Environmental Impact Assessment

Document Stage: Updated
Project Number: 51077-003
July 2020

MLD: Greater Malé Waste-to-Energy Project – Waste to Energy Plant PART C

Prepared by Ministry of Environment of the Republic of Maldives for the Asian Development Bank.

Annex 4

ތިމާވެށްޓަށް އަސަރުކުރާ މިންވަރު ބެލުމުގެ ރިޕޯޓު ގަބޫލުކުރުން

APPROVAL OF ENVIRONMENTAL IMPACT ASSESSMENT

Number: 203-EIARES/438/2017/180 :ނަންބަރު

ތިމާވެށީގެ ގޮތުން ނިންމިގޮތުގެ ބަޔާން ދޫކުރަނީ ކ. ތިލަފުށި ޒޯން 3ގައި ވޭސްޓް މެނޭޖްމަންޓް ފެސިލިޓީއެއް ގާއިމް ކުރުމަށް 15 ހެކްޓަރުގެ ބިމެއް ހިއްކުމުގެ މަޝްރޫއުގެ މަސައްކަތްކުރުމަށްޓަކައި މިނިސްޓްރީ އޮފް އެންވަޔަރަންމަންޓް އެންޑް އެނަރޖީގެ ފަރާތުން 20 ނޮވެމްބަރ 2017 ގައި މުރާޖަޢާކުރުމަށް ހުށަހަޅުއްވާފައިވާ އަދި 12 ޑިސެމްބަރ 2017 ގައި އިތުރު މަޢުލޫމާތު ހުށަހަޅުއްވާފައިވާ ތިމާވެށްޓަށް އަސަރުކުރާ މިންވަރު ބެލުމުގެ ރިޕޯޓާއި ބެހޭ ގޮތުން ނިންމިގޮތް އަންގައިދިނުމަށެވެ. މި މަޝްރޫއުގެ އީ.އައި.އޭ ކޮންސަލްޓަންޓުންނަކީ އަޙްމަދު ޖަމީލް (EIA P07/2017) އަދި އިބްރާހީމް ފާއިޒު (EIA P05/2017) އެވެ.

This Environmental Decision Statement is issued for the purpose of communicating the decision regarding the Environmental Impact Assessment for ***Reclamation of 15 hectares of Land for Development of Regional Waste Management Facility at Thilafushi (Zone III), Kaafu Atoll,*** *which was submitted for evaluation on* ***20th November 2017 by Ministry of Environment and Energy.*** *The EIA consultants of this project are* ***Mr. Ahmed Jameel (EIAP07/2017) and Mr. Ibrahim Faiz (EIA P05/2017).***

1. This Environmental Decision Statement has been issued on behalf of the Environmental Protection Agency (hereinafter referred to as the Ministry) pursuant to the Environmental Impact Assessment Regulations 2012 (2012/R-27) to advise that the Ministry has decided that the proposed Development Proposal can proceed according to the Environmental Impact Assessment Report.

1. ތިމާވެށްޓަށް އަސަރުކުރާ މިންވަރު ބެލުމުގެ ގަވާއިދު 2012 ގެ ދަށުން (މި ލިޔުމުގައި މީގެ ފަހުން މިނިސްޓްރީ ކަމަށް ބަޔާންކުރެވިފައިވާ) އެންވަޔަރަންމަންޓަލް ޕްރޮޓެކްޝަން އެޖެންސީގެ ފަރާތުން މި ތިމާވެށީގެ ގޮތުން ނިންމިގޮތުގެ ބަޔާން ދޫކުރަނީ މަތީގައި ބަޔާންކޮށްފައިވާ ތަރައްޤީގެ މަޝްރޫއު ތިމާވެށްޓަށް އަސަރުކުރާ މިންވަރު ބެލުމުގެ ރިޕޯޓުގައި ބަޔާންކޮށްފައިވާ ގޮތަށް ކުރިއަށް ގެންދިއުމުގެ ހުއްދަ ދިނުމަށެވެ.

321

2. The decision has been made by the Ministry on the following conditions:

    i. In the event the project activity has not commenced within one (1) year from the date of issue, or if the duration of this Environmental Decision Statement has not been extended, this Environmental Decision Statement shall be considered null and void. In order to extend the duration of this Environmental Decision Statement, the Proponent shall write to the Minister for an extension according to Clause 14 of the 2nd Amendment to the Environmental Impact Assessment Regulations 2012.

    ii. In the event the project activities has been delayed for more than one (1) year due to unforeseen circumstances, the Ministry shall have the discretion to extend the duration of the Environmental Decision Statement, or to terminate it. In such circumstances the proponent shall write to the Minister for an extension clearly stating out the reasons for the

321

delay.

iii. The Minister, or his designate, may issue a cessation order requiring persons working on a Development Proposal to cease working until the order is withdrawn, if:

a) This Environmental Decision Statement has been withdrawn or;

b) There has been a breach of the conditions of this Environmental Decision Statement.

iii. ތިރީގައި ދެބައިން ކުރިފަދަ ކަމެއް ދިމާވެއްޖެނަމަ، މިނިސްޓަރު ނުވަތަ އޭނާ އައްޔަން ކުރާފަރާތަކުން، ހިނގުމުން ތަރައްޤީގެ މަޝްރޫޢު ކުރިއަށް ގެންދާ ބަޔަކަށް އެމަސައްކަތް އަމުރު ބާޠިލްކުރަންދެން ހުއްޓުވުން އެންގިދާނެއެވެ.

ހ) މި ތިމާވެށީގޮތުން ނިންމިގޮތުގެ ލިޔުން ބާޠިލުކުރުން ނުވަތަ

ށ) މި ތިމާވެށީގެ ގޮތުން ނިންމިގޮތުގެ ލިޔުމުގެ ޝަރުތުތަކާ ޚިލާފުވުން

iv. It is the Developer's responsibility to undertake all project activities in accordance with the relevant laws and regulations of the Maldives.

iv. މަޝްރޫޢު ހިންގުމާއި ގުޅުންހުރި ހުރިހާ ދިވެހިރާއްޖޭގައި ހިނގަމުންދާ ޤާނޫނުތަކާއި ގަވާއިދުތަކާއި އެއްގޮތަށް މަސައްކަތް ކުރުމަކީ ޑިވެލޮޕަރުގެ ޒިންމާއެކެވެ.

v. The Developer shall submit environmental monitoring report as outlined in Paragraph viii of this Environmental Decision Statement. Failure to submit the requisite monitoring report may result in the suspension or revocation of the permit under this Decision Statement.

v. މި ތިމާވެށީގޮތުން ނިންމިގޮތުގެ ލިޔުމުގެ VIII ވަނަ ޕެރެގްރާފްގައިވާ ގޮތަށް ތިމާވެށީގެ މޮނިޓަރިންގް ރިޕޯޓް ޑިވެލޮޕަރު ހުށަހަޅަން ވާނެއެވެ.

vi. The Developer is aware that under the National Environment Protection Act (Law no. 4/93) and

vi. ޑިވެލޮޕަރާއި ތިމާވެށި ރައްކާތެރިކުރުމާއި ދެމެހެއްޓުމުގެ ޤާނޫނު (ޤާނޫނު ނަންބަރު 4/93) އާއި ތިމާވެށި އަސަރު ވާނެ ...

the Environmental Impact Assessment Regulations the Ministry reserves the right to terminate any activity without compensation if found that such an activity has caused significant, irreversible impacts on the environment.

vii. All mitigation measures proposed in the EIA report for all the phases of the project shall be fully implemented.

viii. The environmental monitoring program outlined in the Environmental Impact Assessment Report shall be undertaken and implemented and summary environmental monitoring reports shall be submitted to the Ministry.

ix. The date of expiry stated in this Environmental Decision Statement is the duration given to commence the project activities approved under this Environmental Decision Statement.

321

x. Once the project activities have started, the Proponent must inform the Environmental Protection Agency, the date of commencement of project activities.

x. މަޝްރޫޢުގެ މަސައްކަތް ފެއްޓެވުމަށްފަހު، ފެށި ތާރީޚު އެންވަޔަރަމަންޓަލް ޕްރޮޓެކްޝަން އޭޖެންސީއަށް ލިޔުމުން އަންގަންވާނެއެވެ.

Date of Issue: 17th December 2017	ދޫކުރި ތާރީޚު : 17 ޑިސެމްބަރ 2017
Date of expiry: 17th December 2018	މުއްދަތު ހަމަވާ ތާރީޚު: 17 ޑިސެމްބަރ 2018
Name: Yazeed Ahmed	ނަން: ޔަޒީދު އަޙްމަދު
Designation: Director, Environment Assessment	މަޤާމު: ޑިރެކްޓަރ، އެންވަޔަރަމަންޓް އެސެސްމަންޓް
Signature:	ސޮއި:

Annex 5

Google Earth Photo Over Thilafushi Island

ADB

Technical Assistance Consultant's Final Report

Project Number: 51077-001
February 2019

Maldives: Greater Male Environmental Improvement and Waste Management Project - Market Study on the Reuse of Incinerator Bottom Ash and Construction and Demolition Waste in the Maldives

Asian Development Bank

CONTENTS

TABLES

FIGURES

ABBREVIATIONS

ADB	Asian Development Bank
CDW	Construction Demolition Waste
CIF	Cost, Insurance and Freight
IBA	Incinerator Bottom Ash
IBA (r-IBA)	Recycled Incinerator Bottom Ash
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incinerator
SWM	Solid Waste Management
tpd	Tons per day
WTE	Waste-to-Energy
TA	Technical Assistance
RCA	Recycled Concrete Aggregates
RC	Recycled Aggregates
STO	State Trading Organization

1. Project

1.1. Project Description

Greater Male' is centrally located in Maldives and is the capital city of the nation. The Male' island and its 32 inhabited islands are categorized as Zone 3 in the National Solid Waste Management Policy. Greater Male' Region lack a proper waste management system. For the last 30 years, waste has been collected, transferred by sea, dumped and burnt at an open dump site at Thilafushi, an island 6km away from Male'. The current practice of waste management poses an environmental and public safety issue. Some waste, often in plastic bags, are lost to the sea during transportation and toxic leachate from the Thilafushi dump site contaminate the ground water. The smoke from burning of waste causes air pollution. The current practice of waste management is not sustainable.

The Greater Male' region (Zone 3) produces 774 tons per day (tpd) of mixed solid waste. The breakdown of waste is given in Table 1 and Table 2 shows the composition of Municipal Solid Waste (MSW). Due to the rapid urbanization and tourism development in Zone 3, it is expected the waste generation would increase to 924 tpd by 2022.

Table 1. Breakdown of Waste by Type

Type	**Amount** (tons per day)	
Construction Demolition Waste	530	68%
Household	149	19%
Resort	48	6%
Commercial	27	3%
Airport	9.3	1.2%
Industrial	6	0.8%
Market	2.5	0.3%
Hazardous	1.5	0.2%
End-of-life vehicles	0.65	0.1%

Table 2. Composition of Municipal Solid Waste

Type of Municipal Solid Waste	
Organic	53%
Paper and cardboard	12%
Plastic	11%
Hazardous (medical)	8%
Metal	3%
Glass	3%
Others	11%

As an alternative to the current unsustainable practice of burning mixed solid waste, Greater Male' Environmental Improvement and Waste Management Project (Project), supported by the Asian Development Bank (ADB), is going to strengthen the solid waste management (SWM) in Zone 3. The Project will establish an integrated SWM system including collection, transfer, treatment using advanced waste-to-energy (WTE) technology, disposal, recycling, dumpsite closure and remediation, public awareness in reduce-reuse-recycle (3R), and strengthening institutional capacities for service delivery and environmental monitoring. The Government will implement the Project in two phases;

> **Phase 1** includes Construction Demolition Waste (CDW) processing facility (200 tpd capacity).
>
> **Phase 2** will consist of a WTE incineration of 500 tpd of Municipal Solid Waste (MSW) and the flammable fraction of the CDW

The incineration process reduces the waste to energy, Incinerator Bottom Ash (IBA) and fly ash. The fly ash will be disposed in a landfill. The IBA can also be disposed in a landfill. However, it is expected 100 to 125 tpd of IBA would be generated and land scarcity in Zone 3 limits the disposal of IBA in landfills. Alternatively, IBA could be treated further to produce recycled IBA (r-IBA) and reused as a building material.

CDW is mixed waste generated from construction and demolition activities. Soil and sand is not considered as CDW in this report as it is usually reused as backfill material. Disposal of CDW in landfills is also challenging due to land scarcity. CDW can be processed as recycled aggregates that could be used in various applications in the construction industry.

1.2. Objective of Technical Assistance

The objective of this assignment is to assess the potential market for IBA and CDW reuse in the Maldives.

1.3. Scope of Technical Assistance

The scope of this Technical Assistance (TA) is to conduct a market assessment for potential IBA and CDW reuse in the Maldives. Current use of aggregates with the aim of identifying potential applications, required national standards, costs, and current and projected demand for recycled IBA and CDW in the Maldives is analyzed. Detailed tasks of this assignment include:

(i) Identify suitable applications for treated IBA and CDW reuse in the Maldives through literature review and surveys.

(ii) Review applicable national standards for the reuse of treated IBA and CDW for the potential applications as identified in (i) and summarize the required material characteristics (e.g. chemical, physical).

(iii) Conduct interviews/surveys with key stakeholders to understand their views on potential reuse, product requirements, and willingness to pay for treated IBA and CDW.

(iv) Collect information on cost and demand of similar construction materials (to IBA and CDW) currently used in the Maldives.

(v) Conduct a market demand analysis for reusing treated IBA and CDW in the Maldives including projections for next 5, 10 and 15 years

(vi) Recommend possible ways/alternatives for maximize IBA and CDW demand/reuse and sustainable business models for the Greater Male context.

(vii) Prepare comprehensive report on the activities (i) to (vi) with key recommendations for IBA treatment and CDW plant design and operation

2. Suitable Applications for Incinerator Bottom Ash

Incineration of MSW releases the energy during combustion. The waste reduces in weight by about 70%. IBA accounts for about 80% of the incombustible residue left [1]. The remaining of the residue is fly ash. Incombustible metals, glasses, ceramics, slag and sand mixture form as IBA and is rich in heavy metals, chlorides, oxides and organic pollutants. IBA require removal of ferrous and non-ferrous metals and further treatment to enhance its reusability. The type of treatment process adopted affects the leaching property and consequently the reusability of r-IBA. Common oxides and heavy metals found in IBA are given in Table 3. The composition of the oxides and heavy metals depend on the characteristics of the MSW but SiO_2 is generally the most abundant oxide in IBA[2].

IBA is similar in its size and appearance to aggregates and hence can be used as a substitute to aggregates in applications aggregates are required. The main factors affecting the reuse of IBA is the suitability of IBA for treatment and processing, the

[1] Lynn, C., Dhir, R., & Ghataora, G. (2016). Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete. *Construction and Building Materials*, 504-517.

[2] Lam, C. H., Ip, A. W., Barford, J. P., & McKay, G. (2010). Use of Incineration MSW Ash: A Review. *Sustainability*, 1943-1968.

attainability of required properties for a given application, and the environmental impact from the reuse of IBA [3].

Reuse of IBA has been studied for the past 40 years. Lynn, Dhir, & Ghataora (2016) studied 76 publications published since 1979 over 18 countries[4] (Figure 1). Reuse of IBA is most prevalent in Europe. In Asia, reuse of IBA is prevalent in Taipei,China, Singapore and Japan where land is scarce.

Table 3. Oxides and heavy metals in incinerator bottom ash[2]

Oxides		Heavy Metals	
SiO_2	K_2O	Ag	Mn
Al_2O_3	Na_2O	As	Ni
CaO	SO_3	Ba	Pb
Fe_2O_3	P_2O_5	Cd	Se
MgO	TiO_2	Co	Zn
		Cr	Sn
		Cu	Sr
		Hg	V

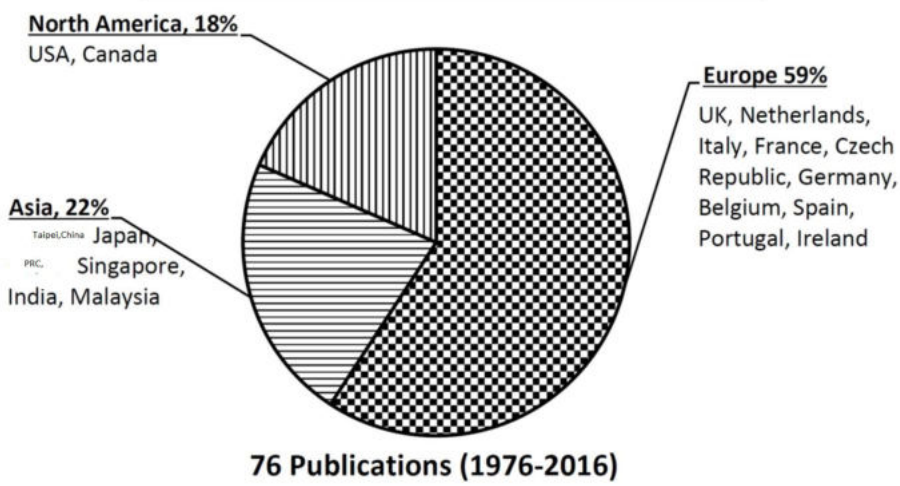


Figure 1.Global distribution of publications on MIBA in concrete applications[4]

---

[3] Lam, C. H., Ip, A. W., Barford, J. P., & McKay, G. (2010). Use of Incineration MSW Ash: A Review. *Sustainability*, 1943-1968.

[4] Lynn, C., Dhir, R., & Ghataora, G. (2016). Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete. *Construction and Building Materials*, 504-517.

There are two main literature that had collected the fragmented studies done and reviewed them in a single work. The work of Lam, Ip, Barford, and McKay[5] categorized the utilization of IBA and fly ash into seven different applications; cement and concrete production, road construction, glasses and ceramics, agriculture, stabilizing agent, adsorbents and zeolite production. Incinerator fly ash is utilized as a stabilizing agent and in zeolite production. Since the scope of this TA is only IBA, applications for incinerator fly ash will not be discussed. Lynn, Dhir, & Ghataora, (2016) had reviewed 76 publications and focused the work on the reuse of IBA as aggregates in concrete applications[6]. Additionally, there is literature that support the utilization of IBA in land reclamation works in Singapore and Japan. The utilization of r-IBA as raw materials in glass, ceramic and blasting grit production is supported by studies[5]. However, there is no glass and ceramic production industry in Maldives and hence reuse of r-IBA for glass and ceramic production is not a practical application in Maldives.

Existing literature was reviewed and the following utilizations of r-IBA are evaluated to determine their potential in Maldives.

i. Cement manufacturing
ii. Concrete production
iii. Masonry and pavement block production
iv. Road construction
v. Land reclamation
vi. Coastal protection systems

---

[5] Lam, C. H., Ip, A. W., Barford, J. P., & McKay, G. (2010). Use of Incineration MSW Ash: A Review. *Sustainability*, 1943-1968.

[6] Lynn, C., Dhir, R., & Ghataora, G. (2016). Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete. *Construction and Building Materials*, 504-517.

2.1. Cement Manufacturing

Calcareous materials like limestone and argillaceous materials like shale and clay are raw materials for cement production. These raw materials provide the reactants CaO, SiO_2, Fe_2O_3 and Al_2O_3 required for cement production. These oxides are also present in IBA (Table 3). Hence, IBA can be used as a substitute raw material in cement manufacturing[7]. However, corrosion of the cement kiln due to chloride ions and heavy metals in IBA can limit its reusability in cement manufacturing. Treatment of IBA is essential to reduce the effects of chloride and heavy metals. Pan, Huang, Kuo, and Lin used the washing treatment process and the cement produced conformed to the Chinese National Standards of Type II cement [8], suggesting the technical feasibility of utilizing treated IBA in cement production.

Maldives does not have a cement manufacturing industry. However, exporting the treated IBA to a cement manufacturer in an Asia is a possible option that could be explored. The requirements of Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal should be met for exporting the treated IBA.

2.2. Concrete Production

Treated IBA can be used as coarse aggregates and fine aggregates in concrete. The physical characteristics of IBA is an important factor that defines the properties of concrete made using IBA.

One of the physical properties of IBA that influence other physical properties of IBA and consequently the properties of concrete made with treated IBA is porosity. The porosity of IBA is higher than that of natural aggregates. Consequently, the absorption of IBA is

[7] Lam, C. H., Ip, A. W., Barford, J. P., & McKay, G. (2010). Use of Incineration MSW Ash: A Review. *Sustainability*, 1943-1968.

[8] Pan, J. R., Huang, C., Kuo, J.-J., & Lin, S.-H. (2008). Recycling MSWI bottom and fly ash as raw materials for Portland cement. *Waste Management*, 1113-1118.

higher. An averaged value of the water absorption is 9.7% and ranges over 2.4 – 15.0 %[9]. The porosity and absorption influence the bond between the cement paste and IBA. Aggregates are used as a fill material for concrete and can take up three quarters of the volume of concrete. Hence the high porosity and absorption of IBA used in concrete increases the porosity and absorption of the hardened concrete.

The high porosity of IBA contributes to the low specific gravity of IBA. The average specific density of IBA is 2.32[8]. This is comparably less than the typical specific density of natural aggregates. The specific density of natural aggregates is between 2.6 and 2.7[10]. The specific density depends on the treatment process as well.

Table 4 summarizes Lynn, Dhir, and Ghataora's review of the 76 publications focusing on the reuse of IBA in concrete[9]. As observed from Table 4, the performance of concrete produced with IBA is lower than concrete with natural aggregates. The workability is reduced due to high absorption of IBA. The compressive strength and tensile strength is lower. The current construction practices are very traditional in Maldives. It is a common practice to add water on site to the concrete mix to improve the workability. However, uncontrolled addition of water can further reduce the compressive strength of concrete. A reduction in compressive strength is translated to a reduction in flexural tensile strength of concrete. Concrete with lower tensile strength is susceptible to early cracking. Furthermore, the presence of chloride ions in IBA with close proximity to the reinforcing steel increases the risk of reduced durability. The existing literature lack a focus on long-term durability.

The practical utilization of IBA in concrete applications is in the early stages[9]. Due to the poor performance of concrete with IBA as aggregates, unreliable workmanship and the associated risks and lack of long-term durability studies, the reuse of r-IBA in structural concrete applications in Maldives is not recommended.

---

[9] Lynn, C., Dhir, R., & Ghataora, G. (2016). Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete. *Construction and Building Materials*, 504-517.

[10] Neville, A. M., & Brooks, J. J. (2010). *Concrete Technology.* Harlow: Pearson Education Limited.

Table 4. Effect on properties of concrete when r-IBA replaced natural aggregates

Property of Concrete	**Change in property when aggregates replaced with IBA**
Slump	Reduces
Cohesiveness	Remains cohesive
Segregation	No segregation
Bleeding	Bleeding reduces
Setting time	Increases
Compressive strength	Decreases
Tensile strength	Decreases
Elastic modulus	Decreases
Shrinkage	Increases
Creep	No significant change
Absorption	Increases
Chloride corrosion	Higher risk
Sulfate attack	No expansion due to sulfate attack
Carbonation resistance	Carbonation depth decreases

2.3. Masonry and Pavement Block Production

Concrete masonry blocks are extensively used in the construction industry. They are mainly used in non-load bearing masonry walls. Concrete masonry blocks used for majority of projects are locally produced. Sand quarried from lagoons are used as fine aggregates in block production. Use of local quarried sand is not a sustainable use of natural resources. Furthermore, the chloride content of the blocks due to the sand quarried from the sea floor can be high. However, supply of local quarried sand is limited and hence some large-scale block producers depend on imported sand.

The unit weight of masonry blocks with IBA is less than normal masonry blocks. This is due to the lower specific gravity of IBA. Since, the absorption of IBA is higher, the water demand during production is higher. The compressive strength of masonry and pavement blocks with IBA is lower. However, since the strength demanded from masonry products is lower, the target strength is achieved in non-load bearing, load bearing, paving and interlocking blocks[11]. Fire resistance performance is comparable to the products made with natural aggregates and no adverse shrinkage cracking is observed when IBA is used as a fine aggregate. Additionally, concrete paving blocks made with IBA exhibited excellent slip resistance and can be classified as having low potential for slip as per BS EN 1333[11].

Furthermore, full-scale operations had been conducted with masonry and pavement blocks made with IBA. There has been reports of spalling in projects carried out in the nineties. This is due to corrosion of the ferrous metal in IBA. However, with advanced treatment methods, the problem of spalling can be easily resolved. Most of the full-scale operations can be deemed successful[11].

Quality of masonry and pavement blocks made with IBA as aggregates is slightly inferior to similar products with natural aggregates. However, the requirements of masonry and pavement products is less than those of structural concrete. Therefore, review of literature suggests that the performance of the products with IBA can be of acceptable standards[11.]

Concrete masonry blocks are extensively used in non-structural applications in Maldives and the reuse of r-IBA is a more sustainable use of materials than the current use of chloride rich quarried sand. Therefore, utilization of r-IBA in concrete masonry and pavement block production has high potential in Maldives.

2.4. Road Construction

Reuse of IBA in road construction is one of the applications where IBA is utilized most in Europe. The research of IBA utilization in road construction is well progressed and

[11] Lynn, C., Dhir, R., & Ghataora, G. (2016). Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete. *Construction and Building Materials*, 504-517.

translated to field applications in countries like Belgium, Denmark, Germany and Netherlands[12].

A typical road cross-section has the wearing course as top surface, the base course and then the sub-base layer. Interlocking concrete blocks has been mostly used for the wearing course layer in Maldives though the use of bituminous asphalt in new roads is increasing. The sub-base layer is constructed on the subgrade, compacted natural soil as the foundation for the road. The base course and the sub-base is constructed with graded aggregates. Treated IBA can replace the natural aggregates used for the base course and sub-base layer[12]. IBA can be used in unbound form, hydraulically bound or bitumen bound form.

Hydraulically bound IBA is often stabilized with cement or lime when used in base layers. Singh and Kumar studied the geotechnical properties of MSWI ash mixed with cement[13]. The particle sizes of the MSWI ash used by Singh, et.al ranges from 75 microns to 1.18mm and suggests the study used IBA. Singh, et.al found that the California Bearing Ratio (CBR) value, Unconfined Compressive Strength (UCS) and Split Tensile Strength (STS) of MSWI increases when mixed with cement and suggests the MSWI mixed with cement can be used as an alternative material for road bases. However, the study of Singh, et.al did not focus on the environmental impacts of MSWI when used in ground works. A similar study in People's Republic of China also indicate the IBA mixed with cement satisfy the strength requirements for use on base and sub-base layers of heavy highway traffic[14]. However, the use of cement can increase the cost of the road construction.

Lynn, Ghataora, and Dhir had done an evaluation of the global experimental data on the use of IBA in road construction[15]. The analysis confirms that unbound IBA meets the grading requirement after standard processing and can be compacted well with

12 Ip, A. W., Barford, J. P., & McKay, G. (2010). Use of Incineration MSW Ash: A Review. *Sustainability*,

Lam, C. H., 1943-1958.

13 Singh, D. & Kumar, A. (2017). Geo-environmental application of municipal solid waste incinerator ash stabilized with cement. *Journal of Rock Mechanics and Geotechnical Engineering*, 370-375.

14 Tang, Q., Gu, F., Chen, H., Lu, C., & Zhang, Y. (2018). Mechanical Evaluation of Bottom Ash from Municipal Solid Waste Incineration Used in Roadbase. *Advances in Civil Engineering*.

15 Lynn, C. J., Ghataora, G. S., & Dhir, R. K. (2017). Municipal incinerated bottom ash (MIBA) characteristics and potential for use in road pavements. *International Journal of Pavement Research and Technology*, 185-201.

performance similar to that of sandy gravel. Unbound IBA meets the requirements of a material suitable for sub-base and is widely used in Denmark and Netherlands. IBA bound with a stabilizing agent like cement or lime can be processed to satisfy the requirements of a sub-base or base-course material by adjusting the binder content. Laboratory results of hydraulically bound IBA shows low density and elastic modulus. However, performance measured in full-scale projects suggests hydraulically bound IBA can be satisfactorily used despite lower laboratory results. Additionally, there are full-scale projects that provides evidence that low contents of IBA can be used to form bituminous bound bases and wearing course layers.

Environmental impact of the IBA used in road construction is as important as the mechanical properties. Lynn, Ghataora, and Dhir, had done an evaluation of global literature published on the environmental impacts of IBA as a road construction material[16]. Lynn, Ghataora, and Dhir's analysis concluded that IBA in unbound form poses the highest risk of leaching heavy metals and contaminants to the ground water but the risk could be minimized by treatment prior to utilization[16]. However, IBA bound with cement or bitumen restricts the leaching and the leachate concentrations were below the utilization and water quality limits. Therefore, the environmental impacts of the reuse of IBA in road construction does not limit its utilization.

Roads in most islands in Maldives are not leveled and paved. Only the capital city Male', Hulhumale' and Villimale' have all the roads paved, either with interlocking concrete paving blocks or asphalt. Some of the larger islands like Laamu Atoll Gan, Seenu Atoll Gan and Fuvahmulah have the main road paved with asphalt. The islands without paved roads create an opportunity for the reuse of IBA. Currently, there are eight road development projects in eight different islands in the tender phase. Similarly, future airport developments are potential applications for the utilization of IBA. However, according to Regional Airports there are no long-term development plans and the recent increase in new airports was politically rationalized.

[16] Lynn, C. J., Ghataora, G. S., & Dhir, R. K. (2018). Environmental impacts of MIBA in geotechnics and road applications. *Environmental Geotechnics*, 31-55.

2.5. Land Reclamation

The utilization of IBA in land reclamation is published in literature. However, this application is only limited to countries like Singapore and Japan where land is scarce.

In Singapore, IBA and marine clay originating from excavation works are solid wastes. It was proposed to use a mixture of stabilized IBA and marine clay as a fill material for land reclamation[17]. The mechanical properties and environmental impact assessments were tested. The literature concluded the reuse of IBA and marine clay matrix is feasible from both geotechnical and environmental perspective[18]. However, it should be highlighted that the polymer-based cementious stabilizer Chemlink SS-331H is a proprietary product.

In Japan, approximately 78% of MSW that is disposed in coastal landfill sites is MSWI ash and 20% of the MSW is disposed in coastal landfills, mostly located in port areas of Tokyo, Nagoya and Osaka[19]. Various studies had showed the geotechnical properties of the landfills improved. Nguyen, Inui, Ikeda, and Katsumi had taken waste mixture samples just before being disposed at coastal landfill site in Osaka Bay area and studied the time dependent geotechnical properties of waste mixtures submerged in landfill leachate or seawater. The composition of the waste mixture was approximately 50% of MSWI ash, 30% of gravel materials like slags, and 20% surplus soil. The study concluded that the shear strength increases and deformation decreases with time and hence waste mixture layers studied could be used as foundation layers with adequate bearing capacity after closure of the coastal landfill sites[20].

---

[17] Guo, L., & Wu, D. -Q. (2018). Study of leaching scenarios for the application of incineration bottom ash and marine clay for land reclamation. *Sustainable Environment Research*, 396-402.

[18] Guo, L., & Wu, D.-Q. (2017). Study of recycling Singapore solid waste as land reclamation filling material. *Sustainable Environment Research*, 1-6.

[19] Nguyen, L. C., Inui, T., Ikeda, K., & Katsumi, T. (2015). Aging effects on the mechanical property of waste mixture in coastal landfill sites. *Soils andFoundations*, 1441-1453.

[20] Nguyen, L. C., Inui, T., Ikeda, K., & Katsumi, T. (2015). Aging effects on the mechanical property of waste mixture in coastal landfill sites. *Soils andFoundations*, 1441-1453.

Land reclamation activities had rapidly increased over the last five years with several islands being reclaimed as a solution to land scarcity. Sand for reclamation is quarried from borrow sites in lagoons.

The reuse of IBA as a landfill material can be a potential alternative to the use of natural sand dredged from the lagoons. However, large quantities of sediments are required for some land reclamation projects and IBA generated might not be adequate for a single project. However, there is the opportunity for blending stabilized IBA with natural sediments during land reclamation. Further research is required to support the reuse of IBA as a blended material in land reclamation.

The duration and frequency of land reclamation is different to IBA generation. Frequency of reclamation projects are discrete and the duration is relatively shorter compared to the large volume of sediments mobilized. However, IBA generation is more continuous and subjected to maturation period as well. If r-IBA is planned to use, large volumes of IBA might be required to be stored for a long period of time. Therefore, even though the reuse of IBA in land reclamation or land filling might be a technically potential application, there might be operational limitations.

2.6. Coastal protection systems

Maldives being a coastal country, reuse of IBA in coastal protection systems can be a potential application. However, literature review revealed that the reuse of IBA in coastal protection systems is an area where there is a gap in literature.

One of the applications for reuse of IBA can be in concrete for quay walls and jetties. However, these are structural applications and due to inadequate performance of concrete with IBA, reuse of IBA in construction of quay walls and jetties is not recommended.

Crushed rocks are commonly used as revetments and breakwaters in Maldives. Alternatively, tetrapods made from concrete can be used and since it is not a structural application IBA can be used as aggregates in tetrapod production. However, durability is a concern and require further research to fully validate this application. A solution to ensure durability can be to design a tetrapod with an inner core made of compacted and hydraulically bound IBA and a more durable shell made of concrete with natural aggregates.

An alternative to tetrapod could be geo-bags. Currently sand, often sourced close to the project site is used as a fill material. Since, IBA can be used in road base layers with acceptable leachate performances, stabilized IBA can potentially be used as a fill material for geo-bags. However, this application is subjected to further research and the intermittent frequency of coastal protection projections should be considered.

3. Suitable Applications for Construction Demolition Waste

Recycling of CDW is practiced widely in some countries. In some countries, approximately 90% of the CDW are recycled[21]. BS 8500 (2002) defines two types of aggregates; Recycled Concrete Aggregates (RCA) and Recycled Aggregates (RC). RCA should have minimum 95% crushed concrete and RC is defined as 100% masonry based crushed aggregates. The quality of both types of CDW aggregates is poor compared to natural aggregates. This is primarily due to the mortar adhered to the natural aggregates. The production method influence the quality and composition of CDW aggregates.

