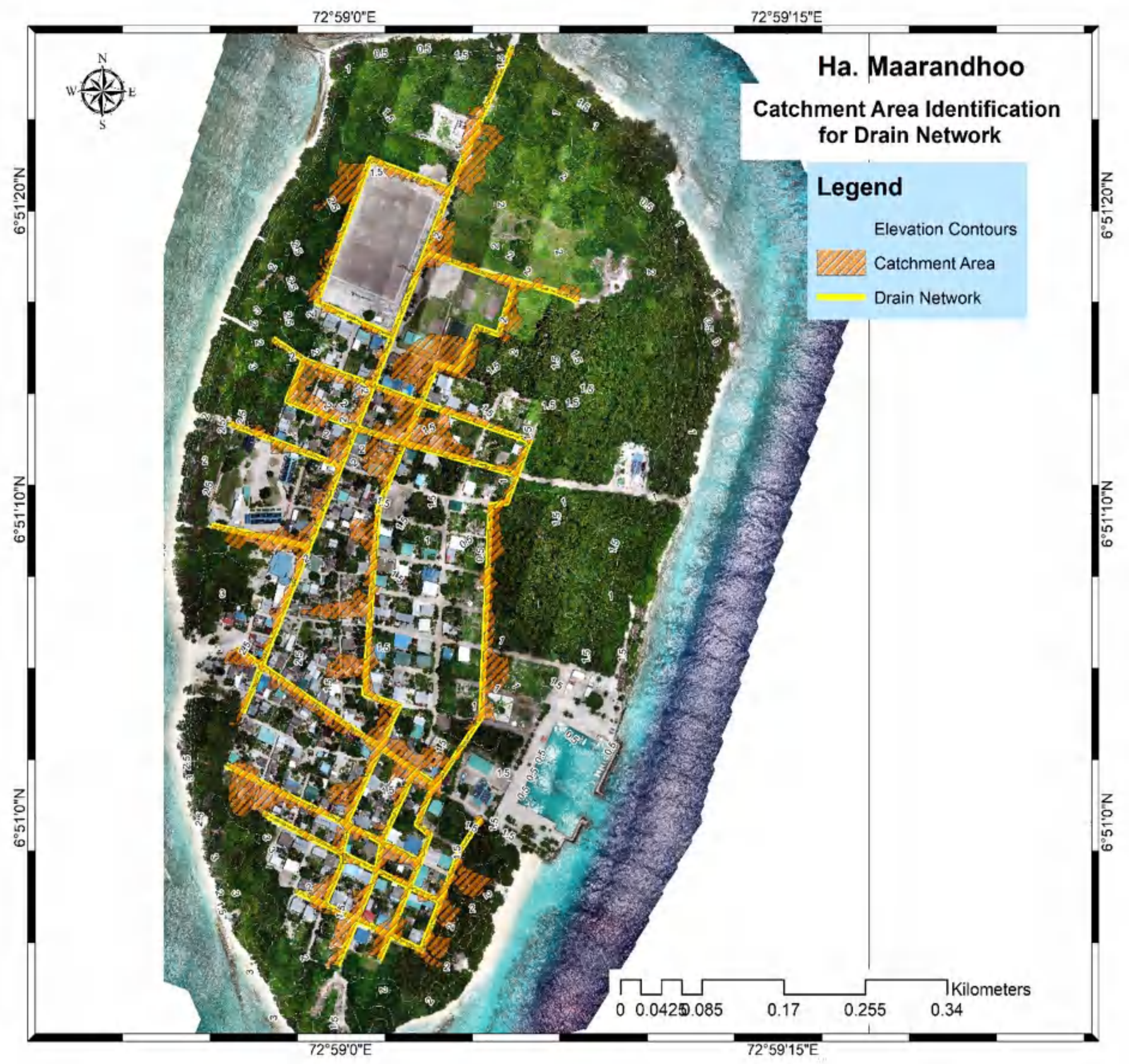


Figure 4-11: Identified catchment areas for the drain capacity calculations

Catchment area for the recharge trench network = 49,287 m^2

Aggregate runoff coefficient for the identified catchment area = 0.45

The following table illustrates the calculated overland flow quantities.

Table 4.24: Calculated overland flow quantities (m^3)

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	1,236	1,402	1,567	1,898
1	839	938	1,082	1,369
3	486	603	691	810
6	280	338	382	439

4.7.2 Soil Conservation Service (SCS) Method

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

Table 4.25: Expected runoff per square meter area for the island and residential area

Duration (Hour)	SCS method					
	General		Wet		Dry	
	Runoff per square meter for island (m^3)	Runoff per square meter for resident (m^3)	Runoff per square meter for island (m^3)	Runoff per square meter for resident (m^3)	Runoff per square meter for island (m^3)	Runoff per square meter for resident (m^3)
Two- years return period						
0.5	9.43E-03	1.80E-02	2.12E-02	3.44E-02	1.17E-03	3.67E-03
1	4.56E-03	9.66E-03	1.31E-02	2.22E-02	2.07E-04	8.32E-04
3	9.68E-04	2.69E-03	5.32E-03	1.01E-02		
6	6.60E-05		1.62E-03	3.66E-03		
9			4.73E-04	1.32E-03		
Five -years return period						
0.5	1.04E-02	1.96E-02	2.26E-02	3.64E-02	1.41E-03	4.31E-03
1	5.84E-03	1.19E-02	1.53E-02	2.57E-02	6.36E-04	1.47E-03
3	1.86E-03	4.58E-03	7.61E-03	1.38E-02		
6	1.79E-04	7.21E-04	2.51E-03	5.27E-03		
9			9.06E-04	2.25E-03		
Ten-year return period						
0.5	1.20E-02	2.22E-02	2.50E-02	4.00E-02	1.86E-03	5.47E-03
1	7.24E-03	1.44E-02	1.77E-02	2.92E-02	6.67E-04	2.27E-03
3	2.75E-03	6.34E-03	9.56E-03	1.69E-02		
6	4.25E-04	1.34E-03	3.50E-03	7.00E-03		
9			1.42E-03	3.26E-03		

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

Table 4.26: Summary of the comparison of the SCS method and Rational Equation method

Duration (Hour)	Rainfall (mm)	Total catchment (m^2)	SCS method						Rational Equation Method (m3)
			General		Wet		Dry		
			Rainfall depth % for runoff	Total runoff (m^3)	Rainfall depth % for runoff	Total runoff (m^3)	Rainfall depth % for runoff	Total runoff (m^3)	
Two- years return period									
0.5	56	49,287	32.8	904	62.39	1,722	6.67	277	1,236
1	38		25.9	484	59.52	1,115	2.23	53	839
3	22		12.4	135	46.56	505	-	-	486
6	12.7		2.1	13	29.27	183	-	-	280
Five -years return period									
0.5	63.5	49,287	31.3	981	58.4	1,827	6.9	331	1,402
1	42.5		28.6	598	61.5	1,288	3.5	123	938
3	27.3		17.1	230	51.3	690	-	-	603
6	15.3		4.8	36	35.0	264	-	-	338
Ten-year return period									
0.5	71	49,287	31.8	1,113	57.2	2,003	7.8	421	1,567
1	49		29.8	720	60.6	1,464	4.7	167	1,082
3	31.3		20.6	318	54.8	845	-	17	691
6	17.3		7.9	67	41.1	351	-	-	382

4.7.3 Capacity Calculation and Sizing of Drain Network

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

Continuity Equation: $\boldsymbol{Q = AV}$

Where;

Q = Design Capacity (m^3/s)
A = Cross Sectional Area of Flow (m^2)
V = Flow Velocity (m/s)

Manning's Equation: $\boldsymbol{V = \frac{1}{n} R^{2/3} S^{1/2}}$

Where;

V= Velocity of Flow (m/s)
n = Manning's Roughness Coefficient
R = Hydraulic Radius (m)
S = Channel Slope

$\boldsymbol{R = A/P}$

Where;

A = Cross Sectional Area of Flow (m^2)
P = Wetted Perimeter (m)

Proposed slope for the drain network (%) = 0.8

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

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

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

Table 4.27: Calculated width of single drain network for respective scenario

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	0.621	0.682	0.742	0.858
1	0.469	0.508	0.563	0.670
3	0.320	0.371	0.408	0.457
6	0.221	0.250	0.271	0.298

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

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

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

Table 4.28: Calculated width of parallel drain network for respective scenario

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	0.378	0.412	0.446	0.512
1	0.289	0.312	0.344	0.406
3	0.201	0.232	0.254	0.282
6	0.140	0.158	0.171	0.188

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

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

5 RESULTS AND RECOMMENDATIONS FOR DETAILED DESIGN

5.1 Conceptual Designs for Managed Aquifer Recharge (MAR)

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

Table 5.1: Proposed recharging structures

Visited Island	Selected recharging methods				
	Roof water recharging	Road runoff recharging	Recharging pond	Aquifer modification/ Barrier wall	Contour drain
Maarandhoo	Yes	Yes	Yes	Yes	No
Muraidhoo	Yes	Yes	Yes	Yes	No
Uligan	Yes	Yes	Yes	No	Yes
Molhadhoo	Yes	Yes	Yes	No	No
Filladhoo	Yes	Yes	Yes	Yes	No

5.1.1 Roof Water Recharging Structures

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

Note: The thickness of the unsaturated zone in the residential area of Filladhoo Island and its surrounding is less than 0.75 m. Therefore, roof water recharging through a recharging well is difficult and it is not proposed for Filladhoo island.

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

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

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

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

Island		Type A	Type B	Total
Maarandhoo	No of Recharging Structures Proposed	39	78	117
	Total Recharging Volume per year (m^3)	6,484	29,198	35,683

Island		Type A	Type B	Total
Muraidhoo	No of Recharging Structures Proposed	106	53	159
	Total Recharging Volume per year (m^3)	24,975	28,084	53,059
Uligan	No of Recharging Structures Proposed	44	88	132
	Total Recharging Volume per year (m^3)	9,672	43,488	53,160
Molhadhoo	No of Recharging Structures Proposed	117	-	117
	Total Recharging Volume per year (m^3)	52,331	-	52,331

5.1.2 Road Runoff Recharging

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

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

Island	Selected Road Length (m)	Daily Recharging Potential (m^3)	Yearly Recharging Potential (m^3)
Maarandhoo	4,165	1,998	101,903
Muraidhoo	3,689	2,403	122,556
Uligan	4,885	3,058	155,976
Molhadhoo	2,805	1,749	117,176
Filladhoo	4,680	3,603	183,760

5.1.3 Recharging Using Recharging Ponds

Recharging ponds were proposed for all the islands considering the depth to the water table, topography, hydraulic conductivity of the Island.

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

Island	No. of Proposed Recharging Ponds	Daily Recharging Potential (m^3)	Yearly Recharging Potential (m^3)
Maarandhoo	2	1,245	66,555
Muraidhoo	1	882	46,512
Uligan	2	1,644	86,904
Molhadhoo	2	3,348	173,808
Filladhoo	2	471	24,327

5.1.4 Application of Aquifer Modifications

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

Table 5-6: Proposed aquifer modifications of the islands

Island	Details
Maarandhoo	Barrier Wall
Muraidhoo	Barrier Wall
Filladhoo	Barrier Wall

5.1.5 Contour Drains

It is noted that a considerable percentage of forest and unused lands are available on Uligan island and a less permeable topmost thin layer rests on the permeable sandy layer. The infiltration capacity of these lands can be improved by constructing contour earth drains. The clogging capacity of the earth drains are high due to adding of plant materials and the infiltration capacity of the drains will be reduced. Therefore, drains shall be designed to bear a higher capacity of runoff.

Drain type	Trapezoidal earth drain
Bottom width	0.5 m
Depth	1 m
Top width	1.5 m
Average Spacing between two drains	100 m
The average Slope angle of a side wall	30^0
The total length of drain	875 m (five segments)
The estimated runoff to proposed drains assuming runoff coefficient (0.2)	200,000 x 0.2 x 0.03908 =1,563 m^3/d
Estimated daily recharging capacity of earth drains	875 x 0.5 x 5.48 =2397 m^3/d
Estimated yearly recharging capacity of the earth drains	122,247 m^3/d

5.2 Social and Environmental Feasibility and Impact of Proposed MAR Systems

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

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

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

5.3 Quantification and Cost Estimation of Proposed Conceptual Designs

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

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

Island		Maarandhoo	Muraidhoo	Uligan	Molhadhoo	Filladhoo
Recharging Well	Type A	702,000	1,908,000	792,000	2,106,000	-
	Type B	1,950,000	1,325,000	2,200,000	-	-
Road runoff recharging	Drain	33,736,500	29,880,900	39,568,500	22,720,500	37,908,000
	Recharging pit	3,156,300	2,797,200	3,685,500	2,116,800	3,534,300
Recharging pond		1,100,000	550,000	1,100,000	1,100,000	1,100,000
Aquifer modification / Barrier wall	Barrier Wall	1,470,000	969,500	-	-	4,025,000

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

Island	Estimated construction cost MVR	Estimated Operation and Maintenance cost (estimated as 3% of capital cost) MVR
Maarandhoo	42,114,800.00	1,263,444.00
Muraidhoo	37,430,600.00	1,122,918.00
Uligan	47,346,000.00	1,420,380.00
Molhadhoo	28,043,300.00	841,299.00
Filladhoo	46,567,300.00	1,397,019.00

5.4 Validation of the Proposed Recharge Structures

5.4.1 Ha. Maarandhoo

Catchment area for the recharge trench network = 49,287 m^2

Aggregate runoff coefficient for the identified catchment area = 0.45

The following table illustrates the calculated overland flow quantities.

Table 5.9: Calculated overland flow quantities (m^3) – Ha. Maarandhoo

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	1,236	1,402	1,567	1,898
1	839	938	1,082	1,369
3	486	603	691	810
6	280	338	382	439

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

Recharging option	Daily Recharge Volume (m^3)	Hourly Recharge Volume (m^3)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m^3)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m^3)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m^3)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m^3)
Roof Recharging	350	15	15	29	58	102
Road Runoff	1,998	83	83	167	333	583
Recharging pond	1,245	52	52	104	208	363
Provision for storage = 228 m^3						
Total Recharge and Storage Volume (m^3)	3,821	377	**377**	**527**	**827**	**1,276**

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that for normal rainfall events the overland flow would be managed for 25 year return period. And in extreme events (30 min rainfall) 31% of the generated overland flow would be managed for the 2-year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1-hour rainfall duration, 63% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.4.2 Ha. Filladhoo

Catchment area for the recharge trench network = 51,327 m^2

Aggregate runoff coefficient for the identified catchment area = 0.44

The following table illustrates the calculated overland flow quantities.

Table 5.11: Calculated overland flow quantities (m^3) – Ha. Filladhoo

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	1,274	1,444	1,615	1,956
1	864	967	1,114	1,410
3	500	621	712	835
6	289	348	393	453

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

Recharging option	Daily Recharge Volume (m^3)	Hourly Recharge Volume (m^3)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m^3)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m^3)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m^3)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m^3)
Roof Recharging	99	4	4	8	16	29
Road Runoff	744	31	31	62	124	217
Recharging pond	471	20	20	39	79	137
Provision for storage = 60 m^3						
Total Recharge and Storage Volume (m^3)	903	95	**95**	**130**	**200**	**306**

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that for normal rainfall events 40% of the overland flow would be managed for 2 year return period. And in extreme events (30 min rainfall) 7% of the generated overland flow would be managed for the 2-year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1-hour rainfall duration, 15% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.4.3 Ha. Muraidhoo

Catchment area for the recharge trench network = 76,967 m^2

Aggregate runoff coefficient for the identified catchment area = 0.47

The following table illustrates the calculated overland flow quantities.

Table 5.13: Calculated overland flow quantities (m^3) – Ha. Muraidhoo

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	2,017	2,287	2,558	3,098
1	1,369	1,531	1,765	2,233
3	792	983	1,127	1,322
6	457	551	623	717

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

Recharging option	Daily Recharge Volume (m^3)	Hourly Recharge Volume (m^3)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m^3)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m^3)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m^3)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m^3)
Roof Recharging	520	22	22	43	87	152
Road Runoff	2,403	100	100	200	401	701
Recharging pond	882	37	37	74	147	257
Provision for storage = 206 m^3						
Total Recharge and Storage Volume (m^3)	4,011	365	**365**	**523**	**840**	**1,316**

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that for normal rainfall events the overland flow would be managed for 2 year return period. And in extreme events (30 min rainfall) 18% of the generated overland flow would be managed for the 2 year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1 hour rainfall duration, 38% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.4.4 Ha. Molhadhoo

Catchment area for the recharge trench network = 48,295 m^2

Aggregate runoff coefficient for the identified catchment area = 0.27

The following table illustrates the calculated overland flow quantities.

able 5.15: Calculated overland flow quantities (m^3) – Ha. Molhadhoo

Duration (Hrs)	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period
0.5	718	815	911	1,103
1	487	545	629	795
3	282	350	401	471
6	163	196	222	255

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

Recharging option	Daily Recharge Volume (m^3)	Hourly Recharge Volume (m^3)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m^3)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m^3)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m^3)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m^3)
Roof Recharging	513	21	21	43	86	150
Road Runoff	3,603	150	150	300	601	1,051
Recharging pond	3,348	140	140	279	558	977
Provision for storage = 151 m^3						
Total Recharge and Storage Volume (m^3)	4,267	323	**323**	**494**	**837**	**1,352**

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that, for normal rainfall events the overland flow would be managed for 25 year return period. And in extreme events (30 min rainfall) 45% of the generated overland flow would be managed for the 2 year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1 hour rainfall duration, 91% of generated overland flow would be manageable for 5 year return period and then gradually decreases for the 10 Yr. and 25 Yr. return periods.

5.4.5 Ha. Uligan

Catchment area for the recharge trench network = 64,549 m^2

Aggregate runoff coefficient for the identified catchment area = 0.31

The following table illustrates the calculated overland flow quantities.

able 5.17: Calculated overland flow quantities (m^3) – Ha. Uligan

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

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

Recharging option	Daily Recharge Volume (m^3)	Hourly Recharge Volume (m^3)	Recharge Volume for 1 Hr. (for 30 min rainfall extreme event) (m^3)	Recharge Volume for 2 Hrs. (for 1 hr rainfall extreme event) (m^3)	Recharge Volume for 4 Hrs. (for 3 hr rainfall event) (m^3)	Recharge Volume for 7 Hrs. (for 6 hr rainfall event) (m^3)
Roof Recharging	521	22	22	43	87	152
Road Runoff	3,058	127	127	255	510	892
Recharging pond	1,644	69	69	137	274	480
Provision for storage = 249 m^3						
Total Recharge and Storage Volume (m^3)	3,828	398	**398**	**547**	**846**	**1,293**

As per the recharging estimations, recharging volumes were estimated for different return periods. And results reveal that, for normal rainfall events the overland flow would be managed for 25 year return period. And in extreme events (30 min rainfall) 36% of the generated overland flow would be managed for the 2 year return period and the percentage of manageable overland flow is decreased gradually for the other return periods. And also for 1 hour rainfall duration, 73% of generated overland flow would be manageable for 2 year return period and then gradually decreases for the 5 Yr., 10 Yr. and 25 Yr. return periods.

5.5 Recommendations for Detailed Design

Fresh groundwater occurs in the form of 'freshwater lenses' in medium to large-scale Maldivian islands and these lenses play an important role in the source of water supply. Also, they are highly susceptible to saline water intrusions due to overpumping and are vulnerable to pollution from the surface and sub-surface waste disposal, particularly from sanitation systems. Also, freshwater lenses are mixed with saline water as a result of seawater flooding and this is common in all visited islands. However, the impact due to seawater flooding is changed from island to island.

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

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

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

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

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

Island	Recharging method or methods used for assessment of existing groundwater amounts	Groundwater amount/predicted recharge(m3/year)	Predicted recharge as a percentage to existing groundwater amount
Maarandhoo	**Recharging method**		
	Roof recharging system	35,682	
	Road runoff recharging system	101,902	
	Recharging pond	66,555	
	Total	204,139	
	Groundwater quantification approaches		
	Water balance method	46,792	436%
	Indirection investigation through the resistivity method	58,262	350%

Island	Recharging method or methods used for assessment of existing groundwater amounts	Groundwater amount/predicted recharge(m3/year)	Predicted recharge as a percentage to existing groundwater amount
Muraidhoo	**Recharging method**		
	Roof recharging system	53,059	
	Road runoff recharging system	122,555	
	Recharging ponds	46,512	
	Aquifer modification(barrier wall)	831	
	Total	228,957	
	Groundwater quantification approaches		
	Water balance method	52,330	437%
	Indirection investigation through the resistivity method	68,152	336%
Filladhoo	**Recharging method**		
	Roof recharging system	8923	
	Road runoff recharging system	37,955	
	Recharging ponds	24,327	
	Total	71,205	
	Groundwater quantification approaches		
	Water balance method	176,845	40%
	Indirection investigation through the resistivity method	207,859	34%
Uligan	**Recharging method**		
	Roof recharging system	53,160	
	Road runoff recharging system	155,975	
	Recharging pond	86,904	
	Contour drain	122,247	
	Total	418,286	
	Groundwater quantification approaches		
	Water balance method	93,210	448%
	Indirection investigation through the resistivity method	149,548	280%

Island	Recharging method or methods used for assessment of existing groundwater amounts	Groundwater amount/predicted recharge(m3/year)	Predicted recharge as a percentage to existing groundwater amount
Molhadhoo	**Recharging method**		
	Roof recharging system	52,160	
	Road runoff recharging system	183,759	
	Recharging pond	173,808	
	Total	409,897	
	Groundwater quantification approaches		
	Water balance method	126,392	324%
	Indirection investigation through the resistivity method	211,487	194%

As per the comparison, the predicted recharging amount through proposed structures in Maarandhoo, Muraidhoo, and Uligan islands are more than 400% higher than the available groundwater amount as per the water balance method due to the selection of large number of roofs (94% of roof area) as well as long road lengths for groundwater recharge. The predicted recharging quantities of Filladhoo are less than 50% compared to the available groundwater amount within the country due to space limitations within the unsaturated zone for recharging.

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

Based on the findings following recommendations could be made.

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

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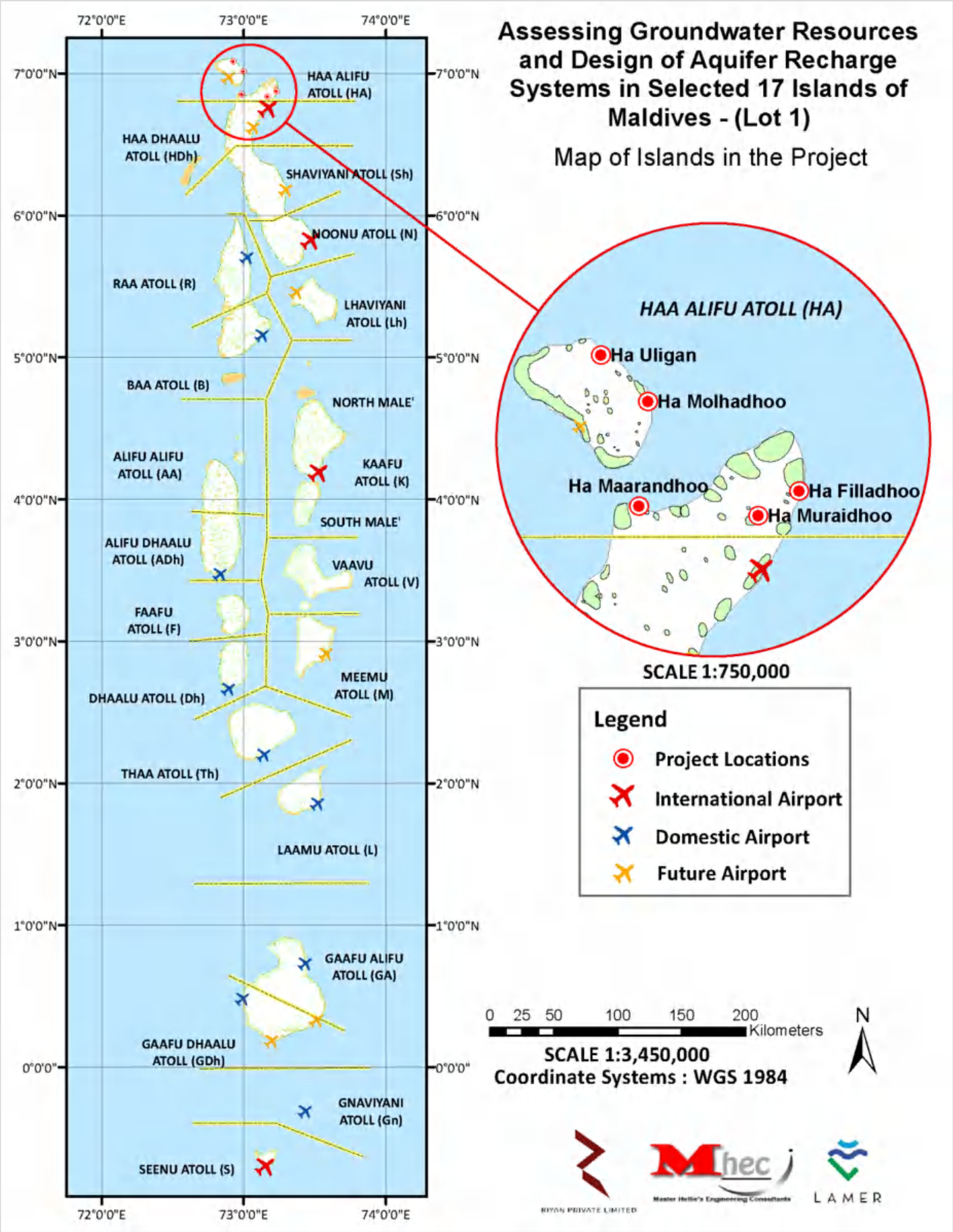
Annex I: Location Map of the Islands


Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives - (Lot 1)
Map of Islands in the Project
HAA ALIFU ATOLL (HA)
Ha Uligan
Ha Molhadhoo
Ha Maarandhoo
Ha Filladhoo
Ha Muraidhoo
SCALE 1:750,000
Legend
Project Locations
International Airport
Domestic Airport
Future Airport
HAA ALIFU ATOLL (HA)
HAA DHAALU ATOLL (HDh)
SHAVIYANI ATOLL (Sh)
NOONU ATOLL (N)
RAA ATOLL (R)
LHAVIYANI ATOLL (Lh)
BAA ATOLL (B)
NORTH MALE'
KAAFU ATOLL (K)
ALIFU ALIFU ATOLL (AA)
SOUTH MALE'
ALIFU DHAALU ATOLL (ADh)
VAAVU ATOLL (V)
FAAFU ATOLL (F)
MEEMU ATOLL (M)
DHAALU ATOLL (Dh)
THAA ATOLL (Th)
LAAMU ATOLL (L)
GAAFU ALIFU ATOLL (GA)
GAAFU DHAALU ATOLL (GDh)
GNAVIYANI ATOLL (Gn)
SEENU ATOLL (S)
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6°0'0"N
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2°0'0"N
1°0'0"N
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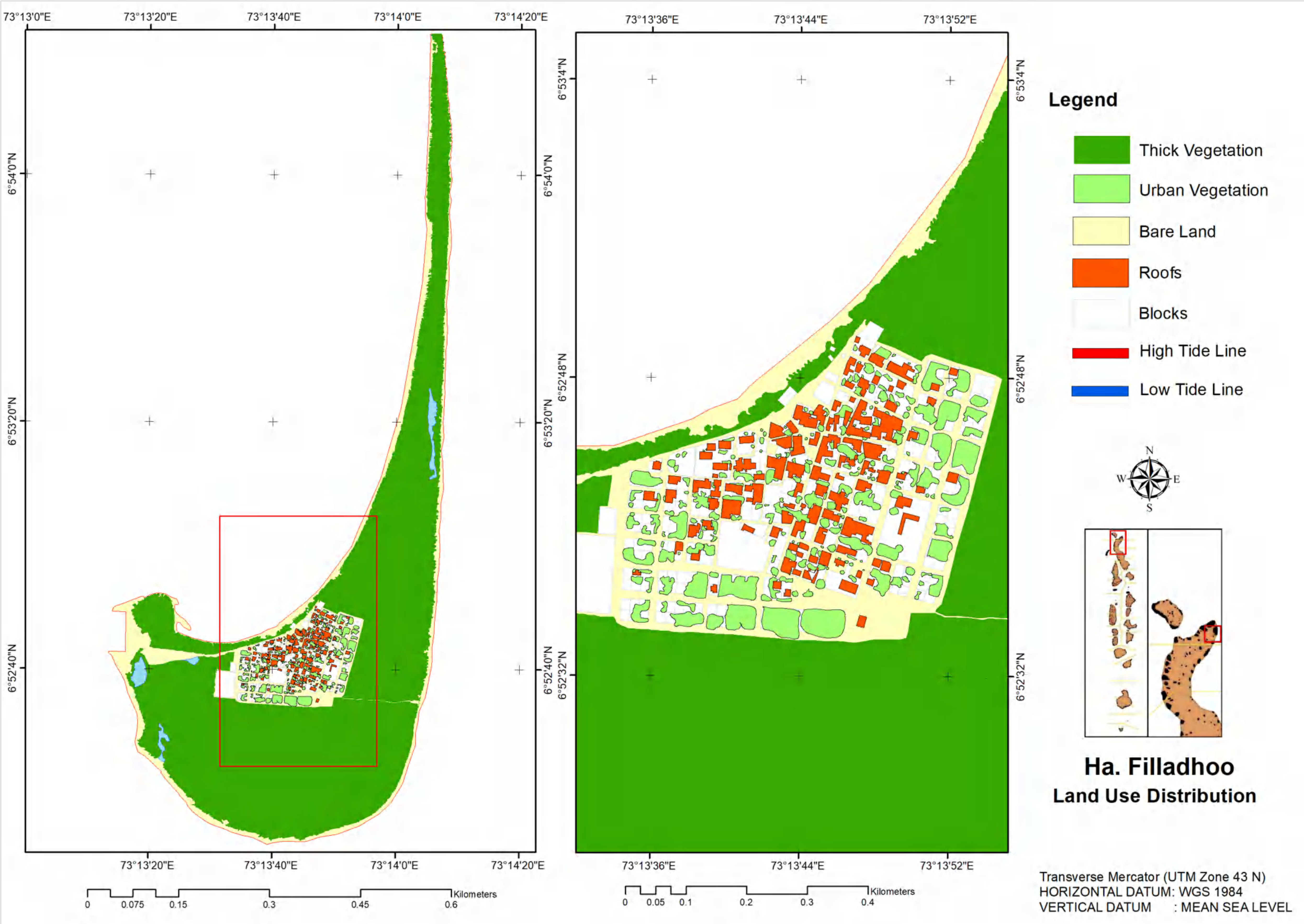
Coordinate Systems : WGS 1984
LAMER

Annex II: Land Use Distribution of Islands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73°13'20"E
73°13'40"E
73°14'0"E
73°14'20"E
6°54'0"N
6°53'20"N
6°52'40"N
73°13'36"E
73°13'44"E
73°13'52"E
6°53'4"N
6°52'48"N
6°52'32"N
Kilometers
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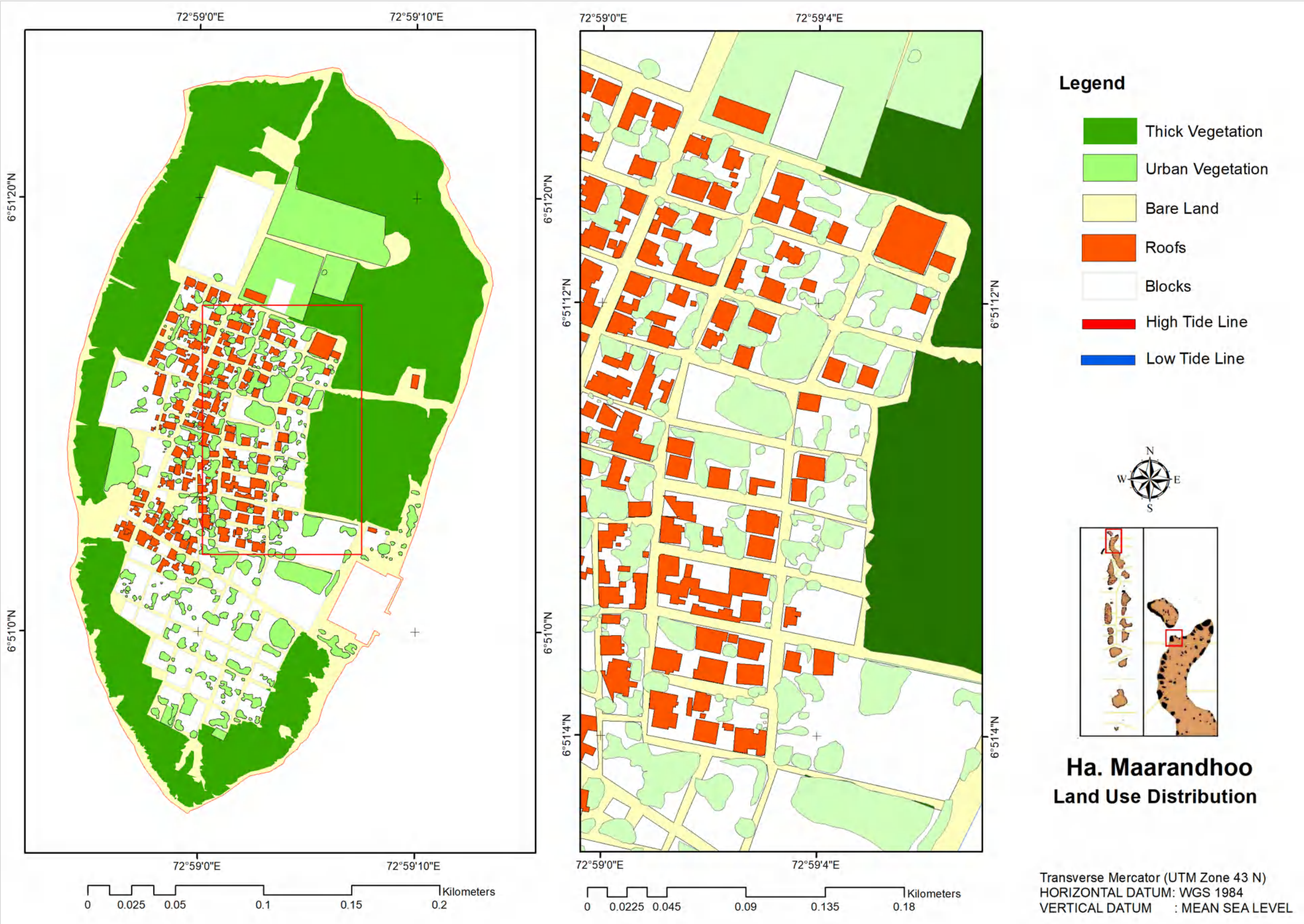
0 0.05 0.1 0.2 0.3 0.4
Legend
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
High Tide Line
Low Tide Line
N
W
E
S
Ha. Filladhoo
Land Use Distribution
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL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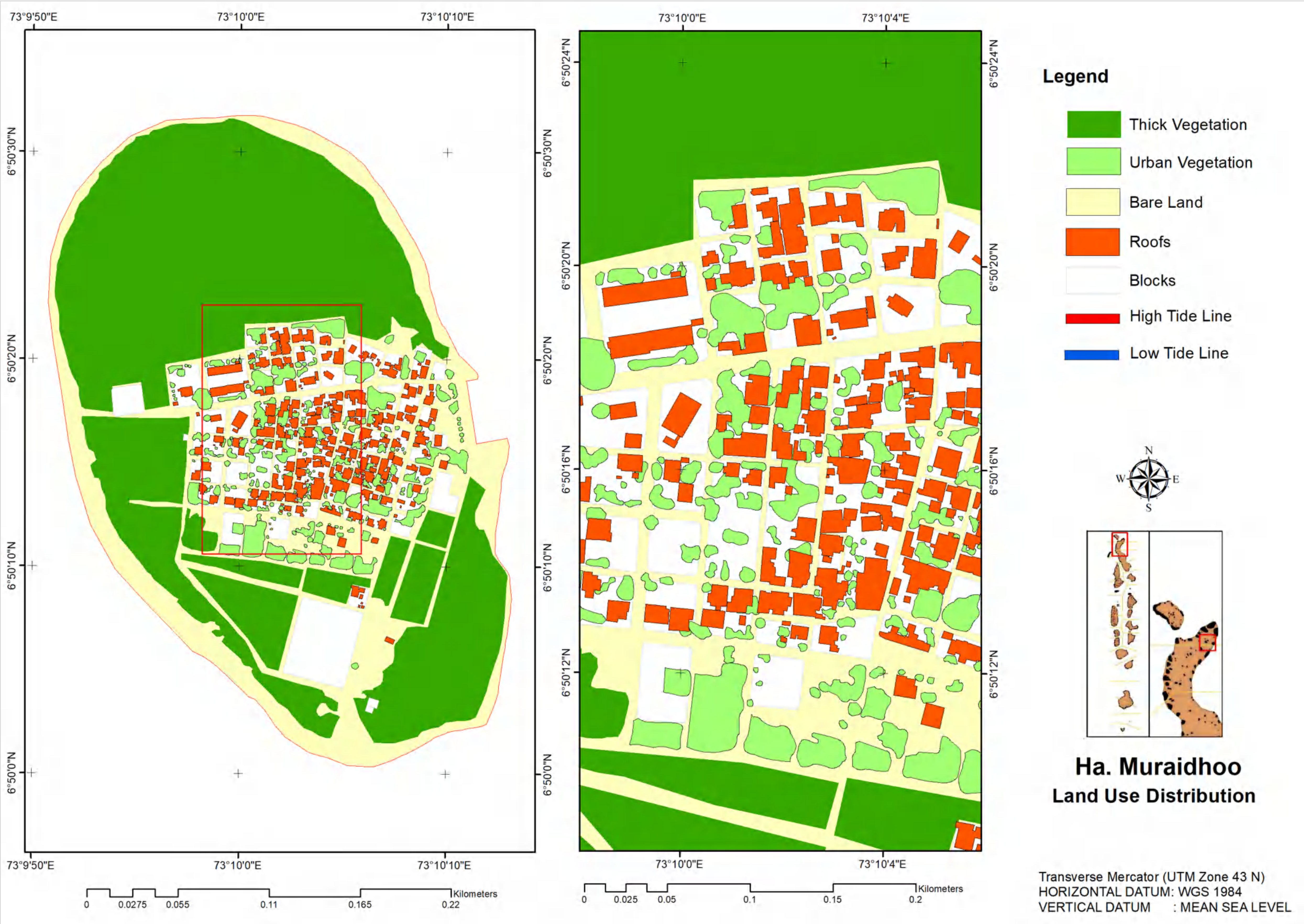
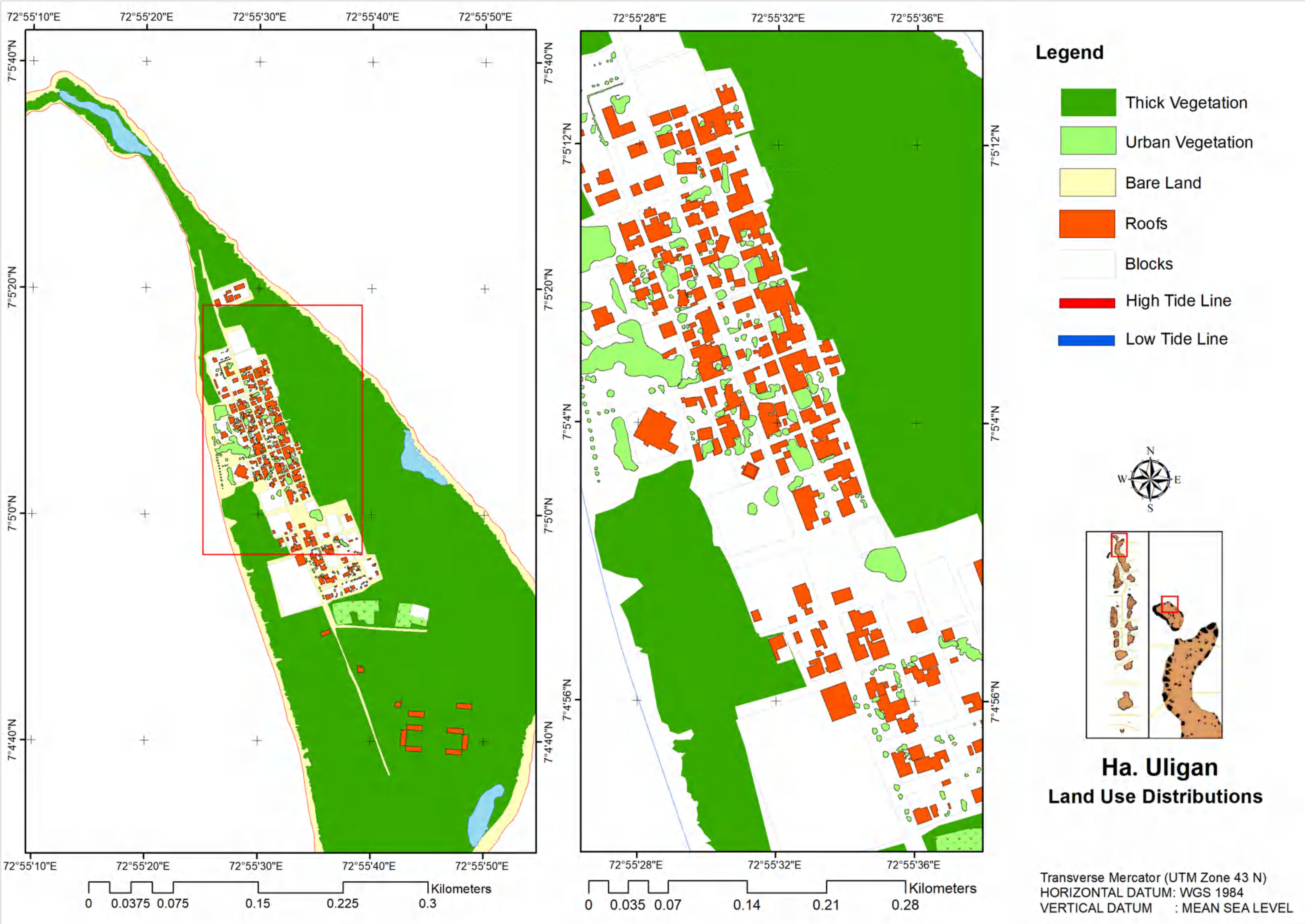
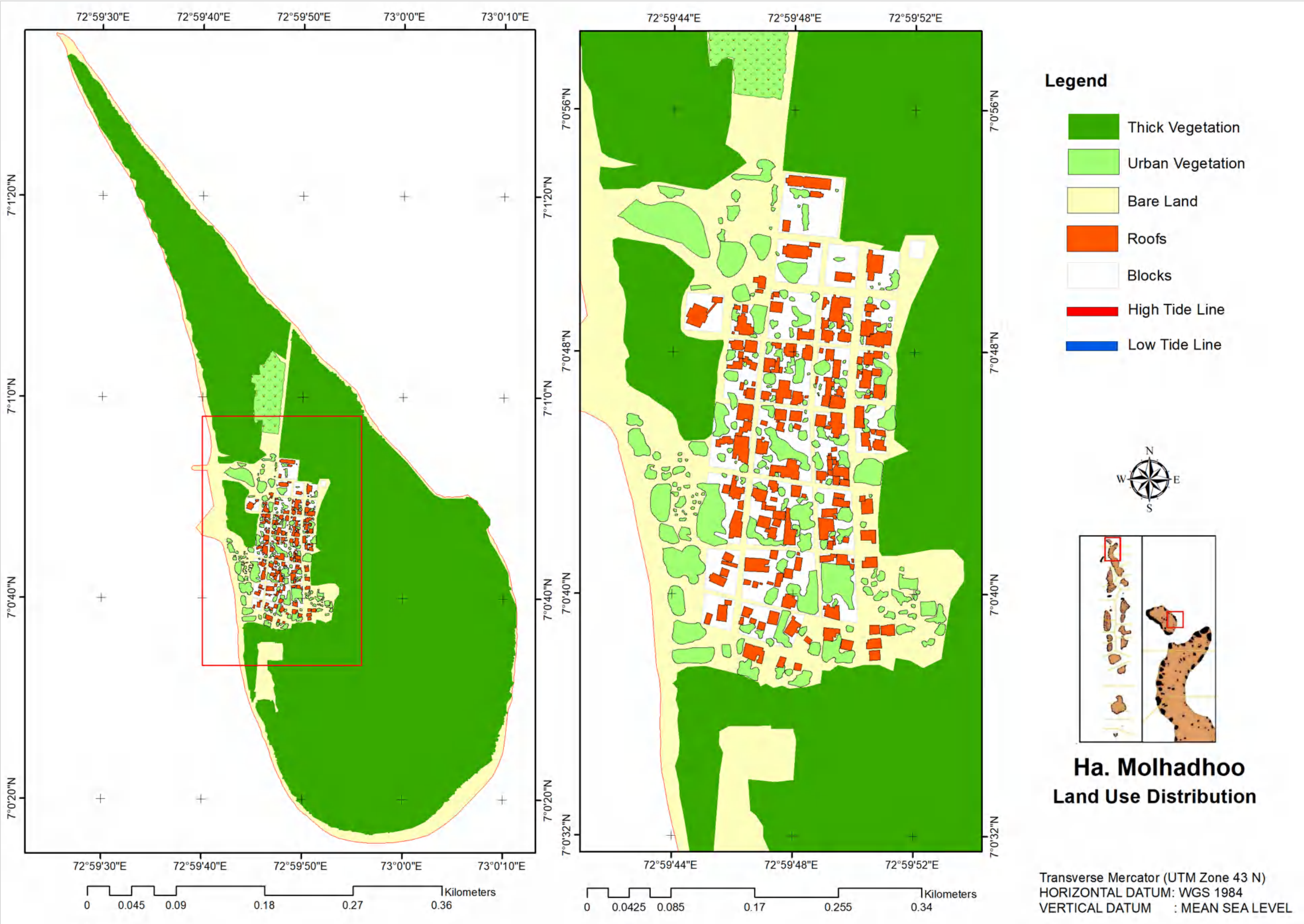
72°59'10"E
6°51'20"N
6°51'0"N
72°59'4"E
6°51'12"N
6°51'4"N
0 0.025 0.05 0.1 0.15 0.2 Kilometers
0 0.0225 0.045 0.09 0.135 0.18 Kilometers
Legend
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
High Tide Line
Low Tide Line
N
W
E
S
Ha. Maarandhoo
Land Use Distribution
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

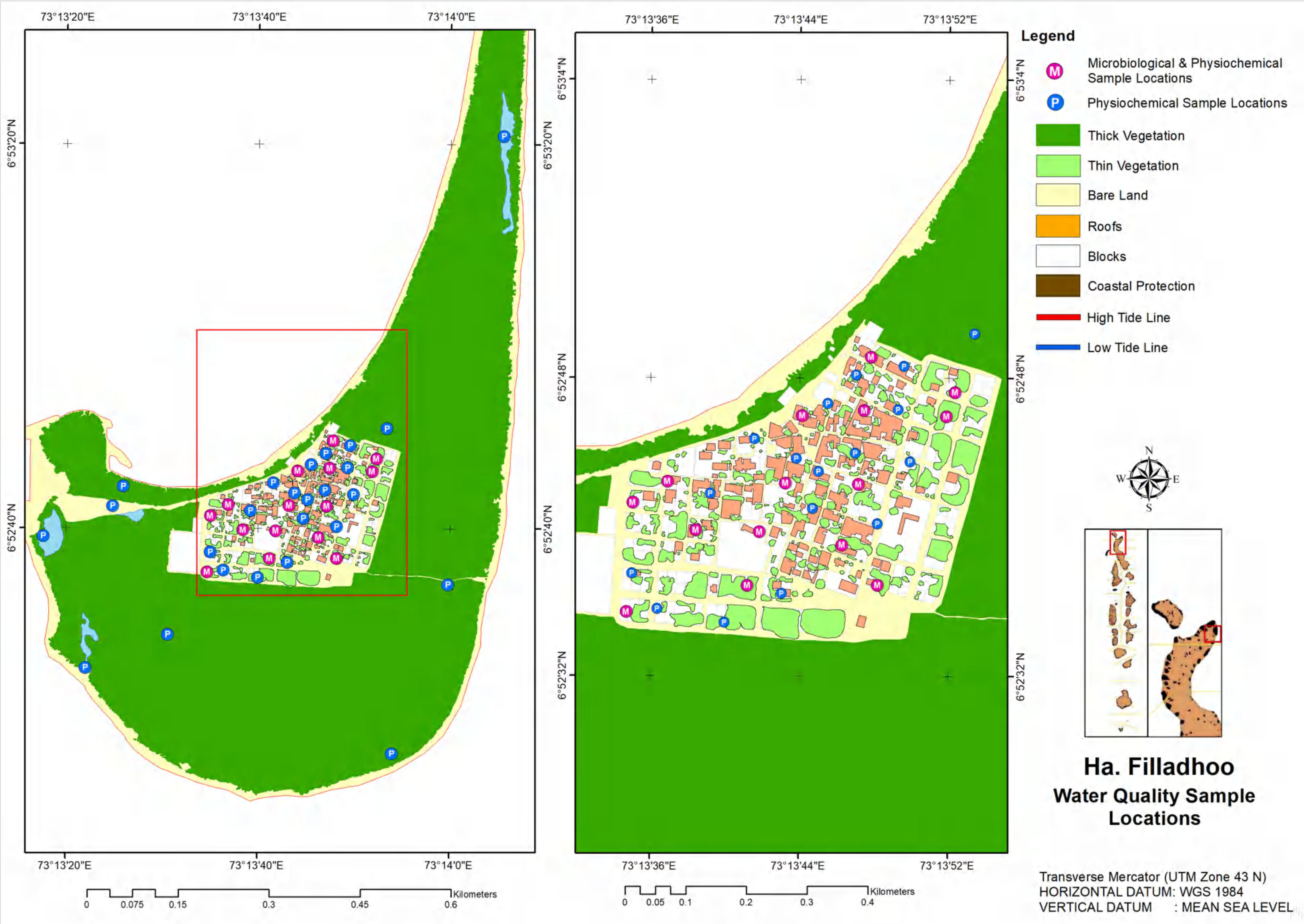

73°9'50"E
73°10'0"E
73°10'10"E
6°50'30"N
6°50'20"N
6°50'10"N
6°50'0"N
Kilometers
0
0.0275
0.055
0.11
0.165
0.22
73°10'4"E
6°50'24"N
6°50'20"N
6°50'16"N
6°50'12"N
0
0.025
0.05
0.1
0.15
0.2
Legend
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
High Tide Line
Low Tide Line
N
W
E
S
Ha. Muraidhoo
Land Use Distribution
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL


72°55'10"E
72°55'20"E
72°55'30"E
72°55'40"E
72°55'50"E
7°5'40"N
7°5'20"N
7°5'0"N
7°4'40"N
0
0.0375
0.075
0.15
0.225
0.3
Kilometers
72°55'28"E
72°55'32"E
72°55'36"E
7°5'12"N
7°5'4"N
7°4'56"N
0
0.035
0.07
0.14
0.21
0.28
Kilometers
Legend
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
High Tide Line
Low Tide Line
N
W
E
S
Ha. Uligan
Land Use Distributions
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

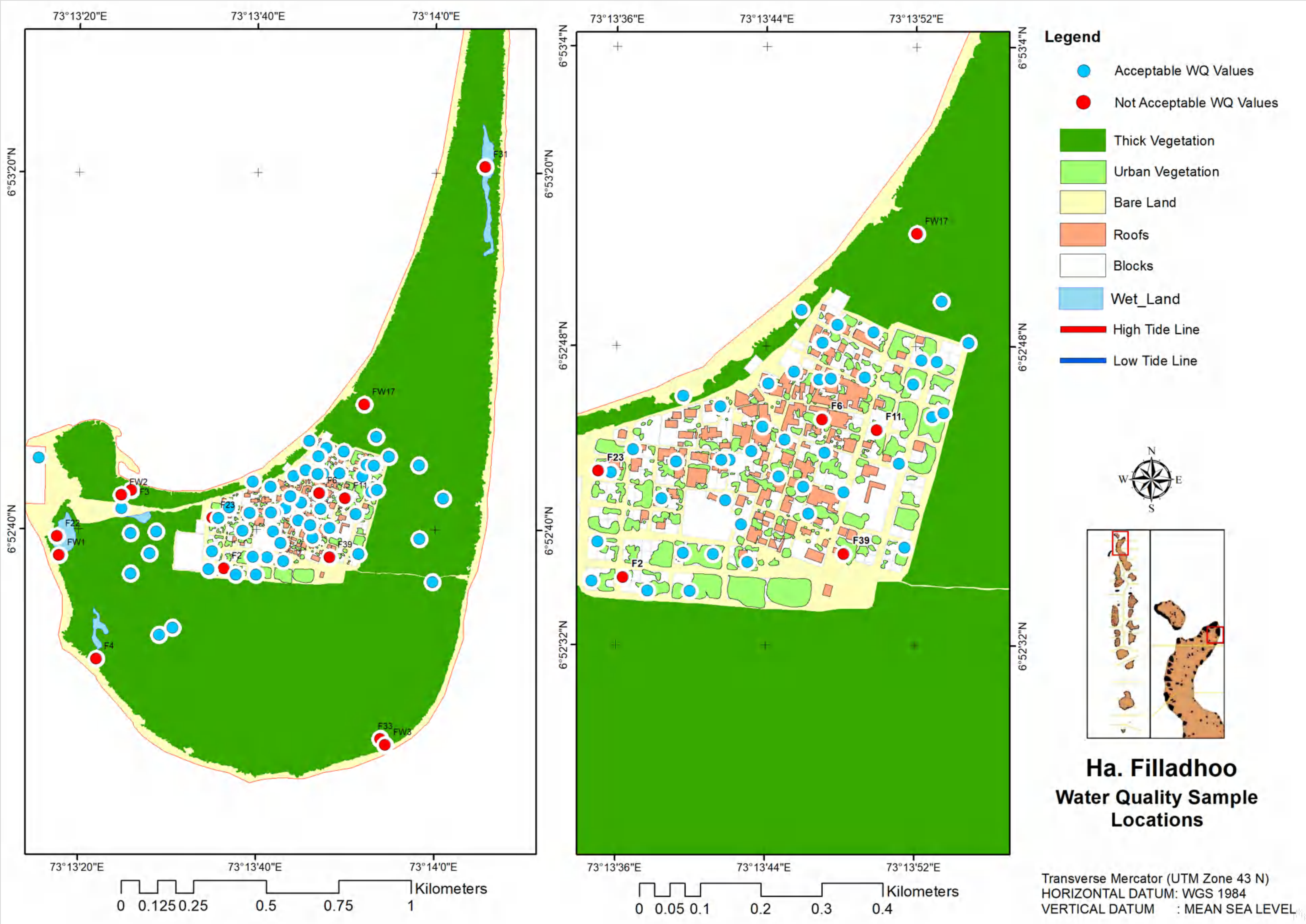


72°59'30"E
72°59'40"E
72°59'50"E
73°0'0"E
73°0'10"E
7°1'20"N
7°1'0"N
7°0'40"N
7°0'20"N
0 0.045 0.09 0.18 0.27 0.36 Kilometers
72°59'44"E
72°59'48"E
72°59'52"E
7°0'56"N
7°0'48"N
7°0'40"N
7°0'32"N
0 0.0425 0.085 0.17 0.255 0.34 Kilometers
Legend
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
High Tide Line
Low Tide Line
N
S
E
W
Ha. Molhadhoo
Land Use Distribution
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

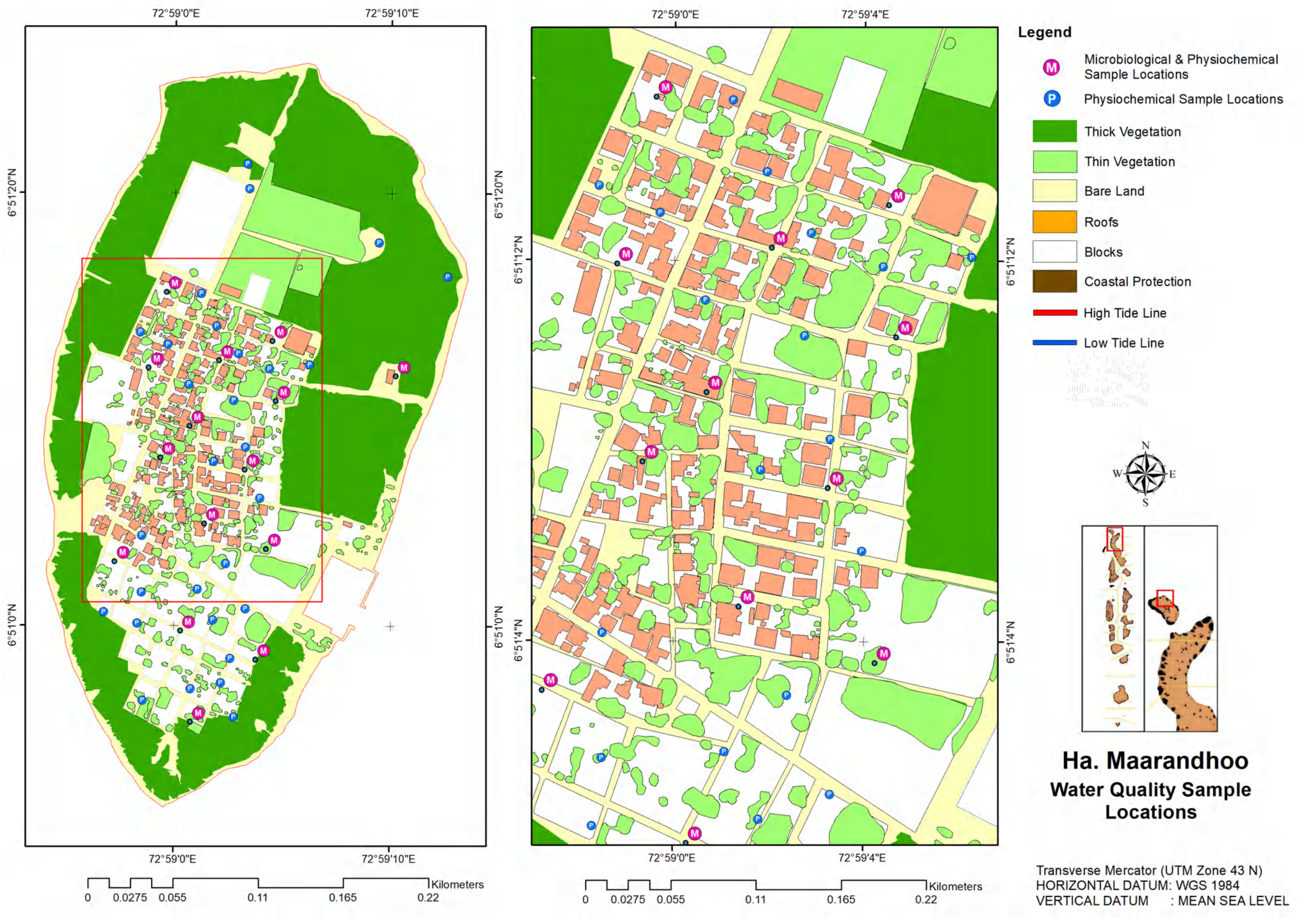
Annex III: Water Quality Sample Locations of the Islands

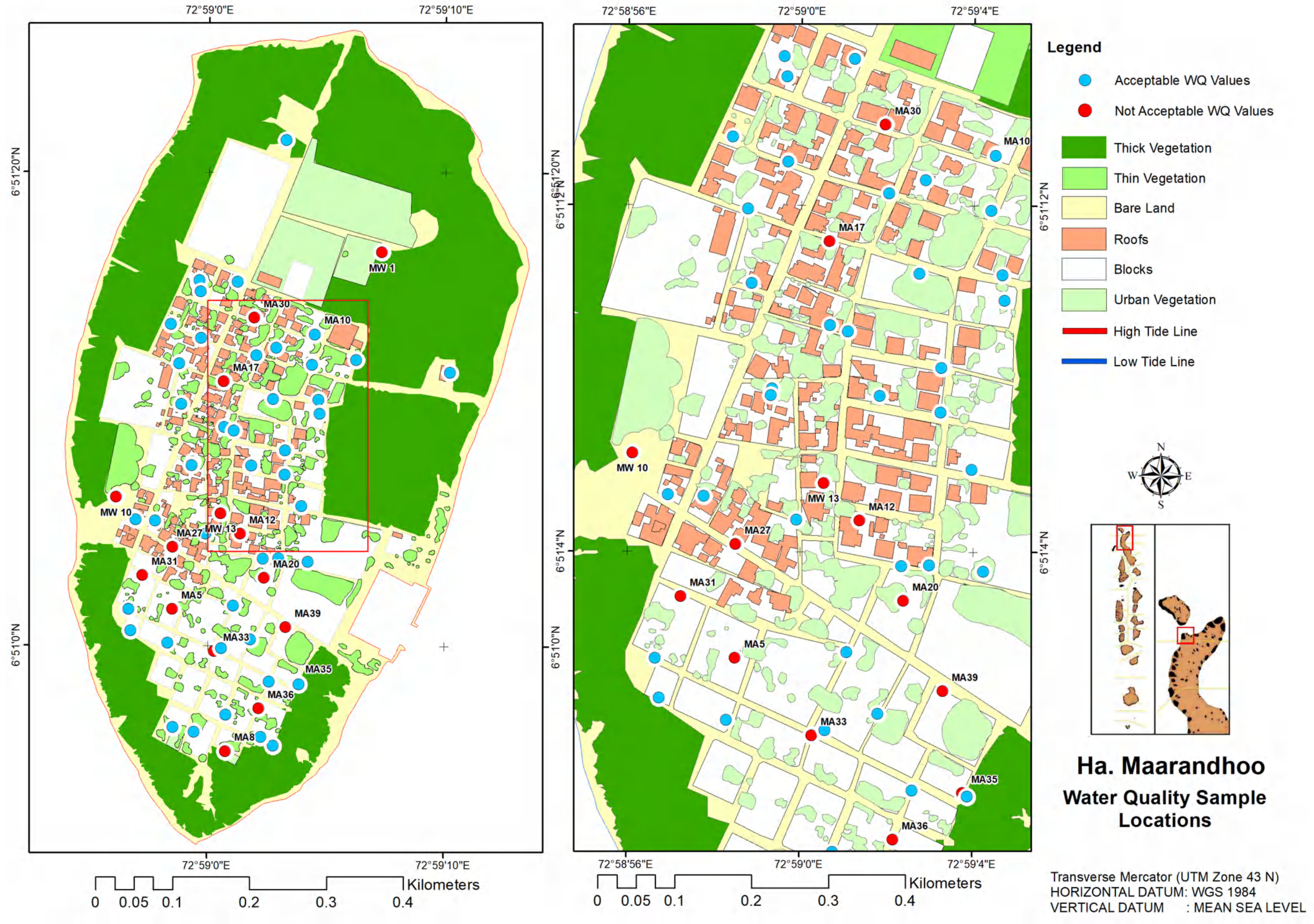


73°13'20"E
73°13'40"E
73°14'0"E
6°53'20"N
6°52'40"N
0 0.075 0.15 0.3 0.45 0.6 Kilometers
73°13'36"E
73°13'44"E
73°13'52"E
6°53'4"N
6°52'48"N
6°52'32"N
0 0.05 0.1 0.2 0.3 0.4 Kilometers
Legend
Microbiological & Physiochemical Sample Locations
Physiochemical Sample Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
W
E
S
Ha. Filladhoo
Water Quality Sample Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL



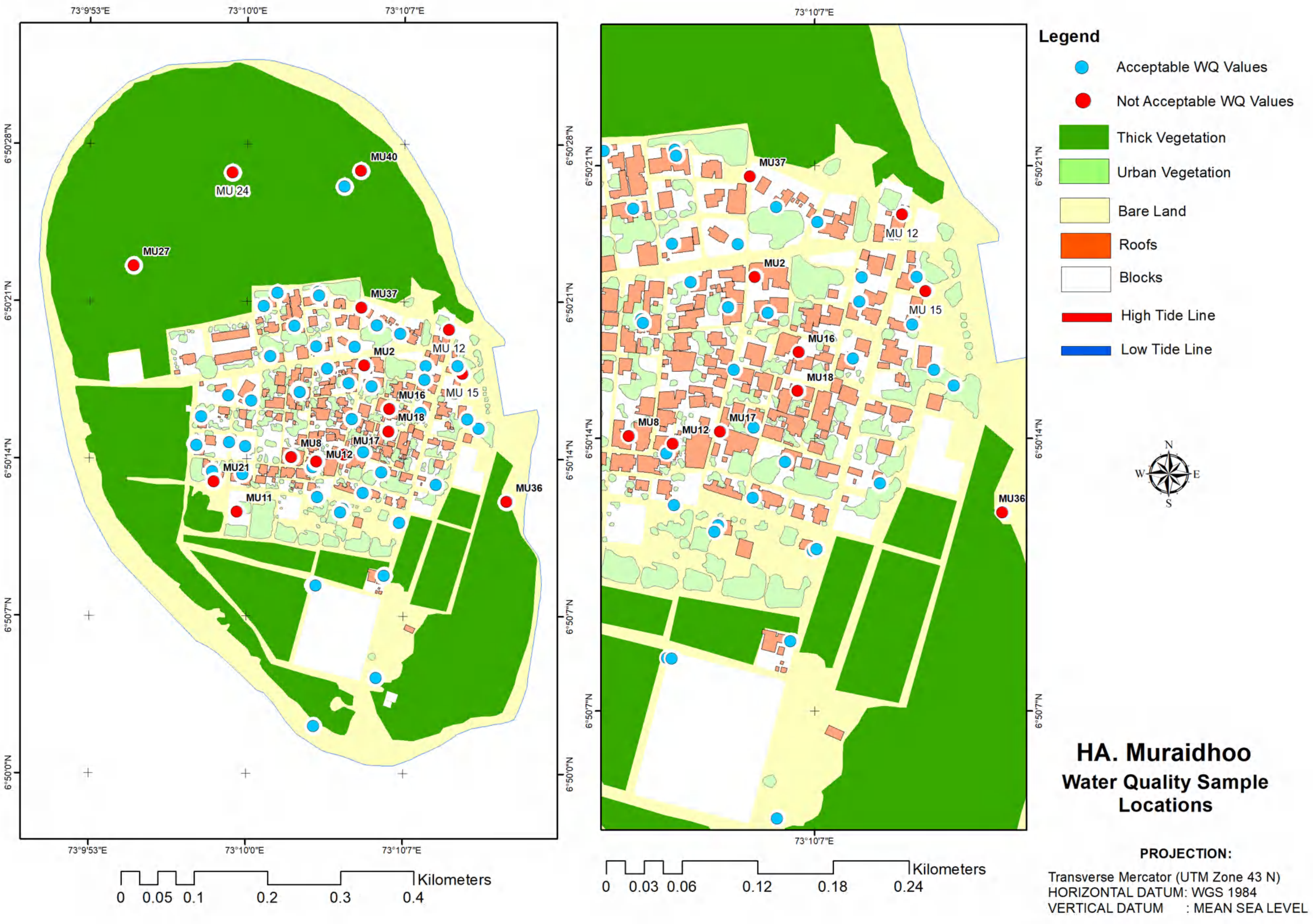
Legend
Acceptable WQ Values
Not Acceptable WQ Values
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
Wet_Land
High Tide Line
Low Tide Line
Ha. Filladhoo
Water Quality Sample Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
Kilometers

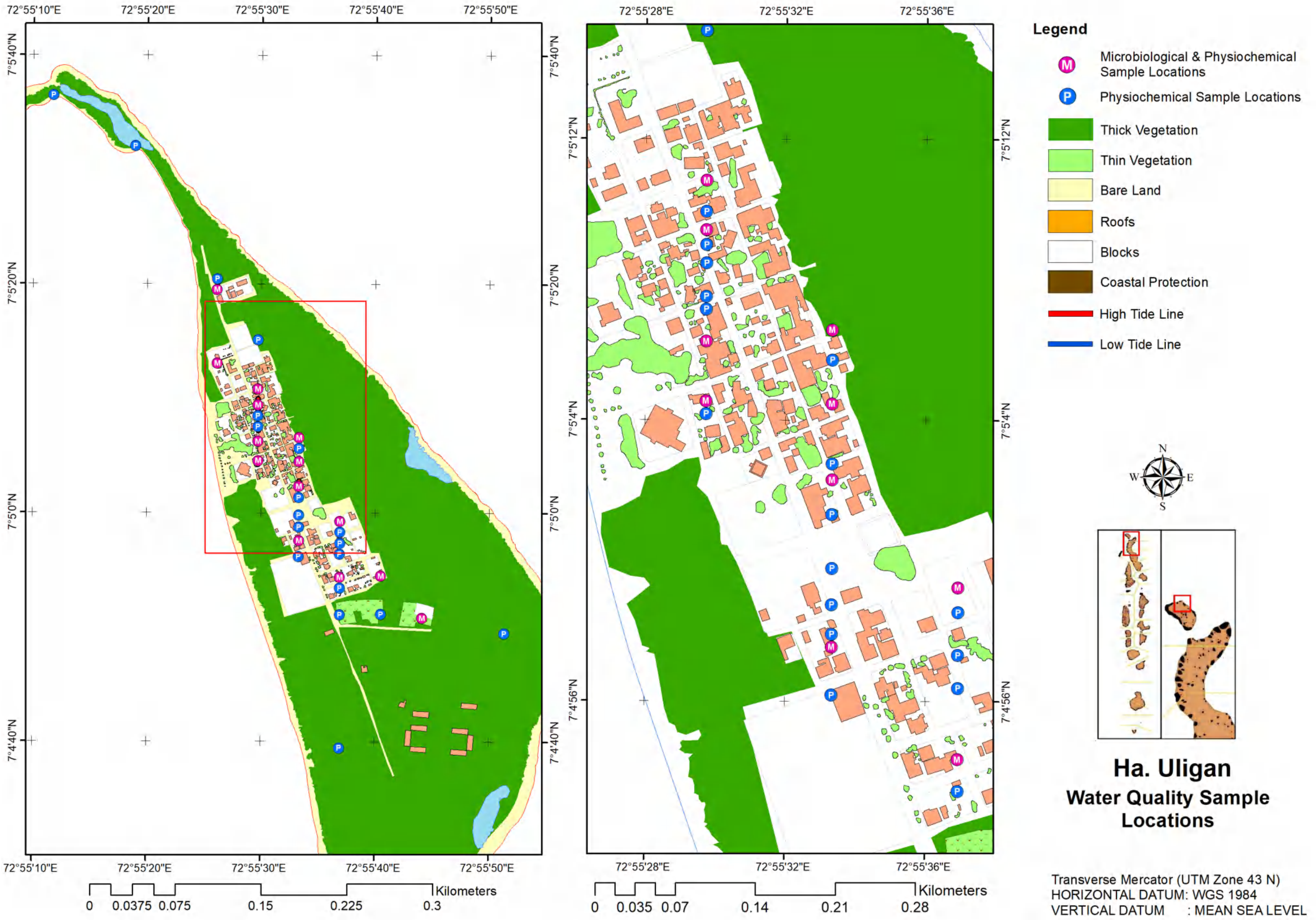

72°59'0"E
72°59'10"E
6°51'20"N
6°51'0"N
Kilometers
0 0.0275 0.055 0.11 0.165 0.22
72°59'4"E
6°51'12"N
6°51'4"N
Legend
Microbiological & Physiochemical Sample Locations
Physiochemical Sample Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
W
E
S
Ha. Maarandhoo
Water Quality Sample Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL



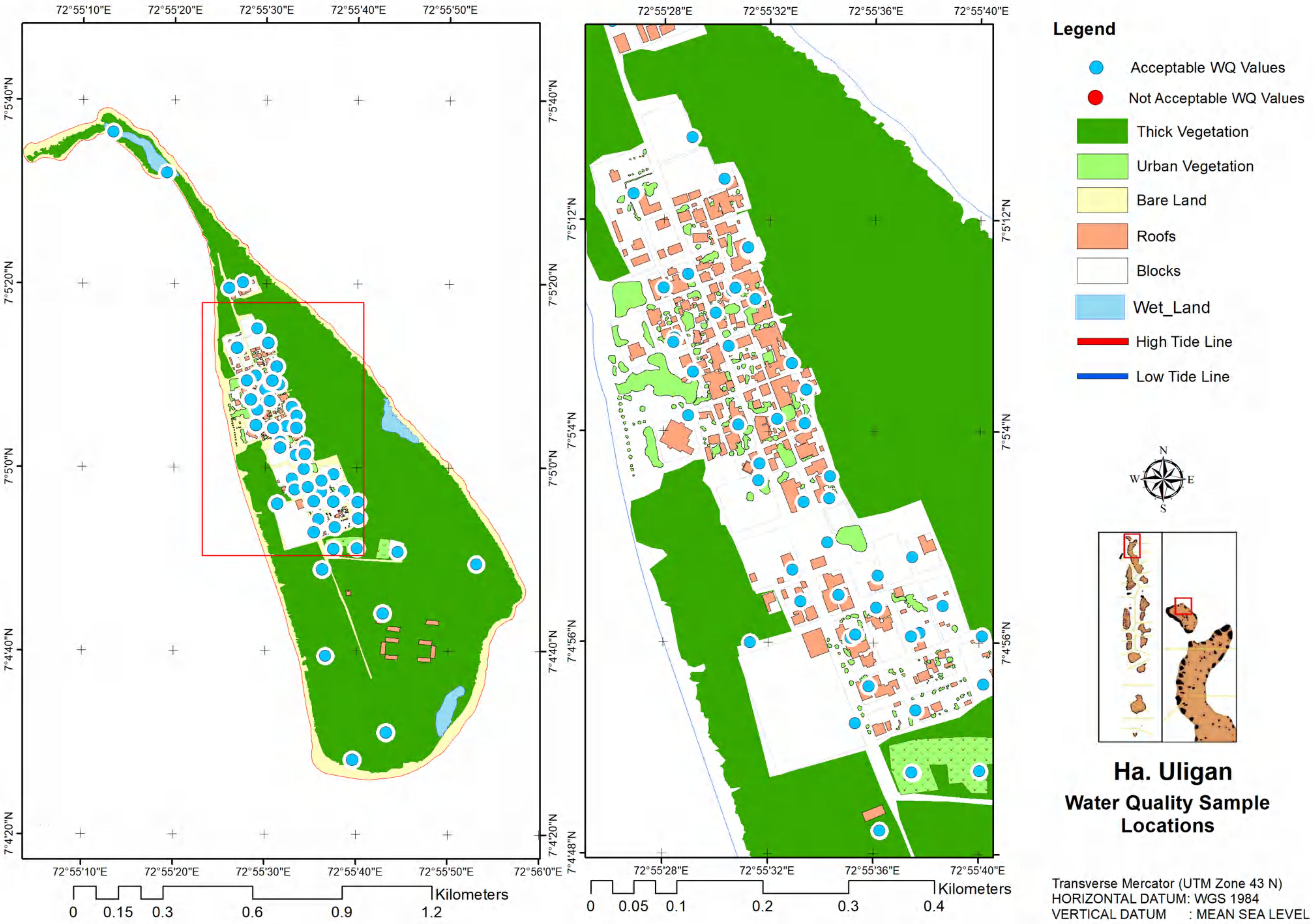
Legend
Acceptable WQ Values
Not Acceptable WQ Values
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Urban Vegetation
High Tide Line
Low Tide Line
Ha. Maarandhoo
Water Quality Sample Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
Kilometers
0 0.05 0.1 0.2 0.3 0.4
72°59'0"E
72°59'10"E
72°58'56"E
72°59'4"E
6°51'20"N
6°51'0"N
6°51'12"N
6°51'4"N
MW 1
MW 10
MW 13
MA30
MA10
MA17
MA12
MA27
MA31
MA20
MA5
MA39
MA33
MA35
MA36
MA8

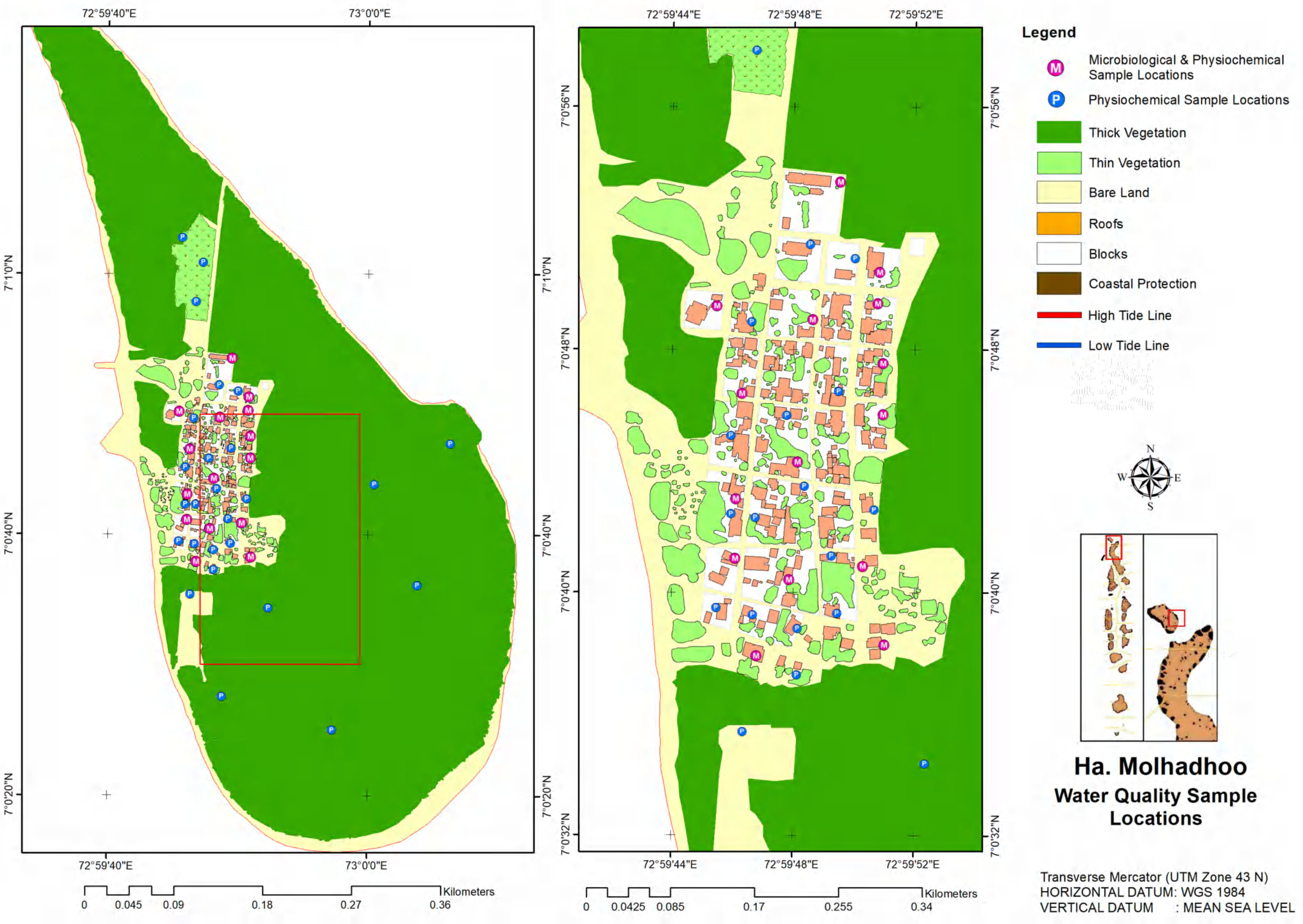

73°9'53"E
73°10'0"E
73°10'7"E
6°50'28"N
6°50'21"N
6°50'14"N
6°50'7"N
6°50'0"N
0 0.05 0.1 0.2 0.3 0.4
Kilometers
0 0.03750.075 0.15 0.225 0.3
Kilometers
Legend
Microbiological & Physiochemical Sample Locations
Physiochemical Sample Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
W
E
S
HA. Muraidhoo
Water Quality Sample Locations
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

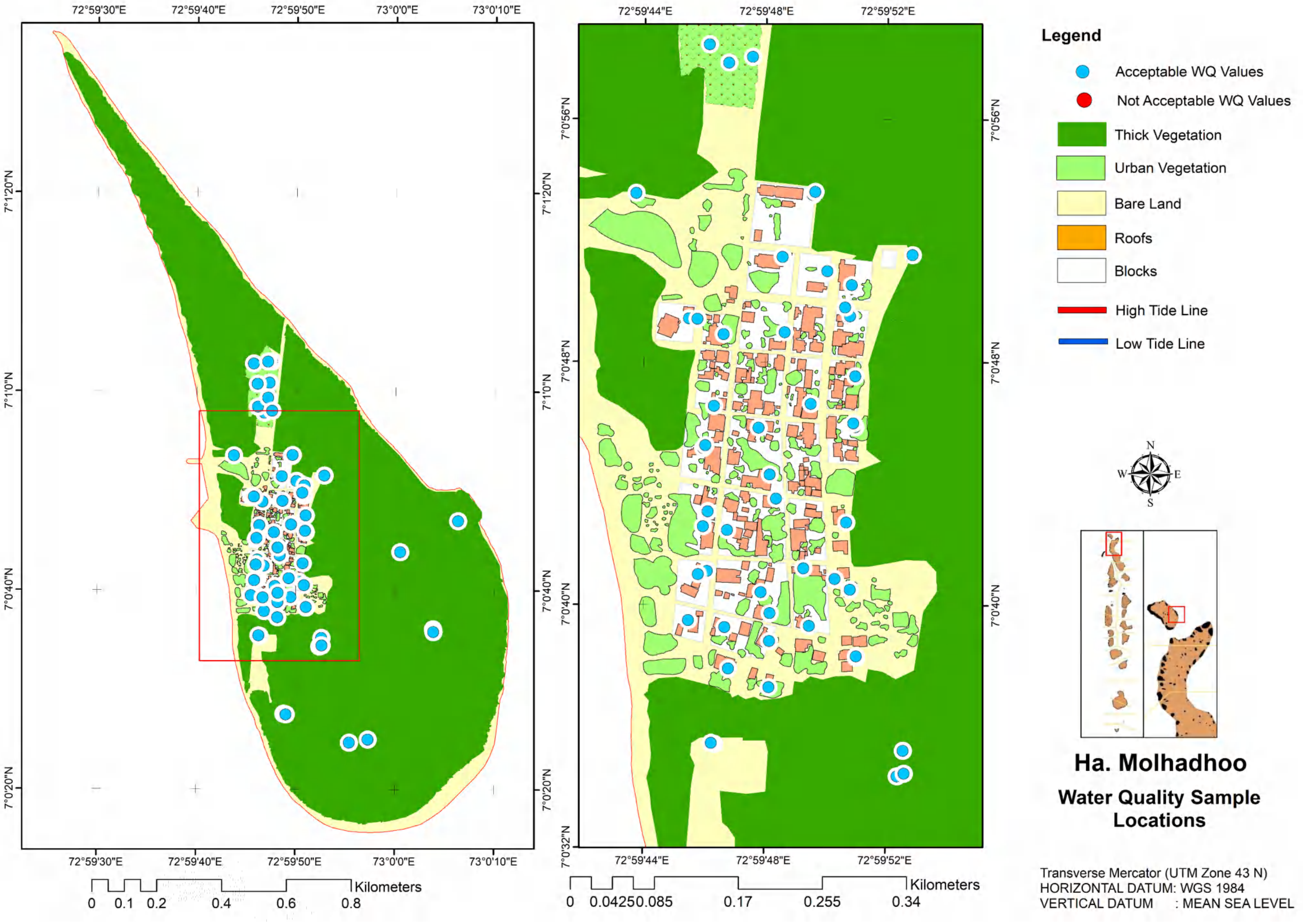

Legend
Acceptable WQ Values
Not Acceptable WQ Values
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
High Tide Line
Low Tide Line
HA. Muraidhoo
Water Quality Sample Locations
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
Kilometers
0 0.05 0.1 0.2 0.3 0.4
0 0.03 0.06 0.12 0.18 0.24
73°9'53"E
73°10'0"E
73°10'7"E
6°50'28"N
6°50'21"N
6°50'14"N
6°50'7"N
6°50'0"N
MU40
MU 24
MU27
MU37
MU2
MU 12
MU 15
MU16
MU18
MU17
MU8
MU12
MU21
MU11
MU36
N
S
E
W



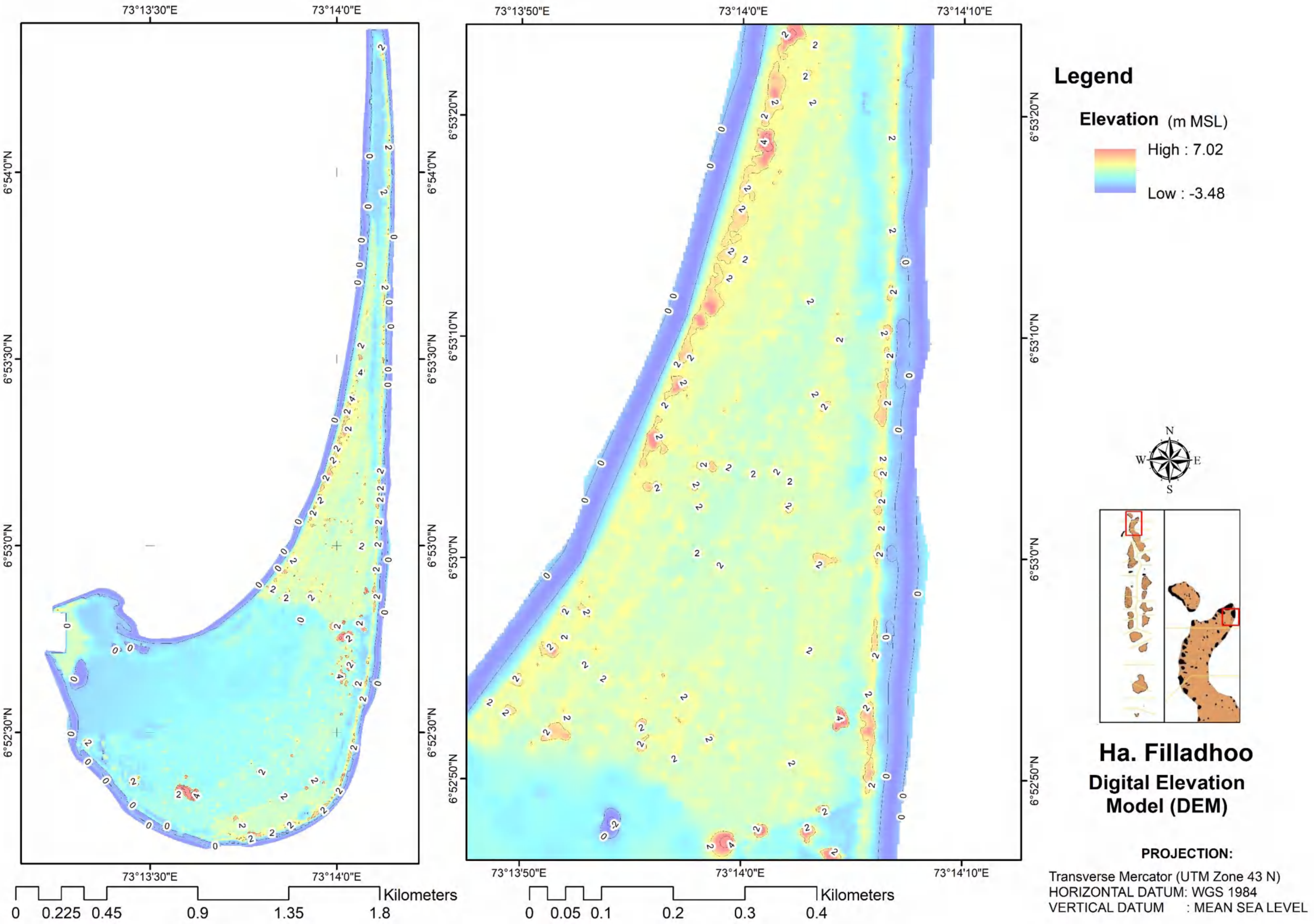
72°55'10"E
72°55'20"E
72°55'30"E
72°55'40"E
72°55'50"E
7°5'40"N
7°5'20"N
7°5'0"N
7°4'40"N
0 0.0375 0.075 0.15 0.225 0.3
Kilometers
72°55'28"E
72°55'32"E
72°55'36"E
7°5'12"N
7°5'4"N
7°4'56"N
0 0.035 0.07 0.14 0.21 0.28
Kilometers
Legend
Microbiological & Physiochemical Sample Locations
Physiochemical Sample Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
W
E
S
Ha. Uligan
Water Quality Sample Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

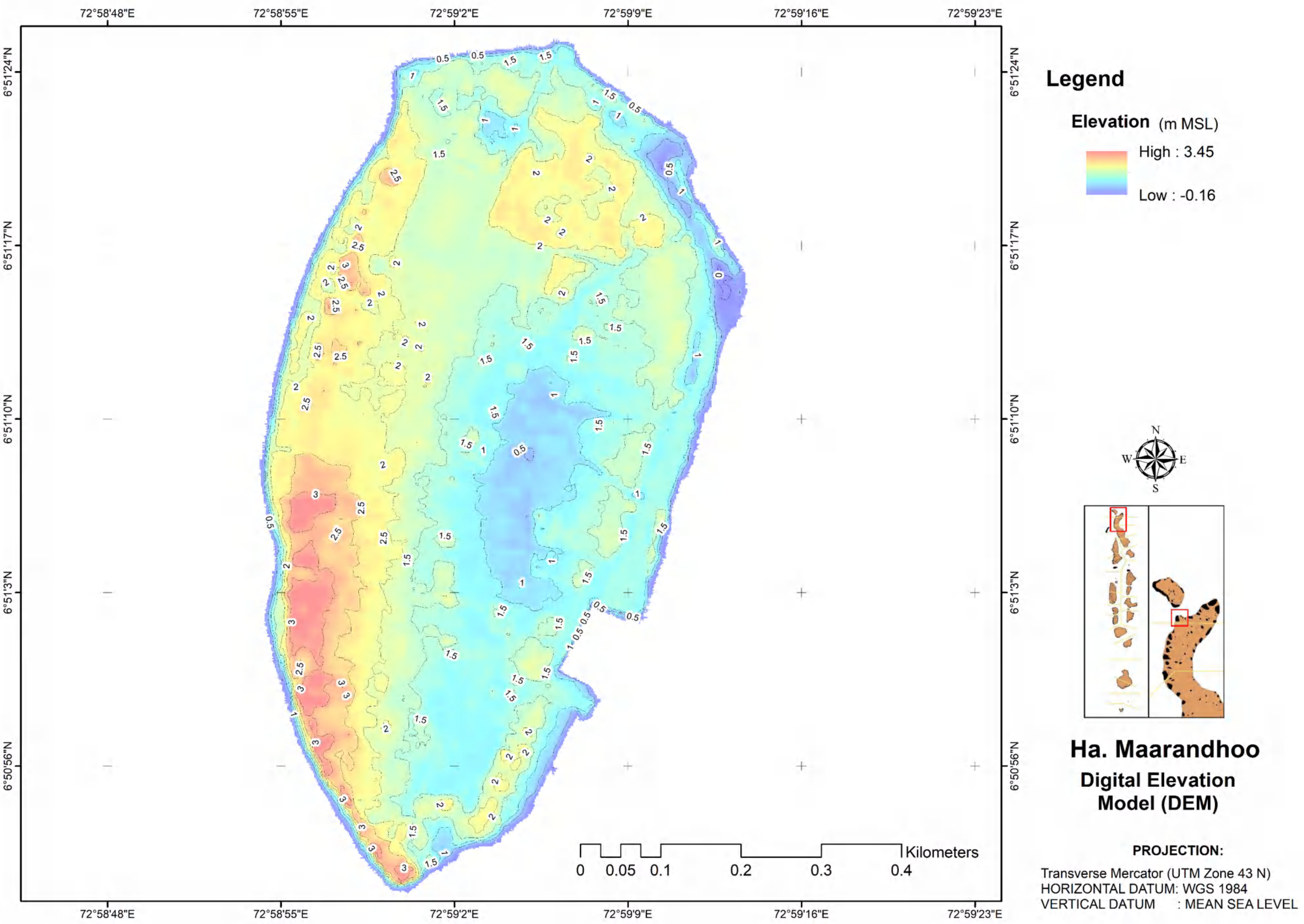

Legend
Acceptable WQ Values
Not Acceptable WQ Values
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
Wet_Land
High Tide Line
Low Tide Line
Ha. Uligan
Water Quality Sample Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
Kilometers
0 0.15 0.3 0.6 0.9 1.2
0 0.05 0.1 0.2 0.3 0.4


72°59'40"E
73°0'0"E
7°1'0"N
7°0'40"N
7°0'20"N
0 0.045 0.09 0.18 0.27 0.36 Kilometers
72°59'44"E
72°59'48"E
72°59'52"E
7°0'56"N
7°0'48"N
7°0'40"N
7°0'32"N
0 0.0425 0.085 0.17 0.255 0.34 Kilometers
Legend
Microbiological & Physiochemical Sample Locations
Physiochemical Sample Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
W
E
S
Ha. Molhadhoo
Water Quality Sample Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

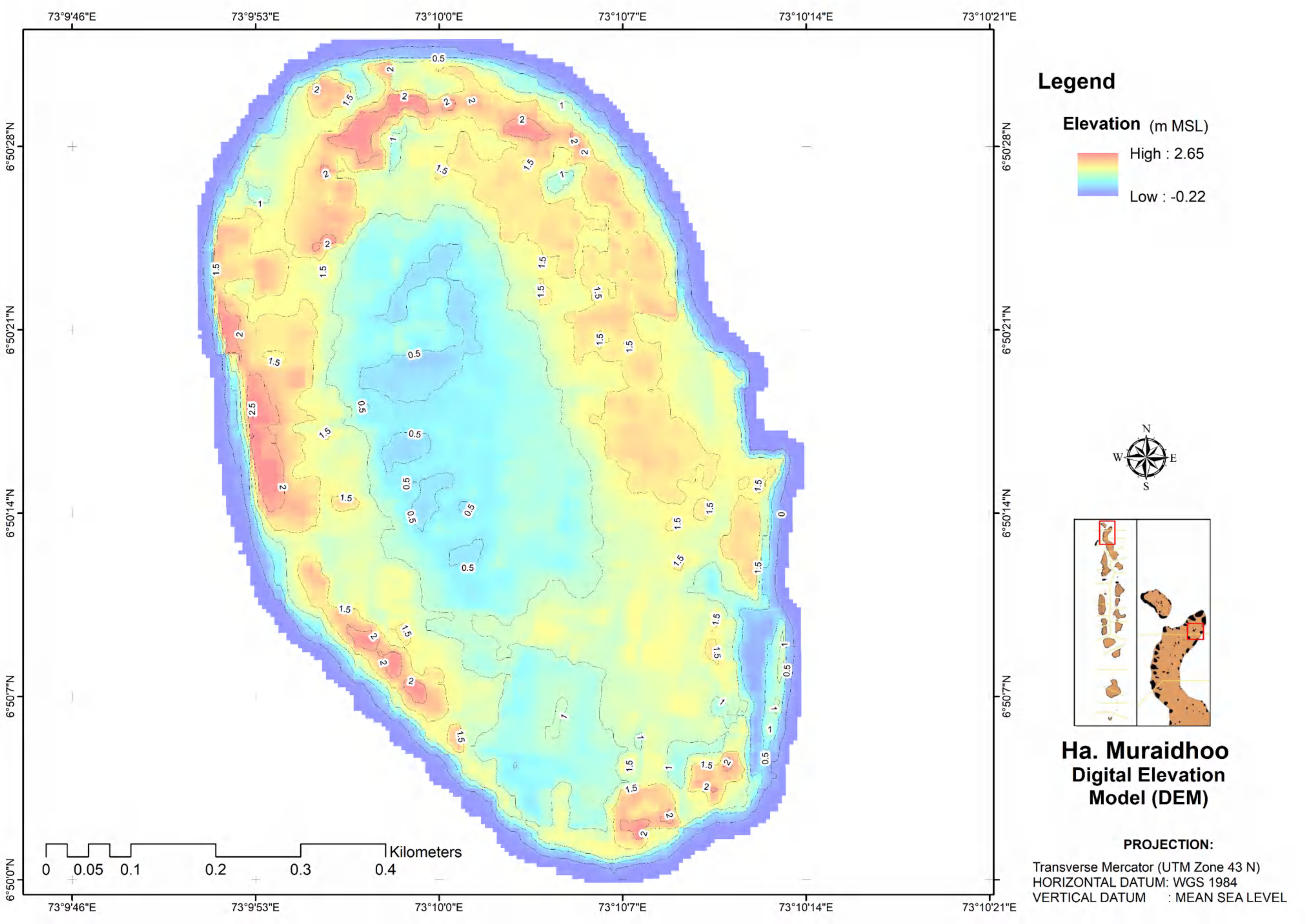

72°59'30"E
72°59'40"E
72°59'50"E
73°0'0"E
73°0'10"E
7°1'20"N
7°1'0"N
7°0'40"N
7°0'20"N
0 0.1 0.2 0.4 0.6 0.8
Kilometers
72°59'44"E
72°59'48"E
72°59'52"E
7°0'56"N
7°0'48"N
7°0'40"N
7°0'32"N
0 0.0425 0.085 0.17 0.255 0.34
Kilometers
Legend
Acceptable WQ Values
Not Acceptable WQ Values
Thick Vegetation
Urban Vegetation
Bare Land
Roofs
Blocks
High Tide Line
Low Tide Line
N
W
E
S
Ha. Molhadhoo
Water Quality Sample Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