Acceptability of CDW aggregates depends on the properties of fresh and hardened concrete incorporating CDW aggregates more than the properties of CDW aggregates itself. Table 5 summarizes the properties of fresh and hardened concrete with CDW aggregates compared to concrete with natural aggregates. As observed from Table 5 the properties of concrete with CDW aggregates is lower than conventional concrete. However, Brito and Saikia had proved that when the partial replacement ratio is less than 30%, the properties of CDW incorporated concrete is comparable to that of conventional concrete and both normal and high-strength concrete could be prepared using CDW aggregates[21]. Furthermore, Brito and Saikia claim that properties of concrete with CDW aggregates could be improved through the mix design[21].

Compared to IBA, CDW aggregates has more potential for reuse in structural concrete in Maldives. The majority of buildings have a concrete frame as the structural form and quay walls and jetties are made of concrete as well. RCA can be used to produce structural concrete and RC can be incorporated into concrete masonry block making. However, since construction of most residential buildings follow traditional methods and concrete is mostly batched volumetrically on site, the risk is high for the reuse of CDW as aggregates in concrete of residential buildings. The risk can be reduced when concrete mixes are designed and tested and batched using a batching plant. Currently, there are very few

[21] Brito, J. d., & Saikia, N. (2013). *Recycled Aggregate: Use of Industrial, Construction and Demolition Waste.* London: Springer

ready-mix concrete producers. Additionally, many old buildings that are being demolished had used sand quarried from lagoons and coral fragments as aggregates. Consequently, the concrete is rich in chloride ions and had caused severe corrosion in old buildings and is one of the main reasons for demolition. Hence, reuse of aggregates made from old buildings constructed using coral fragments would lead to corrosion and would not be accepted by consultants in the industry. Therefore, CDW aggregates should be used in Maldives with caution.

Table 5. Effect on properties of concrete when CDW replaced natural aggregates

Property of Concrete	**Change in property when aggregates replaced with IBA**
Workability	Reduces
Density	Lower
Air-content	Increases
Bleeding	Reduces
Compressive strength	Lower
Split tensile strength	Lower
Flexural strength	Lower
Modulus of Elasticity	Lower
Creep	Increases
Drying shrinkage	Increases
Water absorption	Increases
Chloride permeability	Increases

4. Review of national standards and required material characteristics

Construction Act of 2017 (Act No. 4/2017) and Environment Protection and Preservation Act of 1993 (Act No. 4/93) are the two legislations that could be related to IBA and CDW.

Environment Protection and Preservation Act confers power on a ministry responsible for environment to formulate policies and regulations. Environment Protection and Preservation Act briefly states in clause 7 and 8 that waste, oil and toxic material should be disposed in areas designated by the government, should not damage the environment and if waste burning is adopted it should not harm human health. Ministry of Environment has formulated a National Solid Waste Management Policy in 2008 and revised it in 2015. Ministry of Environment has also issued a Waste Management Regulation (Regulation No. 2013/R-58). Consultation with relevant staff of Ministry of Environment revealed that there are no specific environmental national standards related to IBA and CDW. However, clause 3.1 of Annex 1 of Waste Management Regulation states that International standards should be referred to in cases where there are no national standards. There are no universal standards. Standards differ in each country and reflect factors unique to the specific country. Table 7 shows European Union's minimum waste acceptance criteria for the different categories of waste[22].

Construction Act sets the general principles and confers the power on the ministry to issue regulations to control production, import, testing and use of construction materials. However, currently there are no regulations formulated. Material testing and ensuring compliance to specifications is not widely practiced in Maldives. In circumstance where testing is conducted, only the grading of aggregates and compressive strength of concrete and sometimes masonry blocks is tested. However, when used in non-load bearing walls compressive strength of blocks is not critical. There is no specific standard followed by all the professionals in the construction industry. Some of the standards

[22] Liu, A., Lin, W. Y., & Wang, J. Y. (2015). A review of municipal solid waste environmental standards with a focus on incinerator residues. *International Journal of Sustainable Built Environment*, 165–188.

followed include Australian Standards, British Standards, Indian Standards and standards of American Society for Testing and Materials (ASTM). There are no specific national standards on IBA or CDW. The grading requirements often followed in Maldives is given in Table 6.

Table 6. BS 882:1992 grading requirement for fine aggregates

Sieve size	Percentage by mass passing sieve
10 mm	100
5 mm	89-100
2.36 mm	60-100
1.18 mm	30-100
600 μm	15-100
300 μm	5-70
150 μm	0-150*

* For crushed rock sands the permissible limit is increased to 20%

Table 7. Leaching limits as set out in Council Decision 2003/33/EC

Element or substance	Inert wastes			Non-hazardous wastes			Hazardous waste acceptable at non-hazardous waste landfills			Hazardous waste acceptable at hazardous waste landfills		
	L/S = 2 L/kg	L/S = 10 L/kg	C_0 percolation test	L/S = 2 L/kg	L/S = 10 L/kg	C_0 percolation test	L/S = 2 L/kg	L/S = 10 L/kg	C_0 percolation test	L/S = 2 L/kg	L/S = 10 L/kg	C_0 percolation test
	mg/kg	mg/kg	mg/L	mg/kg	mg/kg	mg/L	mg/kg	mg/kg	mg/L	mg/kg	mg/kg	mg/L
As	0.1	0.5	0.06	0.4	2	0.3	0.4	2	0.3	6	25	3
Ba	7	20	4	30	100	20	30	100	20	100	300	60
Cd	0.03	0.04	0.02	0.6	1	0.3	0.6	1	0.3	3	5	1.7
Cr (total)	–	–	–	4	10	2.5	4	10	2.5	25	70	15
Cu	0.9	2	0.6	25	50	30	25	50	30	50	100	60
Hg	0.003	0.01	0.002	0.05	0.2	0.03	0.05	0.2	0.03	0.5	2	0.3
Mo	0.3	0.5	0.2	5	10	3.5	5	10	3.5	20	30	10
Ni	0.2	0.4	0.12	5	10	3	5	10	3	20	40	12
Pb	0.2	0.5	0.15	5	10	3	5	10	3	25	50	15
Sb	0.02	0.06	0.1	0.2	0.7	0.15	0.2	0.7	0.15	2	5	1
Se	0.06	0.1	0.04	0.3	0.5	0.2	0.3	0.5	0.2	4	7	3
Sn	–	–	–	–	–	–	–	50	–	–	–	–
Zn	2	4	1.2	25	50	15	25	50	15	90	200	60
Cl^-	550	880	450	10000	15,000	8500	10,000	15,000	8500	17,000	25,000	15,000
F^-	4	10	2.5	60	150	40	60	150	40	200	500	120
SO_4^{2-}	560	1000	1500	10,000	20,000	7000	10,000	20,000	7000	25,000	50,000	17,000
Phenol index	0.5	1	0.3	–	–	–	–	–	–	–	–	

5. Stakeholder Product Acceptance and Product Requirements

Stakeholder were identified and interviewed individually. Maldives National Association of Construction Industry (MNACI), contractors, masonry block producers and consultants were interviewed. There were challenges in arranging interviews as some were not available for the interview. Twelve participants were interviewed. Three main questions were asked after a brief explanation of the project, potential applications of r-IBA and processed CDW, and the characteristics and performance of IBA and CDW in various applications. Figure 2 shows the results of the interview. The general response was good with 75% viewing the reuse of IBA and CDW as a good initiative and 65% were willing to buy and use the product. However, almost all the participants imposed a condition on the willingness to buy or use the product. The willingness of potential stakeholders was subjected to the compliance with standard requirements. Some of the participants (25%) view that if the performance of the product made using IBA or CDW satisfy the standards and is similar to the performance of product made with natural aggregates the price of IBA or CDW could be similar to that of natural aggregates. However, 35% of the participants believe the price of IBA or CDW should be 40 – 60% of the price of natural aggregates. A quarter of the participants did not respond to the price question.

It was observed that most of the contractors believe the use of IBA or CDW depend on the approval of consultants and did not suggest any product requirements, other than strength. However, consultants had given additional requirements such as absorption percentage and grading. In general, all participants believed that IBA and CDW aggregates should conform to international standards.

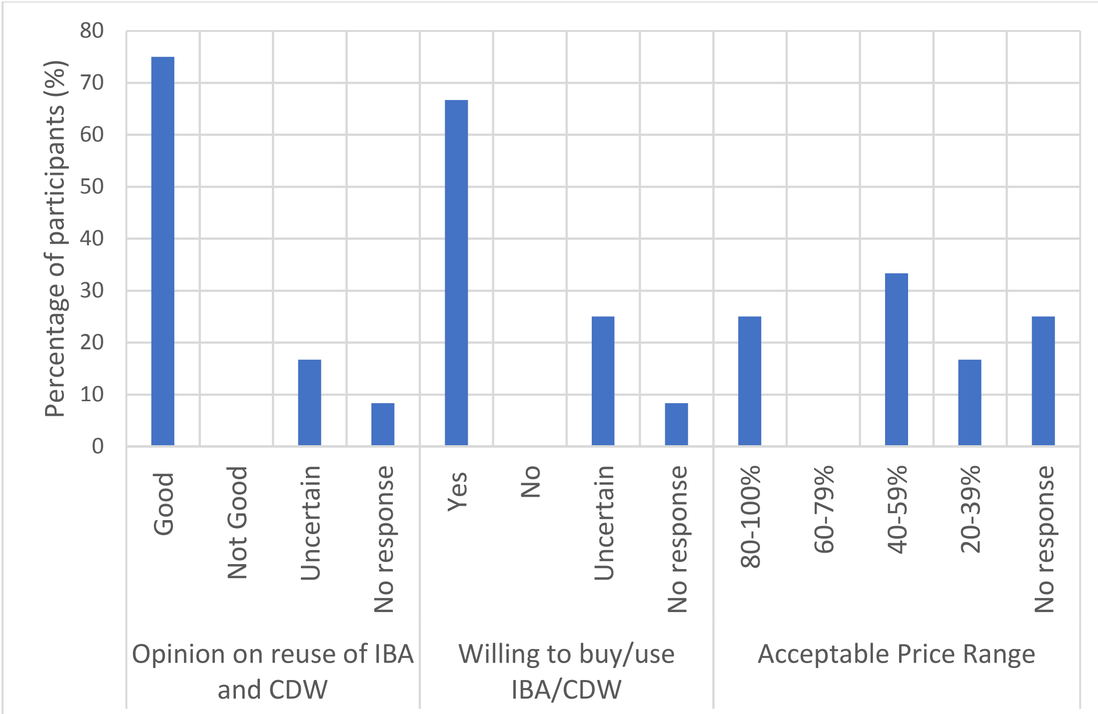


Figure 2. Results of stakeholder consultations on the reuse of IBA and CDW

6. Cost of similar construction materials and current demand

IBA and CDW are substitute products for coarse and fine aggregates used in construction industry. Hence, the demand for IBA and CDW products are expected to be similar to the demand for aggregates. Aggregates is one of the major materials used in construction. The current demand for aggregates should be reflected by the demand in the construction industry. Hence, the trends in the construction industry was first analyzed. The gauges used to determine the current demand is the construction related imports, loans to construction industry, and the building permits issued.

The construction industry is performing progressively as indicated by the gauges. In the first quarter of year 2018, loans for construction of residential housing, guest houses and new resorts observed an annual increase of 19%. During the first half of year 2018 the annual growth in credit to construction industry was registered as 23% and the growth maintained in the third quarter.

Construction related imports is another indicator of the demand in construction industry. The construction related imports increased 51% during the first half of the year 2018 and during the third quarter the growth was 39%. Statistics provided by Maldives Customs Service shows that about 792,800 tons of course aggregates and 495,300 tons of fine aggregates (sand) were imported to Maldives in year 2018 (Table 9). The value of imports of aggregate amounts to USD 48.9 million.

The demand for masonry blocks was captured through interviews. Maldives National Association of Construction Industry (MNACI), one of the largest contractors in Maldives and one of the current major suppliers of concrete masonry blocks to the Greater Male' Region were interviewed. Attempts to access archived information of Maldives Road Development Corporation was not successful. Maldives Road Development Corporation, before its recent liquidation, used to be one of the largest concrete masonry and pavement block production facility in the country. Currently, there are several block producers. Majority of block production facilities operate on a small scale and production is limited to approximately 1000 to 3500 blocks per day. Some of the large contractors operate their own production facilities and produce quantities sufficient for their own projects. Small scale block producers use local sand while in large-scale production, imported manufactured sand is used but local sand is also used to a limited extent.

The composition of the masonry block varies. Some production facilities had adopted a volumetric ratio of 1 units of cement to 5 or 6 units of sand while some production facilities can increase the sand content. Hollow rectangular blocks and solid rectangular blocks are manufactured in Maldives. The width of the blocks currently produced in the market is four inches.

The market rate of unit cost of local sand is approximately USD/kg 0.015. The typical market rate of four inch hollow blocks produced using local sand is USD 0.39 per block, though USD 0.34 per block is available from some of the large-scale producers. The unit price of four inch solid blocks produced using local sand is US 0.52. However, unit price of four-inch masonry hollow blocks produced using imported manufactured sand is USD

0.97. The average production rate of one of the major suppliers interviewed is 15,000 blocks per day. Considering the known masonry block producers in Male' and Hulhumale' and their observed production, it is estimated that approximately 83,000 blocks are produced per day in Male' and Hulhumale'. Estimating 3.5 kg of sand is required per block, production at this rate requires approximately 291 tpd of sand in Male' and Hulhumale'. Adopting 20% as the optimum aggregate replacement level[23], it is estimated 58 tpd of r-IBA are required. The estimated IBA generation of 100 – 125 tpd is more than the quantity required as of year 2019. The demand for r-IBA could be increased through means of government controls on the use of local sand quarried from lagoons.

The current CDW generation is 530 tpd. The proportion that could be recycled and reused is 482 tpd[24]. However, the CDW processing facility proposed to be implemented has a capacity of 200 tpd. The composition of the CDW (Table 8) shows 42.6% of CDW arriving at Male' waste transfer station is concrete and 41% is sand and soil, and 8.1% is rock and gravel resulting from excavation[23]. It is assumed that sand and soil from excavation works will be reused for backfill and landscape works and thus is excluded from the scope of the TA. Therefore, the recycled concrete yield of the processing facility operating at maximum capacity can be estimated as 85 tpd (42.6% of CDW). However, to be conservative for demand estimation purposes, the yield of recycled aggregates is assumed to be same as 200 tpd, the maximum capacity of the processing plant.

There is no data in the feasibility study[23] that suggests concrete and masonry walls are identified separately. On the contrary it seems structural concrete and masonry walls are identified as a single group of concrete. The properties of aggregates derived from structural concrete and concrete masonry walls differ significantly and would influence the potential application for reuse of CDW and the corresponding demand. Additionally, many old buildings that are being demolished had used sand quarried from lagoons or

[23] Lynn, C., Dhir, R., & Ghataora, G. (2016). Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete. *Construction and Building Materials*, 504-517.

[24] Water Solutions and Kocks Ingenieure. (2018). *Feasibility Study for an Integrated Solid Waste Management System for Zone III and Preparation of Engineering Design of the Regional Waste Management Facility at Thilafushi.*

beaches and coral fragments as aggregates. Consequently, the concrete is rich in chloride and had caused severe corrosion and cracking in old buildings. One of the main reasons for demolition is structural damage due to corrosion. Reuse of aggregates made from old buildings constructed using coral fragments would lead to corrosion. Given the uncertainty, it is recommended the concrete processed at the CDW processing plant to be crushed and used as sand for concrete masonry block making. Therefore, it can be assumed that 200 tpd of sand would be generated as recycled concrete.

Approximately 291 tpd of sand is required for block production in Male' and Hulhumale'. The current demand for sand (fine aggregates) in block production is less than the generation of 200 tpd of recycled aggregates and 100 – 125 tpd IBA, out of which 58 tpd can be used for replacement of sand.

Table 8. Estimated composition by weight of CDW[25]

Estimated Composition by Weight for All Loads

Paper		**0.5%**	
	Unwaxed OCC		0.5%
	RC Paper		0.0%
Plastic		**0.5%**	
	Non-bag Film		0.5%
	Polystyrene Packaging		0.0%
	Rigid Plastic		0.0%
	RC Plastic		0.0%
Metal		**0.2%**	
	Major Appliances		0.0%
	HVAC Ducting		0.0%
	Other Ferrous & Non-Ferrous		0.0%
	RC Metal		0.2%
Organic		**0.0%**	
	Prunings, Trimmings, Branches, Stumps		0.0%
	RC Organic		0.0%
Carpet		**0.0%**	
	Carpet		0.0%
	Carpet Padding		0.0%
	RC Carpet		0.0%
Aggregates & Dirt		**91.8%**	
	Dirt, Sand, Soil		41.0%
	Concrete		42.6%
	Asphalt Paving		0.0%
	Brick, Ceramic, Porcelain		0.0%
	Rock, Gravel		8.1%
	RC Aggregates & Dirt		0.0%
Roofing		**0.0%**	
	Roofing		0.0%
	RC Roofing		0.0%
Insulation		**0.0%**	
	Insulation		0.0%
	RC Insulation		0.0%
Wood		**7.1%**	
	Clean Recyclable Lumber, Pallets, Crates		7.1%
	Other Untreated & Recyclable Wood		0.0%
	Painted, Stained, Treated Wood		0.0%
	RC Wood		0.0%
Gypsum		**0.0%**	
	Clean Gypsum Board		0.0%
	Painted Gypsum Board		0.0%
	RC Gypsum		0.0%
Misc. C&D		**0.0%**	
Glass		**0.0%**	
Electronics		**0.0%**	
HHW		**0.0%**	
Special		**0.0%**	
Mixed Residue		**0.0%**	
TOTAL		**100.0%**	

[25] Water Solutions and Kocks Ingenieure. (2018). *Feasibility Study for an Integrated Solid Waste Management System for Zone III and Preparation of Engineering Design of the Regional Waste Management Facility at Thilafushi.*

7. Forecasted demand

The long-term demand is captured using the same three gauges; the construction related imports, loans to construction industry, and the building permits issued. Historic data was obtained and analyzed to see long-term trends. Future projections were done based on historic data and the current situation of the Greater Male' region.

Statistics published by Maldives Monetary Authority shows rapid growth in construction-related imports over last five years[25] (Figure 3). However, a sudden decline in imports was observed in year 2009. This is because of the Global Financial Crisis in year 2009. Despite global recovery from the financial crisis, significant growth in years 2011 to 2012 was not observed because of the restrictions imposed by India on imports of aggregates. Prior to year 2009, construction industry had been experiencing rapid growth for five to six years. The growth in the construction industry since year 2013 is due to numerous public sector investment programme (PSIP) infrastructure projects, private sector investment in real-estate and expansion in tourism sector. As observed from Figure 3, consumption of construction materials is increasingly observed in private and tourism sector. This suggests the growth in resort development and residential property construction.

Loans to construction industry over recent years exhibit industry growth and support the trend observed from construction-related imports. Credit to tourism sector and construction industry has been increasing since second quarter of year 2015 (Figure 4). Growth in tourism sector is mainly due to lending for construction of guesthouses and new resort development. The growth in lending to the construction industry is due to lending for residential and housing purposes[26].

---

[26] Maldives Monetary Authority. (2018). *Annual Report 2017*

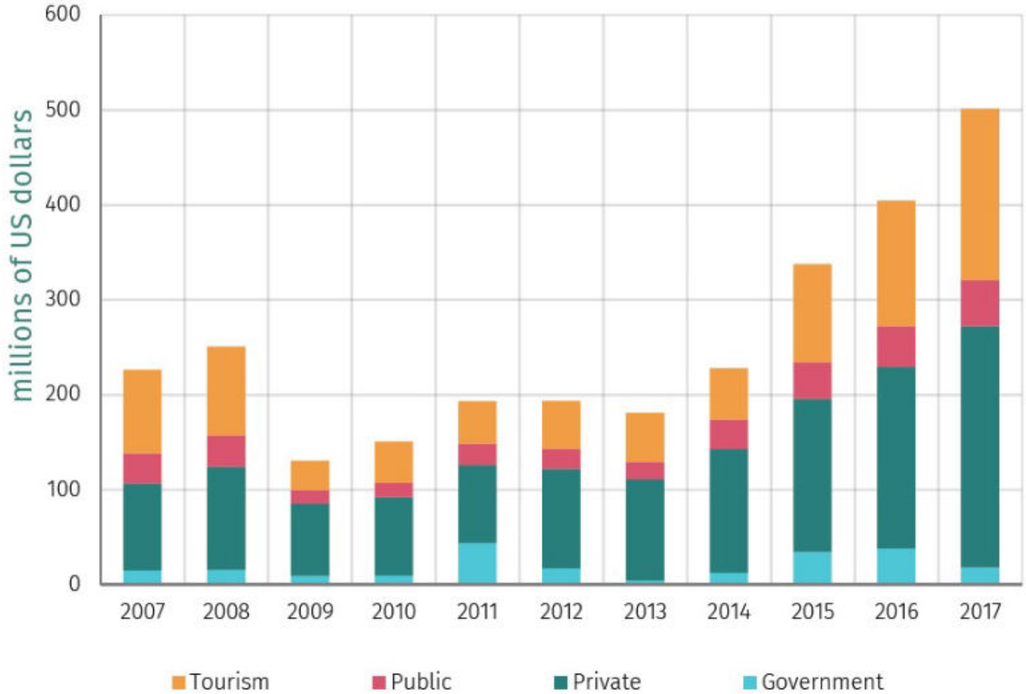


Figure 3. Construction related imports by sector[27]

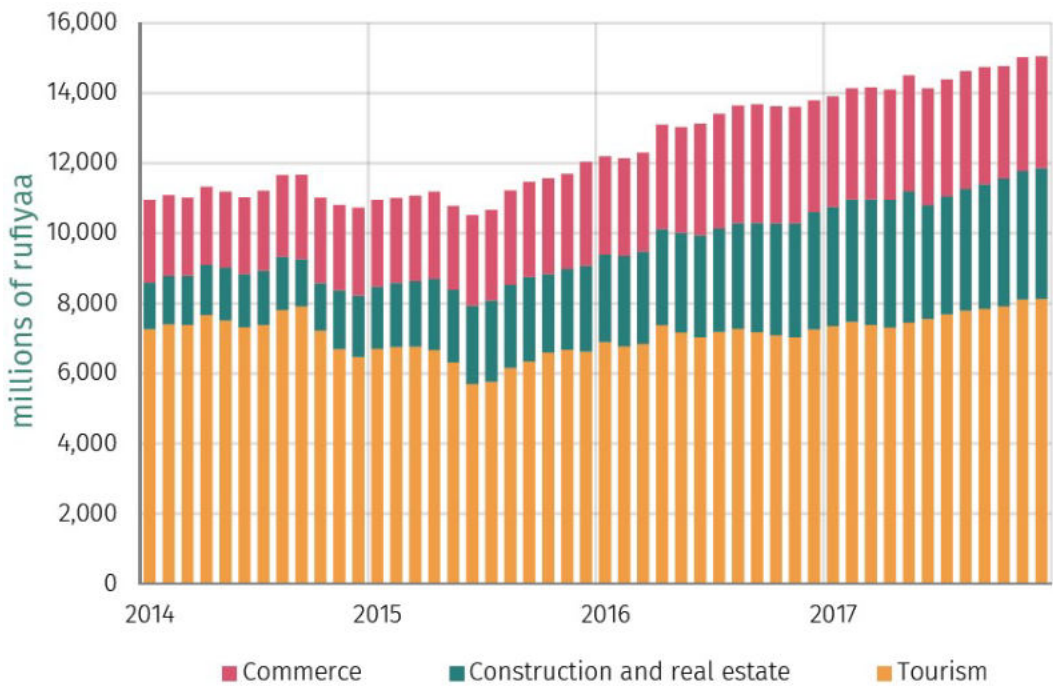


Figure 4. Loans and Advances to the Private Sector by Major Sectors[27]

[27] Maldives Monetary Authority. (2018). *Annual Report 2017*

Building permits is a key indicator of activity in construction industry. There are two types of permits; a permit given to commence construction and a permit given to use the building following completion of construction. Permits are well documented in Male' and Hulhumale'. Building permits available for the last fifteen years is collected and historic trends analyzed (Figure 5). Construction industry prior to year 2009 was a very robust industry with construction permits more than 500 permits annually. The industry was experiencing double digit growth rates[28]. However, the industry came to a halt in year 2009 due to the Global Financial Crisis and it is estimated to have contracted sharply by 16% in 2009 due to delays in major resort development projects owing to declines in capital inflows. Growth for the five years following year 2009 may have been affected by political instability and restrictions in availability of aggregates from India[29]. Since year 2013, with the increase in supply of aggregates, construction of residential buildings has been rapidly increasing and construction activity is similar to the trend observed before the financial crisis.

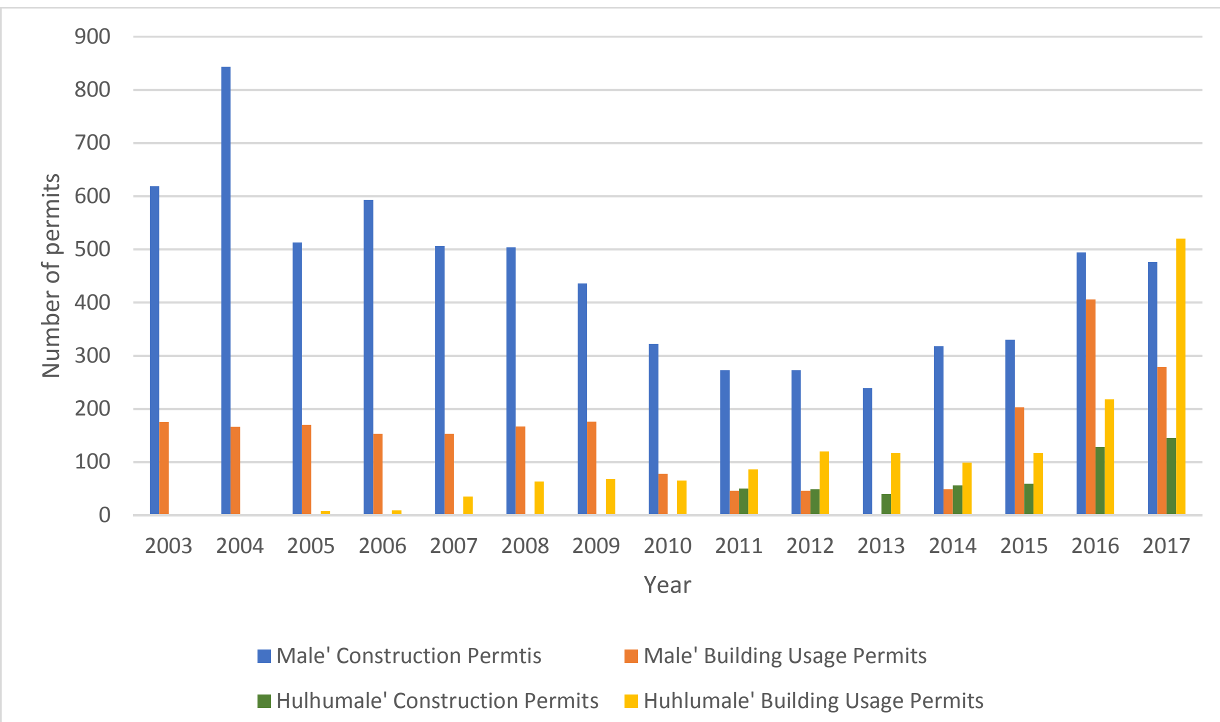


Figure 5. Building permits[30]

[28] Maldives Monetary Authority. (2010). *Annual Report 2009.*
[29] Maldives Monetary Authority. (2014). *Annual Report 2013.*
[30] National Bureau of Statistics, 2004 - 2017

Table 9. Imports of course aggregates and fine aggregates (sand)[31]

Year	Aggregates		Sand	
	Quantity (t)	CIF (MVR)	Quantity (t)	CIF (MVR)
2004	159,426	59,094,523	186,889	57,867,960
2005	191,518	76,128,976	245,979	86,542,799
2006	184,765	82,932,844	258,055	88,612,134
2007	355,762	186,032,748	432,665	200,161,633
2008	327,331	162,881,687	368,997	166,039,942
2009	184,180	86,776,242	165,230	63,140,895
2010	204,082	85,637,549	120,016	53,566,753
2011	267,540	136,810,147	153,877	88,147,309
2012	242,781	138,694,729	84,535	59,297,401
2013	180,492	147,359,782	133,699	105,190,451
2014	270,519	201,915,402	185,217	151,766,876
2015	536,523	344,320,685	226,981	155,857,347
2016	555,891	315,681,933	474,183	168,811,604
2017	803,326	425,625,230	330,156	177,082,708
2018	792,798	413,483,330	495,321	340,574,712

Historic data suggests that the construction industry has been a robust industry. The industry has potential growth due to the undeveloped reclaimed Gulhifalhu island and the recently reclaimed Hulhumale' phase 2. The relative annual growth rates of the last decade, (Figure 6) shows a positive growth. The exception is the year following Global Financial Crisis, where industry experienced a decline. The rate of growth is estimated by finding the average of the percentage growth of the three key indicators in years 2013 – 2017 (Table 10). Over the recent five years, the construction activity in Greater Male' Region has been restored close to the situation before the financial crisis. This is observed from the number of building permits in Figure 5. The average growth in construction related imports, credit to construction industry and construction permits is 22%, 26% and 17%, relatively. The average growth of these three key indicators is 22%.

[31] Maldives Customs Service (2018)

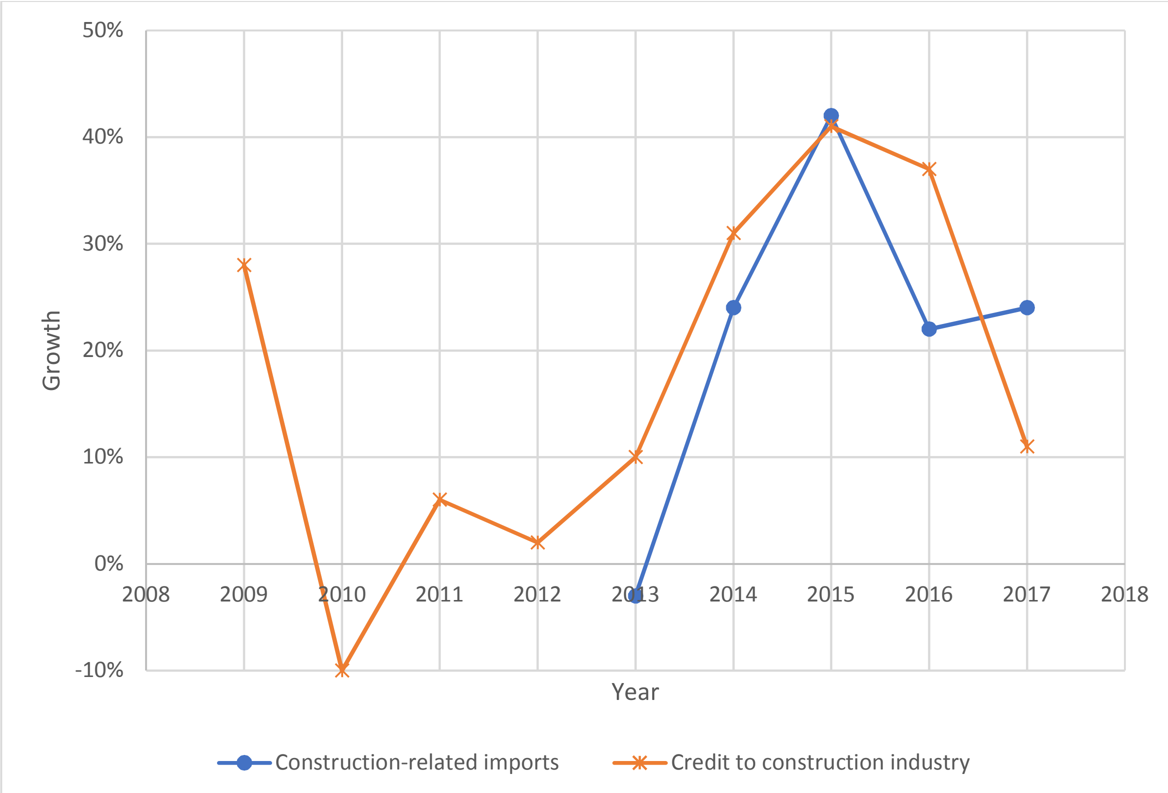


Figure 6. Growth of construction industry relative to preceding year

Table 10. Growth of key indicators of construction industry

Year	Construction-related imports	Credit to construction industry	Construction Permits	Building usage Permits
2017	24%	11%	0%	28%
2016	22%	37%	60%	95%
2015	42%	41%	4%	116%
2014	24%	31%	34%	26%
2013	-3%	10%	-13%	-30%
2012		2%	0%	26%
2011		6%	0%	-8%
2010		-10%	-26%	-41%
2009		28%	-13%	6%

Future total demand in aggregates were estimated based on historic import quantities. The data was obtained from Maldives Customs Services. Quantities of aggregates and sand (fine aggregates) imported to Maldives over last 15 years is shown in Figure 7. It is believed the import quantity of sand obtained is only for river or natural sand and there might be quantities imported in various other names. The trend observed in aggregate imports mirrors the trend observed in the key indicators of the construction industry.

Figure 7.Imports of course aggregates and fine aggregates (sand) over 15 years [32]

Future demand projections are estimated based on historic values using exponential smoothing. Data since year 2011 is taken because Global Financial Crisis is an considered as an extreme and rare event and considering the two years following year 2009 would have affected the accuracy of the forecast. Figure 8 and Table 11 shows the demand forecast of aggregates in the industry for the next 15 years. Figure 9 and Table 12 shows the demand forecast of sand in the industry for the next 15 years. These are the total demand of the industry for aggregates and sand.