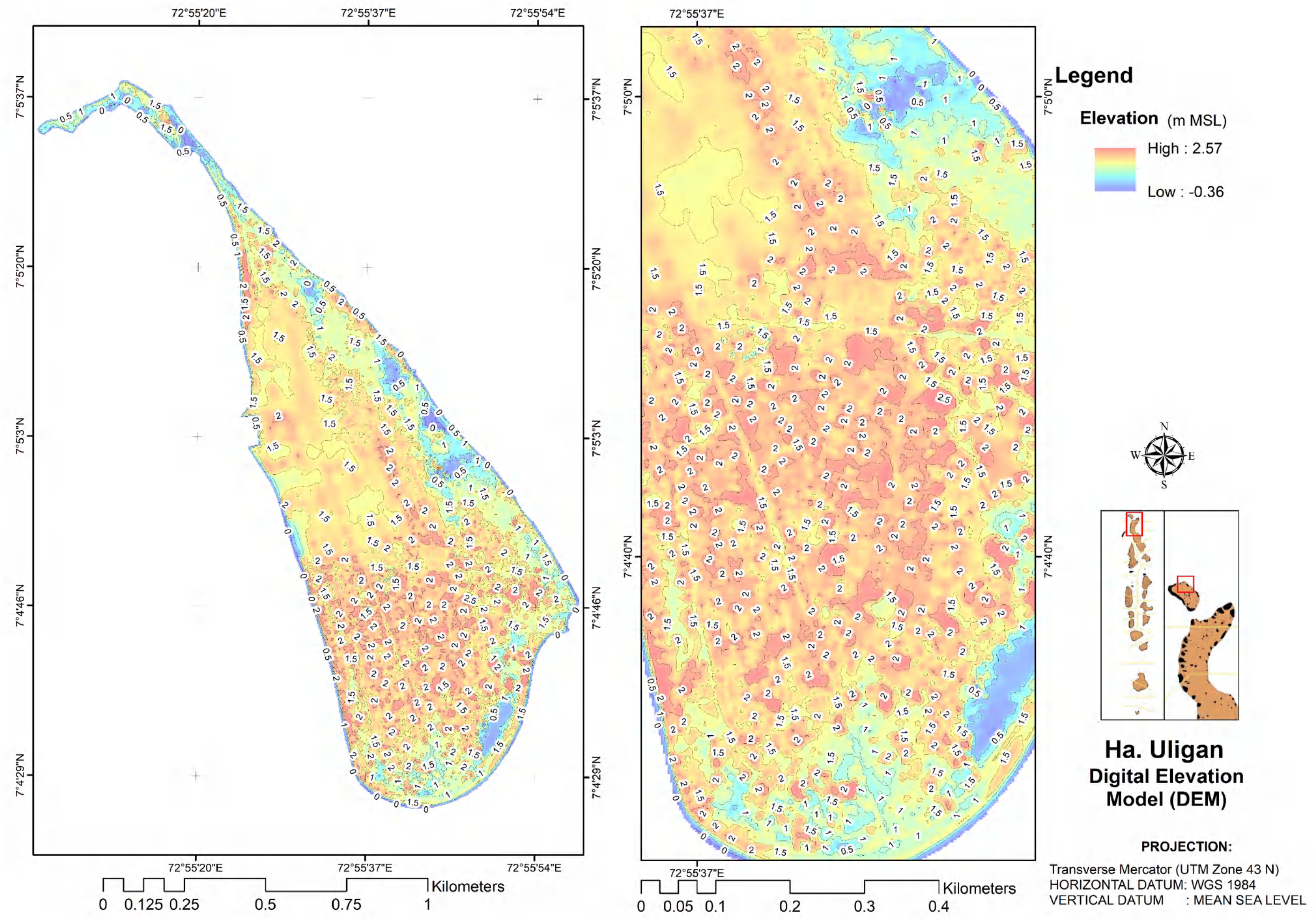
Annex IV: Digital Elevation Model of Islands


73°13'30"E
73°14'0"E
6°54'0"N
6°53'30"N
6°53'0"N
6°52'30"N
0 0.225 0.45 0.9 1.35 1.8 Kilometers
73°13'50"E
73°14'10"E
6°53'20"N
6°53'10"N
6°52'50"N
0 0.05 0.1 0.2 0.3 0.4 Kilometers
Legend
Elevation (m MSL)
High : 7.02
Low : -3.48
N
E
S
W
Ha. Filladhoo
Digital Elevation Model (DEM)
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

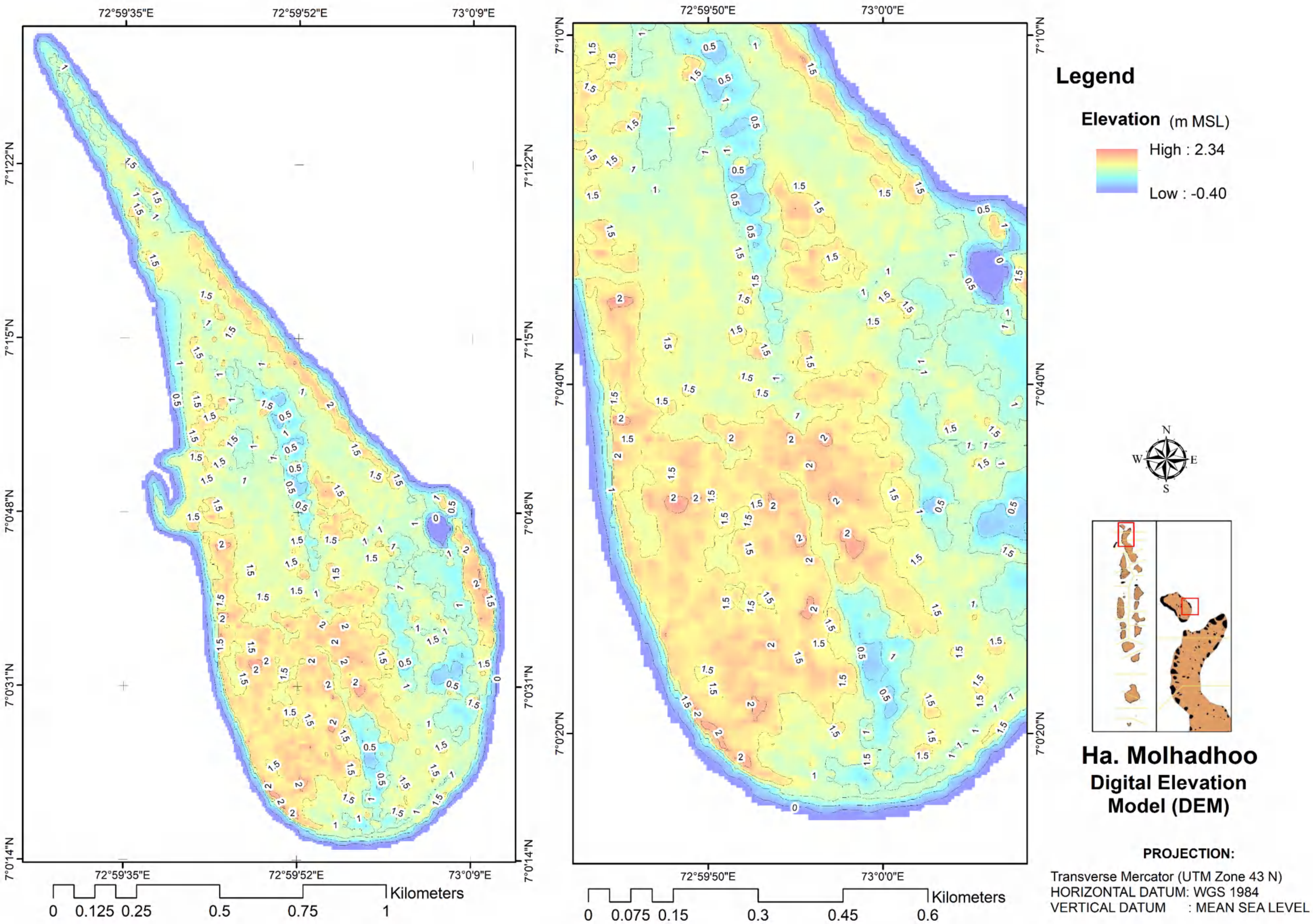


72°58'48"E
72°58'55"E
72°59'2"E
72°59'9"E
72°59'16"E
72°59'23"E
6°51'24"N
6°51'17"N
6°51'10"N
6°51'3"N
6°50'56"N
Legend
Elevation (m MSL)
High : 3.45
Low : -0.16
N
W
E
S
0 0.05 0.1 0.2 0.3 0.4 Kilometers
Ha. Maarandhoo
Digital Elevation Model (DEM)
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

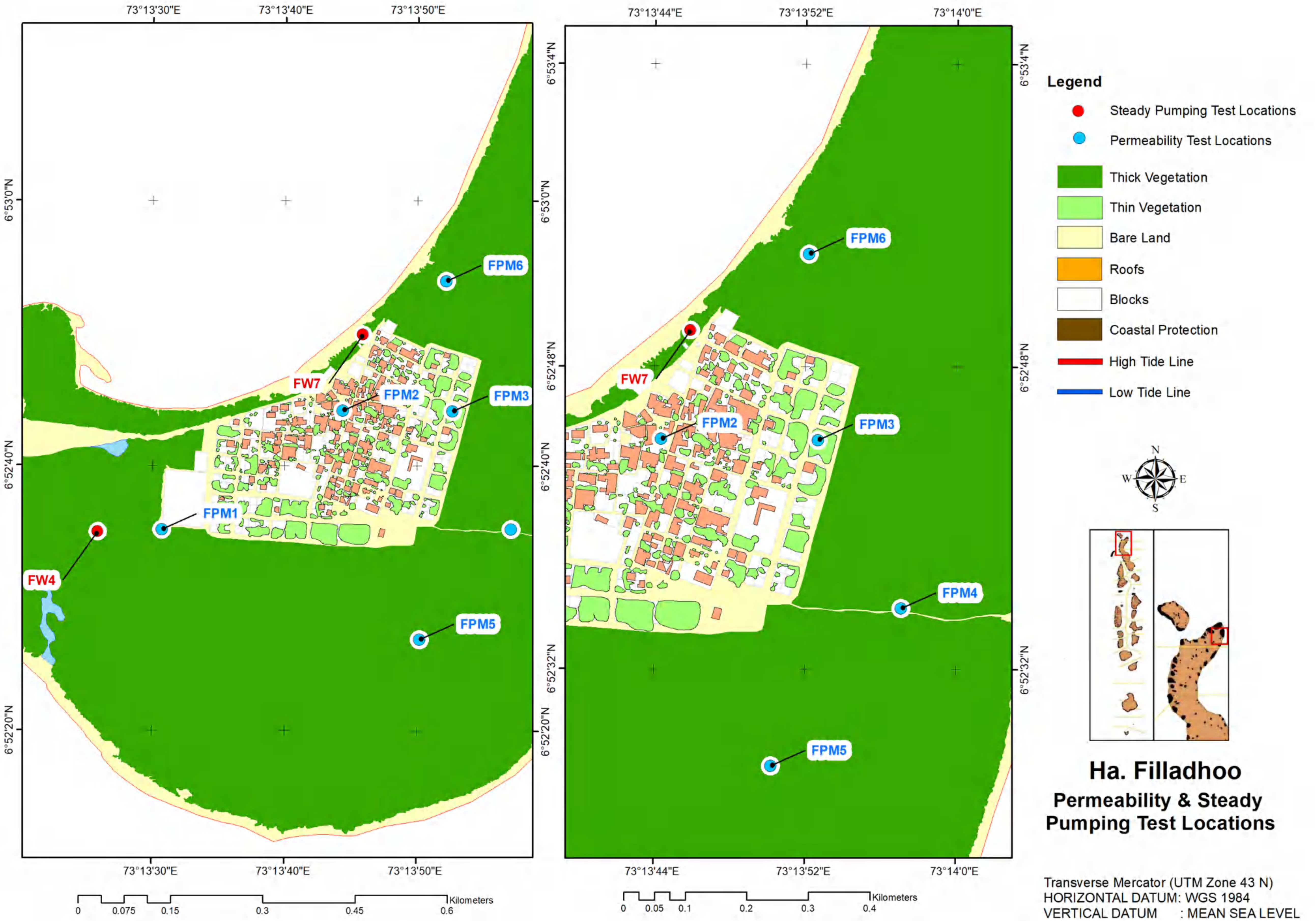

73°9'46"E
73°9'53"E
73°10'0"E
73°10'7"E
73°10'14"E
73°10'21"E
6°50'28"N
6°50'21"N
6°50'14"N
6°50'7"N
6°50'0"N
Legend
Elevation (m MSL)
High : 2.65
Low : -0.22
N
S
E
W
0 0.05 0.1 0.2 0.3 0.4
Kilometers
Ha. Muraidhoo
Digital Elevation Model (DEM)
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

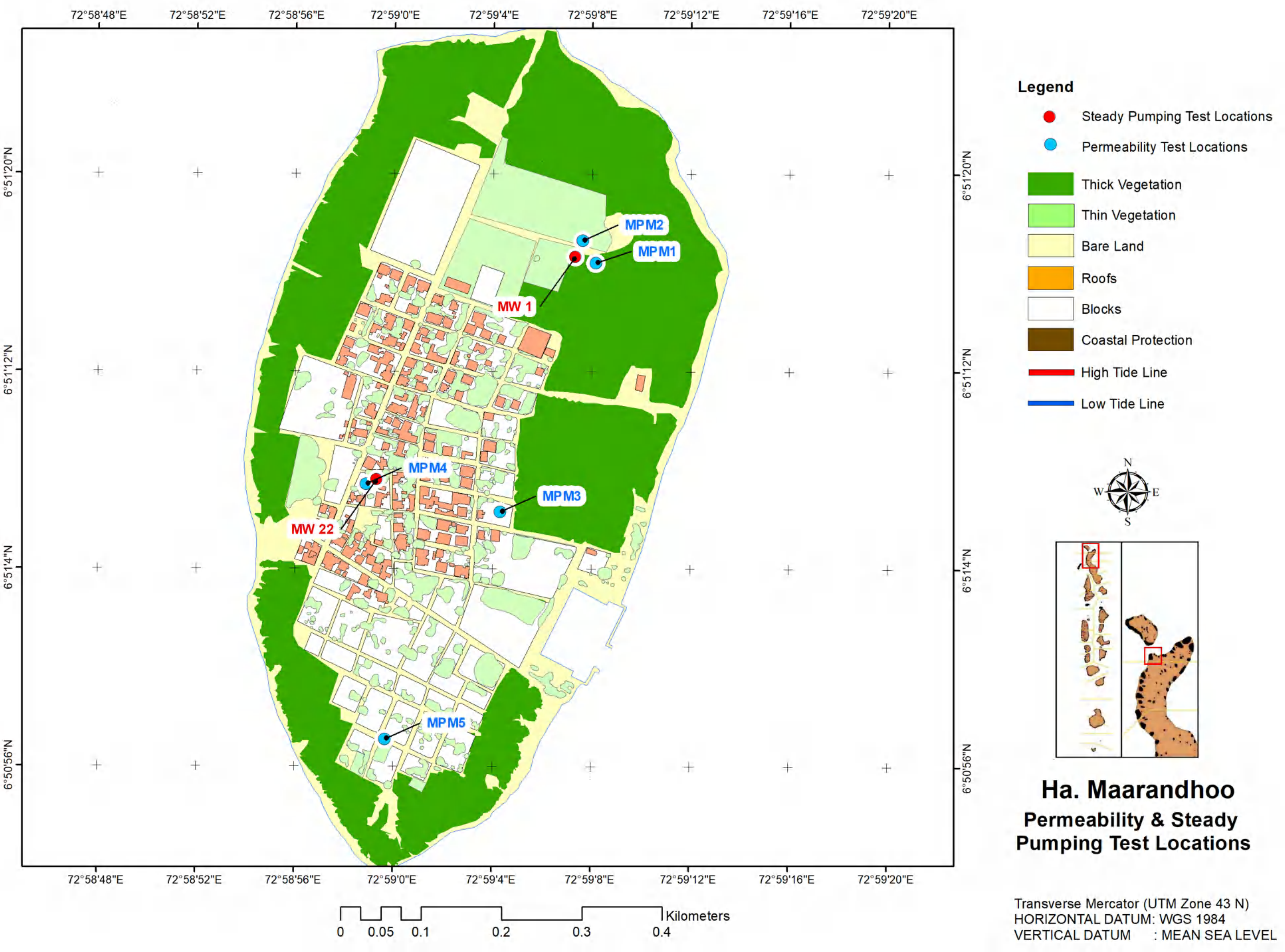


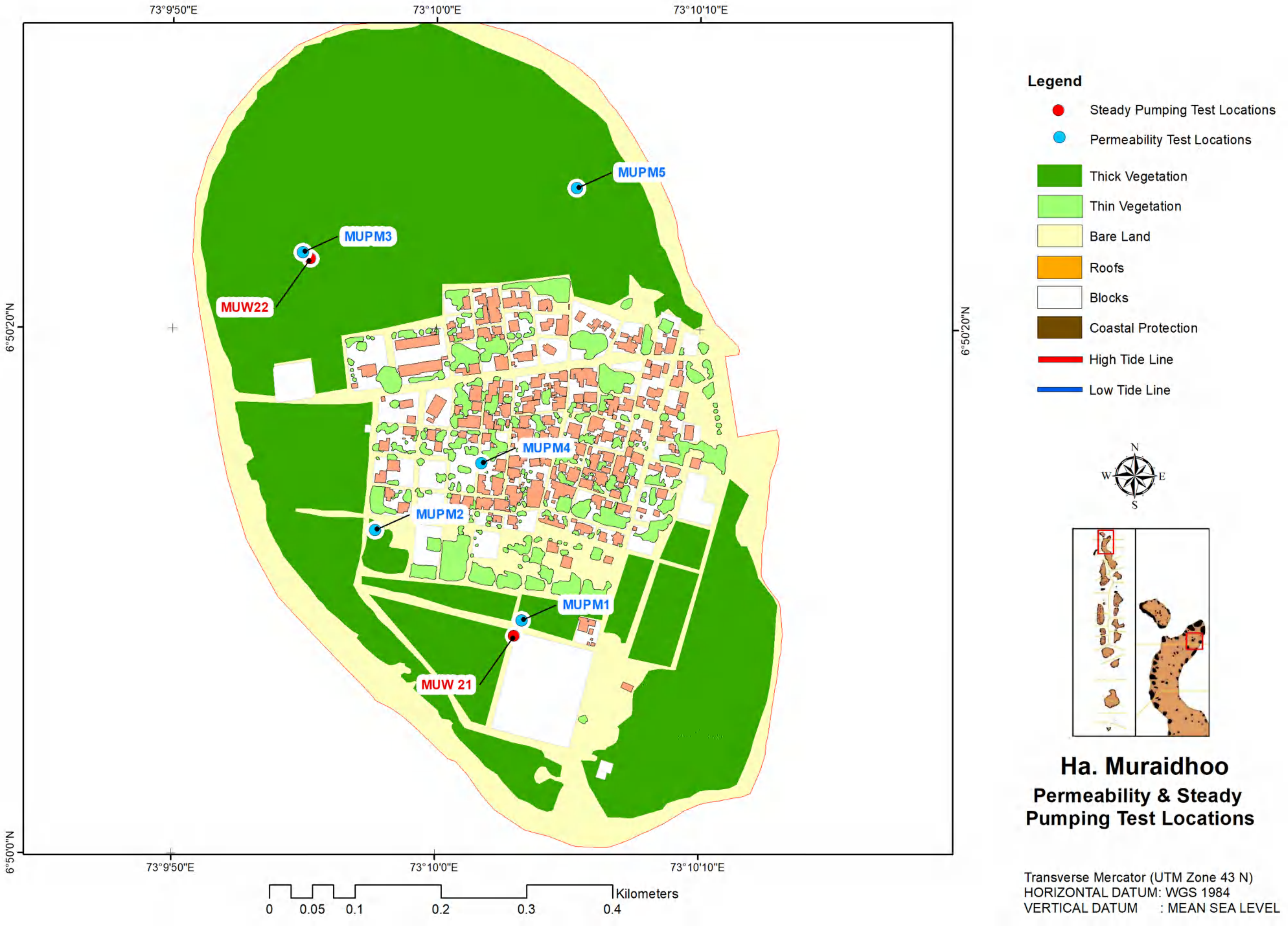
Legend
Elevation (m MSL)
High : 2.57
Low : -0.36
N
S
E
W
Ha. Uligan
Digital Elevation Model (DEM)
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
72°55'20"E
72°55'37"E
72°55'54"E
7°5'37"N
7°5'20"N
7°5'3"N
7°4'46"N
7°4'29"N
7°5'0"N
7°4'40"N
0 0.125 0.25 0.5 0.75 1 Kilometers
0 0.05 0.1 0.2 0.3 0.4 Kilometers

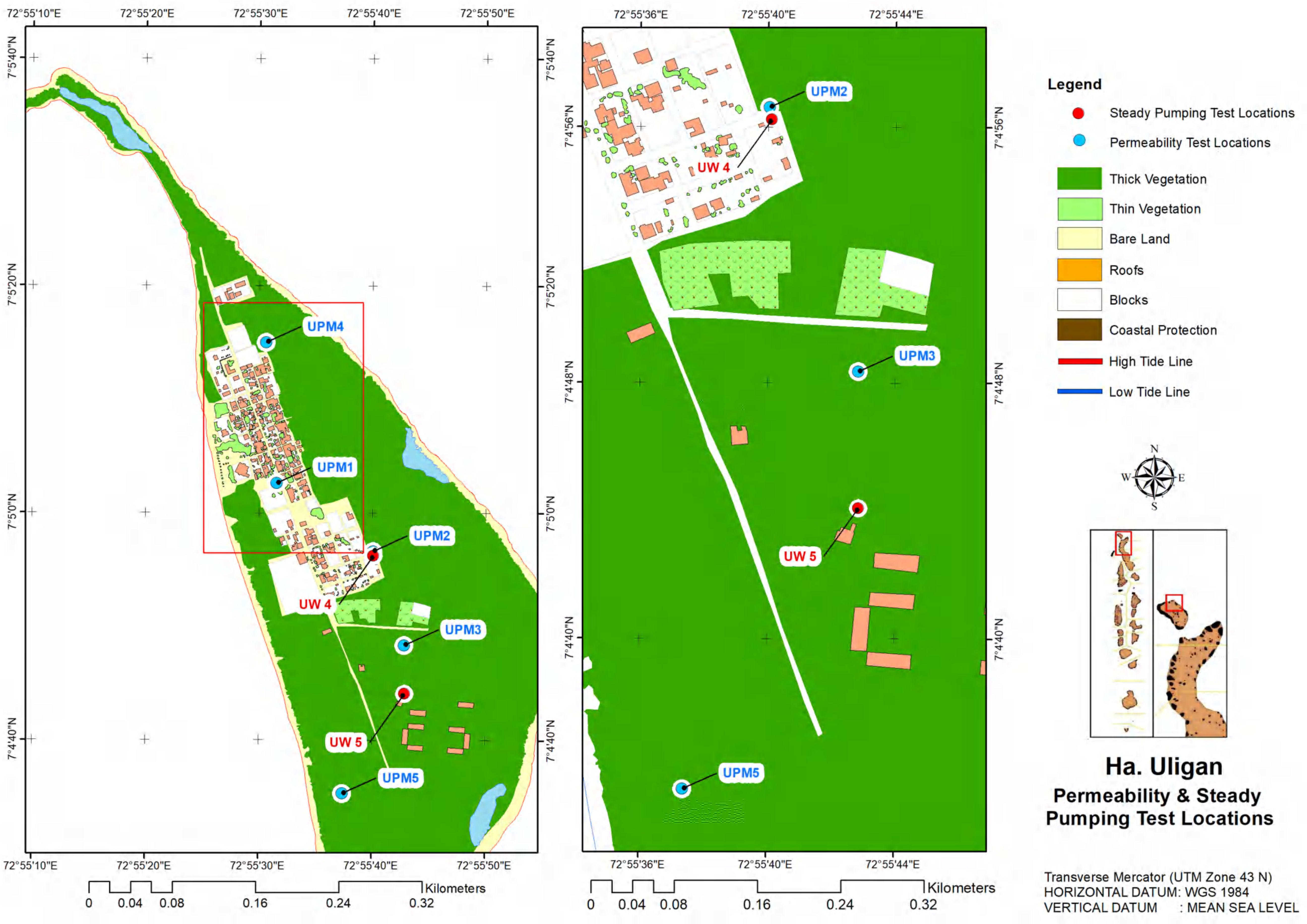

72°59'35"E
72°59'52"E
73°0'9"E
7°1'22"N
7°1'5"N
7°0'48"N
7°0'31"N
7°0'14"N
0 0.125 0.25 0.5 0.75 1 Kilometers
72°59'50"E
73°0'0"E
7°1'0"N
7°0'40"N
7°0'20"N
0 0.075 0.15 0.3 0.45 0.6 Kilometers
Legend
Elevation (m MSL)
High : 2.34
Low : -0.40
N
S
E
W
Ha. Molhadhoo
Digital Elevation Model (DEM)
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

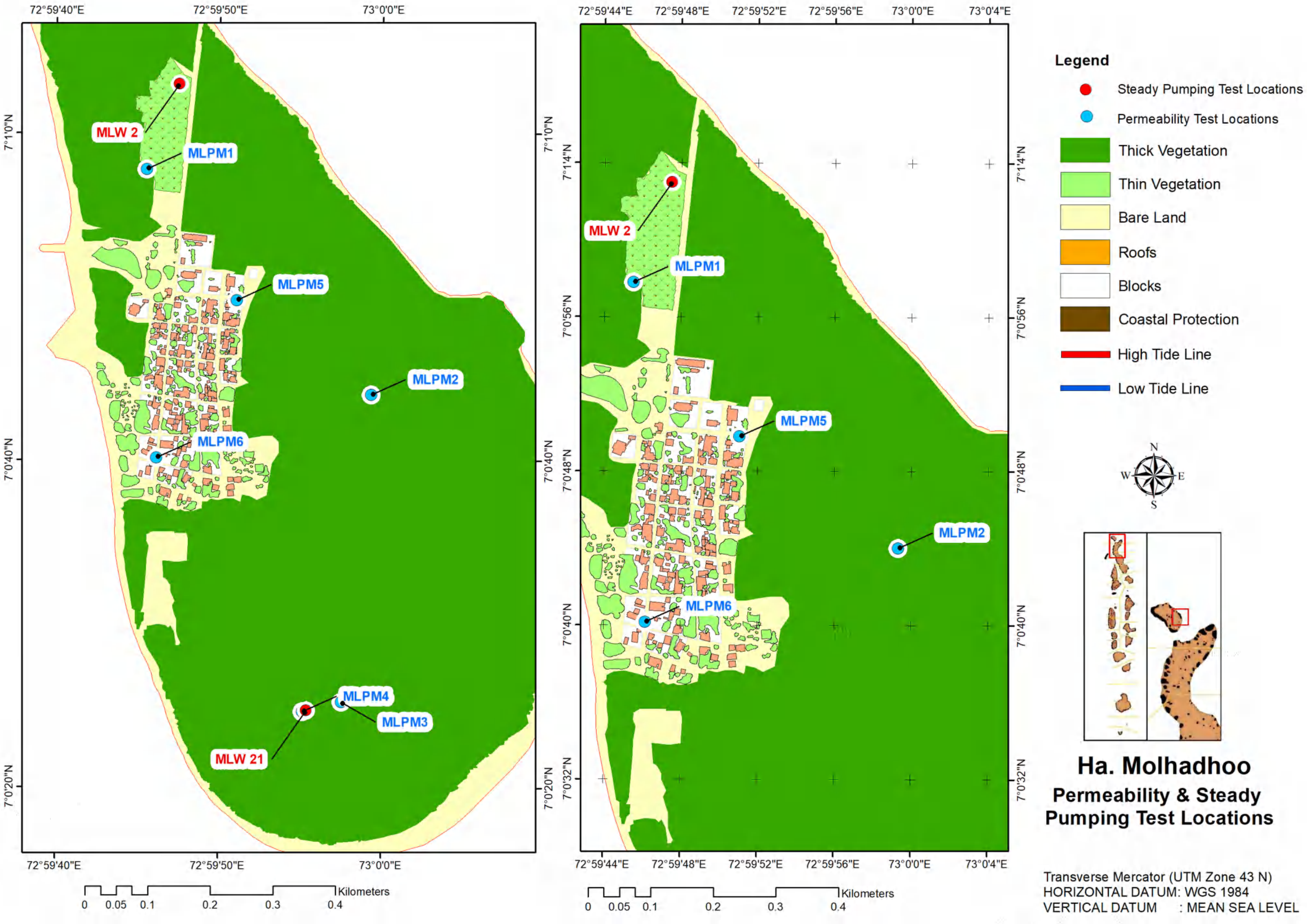
Annex V: Locations of Permeability and Steady Pumping Tests Maps


73°13'30"E
73°13'40"E
73°13'50"E
6°53'0"N
6°52'40"N
6°52'20"N
FPM6
FW7
FPM2
FPM3
FPM1
FW4
FPM5
Kilometers
0
0.075
0.15
0.3
0.45
0.6
73°13'44"E
73°13'52"E
73°14'0"E
6°53'4"N
6°52'48"N
6°52'32"N
FPM4
0
0.05
0.1
0.2
0.3
0.4
Legend
Steady Pumping Test Locations
Permeability Test Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
S
E
W
Ha. Filladhoo
Permeability & Steady Pumping Test Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

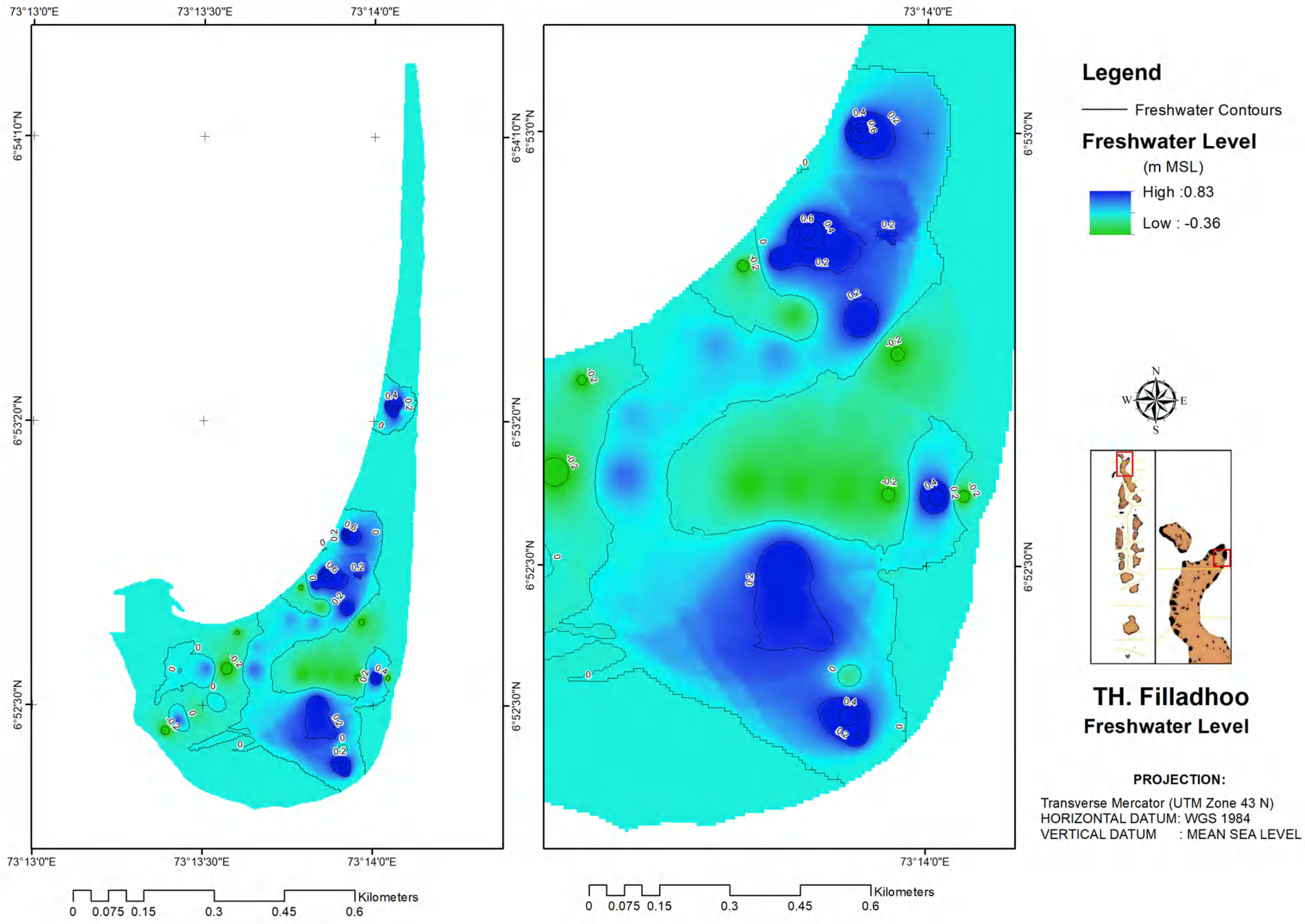

72°58'48"E
72°58'52"E
72°58'56"E
72°59'0"E
72°59'4"E
72°59'8"E
72°59'12"E
72°59'16"E
72°59'20"E
6°51'20"N
6°51'12"N
6°51'4"N
6°50'56"N
MPM2
MPM1
MW 1
MPM4
MPM3
MW 22
MPM5
0 0.05 0.1 0.2 0.3 0.4
Kilometers
Legend
Steady Pumping Test Locations
Permeability Test Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
W
E
S
Ha. Maarandhoo
Permeability & Steady Pumping Test Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL


73°9'50"E
73°10'0"E
73°10'10"E
6°50'20"N
6°50'0"N
MUPM5
MUPM3
MUW22
MUPM4
MUPM2
MUPM1
MUW 21
0
0.05
0.1
0.2
0.3
0.4
Kilometers
Legend
Steady Pumping Test Locations
Permeability Test Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
W
E
S
Ha. Muraidhoo
Permeability & Steady Pumping Test Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

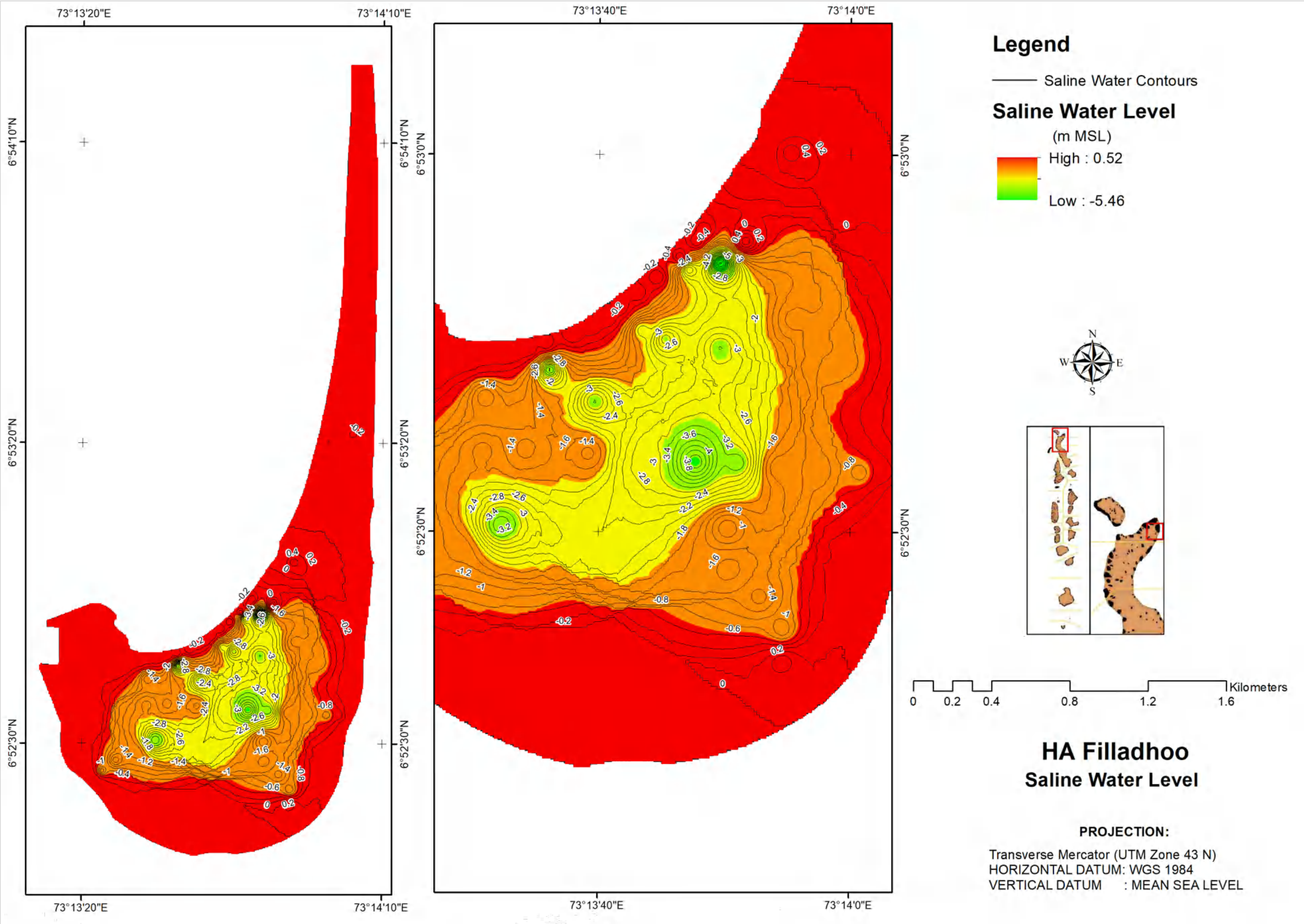

72°55'10"E
72°55'20"E
72°55'30"E
72°55'40"E
72°55'50"E
7°5'40"N
7°5'20"N
7°5'0"N
7°4'40"N
UPM4
UPM1
UPM2
UW 4
UPM3
UW 5
UPM5
72°55'36"E
72°55'40"E
72°55'44"E
7°4'56"N
7°4'48"N
7°4'40"N
0 0.04 0.08 0.16 0.24 0.32 Kilometers
Legend
Steady Pumping Test Locations
Permeability Test Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
S
E
W
Ha. Uligan
Permeability & Steady
Pumping Test Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

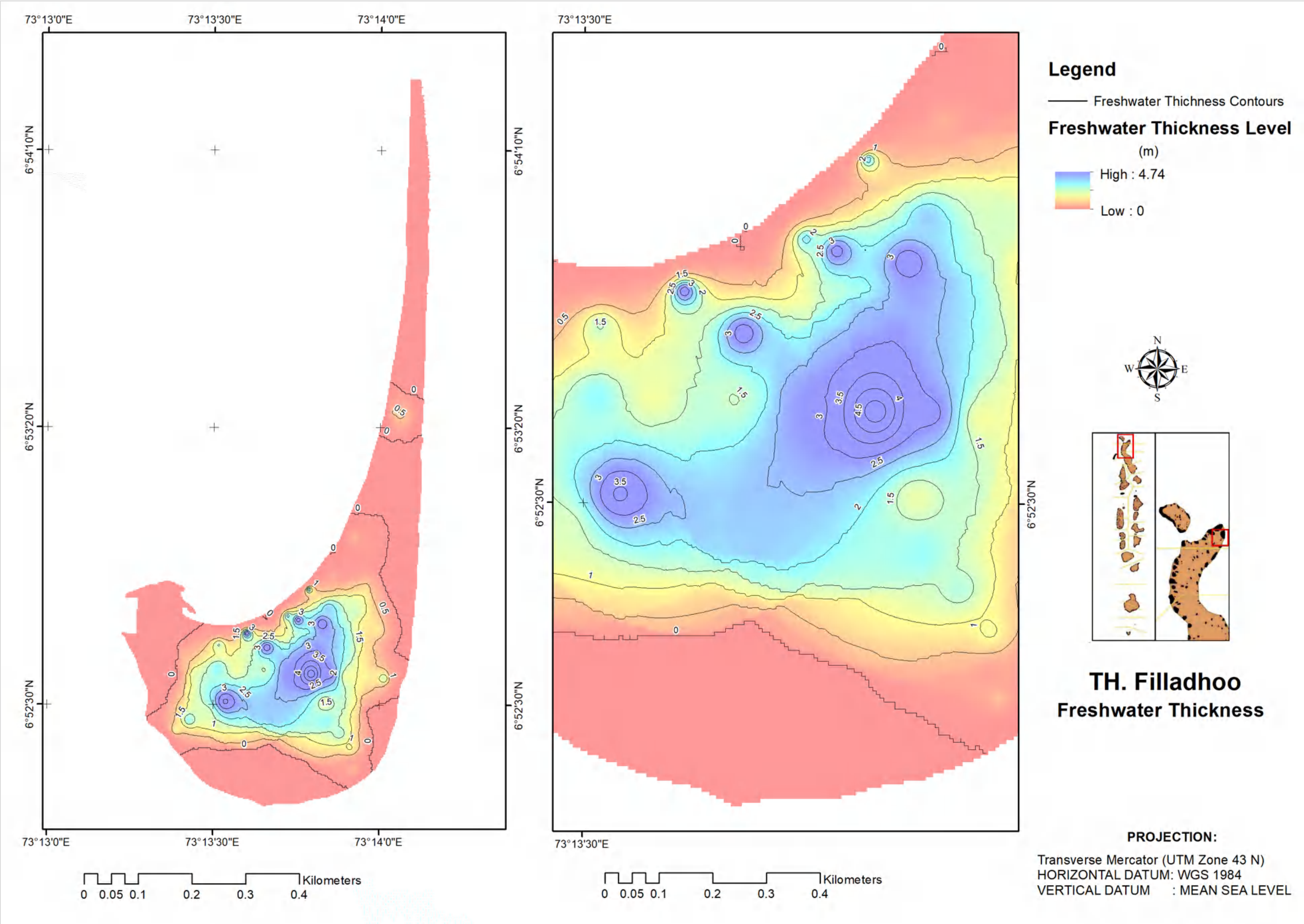

72°59'40"E
72°59'50"E
73°0'0"E
7°1'0"N
7°0'40"N
7°0'20"N
MLW 2
MLPM1
MLPM5
MLPM2
MLPM6
MLPM4
MLPM3
MLW 21
72°59'44"E
72°59'48"E
72°59'52"E
72°59'56"E
73°0'4"E
7°1'4"N
7°0'56"N
7°0'48"N
7°0'40"N
7°0'32"N
Kilometers
0 0.05 0.1 0.2 0.3 0.4
Legend
Steady Pumping Test Locations
Permeability Test Locations
Thick Vegetation
Thin Vegetation
Bare Land
Roofs
Blocks
Coastal Protection
High Tide Line
Low Tide Line
N
W
E
S
Ha. Molhadhoo
Permeability & Steady
Pumping Test Locations
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

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

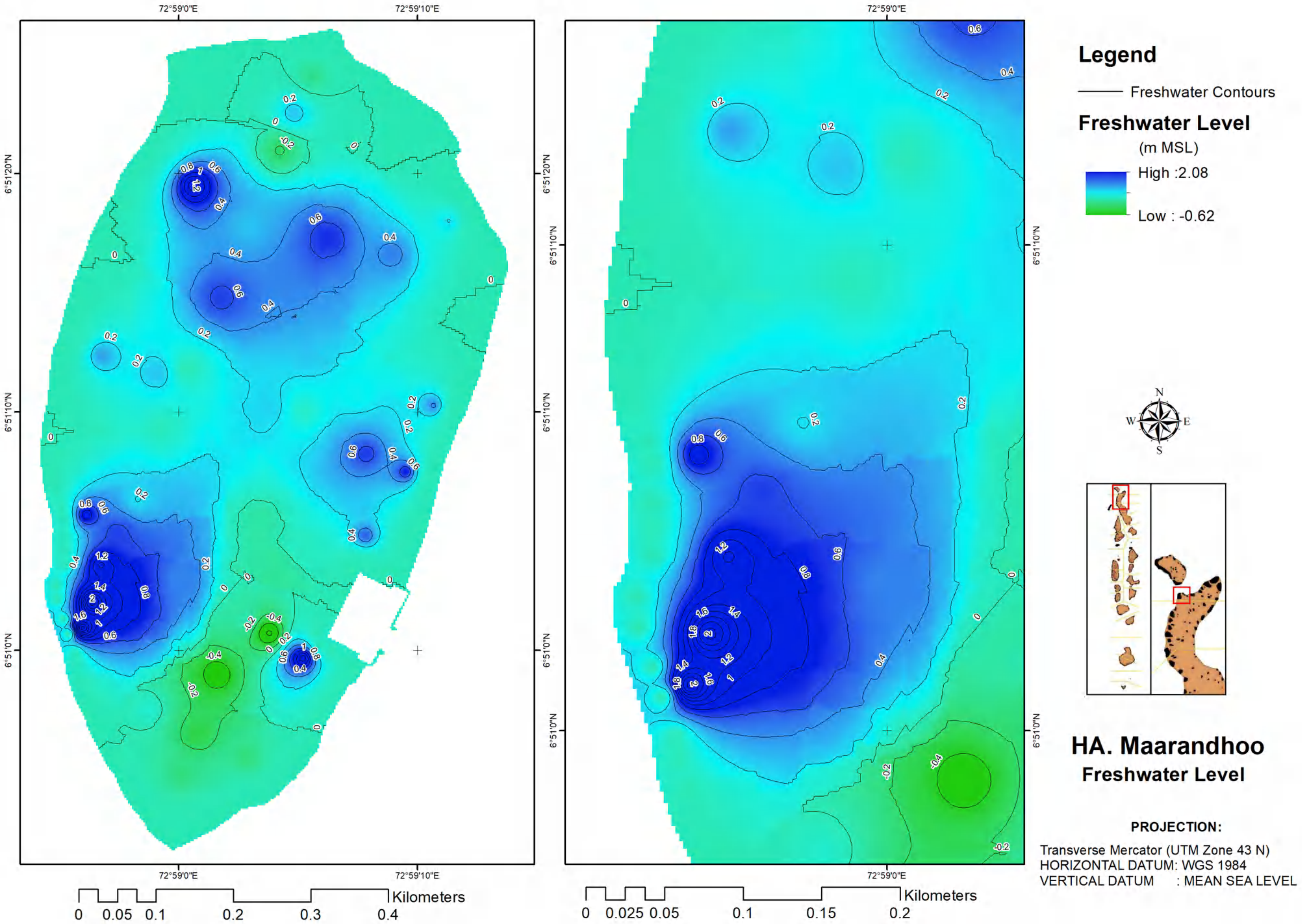


73°13'0"E
73°13'30"E
73°14'0"E
6°54'10"N
6°53'20"N
6°52'30"N
6°53'0"N
Kilometers
0 0.075 0.15 0.3 0.45 0.6
Legend
Freshwater Contours
Freshwater Level
(m MSL)
High :0.83
Low : -0.36
N
W
E
S
TH. Filladhoo
Freshwater Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