[32] Maldives Customs Service (2018

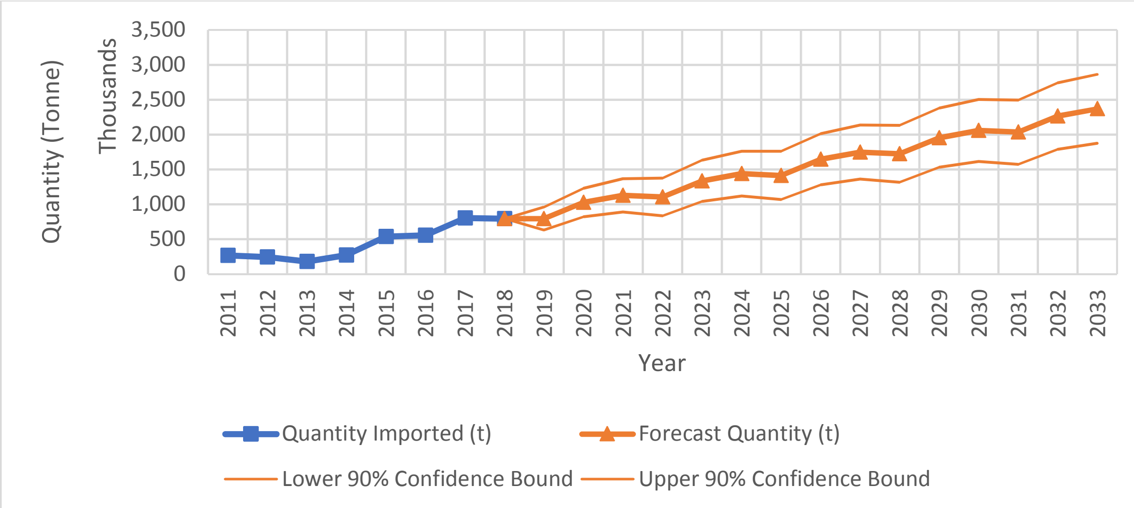


Figure 8. Forecast of course aggregates for 15 years (2018 - 2033)

Table 11. Forecast of course aggregates for 15 years (2018 - 2033)

Year	Quantity Imported (t)	Forecast Quantity (t)	Lower 90% Confidence Bound (t)	Upper 90% Confidence Bound (t)
2011	267,540			
2012	242,781			
2013	180,492			
2014	270,519			
2015	536,523			
2016	555,891			
2017	803,326			
2018	792,798	792,798	792,798	792,798
2019		794,590	630,542	958,638
2020		1,025,770	820,513	1,231,027
2021		1,128,784	889,223	1,368,346
2022		1,104,500	834,815	1,374,185
2023		1,335,679	1,038,913	1,632,446
2024		1,438,694	1,117,056	1,760,333
2025		1,414,410	1,069,571	1,759,249
2026		1,645,589	1,279,015	2,012,163
2027		1,748,604	1,361,461	2,135,747
2028		1,724,320	1,317,546	2,131,094
2029		1,955,499	1,529,999	2,380,999
2030		2,058,514	1,615,032	2,501,996
2031		2,034,230	1,573,378	2,495,082
2032		2,265,409	1,787,819	2,743,000
2033		2,368,424	1,874,620	2,862,227

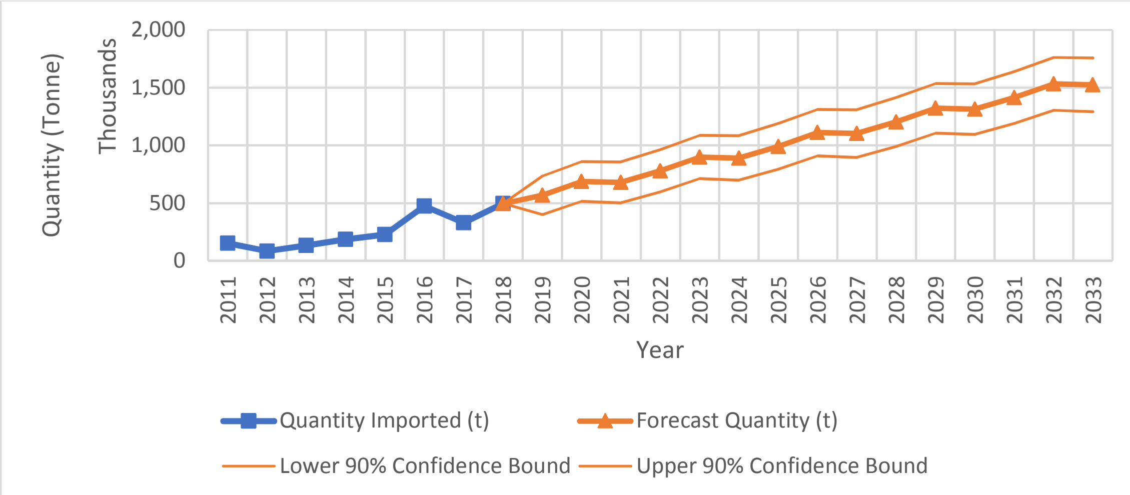


Figure 9. Forecast of fine aggregates (sand) for 15 years (2018 - 2033)

Table 12. Forecast of fine aggregates (sand) for 15 years (2018 - 2033)

Year	Quantity Imported (t)	Forecast Quantity (t)	Lower 90% Confidence Bound (t)	Upper 90% Confidence Bound (t)
2011	153,877			
2012	84,535			
2013	133,699			
2014	185,217			
2015	226,981			
2016	474,183			
2017	330,156			
2018	495,321	495,321	495,321	495,321
2019		568,631	401,394	735,869
2020		688,224	515,758	860,690
2021		680,146	502,565	857,726
2022		779,772	597,143	962,401
2023		899,364	711,822	1,086,906
2024		891,286	698,919	1,083,653
2025		990,912	793,766	1,188,059
2026		1,110,505	908,692	1,312,317
2027		1,102,427	896,018	1,308,835
2028		1,202,053	991,080	1,413,026
2029		1,321,645	1,106,204	1,537,086
2030		1,313,567	1,093,715	1,533,419
2031		1,413,193	1,188,952	1,637,434
2032		1,532,786	1,304,240	1,761,332
2033		1,524,708	1,291,904	1,757,511

There is no historic data available to use exponential smoothing to forecast the sand required for concrete masonry block making. The current demand is approximately 291 tpd of sand for block production in Male' and Hulhumale'. The demand of sand required for concrete masonry block making in the next 15 years is forecasted by assuming a linear growth equal to the estimated industry growth rate of 22%. However, computing growth at a rate of 22% for 15 years result in an exponential growth and is not realistic. Hence, linear growth at 22% is only computed for five years and used as historical values to use exponential smoothing to forecast for the next 10 years. The forecasted demand is shown in Figure 10 and the quantities are given in Table 13. The projected quantity of IBA and recyclable CDW is estimated in the feasibility study (Table 14). The projected IBA and recyclable CDW quantities are compared with the forecasted demand of sand required in block production (Figure 11). The quantity of CDW aggregates is initially more than the forecasted demand of sand used in block production. However, since year 2021, the demand of sand, including the lower bound, is more than the total IBA and CDW recyclables generated.

Figure 10. Demand forecast of fine aggregates (sand) required in concrete masonry block production for 15 years (2018 – 2033)

Table 13. Demand forecast of fine aggregates (sand) required in concrete masonry block production for 15 years (2018 – 2033)

Year	Forecast Quantity (t)	Lower 90% Confidence Bound (t)	Upper 90% Confidence Bound (t)
2018	90,210		
2019	110,056		
2020	134,269		
2021	163,808		
2022	199,845	199,845	199,845
2023	223,809	214,076	233,542
2024	251,494	240,607	262,380
2025	279,178	267,246	291,110
2026	306,862	293,965	319,760
2027	334,547	320,748	348,346
2028	362,231	347,583	376,880
2029	389,916	374,462	405,370
2030	417,600	401,377	433,823
2031	445,285	428,325	462,244
2032	472,969	455,301	490,637
2033	500,653	482,301	519,006

Table 14. Projection of IBA and CDW aggregates generation (Feasibility Study, 2017)

Year	Recyclables of CDW	IBA generated
2018	151572	
2019	153664	
2020	155787	
2021	157944	
2022	160134	
2023	162358	43125
2024	164617	43125
2025	166911	43125
2026	169242	43125
2027	171608	43125
2028	174012	43125
2029	176454	43125
2030	178934	43125
2031	181453	43125
2032	184012	43125
2033	186611	43125

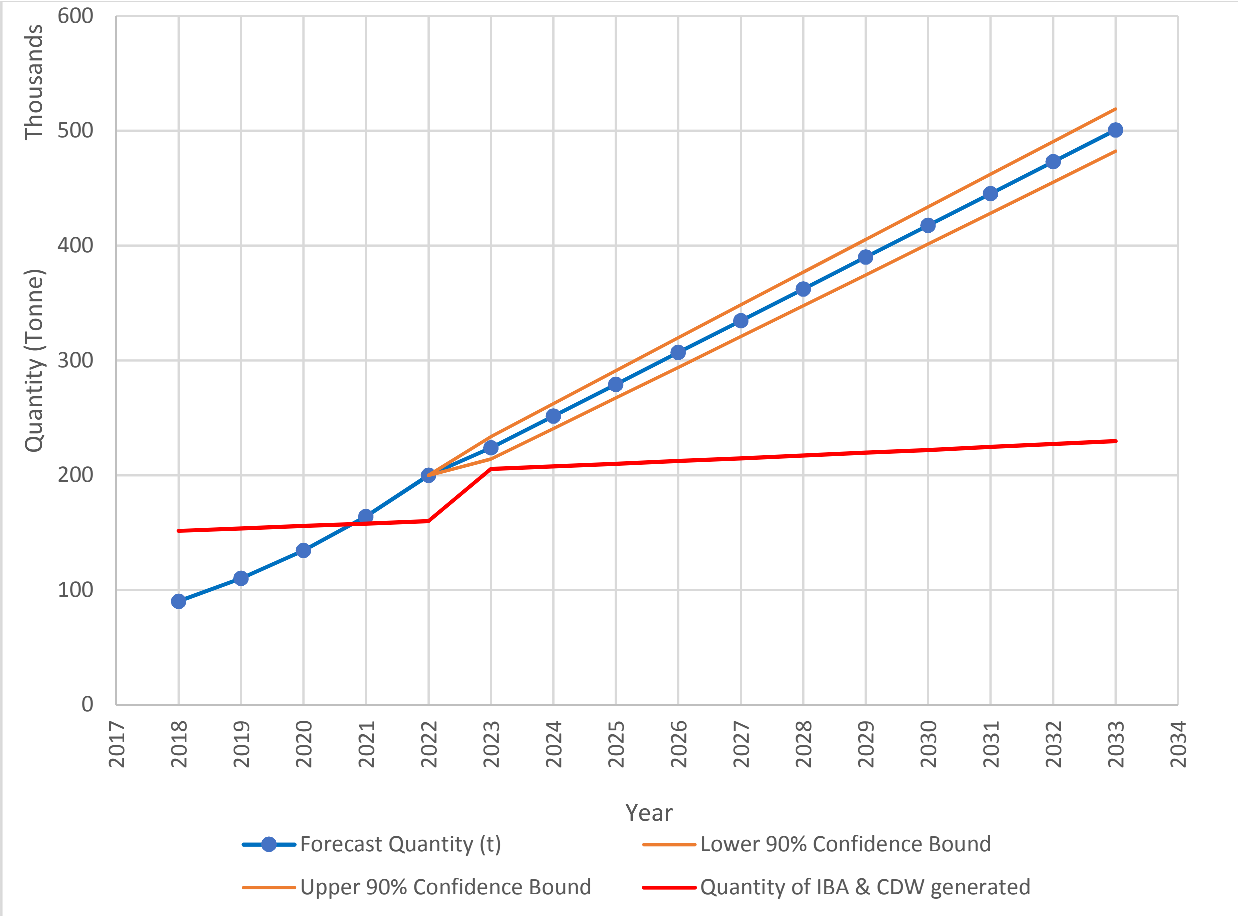


Figure 11. Comparison of forecasted sand required for concrete block production against IBA and CDW generated

A sensitivity analysis was done to evaluate consumption of IBA and CDW in various market share scenarios. The Figure 11 represents IBA and CDW consumptions when 100% market penetration is adopted. Three alternative scenarios were considered; 90%, 80% and 60% of the market share (Figure 12 and Table 15), instead of the 100% market share represented in Figure 11. When 100% market penetration is possible, all the IBA and CDW generated can be consumed by the block production industry. However, when market share reduces to 90% of the forecasted demand, not all IBA and CDW that is generated is consumed in year 2023. Similarly, when market share reduces to 80% of the forecasted demand, there are some IBA and CDW left over in years 2023 and 2024. When the market share reduces to 60% of the forecasted demand, there are some IBA and CDW left over in years 2023 to 2028. The left over IBA and CDW could be used for other purposes like screeds as suggested by the participants interviewed. It is recommended to try to achieve 100% market share. This can be achieved easily by drastically reducing the price of IBA and CDW. IBA and CDW are substitute products to natural aggregates and price is the driving factor that drives demand in substitute products.

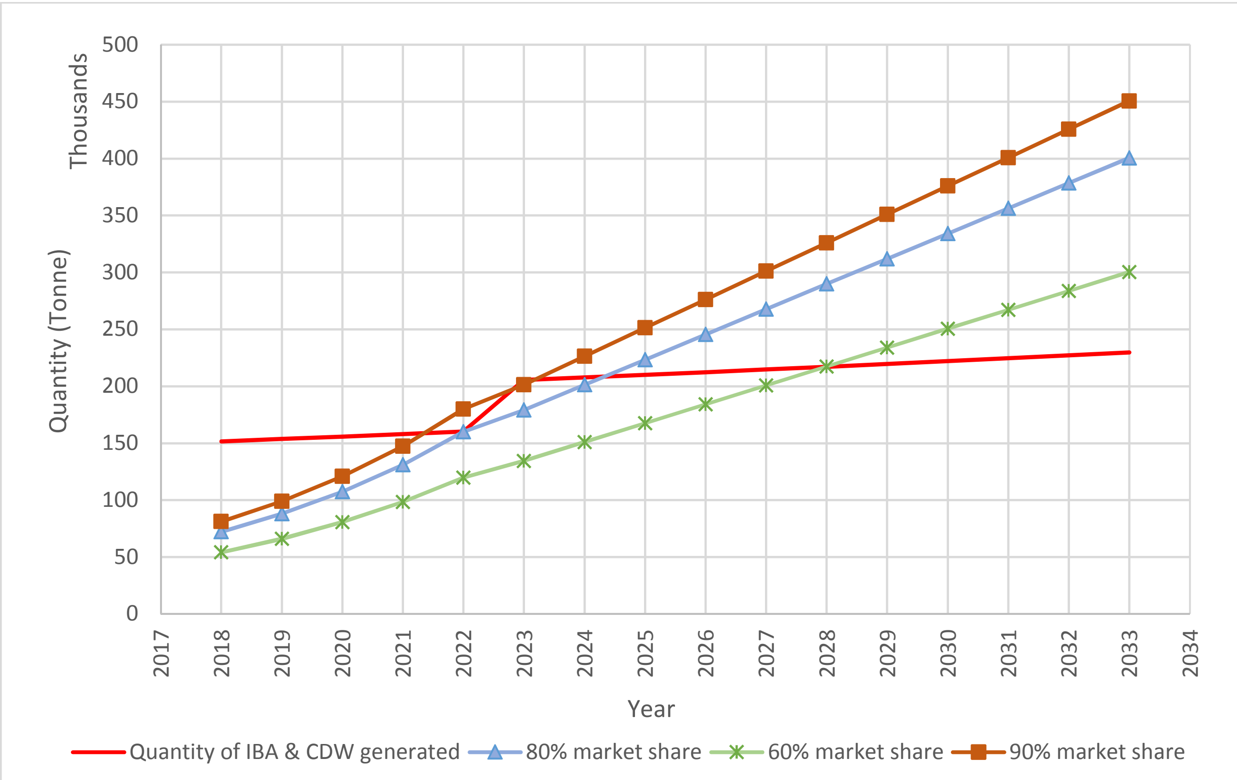


Figure 12. Sensitivity analysis of demand for IBA and CDW in concrete masonry block production

Table 15. Sensitivity analysis of demand for IBA and CDW in concrete masonry block production

Year	90% market share				80% market share				60% market share			
	20% IBA (t)	Unused IBA (t)	80% CDW (t)	Unused CDW (t)	20% IBA (t)	Unused IBA (t)	80% CDW (t)	Unused CDW (t)	20% IBA (t)	Unused IBA (t)	80% CDW (t)	Unused CDW (t)
2018			81,189	70,383			72,168	79,404			54,126	97,446
2019			99,051	54,613			88,045	65,619			66,034	87,630
2020			120,842	34,945			107,415	48,372			80,561	75,226
2021			147,427	10,517			131,046	26,898			98,285	59,659
2022			179,861	0			159,876	258			119,907	40,227
2023	40,286	2,839	161,143	1,215	35,809	7,316	143,238	19,120	26,857	16,268	107,428	54,930
2024	45,269	0	181,075	0	40,239	2,886	160,956	3,661	30,179	12,946	120,717	43,900
2025	50,252	0	201,008	0	44,668	0	178,674	0	33,501	9,624	134,005	32,906
2026	55,235	0	220,941	0	49,098	0	196,392	0	36,823	6,302	147,294	21,948
2027	60,218	0	240,874	0	53,527	0	214,110	0	40,146	2,979	160,582	11,026
2028	65,202	0	260,807	0	57,957	0	231,828	0	43,468	0	173,871	141
2029	70,185	0	280,739	0	62,387	0	249,546	0	46,790	0	187,160	0
2030	75,168	0	300,672	0	66,816	0	267,264	0	50,112	0	200,448	0
2031	80,151	0	320,605	0	71,246	0	284,982	0	53,434	0	213,737	0
2032	85,134	0	340,538	0	75,675	0	302,700	0	56,756	0	227,025	0
2033	90,118	0	360,470	0	80,105	0	320,418	0	60,078	0	240,314	0

8. Sustainable Business Model

The reuse of IBA and CDW as an exported alternative raw material in cement manufacturing, in structural concrete, as a fill material for road bases and sub-base layers, and fill material for land reclamation can be technically feasible as suggested by literature review. However, the financial feasibility or technical uncertainties in the Maldives context limits the reuse of IBA and CDW in many applications that might be viable in other countries.

Considering the logistics involved, the quantity of IBA available for exporting to a cement manufacturer is too small to achieve economies of scale. Similarly, uncertainties in the characteristics of CDW and low performance of IBA replaced concrete limits the reuse of IBA and CDW in structural concrete. The reuse of IBA in road construction is practiced widely in Europe and IBA is used for land reclamation in Japan port areas. However, due to the intermittent frequency and the large volumes of materials required for road and reclamation projects, the reuse of IBA or CDW is not viable for such projects in Maldives.

Concrete masonry block making is an application that has potential for the reuse of IBA and CDW aggregates in Maldives. Based on literature review, the replacement of sand with IBA is technically feasible. The performance of the blocks with r-IBA meets the required standards. Moreover, the demand forecast of sand required in 2023, the planned year to commence incineration of waste, is greater than the amount of IBA generated. Hence, all the IBA produced can be utilized. Similarly, it is recommended to crush CDW to sand size particles and reuse it for masonry block making. The forecasted demand of sand required for block production and the CDW aggregates generated become equal in year 2020, and then the demand is higher than supplied by CDW aggregates. Hence, all the CDW produced can be utilized in the block making industry, assuming 10% market penetration.

There are two business options. The first option is the CDW processing plant operator adopting forward integration and become either a supplier of IBA and CDW aggregates as raw materials to the market or starting a block production business. The consultant does not recommend the first option because the amount of IBA and CDW aggregates generated is much less than the market demand. To create a demand for the product, the operator should ensure reliability of the availability of the product in quantities demanded by the market. This concern was raised by one of the large contractors interviewed. The contractor noted he would be willing to purchase IBA and CDW at a lower cost for his block production if a continuous stream of raw materials is ensured. The contractor highlighted that IBA and CDW depends on the availability of waste, which can be variable, and hence questioned the reliability of the availability. Furthermore, IBA and CDW would probably be used to replace part of the natural sand used. Hence, contractors or block producers would like to get all the required sand from one place. In such cases, the operator might be required to get into the business of importing sand.

The second option is to use an intermediately aggregate supplier like State Trading Organization (STO) instead of directly selling it to the market. This option is more recommendable because it eliminates the risks and costs associated with trading with the market directly. STO is one of the major aggregates supplier and has established customer bases and distribution networks. Hence, adopting the second option is financially more attractive.

Table 16 shows the price comparison of different types of sand used for block production. The price of IBA and CDW aggregates are the prices suggested by the consultant in the feasibility study. As observed the unit price of IBA and CDW aggregates are significantly cheaper. Since the materials are substitute goods, a drastic reduction in price would increase the demand for the IBA and CDW aggregates, provided the performance is assured.

Table 16. Price comparison of sand used for concrete masonry block production and IBA and CDW

	Price (MRV/Mg)	**Price (USD/Mg)**
Sand (fine aggregates)	794.18	51.5
Local sand	225	14.59
IBA	77.1	1 – 5
CDW aggregates	33.55	1 – 2.18

9. Recommendations

Concrete masonry block and pavement block production is a potential application for utilization of IBA and CDW in Maldives. Use of IBA and CDW in non-structural applications such as use in floor screed concrete could be a potential market too.

The demand forecast shows the generation of IBA and CDW could be less than the demand required by the block production industry, provided 100% market penetration is possible. It is recommended that Government should promote the use of IBA and CDW through campaigns to assure the technical and safety suitability of the waste products.

The general response of stakeholders consulted is promising and many are willing to accept the product if the price is significantly lower than natural aggregates and the performance of the product meets the standards, often international standards.

There are no existing local standards directly related to IBA or CDW, mainly because these are new products in the Maldivian market. However, new regulations governing the reuse of IBA and CDW should be expected soon as Ministry of Environment is in the process of formulating environmental regulations to IBA and CDW. Hence, it is suggested that treating of IBA and CDW is critical to ensure the characteristics and performance confirms to international best practices and consequently the acceptance of r-IBA and processed CDW as a building material in Maldives.

It is recommended to introduce the products to the market through intermediately aggregates supplier. Additionally, the price should be significantly lower than natural aggregates to drive the demand for IBA and CDW.

10. References

Brito, J. d., & Saikia, N. (2013). *Recycled Aggregate: Use of Industrial, Construction and Demolition Waste.* London: Springer.

Guo, L., & Wu, D. -Q. (2018). Study of leaching scenarios for the application of incineration bottom ash and marine clay for land reclamation. *Sustainable Environment Research*, 396-402.

Guo, L., & Wu, D.-Q. (2017). Study of recycling Singapore solid waste as land reclamation filling material. *Sustainable Environment Research*, 1-6.

Lam, C. H., Ip, A. W., Barford, J. P., & McKay, G. (2010). Use of Incineration MSW Ash: A Review. *Sustainability*, 1943-1968.

Liu, A., Lin, W. Y., & Wang, J. Y. (2015). A review of municipal solid waste environmental standards with a focus on incinerator residues. *International Journal of Sustainable Built Environment*, 165–188.

Lynn, C. J., Ghataora, G. S., & Dhir, R. K. (2017). Municipal incinerated bottom ash (MIBA) characteristics and potential for use in road pavements. *International Journal of Pavement Research and Technology*, 185-201.

Lynn, C. J., Ghataora, G. S., & Dhir, R. K. (2018). Environmental impacts of MIBA in geotechnics and road applications. *Environmental Geotechnics*, 31-55.

Lynn, C., Dhir, R., & Ghataora, G. (2016). Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete. *Construction and Building Materials*, 504-517.

Maldives Monetary Authority . (2014). *Annual Report 2013.*

Maldives Monetary Authority. (2010). *Annual Report 2009.*

Maldives Monetary Authority. (2018). *Annual Report 2017.*

Neville, A. M., & Brooks, J. J. (2010). *Concrete Technology.* Harlow: Pearson Education Limited.

Nguyen, L. C., Inui, T., Ikeda, K., & Katsumi, T. (2015). Aging effects on the mechanical property of waste mixture in coastal landfill sites. *Soils andFoundations*, 1441-1453.

Pan, J. R., Huang, C., Kuo, J.-J., & Lin, S.-H. (2008). Recycling MSWI bottom and fly ash as raw materials for Portland cement. *Waste Management*, 1113-1118.

Singh, D., & Kumar, A. (2017). Geo-environmental application of municipal solid waste incinerator ash stabilized with cement. *Journal of Rock Mechanics and Geotechnical Engineering*, 370-375.

Tang, Q., Gu, F., Chen, H., Lu, C., & Zhang, Y. (2018). Mechanical Evaluation of Bottom Ash from Municipal Solid Waste Incineration Used in Roadbase. *Advances in Civil Engineering*.

Water Solutions and Kocks Ingenieure. (2018). *Feasibility Study for an Integrated Solid Waste Management System for Zone III and Preparation of Engineering Design of the Regional Waste Management Facility at Thilafushi.*

Fly Ash Management Plan
(Handling of Air Pollution Control Residues)
Greater Male Waste-to-Energy Project

1 Generation of Air Pollution Control Residues

As per Employer's Requirements (ERQ) of the envisaged DBO Contract, the Air Pollution Control (APC) system shall consist of a semi-dry or dry system that will generate hazardous residues containing the acid and organic flue gas components and heavy metals in a soluble form which require careful handling. The volume of APC residues depends on the type of absorbent used to clean the flue gases. According to a preliminary mass balance prepared during the feasibility study around 50 kg APC residues per tonne of waste will be generated. In total, approx. 8,500 tonnes are expected to be generated every year if the facility runs at full capacity. According to the European BAT Reference Document for Waste Incineration (BREF) Document that is to be applied, APC residues including the fly ash that is retained by the APC system must not be commingled with the boiler ash and the bottom ash.

APC residues are regarded in all countries that are incinerating waste as hazardous due to their heavy metal content in an easily leachable form. Subject to the absorbent and, of course, the type of waste incinerated, the composition of the APC residues may be characterised as listed in Table 1 (heavy metals highlighted in dark grey).

Table 1: Components of the residues of a semidry/dry APC system[1]

Element	Content in mg/kg
Ca	110,000 – 350,000
K	5,900 – 40,000
Mg	5,000 – 14,000
Na	7,600 – 29,000
Si	36,000 – 120,000
Cl	62,000 – 380,000
S	1,400 – 25,000
Al	12,000 – 83,000
Fe	2,600 – 71,000
As	18 – 530
Ba	51 – 14,000
Cd	140 – 300
Cr	73 - 570
Cu	16 – 1,700
Hg	0.1 – 51
Mn	200 – 900
Mo	9 – 29
Ni	19 – 710
Pb	2,500 – 10,000
Sb	300 – 1,100
V	8 – 62

[1] according to Chandler, Eighmy, Hartlém, Hjelmar, Kosson, Sawell, von der Sloot, Vehlow: Municipal solid waste incinerator residues (1997), cited in Management of APC residues from WtE Plants, ISWA 2008

Zn	7,000 – 20,000

Besides the combustion conditions in the furnace (2 sec, 850°C), the homogeneity of the conditions across the furnace cross section and a sufficient turbulence in the post combustion chamber is an important parameter to control the dioxin and furan contents of the APC residues. Measurements in UK from 2004 revealed concentration between 800 and 1,750 ng TEQ/kg while eluates did not show a significant level above background contamination which was between 0.4 and 2 pg/l[2].

2 Envisaged APC residue treatment and other nations current disposal practices

Because no worldwide methodology or guideline on how to deal with APC residues in an environmentally sound and technically feasible manner has been established, most nations do follow their own approach which again is subject to the local conditions such as availability of disposal sites, national legislation and the costs of the APC residue treatment.

In Germany, APC residues from dry/semi-dry system are usually stored in old salt mines as backfilling material (only if water ingress can be ruled out). Facilities in France with bicarbonate as absorbent apply an extraction of heavy metals at pH 9 and thus try to reuse the bicarbonate (which yet contains chloride) from the so obtained brine. As disposal option for the heavy metals, hazardous waste landfills are used. Dutch facility uses big bags with inlet liners and douses the APC residues during unloading with water to trigger pozzolanic reactions. By this, the APC residues solidify while the inlet liners of the big bags prevent water seepage into the big bags.

In the USA, APC residues are stored mostly in hazardous waste landfills. Some facilities use the bottom ash to stabilise the APC residues (due to pozzolanic effect of bottom ash after dousing with water).

Some Japanese facilities (appr. 30) vitrify both the bottom ash and APC residues, thus obtaining a highly concentrated and salt-rich residue (which is difficult to handle though). Costs for this kind of treatment are significant and can be as high as $500/tonne of residue.

Deliberately, a stabilisation/solidification of the APC residues or any other treatment method was not explicitly prescribed to allow the DBO Contractor to develop a solution that meets the local requirements. Adding cement, for example, can, subject to the absorbent used in the APC system, triple the amount of residues to be landfilled which may be a costly undertaking in the Maldives. Hence, other pozzolanic reaction inducing additives have to be selected if the Contractor opts for such a solution. Space requirements for storing the stabilised bricks while they undergo the transformation was another factor which cannot be ignored. A plant to process around 25 tonnes per day requires 40mx20m, most of the space for storage to allow the bricks to solidify – up to 8 weeks.

[2] Testing of residues from incineration of municipal solid waste, UK Environment Agency, 2004

Whether and to what extent, the DBO Contractor will use the residues after the bottom ash treatment to trigger a pozzolanic reactions, shall be left to the sole discretion of the Contractor which is in line with the general principles of a DBO contract to stimulate the competition of the bidders to present the technically most robust but an economically attractive solution.

Because the Maldives do not have a comprehensive environmental regulatory framework yet, the European standards that according to the BREF Document do require a separate handling of the bottom ash and the APC residues are regarded as the best option to maximise the reuse of the bottom ash and to concentrate the toxic substances within the smallest volume of residues, i.e. the APC residues. Since the BREF Document does not define the landfilling and the treatment of the APC residues and a DBO Contractor may have a preference for the one or other treatment option, it shall be left to the DBO Contractor to develop the solution against the standards that are defined in the ERQ.

During the design review, the Contractor has to provide the full documentation of for the APC residue handling. In the event it does not meet good international industrial practice or does not achieve the desired design standards, the Employer has any right to request modification.

3 Design Build Requirements as per ERQ

To avoid any impact to the environment and to the Contractor’s personnel safety, the Contractor’s design shall consider the following for conveying and loading APC residues:

- APC residues shall not be mixed with bottom or boiler ash prior to the bottom ash treatment.
- APC residues shall be conveyed in closed conveying systems that end up in storage silos whose exhaust air can be dedusted via a central dedusting system.
- The top of the bag filter housing shall be enclosed and shall be connected to the central dedusting system (while pulling/replacing bag-filter hoses).
- Discharging the APC residues from the silos into water-tight jumbo bags (with inlet) or into the transfer vehicles shall be carried out via dust-tight discharging chutes.
- APC residues shall be treated by either stabilization/solidification or via triggered pozzolanic reaction prior to landfilling to limit the leachability of heavy metals.

The ERQ request the Contractor to design and construct the landfill for the APC residues according to the European Landfill Directive 1999/31/EC and its latest amendment 2018/850/EC. The design of the landfill – i.e. whether a single compartment or different compartments for the APC residues and the remaining bottom ash – shall be subject to the design considerations of the Contractor. In any case, the Contractor shall take account of the following:

- The barrier system shall encompass an artificially completed/reinforced geological barrier (thickness shall be not less than 0.5 m) that can offer an equivalent protection as defined in the European Landfill Directive 1999/31/EC for hazardous wastes. An impermeable artificial liner for at least the compartment that is designated for the APC residues shall be provided. Given that Maldivian soils do not offer a geological barrier having a hydraulic conductivity of less than 10^{-9} m/s and a thickness of more than 5 m, the artificial geological barrier is the only way to apply to multi-barrier system.

- The compartment, if any, for the residues from the bottom ash processing shall be provided with an artificially completed geological barrier. Its thickness shall not be less than 0.5 m and shall meet the hydraulic resistance requirements for non-hazardous waste as stipulated in the European Landfill Directive.
- The barrier system shall be designed to allow minimizing the leachate generation by dividing the compartments into cells that will accommodate waste subsequently according to the filling plan of the landfill.
- The lower level of the engineered barrier shall be no deeper than 1.5 meters above mean sea level and in accordance with the applicable environmental standards;
- Prior to construction, the Contractor shall prepare a test pad to demonstrate the effectiveness of the proposed engineered barrier.
- In the design of the Contractor, a composite cover system shall be included (see also operational requirements).

For the leachate management, the Contractor shall take into consideration the following:

- The design shall warrant a minimized leachate generation applying means, such as, but not limited to, constructing a shed above the hazardous waste compartment, separating not contaminated water from leachate by installing gate valves, constructing bunds to control the leachate flows, etc.
- The design of the Contractor shall take account of that leachate from different compartments for APC residues and residues from the bottom ash processing are collected and treated so that the leachate discharge standards are met any time. Applying strictest discharge standards is the only way to control the APC residue disposal in the Maldives case.
- The Contractor shall design and build or organize a system for the safe collection, transport and disposal of the LTP concentrate.
- Subject to its design, the Contractor shall re-inject the concentrate after the leachate treatment in the air pollution control system or shall evaporate it. In the latter case, the residues shall be disposed on the landfill so that no accumulation of the highly soluble material is to be concerned.
- Monitoring wells to detect any potentially escaping leachate shall be installed.

4 Requirements during Operation Service Period

Focusing on the APC residues, during landfilling the Contractor shall consider:

- APC revenues shall be disposed safely to landfill meeting the European standards (1999/31/EC) as defined for hazardous waste. Safe disposal means that APC residues shall be unloaded either into water-tight jumbo bags in a semi-solid state (after dousing with water) or shall be stabilized/solidified. Given that APC residues are the only type of hazardous waste, no acceptance tests are needed.
- The Contractor shall dispose of all APC residues and any other residual wastes (i.e. excluding bottom ash for recycling and valuable wastes to be exported for reuse) to the dedicated landfill cells located within the Site, in accordance with the approved

Residual Waste Plan which requests the Contractor to assign the landfill areas for the disposal of the APC residues.