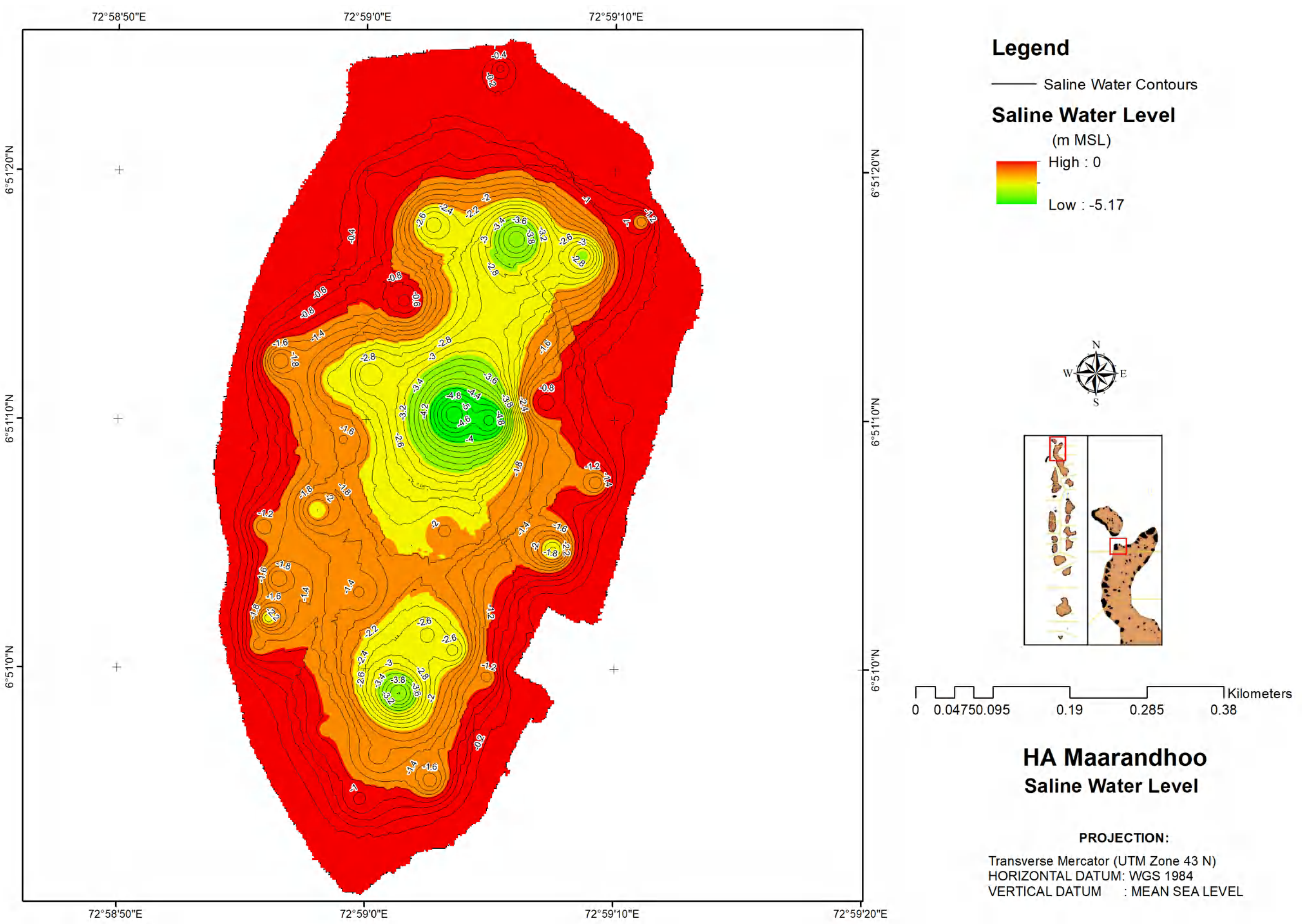

Legend
Saline Water Contours
Saline Water Level
(m MSL)
High : 0.52
Low : -5.46
N
S
E
W
0
0.2
0.4
0.8
1.2
1.6
Kilometers
HA Filladhoo
Saline Water Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
73°13'20"E
73°14'10"E
6°54'10"N
6°53'20"N
6°52'30"N
73°13'40"E
73°14'0"E
6°53'0"N
6°52'30"N



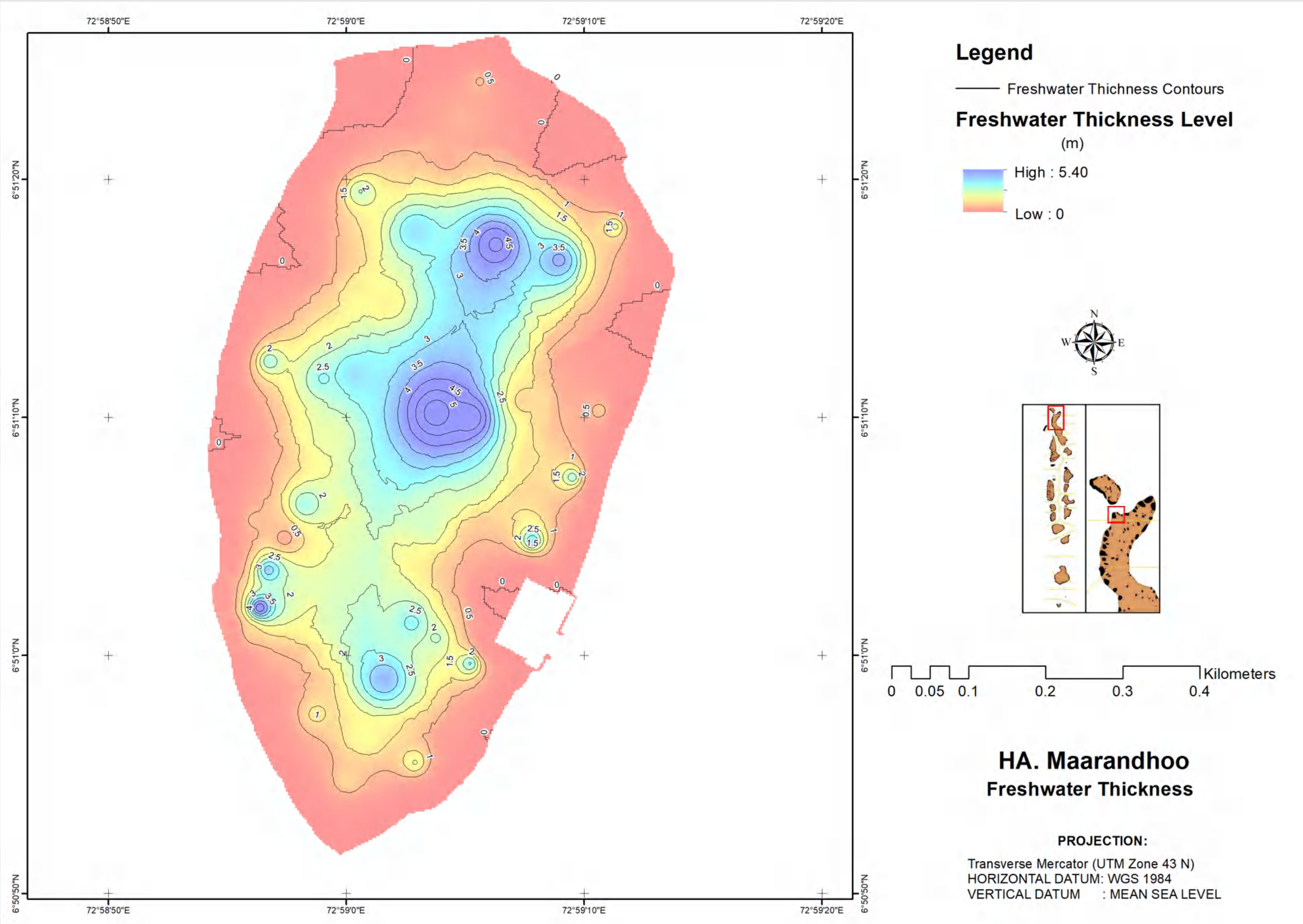
Legend
Freshwater Thichness Contours
Freshwater Thickness Level
(m)
High : 4.74
Low : 0
N
S
E
W
TH. Filladhoo
Freshwater Thickness
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
73°13'0"E
73°13'30"E
73°14'0"E
6°54'10"N
6°53'20"N
6°52'30"N
Kilometers
0 0.05 0.1 0.2 0.3 0.4

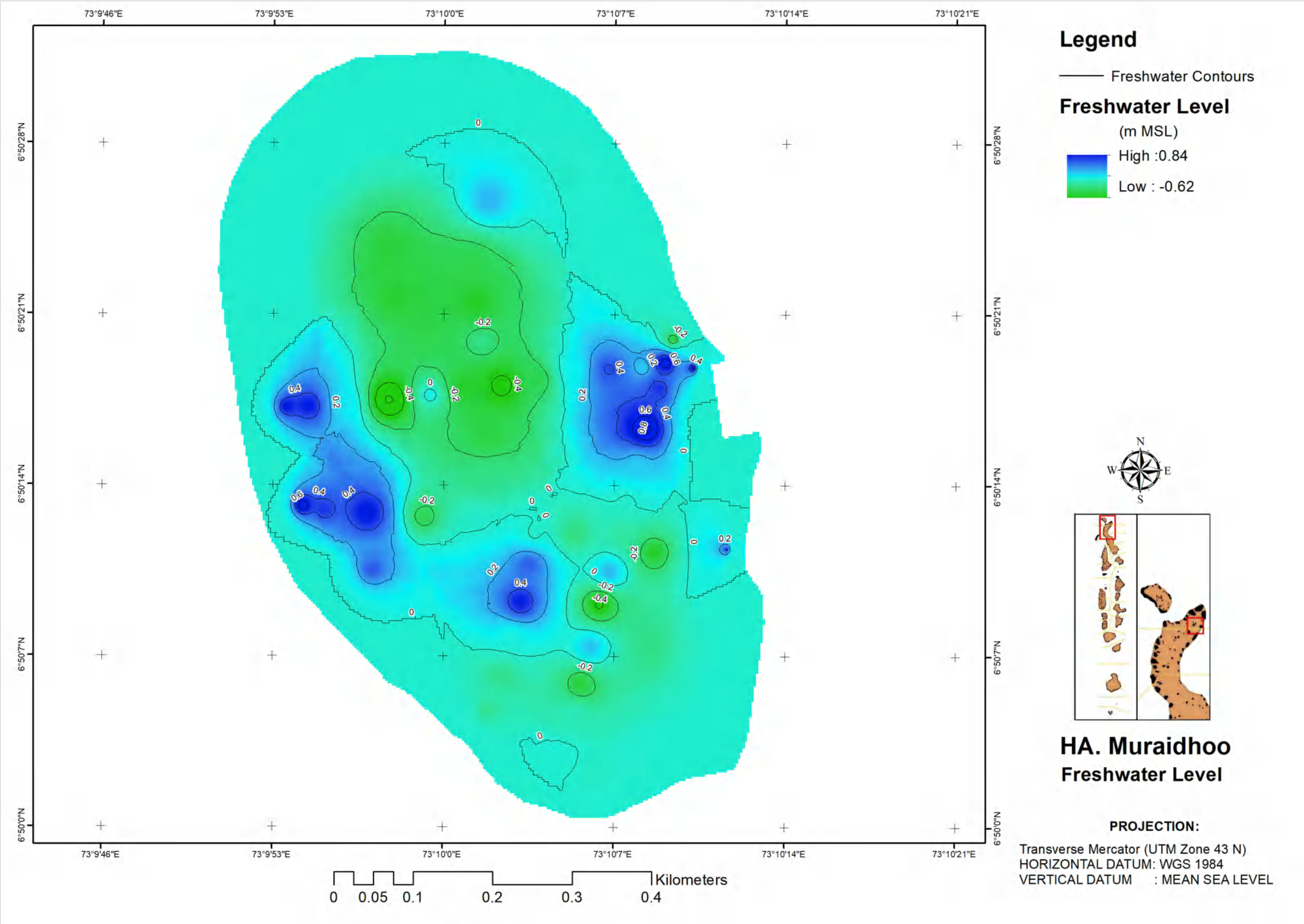


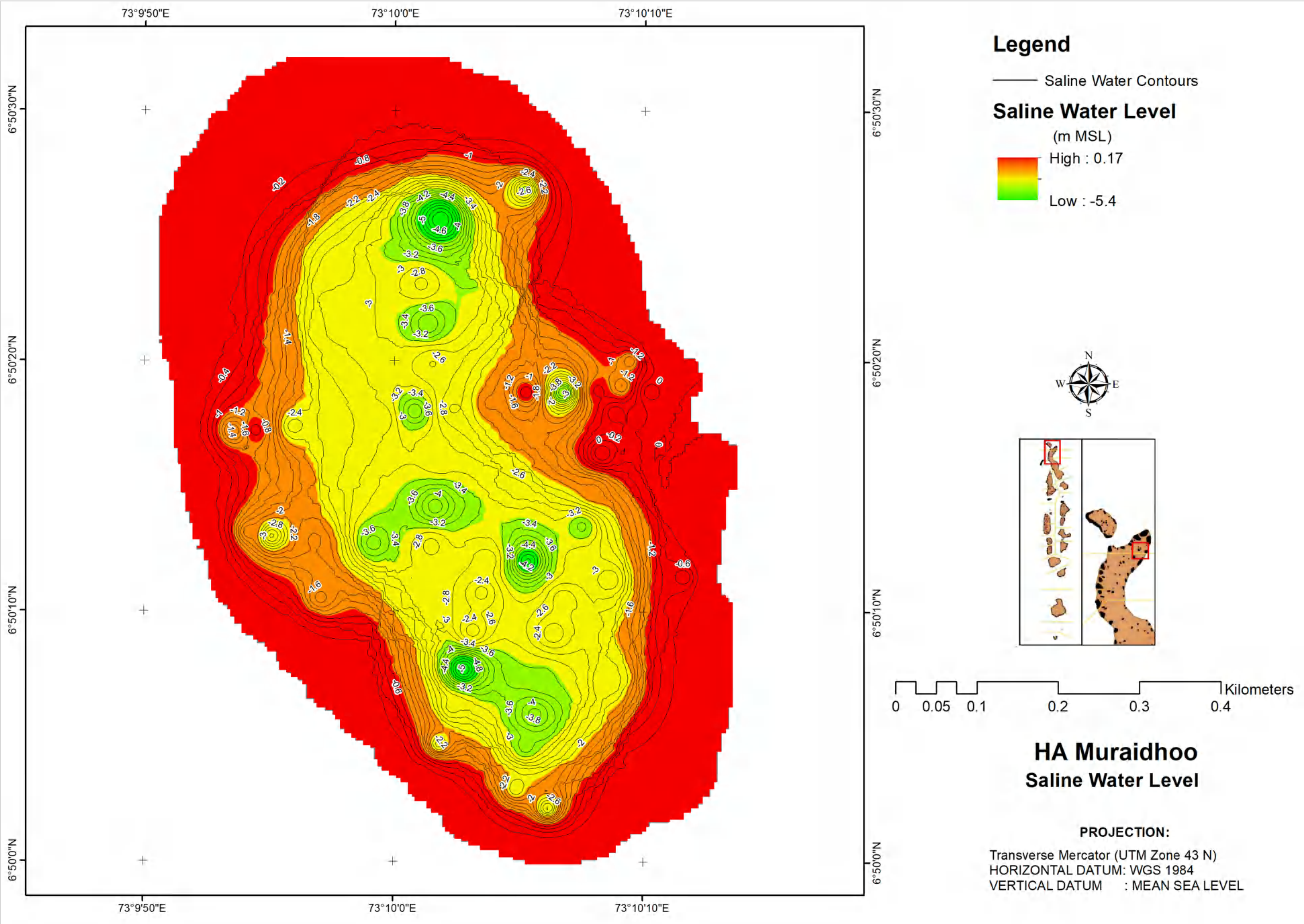
Legend
Freshwater Contours
Freshwater Level
(m MSL)
High :2.08
Low : -0.62
N
S
E
W
HA. Maarandhoo
Freshwater Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
Kilometers
0 0.05 0.1 0.2 0.3 0.4
Kilometers
0 0.025 0.05 0.1 0.15 0.2
72°59'0"E
72°59'10"E
6°51'20"N
6°51'10"N
6°51'0"N

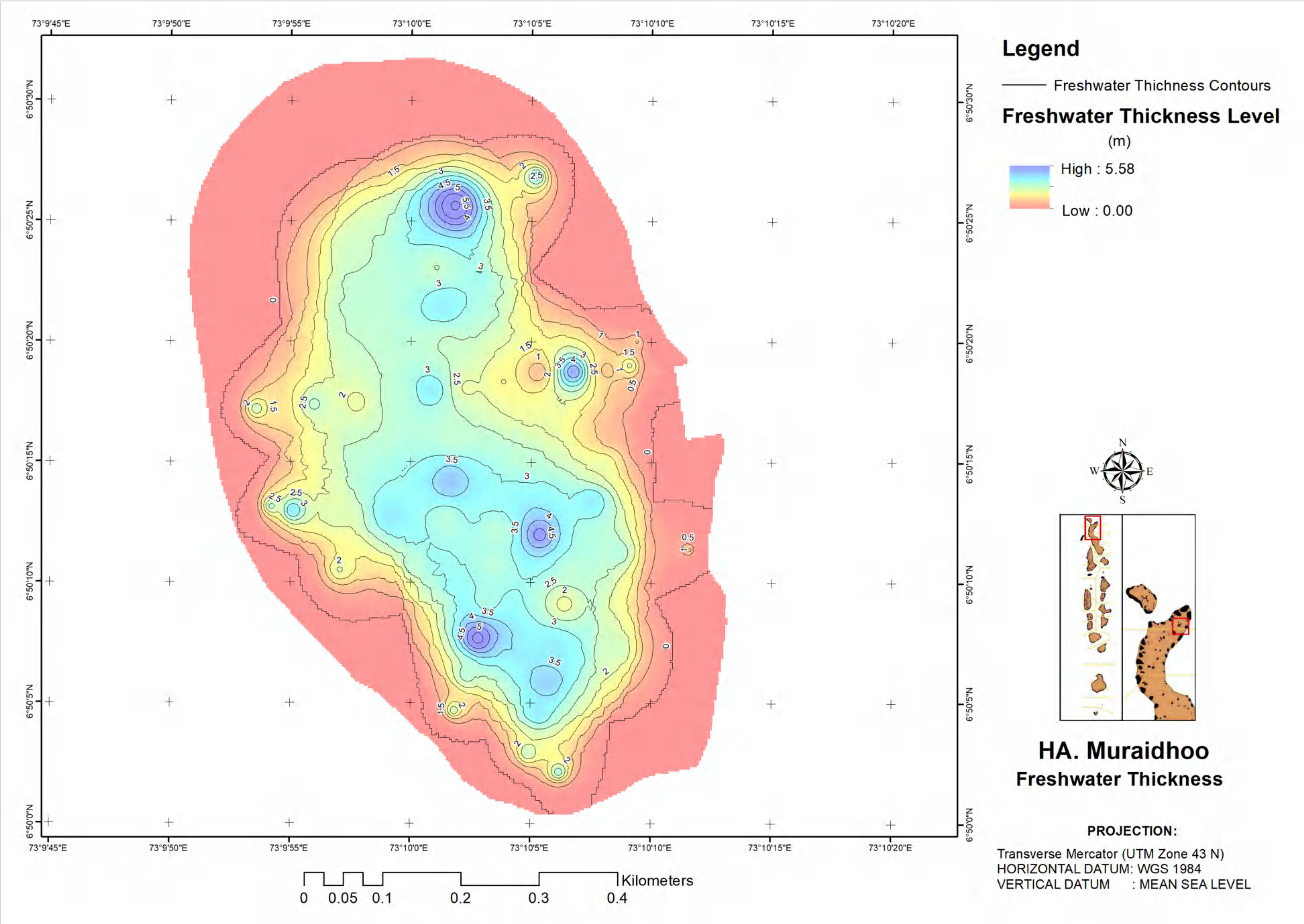


Legend
Saline Water Contours
Saline Water Level
(m MSL)
High : 0
Low : -5.17
N
S
E
W
0 0.04750.095 0.19 0.285 0.38 Kilometers
HA Maarandhoo
Saline Water Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
72°58'50"E
72°59'0"E
72°59'10"E
72°59'20"E
6°51'20"N
6°51'10"N
6°51'0"N


Legend
Freshwater Thichness Contours
Freshwater Thickness Level
(m)
High : 5.40
Low : 0
N
W
E
S
Kilometers
0
0.05
0.1
0.2
0.3
0.4
HA. Maarandhoo
Freshwater Thickness
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
72°58'50"E
72°59'0"E
72°59'10"E
72°59'20"E
6°51'20"N
6°51'10"N
6°51'0"N
6°50'50"N


Legend
Freshwater Contours
Freshwater Level
(m MSL)
High :0.84
Low : -0.62
HA. Muraidhoo
Freshwater Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
0 0.05 0.1 0.2 0.3 0.4
Kilometers


73°9'50"E
73°10'0"E
73°10'10"E
6°50'30"N
6°50'20"N
6°50'10"N
6°50'0"N
Legend
Saline Water Contours
Saline Water Level
(m MSL)
High : 0.17
Low : -5.4
N
S
E
W
0 0.05 0.1 0.2 0.3 0.4
Kilometers
HA Muraidhoo
Saline Water Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL


Legend
Freshwater Thichness Contours
Freshwater Thickness Level
(m)
High : 5.58
Low : 0.00
N
W
E
S
HA. Muraidhoo
Freshwater Thickness
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
Kilometers
0 0.05 0.1 0.2 0.3 0.4
73°9'45"E
73°9'50"E
73°9'55"E
73°10'0"E
73°10'5"E
73°10'10"E
73°10'15"E
73°10'20"E
6°50'30"N
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6°50'20"N
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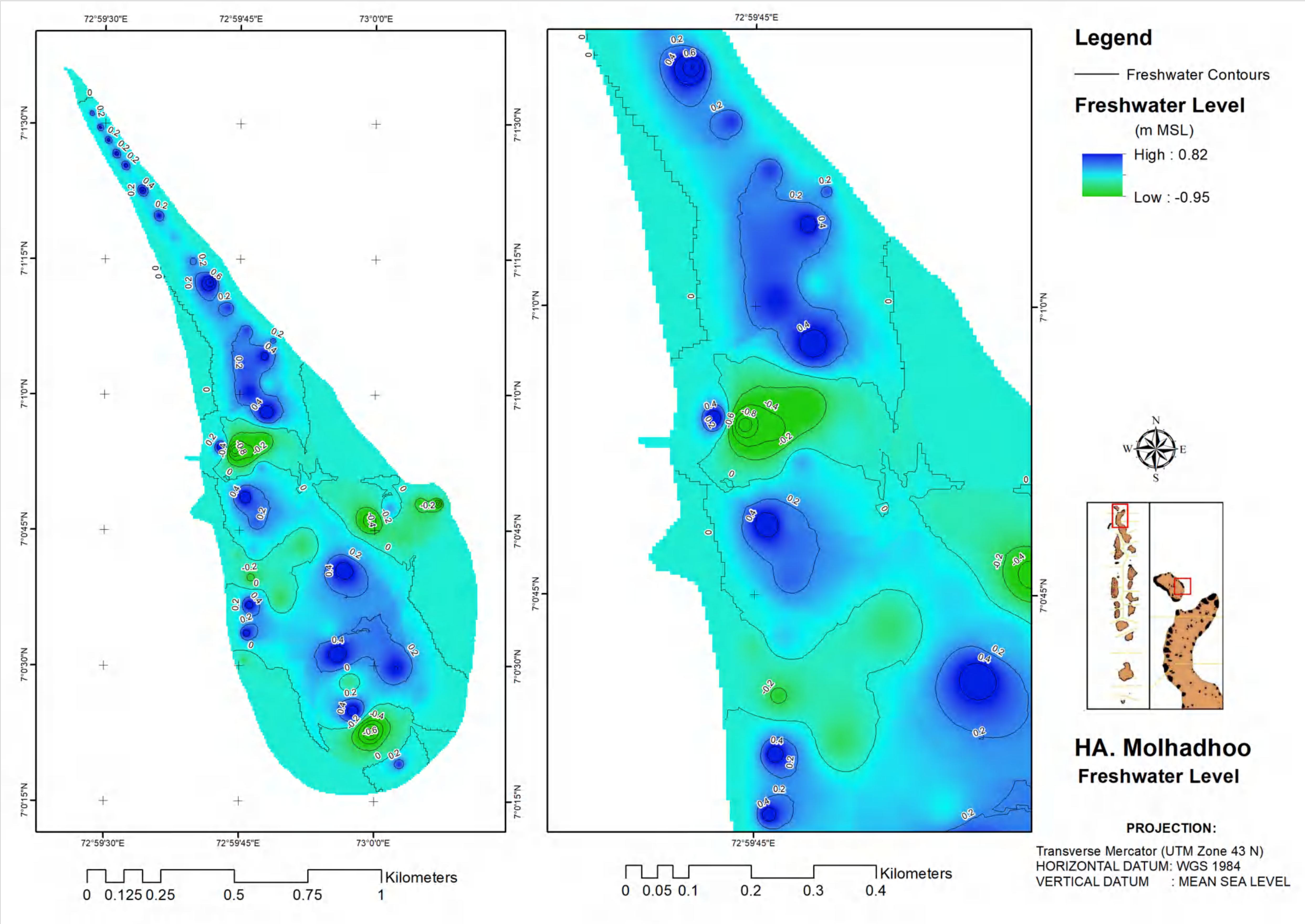
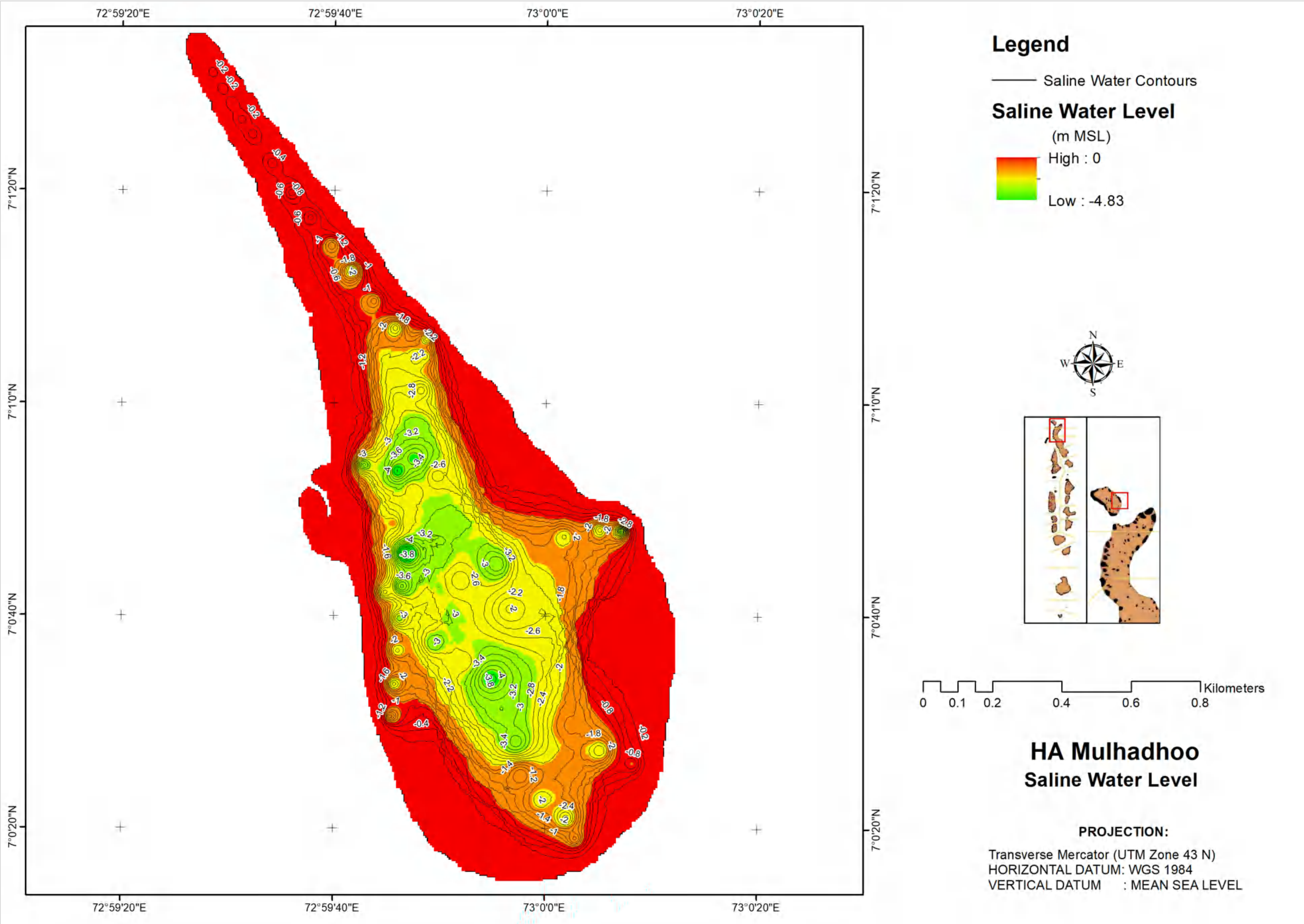
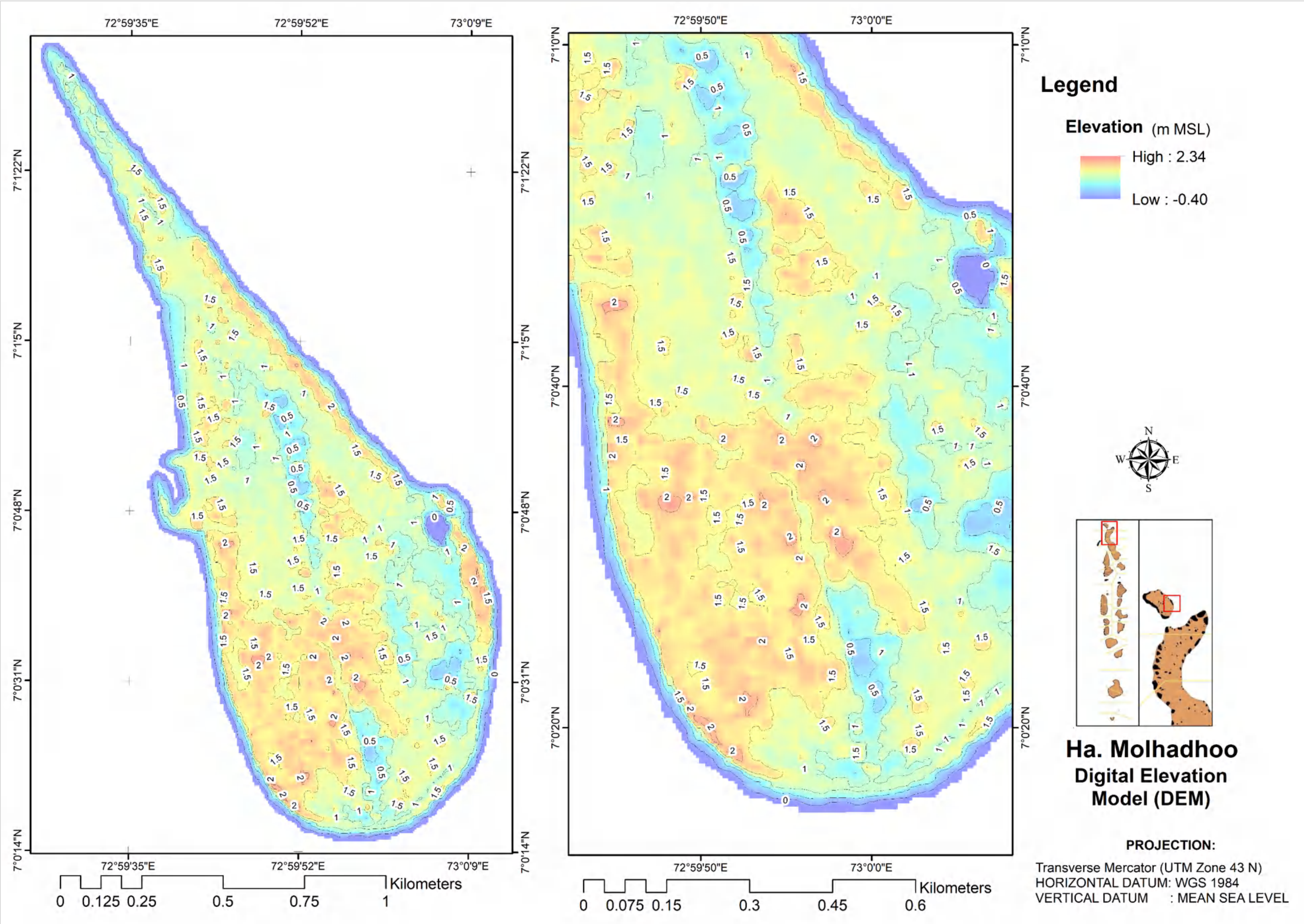
6°50'5"N
6°50'0"N

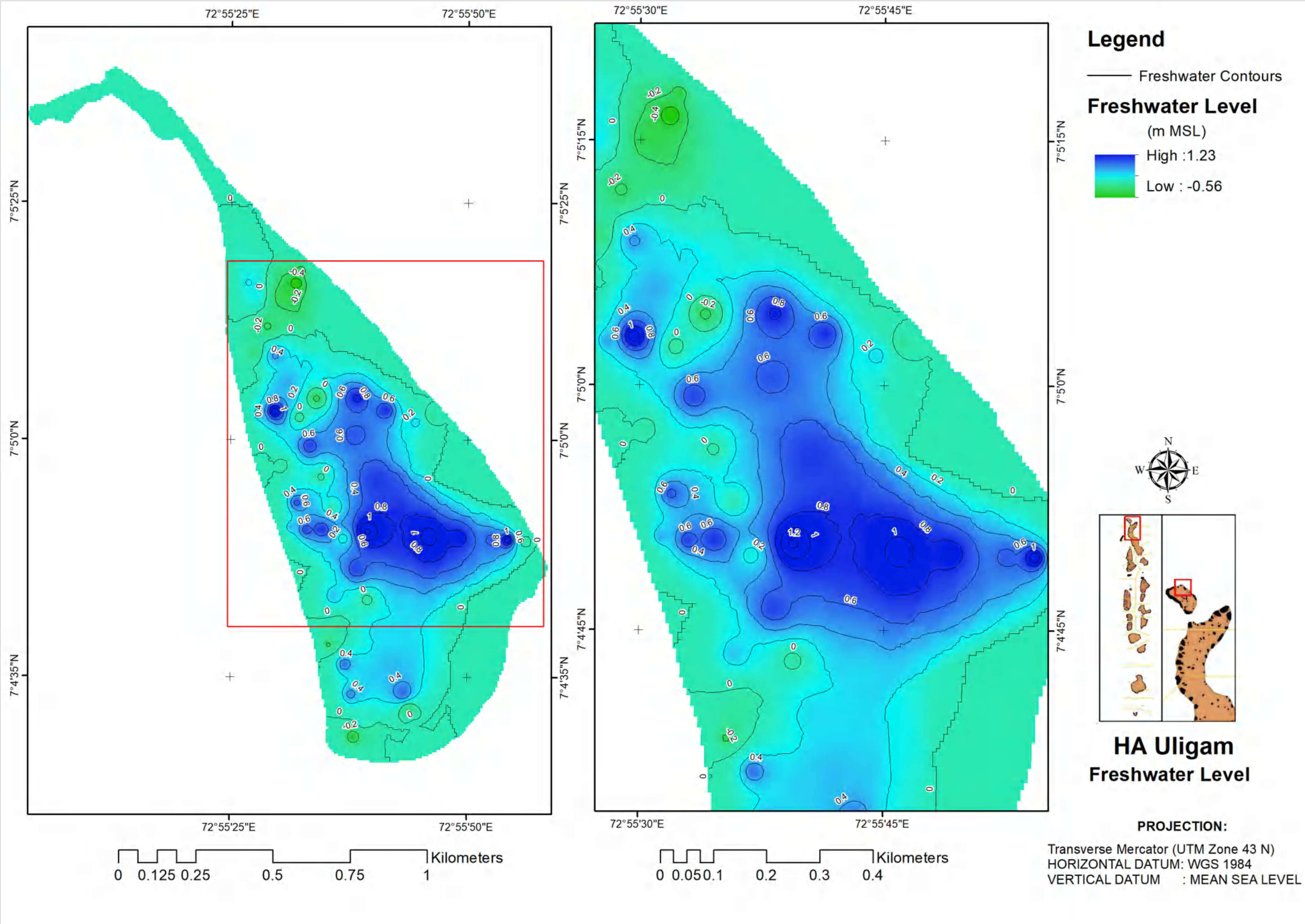

Legend
Freshwater Contours
Freshwater Level
(m MSL)
High : 0.82
Low : -0.95
HA. Molhadhoo
Freshwater Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
Kilometers
0 0.125 0.25 0.5 0.75 1
Kilometers
0 0.05 0.1 0.2 0.3 0.4
72°59'30"E
72°59'45"E
73°0'0"E
7°1'30"N
7°1'15"N
7°1'0"N
7°0'45"N
7°0'30"N
7°0'15"N

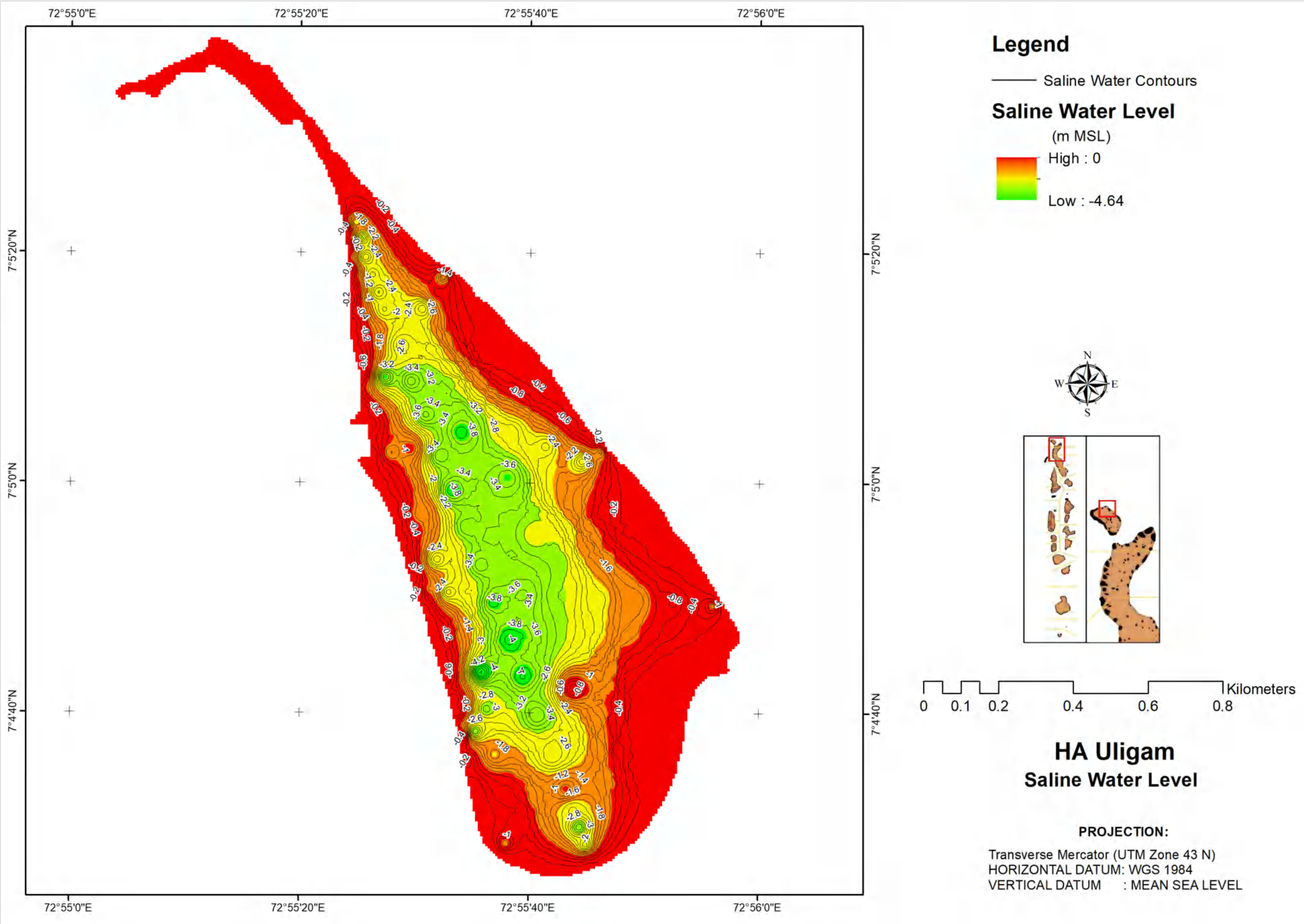


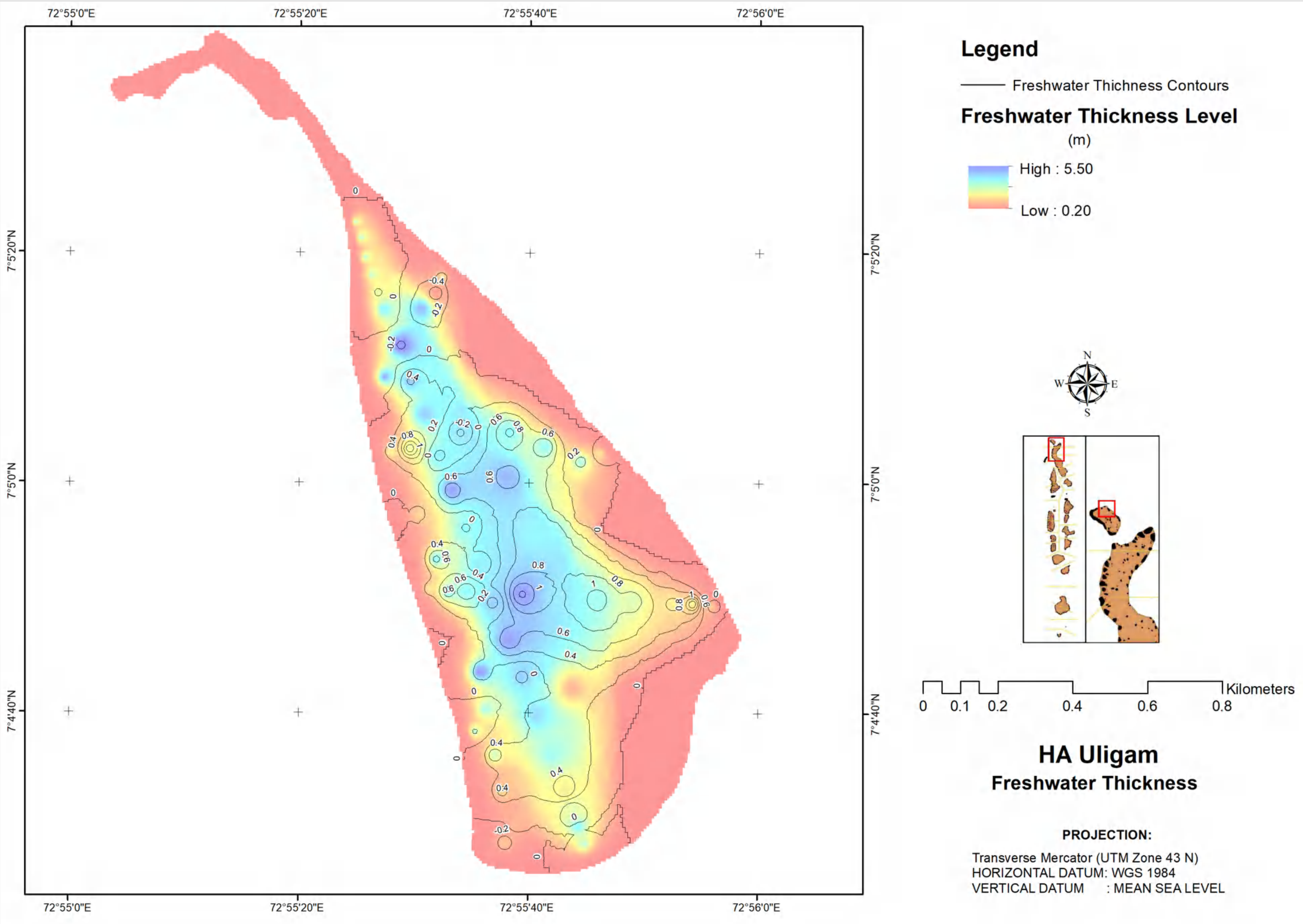
72°59'20"E
72°59'40"E
73°0'0"E
73°0'20"E
7°1'20"N
7°1'0"N
7°0'40"N
7°0'20"N
Legend
Saline Water Contours
Saline Water Level
(m MSL)
High : 0
Low : -4.83
N
S
E
W
0
0.1
0.2
0.4
0.6
0.8
Kilometers
HA Mulhadhoo
Saline Water Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL



72°59'35"E
72°59'52"E
73°0'9"E
7°1'22"N
7°1'5"N
7°0'48"N
7°0'31"N
7°0'14"N
0 0.125 0.25 0.5 0.75 1
Kilometers
72°59'50"E
73°0'0"E
7°1'0"N
7°0'40"N
7°0'20"N
0 0.075 0.15 0.3 0.45 0.6
Kilometers
Legend
Elevation (m MSL)
High : 2.34
Low : -0.40
N
W
E
S
Ha. Molhadhoo
Digital Elevation Model (DEM)
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL


72°55'25"E
72°55'50"E
7°5'25"N
7°5'0"N
7°4'35"N
72°55'30"E
72°55'45"E
7°5'15"N
7°4'45"N
Legend
Freshwater Contours
Freshwater Level
(m MSL)
High :1.23
Low : -0.56
N
S
E
W
HA Uligam
Freshwater Level
Kilometers
0 0.125 0.25 0.5 0.75 1
Kilometers
0 0.05 0.1 0.2 0.3 0.4
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL


72°55'0"E
72°55'20"E
72°55'40"E
72°56'0"E
7°5'20"N
7°5'0"N
7°4'40"N
Legend
Saline Water Contours
Saline Water Level
(m MSL)
High : 0
Low : -4.64
N
S
E
W
0
0.1
0.2
0.4
0.6
0.8
Kilometers
HA Uligam
Saline Water Level
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL



Prepared by Riyan and MHEC

Annex VII: Assessment of Hydrogeology

The island wise hydrogeological assessments are discussed below separately.

HA Filladhoo

Geology and hydrogeology of the island

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation in wider areas (southern part) of the island. However thin areas (northern part) of the island are composed of topsoil and hard fresh coral rock only. The thickness of the overburden (unconsolidated layer and weathered layer) within Filladhoo island varies from place to place with a maximum of 6.7 m and a very shallow overburden occurs at the northern part of island.

The summarized details of the geological profile are given below.

- Thickness of the beach sand and top layer varies from 0.4 m to 1.0 m
- Thickness of sandy coral layer varies from 0.0 m to 2.0 m
- Thickness of weathered coral layer varies from 0.0 m to 4.0 m

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

The occurrence of weak layers is common in fresh coral formations at different depth horizons due to the occurrence of different types of coral formations within subsurface formations. The sand rich depositional areas are observed at north-western parts of the island along the beach stretch. There beach sand and coral sand layer exist as the top layer. However hard fresh coral rock exposed southern and eastern sides of the beach areas.

Hydrogeology

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

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

Fresh groundwater of the island occurs as a lens. Middle part of fresh water lens rests on the fresh coral formation and its outer area rests on saline water. Basically, geometry of the fresh water lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 0.83 m above MSL at middle parts of the island. The maximum thickness of the fresh water lens is about 7.80 m by considering the EC > 2500 µs/cm and it reduces toward the rim area of the lens Figure 1. It is noted that several upcoming zones have developed within fresh water lenses due to higher groundwater extraction.

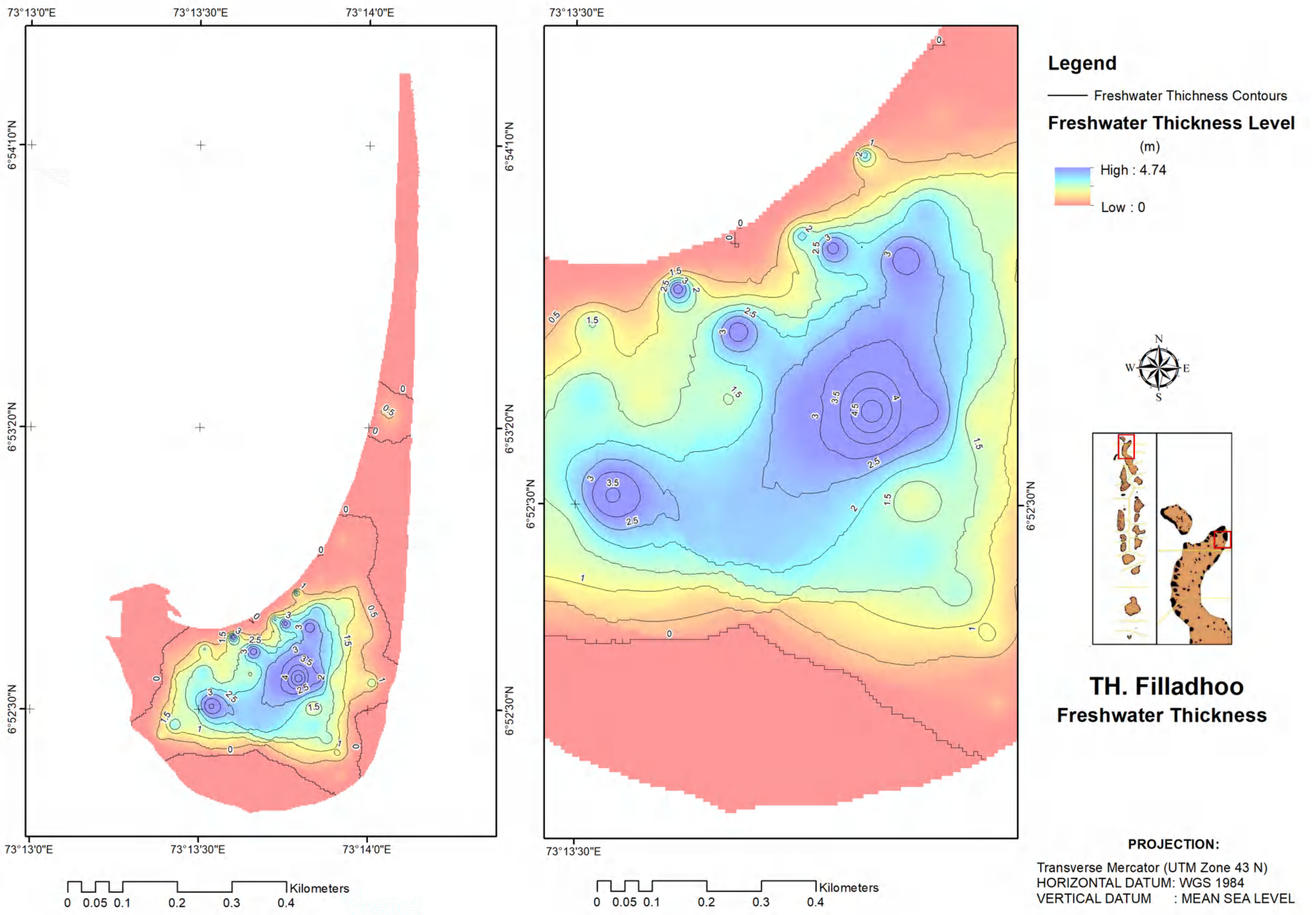


Figure 1: Fresh water thickness map of Filladhoo Island

As per the report, calculated groundwater storage by considering the 15% porosity is about 207,859m3 with a maximum FWL thickness of 0.64 ± 0.91 m.

Groundwater chemistry and its variation

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

About 40 water samples have been analyzed for EC(µs/cm), pH, Turbidity(NTU), DO(ppm), Temperature(C^0), Salinity(PSU), Nitrate(mg/l), Ammonia(mg/l), and Phosphate(mg/l). Bacteriological analysis was done in 15 places and results revealed that all wells are contaminated with different proportions (total coliform- (143-2420) MPN/100 ml, fecal coliform – (0-2420) MPN/100 ml) as per the WHO guidelines. It is noted that fecal coliform is not observed in samples (F 10, F 23, F34, F 36, and F 39). In addition, EC was measured in 31 locations. The sampling points are given in Figure 2.

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

Table 1: Comparison of WQ results based on land usage

Land Use	No. of samples	Results are lined with conditions	Increment of measured parameters	Remark
Residential area	41	36	F2, F11, F6, F 23, F 39	Enrichment of Ammonia due to anthropogenic activities.
Agricultural area	13	13		
Other areas	17	8	F3, F4, F22, F31 FW3, FW1, FW2 FW17, FW 33	F 3, F 4, F22, F31, F 33. These points are located within water logged area and sea water is mixing with lake water at water logged area. FW 1,FW2,FW3, FW17-High EC due to it is close to sea.
Total	71	57	14	

Note:

1) EC>2500 µs/cm (water could be used for potable and non-potable use depending of EC.

2) Nitrate (>50 mg/l), Phosphate (>2 mg/l), and ammonia (>0.5 mg/l) as per WHO guidelines.

The water quality records of contaminated points as per note (1 & 2) are given in Table 2: Water quality records of contaminated points

Table 2: Water quality records of contaminated points

Sampling points	EC-µS/cm	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
F23	529.00	7.70	1.10	0.26	5.10
F2	1157.00	7.60	1.00	2.50	0.39
F39	1065.00	6.90	5.50	0.69	1.53

Sampling points	EC-µS/cm	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
F11	1204.00	7.00	46.60	4.80	0.28
F6	1013.00	7.70	43.50	0.83	1.46
FW17	3850.00	ND	ND	ND	ND
F33	46.74	8.40	4.80	0.78	0.25
FW3	19900	ND	ND	ND	ND
F4	12.99	8.10	5.40	1.38	0.19
FW1	14000	ND	ND	ND	ND
F22	12.83	7.80	2.70	0.73	0.05
FW2	6440	ND	ND	ND	ND
F3	54.11	7.80	5.80	0.63	0.05
F31	29.92	8.20	5.50	1.63	0.28

Note: ND- Not measured

Aquifer properties

Hydraulic conductivity(permeability) and transmissivity were estimated by conducting the permeability test and pumping tests respectively. Tested locations are given in Figure 3

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

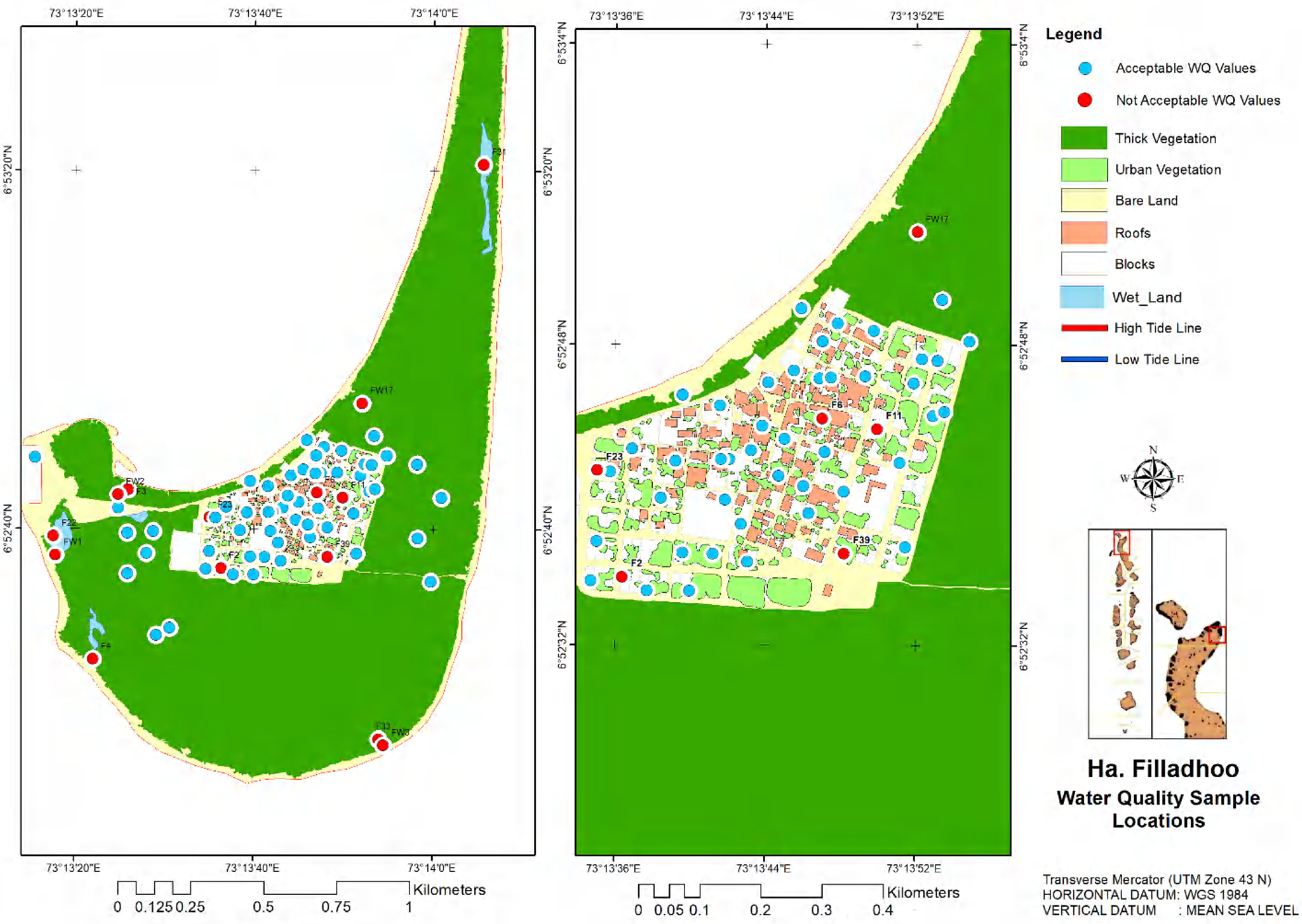


Figure 2: Location of groundwater sampling points in Filladhoo Island

Figure 3: Tested locations (pumping test and Hydraulic conductivity) in Filladhoo Island

Hydraulic conductivity of unsaturated formation

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

Table 3: Estimated hydraulic conductivity values for HA Filladhoo

Point	Hydraulic conductivity(m/d)
FMP 1	1.16
FMP 2	3.85
FMP 3	0.51
FMP 4	0.47
FMP 5	1.93
FMP 6	0.43

The measured hydraulic conductivity values ranged from a minimum of 0.47 m/d to a maximum of 3.85 m/d, with an average of 1.39 m/d. The average value of 1.39 m/d is considered for the estimation of the groundwater flow velocities of the island.

Pumping test

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

Table 0.4: Pumping test results for HA Filladhoo

Dug well	Transmissivity (m^2/s)	Drawdown(m)	EC -before pumping- µs/cm	EC-End of pumping- µs/cm
FLW 1	0.0051	0.46	1190	1190
FLW 2	0.0038	0.44	1150	1150

Abbreviation: EC- Electrical conductivity

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 not increased.

- For FLW 1, EC has not increased, and average EC is about 1190 µs/cm.
- For FLW 2, EC has not increased, and average EC is about 1150 µs/cm.

Groundwater flow and flow velocity

As per the groundwater level map Figure 5, groundwater lens is observed at middle part of the island.

The groundwater velocity map for the island Figure 6 was developed by using calculated average hydraulic conductivity of the island and assuming porosity of 15% . The calculated velocity of the groundwater varies from place to place with a maximum of 1.6 m/day. The flow velocity over 90% of the land area is less than 0.1 m/day.

The estimated maximum retention time of the groundwater within the island for velocity of 0.1 m/day and 0.30 m/d is about 160 months and 53 months respectively. As per the velocity map, the groundwater recharging shall be done at middle part of island. In addition, recharging structures are to be constructed in order to increase the retention time and to control the controlling the sea water flooding. The details of the structures will be discussed under chapter 6.

Sea water flooding.

It is noted that sea water flooding areas (marked in red) along the coastal line are observed during the field Figure 4. There are wetland areas in the island and biggest one is at southwest side of the island. In addition, several small water logged areas has developed at the area close to the eastern and southern beach. During the rainy period, overland flow is added to water logged area while sea water flowing to the water logged area as results of tidal action.

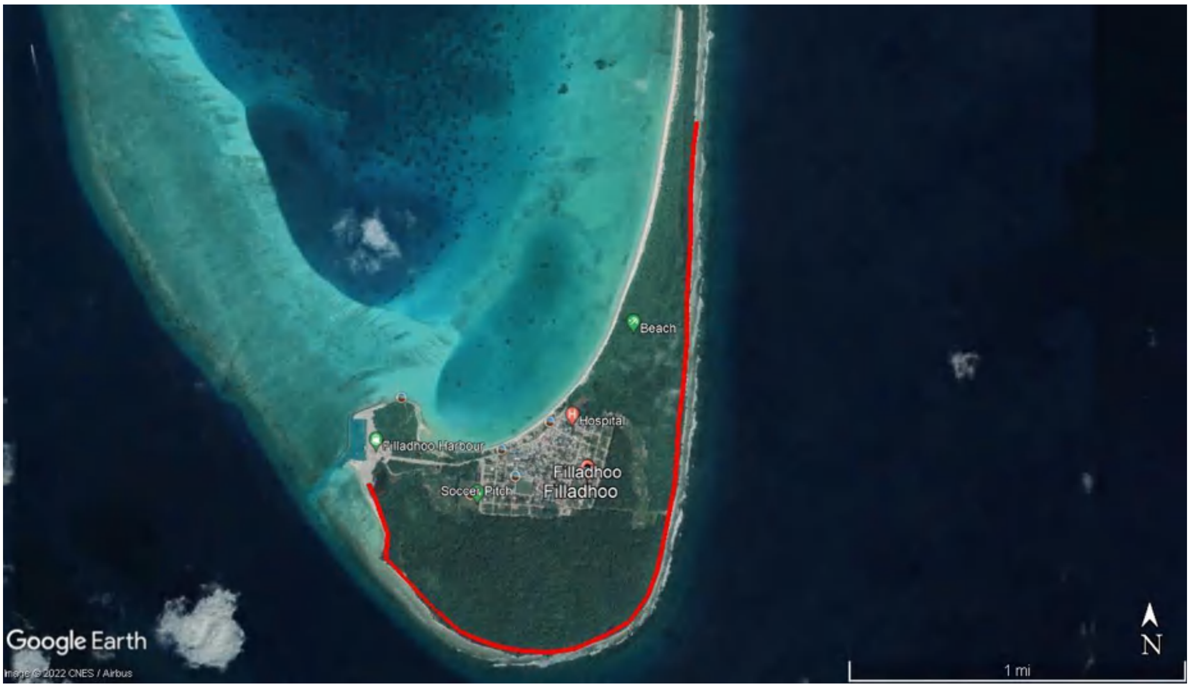


Figure 4: Sea water flooding areas in Filladhoo island

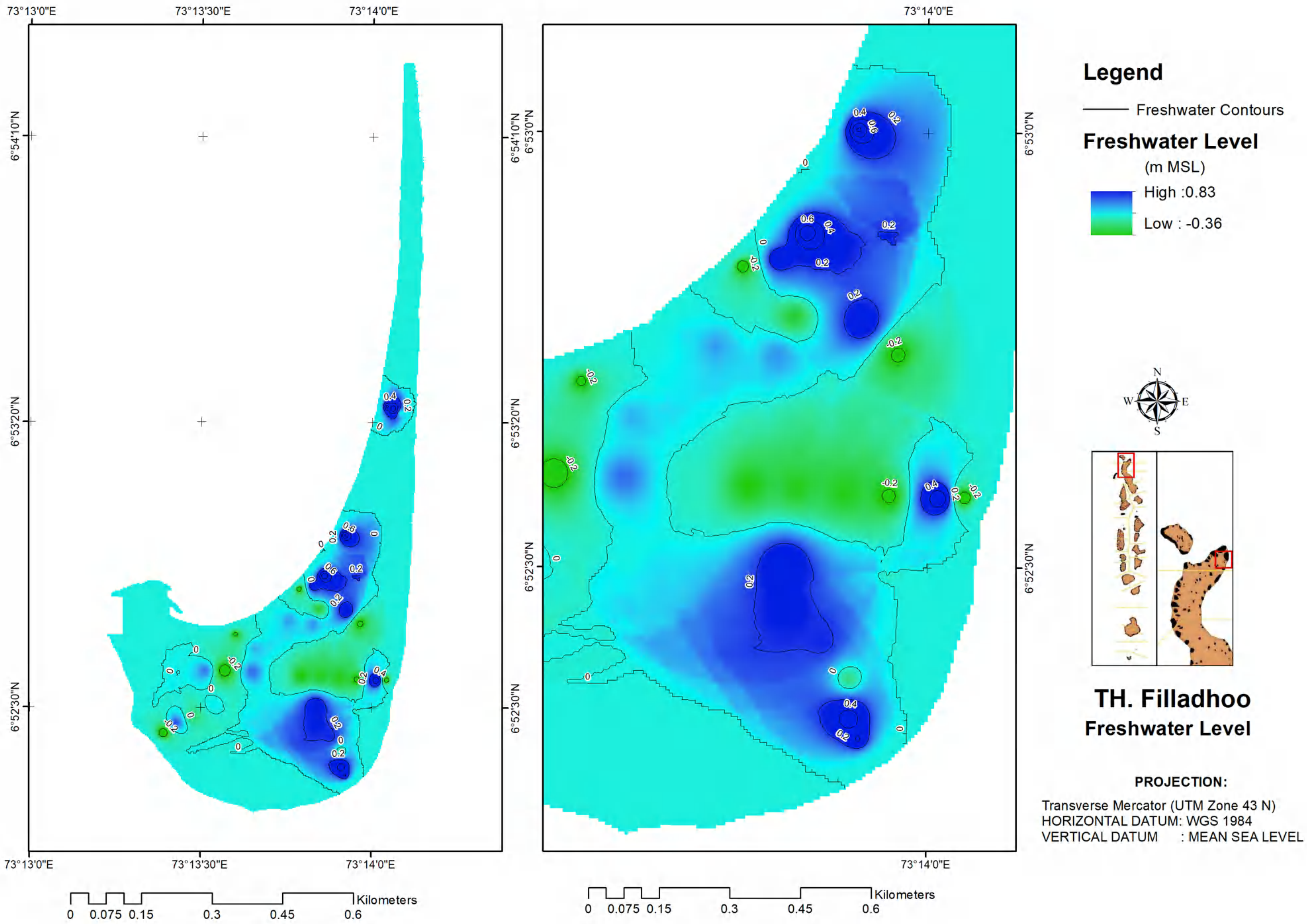


Figure 5: Groundwater level map of the Filladhoo Island

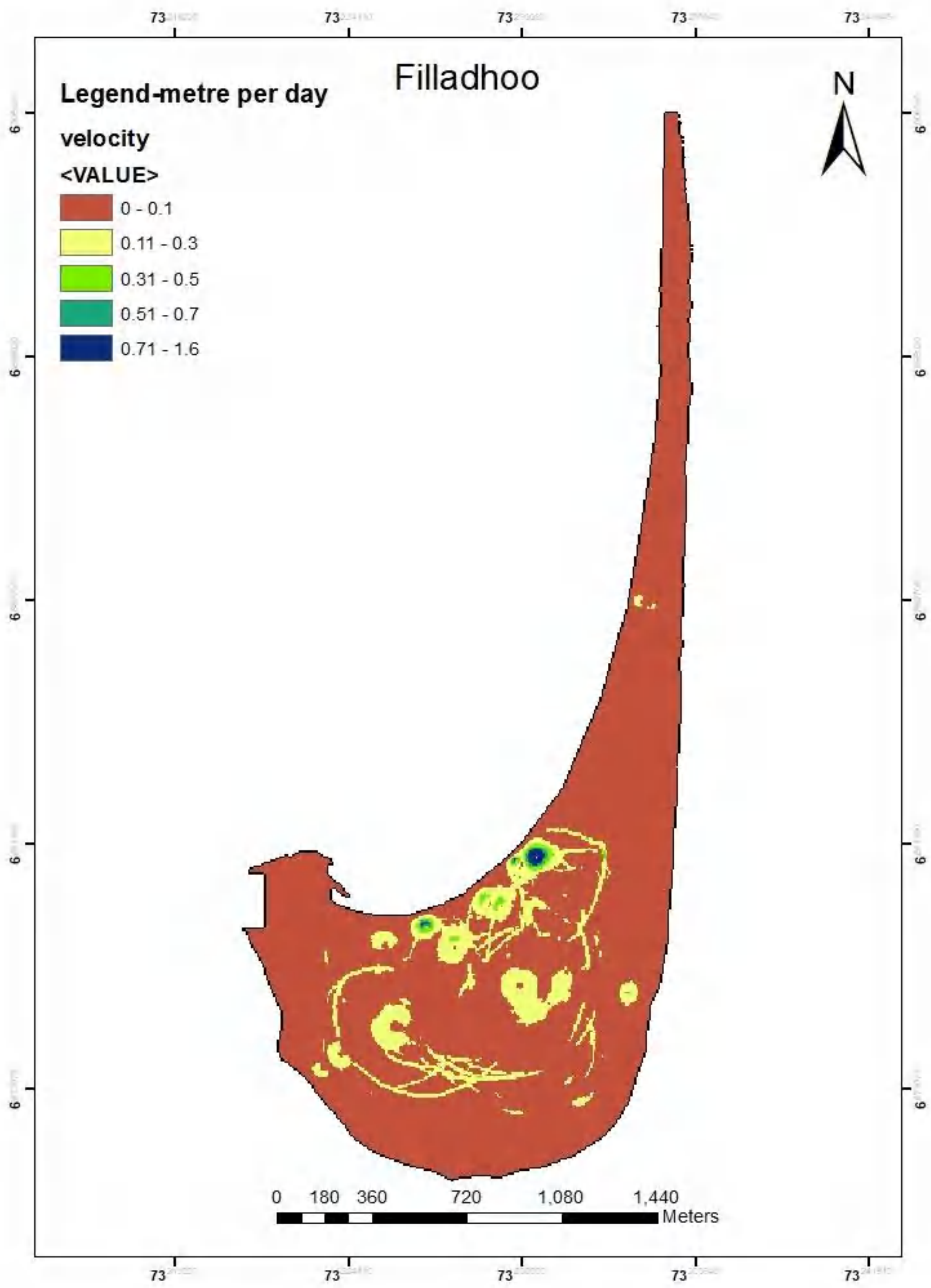


Figure 6: Flow velocity map of the Filladhoo island

HA Maarandhoo

Geology and hydrogeology of the island.

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation. The thickness of the overburden (unconsolidated layer and weathered layer) within Maarandhoo island varies from place to place with a maximum of 6 m.

The summarized details of the geological profile are given below.

- Thickness of the topsoil layer varies from 0.0 to 0.5 m
- Thickness of the beach coral sand layer varies from 0.2 m to 1.5 m. In western beach areas mostly beach coral sand exists as the top layer.
- Thickness of weathered coral layer varies from 0.2 m to 3.8 m.

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

The depth to fresh hard coral layer varies along the coastal line with maximum of 1 m based on indirect measurements.

Hydrogeology

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

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

Fresh groundwater of the island occurs as a lens. Middle part of fresh water lens rests on the fresh coral formation and its outer area rests on saline water. Basically, geometry of the fresh water lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 2.08 m above MSL in the middle parts of the island. The maximum thickness of the fresh water lens Figure 7.It is noted that several upcoming zones has developed within fresh water lenses due to higher groundwater extraction. During the rainy period, groundwater discharging conditions could be expected at low elevated area.

As per the baseline report, the freshwater lens (FWL) volume calculated based on ER transect test data is 58,262 m^3 with a maximum FWL thickness of 1.13 ± 1.13 m.

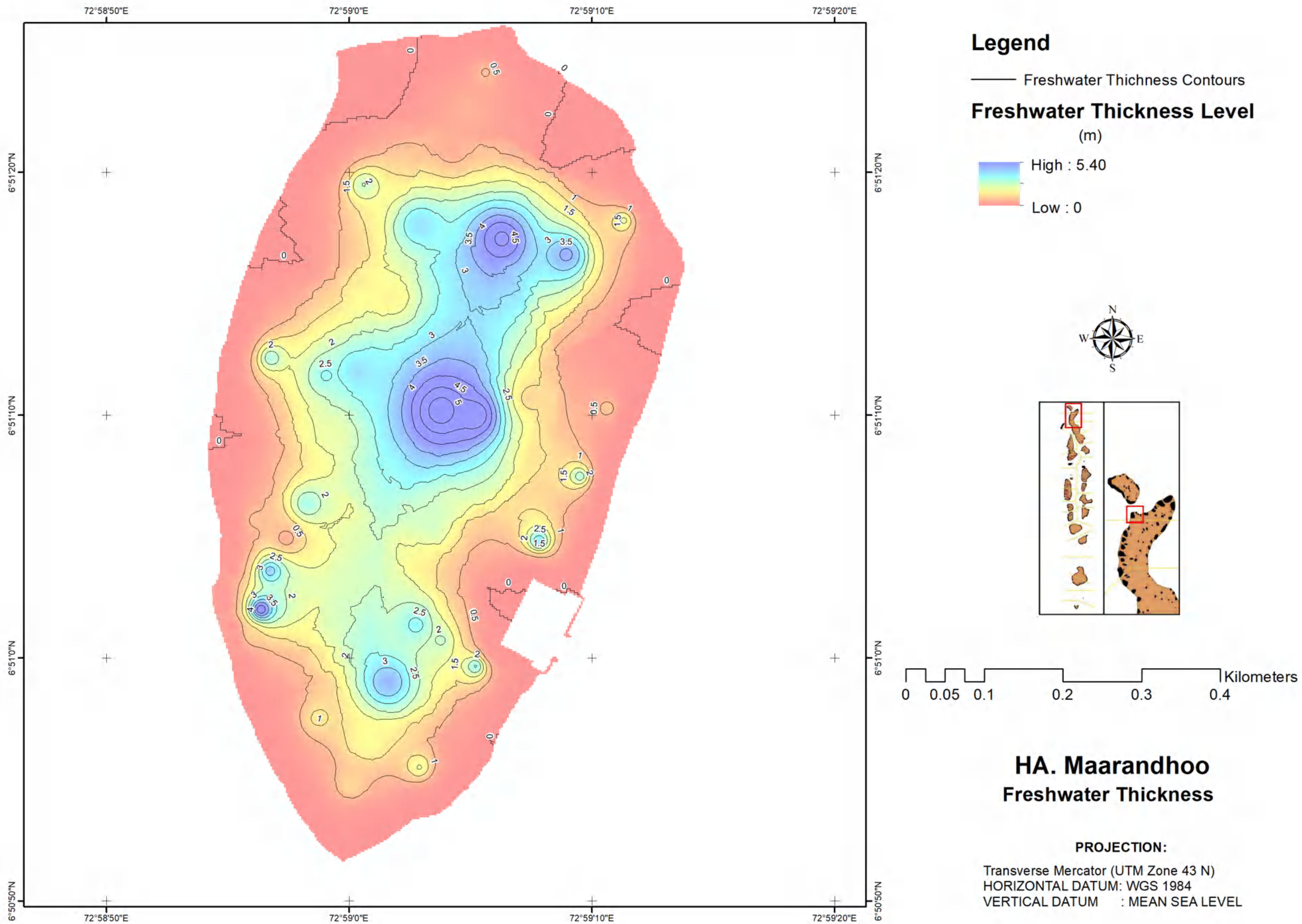


Figure 7: Fresh water thickness map of Maarandhoo Island

Groundwater chemistry and its variation.

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

About 40 water samples have been analyzed for EC(µs/cm), pH, Turbidity(NTU), DO(ppm), Tem(C0), Salinity(PSU), Nitrate(mg/l), Ammonia(mg/l), and Phosphate(mg/l). Bacteriological analysis was done in 15 places and results revealed that all wells are contaminated with different proportions (total coliform- (120-2420) MPN/100 ml, fecal coliform – (0-308) MPN/100 ml) as per the WHO guidelines. It is noted that fecal coliform is not observed in samples (MA 6, MA 8, MA 12, MA 19, MA 28). In addition, EC was measured in 22 locations. The sampling points are given in Figure 8.

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

Table 5: Comparison of WQ results based on land usage

Land Use	No. of samples	Results are lined with conditions	Increment of measured parameters	Remark
Residential area	59	44	MA27,MA12,MW 13,MA17,MA30,M A10, MW10,MA31,MA 5, MA20, MA33,MA39, MA8, MA36,MA35	Enrichment of EC in wells(MA 10,MA 27, MW 13, MA 31,MA 33, and MA 30) are due to higher groundwater extraction. Enrichment of EC in MW 10 is due to well is close to sea. Enrichment of nitrate and ammonia in wells(MA5, MA20, MA12, MA 17,MA39, MA8, MA36, and MA35) are due to anthropogenic activities
Other area	3	2	MW1,	Enrichment of EC in MW 1 is due to higher groundwater extraction.
Total	62	46	16	

Note:
1) EC > 2500 µs/cm (water could be used for potable and non-potable use depending of EC.
2) Nitrate (> 50 mg/l), Phosphate (> 2 mg/l), and ammonia (> 0.5 mg/l) as per WHO guidelines.
The water quality records of contaminated points as per note (1 & 2) are given in below table.

Table 6: Water quality records of contaminated points

Sampling points	EC-µS/cm	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
MA27	2998.00	7.90	44.20	0.24	1.80
MA12	2090.00	7.10	83.20	0.11	0.19
MW13	1660.00	8.10	1.00	0.11	0.23

Sampling points	EC-µS/cm	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
MA17	1555.00	7.80	115.90	0.14	0.71
MA30	3115.00	7.80	26.00	0.08	0.09
MA10	2656.00	7.80	20.80	0.09	0.21
MW1	2600.00	ND	ND	ND	ND
MW10	3060.00	ND	ND	ND	ND
MA31	4065.00	7.40	45.00	0.20	0.18
MA5	2439.00	7.00	118.20	0.20	0.19
MA20	898.00	8.10	57.50	0.15	0.05
MA33	2753.00	7.20	5.80	0.18	0.21
MA39	1388.00	7.40	50.10	0.12	0.31
MA8	660.00	7.80	84.20	0.17	0.05
MA35	1584.00	8.00	59.20	0.14	0.09
MA36	1300.00	7.50	158.20	2.49	0.36

Note: ND- Not measured

Aquifer properties

Hydraulic conductivity(permeability) and transmissivity were estimated by conducting the permeability test and pumping tests respectively. Tested locations are given in Figure 9.

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

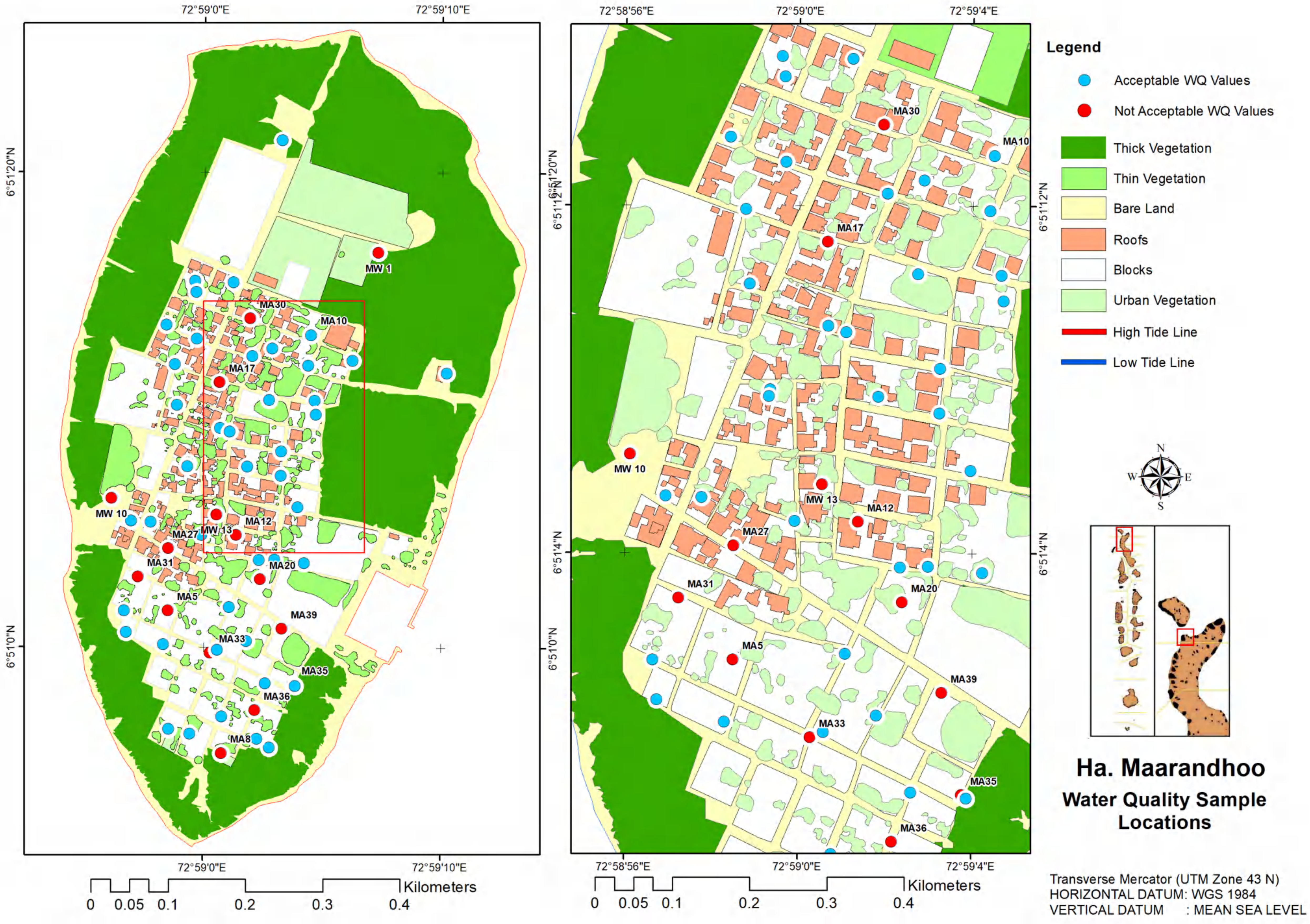


Figure 8: Location of groundwater sampling points in Maarandhoo Island

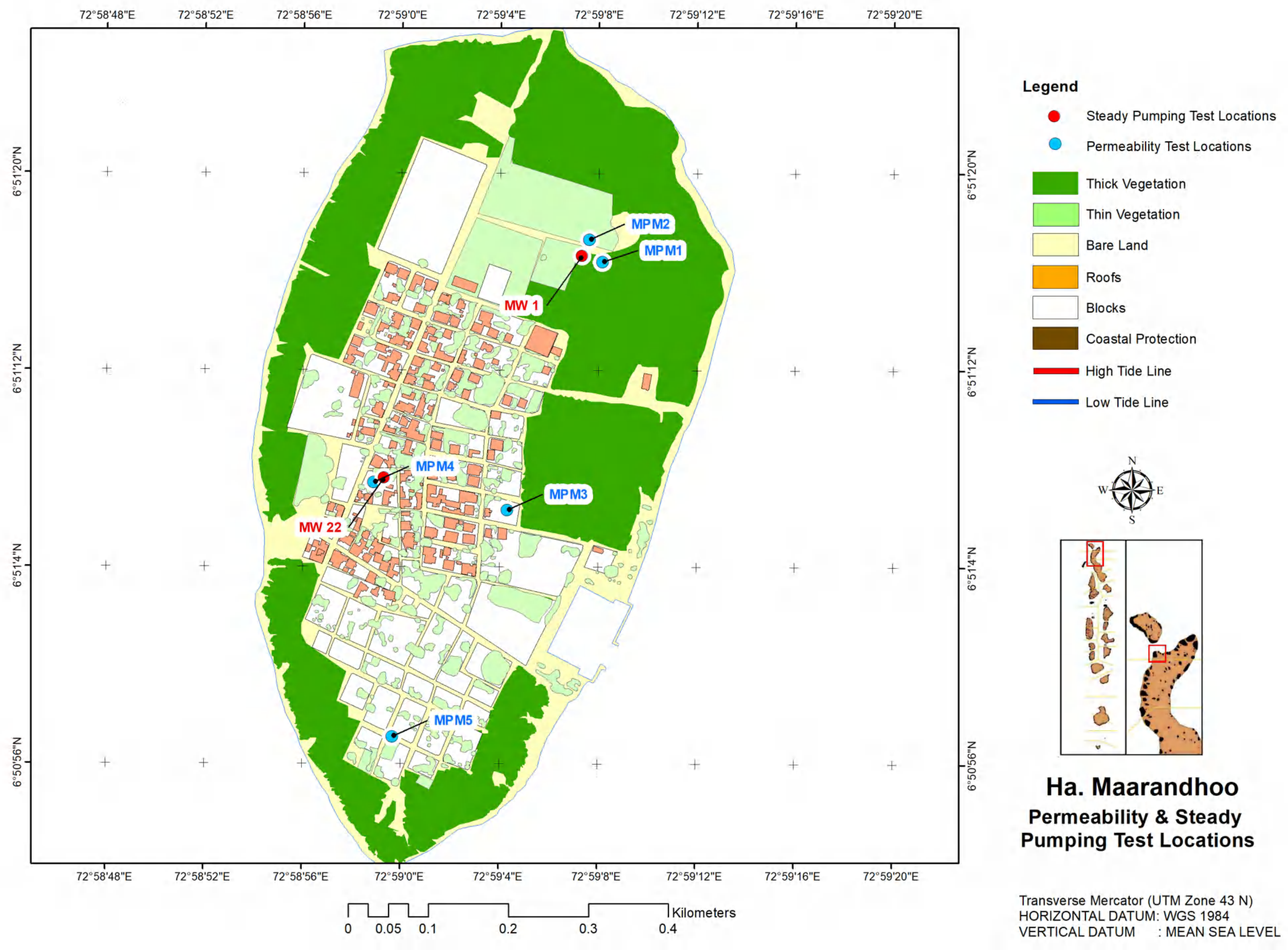


Figure 9: Tested locations (pumping test and Hydraulic conductivity) in Maarandhoo

Hydraulic conductivity of unsaturated formation

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

Table 0.7: Estimated hydraulic conductivity values for HA Maarandhoo

Point	Hydraulic conductivity (m/d)
MPM 1	4.69
MPM 2	5.81
MPM 3	4.36
MPM 4	2.98
MPM 5	2.89

The measured hydraulic conductivity values ranged from a minimum of 2.89 m/d to a maximum of 4.69 m/d, with an average of 4.15 m/d.

Pumping test

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

Table 8: Pumping test results for HA Maarandhoo

Dug well	Transmissivity (m^2/s)	Drawdown(m)	EC -before pumping- µs/cm	EC-End of pumping- µs/cm
MD 1	0.0089	0.17	2600	4100
MD 22	0.0059	0.445	1490	2400

Abbreviation: EC- Electrical conductivity

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.

Groundwater flow and flow velocity

As per the groundwater level map Figure 11, three groundwater zones with relatively higher head are developed within the fresh water lens. It is noted that groundwater zones with low head are developed at the areas between high groundwater level zones and areas close to the coastal line.

The groundwater velocity map for the island Figure 12 was developed by using calculated average hydraulic conductivity of the island and assuming porosity of 15%. The calculated velocity of the groundwater varies from place to place with a maximum of 1.6 m/day. The flow velocity over 80% of the land area is less than 0.3 m/day. It is noted that several small high velocity zones are developed at low elevated areas due to lowering of groundwater level.

The estimated maximum retention time of the groundwater within the island for velocity of 0.3 m/day is about 27 months. As per the velocity map, the groundwater recharging shall be done at middle part of island. In addition, recharging structures are constructed in order to increase the retention time and to control the controlling the sea water flooding. The details of the structures will be discussed under chapter 6.

Sea water flooding.

It is noted that sea water flooding areas (marked in red) along the coastal line are observed during the field Figure 10. The elevation of the western beach is relatively higher with compared to other areas. The fresh water in the forest area are contaminated with sea water as result of sea water flooding.

Figure 10: Sea water flooding areas in Maarandhoo island

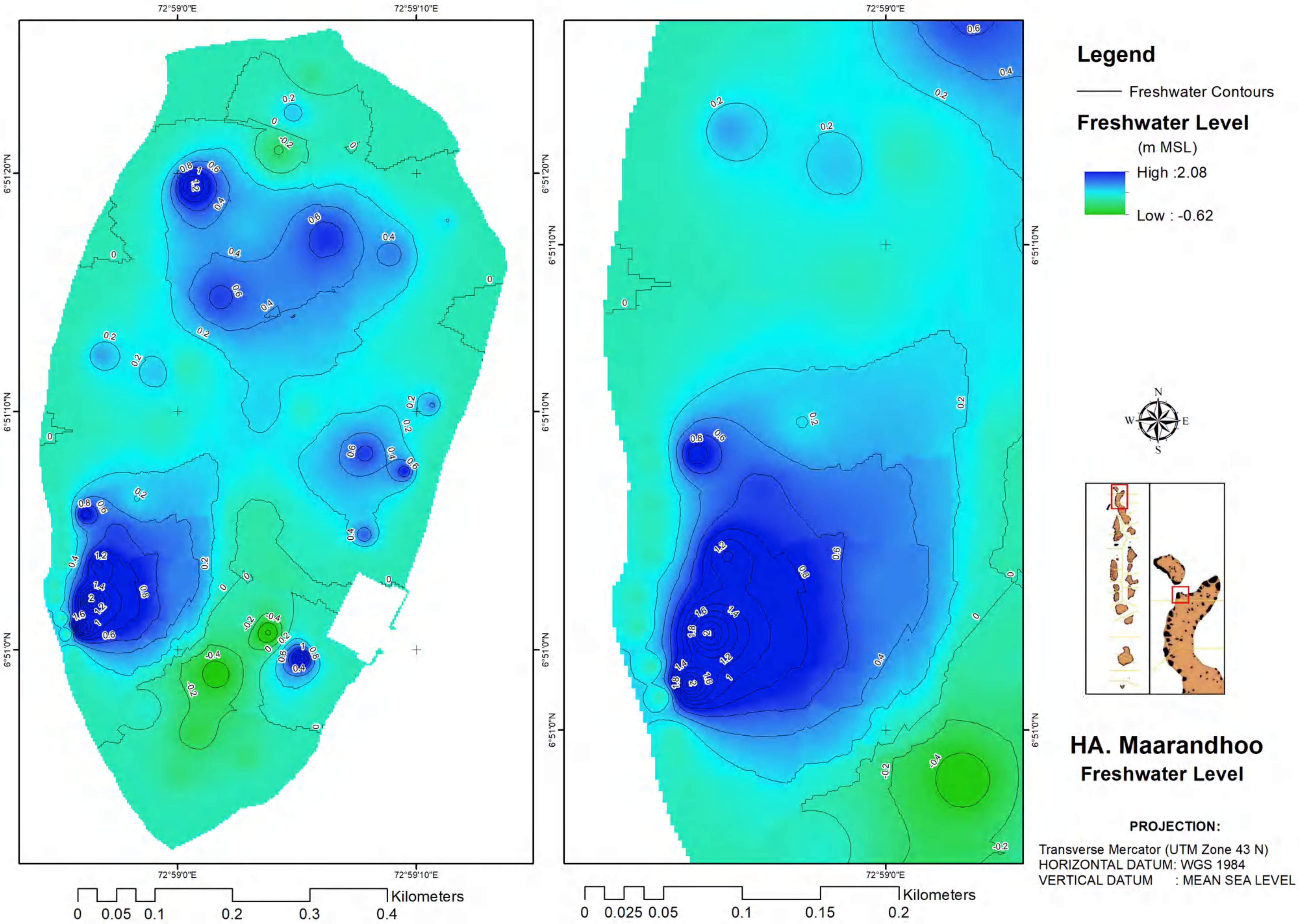


Figure 11: Groundwater level map of the Maarandhoo Island

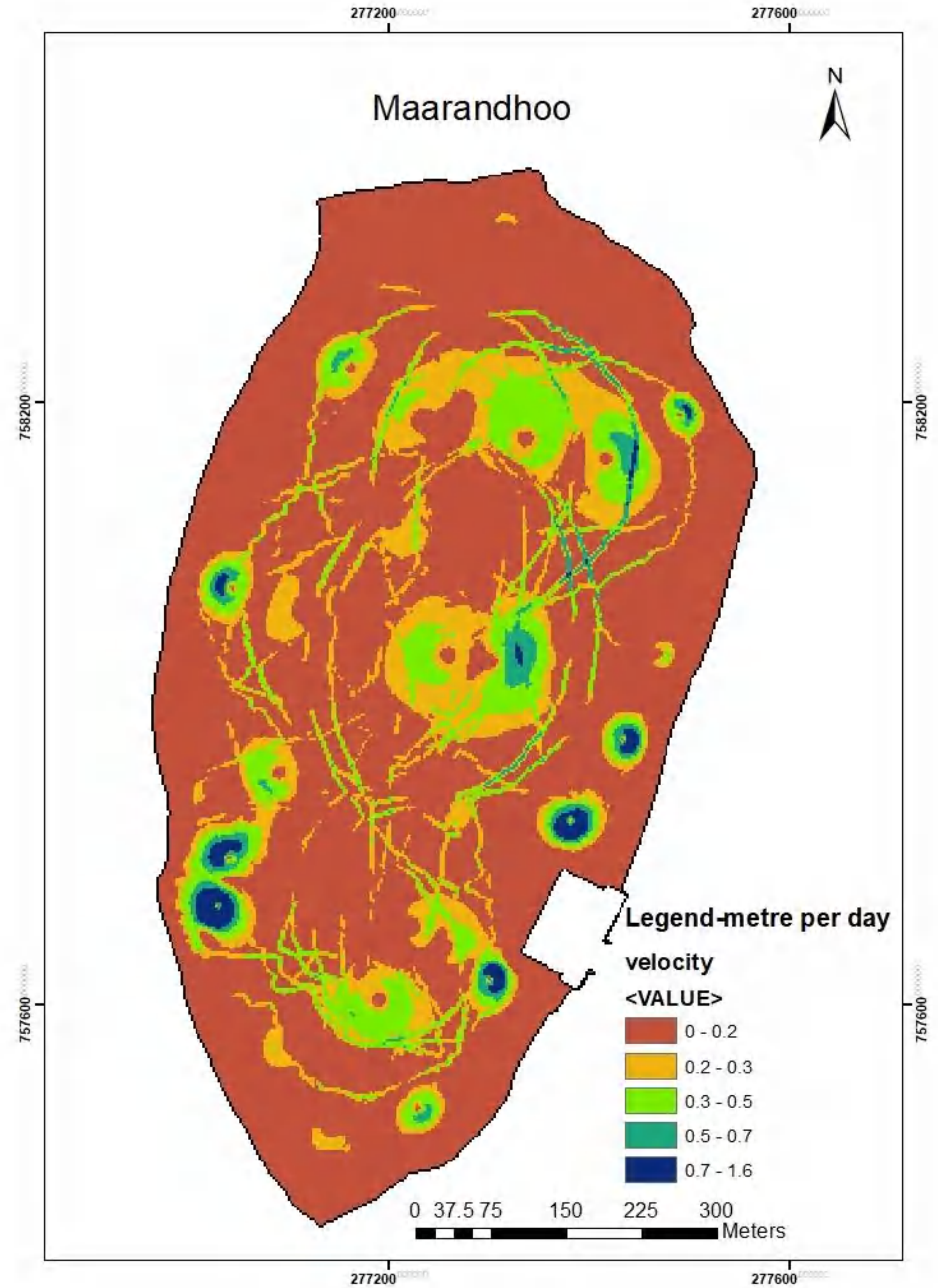


Figure 12: Flow velocity map of the Maarandhoo Island

HA Muraidhoo

Geology and hydrogeology of the island.