- The method of APC residue disposal shall be as detailed in the Contractor's approved Operation and Maintenance Plan and the Contractor's approved Annual Residual Waste Plan. The Contractor shall arrange all APC disposal as necessary to achieve the most efficient use of the available landfill volume.
- The Contractor shall minimize the generation of leachate by applying control measures including, but not limited to, closing gate valves where appropriate, covering landfill areas that are not needed as working face with impermeable liners, preparing an optimized Residual Waste Plan.
- During the Operation Service Period, the Contractor shall prepare a closure plan that shall including the following:
  - A stability calculation of the envisaged final shape of the landfill body demonstrating its stability considering appropriate friction and slippage coefficients of the materials landfilled and the cover layers applied.
  - A contour layer to smoothen the final shape of the landfill body.
  - A complemental dual cover system for the hazardous APC residues so that in the event one layer fails the other layer can withstand the ingress of water. In the event a mineral layer is applied, the layer shall provide a calculated percolation rate similar to a mineral layer of at least 0.5 m thickness having a permeability coefficient of not greater than $5x10^{-10}$ m/s at a constant water head of 0.3 m. If a geomembrane is used, its thickness shall be not less than 2.0 mm.
  - A leakage control system shall be applied for the dual cover system.
  - A sufficiently dimensioned drainage layer (thickness $\geq$ 0.3 m, permeability coefficient $\geq 5x10^{-3}$ m/s).
  - A recultivation layer incl. a natural vegetal cover (thickness > 0.5 m) that meets the local conditions
- The leakage control system shall be operated after closure of the landfill (sub)cells. Samples shall be taken every quarter and fingerprint analyses shall be carried out.
- Samples from the monitoring wells shall be analyzed regularly (at least once per quarter) for parameters such as PAHs, phenols, cadmium, chromium (hexavalent and total), copper, iron, lead, mercury, nickel, zinc.

Requirements towards the APC residues handling and the components necessary to retain APC residues include:

- The Contractor shall handle and dispose of all APC residues and ensure that processing is conducted in a manner that prevents fugitive emissions and escape of dust.
- Bag filter hoses shall be replaced only if the central dedusting system is operational.
- Unloading the silos shall be carried out using dust-tight unloading chutes only.
- The area around the APC residues silo shall be kept clean at all times and spills shall be dealt with immediately.
- The driver of the APC residues transport vehicle shall be required to use personal protective equipment during loading and unloading to prevent the inhalation of dust and fumes.

Environmental and Social Impact Assessment for the Regional Solid Waste Management Facility (RSWMF) Thilafushi

Marine Survey Report

Thilhafushi house reef. Photo by: Water Solutions

Prepared by: Abdul Aleem (EIA P03/2019), Mohamed Umar (EIA P02/2019) & Abdulla Fazeel

23rd September 2019

Contents

List of Figure

1 Introduction

The marine environment survey of Thilafushi covered the shallow lagoon, deep lagoon, reef-flat, and reef slope of the house reef of areas of Thilafushi Island. Thilafushi consists of deep, shallow lagoon, reef flat and reef slope areas. More than half of the shallow lagoon or reef flat area is now reclaimed. The south wing of Thilafushi is wider compared to north wing. The widest reef flat area is on the south wing on the west side of the reef. The enclosed deep lagoon area towards east is well protected with very restricted water movement. This area is used by vessels as a mooring basin. The stagnant water coupled with waste dumping in this area has degraded the lagoon environment on the east side. The deep lagoon of this area has very low visibility, the bottom substrate of the deep lagoon consists mainly of sand. Towards the east of deep lagoon, the bottom substrate is mainly mud and garbage debris.

2 Scope of work

The marine survey at Thilafushi has been conducted to cover the marine component of the TOR for the EIA for the Establishment of the Regional Waste Management Center for Zone III issued by EPA. Hence the TOR requested to assemble, evaluate and present baseline data on the relevant environmental characteristics of the study area, focused on the marine environment. Aspects of the environment shall be described to the extent necessary for assessment of the environmental impacts of the proposed development. The extent and quality of the available data shall be characterized indicating significant information deficiencies and any uncertainties associated with the prediction of impacts.

All available data from previous studies, if available shall be presented. Information required includes the following:

Assessment of the marine environment should be undertaken from all locations from which data was taken in 2011 EIA report. This assessment should cover coral cover and fish census information. Plankton Assessment from 05 different locations around Thilafushi. Areas of special sensitivity including coral reefs and marine protected areas near Thilafushi shall be marked on a map and described. This shall include environmentally sensitive areas, protected areas and significant dive sites.

3 Methodology

A coral reef survey of Thilafushi reef was carried out to establish a baseline of the existing coral reef environment. The baseline assessment assessed the diversity and abundance of coral reef, fish, and significant invertebrates that are commonly associated with the reef environment of Maldives. The method involved determining percentage of various benthic substrate (categories) using standard benthic categories for coral reef benthic substrate sampling as described by Hodgson et.al (2006) in Reef Check Instruction Manual: A Guide to Reef Check Coral Reef Monitoring.

Site selection for the marine survey was based on the location of the WTE, existing dumpsite, and proposed hotwater outfall and seawater intake and as well as control sites for future monitoring purposes. At survey sites M1 to M7 benthic composition and fish abundance was surveyed at depths of 5 meters and 10 meters and at survey sites M8 to M10, surveys were done to a depth of 30 metres along the reef profile. A Manta Tow survey was conducted along 500 metres from M9 to M10 along the reef edge on the southern side of Thilafushi at both 5 and 10 metres. The inner lagoon was not surveyed as the area is not of ecological importance.

The marine benthic and fish surveys at Thilafushi Island was focused on 10 sites. Plankton tows and water samples were done at 7 sites on 23rd – 24th April 2018. Marine surveys were done at marine sites M1 to M7 on 23rd – 24th April 2018 2018. Three sites, M8 to M10 were surveyed on 1st September 2019 as more detail marine survey was requested to locate the hot water discharge location on southern side of Thilafushi. These three sites were chosen within a 500 m zone on the southern side of Thilafushi as shown in Figure 3. M8 was one of the potential site to locate the hot water discharge outfall.

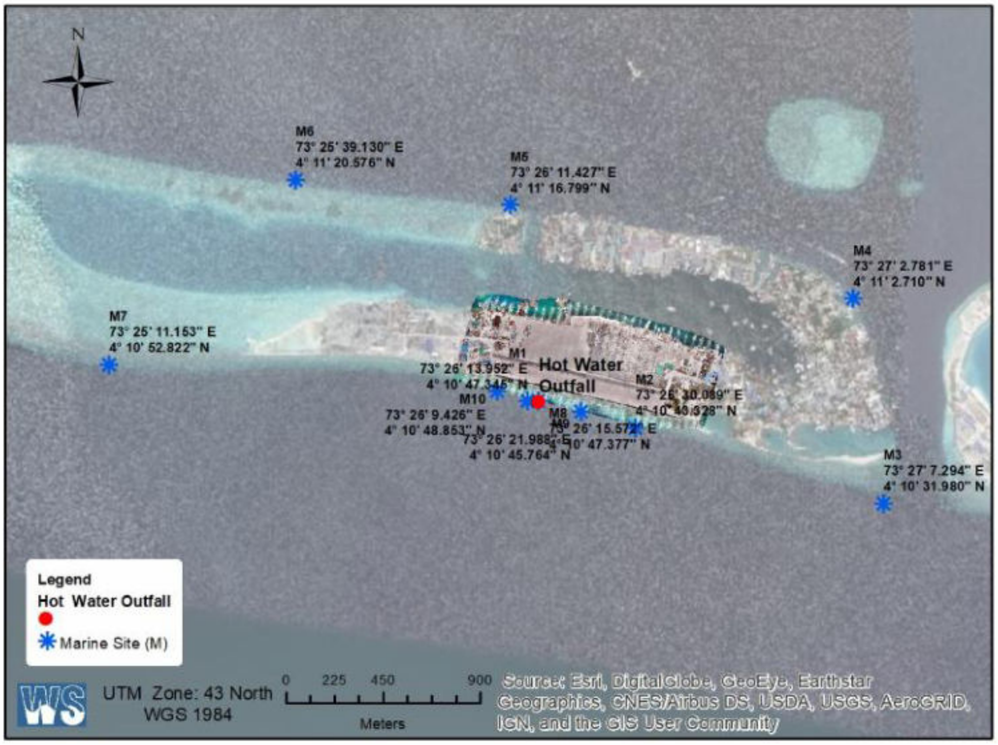


Figure 1: Marine surveyed locations with coordinates in 23rd – 24th April 2018 and 1st September 2019

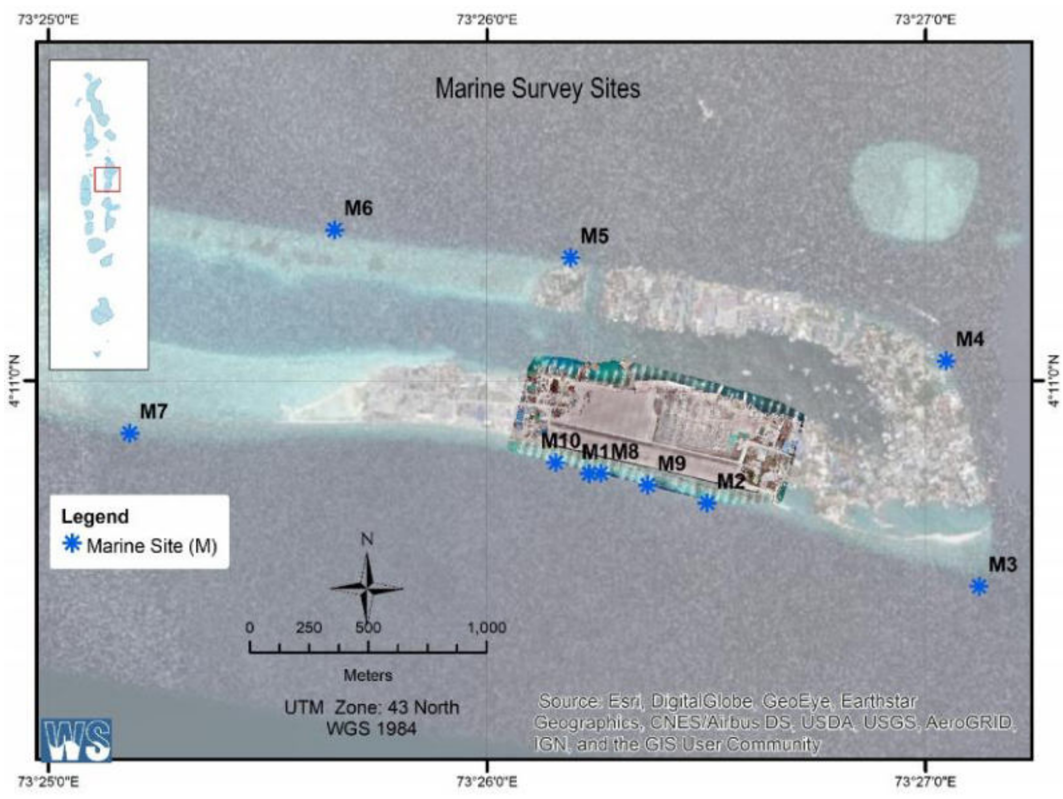


Figure 2: Marine surveyed locations with coordinates in 23rd – 24th April 2018 and 1st September 2019

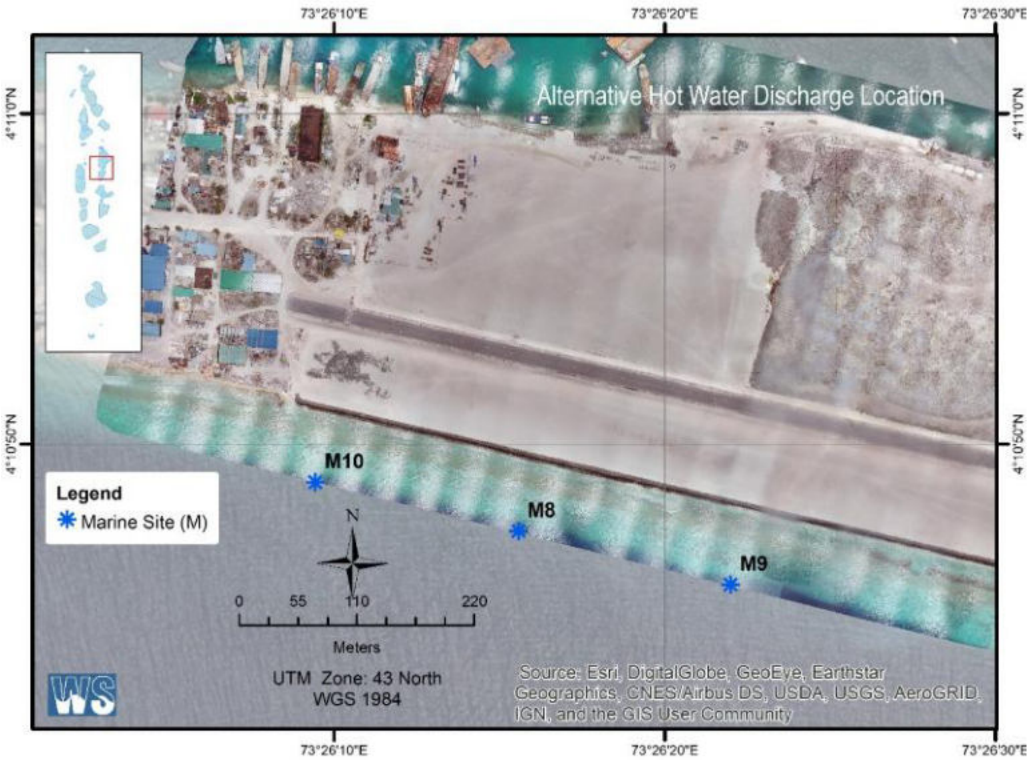


Figure 3: Marine surveyed locations on 1st September 2019

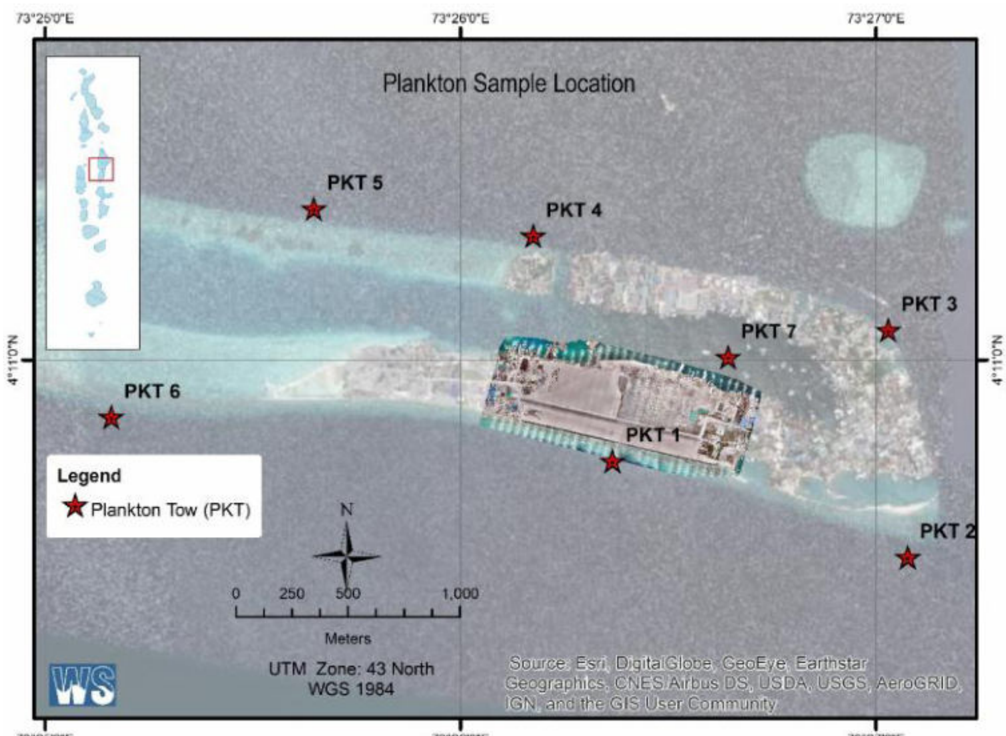


Figure 4: Plankton tows and water sampled location on 23rd – 24th April 2018

3.1 Benthic Survey

All surveys were carried out by underwater SCUBA diving. The marine surveys were carried out by surveyors who had been trained to undertake Reef Check surveys as outlined in the Reef Check Instruction Manual: A Guide to Reef Check Coral Reef Monitoring (2006). Based on the Guide to Reef Check Coral Reef Monitoring (2006) photo quadrat surveys were done in order to measure the benthic composition 10 sites (M1-M10) located on areas on the outer reef around Thilafushi island. At the survey sites M1 to M7 benthic composition and fish abundance was surveyed at depths of 5 meters and 10 meters. At survey sites M8 to M10, marine surveys were done to a depth of 30 metres along the reef profile.

3.1.1 Surveys in April 2018

The photo quadrat surveys were undertaken at marine site M1 to M7. A transect line of 20 metres at each site is set out, the surveyor then places a half a metre quadrat made from PVC along the transect line and takes a photo directly from vertically above. The second photo is then taken along in the same manner after approximately 1 m away from the first photo. In this manner, photos are taken along the transect line and in total, 10 photos on each transect line are taken. In each of the sites 4 transects were place in two depths (5 & 10m). The surveys were undertaken on 23-24 April 2018.

3.1.2 Reef profile Survey in September 2019

Marine survey sites M8 to M10, were three additional sites surveyed using photo quadrat methods. Unlike the conventional reef transect surveys, the three sites were assessed for benthic composition by undertaking photo quadrates from the top reef up to 30 metres, along the reef profile.

Before start of the survey, the starting points were marked using a plastic bottle tied with a rope and weight at its end. The weight rested at the top reef, approximately 5 metres from the reef slope. This allowed the divers to descent from the exact required location up to 30 metres.

Photos were taken using the half metre quadrat made from PVC along the transect line (vertical) and takes a photo directly from above. The second photo is then taken along in the same manner after approximately 1 below the first photo. In this manner, photos are taken along the transect line.

3.1.3 Manta Tow survey in September 2019

A Manta Tow survey was conducted along 500 metres from M9 to M10 along the reef edge on the southern side of Thilafushi at both 5 and 10 metres. Manta towed was conducted by swimming along the stretch and recording the observations on an underwater slate. The tow at 5 metres was undertaken with the help of a boat which towed the swimmer along the survey stretch using a rope.

The parameters observed include percentage cover of live coral, other benthic organisms, substrate diversity of the reef in terms of benthic and pelagic life. Overall status of the reef along this stretch was determined based on this survey and the results are outlined below.

4 Data Processing methodology

Analysis of the photos was done using a computer program called, CPCe (Coral Point Count with Excel extensions). This is an internationally recognized software used all over the word to assess the benthic composition of the reefs. In this programme, photographs are analyzed using pre-defined benthic categories. Depending on the type of survey, these categories can be user defined at any given level. Users can have very complex levels ranging from individual coral families or have broader assessment categories. As the objective of this survey was to assess the impact of dredging and reclamation, it made sense to use a broader categories. Hence, benthic categories adopted by the Reef Check protocol were utilized. A text file containing these categories was created and imported to CPCe. The Reef Check protocol allows categorizing life forms followed under the Reef Check protocol, which emphasizes on benthic composition categorizing such as hard corals, sand, rock and others. The emphasis is not on recording corals to their species levels, but rather the general coral and other life forms such as hard and soft corals. This method is more accurate as the percentage of healthy coral cover and other life forms can be more accurately recorded even by a non-experienced surveyor.

The following are definition of benthic categories used in this survey.

- **HC:** All living coral including bleached coral; includes fire, blue and organ pipe corals
- **SC**: Include zoanthids but not anemones (OT)
- **DC**: Coral that has died within the past year; appears fresh and white or with corallite structures still recognizable
- **ALG**: All macro-algae except coralline, calcareous and turf (record the substrate beneath for these); Halimeda is recorded as OT; turf is shorter than 3cm.
- **SP**: All erect and encrusting sponges (but no tunicates).
- **RC**: Any hard substrate; includes dead coral more than 1 year old and may be covered by turf or encrusting coralline algae, barnacles, etc.
- **RB**: Reef rocks between 0.5 and 15cm in diameter
- **SD**: Sediment composed of particles of less than 0.5cm in diameter; in water, falls quickly to the bottom when dropped.
- **SI**: Sediment that remains in suspension if disturbed; recorded if color of the underlying surface is obscured by silt.
- **OT**: Any other sessile organism including sea anemones, tunicates, gorgonians or non-living substrate.
- **SG**: All types of sea grass observed categorized in the field SG.

Each of the 10 photos from transect are imported, cropped and prepared for analysis. The CPCe program then generates a matrix of random points overlaid on the image for each point to be visually identified. Users can then input the defined categories for each photo and once all the photos are analysed, the results are displayed on a table.

5 Results of the marine survey

5.1 Status of site 1 (M1)

Site 1 was selected from the Southern rim of the island reef. The site was chosen as the site was adjacent to the proposed waste rehabilitation centre. The substrate at the site is dominated by rock at depths of 5 (58 ± 14.2%) and 10 (64.5 ± 2.78) meters respectively. Hard coral cover was observed to be moderate at the site at depths of 5 (19.5 ± 5.91) and 10 (21 ± 2.68) meters. Massive porites were the dominating the group of hard coral observed at the site at both the depths. Fishes observed to be abundant at a depth of 5 meters were surgeon fishes, damselfishes and butterfly fishes. Fishes observed to be abundant at a depth of 10 meters were anthias, damselfishes and triggerfishes. The following graph outlines the status of site 1(M1) at depths of 5 and 10 meters.

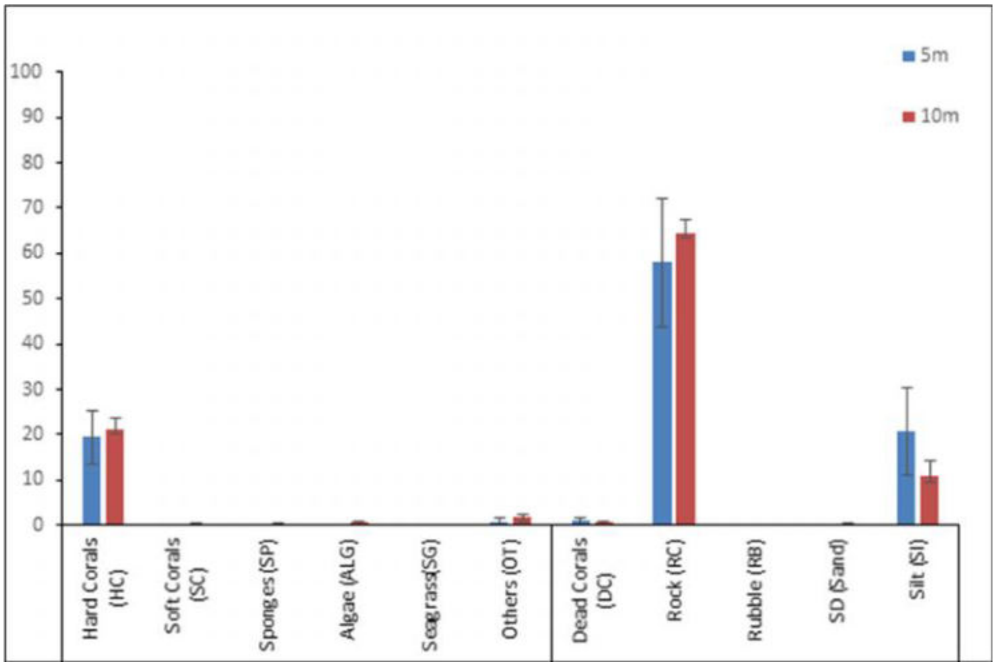


Figure 5: Percentage benthic composition at site 1(M1) at depths of 5 and 10 meters ± Standard Error (SE) (23rd April 2018).

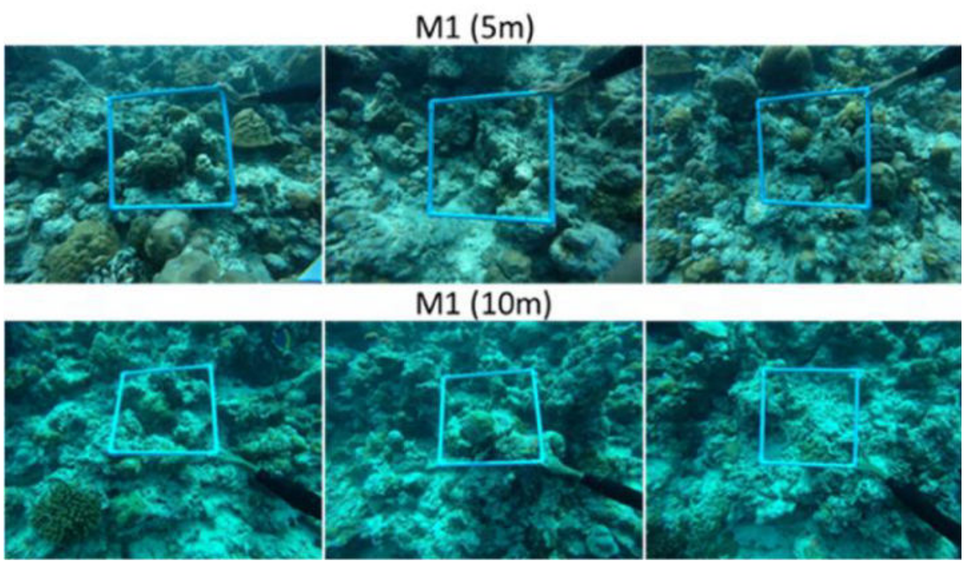


Figure 6: Photos taken from site 1 at depths of 5 and 10 meters (M1) (23rd April 2018).

5.2 Status of site 2 (M2)

Site 2 was selected from the Southern rim of the island reef east of site 1. The site was chosen as the site was adjacent to the proposed waste rehabilitation centre. The substrate at the site is dominated by rock at depths of 5 (71.25 ± 3.86%) and 10 (63 ± 6.14) meters respectively. Hard coral cover was observed to be moderate at the site at depths of 5 (22.25 ± 2.95) and 10 (23.25 ± 5.17) meters. Massive porites were the dominating group of hard coral observed at the site at both the depths. Fishes observed to be abundant at depth of 5 meters were anthias, surgeon fishes, damselfishes, parrotfishes, triggerfishes and butterfly fishes. Fishes observed to be abundant at depth of 10 meters were anthias, damselfishes, butterfly fishes and triggerfishes. The following graph outlines the status of site 2(M2) at depths of 5 and 10 meters.

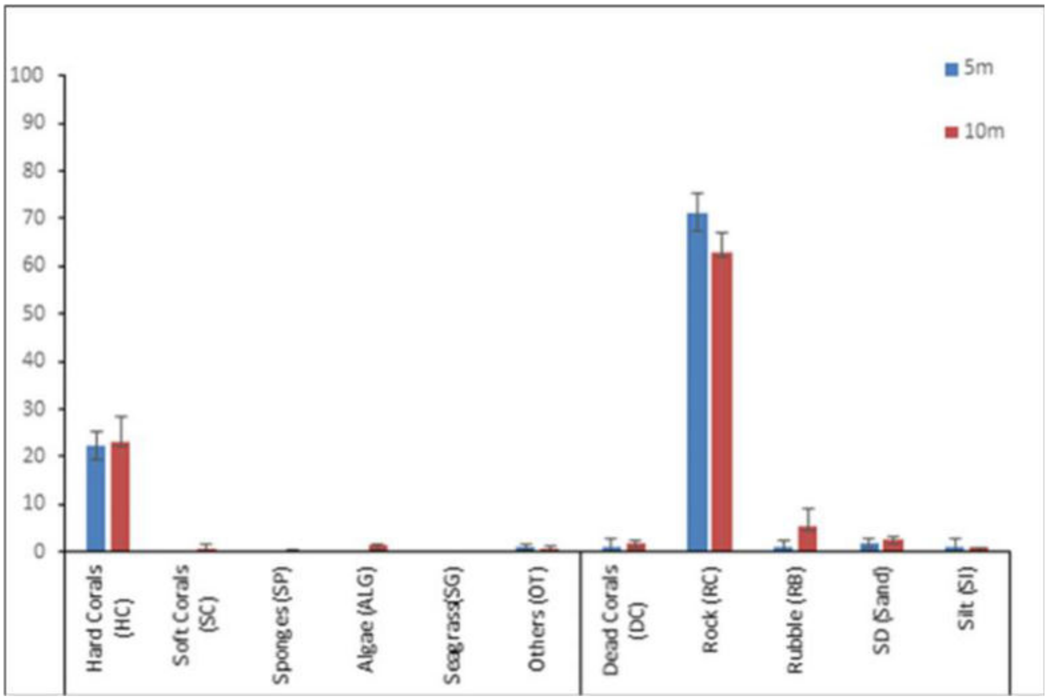


Figure 7: Percentage benthic composition at site 2 (M2) ± SE (24th April 2018).

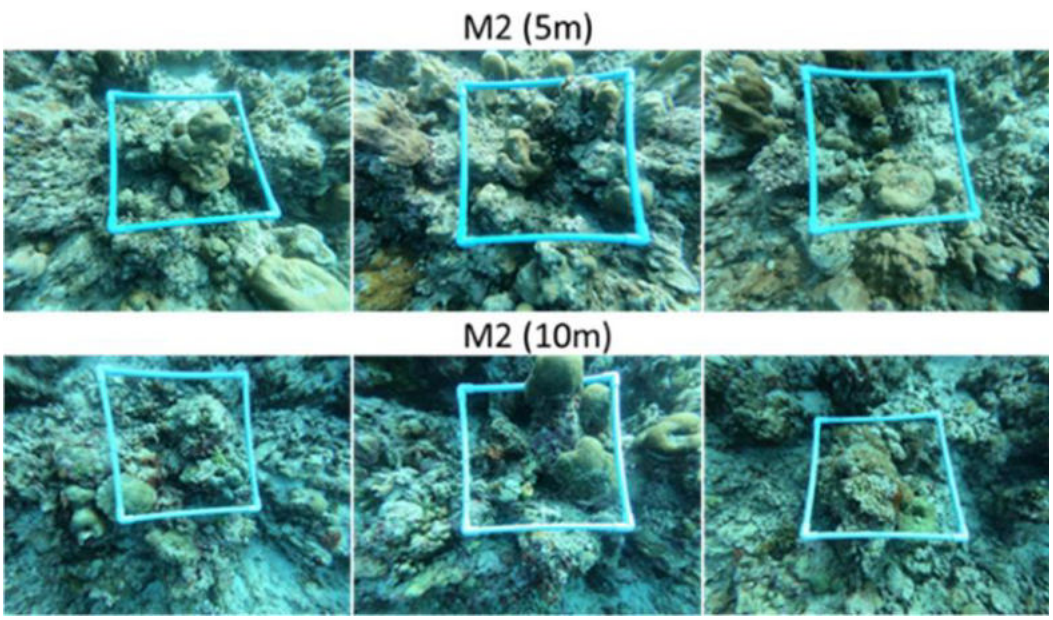


Figure 8: Photos taken from site 2 (M2) (24th April 2018).

5.3 Status of site 3 (M3)

Site 3 was selected from the Southern eastern corner of the island reef. The site was chosen as a control site as well as to get a broader understanding of the ecological baseline around the reef. The substrate at the site is dominated by rock at depths of 5 (76.25 ± 2.10%) and 10 (65.75 ± 2.46) meters respectively. Hard coral cover was observed to be moderate at the site at depths of 5 (17 ± 2.48) and 10 (16.5 ± 0.65) meters. Massive porites were the dominating group of hard coral observed at the site at both the depths. Fishes observed to be abundant at a depth of 5 meters were surgeon fishes and jacks and trevallies. Fishes observed to be abundant at a depth of 10 meters were anthias, damselfishes and triggerfishes. The following graph outlines the status of site 3(M3) at depths of 5 and 10 meters.

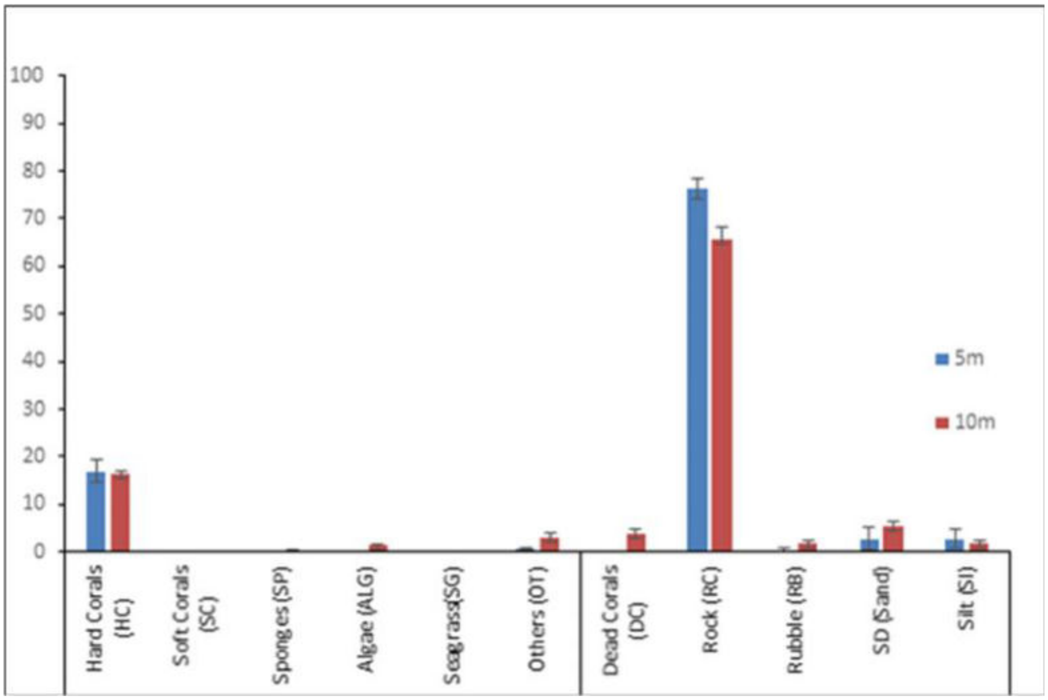


Figure 9: Percentage benthic composition at site 3 (M3) ± SE (23rd April 2018).