Geology

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

The summarized details of the geological profile are given below.

- Thickness of the top layer varies from 0.5 m (middle of island) up to 1.0 m (coastal rim)
- Thickness of the beach coral sand layer varies from 0.2 m to1.0 m.
- Thickness of weathered coral layer varies up 5 m. Thickness of weathered layer at middle part of the island is about 5 m while thickness at coastal areas is about 0.2 m.

The elevation of the island varies from -0.22 m to 2.65 m and generally flatland through the island with rim of elevated areas. The topsoil layer thick (1m) in coastal areas and middle of the island is thin (0.5m).

As the compositional and structural differences of coral formation, differential weathering could be observed in cross section N-S. Cross section N-S clearly shows few deep weathered zones. However, in the cross-section E-W in the island shows uniform weathering and general trend is central part of the island show higher weathering compared to the coastal area.

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

Hydrogeology

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

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

Fresh groundwater of the island occurs as a lens. Middle part of fresh water lens rests on the fresh coral formation and its outer area rests on saline water. Basically, geometry of the fresh water lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 0.84 m above MSL in the middle parts of the island. It is noted that several upcoming zones has developed within fresh water lenses due to higher groundwater extraction. The maximum thickness of the fresh water lens is about 5.58 m by considering he EC > 2500 µs/cm and it reduces toward the rim area of the lens Figure 13.

The freshwater lens (FWL) volume calculated based on ER transect test data and 15% porosity is " 68,152 m^3 with a maximum FWL thickness of 1.33 ± 1.27 m.

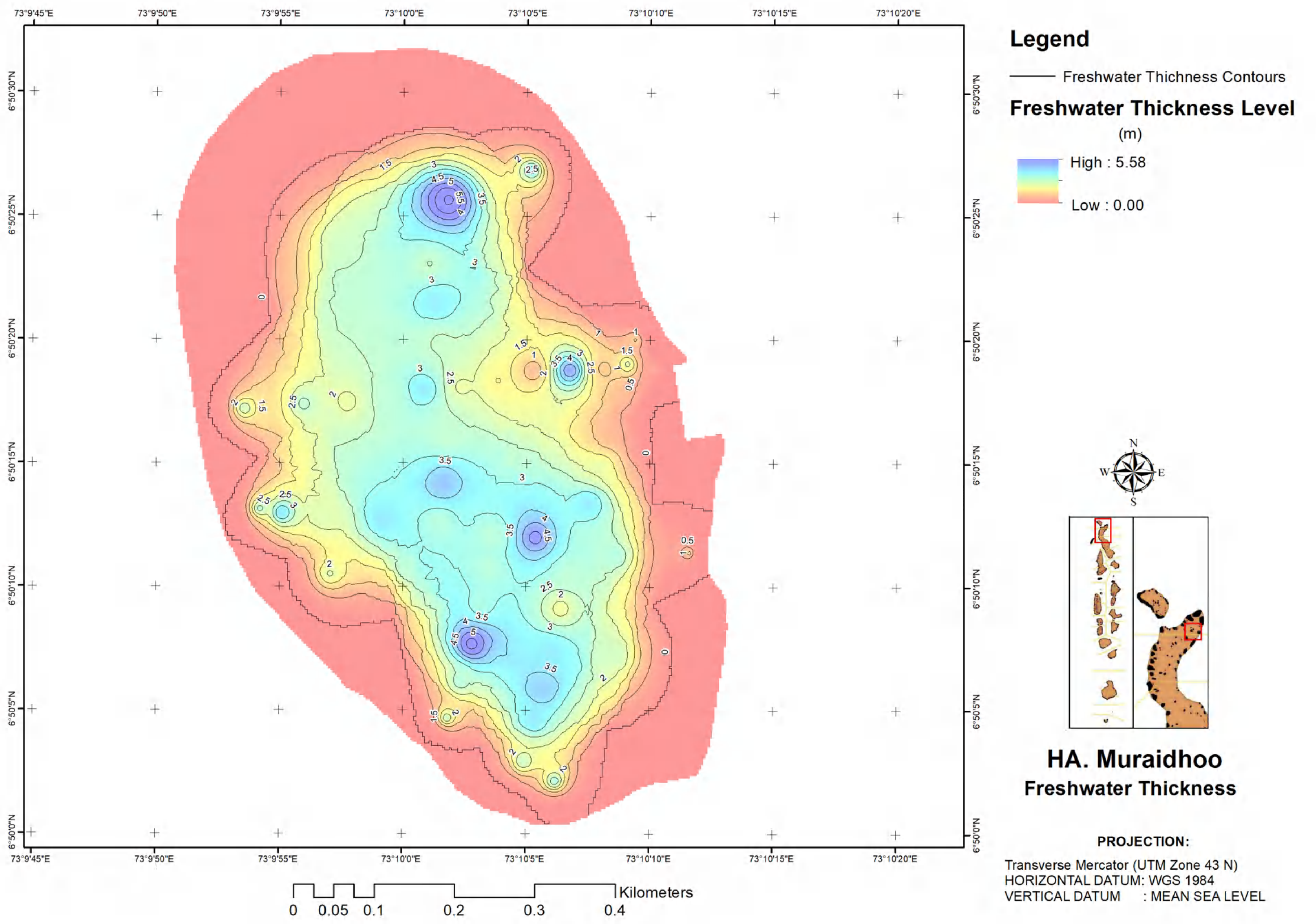


Figure 13: Fresh water thickness map of Muraidhoo Island

Groundwater chemistry and its variation.

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

About 40 water samples have been analyzed for EC(µs/cm), pH, Turbidity(NTU), DO(ppm), Tem(C^0), Salinity(PSU), Nitrate(mg/l), Ammonia(mg/l), and Phosphate(mg/l). Bacteriological analysis was done in 15 places and results revealed that all wells are contaminated with different proportions (total coliform- (43-2420) MPN/100 ml, fecal coliform – (19-980) MPN/100 ml) as per the WHO guidelines. In addition,EC was measured in 28 locations. The sampling points are given in Figure 0-14.

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

Table 9: Comparison of WQ results based on land usage

Land Use	Number of samples	Results are lined with conditions	Increment of measured parameters	Remark
Residential area	59	48	MU11, MU12, MU8, MU21 MUW15, MU16, MU17, MU18,MU2,MU37,MUW 12	Enrichment of EC in MUW 12, MUW 15, and MU 37 are due to higher groundwater extraction and these places are closer to beach line. Enrichment of nitrate and ammonia are due to anthropogenic activities
Other areas	9	5	MU 27, MUW 24, MU36,MU40	Enrichment of EC is due to sea water maxing due to sea water flooding.
Total	68	53	15	

Note:
1) EC > 2500 µs/cm (water could be used for potable and non-potable use depending of EC.
2) Nitrate (> 50 mg/l), Phosphate (> 2 mg/l), and ammonia (> 0.5 mg/l) as per WHO guidelines.

The water quality records of contaminated points as per note (1 & 2) are given in below Table 10: Water quality records of contaminated points.

Table 10: Water quality records of contaminated points

Sampling points	EC-µS/cm	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
MU11	1033	7.63	0.70	5.06	0.54
MU12	1151	7.32	25.10	2.25	0.37
MU8	1526	7.22	0.80	12.25	0.35
MU21	789	7.88	7.10	5.19	0.35
MU15	972	7.48	2.10	0.09	0.23

Sampling points	EC-µS/cm	pH	Nitrates (mg/L)	Ammonia (mg/L)	Phosphates (mg/L)
MU16	1284	7.63	17.50	0.71	0.27
MU17	1629	7.43	12.20	1.64	0.57
MU18	184	7.49	17.20	0.74	0.24
MU2	1652	7.30	104.80	0.26	0.36
MU37	2924	7.49	1.00	0.13	0.41
MU27	6528	8.10	2.10	0.12	0.15
MU36	508260	7.35	3.70	0.62	0.17
MU40	6420	7.41	42.80	0.59	0.27
MUW 24	5780	ND	ND	ND	ND
MUW 12	3720	ND	ND	ND	ND
MUW 15	4110	ND	ND	ND	ND

Note: ND- Not measured

Aquifer properties

Hydraulic conductivity(permeability) and transmissivity were estimated by conducting the permeability test and pumping tests respectively. Tested locations are given in Figure 0-15.

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

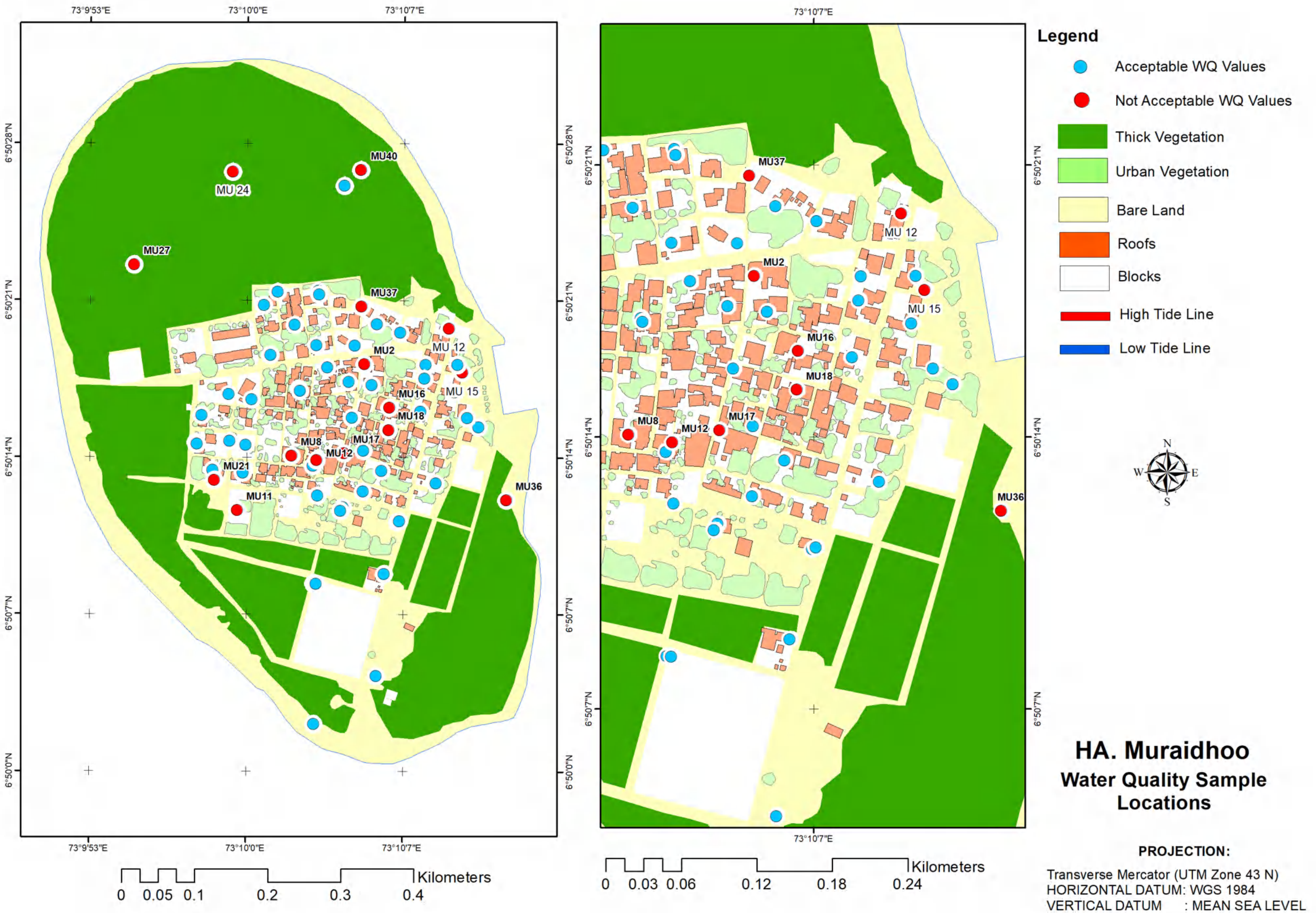


Figure 0-14: Location of groundwater sampling points in Maarandhoo Island

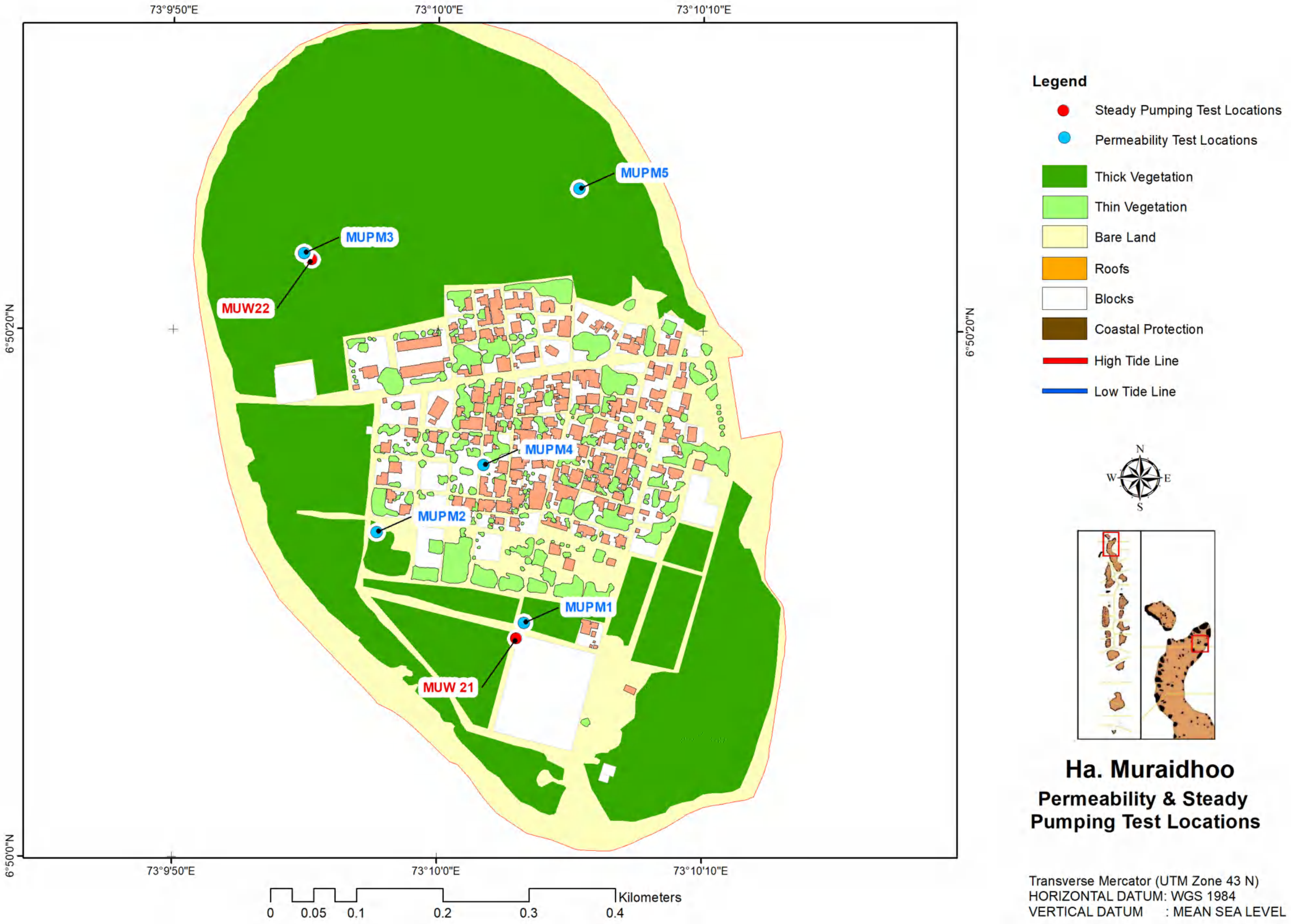


Figure 0-15: Tested locations (pumping test and Hydraulic conductivity) in Muraidhoo Island

Hydraulic conductivity of unsaturated formation

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

Table 11: Estimated hydraulic conductivity values for HA Muraidhoo

Point	Hydraulic conductivity(m/d)
MUPM 1	1.75
MUPM 2	3.81
MUPM 3	14.99
MUPM 4	0.44
MUPM 5	8.14

The measured hydraulic conductivity values ranged from a minimum of 0.44 m/d to a maximum of 14.99 m/d, with an average of 5.88 m/d. The average value of 5.88 m/d is considered for estimation of the groundwater flow velocities of the island. MUPM 4 is located within mosques premises.

Pumping test

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

Table 12: Pumping test results for HA Muraidhoo

Dug well	Transmissivity (m^2/s)	Drawdown(m)	EC -before pumping- µs/cm	EC-End of pumping- µs/cm
MU 21	0.0012	0.36	1090	1090
MU 22	0.0005	0.18	3880	4480

Abbreviation: EC- Electrical conductivity

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

Groundwater flow and flow velocity

As per the groundwater level map Figure 17, three groundwater zones with relatively higher head are developed at eastern, western, and southern part of the fresh water lens.

It is noted that groundwater zones with low head are developed mainly at middle part of the lenses between groundwater zone with higher head. The some of low groundwater zones could be occurred due to higher groundwater extraction.

The groundwater velocity map for the island Figure 18was developed by using calculated average hydraulic conductivity of the island and assuming porosity of 15% . The calculated velocity of the groundwater varies from place to place with a maximum of 1.37 m/day.

The estimated maximum retention time of the groundwater within the island for velocity of 0.3 m/day is about 26 months. As per the velocity map, the groundwater recharging shall be done at middle part of island. In addition, recharging structures are to be constructed in order to increase the retention time and to control the controlling the sea water flooding. The details of the structures will be discussed under chapter 6.

Sea water flooding.

It is noted that sea water flooding areas (marked in red) along the coastal line are observed during the field Figure 16. There is wetland at southeastern side of the island developed parallel to the beach. Also, southern end has been affected due to sea erosion. During the tidal period, sea water flooding is very common at the southern side of the island.

Figure 16: Sea water flooding areas in Muraudhoo island

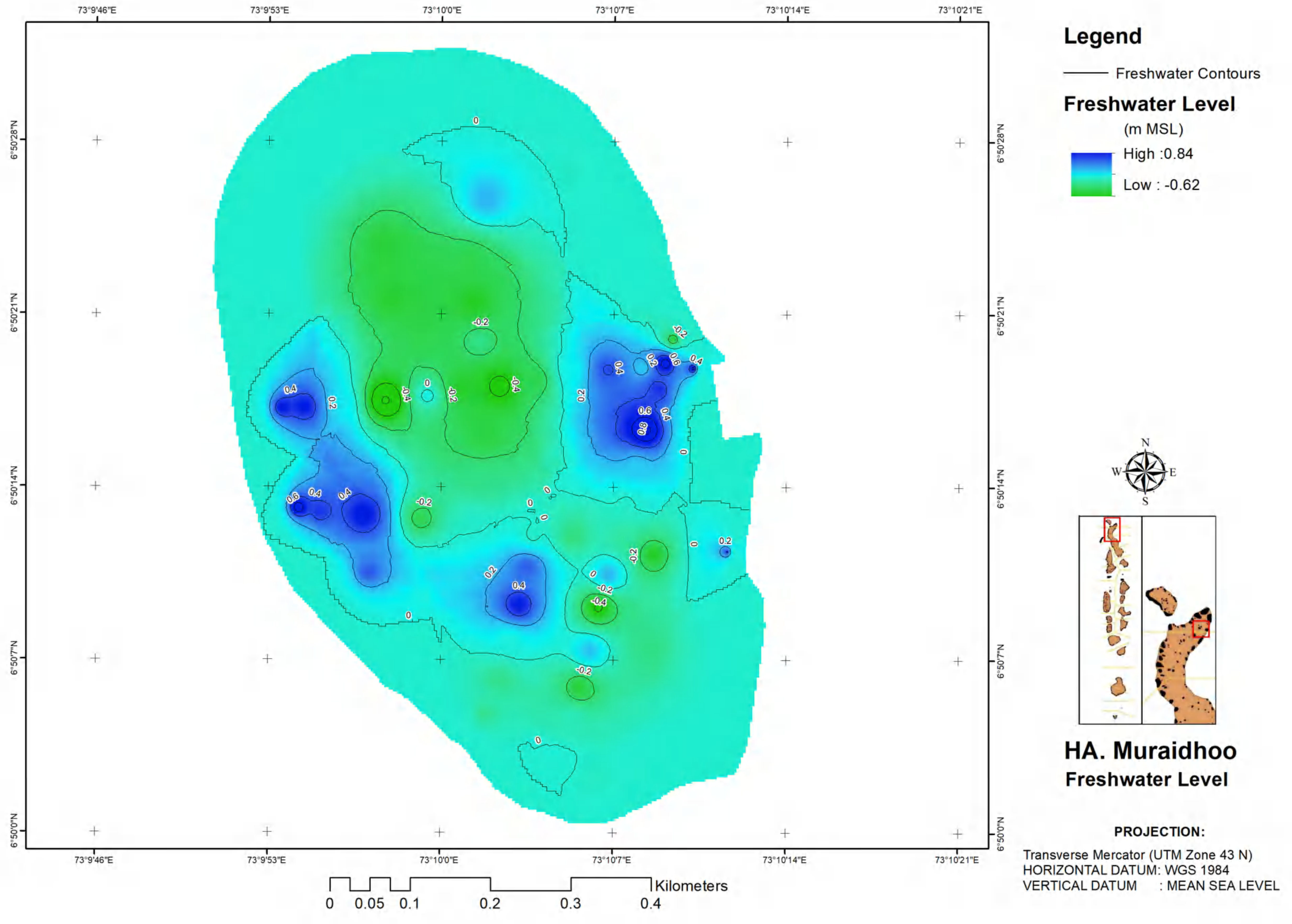


Figure 17: Groundwater level map of the Muraidhoo Island

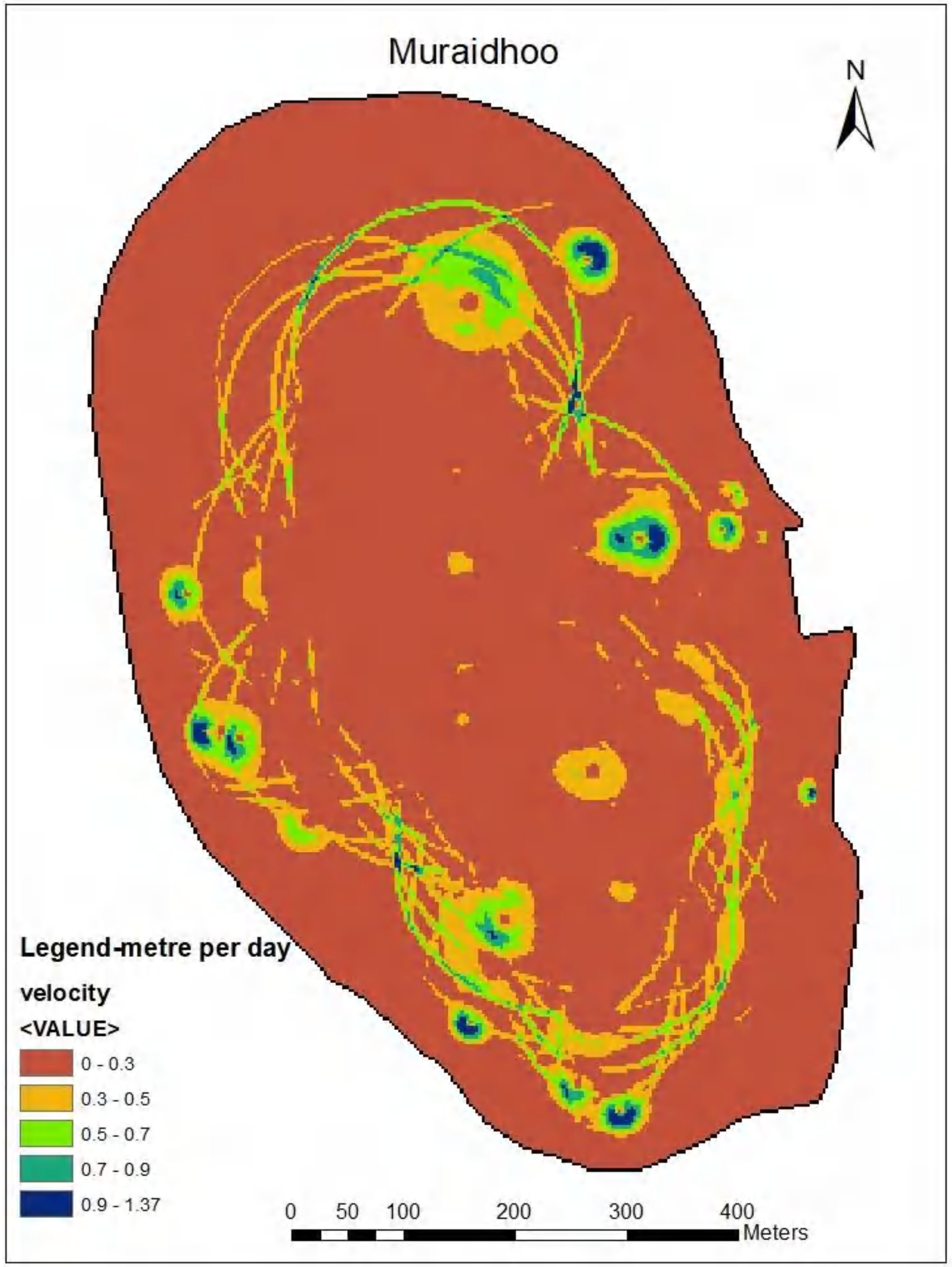


Figure 18: Flow velocity map of the Muraidhoo Island

HA Uligan

Geology and hydrogeology of the island.

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation. The thickness of the overburden (unconsolidated layer and weathered layer) within Uligan island varies from place to place with a maximum of 6.5 m.

The summarized details of the geological profile are given below.

- Thickness of the top layer varies up to 1.0 m
- Thickness of the beach coral sand layer varies from 1.0 m to 1.5 m. In beach areas mostly beach coral sand exists as the top layer.
- Thickness of weathered coral layer varies up to 4 m.

As the compositional and structural differences of coral formation, differential weathering could be observed in cross section N-S. Cross section N-S clearly shows several deep weathered zones. In the cross-section E-W in the island shows uniform weathering and the general trend is Western part of the island show higher weathering compared to the Eastern part of the island.

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

Hydrogeology

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

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

Fresh groundwater of the island occurs as a lens over saline water. Basically, geometry of the freshwater lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 1.23 m above MSL in the middle parts of the island. It is noted that several upcoming zones have developed within fresh water lenses due to higher groundwater extraction. The maximum thickness of the freshwater lens is about 5.50 m by considering he EC > 2500 µs/cm and it reduces toward the rim area of the lens Figure 19.

The freshwater lens (FWL) volume calculated based on ER transect test data and 15% porosity is 149,548 m3 with a maximum FWL thickness of 2.90 ± 0.83 m.

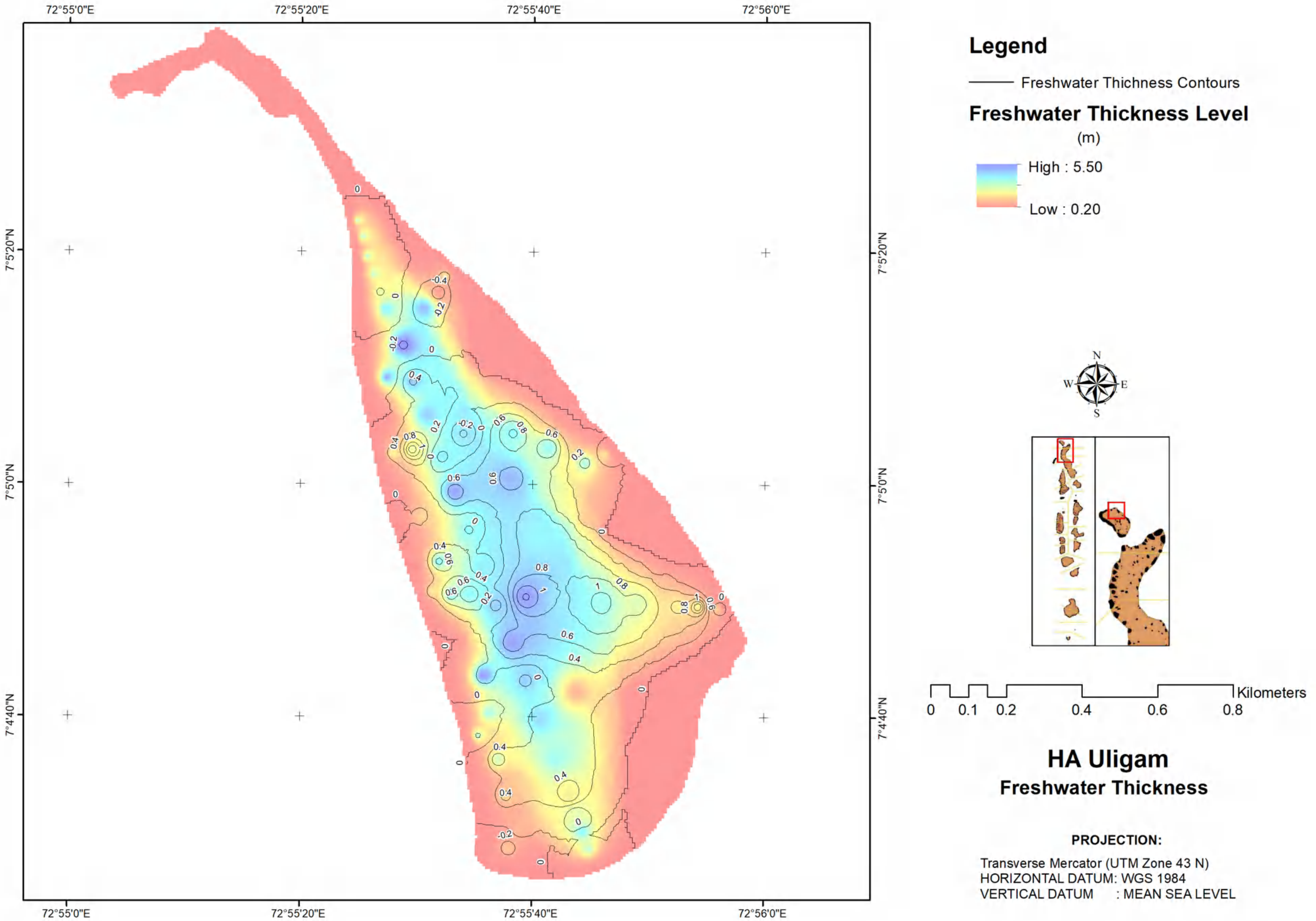


Figure 19: Fresh water thickness map of Uligan Island

Groundwater chemistry and its variation.

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

About 40 water samples have been analyzed for EC(µs/cm), pH, Turbidity(NTU), DO(ppm), Tem(C0), Salinity(PSU), Nitrate(mg/l), Ammonia(mg/l), and Phosphate(mg/l). Bacteriological analysis was done in 14 places and results revealed that all wells are contaminated with fecal coliform in different proportions (total coliform- (165-2420) MPN/100 ml) as per the WHO guidelines. In addition, EC was measured in 21 locations. The sampling points are given in Figure 20.

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

Table 13: Comparison of WQ results based on land usage

Land Use	Number of samples	Results are lined with conditions	Increment of measured parameters	Remark
Residential area	46	46		No contamination recorded as per note(1 and 2)
Agricultural area	4	4		No contamination recorded as per note(1 and 2)
Industrial area	2	2		No contamination recorded as per note(1 and 2)
Other areas	10	10		No contamination recorded as per note(1 and 2)
Total	62	62		

Note:
1) EC > 2500 µs/cm (water could be used for potable and non-potable use depending of EC.
2) Nitrate (> 50 mg/l), Phosphate (> 2 mg/l), and ammonia (> 0.5 mg/l) as per WHO guidelines.

Aquifer properties

Hydraulic conductivity(permeability) and transmissivity were estimated by conducting the permeability test and pumping tests respectively. Tested locations are given in Figure 21.

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

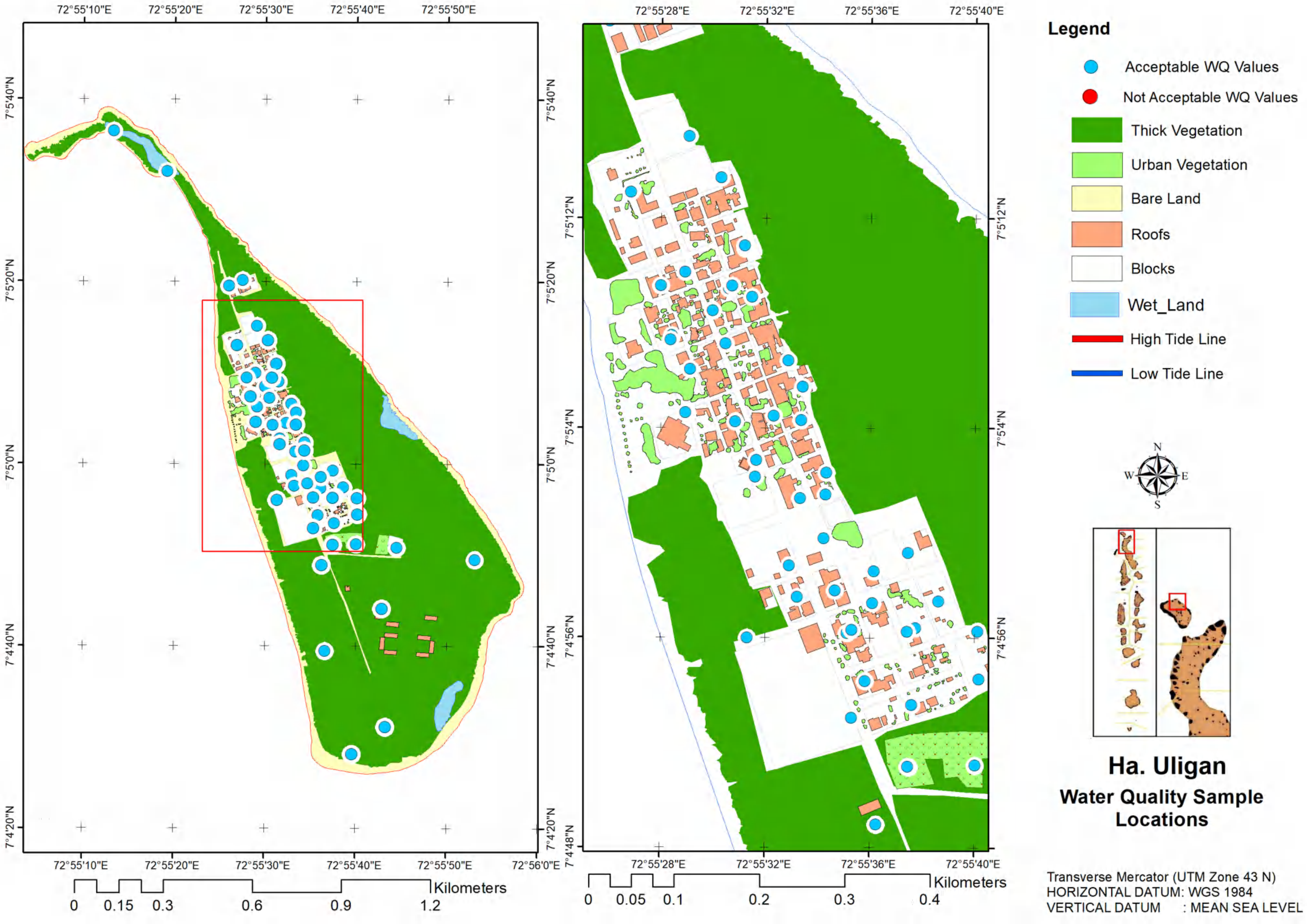


Figure 20: Location of groundwater sampling points in Uligan Island

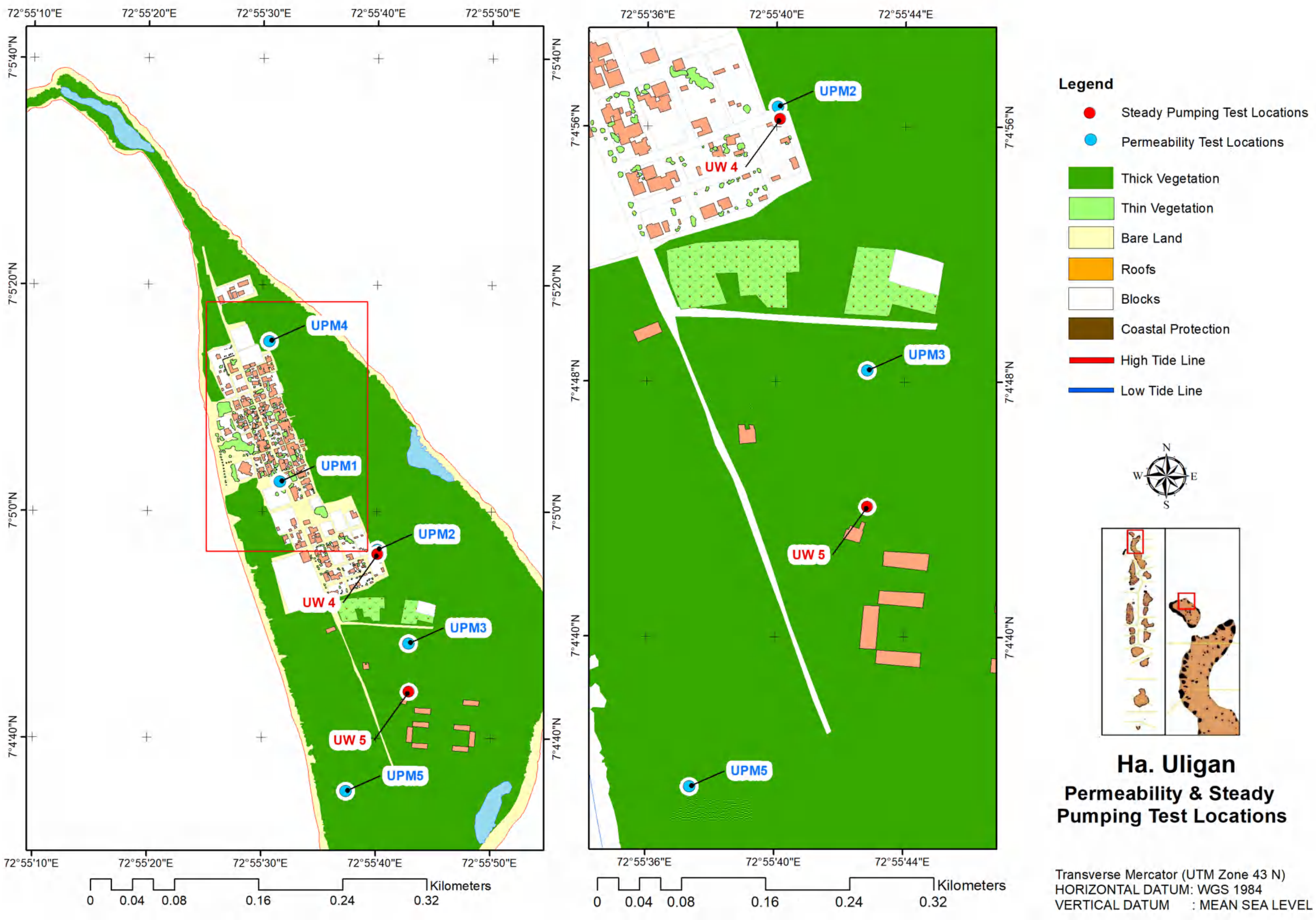


Figure 21: Tested locations (pumping test and Hydraulic conductivity) Uligan Island

Hydraulic conductivity of unsaturated formation

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

Table 14: Estimated hydraulic conductivity values for HA Uligan

Point	Hydraulic conductivity(m/d)
UPM 1	3.09
UPM 2	3.88
UPM 3	3.34
UPM 4	9.14
UPM 5	7.95

The measured hydraulic conductivity values ranged from a minimum of 3.09 m/d to a maximum of 9.14 m/d, with an average of 5.48 m/d. The average value of 5.48 m/d is considered for estimation of the groundwater flow velocities of the island.

Pumping test

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

Table 15: Pumping test results for HA Uligan

Dug well	Transmissivity (m^2/s)	Drawdown(m)	EC -before pumping- µs/cm	EC-End of pumping- µs/cm
UW 4	0.0051	0.42	650	650
UW 5	0.0091	0.55	1370	1370

Abbreviation: EC- Electrical conductivity

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 not increased.

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

Groundwater flow and flow velocity

As per the groundwater level map Figure 23, groundwater zone with relatively higher head are developed in middle part of the fresh water lenses. Also, it is noted that small groundwater zones with low head are developed mainly at rim area of the lenses due to higher groundwater extraction.

The groundwater velocity map for the island Figure 24 was developed by using the calculated average hydraulic conductivity of the island and assuming porosity of 15%. The calculated velocity of the groundwater varies from place to place with a maximum of 1.3 m/day and higher velocity zones mainly occur at the western rim area of the lens. The flow velocity over 80% of the land area is less than 0.2 m/day.

The estimated maximum retention time of the groundwater within the island for a velocity of 0.2 m/day is about 55 months. As per the velocity map, the groundwater recharging shall be done at the middle part of island. In addition, structures are to be constructed in order to increase the retention time and to control the controlling the sea water flooding. The details of the structures will be discussed under chapter 6.

Sea water flooding.

It is noted that sea water flooding areas (marked in red) along the coastal line are observed during the field Figure 22.

Figure 22: Sea water flooding areas in Uligan island

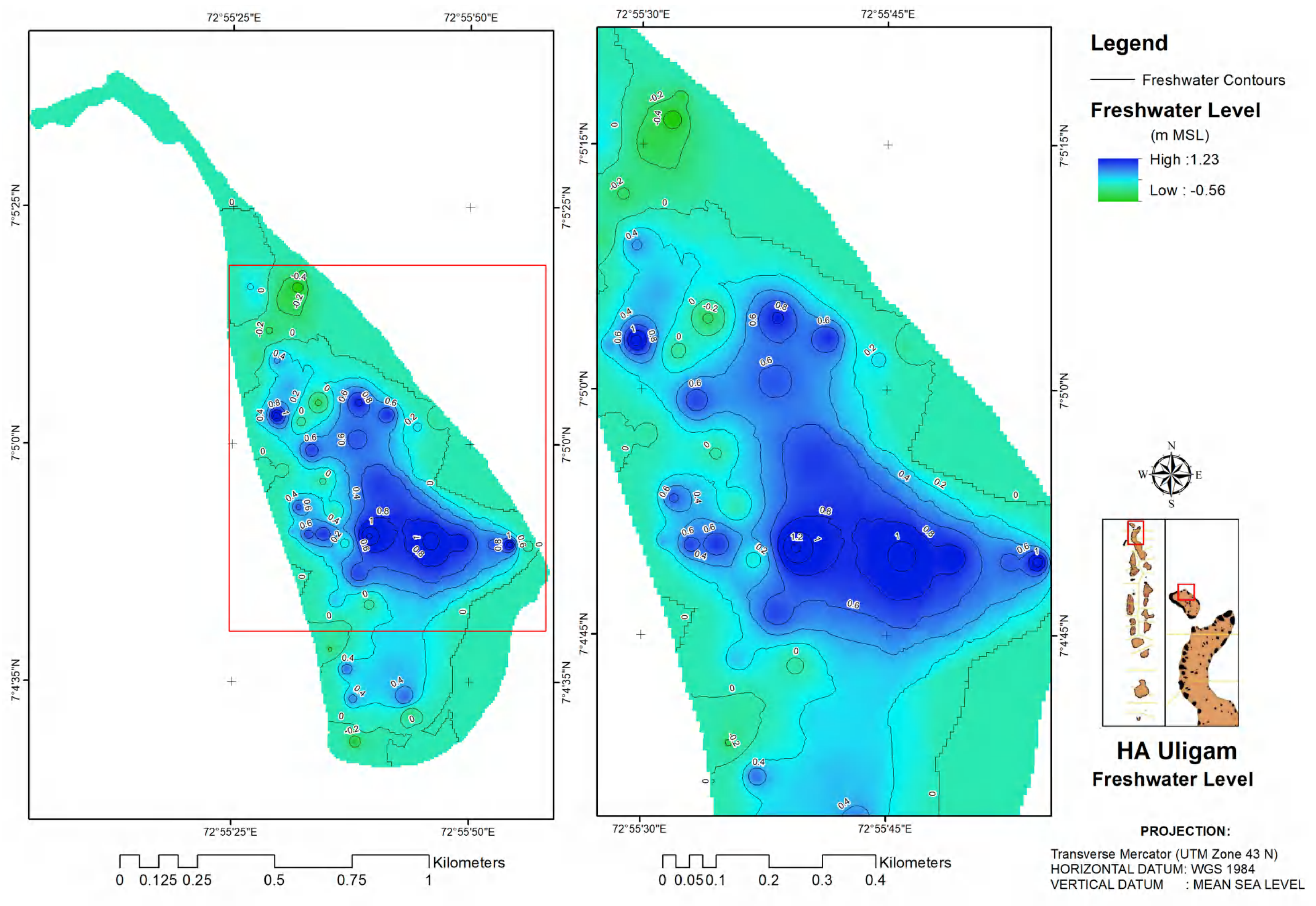


Figure 23: Groundwater level map of the Uligan Island

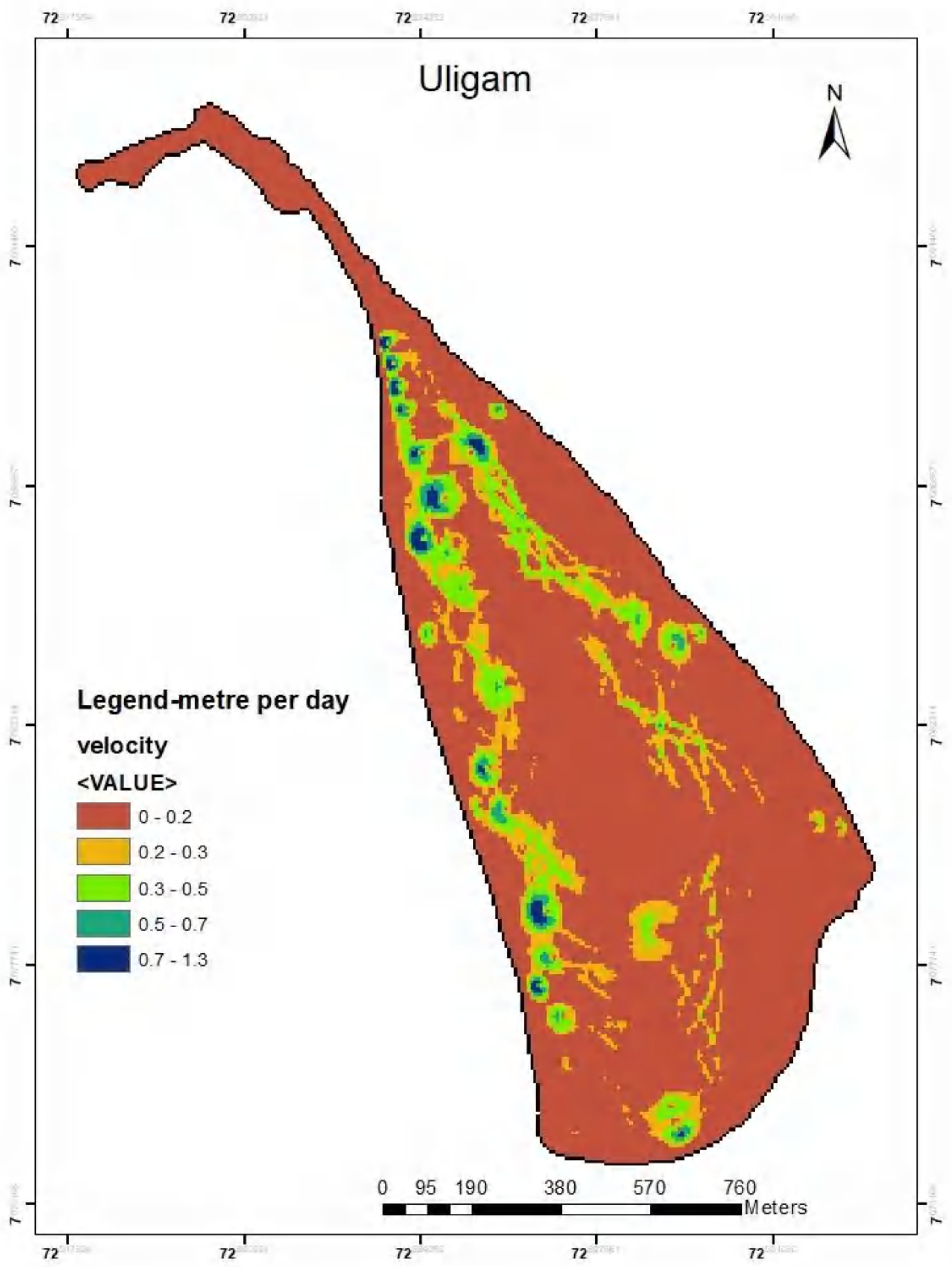


Figure 24: Flow velocity map of the Uligan Island

Ha. Molhadhoo

Geology and hydrogeology of the island.

Geology

Geologically, this island is composed of sedimentary rocks made of different types of corals. It was noted that unconsolidated sediments and weathered coral layers rest on the fresh coral formation. The thickness of the overburden (unconsolidated layer and weathered layer) within Molhadhoo island varies from place to place with a maximum of 5.5 m.

The summarized details of the geological profile are given below.

- Thickness of the top layer varies up to 0.5 m
- Thickness of the beach coral sand layer varies from 0.3 m to 2 m. In beach areas mostly beach coral sand exists as the top layer.
- Thickness of weathered coral layer varies from 0.2 m to 3 m. Thick of weathered layer is located at middle part of the island.

The thickness of the topsoil layer varies up to 0.5m. Beach coral sand layer about 0.3m thickness in beach areas and about 2m thickness in the middle of the island. In southern beach areas mostly beach coral sand exists as the top layer. The weathered coral rock depth is varying between 0.2m (coastal areas) to about 3m (middle of island). According to the compositional and structural differences of coral formation, differential weathering could be observed. Also, deep weathering is observed at the middle part of the island compared to other areas.

The occurrence of weak layers is common in the fresh coral formations at different depth horizons due to the occurrence of different types of coral formations within subsurface formations. The depth to fresh coral layer varies along the coastal area with maximum of 1-2 m based on indirect measurements.

Hydrogeology of the island

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

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

Fresh groundwater of the island occurs as a lens. The middle part of the fresh water lens rests on the fresh coral formation and its outer area rests on saline water. Basically, the geometry of the fresh water lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 0.82 m above MSL in the middle parts of the island. It is noted that several upcoming zones has developed within fresh water lenses due to higher groundwater extraction. The maximum thickness of the fresh water lens is about 5.06 m by considering the EC > 2500 µs/cm and it reduces toward the rim area of the lens Figure 25.

The lower part of the overburden (lower part of unconsolidated formation, weathered layer, and partly weathered layer) are water bearing. The lower part of the unconsolidated formation completely weathered layer, and partly weathered layer behaves as a single unit and acts as an unconfined aquifer. The aquifer properties of the three layers are different and geologically, completely weathered layer shows more homogeneous behavior than the partly weathered layer and unconsolidated formation.

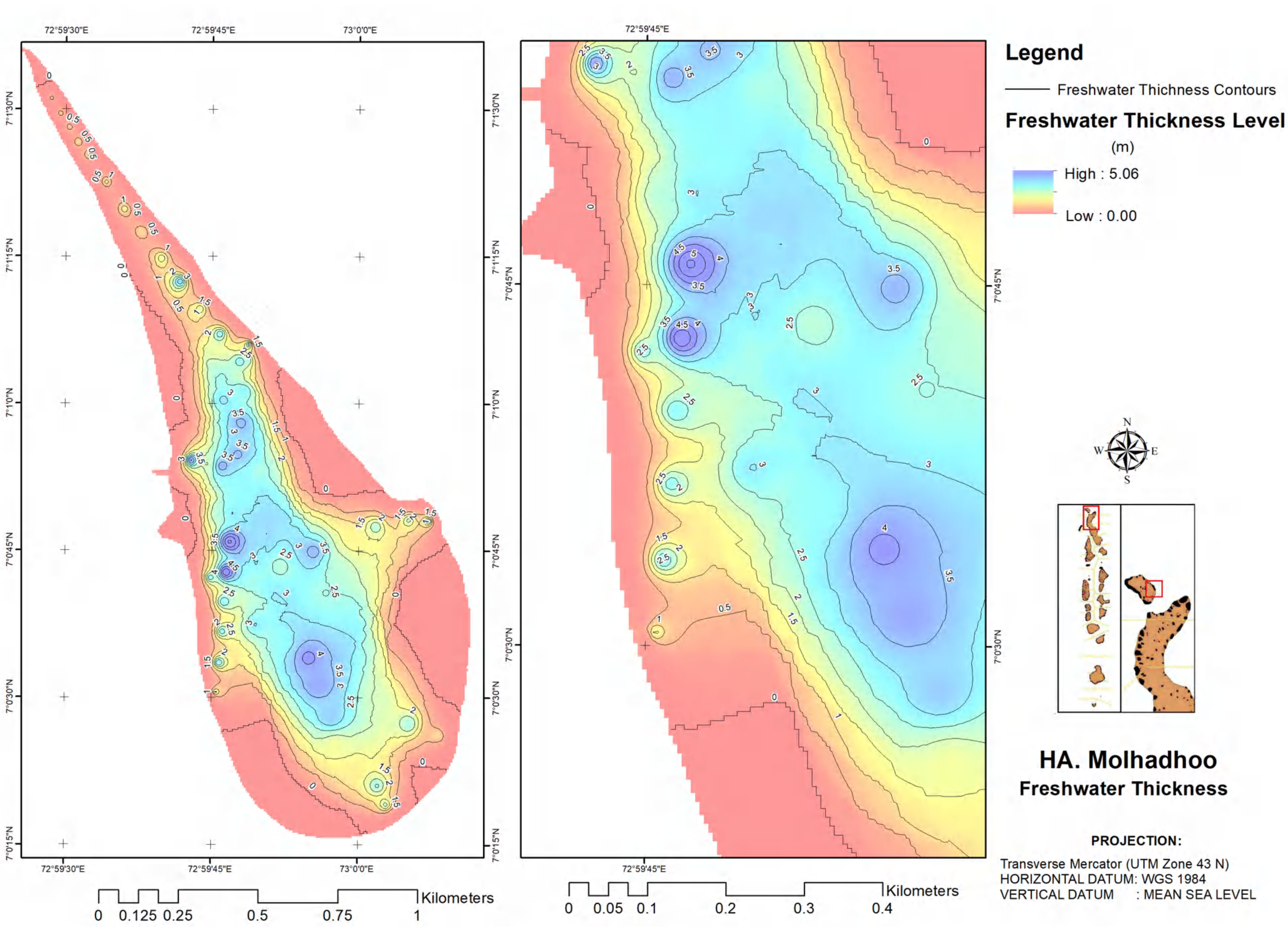


Figure 25: Fresh water thickness map of Molhadhoo Island

Porosity of the completely weathered layer and unconsolidated layer is higher than the porosity of the partly weathered layer.

Fresh groundwater of the island occurs as a lens. The middle part of fresh water lens rests on the fresh coral formation and its outer area rests on saline water. Basically, the geometry of the fresh water lens varies with the groundwater recharge and discharge conditions. As per the baseline assessment report, the standing maximum groundwater level is 1.28 m above MSL in the middle parts of the island. The maximum thickness of the fresh water lens is about 2.85 m by considering he EC > 1500 µs/cm and it reduces toward the rim area of the lens Figure 25.

As per the report, the freshwater lens (FWL) volume calculated based on ER transect test data and 15% porosity is 211,487 m3 with a maximum FWL thickness of 1.18 ± 1.19 m.

Groundwater chemistry and its variation.

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

About 40 water samples have been analyzed for EC(µs/cm), pH, Turbidity(NTU), DO(ppm), Tem(C0), Salinity(PSU), Nitrate(mg/l), Ammonia(mg/l), and Phosphate(mg/l). Bacteriological analysis was done in 15 places and results revealed that all wells are contaminated with fecal coliform in different proportions (total coliform- (15-2420) MPN/100 ml, fecal coliform – (1-196) MPN/100 ml) as per the WHO guidelines. In addition, EC was measured in 23 locations within the island. The sampling points are given in Figure 26.

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

Table 16: Comparison of WQ results based on land usage

Land Use	Number of samples	Results are lined with conditions	Increment of measured parameters	Remark
Residential area	36	36		No contamination recorded as per note(1 and 2)
Agricultural area	9	9		No contamination recorded as per note(1 and 2)
Industrial area	4	4		No contamination recorded as per note(1 and 2)
Other areas	15	15		No contamination recorded as per note(1 and 2)
Total	64	64		

Note:
1) EC > 2500 µs/cm (water could be used for potable and non-potable use depending of EC.
2) Nitrate (> 50 mg/l), Phosphate (> 2 mg/l), and ammonia (> 0.5 mg/l) as per WHO guidelines.

Aquifer properties

Hydraulic conductivity(permeability) and transmissivity were estimated by conducting the permeability test and pumping tests respectively. Tested locations are given in Figure 27.

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

Hydraulic conductivity of unsaturated formation

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

Table 17: Estimated hydraulic conductivity values for Muraidhoo

Point	Hydraulic conductivity(m/d)
MLPM 1	7.72
MLPM 2	21.40
MLPM 3	11.31
MLPM 4	10.60
MLPM 5	14.69
MLPM 6	1.22

The measured hydraulic conductivity values ranged from a minimum of 1.22 m/d to a maximum of 21.40 m/d, with an average of 11.16 m/d. The average value of 11.16 m/d is considered for the estimation of the groundwater flow velocities of the island. Low hydraulic conductivity is located at old mosques land and the upper part is filled soil.

Pumping test

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

Table 18: Pumping test results for Muraidhoo

Dug well	Transmissivity (m^2/s)	Drawdown(m)	EC -before pumping- µs/cm	EC-End of pumping- µs/cm
MOD 1	0.008	0.095	700	790
MOD 21	0.032	0.17	1580	1620

Abbreviation: EC- Electrical conductivity

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 MOD 1, EC (Electrical conductivity) increases from 700 µs/cm to 790 µs/cm.
- For MOD 21, EC (Electrical conductivity) increases from 1580 µs/cm to 1620 µs/cm.

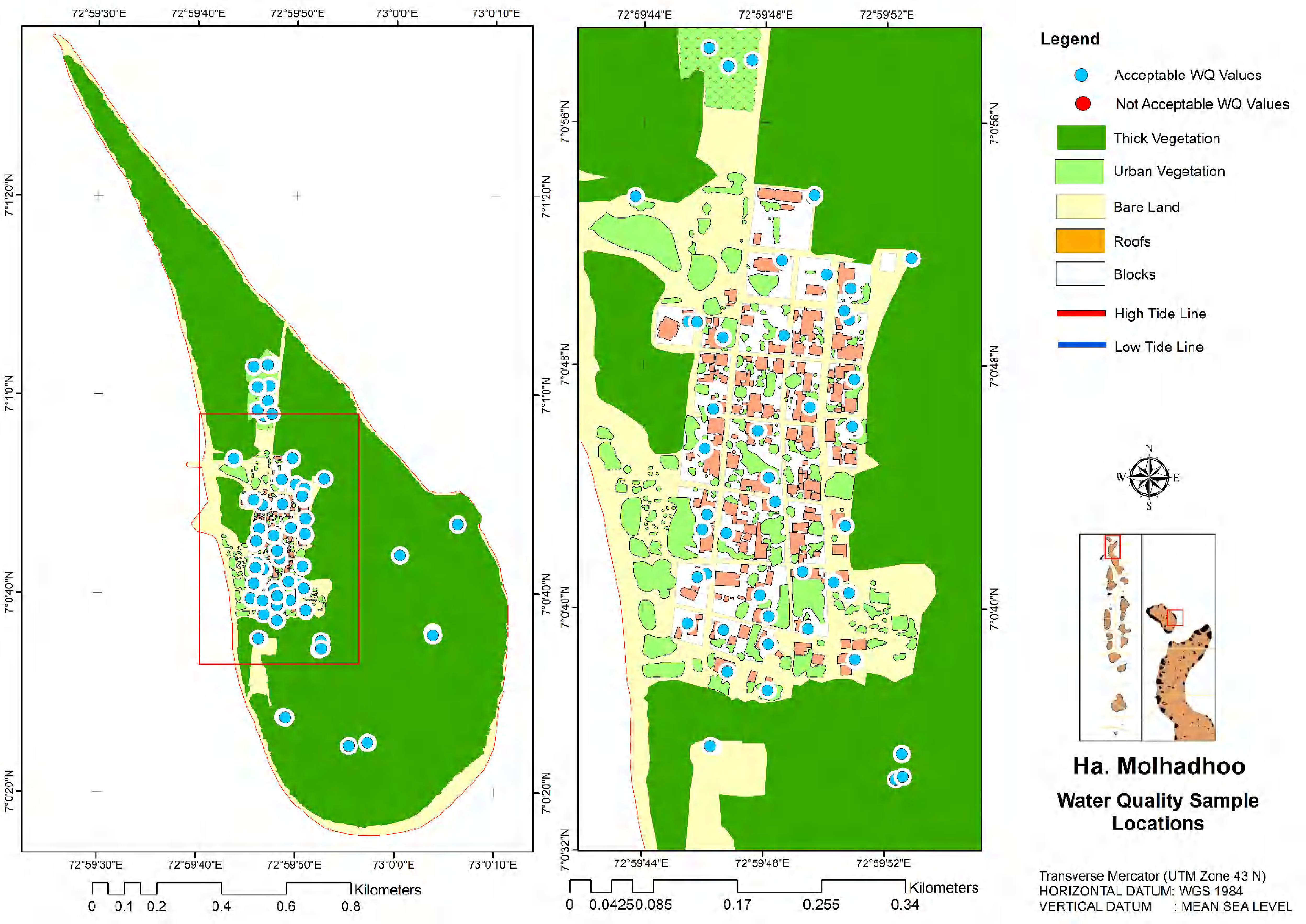


Figure 26: Location of groundwater sampling points in Molhadhoo Island

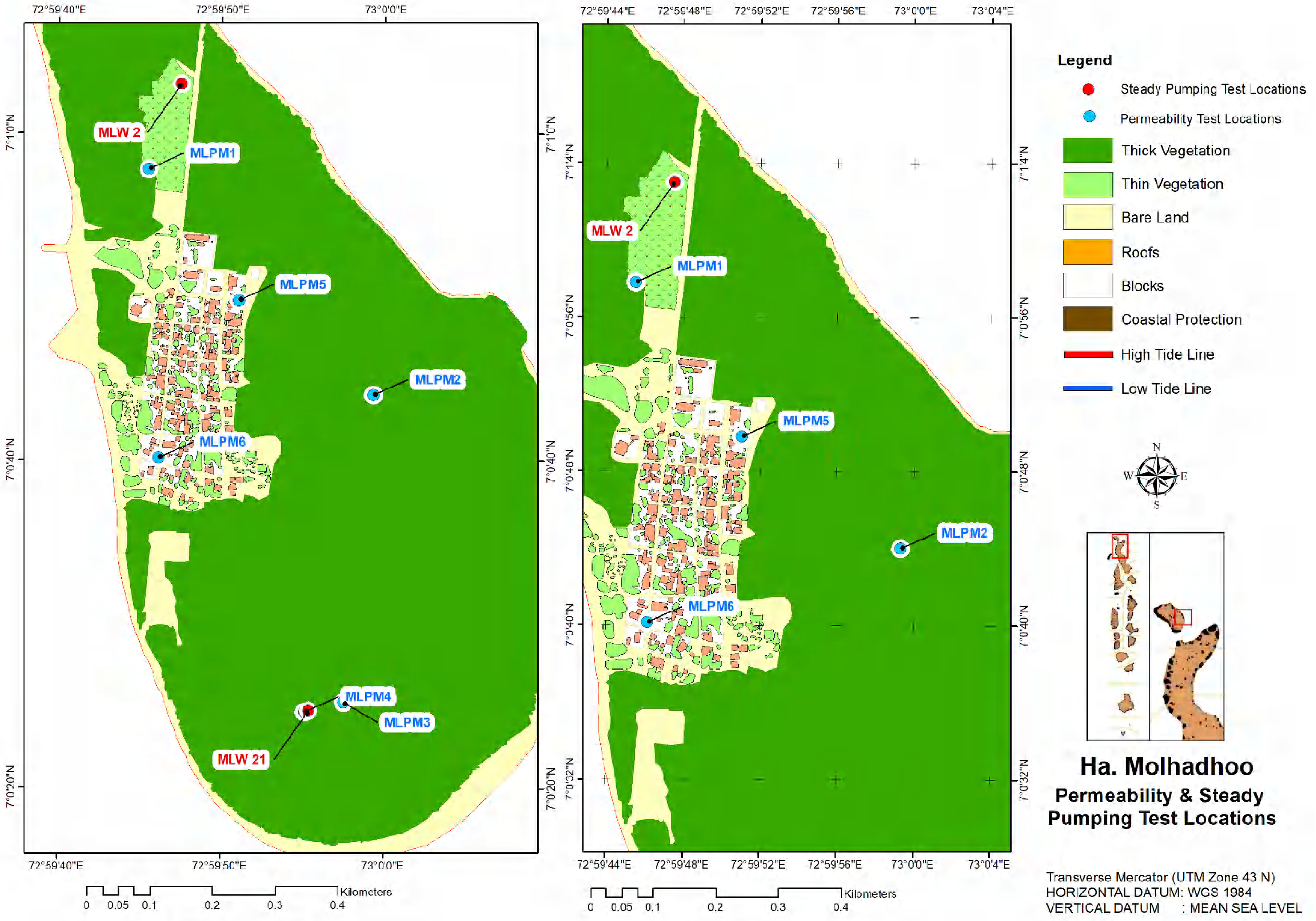


Figure 27: Tested locations (pumping test and Hydraulic conductivity) in Molhadhoo

Groundwater flow and flow velocity.

As per the groundwater level map Figure 29, several small groundwater zones with the higher head are developed at the middle part of the island. In addition, several small fresh groundwater patches with low head are developed within the high head groundwater zones in the island. The some of low groundwater zones could be occurred due to higher groundwater extraction.

The groundwater velocity map for the island Figure 30 was developed by using the calculated average hydraulic conductivity of the island and assuming porosity of 15% . The calculated velocity of the groundwater in island is low and it is up to a maximum of 1.3 m/day. The flow velocity over 80% of the land area is less than 0.2 m/day. The general groundwater flow direction of the wider area of the island is west to east.

The estimated maximum retention time of the groundwater within the island for the velocity of 0.2 m/day is about 66 months. As per the velocity map, the groundwater recharging shall be done at the middle part of island. In addition, recharging structures are to be constructed in order to increase the retention time and to control the controlling the sea water flooding. The details of the structures will be discussed under chapter 6.

Sea water flooding

It is noted that sea water flooding areas (marked in red) along the coastal line are observed during the field Figure 28.It is noted that water logged area is located on the eastern side close to beach. During the rainy period, overland flow and seepages flow to the sea through water logged area while sea water flows to the water logged area as result of tidal action. Recently, it is noted that brackish water wetland has converted to fresh water wetland due to non-mixing of sea water sufficiently.

Figure 28: Sea water flooding areas in Molhadhoo island

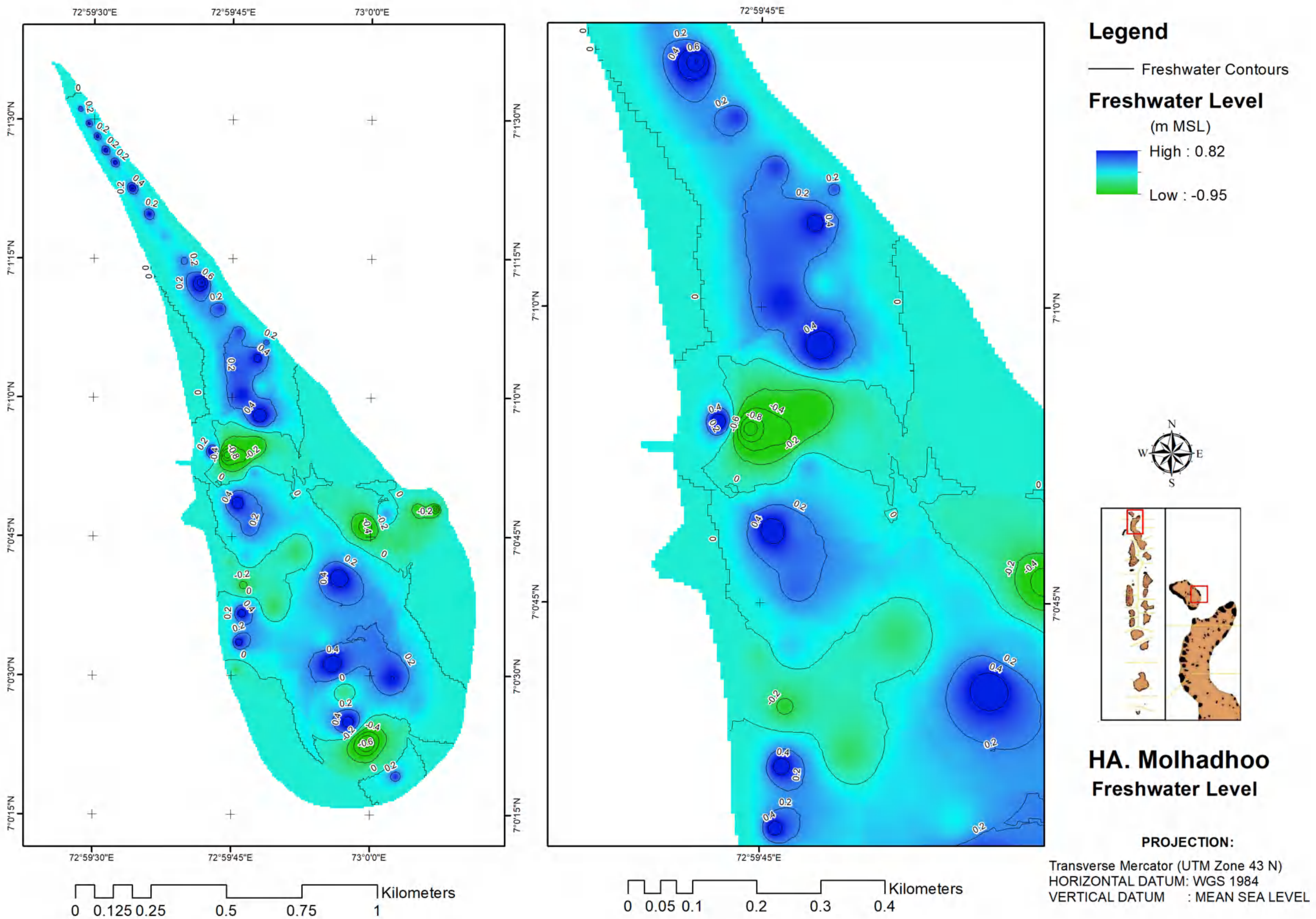


Figure 29: Groundwater level map of the Molhadhoo Island

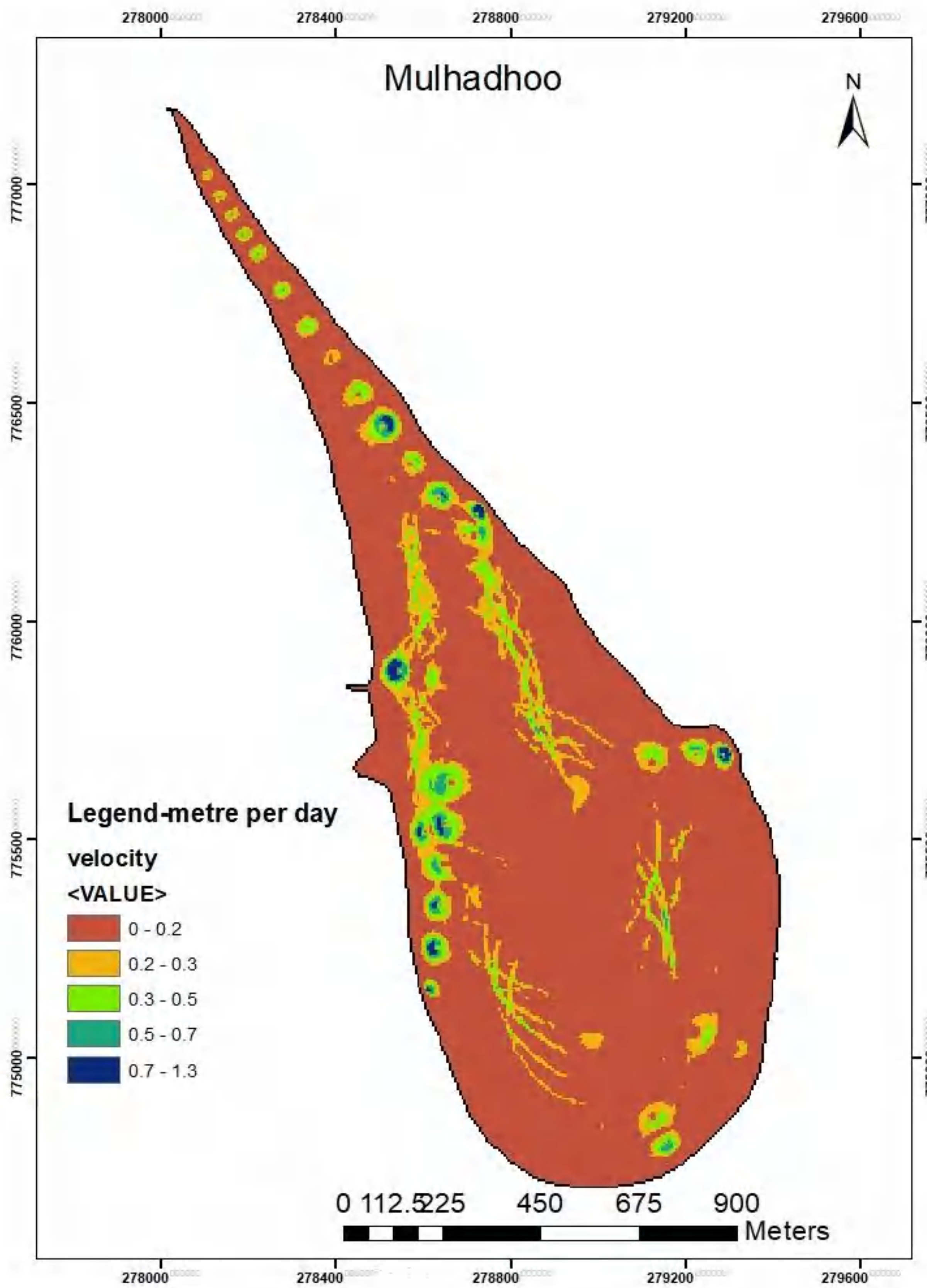
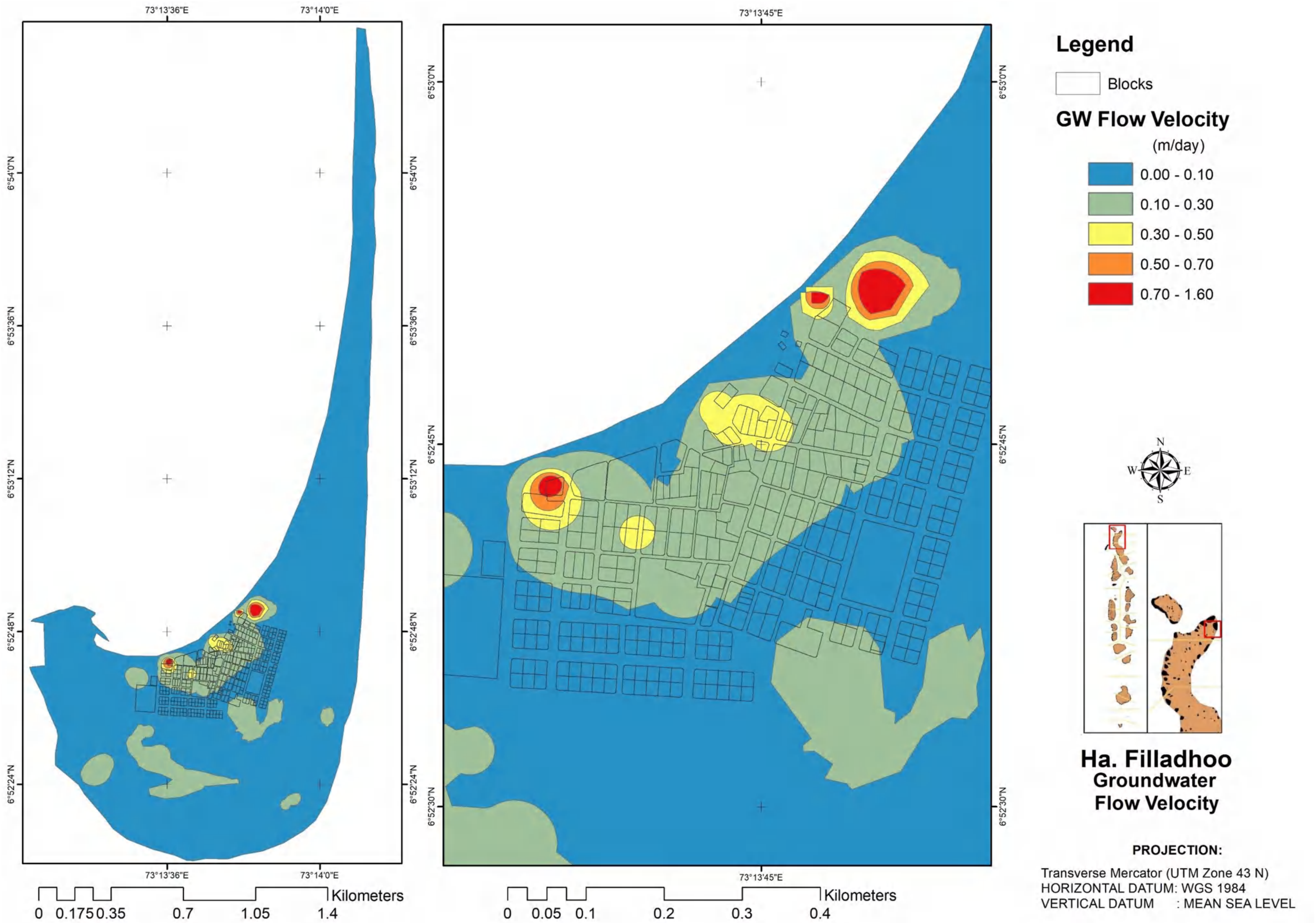


Figure 30: Flow velocity map of the Molhadhoo Island

Annex VIII: Groundwater Flow Velocity Distribution of the Islands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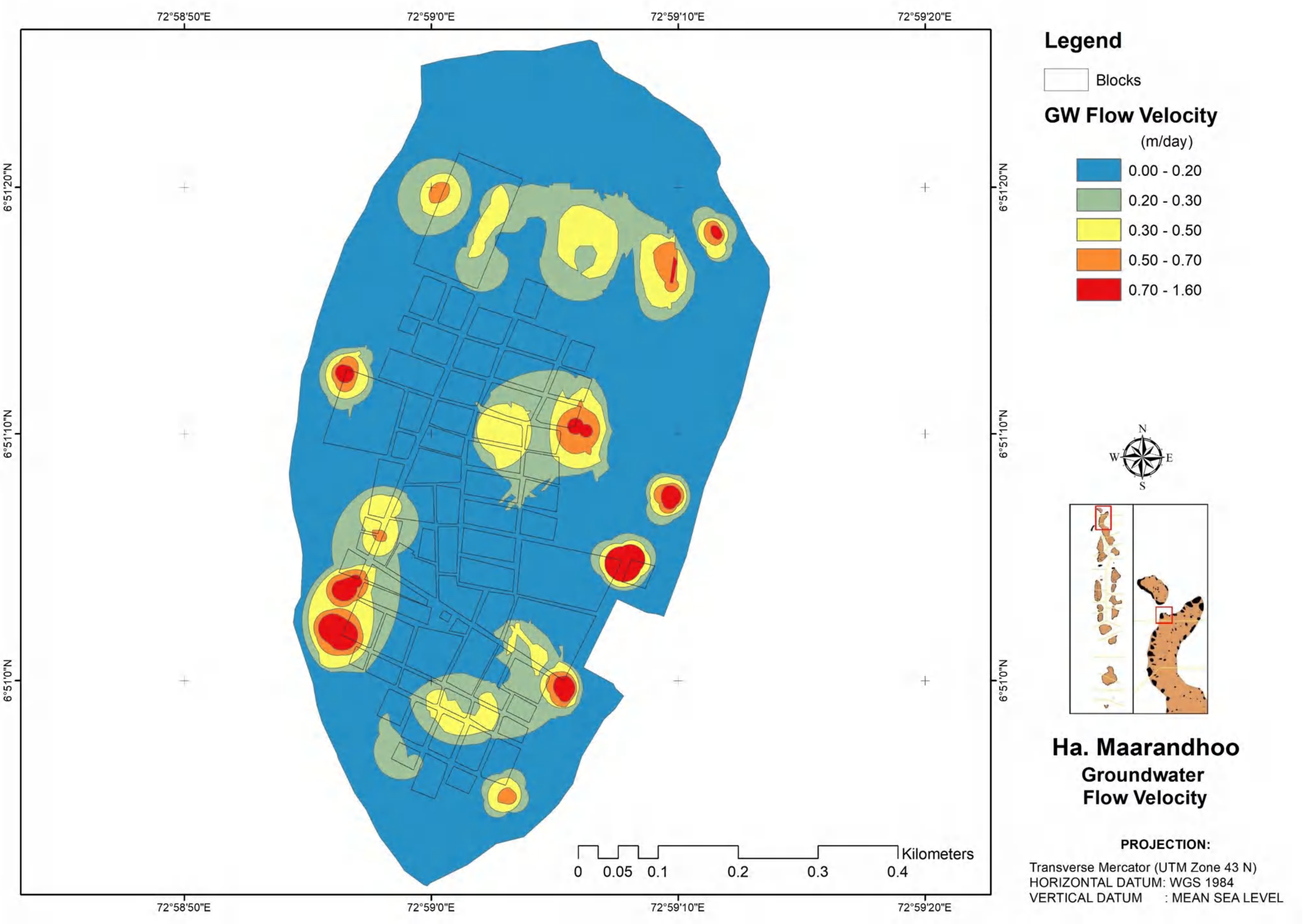
73°14'0"E
6°54'0"N
6°53'36"N
6°53'12"N
6°52'48"N
6°52'24"N
0 0.175 0.35 0.7 1.05 1.4
Kilometers
73°13'45"E
6°53'0"N
6°52'45"N
6°52'30"N
0 0.05 0.1 0.2 0.3 0.4
Kilometers
Legend
Blocks
GW Flow Velocity
(m/day)
0.00 - 0.10
0.10 - 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 1.60
N
W
E
S
Ha. Filladhoo
Groundwater
Flow Velocity
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL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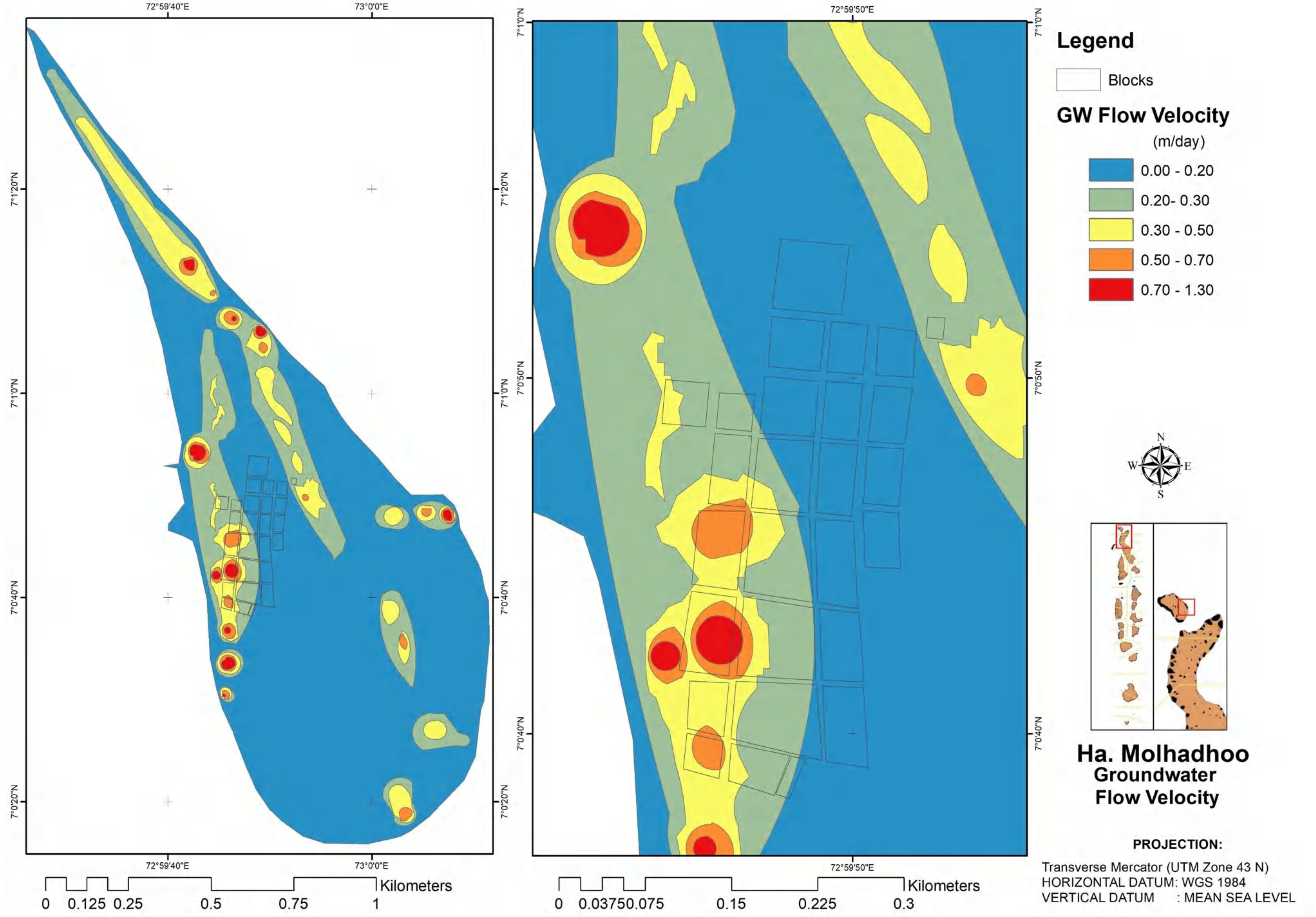
72°59'0"E
72°59'10"E
72°59'20"E
6°51'20"N
6°51'10"N
6°51'0"N
0 0.05 0.1 0.2 0.3 0.4 Kilometers
Legend
Blocks
GW Flow Velocity
(m/day)
0.00 - 0.20
0.20 - 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 1.60
N
W
E
S
Ha. Maarandhoo
Groundwater
Flow Velocity
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL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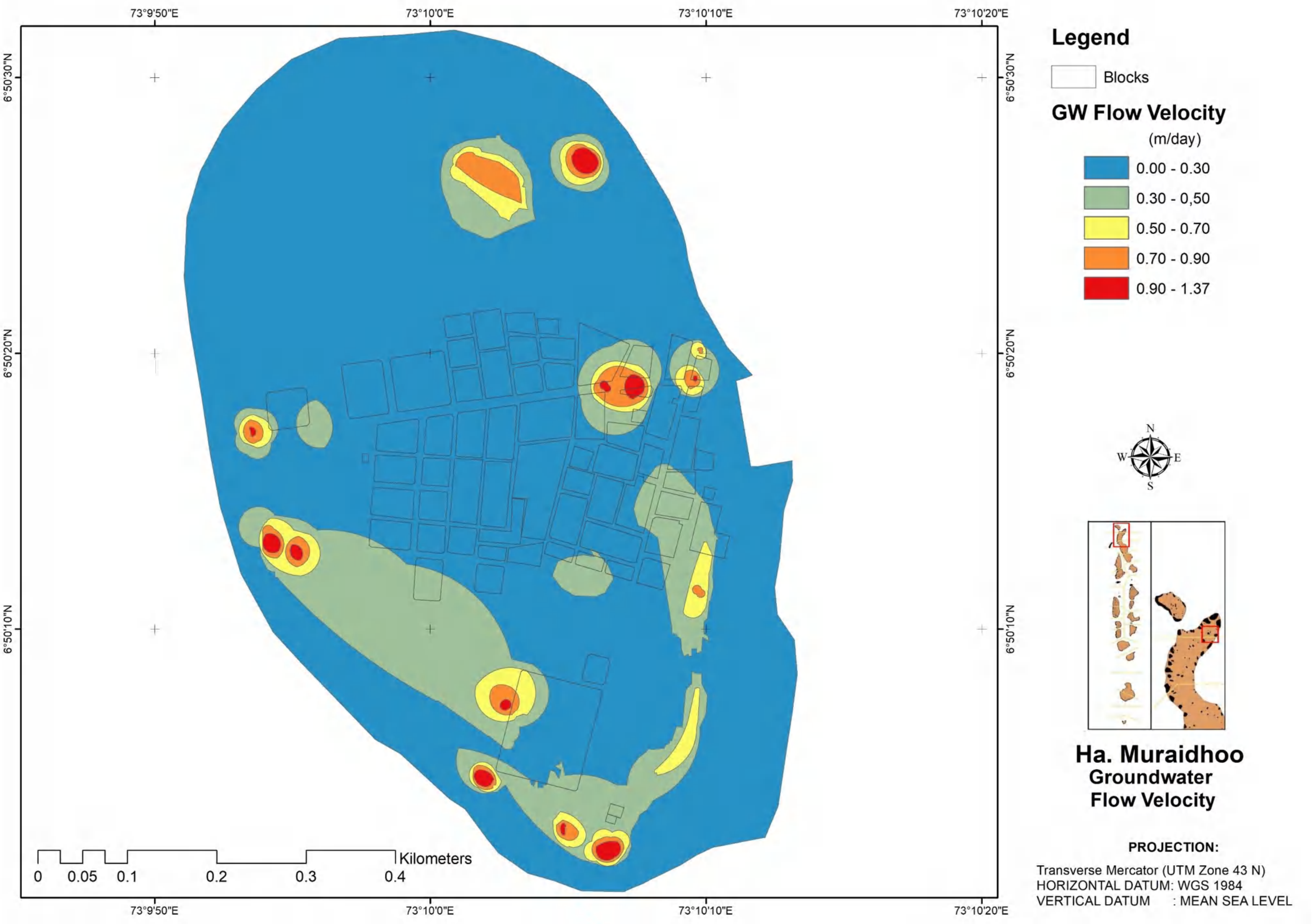
73°0'0"E
7°1'20"N
7°1'0"N
7°0'40"N
7°0'20"N
0 0.125 0.25 0.5 0.75 1 Kilometers
72°59'50"E
7°1'0"N
7°0'50"N
7°0'40"N
0 0.03750.075 0.15 0.225 0.3 Kilometers
Legend
Blocks
GW Flow Velocity
(m/day)
0.00 - 0.20
0.20- 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 1.30
N
W
E
S
Ha. Molhadhoo
Groundwater
Flow Velocity
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL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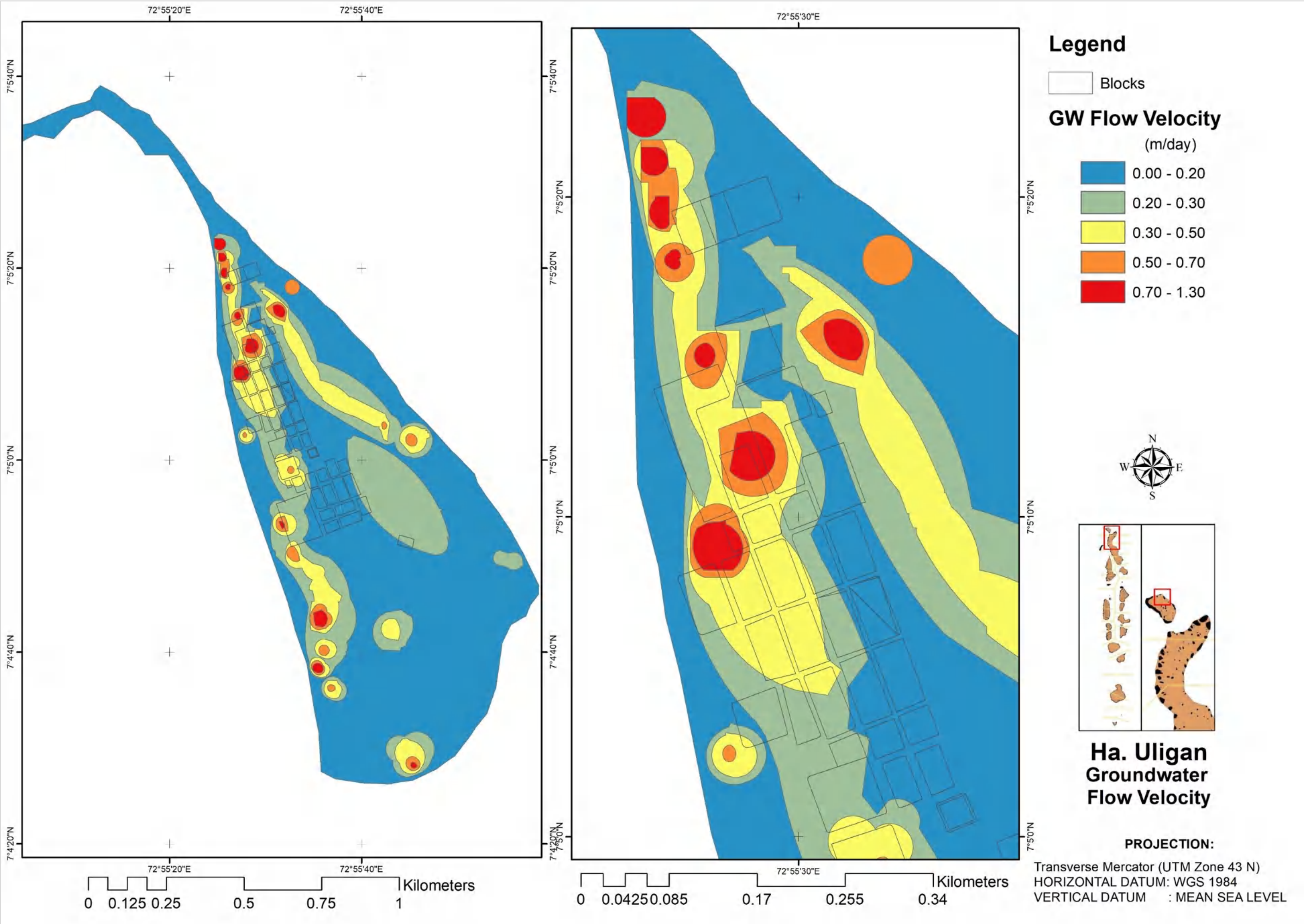
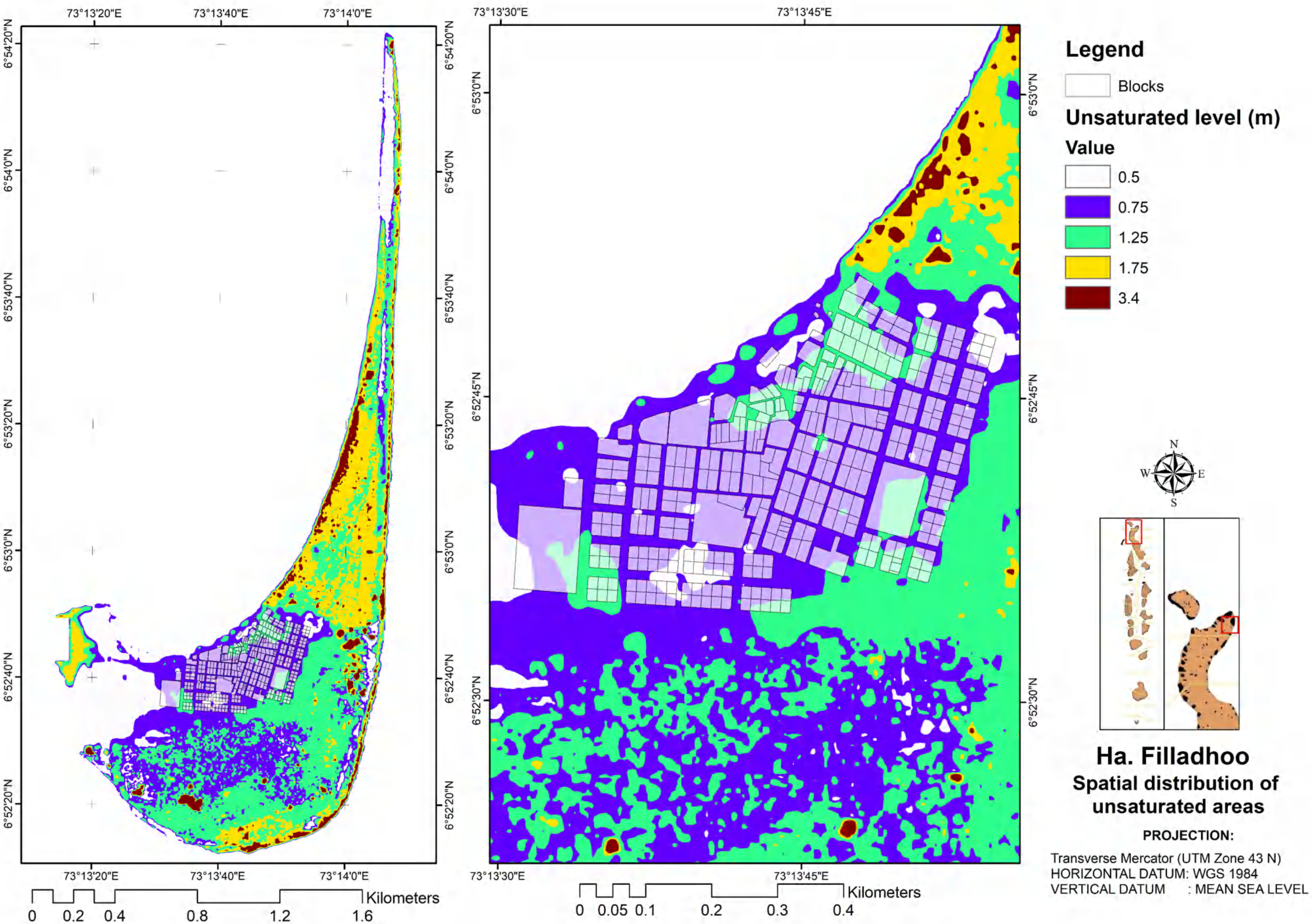
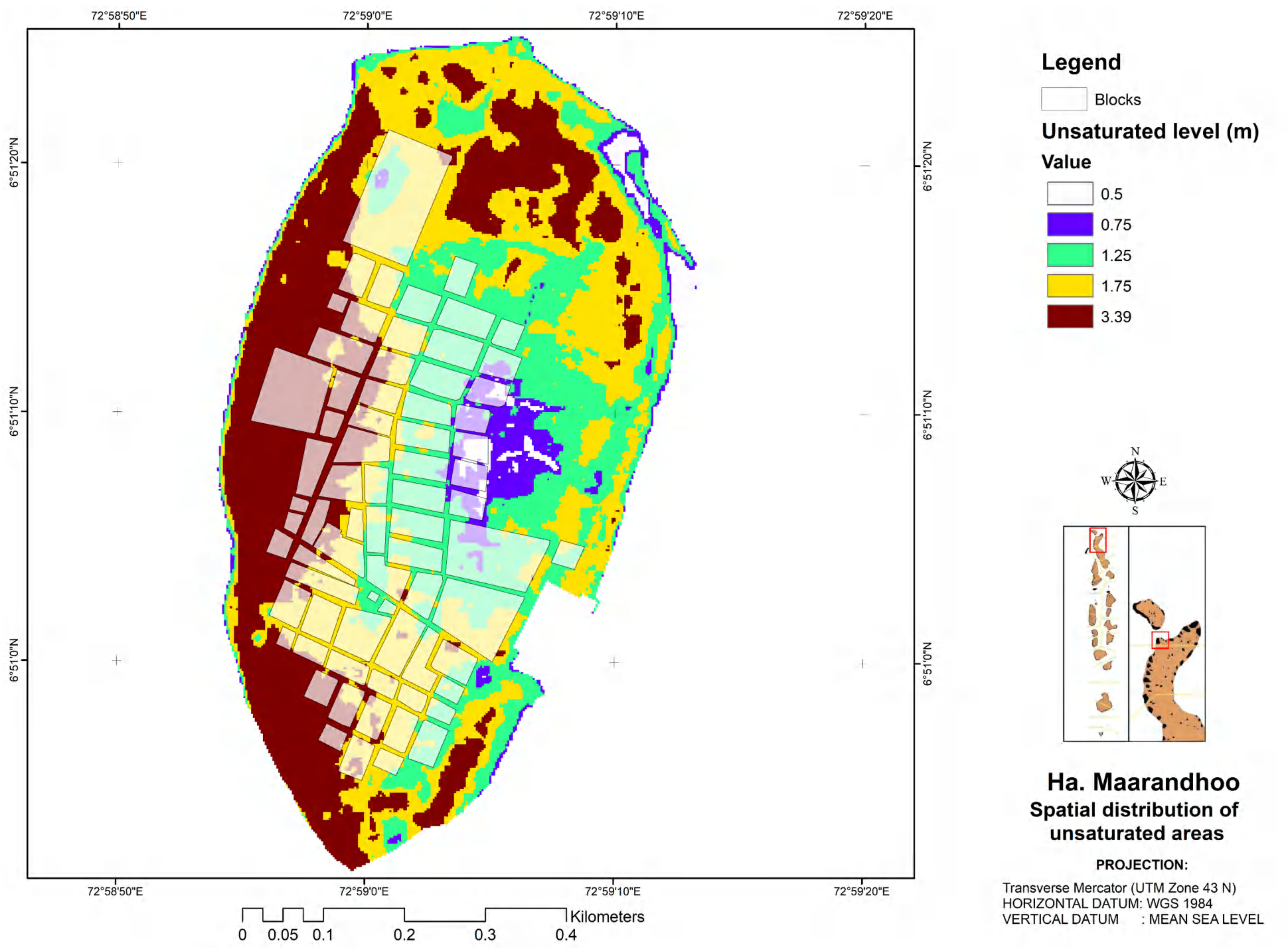
73°10'0"E
73°10'10"E
73°10'20"E
6°50'30"N
6°50'20"N
6°50'10"N
Legend
Blocks
GW Flow Velocity
(m/day)
0.00 - 0.30
0.30 - 0,50
0.50 - 0.70
0.70 - 0.90
0.90 - 1.37
N
W
E
S
0 0.05 0.1 0.2 0.3 0.4
Kilometers
Ha. Muraidhoo
Groundwater
Flow Velocity
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL