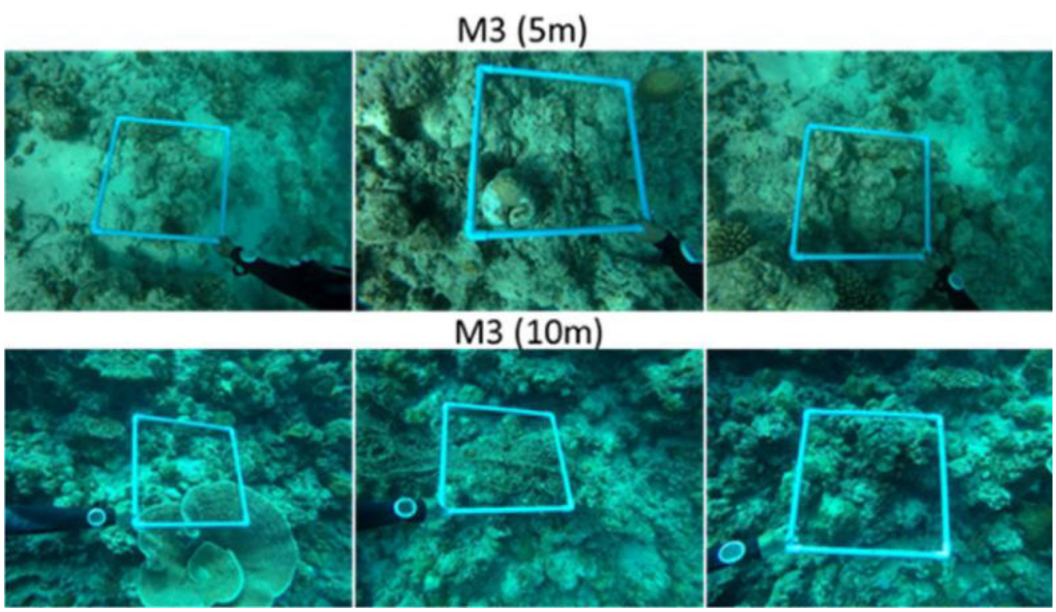


Figure 10: Photos taken from site 3 (M3) (23rd April 2018).

5.4 Status of site 4 (M4)

Site 4 was selected from the North-eastern rim of the island reef. The site was chosen as a control site as well as to get a broader understanding of the ecological baseline around the reef. The substrate at the site is dominated by rubble at depths of 5 (67 ± 4.49%) and 10 (60 ± 6.42) meters respectively. Hard coral cover was not observed at the site at depths of 5 and 10 meters. Fishes observed to be abundant at a depth of 5 meters were surgeon fishes, butterfly fishes and fusiliers. Fishes observed to be abundant at a depth of 10 meters were only fusiliers. The following graph outlines the status of site 4(M4) at depths of 5 and 10 meters.

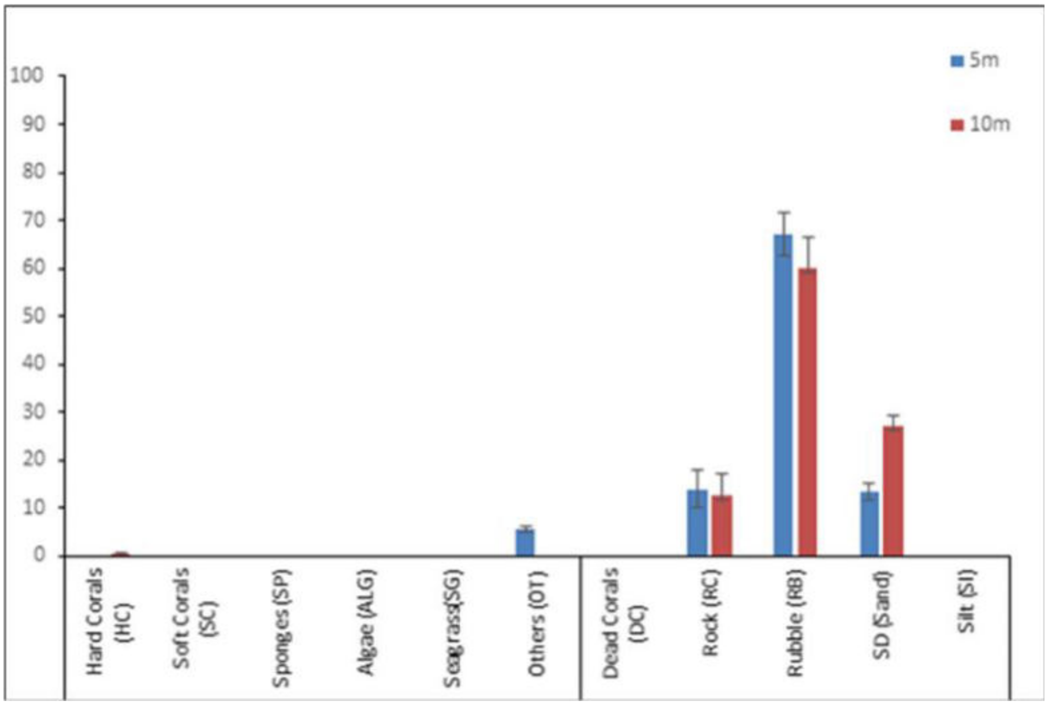


Figure 11: Percentage benthic composition at site 4 (M4) ± SE (24th April 2018).

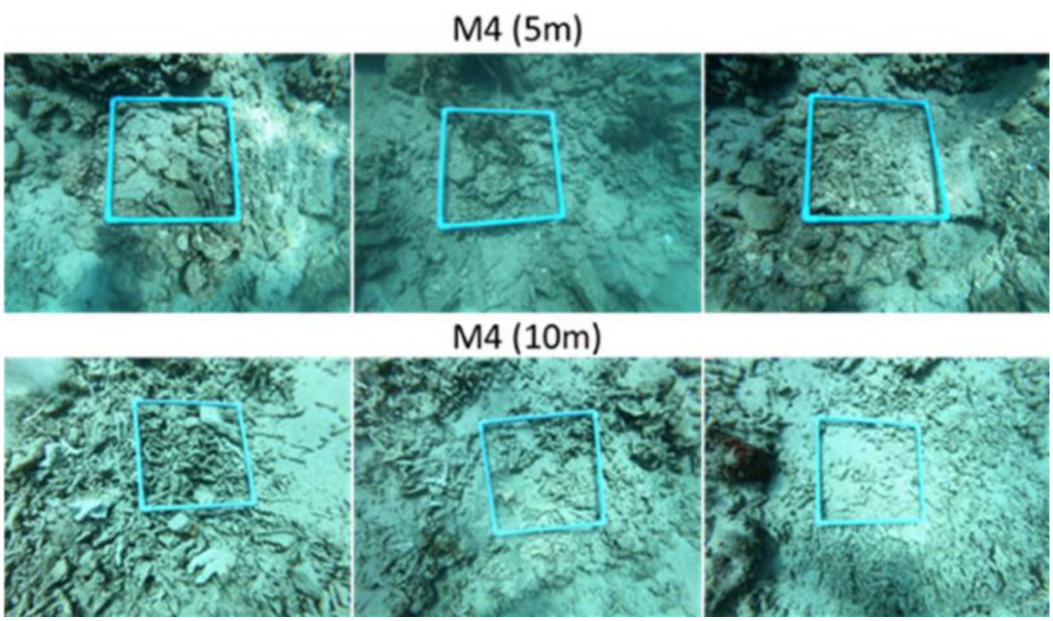


Figure 12: Photos taken from site 4 (M4) (24th April 2018).

5.5 Status of site 5 (M5)

Site 5 was selected from the Northern rim of the island reef close proximity to the entrance channel. The site was chosen as a control site as well as to get a broader understanding of the ecological baseline around the reef. The substrate at the site is dominated by rock at depths of 5 (46.75 ± 6.28%) and 10 (51.5 ± 5.81) meters respectively. Hard coral cover was observed to be low at the site at depths of 5 (5 ± 1.58) and 10 (4.25 ± 0.75) meters. Massive porites were the dominating group of hard coral observed at the site at both the depths. Fishes observed to be abundant at a depth of 5 meters were surgeon fishes and parrotfishes. Fishes observed to be abundant at a depth of 10 meters were surgeon fishes, damselfishes and triggerfishes. The following graph outlines the status of site 5(M5) at depths of 5 and 10 meters.

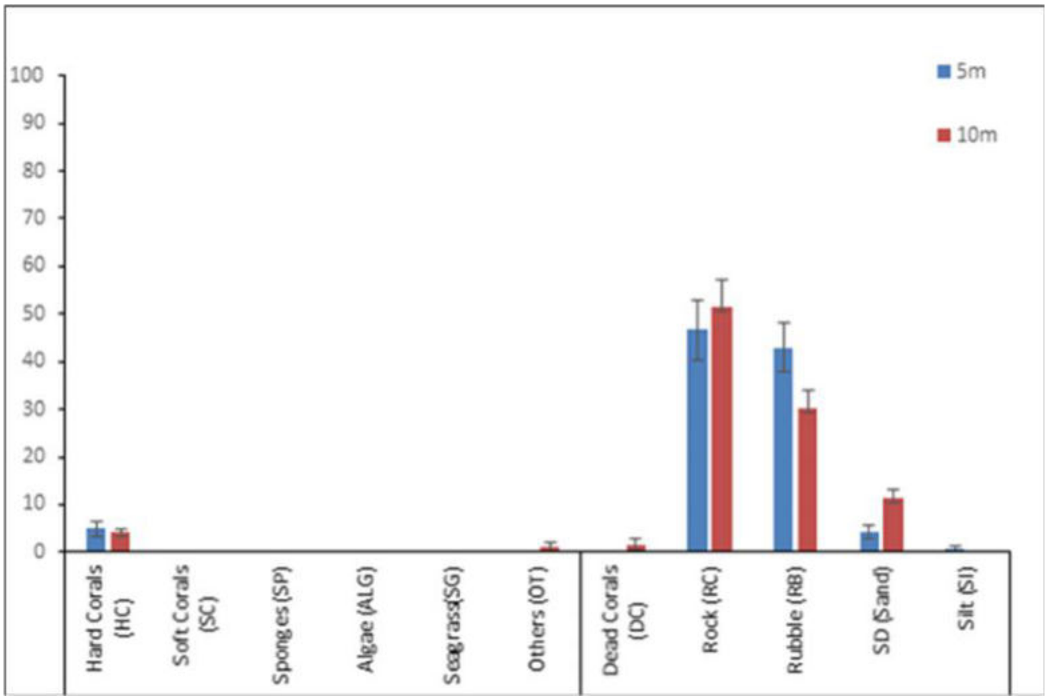


Figure 13: Percentage benthic composition at site 5 (M5) ± SE (24th April 2018).

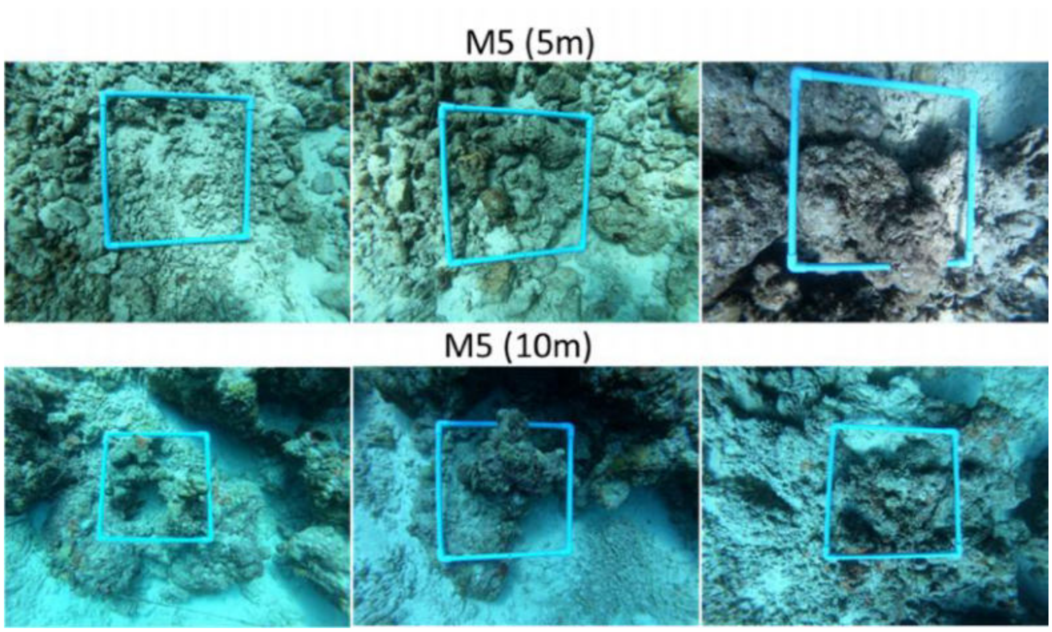


Figure 14: Photos taken from site 5 (M5) (24th April 2018).

5.6 Status of site 6 (M6)

Site 6 was selected from the Northern rim of the island reef west of site 5. The site was chosen as a control site as well as to get a broader understanding of the ecological baseline around the reef. The substrate at the site is dominated by rock at depths of 5 (80.5 ± 4.19%) and 10 (36.5 ± 5.85) meters respectively. Hard coral cover was observed to be low at the site at depths of 5 (8.75 ± 2.53) and 10 (14 ± 2.58) meters. Particular group of hard corals were not observed to dominate the substratum. A diverse group of corals from groups such as Acropora, Pocillopora and Porites were observed at the site. Fishes observed to be abundant at a depth of 5 meters were surgeon fishes, wrasses, triggerfishes, damselfishes and butterfly fishes. Fishes observed to be abundant at a depth of 10 meters were surgeon fishes, damselfishes, triggerfishes and butterfly fishes. The following graph outlines the status of site 6(M6) at depths of 5 and 10 meters.

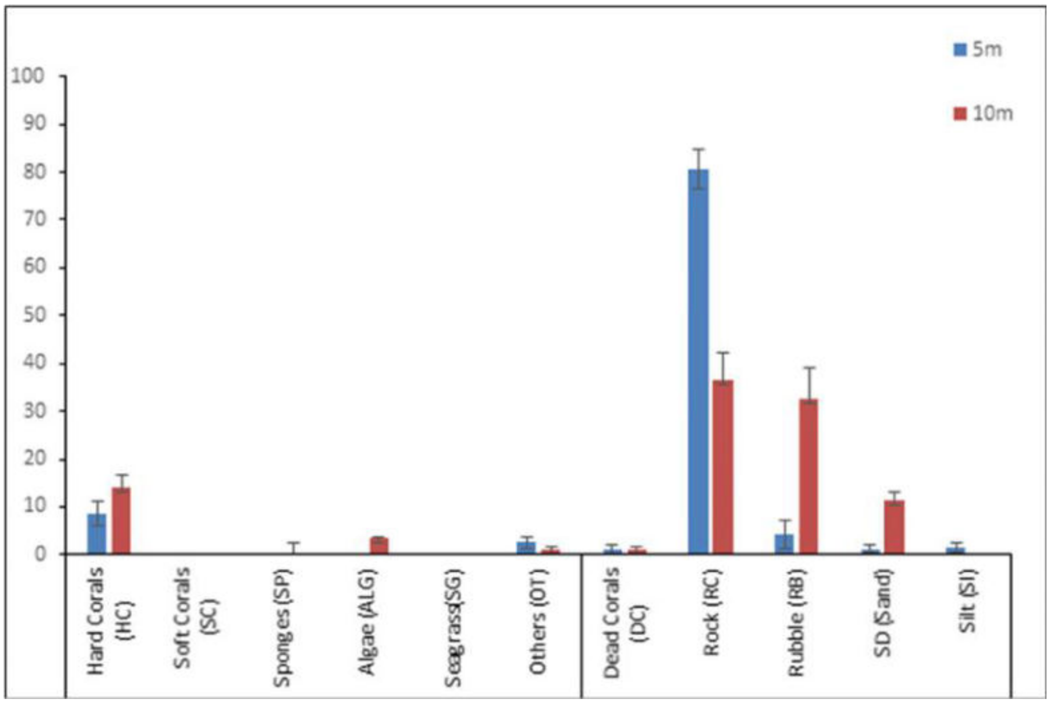


Figure 15: Percentage benthic composition at site 6 (M6) ± SE (24th April 2018).

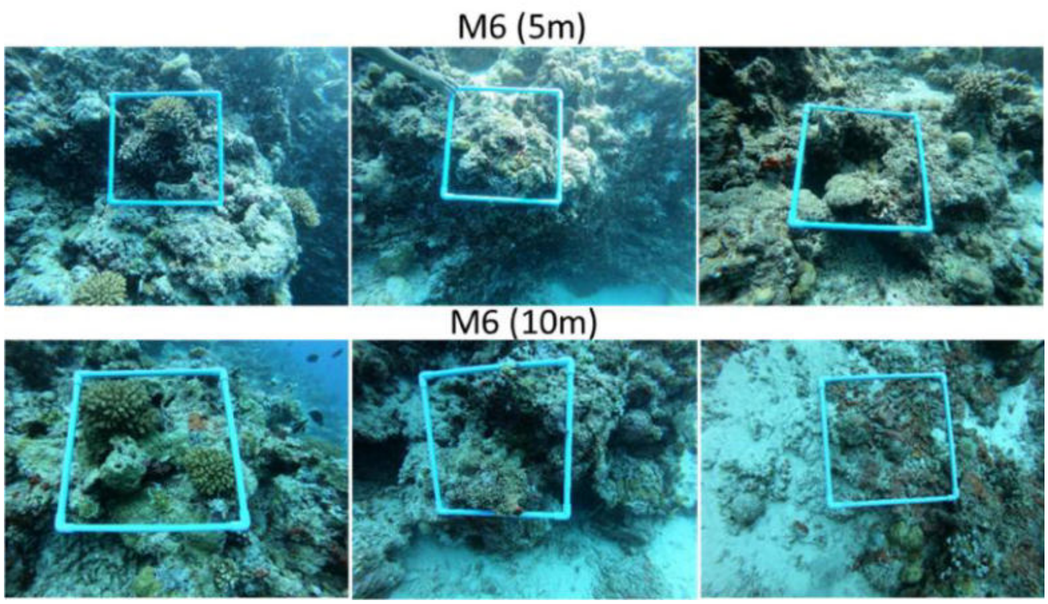


Figure 16: Photos taken from site 6 (M6) (24th April 2018).

5.7 **Status of site 7 (M7)**

Site 7 was selected from the Southern rim of the island reef west of site 1. The site was chosen as a control site as well as to get a broader understanding of the ecological baseline around the reef. The substrate at the site is dominated by rock at depths of 5 (76 ± 5.87%) and 10 (77.75 ± 3.33) meters respectively. Hard coral cover was observed to be low at 5 meters (5 ± 1%) and moderate in 10 meters (17.5 ± 3.2). Massive porites were the dominating group of hard coral observed at the site at both the depths. Fishes observed to be abundant at a depth of 5 meters were surgeon fishes, damselfishes and butterfly fishes. Fishes observed to be common at a depth of 10 meters were surgeon fishes. The following graph outlines the status of site 7(M7) at depths of 5 and 10 meters.

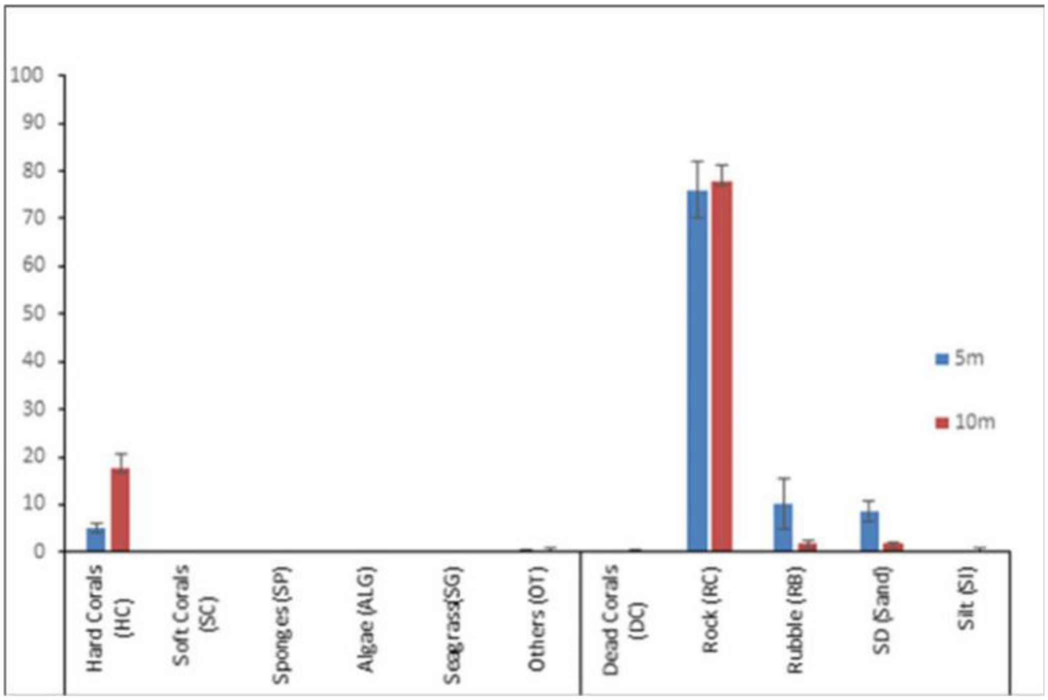


Figure 17: Percentage benthic composition at site 7 (M7) ± SE (23rd April 2018).

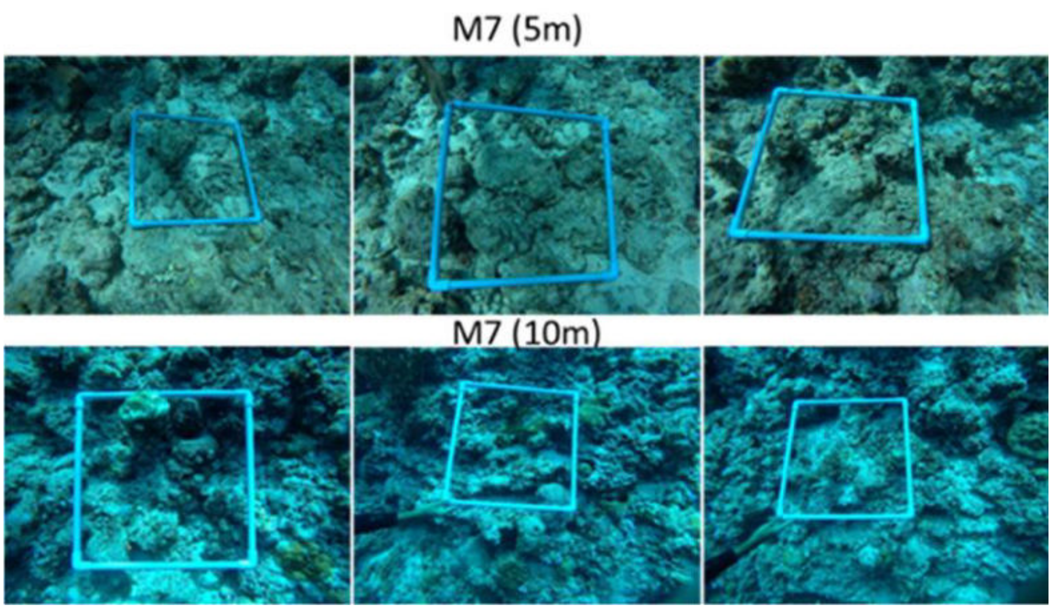


Figure 18: Photos taken from site 7 (M7) (23rd April 2018)

5.8 Observation during the marine survey in 2019

The highest coral cover was observed at the depth of 10 meters in site M2 adjacent to the current waste dumping area. The results are highlighted in the figure below. Therefor there is the possibility the leachate from land fill are not having negative impacts on the reef at site M2.

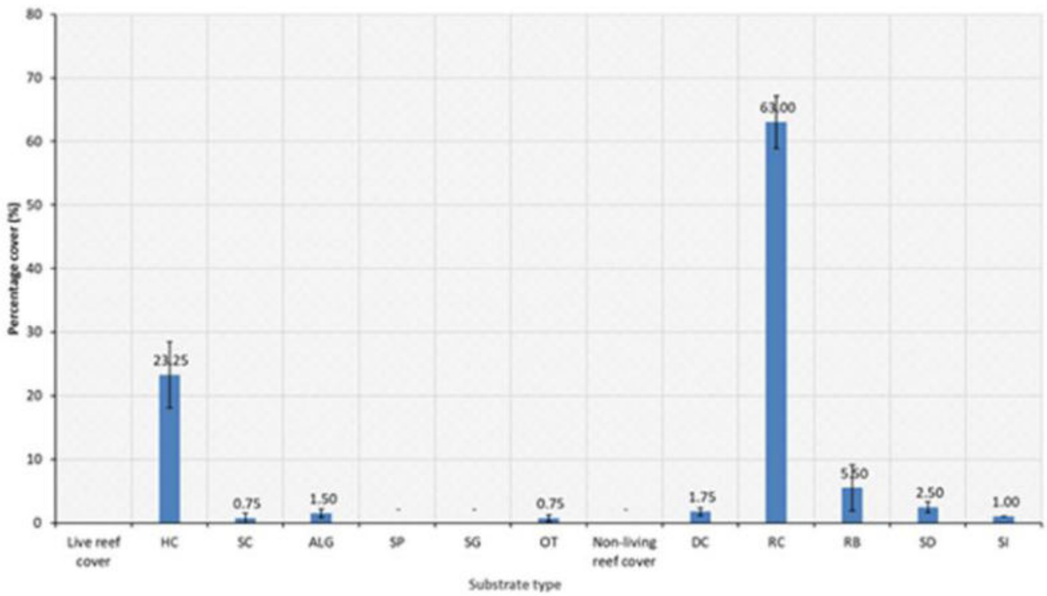


Figure 19: Percentage benthic composition at site 2(M2) at a depth of 10 meter ± standard error (SE).

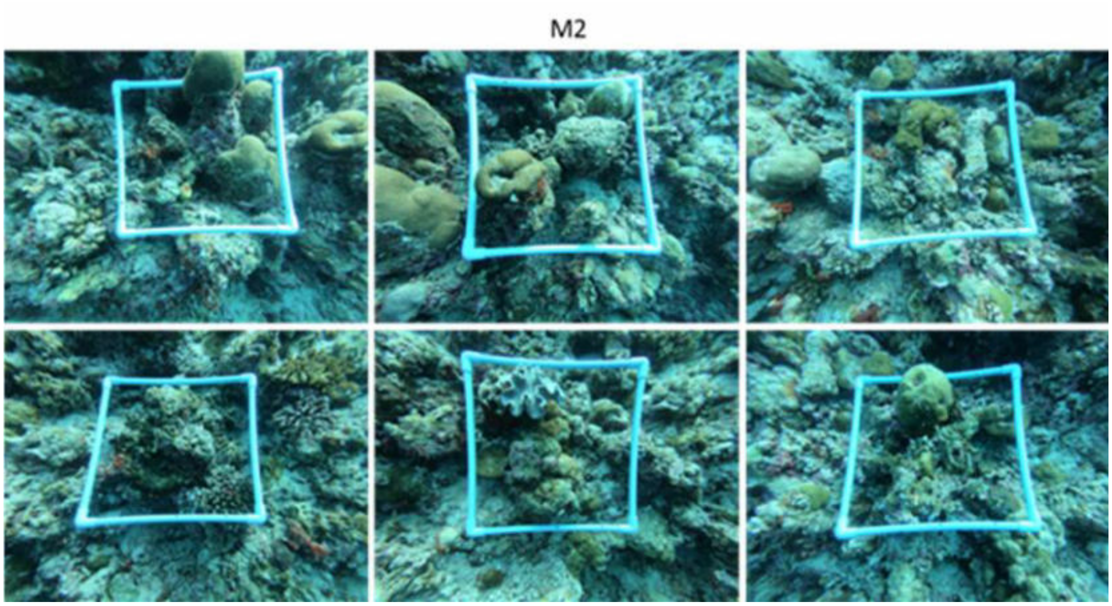


Figure 20: Photos compiled from site 2 (M2) at a depth of 10 meters.

5.9 Status of site M8

Site M8 was selected from the Southern rim of the island reef. The site was chosen as this is the proposed location for the hot water discharge outfall. The substrate at the site is dominated by silt along the entire transect line (43 ± 11.69%). Hard coral cover was observed to be low (8 ± 2.71). Massive porites were the dominating the group of hard coral observed at the site. Fishes observed to be very rare. It is to be noted that just a week prior to the survey, due to the severe weather, this entire stretch of reef has been hit by strong waves causing the sediments on the western side of the Thilafuhi to be spread along most part of the southern side. This has resulted in large areas of the reef being covered with silt. The following image illustrates the reef slope characteristics at site M10.

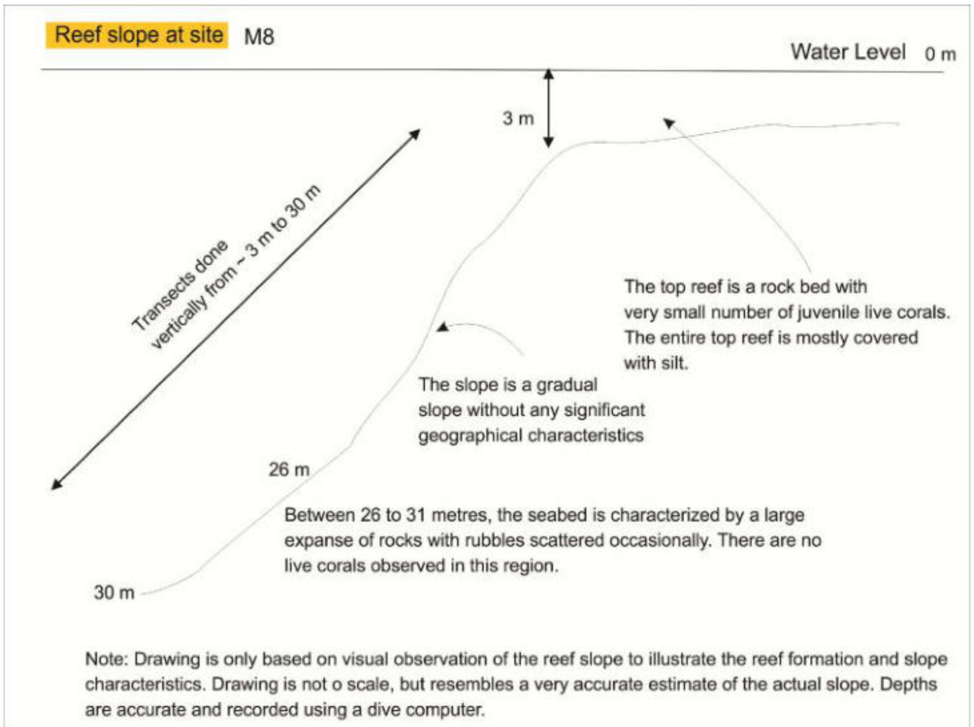


Figure 21: Reef slope characteristics at M8 (1st September 2019).

The following graph outlines the status of site M8.

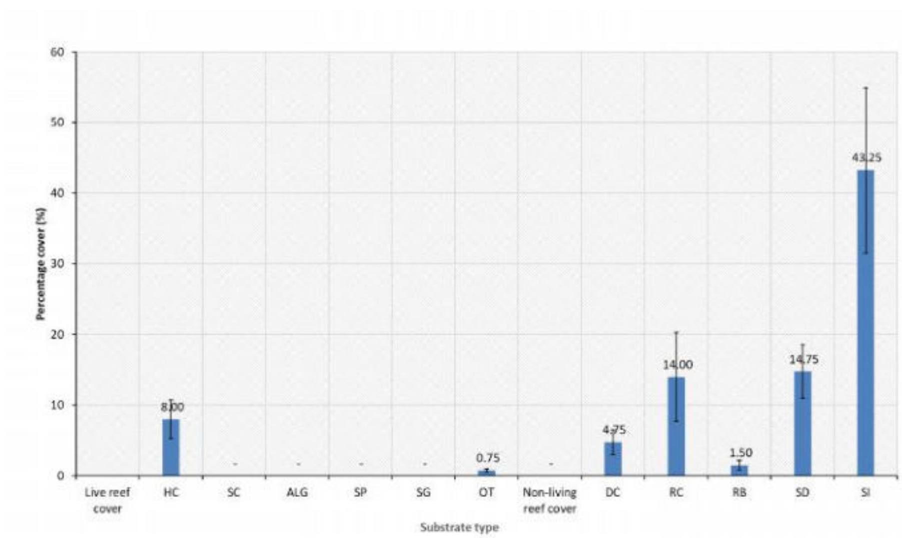


Figure 22: Percentage benthic composition at site M8 at depths from ~ 3 to 30 meters ± Standard Error (SE) (1st September 2019).

5.10 Status of site M9

Site M9 was also selected from the Southern rim of the island reef east of site 1. The substrate at the site is dominated by silt (64.5 ± 3.77%). Hard coral cover was observed to be low along the surveyed depths from approximately 3 to 30 metres (10.75 ± 3.22). Massive porites were the dominating group of hard coral observed at the site. Fishes observed were very low and includes anthias and surgeon fishes (refer to the fish census table for details). The following graph outlines the status of site M9.

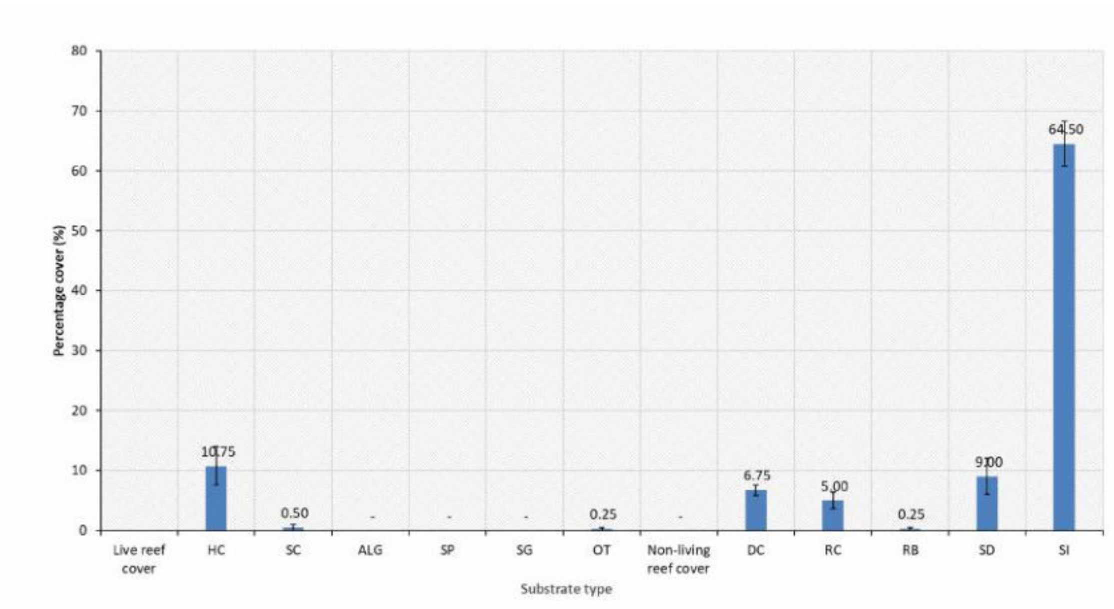


Figure 23: Percentage benthic composition at site M9 at depths from ~ 3 to 30 meters ± SE (1 September 2019).

The following image illustrates the reef slope characteristics at site M9.

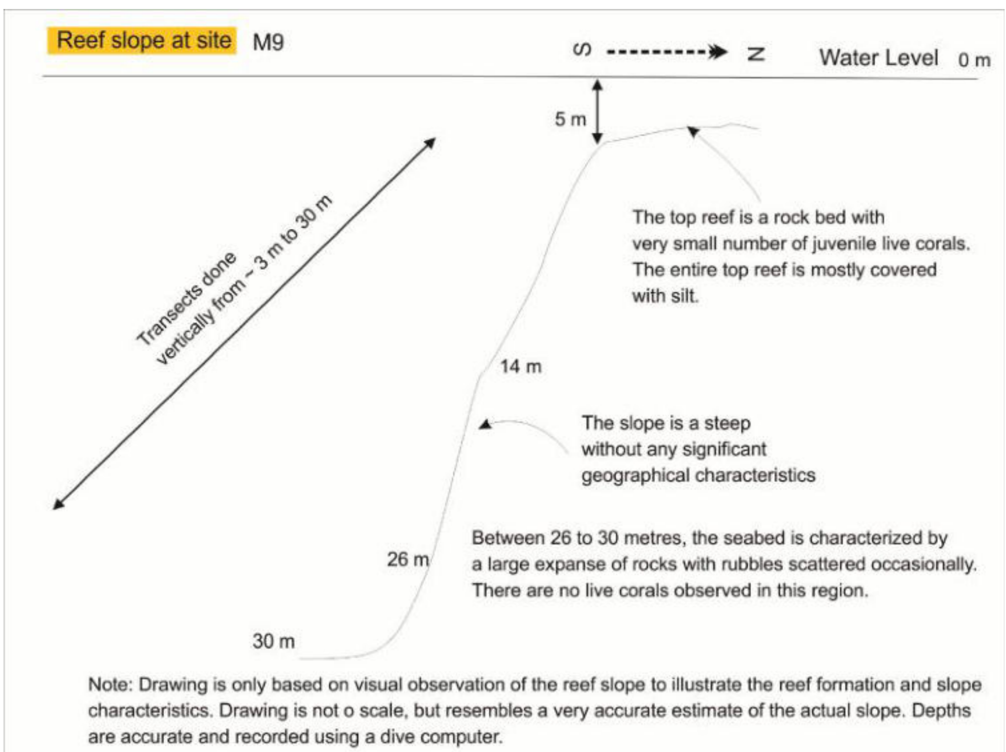


Figure 24: Reef slope characteristics at M9 (1 September 2019).

5.11 Status of site M10

Site M10 was also selected from the Southern side of the island reef. The following image illustrates the reef slope characteristics at site M10.

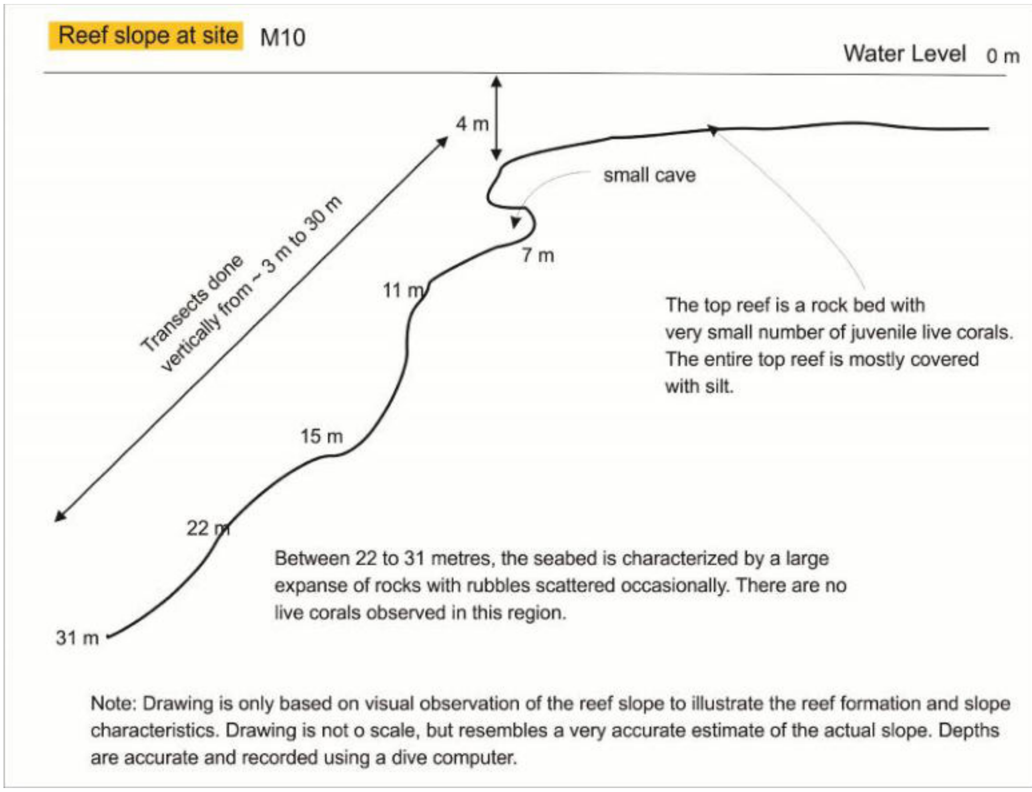


Figure 25: Reef slope characteristics at M10 (1 Sept 2019).

The substrate at the site is dominated by silt (58.50 ± 4.57 %). Hard coral cover was observed to be moderate (23.75 ± 7.43). Massive Porites were the dominating group of hard coral observed at the site. Fishes observed to be very low. The following graph outlines the status of site M10.

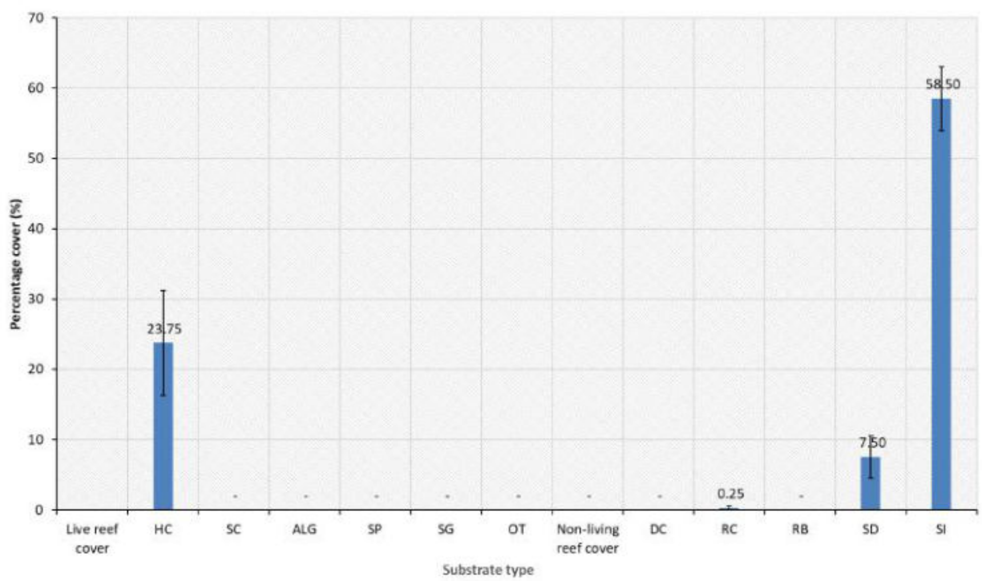


Figure 26: Percentage benthic composition at site M10 ± SE (1 Sept 2019).

5.12 Manta Tow between M9 and M10

The following table outlines the results of the Manta Tow survey that was carried out on 1st September from M9 to M10

Table 1: Manta Tow survey results of approximate substrate cover around the reef edge

	Love Coral cover%	**Dead coral cover%**	**Soft corals cover%**	**Rock cover %**	**Rubble cover %**	**Silt cover %**	**Benthic diversity**	**Fish diversity**
5 metres								
	5	8	-	15	2	70	low	low
10 metres								
	10	6	-	27	7	50	Low	low

The Manta Tow survey showed that coral reef system along the surveyed stretch is not in very good conditions in term of percentage live coral cover, diversity of corals, benthic and pelagic life. The overall live coral cover of the reef system appeared to be approximately 5% at 5 metres and approximately 10% at 10 metres. The reef substrate at both these depths were dominated by silt. Abundance and diversity of fish was also lower along the stretch. The live coral cover was highest at 10 metres. The corals inmost abundance were massive type coral head belonging to the genus Porites.

5.12.1 Protected marine species

During the Manta tow survey, no protected marine species such as sharks or were observed and recorded.

5.12.2 Reef Aesthetics

This attribute was assessed by visual observations based on the observer's judgment and experience of the relative merits of a reefs in the Maldives. This value judgment incorporated coral cover, diversity of life forms, fish life, reef structure and general appeal. The following categories were used to determine aesthetics of the reef system:

a. Very poor (mostly dead corals, pelagic life not abundant and diversity very low, structure uniform).
b. b. Poor (Lot of dead corals, pelagic life not abundant and diversity low, some differences in structure).
c. c. Average (Live corals about 10%, pelagic life abundant, diversity low, some structural variations exists).
d. d. Good (Live corals about 20% pelagic life abundant, diverse, structural variations exists).
e. e. Very good (Live corals about 30%, pelagic life abundant, diverse, overhangs, and other structures).
f. f. Excellent (Live corals over 40%, pelagic life very abundant, very diverse, lots of different structures, overhangs, caves, gullies, and different habitat types exists.

Reef aesthetics of Thilafushi's coral reef system (along the 500 metres) is regarded as very poor, given that substantial level of the reef is covered in sill and poor diversity of life forms. Fish life and abundance are very poor at the time of surveying and generally this stretch of reef can be considered to be very poor.

5.13 Fish Diversity and Abundance (April 2018)

The amount and type of fish present at a given site can be a good indicator of the marine environment. For example, increased grazers are generally a sign of increased nutrients in the area, thus decreased coral cover and increased algal cover. 15-minute fish counts were done in sites M1-M7 in depths of 5 and 10m. The counts include Mega fauna in addition to fishes. The fishes were identified to family level, however some protected species such as the napoleon wrasse, were identified to species level. The following table outlines the fish count survey at all the sites.

Table 2: Fish abundances observed at sites 1 to 7 at a depth of 5 and 10 meters.

Family/Subfamily	**Site M1**		**Site M2**		**Site M3**		**Site M4**		**Site M5**		**Site M6**		**Site M7**	
Depth	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**
Anthias (Anthiadinae)	R	A	A	A	R	A	C	-	R	C	C	C	R	-
Surgeonfishes (Acanthuridae)	A	C	A	C	A	C	A	C	A	A	A	A	A	C
Wrasses (Labridae)	C	C	-	C	-	-	C	C	C	C	A	-	C	-
Parrotfishes (Scaridae)	C	C	A	C	R	R	C	R	A	-	C	C	C	-
Triggerfishes (Balistidae)	C	A	A	A	-	A	R	-	C	A	A	A	C	-
Boxfishes (Ostraciidae)	-	-	R	-	-	-	-	-	-	-	-	-		-
Damselfishes (Pomacentridae)	A	A	A	A	-	A	C	-	R	A	A	A	A	-
Groupers (Serranidae)	R	-	R	R	R	-	R	-	R	R	R	R	R	-
Moorish idol (Zanclidae)	R	R	R	R	R	R	R	R	C	R	R	R	R	R
Butterflyfishes (Chaetodontidae)	A	C	A	A	C	C	A	C	R	C	A	A	A	-
Goatfishes (Mullidae)	-	-	R	R	-	-	C	C	R	-	R	-	R	-
Hawkfishes(Cirrhitidae)	-	-	R	R	R	-	-	-	R	-	R	-	-	-
Threadfin and Whiptail breams (Scolopsis)	-	-	-	R	-	-	-	-	-	-	-	-	-	-
Octopus (Octopodidae)	-	-	R	-	-	-	-	-	-	-	-	-	-	-
Fusiliers (Caesionidae)	-	-	-	-	-	-	A	A	-	-	-	-	-	-
Rabbitfishes (Siganidae)	-	-	-	-	-	-	R	-	-	-	R	-	-	-
Gobies (Gobiidae)	-	-	-	-	R	-	-	R	R	-	-	-	-	-
Pipefishes and seahorses (Syngnathinae)	-	-	-	-	-	-	R	-	R	R	-	-	-	-
Puffers (Tetraodontidae)	-	-	-	-	R	-	R	-	C	-	R	-	-	-
Emperors or scavengers (Lethrinidae)	-	-	-	-	-	-	-	-	C	-	R	-	-	-
Jacks and Trevalleys (Carangidae)	-	-	-	-	A	-	-	-	R	-	-	-	-	-

Family/Subfamily	Site M1		Site M2		Site M3		Site M4		Site M5		Site M6		Site M7	
Depth	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**
Angelfishes (Pomacanthidae)	-	-	-	-	-	-	-	-	R	-	R	R	-	-
Lizardfishes (Synodontidae)	-	-	-	-	-	-	-	-	R	-	-	-	-	-
Squirrelfishes, soldierfishes (Holocentridae)	-	-	-	-	-	-	-	-	-	-	R	-	-	-
Grunts and Sweetlips (Haemulidae)	-	-	-	-	-	-	-	-	-	R	R	-	-	-
Eels and Morays (Anguilliformes)	-	-	-	-	-	R	-	-	-	-	-	-	-	-
Napoleon Wrasse (Cheilinus undulatus)	-	-	-	-	-	R	-	-	-	-	-	-	-	-
Sharks & Rays (Elasmobranchii)	-	-	-	-	-	R	-	-	-	-	-	-	-	-
Sea Turtles (Chelonioidea)	-	-	-	-	-	R	-	-	-	-	-	-	-	-

A= Abundant (Meaning that during the 15-minute time swim survey, species counts were recorded more than 50, hence it is difficult to count their numbers). C=Common (Meaning that during the 15-minute time swim survey, they were spotted occasionally and throughout the survey, but their numbers were less than 50). R=Rare (Meaning that during the survey, only few of these species were observed, often 1 or 2

5.14 Fish Diversity and Abundance (September 2019)

The following table outlines the results of the fish counts along the survey points which was conducted from approximately 3 meters up to 30 meters at each site.

Table 3: Fish abundances observed at sites M8, M9 & M10 on 1st September 2019.

Family/Subfamily	Site M8	Site M9	Site M10
Anthias (Anthiadinae)	-	C	R
Surgeonfishes (Acanthuridae)	R	C	R
Wrasses (Labridae)	-	-	-
Parrotfishes (Scaridae)	R	-	R
Triggerfishes (Balistidae)	-	-	-
Boxfishes (Ostraciidae)	-	-	-
Damselfishes (Pomacentridae)	-	-	-
Groupers (Serranidae)	-	-	-
Moorish idol (Zanclidae)	-	-	-
Butterflyfishes (Chaetodontidae)	-	-	-
Goatfishes (Mullidae)	-	-	-
Hawkfishes(Cirrhitidae)	-	-	-
Threadfin and Whiptail breams (Scolopsis)	-	-	-
Octopus (Octopodidae)	-	-	-
Fusiliers (Caesionidae)	R	-	R
Rabbitfishes (Siganidae)	-	-	-
Gobies (Gobiidae)	R	-	R
Pipefishes and seahorses (Syngnathinae)	-	-	-
Puffers (Tetraodontidae)	-	-	-
Emperors or scavengers (Lethrinidae)	-	-	-
Jacks and Trevalleys (Carangidae)	-	-	-

A= Abundant (Meaning that during the 15-minute time swim survey, species counts were recorded more than 50, hence it is difficult to count their numbers). C=Common (Meaning that during the 15-minute time swim survey, they were spotted occasionally and throughout the survey, but their numbers were less than 50). R=Rare (Meaning that during the survey, only few of these species were observed, often 1 or 2.

5.14.1 Plankton tows

Plankton are the base of the marine food chain. The phytoplankton and zoo plankton abundances in the area could possibly be affected by the presence of heavy metals. If the plankton community is thriving in these areas the heavy metals maybe bio accumulating in the food chain. Therefore plankton counts were done around Thilafushi Island in order to establish a baseline. A plankton net of 50µm mesh was built to carry out the survey. The plankton tows were carried out at sites where the marine water samples were collected.

5.14.1.1 Data Collection methodology

A plankton net of opening 0.48 x 0.48 m was tied to a 20m rope and released from a vessel. The net was allowed to drift for 20 meters and then towed towards the boat. Any organisms or particles larger than 50µm gets caught up in the net and collected in the cod end.

5.14.1.2 Data processing methodology

5.14.1.2.1 Zooplankton

Analyses of the samples were done using a microscope using a Sedgewick rafter counting chamber. The chamber has a volume of approximately 1ml. The samples collected from the net were approximately 150 – 250ml in volume. For the zooplankton count, the samples were transferred to a beaker diluted to approximately 500 – 900 ml and the volume recorded. The purpose of dilution is to reduce the number of plankton in the optical view of the microscope for ease of counting. Two sub-samples were counted from each sample. To calculate Total count in the sample, the counts in the subsamples were averaged. Thereafter the average value in the sub samples were multiplied with the total Volume in the diluted sample to obtain the Total count in the Sample. From the Total count in the sample and from the opening area of the net and the distance towed, the abundance of zooplankton per meter cube was calculated using the formula, Abundance = Total Count in the Sample/(Distance towed x Opening area). During the survey the zoo plankton were classified into Rotifera, Protozoa, Chordata, Mollusca, Annelida, Cnidaria, Crustacea and Chaetognatha. Additionally, Copepods were classified into three groups, Calanoida, Cyclopoida and Harpacticoida.

5.14.1.2.2 Phytoplankton

Analyses of the samples were done using a microscope using a Sedgewick rafter counting chamber. The chamber has a volume of approximately 1ml. The samples collected from the net were approximately 150 – 250ml in volume. For the phytoplankton count, the samples were transferred filtered through a 200µm sieve to remove large zooplankton for ease of counting. Thereafter the sample was transferred to a beaker, and diluted to approximately 500 – 900 ml and the volume recorded. The purpose of dilution is to reduce the number of plankton in the optical view of the microscope for ease of counting. Two sub-samples were counted from each sample. To calculate Total count in the sample the counts in the subsamples were averaged. Thereafter the average value in the sub samples was multiplied with the total Volume in the diluted sample to obtain the Total count in the Sample. From the Total count in the sample and from the opening area of the net and the distance towed, abundance of zooplankton per meter cube was calculated using the formula, Abundance = Total Count in the Sample/(Distance towed x Opening area).

5.14.1.3 Limitations of the methodology

The above method gives approximate estimates of abundances for each group/genera of plankton. Using a Sedgewick rafter to count zooplankton limits the subsample volume to 1ml thus, rare groups in plankton would likely not be observed in the counts. The method is reliable to estimate the total abundance of common groups of Zooplankton which are greater than 50µm in size and phytoplankton greater than 50 µm and less than 200µm.

5.14.1.4 Plankton abundance

5.14.1.4.1 Zooplankton

5.14.1.4.1.1 Common Phyla

Crustaceans were observed to be of the highest abundance amongst the zooplankton from all 7 sites. Additionally, the highest abundance of zoo plankton was observed from site 7 (PKT 7). The lowest abundance of zooplankton was observed from site 5. The table and figures below outline the variation in zooplankton abundance between the sites.

Table 4: Abundance of common phyla of zooplankton from sites PKT 1 to PKT 7.

Phyla	**Abundance at sites (Individuals/m^3)**						
	PKT 1	**PKT 2**	**PKT 3**	**PKT 4**	**PKT 5**	**PKT 6**	**PKT 7**
Rotifera	174	760	1,270	293	195	814	1,519
Protozoa	260	2,170	1,563	1,172	781	1,628	868
Chordata	347	705	1465	977	391	746	217
Mollusca	87	163	391	NA	98	339	217
Annelida	174	54	98	NA	98	68	NA
Cnidaria	217	380	98	488	NA	NA	NA
Crustacea	3,212	7,378	16,113	9,277	1,465	6,782	21,267
Chaetognatha	43	109	488	98	NA	NA	217
Total Zooplankton	7,769	19,151	37,598	21,582	4,492	17,158	45,573

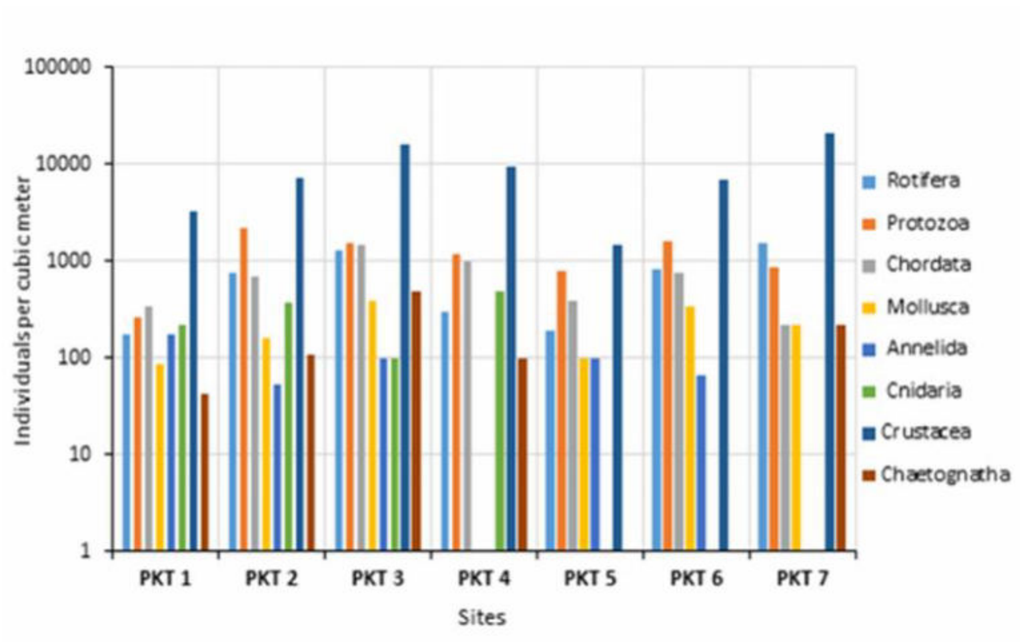


Figure 27: Abundance of common phylum of zooplankton from sites PKT 1 to PKT 7.

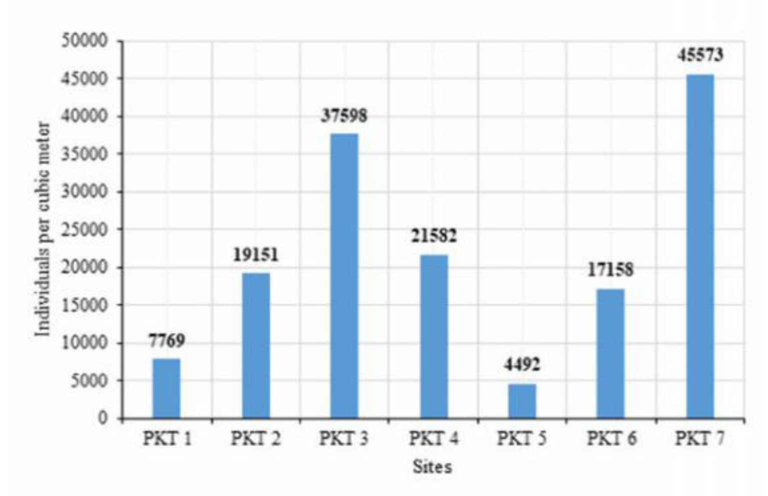


Figure 28: Total abundance of zooplankton from sites PKT 1 to PKT 7.

5.14.1.4.1.2 Copepods

The dominating group of copepods observed in the sites were calanoids. The highest abundance of copepods were observed at site 7 and the lowest abundance of copepods at site 5. The table and figure below outlines the variation in copepod abundance between the sites.

Table 5: Abundance of copepods from sites PKT 1 to PKT 7.

Order	Abundance at Sites (Individuals/m^3)						
	PKT 1	PKT 2	PKT 3	PKT 4	PKT 5	PKT 6	PKT 7
Calanoida	1693	2767	6543	3516	684	2509	11502
Cyclopoida	260	434	1367	391	195	543	1085
Harpacticoida	391	163	195	684	195	407	651

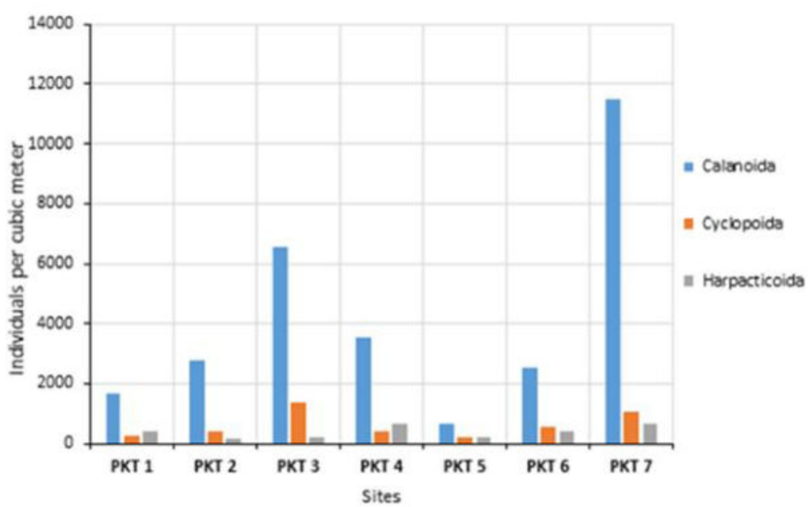


Figure 29: Abundance of copepods from sites PKT 1 to PKT 7.

5.14.1.4.2 Phytoplankton

Diatoms were observed to be of the highest abundance, amongst the phytoplankton from all 7 sites. Additionally, the highest abundance of phytoplankton was observed from site 7 (PKT 7). Additionally, the lowest abundance of phytoplankton were observed from site 5. The Figures below show the variation in phytoplankton abundance between the sites.

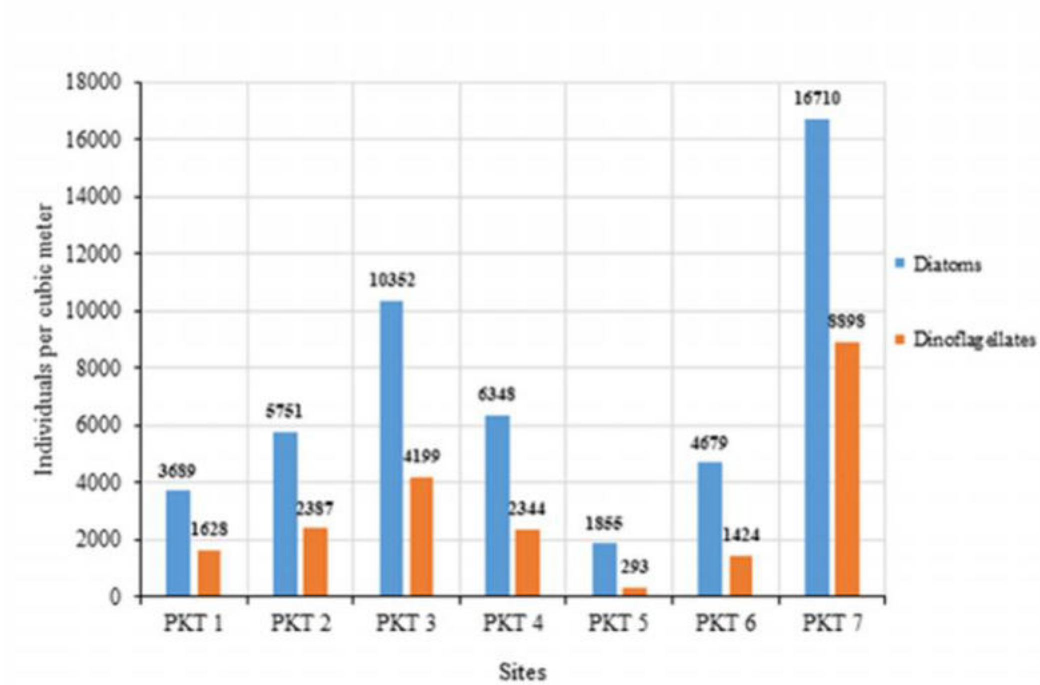


Figure 30: Abundance of diatoms and dinoflagellates from sites PKT 1 to PKT 7.

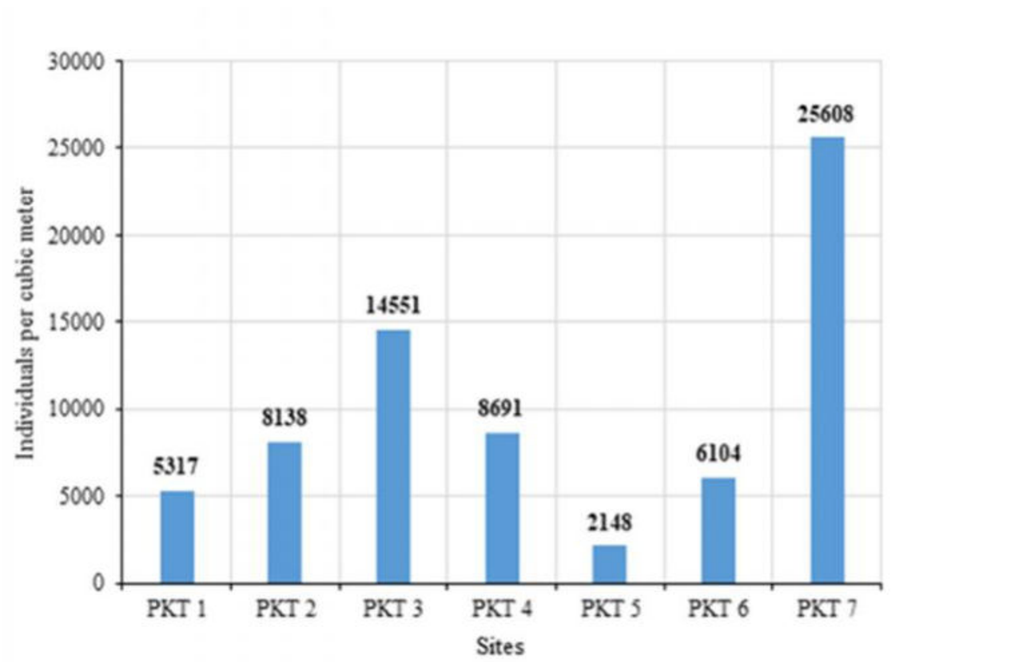


Figure 31: Total abundance of phytoplankton from sites PKT 1 to PKT 7.

6 Conclusion

The coral reef of Thilafushi has been under a lot of stress over the past two decades from the various industrial activities and developments that have occurred on this once barren reef. Over the years, the coral reef has undergone significant direct and indirect impacts resulting from the evolution of this artificial island that has been reclaimed initially from waste and later expanded in a more ecologically sound manner.

Surveys were undertaken in April 2018 and September 2019 to assess the coral reef and its health. The initial surveys were carried out in April 2018 which indicates that the highest coral cover was prevalent at a depth of 10 meters in site M2. This site is adjacent to the current waste dumping area. Therefor based on this results, there is the possibility that one can conclude that the leachate from land fill is not having a significant negative impacts on the reef at site M2 in terms of coral cover. On the overall, the reef around Thilafushi does not indicate a very healthy reef with average coral cover below 20% in most of the surveyed sites (based on the surveys done in April 2018).