Legend
Blocks
GW Flow Velocity
(m/day)
0.00 - 0.20
0.20 - 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 1.30
Ha. Uligan
Groundwater
Flow Velocity
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
Kilometers
0 0.125 0.25 0.5 0.75 1
Kilometers
0 0.0425 0.085 0.17 0.255 0.34
72°55'20"E
72°55'40"E
72°55'30"E
7°5'40"N
7°5'20"N
7°5'0"N
7°4'40"N
7°4'20"N
7°5'10"N
N
S
E
W

Annex IX: Spatial Distribution of Unsaturated Areas of the Islands


Legend
Blocks
Unsaturated level (m)
Value
0.5
0.75
1.25
1.75
3.4
N
W
E
S
Ha. Filladhoo
Spatial distribution of unsaturated areas
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL
73°13'20"E
73°13'40"E
73°14'0"E
6°54'20"N
6°54'0"N
6°53'40"N
6°53'20"N
6°53'0"N
6°52'40"N
6°52'20"N
0 0.2 0.4 0.8 1.2 1.6 Kilometers
73°13'30"E
73°13'45"E
6°53'0"N
6°52'45"N
6°52'30"N
0 0.05 0.1 0.2 0.3 0.4 Kilometers

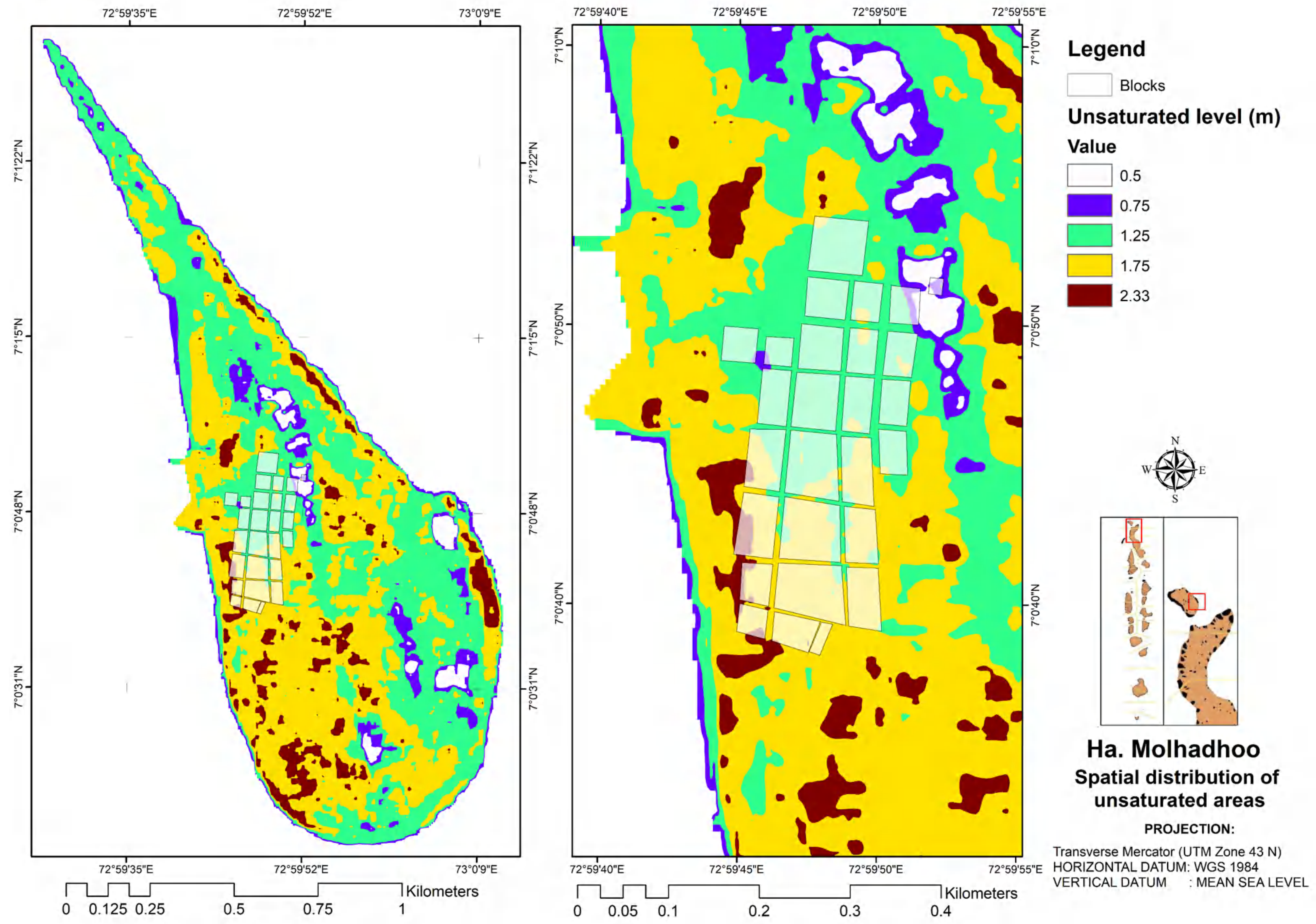


Ha. Maarandhoo

Spatial distribution of unsaturated areas

PROJECTION:

Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL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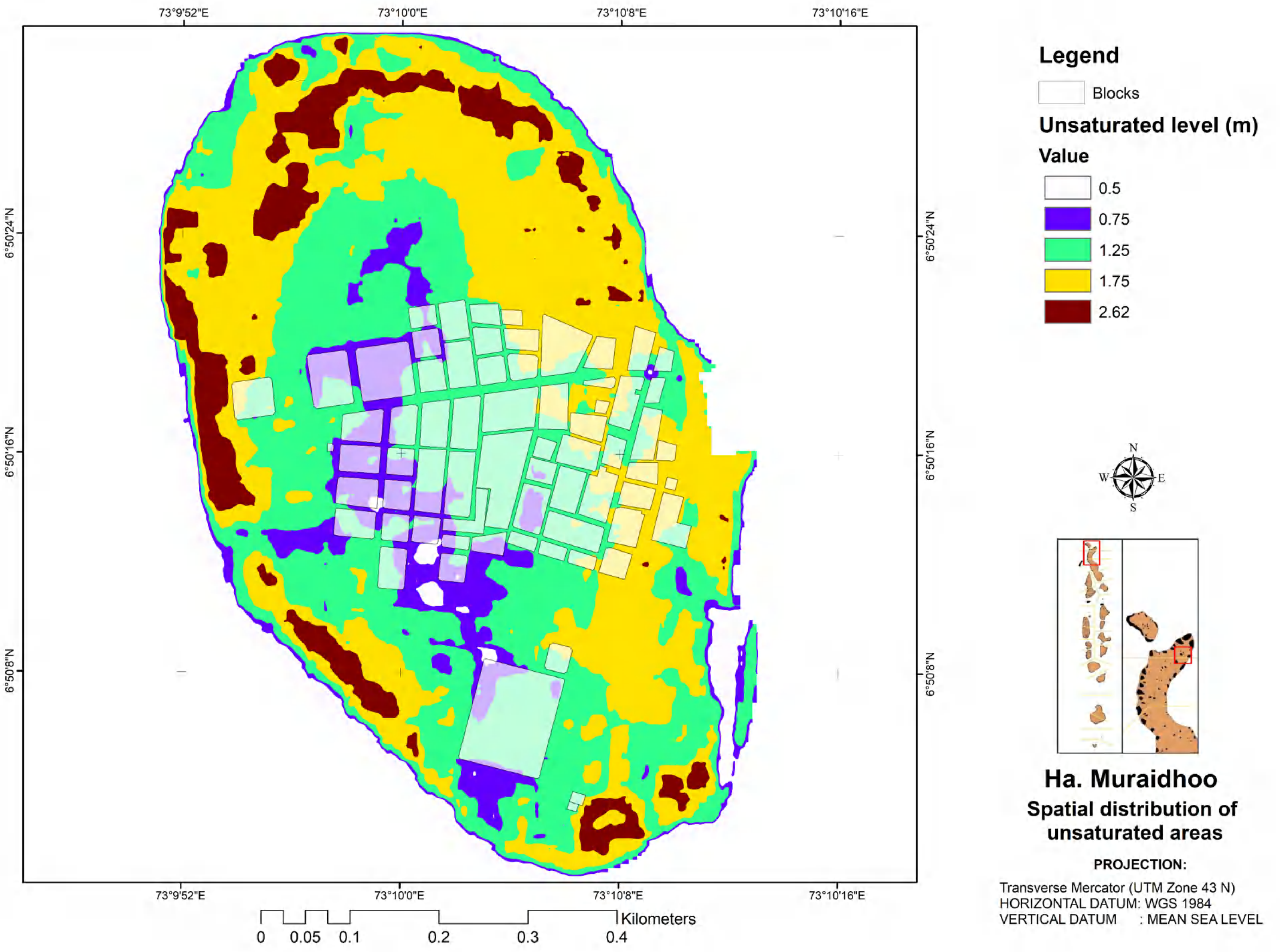
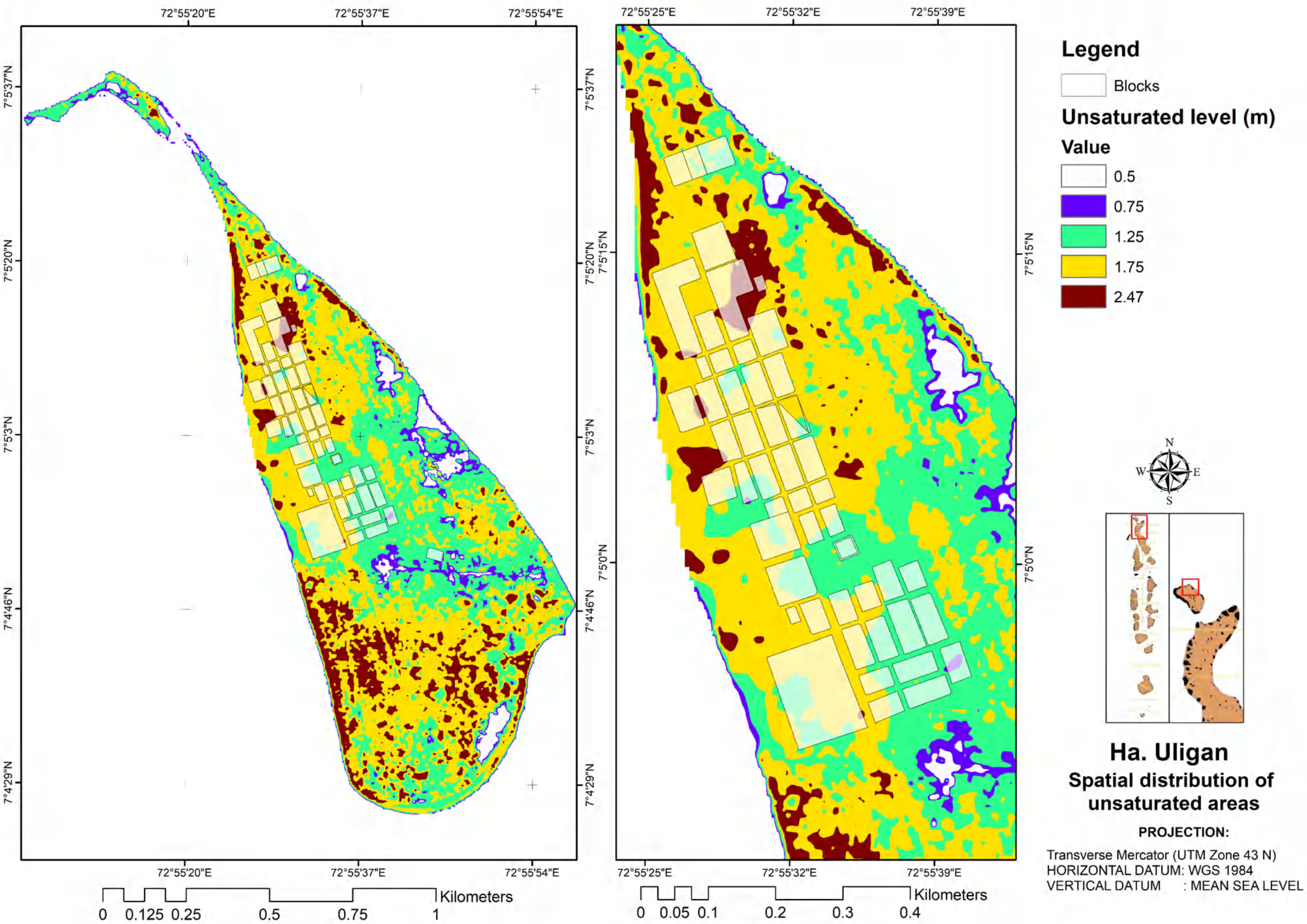
72°59'52"E
73°0'9"E
7°1'22"N
7°1'5"N
7°0'48"N
7°0'31"N
0 0.125 0.25 0.5 0.75 1 Kilometers
72°59'40"E
72°59'45"E
72°59'50"E
72°59'55"E
7°1'0"N
7°0'50"N
7°0'40"N
0 0.05 0.1 0.2 0.3 0.4 Kilometers
Legend
Blocks
Unsaturated level (m)
Value
0.5
0.75
1.25
1.75
2.33
N
W
E
S
Ha. Molhadhoo
Spatial distribution of unsaturated areas
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL


73°9'52"E
73°10'0"E
73°10'8"E
73°10'16"E
6°50'24"N
6°50'16"N
6°50'8"N
0
0.05
0.1
0.2
0.3
0.4
Kilometers
Legend
Blocks
Unsaturated level (m)
Value
0.5
0.75
1.25
1.75
2.62
N
W
E
S
Ha. Muraidhoo
Spatial distribution of unsaturated areas
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL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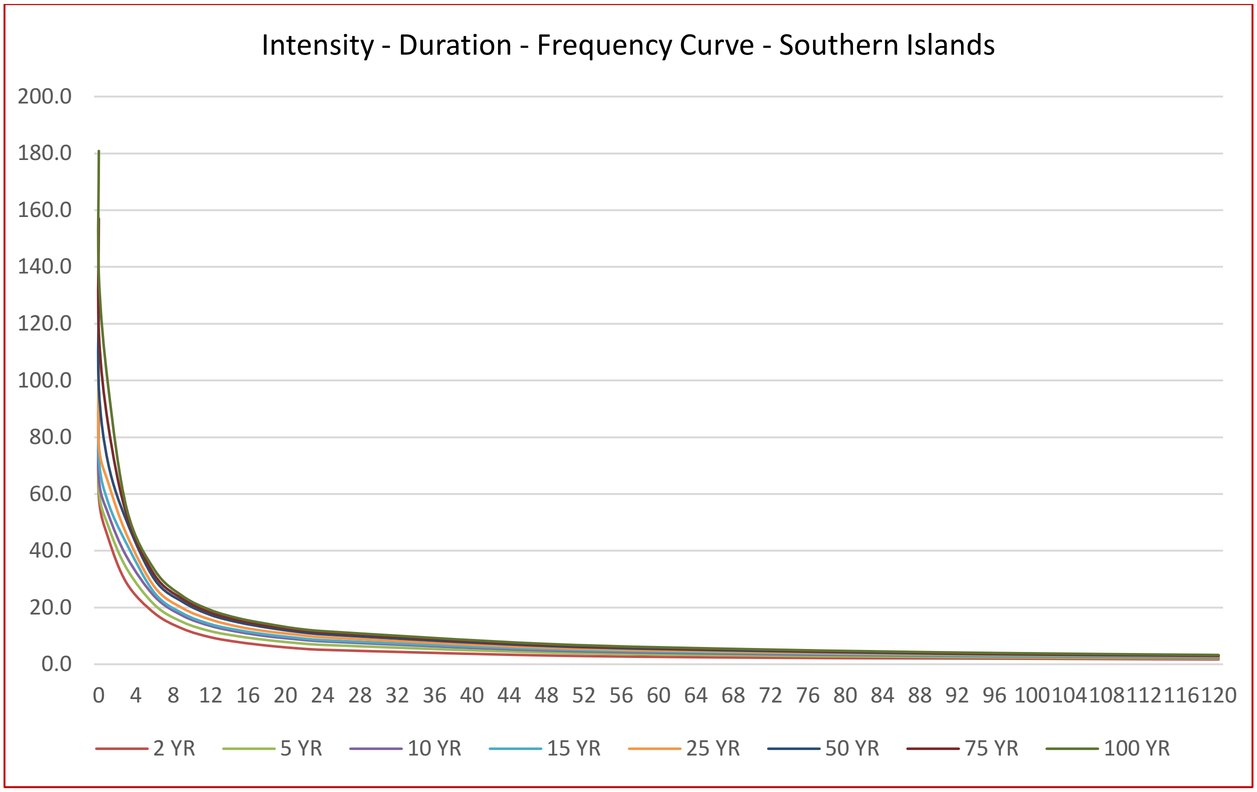
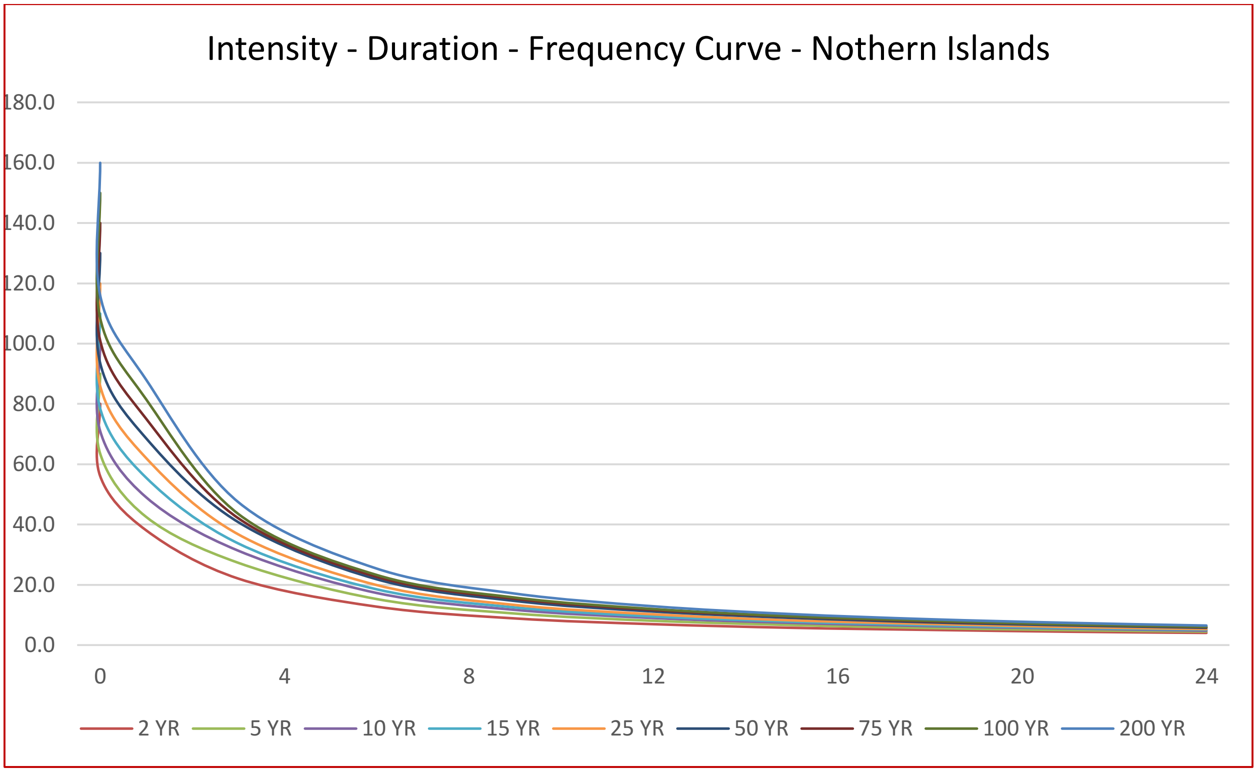
72°55'37"E
72°55'54"E
7°5'37"N
7°5'20"N
7°5'3"N
7°4'46"N
7°4'29"N
72°55'25"E
72°55'32"E
72°55'39"E
7°5'15"N
7°5'0"N
0 0.125 0.25 0.5 0.75 1 Kilometers
0 0.05 0.1 0.2 0.3 0.4 Kilometers
Legend
Blocks
Unsaturated level (m)
Value
0.5
0.75
1.25
1.75
2.47
N
W
E
S
Ha. Uligan
Spatial distribution of unsaturated areas
PROJECTION:
Transverse Mercator (UTM Zone 43 N)
HORIZONTAL DATUM: WGS 1984
VERTICAL DATUM : MEAN SEA LEVEL

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

Developed IDF Curves for Northern and Sourthern Islands





Intensity - Duration - Frequency Table (Southern Islands)

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

Intensity - Duration - Frequency Table (Northern Islands)

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

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

Example: Ha. Maarandhoo Island

Land Use: Three land use types are observed in the island and details of the calculation are given below.

Land use	Area(m^2)	CN value for land use	CN value for soil types	Used CN value for SCS method (results from overlay)
Bare/Vacant land	111,745	69	79	74
Forest/coconut	232,516	55	79	67
Residential/ Built	113,635	79	79	79

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

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

SCS equation.

Pe(inch) = $(P-0.2S)^2/(P+0.8S)$.
Fa = P-Pe-Ia.

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

For dry condition: CN (dry) =4.2 CN(normal)/(10-0.58 CN(normal))
For wet condition: CN(wet) = 23 CN(normal)/(10 + 0.13 CN(normal))

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

Duration (Hours)	Excess rainfall for run off(inch)								
	General Condition			Wet Condition			Dry Condition		
	1	2	3	1	2	3	1	2	3
For two years return Period									
0.5	0.51	0.29	0.72	1.17	0.87	1.38	0.04	-	0.15
1	0.24	0.10	0.39	0.72	0.49	0.89	-	-	0.03
3	0.04	0.00	0.11	0.29	0.16	0.40	-	-	-
6	-	-	0.01	0.09	0.03	0.15	-	-	-
9	-	-	-	0.02	0.00	0.05	-	-	-
15	-	-	-	-	-	0.01	-	-	-
24	-	-	-	-	-	-	-	-	-
For five years return Period									
0.5	0.56	0.32	0.78	1.24	0.94	1.46	0.06	-	0.17
1	0.31	0.15	0.48	0.85	0.60	1.03	0.01	-	0.06
3	0.09	0.02	0.18	0.42	0.26	0.55	-	-	-
6	-	-	0.03	0.14	0.06	0.21	-	-	-
9	-	-	-	0.05	0.01	0.09	-	-	-
15	-	-	-	0.01	-	0.02	-	-	-
24	-	-	-	-	-	-	-	-	-

Duration (Hours)	Excess rainfall for run off(inch)								
	General Condition			Wet Condition			Dry Condition		
	1	2	3	1	2	3	1	2	3
For ten years return Period									
0.5	0.65	0.39	0.89	1.38	1.05	1.60	0.08	-	0.22
1	0.39	0.20	0.57	0.98	0.71	1.17	0.02	-	0.09
3	0.14	0.05	0.25	0.53	0.34	0.68	-	-	-
6	0.01	-	0.05	0.19	0.09	0.28	-	-	-
9	-	-	-	0.08	0.02	0.13	-	-	-
15	-	-	-	0.01	-	0.04	-	-	-
24	-	-	-	-	-	-	-	-	-
1) Bare land (CN number-74)									
2) Forest / coconut Land (CN number-67)									
3)Residential area (CN number-79)									

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

Duration (Hours)	Estimated continuous abstraction(inch)								
	General Condition			Wet Condition			Dry Condition		
	1	2	3	1	2	3	1	2	3
For two years return Period									
0.5	1.11	1.05	1.07	0.86	1.01	0.73	0.58	-	0.90
1	0.81	0.67	0.84	0.74	0.82	0.64	0.05	-	0.45
3	0.38	0.13	0.48	0.53	0.52	0.50	-	-	-
6	-	-	0.16	0.32	0.24	0.34	-	-	-
9	-	-	-	0.17	0.05	0.22	-	-	-
15	-	-	-	0.01	-	0.08	-	-	-
24	-	-	-	-	-	-	-	-	-

Duration (Hours)	Estimated continuous abstraction(inch)								
	General Condition			Wet Condition			Dry Condition		
	1	2	3	1	2	3	1	2	3
For five years return Period									
0.5	1.15	1.11	1.10	0.88	1.04	0.74	0.66	-	0.97
1	0.91	0.79	0.91	0.78	0.89	0.67	0.21	-	0.59
3	0.53	0.32	0.61	0.61	0.63	0.55	-	-	-
6	0.12	-	0.26	0.39	0.33	0.39	-	-	-
9	-	-	-	0.24	0.14	0.27	-	-	-
15	-	-	-	0.09	-	0.15	-	-	-
24	-	-	-	-	-	-	-	-	-
For ten years return Period									
0.5	1.22	1.20	1.16	0.90	1.08	0.75	0.79	-	1.08
1	0.99	0.90	0.98	0.81	0.94	0.70	0.37	-	0.72
3	0.64	0.46	0.70	0.66	0.71	0.59	-	-	-
6	0.22	-	0.35	0.45	0.41	0.44	-	-	-
9	-	-	-	0.30	0.21	0.32	-	-	-
15	-	-	-	0.14	-	0.19	-	-	-
24	-	-	-	-	-	-	-	-	-

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

Duration (Hours)	General condition		Wet condition		Dry condition	
	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)
Land Use: Bare land						
For two year return period						
0.5	1,454	3,150	3,309	2,441	120	1,643
1	691	2,302	2,045	2,095		152
3	127	1,065	831	1,508		
6			247	907		
9			63	487		
15				24		
24						
For five year return period						
0.5	1,599	3,273	3,530	2,488	157	1,873
1	893	2,570	2,400	2,209	124	2121
3	268	1,506	1,191	1,730		
6		343	387	1,102		
9			132	686		
15			15	244		
24						

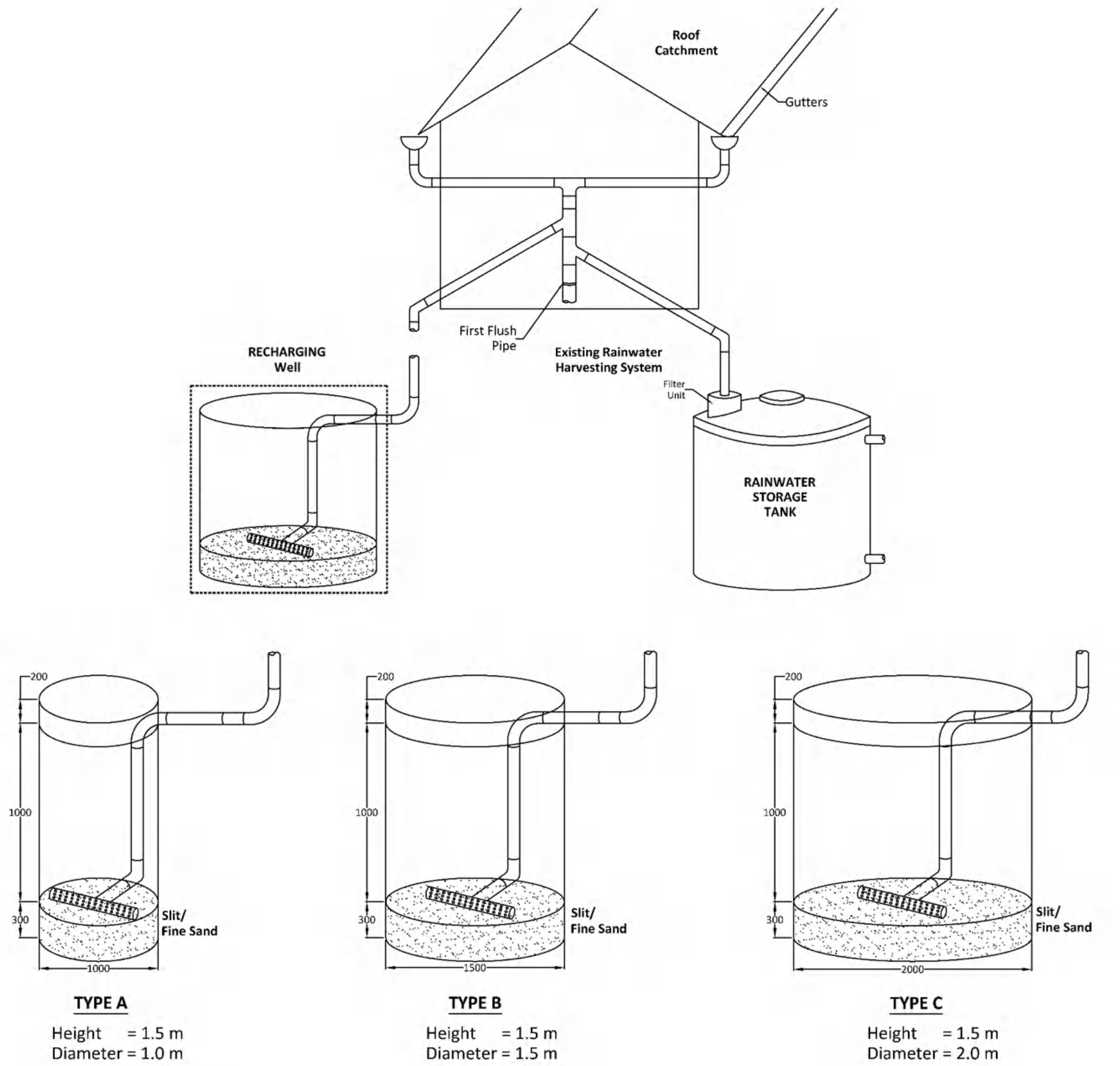
Duration (Hours)	General condition		Wet condition		Dry condition	
	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)
For ten year return period						
0.5	1,850	3,469	3,904	2,561	230	2,248
1	1,112	2,820	2,768	2,311	47	1,044
3	408	1,824	1,498	1,881		
6	42	625	543	1,270		
9			213	851		
15			39	388		
24						
Land Use: Forest/Coconut land						
For two year return period						
0.5	813	2,989	2,473	2,879		
1	297	1,895	1,404	2,338		
3	11	381	461	1,480		
6			82	674		
9			4	148		
15						
24						
For five year return period						
0.5	918	3,153	2,665	2,955		

Duration (Hours)	General condition		Wet condition		Dry condition	
	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)
1	426	2,236	1,698	2,513		
3	63	909	727	1,796		
6			163	929		
9			27	394		
15						
24						
For ten year return period						
0.5	1,103	3,414	2,994	3,074		
1	573	2,558	2,008	2,673		
3	133	1,298	965	2,016		
6			262	1,153		
9			64	602		
15						
24						
Land Use: Residential area_						
For two year return period						
0.5	2,050	3,039	3,904	2,063	417	2,551
1	1,098	2,381	2,527	1,829	95	1,264
3	305	1,373	1,145	1,412		

Duration (Hours)	General condition		Wet condition		Dry condition	
	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)
6	30	463	415	956		
9			150	617		
15			17	224		
24						
For five year return period						
.7	2,225	3,133	4,141	2,094	490	2,747
1	1,356	2,592	2,919	1,907	167	1,661
3	521	1,739	1,565	1,573		
6	82	746	599	1,107		
9			256	780		
15			63	414		
24						
For ten year return period						
0.5	2,524	3,281	4,540	2,143	622	3,063
1	1,632	2,786	3,320	1,977	258	2,039
3	720	1,998	1,916	1,680		
6	153	1,000	795	1,235		
9	0	0	370	911		
15	0	0	109	535		
24	0	0	0	0		

Duration (Hours)	General condition		Wet condition		Dry condition	
	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)	Run off(m^3/d)	Estimated soil abstraction(m^3/d)
For island						
For two year return period						
0.5	4,317	9,178	9,686	7,383	537	4,194
1	2,086	6,578	5,976	6,262	95	1,416
3	443	2,819	2,437	4,399		
6	30	463	744	2,536		
9			217	1,252		
15			17	248		
24						
For five year return period						
0.5	4,741	9,558	10,337	7,537	647	4,620
1	2,674	7,398	7,018	6,629	291	3,782
3	852	4,155	3,483	5,098		
6	82	1,089	1,149	3,138		
9			415	1,859		
15			77	658		
24						
For ten year return period-						
0.5	5,478	10,164	11,438	7,778	852	5,310
1	3,317	8,165	8,095	6,961	305	3,084
3	1,261	5,121	4,379	5,577		
6	195	1,625	1,601	3,659		
9			648	2,364		
15			148	923		
24						

Annex XI: Conceptual Designs for Recharging Well



Map Title : Conceptual Design For Roof Recharging Wells

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

Deliverable : Feasibility Concept Design Report

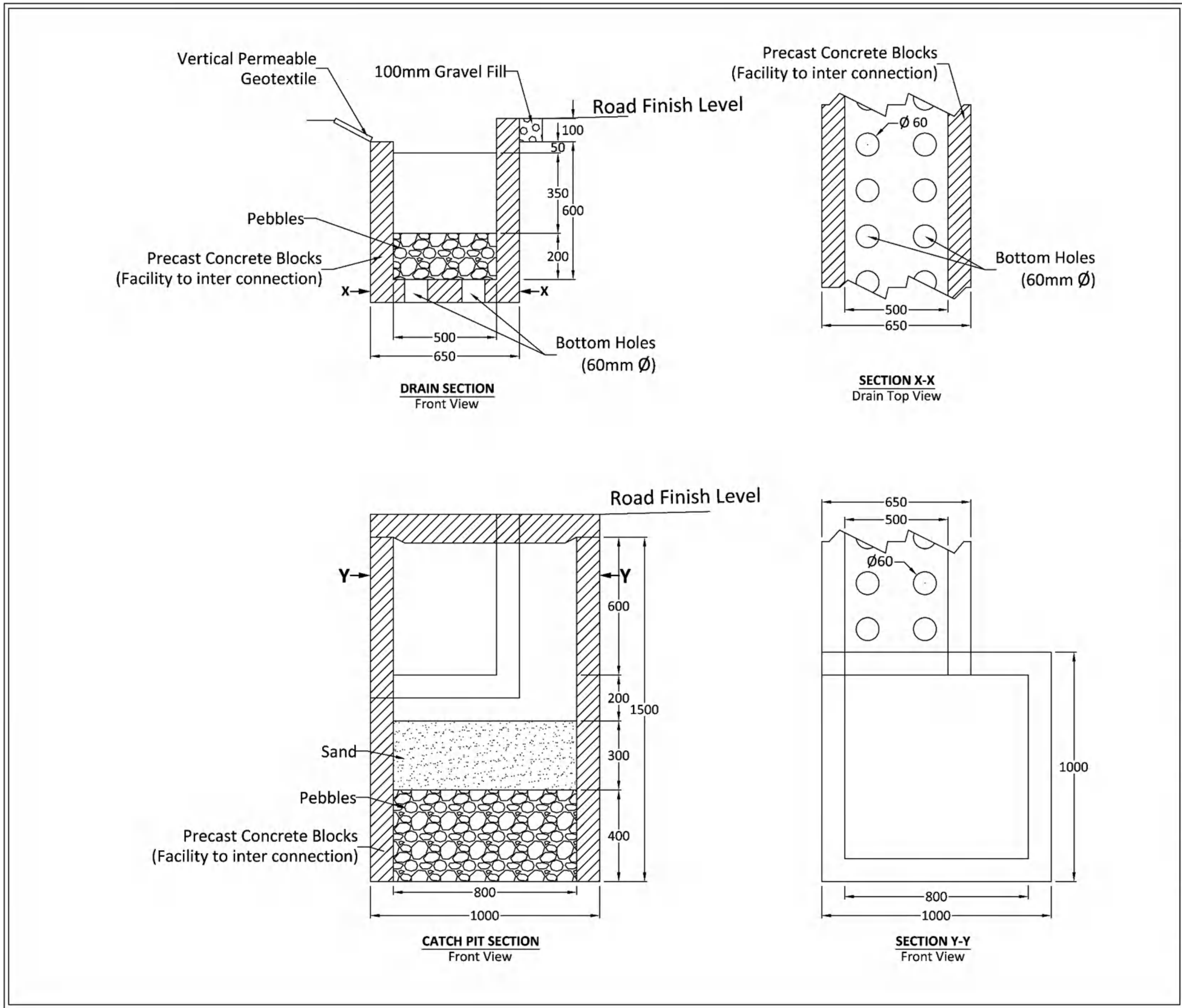
Project : Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives (Lot 1)

Client : Ministry of Environment, Climate Change and Technology

Consultant :

Purpose : Consultation

Annex XII: Conceptual Designs for Road Runoff Recharge



Map Title : Conceptual Design For Road Runoff Recharging System

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

Deliverable : Feasibility Concept Design Report

Project : Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives (Lot 1)

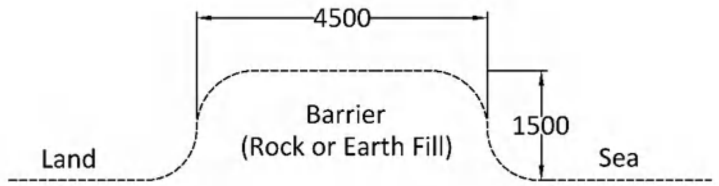
Client : Ministry of Environment, Climate Change and Technology

Consultant :

Purpose : Consultation

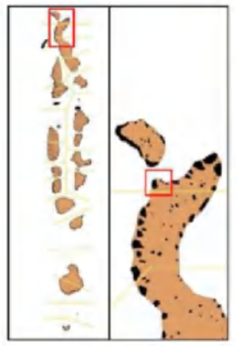
Annex XIII: Conceptual Designs for Aquifer Modifications

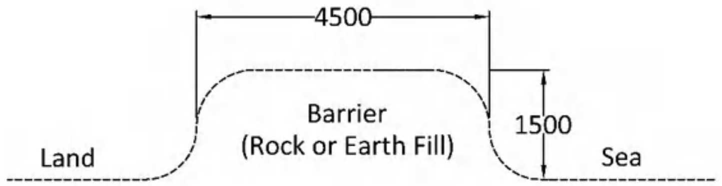
Proposed Managed Aquifer Recharge (MAR) Systems for Ha. Filladhoo



SECTION X-X
Aquifer Modification for Ha. Filladhoo

Proposed Managed Aquifer Recharge (MAR) Systems for Ha. Maarandhoo





SECTION Y-Y
Aquifer Modification for Ha. Maarandhoo

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

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

Deliverable :
Feasibility Concept Design Report

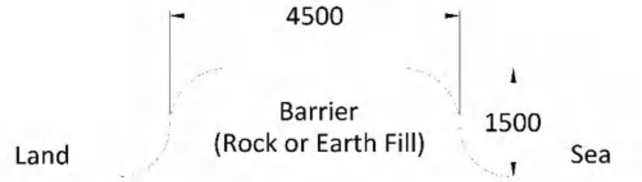
Project : Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives (Lot 1)

Client : Ministry of Environment, Climate Change and Technology

Consultant :

Purpose : Consultation

Proposed Managed Aquifer Recharge (MAR) Systems for Ha. Muraidhoo



SECTION A-A

Aquifer Modification for Ha. Muraidhoo

Map Title :

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

Geodetic Parameters :

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

Deliverable :

Feasibility Concept Design Report

Project : Assessing Groundwater Resources and Design of Aquifer Recharge Systems in Selected 17 Islands of Maldives (Lot 1)

Client : Ministry of Environment, Climate Change and Technology

Consultant :

Purpose : Consultation