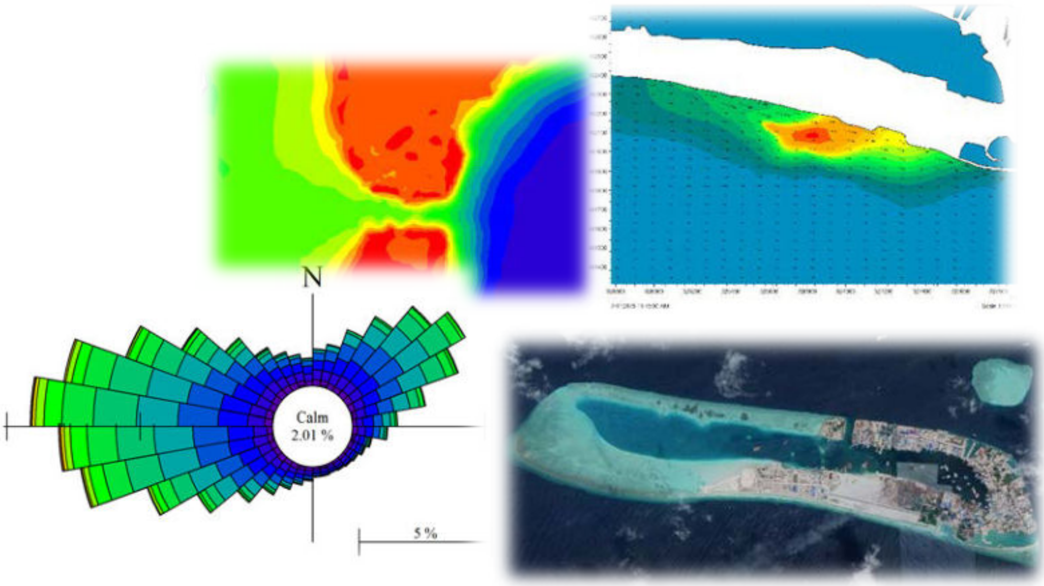
A new set of surveys were conducted in three sites, M8, M9, M10, on 1st September 2019. This detail marine survey was carried out along a 500 m coastal stretch of house reef on southern site of Thilafushi between M9 and M10. The results indicate that very few (or none at all) marine species are found at a depth of less than 10 m along this stretch. The survey also revealed further that no significant marine life such as live corals, fishes or other pelagic organisms was found at greater depths from 10 m to 30 m along this stretch of house reef. The marine survey carried out in September 2019 found that the reef profiles at M8, M9 and M10 are very identical and at any of these sites, an outfall could be laid. Geographically, these three sites does not pose major challenges when it comes to laying an outfall pipe. There were no sensitive corals nor benthic cover recorded in any of these sites nor are any odd slope formations there.

The reef slope at surveyed sites M8, M9 and M10 is characterized by a wall with the majority of the benthic composition being mainly rubble and silt. Along these sites, from a depth of approximately 20 meters and below, there is no live coral cover and the fish life is virtually none existent at the time of the survey on 1st September 2019. The southern side of Thilafushi is also exposed to a lot of sedimentation during south-west monsoon, which causes dispersion of sediments along a large area of the reef. This is the reason why the percentage of silt along M8, M9 and M10 were so high during the surveys undertaken in September 2019.

During the surveys in April 2018, one sea turtle was recorded. Sea turtles are very commonly observed throughout the Maldives due to their protected state. Their numbers have grown significantly since they were declared as a protected species in the 1980's. Since then, turtles are observed in a lot of reefs throughout the Maldives. Thilafushi being an artificial island does not possess the right coastal ecology for turtles to lay their eggs and no reports of turtle nests nor eggs have been reported to have been spotted from Thilafushi beaches. Hence, this single observation of a turtle can be confidently declared as an occasional occurrence.

Water Solutions Pvt. Ltd.

Effluent Dispersion Modelling at Thilafushi Island, Maldives



Model Rerun

Final Report

July 2020

Lanka Hydraulic Institute Ltd
Coast and Water

Client	Client's Representative
Water Solutions Pvt. Ltd	Mr. Ahmed Jameel

Project	Project No.
Effluent Dispersion Modelling at Thilafushi Island, Maldives – Model Rerun	2009

Authors	Date
Eng. Lakshan Fernando Eng. (Ms) Nalika Engiliyage Eng. (Ms) Ganga Caldera	July 2020
	Approved by Eng. J.K.P. Kurukulasuriya Eng. Dr. K. Raveenthiran

Revision		By	Checked	Approved	Date

Key words	Classification
Wind - Wave Transformation Hydrodynamic Thermal Dispersion	☐ Open ☐ Internal ☒ Proprietary

Distribution	No. of Copies:	
	Soft	**Hard**
Water Solutions Pvt. Ltd 1st Floor, Ma.Fas Eri, Ameenee Magu, Male, Maldives.	01	02

Lanka Hydraulic Institute Ltd

177, John Rodrigo Mawatha, Katubedda, Moratuwa, Sri Lanka.
Tel. Nos. 2650409 / 2650471 / 2650472-3, Fax No. 2650470 - Email: lhi@lhi.lk

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Water Solutions Pvt Ltd (WS) is currently assisting Ministry of Environment and Energy (MEE) to undertake an Environmental Impact Assessment (EIA) for Waste Management Project at Thilafushi Island, Maldives. As part of the project, an incinerator is proposed to burn waste material and seawater through an intake will be used to cool condenser. After cooling process, the hot seawater will be re-discharged through outfalls into the sea. As part of the EIA work, the dispersion behaviour of the discharged hot water need to assessed.

Lanka Hydraulic Institute Ltd (LHI) engaged with Water Solutions Pvt Ltd to simulate the effluent dispersion of heat plumes through numerical modelling. The first set of models was simulated in 2018 and the final report was submitted in October 2018. Later, Water Solutions Pvt Ltd requested Lanka Hydraulic Institute Ltd to rerun the model for different outfall orientation and discharge. Hence this report presents the model results for the newly proposed system.

This report includes six chapters. Background of the project and basic methodology used in the study are given in Chapter 1. The details of collected wind data and analysis of it are given in Chapter 2. Wave transformation method and model usage for wave generation are discussed in detail in Chapter 3. In order to assess the water circulation, a set of hydrodynamic models was performed; those methods and results are discussed under Chapter 4. As the main part of study, thermal dispersion modelling system and discussion of its results are presented in Chapter 5. Finally the conclusions are given in Chapter 6.

1.1 Background

The Thilafushi Island is located in North Male Atoll, Maldives, and around 7km westwards to Male City (Figure 1.1). Presently, the island is used as the main waste dumping site in the country capital Male and its adjacent inhabited islands and the airport at Hulhule. The Government of the Maldives has identified solid waste disposal as a priority problem and decided to implement a solid waste management plan to minimize the environmental problem.

As a part of the project, an incinerator has been proposed to burn the waste. The cooling system of incinerator will run using sea water as coolant. The dispersion of hot water in marine environment is required to assess with respect to the coastal process of region.

This island is subjected to two monsoon period namely South-West and Nort-East; South West monsoon is considered as from May to November while North East as from December to April. Energy of swell waves approach from southern Indian Ocean may reduce due to diffraction and other interaction of other atoll reefs, and mainly sea waves are affected to the island. Sea currents are developed around the island reef mainly wind, wave and tidal effect.

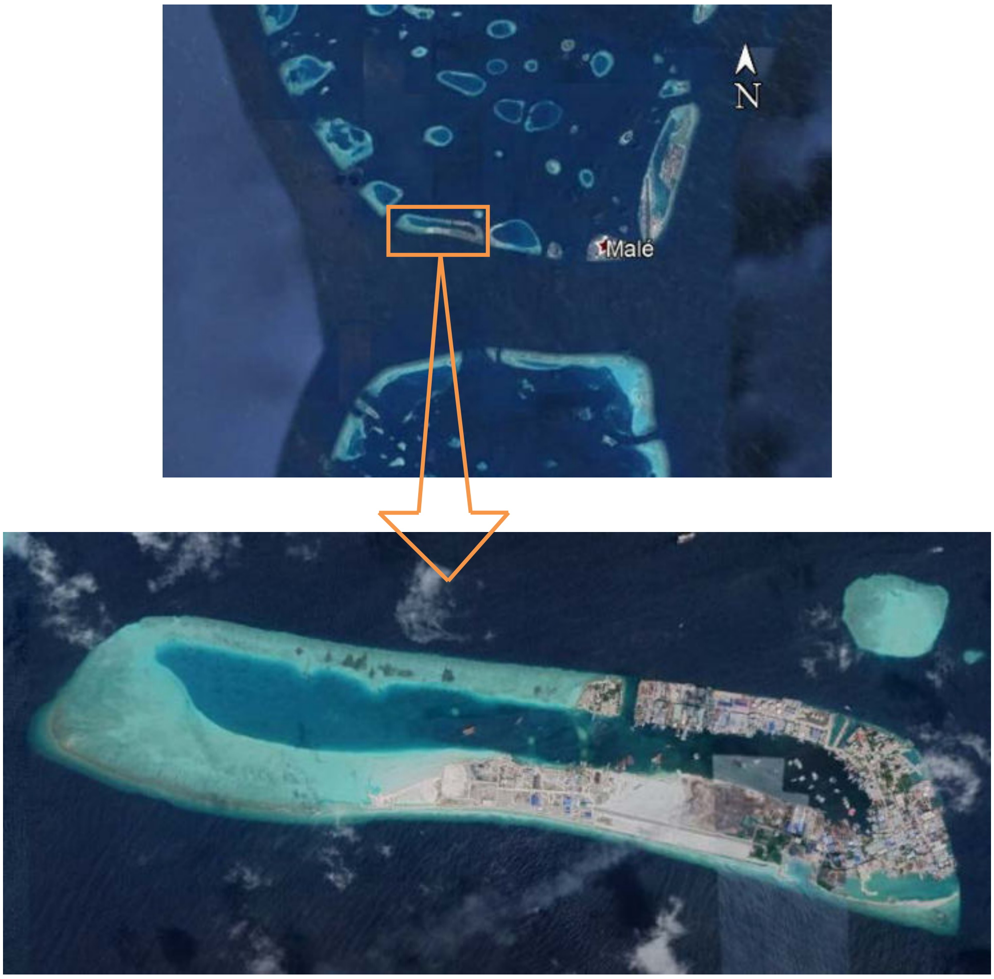


Figure 1.1: Location of Thilafushi Island

1.2 Objective of the Study

The discharge of effluent in the coastal area is a sensitive issue in the context of environmental conservation and therefore dispersion of the effluent requires proper assessment to ensure that nearshore coastal environment will not be subjected to pollution and health risk due to discharged effluent. For this purpose it is extremely essential to ensure that effluent constituent is diluted to acceptable levels within the receiving water in the immediate vicinity of discharge point. Secondly, the advection dispersion of the effluent should be favourable to the environment for every monsoon period.

The objective of this modelling task is to simulate the dynamic behaviour of hot water discharged through the outfall, and to assess the impacts on the surrounding areas of the outfalls, near-shore areas and beaches.

1.3 Basic Methodology of Study

Since the hot water dispersion is to be assessed for different monsoons and tidal conditions, at the first stage, wave conditions and tidal conditions require to be developed at site location. In order to develop wave conditions for different monsoon periods at site location, long period wind data was used in a Wind-Wave Transformation Model (MIKE 21 SW). In order to find out current conditions, a Hydrodynamic Model (MIKE 21 HD) was utilised with giving wind/wave condition and tidal variation as input parameters. After that thermal dispersion model, CORMIX was used to find out initial dilution in near field and its results were further applied to the Hydrodynamic Model couple with thermal dispersion tool to assess the dilution in 2D plain.

Main activities of study are given below.

1. Obtain and analyze of UK Met Office (UKMO) wind data at site location.
2. Develop model bathymetries using Admiralty Chart Maps and measured data
3. Find out wave condition near the site using Wind-Wave Transformation Model (MIKE 21 SW)
4. Simulate a regional Hydrodynamic Model using known tidal boundaries in order to find out hydrodynamic conditions at local model boundaries.
5. Simulate local Hydrodynamic Model with applying wind, wave and tidal condition and find out current condition at site for different monsoons.
6. Apply current conditions obtained from Hydrodynamic Model in CORMIX model and find out initial dilution in near field.
7. Simulate again Hydrodynamic Model couple with thermal dispersion tool and applying CORMIX model results to assess the dilution in 2D plain.

2 WIND DATA AND WAVE GENERATION

The wind data was obtained based on the hind-cast data from Numerical Weather Prediction Atmospheric Global model of the UK Met Office (UKMO). The available nearest suitable data point (3.984 N, 73.477 E) which located in the South Male Atoll was selected with considering fetch length and open sea area which would be adopted in the wind wave model (Figure 2.1). Real time observational data from satellite wind radar, ship and buoy data were (and are) assimilated into the atmospheric model. This process strives to give the best possible rendition of the 'surface' wind field at analysis or run time, in order to give an optimum forecast. In effect, the atmospheric wind fields represent a hybrid of numerical and real data. It is the analysis time steps of these models of whatever resolution which go to make up the archive on which hind-casts are based.

Wind speed and wind direction for 30 years during January 1986 to June 2016 were utilized for the study. The data set contents 89,112 no of records with the interval of 3 hours. Analyses were carried out to assess the distribution of wind parameters and given in the Figure 2.2 and the Table 2.1.

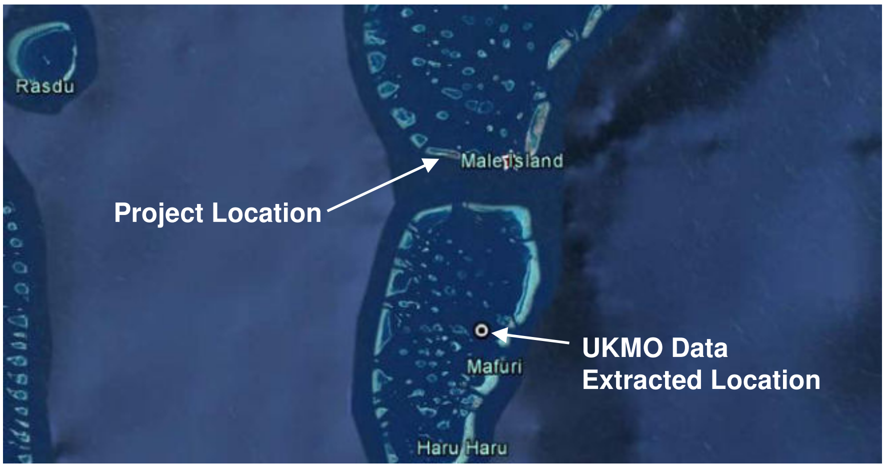


Figure 2.1: Wind Data Extracted Location

2.1 Analysis of UKMO Wind Data

Analysis of raw data before apply it in the model is an essential part in wind - wave transformation numerical modelling process to gain an idea about the wind climates of the region. Therefore analyses for UKMO data were carried out based on wind speed and direction.

Figure 2.2 illustrates clearly wind distribution pattern in 360° angle. The length of slices represents the percentage of occurrence while the colour code for the wind speeds. Furthermore, Table 2.1 shows the occurrence of wind by values in different directions and various speeds. According to the analysis, two dominant wind directions can be observed; i.e. West and North-East. The wind reached from South- East quadrant is negligible.

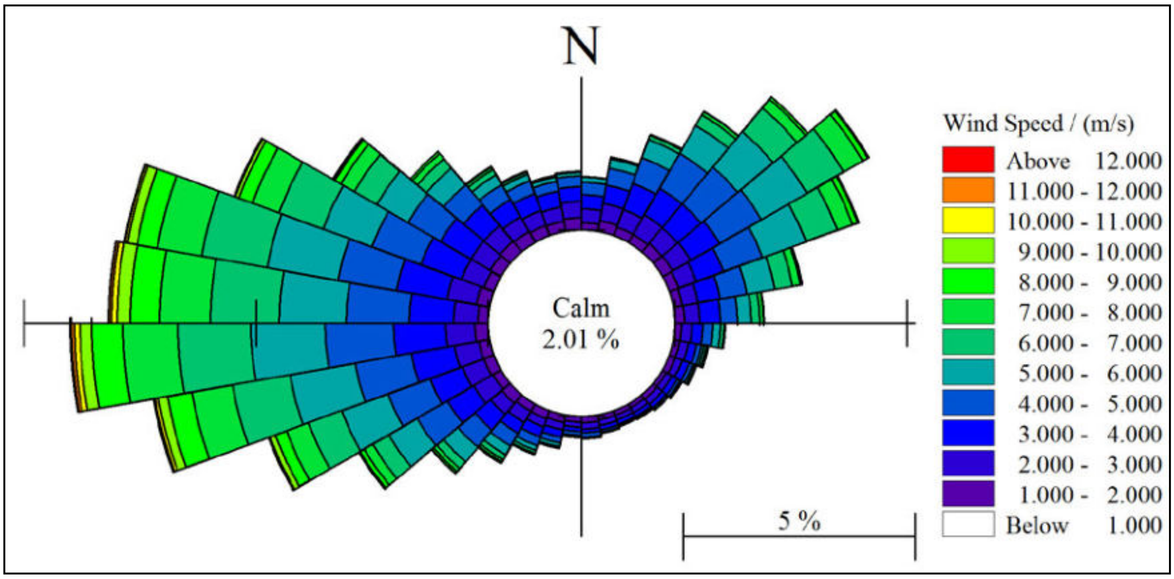


Figure 2.2: Annual Distribution of Wind

Table 2.1: Directional Distribution of Wind Statistics (Percentage Occurrence for Wind Speed vs Wind Direction)

Speed (m/s) \ Dir (Deg.N)	0 -- 10	10 -- 20	20 -- 30	30 -- 40	40 -- 50	50 -- 60	60 -- 70	70 -- 80	80 -- 90	90 -- 100	100 -- 110	110 -- 120	120 -- 130	130 -- 140	140 -- 150	150 -- 160	160 -- 170	170 -- 180	180 -- 190	190 -- 200	200 -- 210	210 -- 220	220 -- 230	230 -- 240	240 -- 250	250 -- 260	260 -- 270	270 -- 280	280 -- 290	290 -- 300	300 -- 310	310 -- 320	320 -- 330	330 -- 340	340 -- 350	350 -- 360	Total
0 – 1	0.03	0.06	0.06	0.05	0.06	0.07	0.06	0.04	0.09	0.03	0.03	0.05	0.04	0.06	0.05	0.04	0.05	0.08	0.03	0.06	0.07	0.06	0.06	0.06	0.07	0.06	0.11	0.03	0.08	0.07	0.08	0.06	0.07	0.06	0.06	0.03	2.07
1 – 2	0.17	0.24	0.20	0.21	0.24	0.26	0.21	0.19	0.20	0.14	0.14	0.14	0.10	0.12	0.10	0.10	0.11	0.12	0.11	0.16	0.19	0.18	0.24	0.21	0.23	0.24	0.30	0.23	0.30	0.23	0.27	0.29	0.27	0.24	0.23	0.18	7.07
2 – 3	0.29	0.38	0.43	0.48	0.44	0.45	0.43	0.35	0.34	0.23	0.19	0.16	0.15	0.14	0.13	0.11	0.11	0.13	0.12	0.17	0.19	0.28	0.32	0.49	0.51	0.53	0.64	0.53	0.64	0.54	0.48	0.45	0.39	0.34	0.31	0.29	12.16
3 – 4	0.31	0.40	0.57	0.67	0.67	0.72	0.60	0.49	0.42	0.24	0.19	0.16	0.13	0.10	0.09	0.09	0.09	0.08	0.08	0.16	0.22	0.27	0.44	0.65	0.73	0.96	1.10	0.95	1.13	0.92	0.77	0.58	0.41	0.38	0.35	0.26	16.39
4 – 5	0.26	0.38	0.58	0.86	1.03	1.05	0.90	0.61	0.37	0.20	0.10	0.08	0.07	0.03	0.04	0.04	0.05	0.09	0.08	0.13	0.20	0.31	0.48	0.75	0.97	1.26	1.48	1.36	1.31	1.11	0.82	0.55	0.38	0.29	0.21	0.19	18.62
5 – 6	0.10	0.19	0.42	0.68	0.99	1.13	1.00	0.59	0.30	0.16	0.06	0.05	0.03	0.03	0.03	0.01	0.04	0.05	0.04	0.07	0.11	0.21	0.41	0.70	1.07	1.40	1.63	1.45	1.51	1.15	0.75	0.48	0.23	0.14	0.09	0.08	17.39
6 – 7	0.02	0.04	0.09	0.26	0.69	0.90	0.72	0.39	0.19	0.08	0.05	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.03	0.04	0.06	0.11	0.20	0.40	0.76	1.24	1.56	1.49	1.43	0.98	0.57	0.25	0.12	0.07	0.03	0.02	12.89
7 – 8	0.00	0.01	0.03	0.08	0.23	0.47	0.35	0.18	0.08	0.03	0.03	0.02	0.01	0.01				0.01	0.02	0.02	0.02	0.06	0.09	0.21	0.50	0.90	1.16	1.07	0.98	0.62	0.33	0.15	0.05	0.03	0.00	0.01	7.78
8 – 9		0.00	0.03	0.02	0.05	0.12	0.11	0.04	0.01	0.01	0.02	0.00							0.01	0.00	0.01	0.02	0.04	0.09	0.25	0.52	0.65	0.62	0.43	0.30	0.14	0.04	0.03	0.02			3.60
9 – 10				0.02	0.04	0.05	0.03	0.00	0.00	0.00	0.00										0.00	0.01	0.01	0.02	0.12	0.21	0.24	0.28	0.21	0.08	0.04	0.01	0.00				1.39
10 – 11						0.00	0.01															0.01	0.00	0.01	0.03	0.06	0.13	0.12	0.06	0.02	0.02	0.00					0.47
11 – 12																									0.01	0.02	0.06	0.04	0.02	0.01	0.00	0.01					0.18
12 – 13																									0.01	0.01	0.04	0.01	0.01	0.01	0.00						0.09
13 – 14																								0.00			0.01	0.01									0.02
14 – 15																											0.00										0.00
15 – 16																												0.00									0.00
Total	1.18	1.70	2.42	3.33	4.44	5.22	4.42	2.86	2.00	1.12	0.81	0.69	0.54	0.51	0.44	0.41	0.47	0.58	0.51	0.81	1.08	1.53	2.28	3.60	5.26	7.42	9.13	8.22	8.09	6.03	4.27	2.89	1.95	1.56	1.28	1.06	100

3 WAVE CLIMATE MODELLING

3.1 Introduction

Wave climate condition is one of main input parameter for the hydrodynamic model. Therefore it is required to develop wave climate conditions for different monsoons in order to set up the hydrodynamic model. The wave data is not available for the desired location on the sea fit for usage. Most of the time wave data measured point is far away from the project location and it has to be transformed to a desired location by a model. In this case, MIKE 21 numerical wave model was used for wind wave generation and transformation process. The objectives of the wave climate modelling of this scheme is establishing nearshore wave climate at the site.

3.2 Model Used – MIKE 21 SW Model System

MIKE 21 SW includes a new generation spectral wind-wave model based on unstructured mesh. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. It includes two different formulations, namely, directional decoupled parametric formulation and fully spectral formulation. The directional decoupled parametric formulation is based on a parameterization of the wave action conservation equation. The parameterization is made in the frequency domain by introducing the zeroth and first moment of the wave action spectrum as dependent variables. The fully spectral formulation is based on the wave action conservation equation, where the directional-frequency wave action spectrum is the dependent variable.

The basic conservation equations are formulated in either Cartesian co-ordinates for small-scale applications or Polar Spherical co-ordinates for large-scale applications.

MIKE 21 SW includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white capping
- Dissipation due to bottom friction
- Dissipation due to depth induced wave breaking
- Refraction and shoaling due to depth variation
- Wave-current interaction
- Effect of time varying water depth and flooding and drying

The discretization of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action.

3.3 Model Setup

MIKE 21 SW model was used to generate waves and transfer them to the proposed site location base on UKMO wind data. All data set obtained from UKMO; i.e. 3 hour interval data from 1986 to 2016 were transferred to the site location.

The model was established by digitizing from the Admiralty charts No. 1013 & 3323, and near shore bathymetry data which were provided by WS. The preparation of model bathymetry was completed using flexible mesh as a requirement of SW model with reference to the Mean Sea Level. Figure 3.1 shows the regional model bathymetry of MIKE 21 SW model.

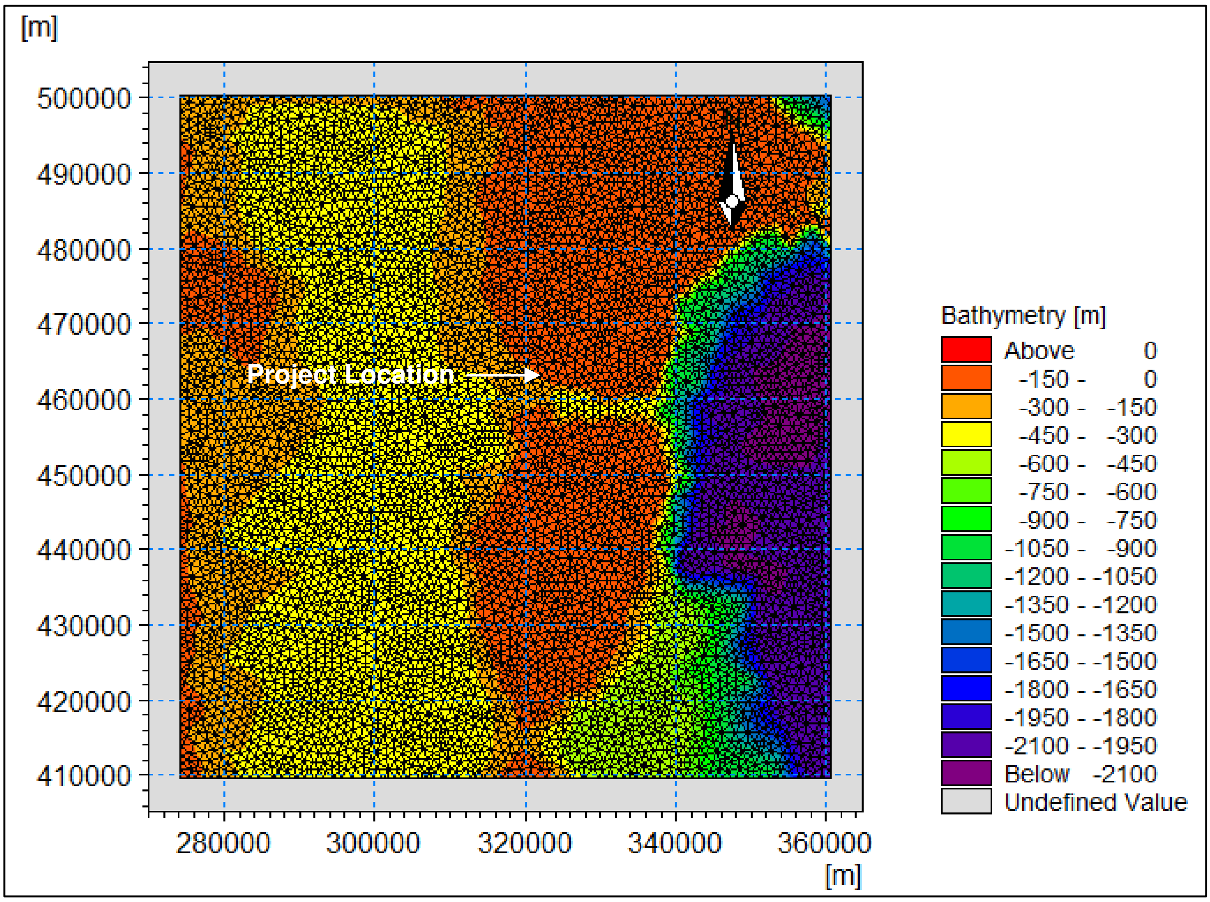


Figure 3.1: Wave Model Bathymetry - Regional

Additionally, a local model was also incorporated to improve the performance and accuracy of results. Then deep sea wind generated waves were transferred to 300m depth by regional model and then analysed wave data were further transferred to the site location by local model. The selected local model which the offshore boundary laid on around 300m depth is shown in Figure 3.2.

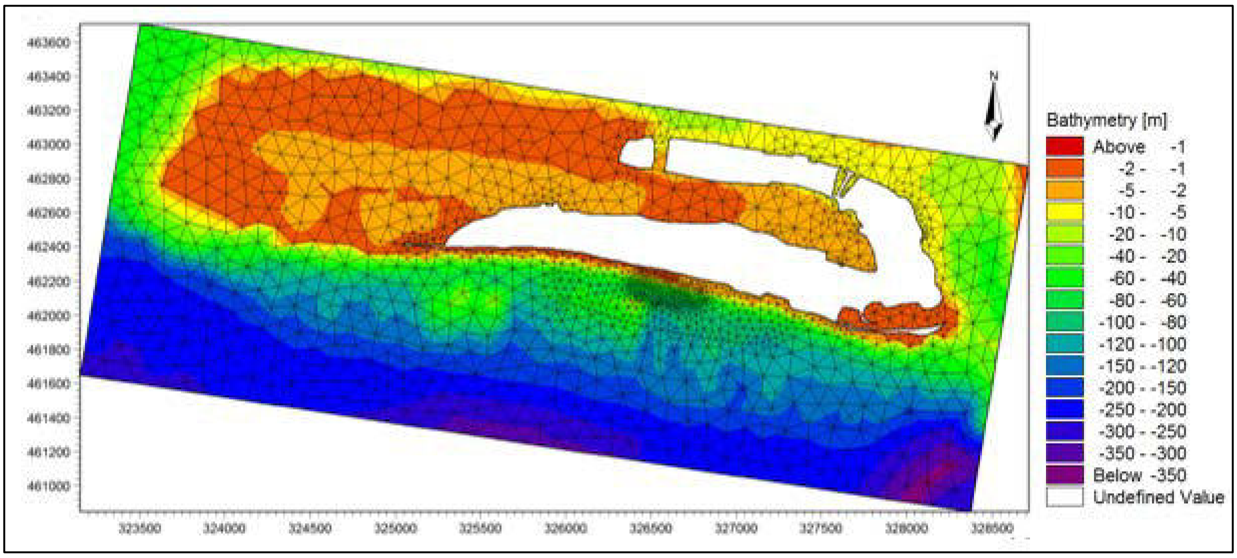


Figure 3.2: Wave Model Bathymetry - Local

3.4 Model Results

The wave analysis details of results obtained from the regional model at 300m depth are given below. The extracted results were analysed considering different seasons such as annual, South-West and North-East monsoon periods. South West monsoon was considered as from May to November while North East as from December to April. Tables 3.1 to 3.6 indicate the percentage of occurrence of waves, and their average peak wave period corresponding to the wave height and direction while Figures 3.3 to 3.5 graphically illustrate the wave height distribution patter in 360° angle.

Table 3.1: Annual Directional Distribution of Wave Height at 300m Depth (Percentage of Occurrence)

Hs (m) \ Dir (Deg.N)	0 -- 10	10 -- 20	20 -- 30	30 -- 40	40 -- 50	50 -- 60	60 -- 70	70 -- 80	80 -- 90	90 -- 100	100 -- 110	110 -- 120	120 -- 130	130 -- 140	140 -- 150	150 -- 160	160 -- 170	170 -- 180	180 -- 190	190 -- 200	200 -- 210	210 -- 220	220 -- 230	230 -- 240	240 -- 250	250 -- 260	260 -- 270	270 -- 280	280 -- 290	290 -- 300	300 -- 310	310 -- 320	320 -- 330	330 -- 340	340 -- 350	350 -- 360	Total
0 -- 0.2	0.71	0.88	0.99	1.17	1.36	1.30	1.30	1.05	0.80	0.67	0.47	0.41	0.32	0.33	0.28	0.26	0.25	0.28	0.29	0.36	0.43	0.53	0.62	0.78	0.89	1.01	1.10	1.31	1.20	1.14	1.11	0.98	0.83	0.81	0.73	0.69	27.64
0.2 -- 0.4	0.19	0.32	0.49	0.99	1.73	2.78	3.30	2.53	1.47	0.76	0.43	0.27	0.23	0.17	0.15	0.13	0.14	0.13	0.15	0.18	0.25	0.37	0.58	1.03	1.52	2.41	2.93	2.76	2.04	1.27	0.72	0.46	0.28	0.19	0.16	0.16	33.67
0.4 -- 0.6		0.00	0.01	0.02	0.09	0.44	1.06	0.90	0.41	0.18	0.11	0.07	0.03	0.02	0.01	0.01	0.01	0.02	0.02	0.05	0.12	0.22	0.59	1.59	3.40	4.53	4.29	2.76	1.31	0.41	0.14	0.05	0.01	0.01			22.88
0.6 -- 0.8			0.00	0.00	0.01	0.01	0.03	0.03	0.01	0.00	0.01	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.01	0.05	0.15	0.52	2.17	3.58	2.84	1.15	0.30	0.04	0.00	0.00	0.00	0.00			10.95
0.8 -- 1			0.00	0.00	0.00		0.00	0.00	0.00	0.00			0.00		0.00	0.00	0.00					0.00	0.03	0.13	0.81	1.56	0.97	0.19	0.03	0.00		0.00		0.00			3.75
1 -- 1.2			0.00	0.00	0.00	0.00										0.00			0.00				0.00	0.01	0.18	0.42	0.19	0.03	0.00		0.00		0.00				0.85
1.2 -- 1.4		0.00	0.00		0.00	0.00										0.00	0.00	0.00							0.02	0.11	0.04						0.00	0.00			0.17
1.4 -- 1.6					0.00			0.00	0.00																0.00	0.01	0.00				0.00	0.00	0.00	0.00			0.03
1.6 -- 1.8				0.00		0.00	0.00		0.00						0.00											0.00	0.00	0.00			0.00	0.00		0.00			0.01
1.8 -- 2					0.00			0.00													0.00		0.00														0.01
2 -- 2.2					0.00	0.00		0.00	0.00										0.00	0.00											0.00			0.00			0.01
Above 2.2		0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00				0.00				0.00		0.00	0.00							0.00		0.00				0.02
Total	0.90	1.20	1.49	2.19	3.19	4.53	5.69	4.52	2.68	1.61	1.02	0.74	0.58	0.52	0.44	0.39	0.41	0.43	0.46	0.59	0.82	1.15	1.97	4.06	8.98	13.64	12.36	8.20	4.87	2.85	1.97	1.49	1.12	1.02	0.90	0.85	100.00

Table 3.2: Annual Directional Distribution of Peak Wave Period at 300m Depth

Hs (m) \ Dir (Deg.N)	0 -- 10	10 -- 20	20 -- 30	30 -- 40	40 -- 50	50 -- 60	60 -- 70	70 -- 80	80 -- 90	90 -- 100	100 -- 110	110 -- 120	120 -- 130	130 -- 140	140 -- 150	150 -- 160	160 -- 170	170 -- 180	180 -- 190	190 -- 200	200 -- 210	210 -- 220	220 -- 230	230 -- 240	240 -- 250	250 -- 260	260 -- 270	270 -- 280	280 -- 290	290 -- 300	300 -- 310	310 -- 320	320 -- 330	330 -- 340	340 -- 350	350 -- 360	Average
0 -- 0.2	1.8	1.9	1.9	1.9	2.0	2.0	2.0	2.0	1.9	2.0	1.9	1.8	1.9	1.9	1.8	1.8	2.1	1.9	1.9	1.8	1.7	1.7	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.7	1.7	1.9
0.2 -- 0.4	2.3	2.5	2.5	2.5	2.5	2.6	2.7	2.7	2.7	2.7	2.7	2.8	2.8	2.8	2.8	3.0	3.1	3.2	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	2.8	2.7	2.6	2.5	2.4	2.4	2.4	2.8
0.4 -- 0.6		9.1	7.8	7.0	3.2	3.0	3.1	3.1	3.1	3.2	3.4	3.5	3.3	4.3	7.6	8.5	4.8	8.8	3.6	3.6	3.7	3.8	3.8	3.8	3.8	3.7	3.7	3.6	3.5	3.3	3.4	3.2	3.6	4.9			3.6
0.6 -- 0.8			11.6	10.9	12.4	8.7	7.3	5.3	6.4	5.2	3.5	6.5	13.3	11.5	13.4			19.9	4.0	9.7	4.2	4.2	4.3	4.3	4.2	4.2	4.1	4.0	3.9	3.7	8.9	14.7	13.5	12.9			4.2
0.8 -- 1			13.0	14.1	14.7		10.7	12.2	11.0	12.7			11.8		19.4	7.9	7.0					4.7	5.3	4.6	4.6	4.5	4.4	4.3	4.2	4.1		14.2		12.4			4.5
1 -- 1.2			12.3	10.9	15.9	12.2										12.1			12.3				5.0	5.0	4.9	4.8	4.7	4.6	10.9		13.0		16.3				5.1
1.2 -- 1.4		13.5	12.7		16.6	13.8										13.1	9.8	14.4							5.2	5.1	5.0						14.4	14.0			6.0
1.4 -- 1.6					16.7			14.1	12.8																5.5	5.3	5.2				11.8	14.3	18.8	18.0			9.2
1.6 -- 1.8				13.0		14.2	11.2		14.5						21.2											5.4	5.4	11.6			13.6	16.0		15.8			13.4
1.8 -- 2					15.6			13.0													12.7		18.8														14.8
2 -- 2.2					12.8	13.4		14.7	16.9										10.9	12.2											19.8			14.2			15.3
Above 2.2		17.7	15.1		10.1	12.8	16.4	12.8	15.6	19.6		16.8	13.1				20.9				16.4		15.3	15.4							16.2		15.3				16.3
Average	1.9	2.1	2.3	2.2	2.4	2.5	2.6	2.6	2.6	2.5	2.4	2.3	2.4	2.3	2.5	2.4	2.5	2.5	2.3	2.3	2.4	2.6	3.0	3.3	3.7	3.7	3.5	3.2	2.9	2.5	2.3	2.1	2.0	2.0	1.9	1.8	3.0

Table 3.3: Directional Distribution of Wave Height for South-West Monsoon at 300m Depth (Percentage of Occurrence)

Dir (Deg.N) / Hs (m)	0 -- 10	10 -- 20	20 -- 30	30 -- 40	40 -- 50	50 -- 60	60 -- 70	70 -- 80	80 -- 90	90 -- 100	100 -- 110	110 -- 120	120 -- 130	130 -- 140	140 -- 150	150 -- 160	160 -- 170	170 -- 180	180 -- 190	190 -- 200	200 -- 210	210 -- 220	220 -- 230	230 -- 240	240 -- 250	250 -- 260	260 -- 270	270 -- 280	280 -- 290	290 -- 300	300 -- 310	310 -- 320	320 -- 330	330 -- 340	340 -- 350	350 -- 360	Total
0 -- 0.2	0.09	0.09	0.08	0.06	0.07	0.03	0.04	0.05	0.07	0.09	0.08	0.08	0.15	0.21	0.24	0.20	0.25	0.31	0.38	0.49	0.60	0.74	0.84	1.13	1.18	1.17	1.19	1.32	1.04	0.79	0.68	0.45	0.30	0.21	0.19	0.10	15.00
0.2 -- 0.4	0.00		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.08	0.13	0.15	0.21	0.22	0.27	0.35	0.45	0.65	1.10	1.88	2.55	3.87	4.13	3.52	2.08	1.11	0.57	0.27	0.13	0.04	0.03	0.02	23.96
0.4 -- 0.6			0.01	0.00	0.00		0.01	0.00		0.00	0.00	0.00		0.01	0.01	0.01	0.02	0.03	0.05	0.10	0.23	0.37	1.07	3.00	6.42	8.04	7.35	4.46	2.04	0.66	0.24	0.06	0.00	0.00			34.20
0.6 -- 0.8			0.01	0.01	0.01		0.01							0.00	0.00				0.00	0.00	0.02	0.08	0.31	1.03	4.22	6.25	4.86	1.94	0.57	0.09	0.01						19.41
0.8 -- 1				0.00	0.00		0.00	0.01					0.00			0.00						0.00	0.04	0.22	1.24	2.47	1.63	0.33	0.07	0.01							6.03
1 -- 1.2			0.01	0.00	0.00	0.00													0.00				0.00	0.02	0.19	0.49	0.33	0.05	0.01				0.00				1.10
1.2 -- 1.4			0.00		0.00											0.00		0.01							0.01	0.11	0.07										0.21
1.4 -- 1.6											0.01														0.01	0.02	0.01				0.00	0.00					0.05
1.6 -- 1.8				0.00			0.00		0.00																	0.00	0.00	0.00									0.02
1.8 -- 2					0.01			0.00																													0.01
2 -- 2.2						0.00			0.00										0.00	0.00																	0.01
Above 2.2			0.00		0.00	0.00			0.00														0.00														0.01
Total	0.09	0.09	0.12	0.08	0.10	0.05	0.07	0.07	0.09	0.11	0.10	0.10	0.18	0.30	0.37	0.37	0.49	0.58	0.70	0.95	1.30	1.85	3.36	7.28	15.82	22.44	19.56	11.61	5.80	2.65	1.49	0.79	0.44	0.25	0.22	0.12	100.00

Table 3.4: Directional Distribution of Peak Wave Period for South-West Monsoon at 300m Depth

Dir (Deg.N) / Hs (m)	0 -- 10	10 -- 20	20 -- 30	30 -- 40	40 -- 50	50 -- 60	60 -- 70	70 -- 80	80 -- 90	90 -- 100	100 -- 110	110 -- 120	120 -- 130	130 -- 140	140 -- 150	150 -- 160	160 -- 170	170 -- 180	180 -- 190	190 -- 200	200 -- 210	210 -- 220	220 -- 230	230 -- 240	240 -- 250	250 -- 260	260 -- 270	270 -- 280	280 -- 290	290 -- 300	300 -- 310	310 -- 320	320 -- 330	330 -- 340	340 -- 350	350 -- 360	Average
0 -- 0.2	1.4	2.5	4.8	2.1	2.4	2.4	1.3	1.4	2.7	1.6	1.8	1.7	2.1	1.9	1.9	1.8	1.8	1.9	1.8	1.8	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.9	1.9	1.8	1.8	1.7	2.0	1.6	1.6	1.9
0.2 -- 0.4	2.2		5.3	4.1	6.1	8.6	3.7	10.3	11.5	7.9	2.5	3.7	2.7	2.7	2.8	3.0	2.9	3.1	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	2.9	2.8	2.7	2.5	2.4	2.4	2.4	3.0
0.4 -- 0.6			11.7	9.3	10.1		12.2	7.9		7.9	15.7	8.1		6.8	3.3	5.9	3.8	3.5	3.5	3.7	3.8	3.8	3.8	3.8	3.8	3.7	3.7	3.6	3.5	3.4	3.2	3.1	3.1	13.0			3.7
0.6 -- 0.8			11.5	9.0	9.9		12.7							11.5	17.2				4.0	4.2	4.2	4.2	4.3	4.2	4.2	4.2	4.1	4.0	3.9	3.7	3.6						4.2
0.8 -- 1				14.1	16.1		10.7	12.2					11.8			7.9						4.6	4.7	4.6	4.6	4.5	4.4	4.3	4.2	4.1							4.5
1 -- 1.2			12.3	10.3	13.1	13.0													12.3				4.9	5.0	4.9	4.8	4.7	4.6	10.9				18.7				5.1
1.2 -- 1.4			12.7		16.6											13.1		13.5							5.2	5.1	5.0										5.9
1.4 -- 1.6											14.3														5.5	5.3	5.2				11.8	13.6					8.6
1.6 -- 1.8				13.0			11.2		14.5																	5.4	5.4	11.6									11.1
1.8 -- 2					15.6			13.0																													14.7
2 -- 2.2						13.4			13.1										10.9	12.2																	12.6
Above 2.2			15.8		10.1	12.8			20.0														15.3														11.5
Average	1.5	2.5	6.8	4.0	6.2	7.1	6.0	4.4	5.8	2.6	3.5	2.0	2.4	2.3	2.3	2.6	2.4	2.5	2.5	2.5	2.6	2.7	3.1	3.3	3.7	3.7	3.6	3.3	3.0	2.7	2.4	2.1	2.0	2.2	1.7	1.7	3.4

Table 3.5: Directional Distribution of Wave Height for North East Monsoon at 300m Depth (Percentage of Occurrence)

Hs (m) \ Dir (Deg.N)	0 -- 10	10 -- 20	20 -- 30	30 -- 40	40 -- 50	50 -- 60	60 -- 70	70 -- 80	80 -- 90	90 -- 100	100 -- 110	110 -- 120	120 -- 130	130 -- 140	140 -- 150	150 -- 160	160 -- 170	170 -- 180	180 -- 190	190 -- 200	200 -- 210	210 -- 220	220 -- 230	230 -- 240	240 -- 250	250 -- 260	260 -- 270	270 -- 280	280 -- 290	290 -- 300	300 -- 310	310 -- 320	320 -- 330	330 -- 340	340 -- 350	350 -- 360	Total
0 -- 0.2	1.31	1.73	2.15	2.52	2.85	2.81	2.76	2.01	1.42	1.01	0.65	0.53	0.31	0.28	0.18	0.12	0.16	0.08	0.07	0.07	0.15	0.12	0.07	0.13	0.16	0.20	0.27	0.31	0.33	0.48	0.70	0.87	0.85	0.98	1.04	1.18	30.86
0.2 -- 0.4	0.62	0.98	1.59	3.31	5.87	9.57	11.03	7.95	4.07	1.84	0.87	0.60	0.33	0.22	0.12	0.07	0.04		0.02	0.01	0.02	0.03	0.02	0.07	0.11	0.20	0.31	0.49	0.55	0.51	0.45	0.53	0.43	0.42	0.42	0.46	54.14
0.4 -- 0.6		0.01	0.01	0.07	0.34	1.67	4.06	3.32	1.42	0.62	0.33	0.20	0.05	0.01	0.03	0.01			0.00		0.01	0.02	0.00	0.04	0.20	0.21	0.30	0.17	0.13	0.10	0.07	0.03	0.02	0.01		0.01	13.49
0.6 -- 0.8					0.01	0.01	0.10	0.11	0.01	0.01	0.02	0.00	0.00									0.01	0.00		0.11	0.33	0.18	0.03	0.00		0.00		0.00				0.95
0.8 -- 1																							0.02	0.02	0.16	0.18	0.02							0.00			0.41
1 -- 1.2				0.00												0.00								0.01	0.06	0.01					0.00						0.10
1.2 -- 1.4		0.00																							0.00												0.01
1.4 -- 1.6																																	0.00	0.00			0.01
1.6 -- 1.8															0.00																0.00	0.00					0.01
1.8 -- 2																																					
2 -- 2.2																																		0.00			0.00
Above 2.2								0.00	0.00	0.00							0.00																				0.02
Total	1.94	2.73	3.75	5.89	9.08	14.06	17.95	13.40	6.93	3.48	1.87	1.33	0.69	0.52	0.34	0.20	0.20	0.08	0.10	0.09	0.19	0.17	0.13	0.26	0.79	1.13	1.08	1.00	1.02	1.09	1.23	1.44	1.31	1.43	1.45	1.64	100.00

Table 3.6: Directional Distribution of Peak Wave Period for North East Monsoon at 300m Depth

Hs (m) \ Dir (Deg.N)	0 -- 10	10 -- 20	20 -- 30	30 -- 40	40 -- 50	50 -- 60	60 -- 70	70 -- 80	80 -- 90	90 -- 100	100 -- 110	110 -- 120	120 -- 130	130 -- 140	140 -- 150	150 -- 160	160 -- 170	170 -- 180	180 -- 190	190 -- 200	200 -- 210	210 -- 220	220 -- 230	230 -- 240	240 -- 250	250 -- 260	260 -- 270	270 -- 280	280 -- 290	290 -- 300	300 -- 310	310 -- 320	320 -- 330	330 -- 340	340 -- 350	350 -- 360	Average
0 -- 0.2	1.8	1.9	1.9	1.9	2.0	2.0	2.0	2.0	1.9	2.1	1.8	1.8	1.8	1.8	2.2	1.8	2.4	2.1	2.8	1.9	2.0	1.5	1.9	1.9	1.6	1.8	1.7	1.8	1.9	1.9	1.9	1.8	1.7	1.8	1.8	1.8	1.9
0.2 -- 0.4	2.3	2.4	2.4	2.4	2.5	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.9	2.8	2.8	2.9	3.1		2.5	2.6	2.9	2.8	3.1	2.8	3.0	2.9	3.0	2.9	2.9	2.8	2.7	2.6	2.5	2.4	2.4	2.3	2.6
0.4 -- 0.6		6.5	5.0	2.9	3.0	3.0	3.0	3.1	3.1	3.1	3.2	3.2	3.3	3.2	7.4	7.2			7.6		3.8	3.9	3.7	3.7	3.8	3.7	3.6	3.5	3.4	3.3	3.7	3.1	3.0	2.9		2.8	3.1
0.6 -- 0.8					3.2	3.3	3.4	3.6	3.4	8.7	3.5	3.6	14.2									4.3	4.5		4.3	4.2	4.1	3.9	3.8		10.0		13.5				4.1
0.8 -- 1																							6.9	4.8	4.6	4.5	4.4							12.4			4.8
1 -- 1.2				14.5												12.1								4.9	4.9	4.9					13.0						6.1
1.2 -- 1.4		13.5																							5.2												9.3
1.4 -- 1.6																																	18.8	18.0			18.4
1.6 -- 1.8															21.2																13.6	13.3					16.0
1.8 -- 2																																					
2 -- 2.2																																		14.2			14.2
2.2 -- 2.4								12.8	11.1	19.6							20.9																				17.5
Average	2.0	2.1	2.2	2.2	2.4	2.5	2.6	2.7	2.6	2.7	2.5	2.5	2.5	2.2	3.1	2.8	3.0	2.1	3.0	2.0	2.2	2.1	3.2	2.7	3.6	3.5	3.1	2.7	2.6	2.4	2.4	2.2	2.1	2.1	1.9	1.9	2.5

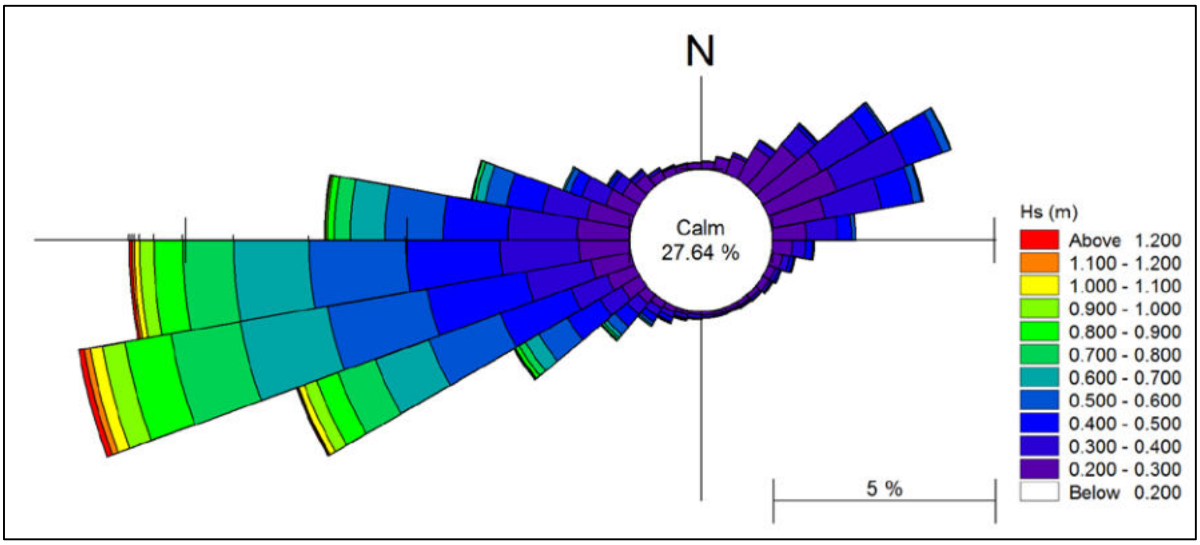


Figure 3.3: Annual Wave Height Distribution at 300m Depth

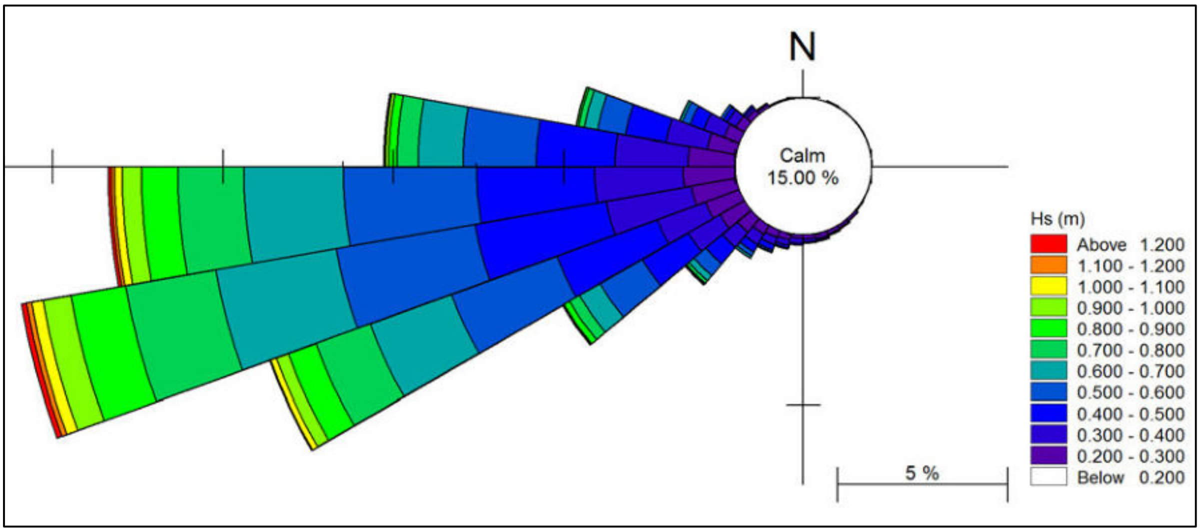


Figure 3.4: Wave Height Distribution for South-West Monsoon at 300m Depth

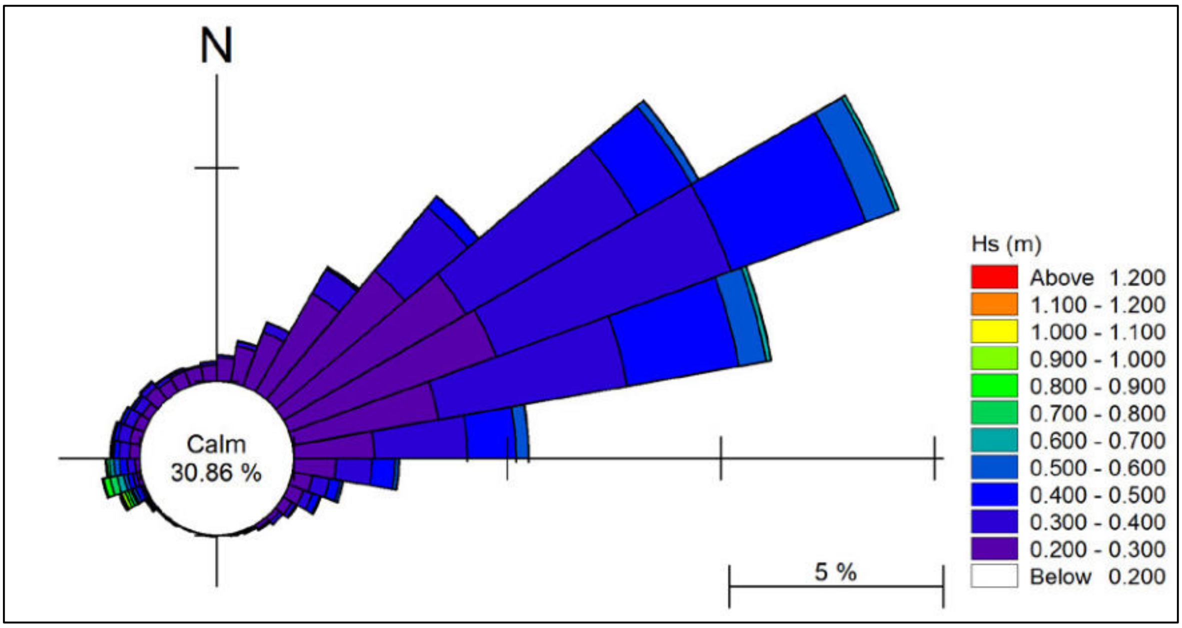


Figure 3.5: Wave Height Distribution for North-East Monsoon at 300m Depth

4 HYDRODYNAMIC MODELLING

In order to compute water circulation with effect of tidal flow, wave and wind in and around the study area, a hydrodynamic model required to be carried out. Hence, the numerical model, MIKE 21 HD was used in this process.

4.1 MIKE 21 Hydrodynamic Model System

MIKE 21 HD (Flexible Mesh) model developed by Danish Hydraulic Institute was used for the simulation. It is a modelling system for 2D free-surface flows and applicable to the simulation of hydraulic and environmental phenomena in lakes, rivers, estuaries, bays, coastal areas and seas in response to a variety of forcing functions including tide, wind, wave and river flow. The HD module allows you to specify a variety of hydrographic boundary conditions, initial conditions, bed resistance and wind forcing. It also allows you to include different types of sources and sinks as well as a number of different structures. It provides the hydrodynamic basis for the computations performed in the environmental hydraulics and sediment transport modules.

4.2 MIKE 21 HD Model Set Up

4.2.1 Model Bathymetry

Same as the wave model, Admiralty charts and bathymetry data provided by the client were used for the development of model bathymetry. Since tidal variation would be applied as main boundary condition for the regional model, availability of tidal data was considered when setting up the model. Tidal boundaries were developed using MIKE 21 Toolbox Tide developer considering 25km away from Thilafushi in North and South directions, and 45km in West and East direction. Therefore the regional model covers the model area of 50km in north-south way and 90km east-west way. Figure 4.1 illustrates the bathymetry of regional model and position of the local model on it. Local model was selected considering the bathymetry, and kept offshore boundary at 300m depth.

Triangular flexible mesh was generated by MIKE 21 Bathymetry Creator Tool while considering finer mesh size for more concern area. The UTM 43 coordinate system was used for (x, y) coordinates and Mean Sea Level (MSL) was used as the elevation datum. The local bathymetry with mesh is given in Figure 4.2.

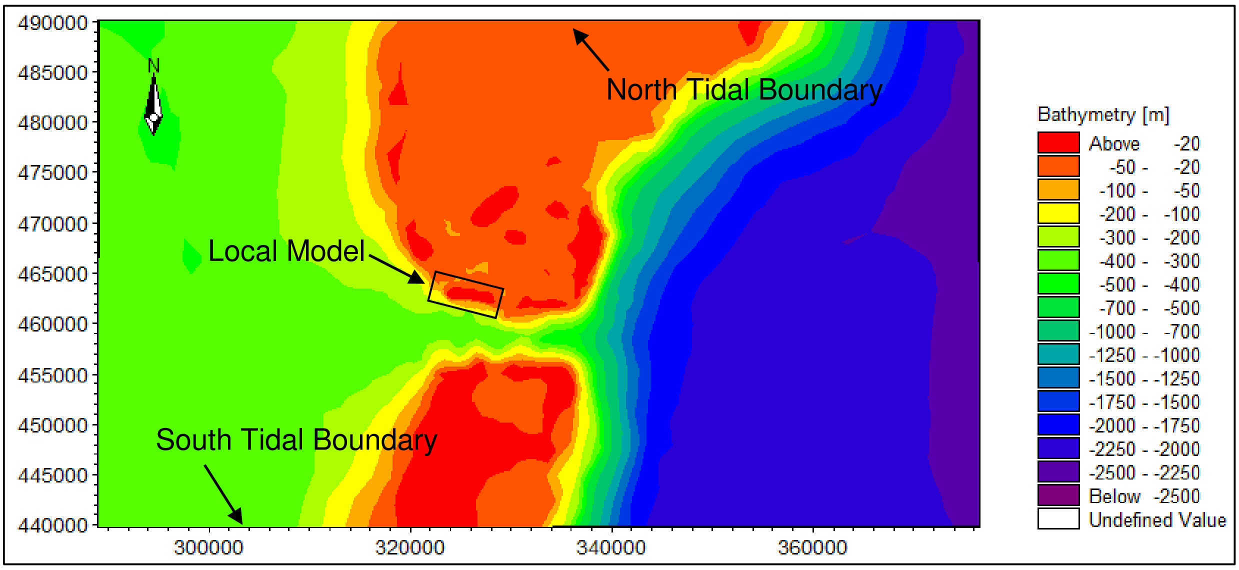


Figure 4.1: Bathymetry for Regional Hydrodynamic Model

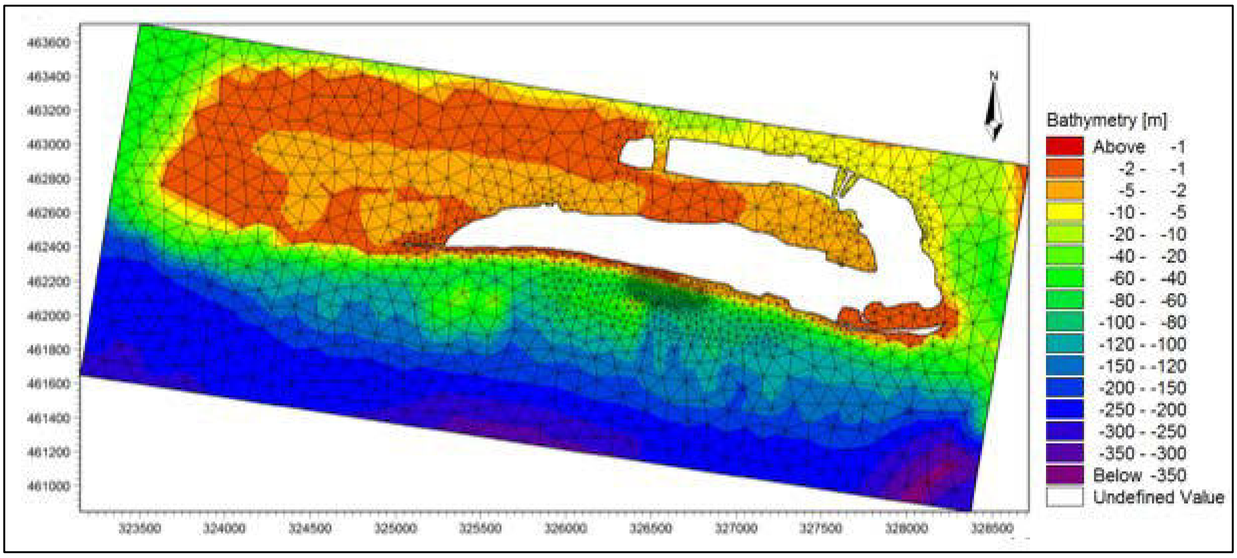


Figure 4.2: Bathymetry for Local Hydrodynamic Model

4.2.2 Simulation Period

The regional model was run for one month period for each South-West and North-East monsoon and the local model was run for three days for each monsoon which covering spring and neap tide. The regional model was run with the time step of 3s and the local model with 1s.

4.2.3 Boundary Conditions

The tide levels of the boundaries are used as boundary conditions for regional model. Time series of water levels were predicted using MIKE 21 Toolbox Tide developer for north and south tidal boundaries as indicated in Figure 4.1. Representative predicted tidal plots in north and south boundaries for few days in South-West Monsoon are shown in Figures 4.3 and 4.4.

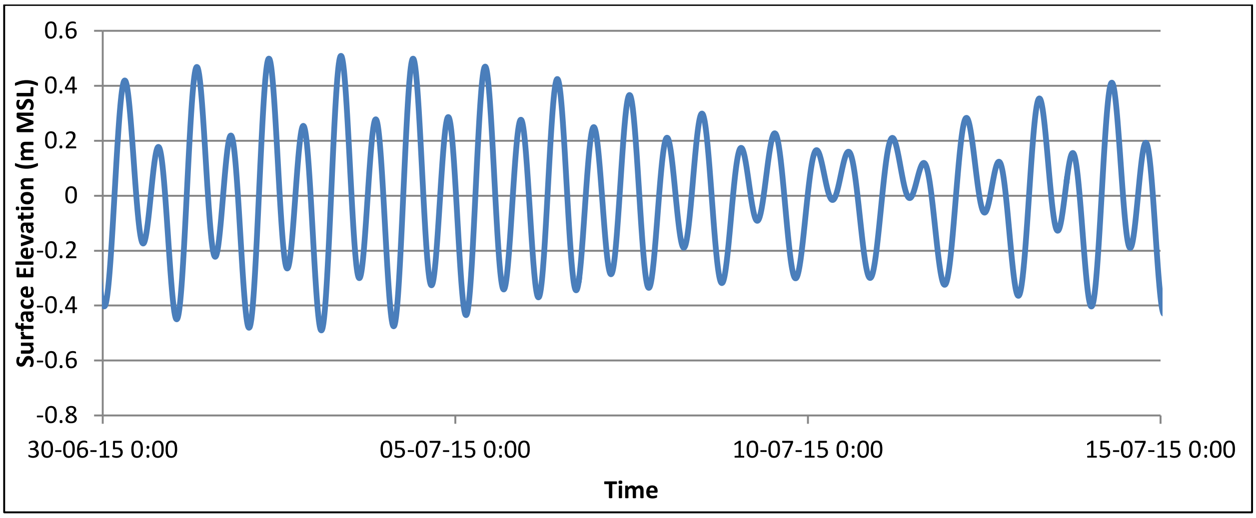


Figure 4.3: Predicted Tide in North Boundary

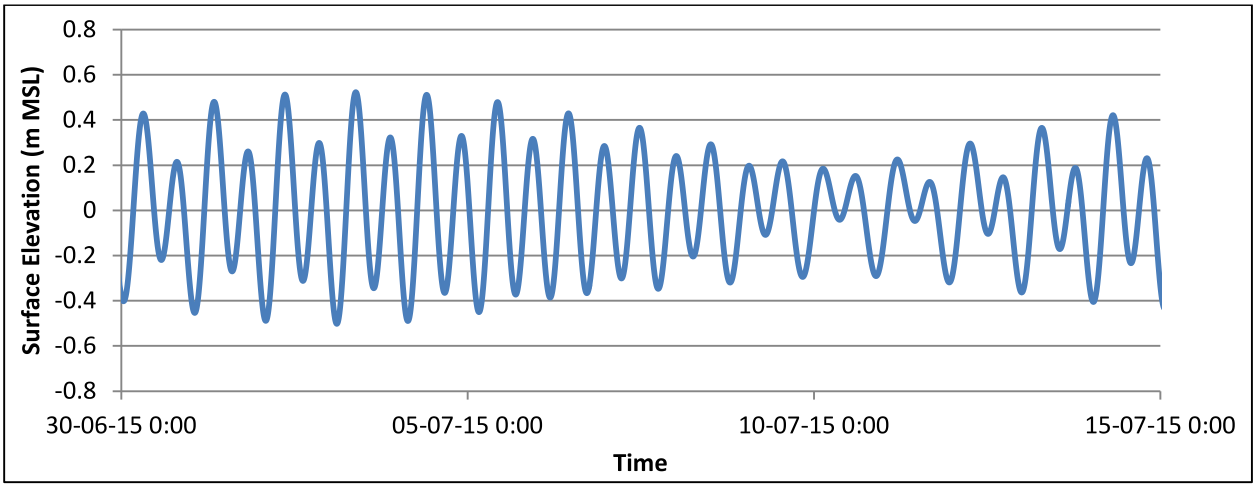


Figure 4.4: Predicted Tide in South Boundary

Water levels and discharges extracted from regional model at the boundaries of the local model were used as boundary conditions for the local model.

4.2.4 Wave and Wind Conditions

Local model was run for average wave/wind condition for both monsoons. The average condition was selected considering 50% of occurrence line of wave height of the wave data extracted at 300m depth from wave transformation model (MIKE 21 SW). In this process, most dominant directional bands were selected for the calculations (as coloured in Table 3.3 to 3.6). Same as wave, 50% of occurrence line of wind speed of UKMO wind data was selected to obtain corresponding wind speed. The selected wave and wind conditions are given in following table and both wind and wave conditions were applied at the same time in the model for each monsoon.

Monsoon	Wave Condition			Wind Condition	
	Hs (m)	Tp (s)	Direction (deg)	Speed (m/s)	Direction (deg)
SW	0.49	3.6	260	5.75	270
NE	0.26	2.4	60	5.02	55

Table 4.1: Applied Wave/Wind Conditions for the Local Hydrodynamic Model

4.3 MIKE 21 HD Model Calibration

Calibration was done for predicted tide levels at Male considering the variation of surface elevations. Figure 4.5 shows the water level comparison between model values and predicted tide at male. The bed roughness was used as the calibration parameter and Manning's Number of 32 was set as the suitable values for the calibration.

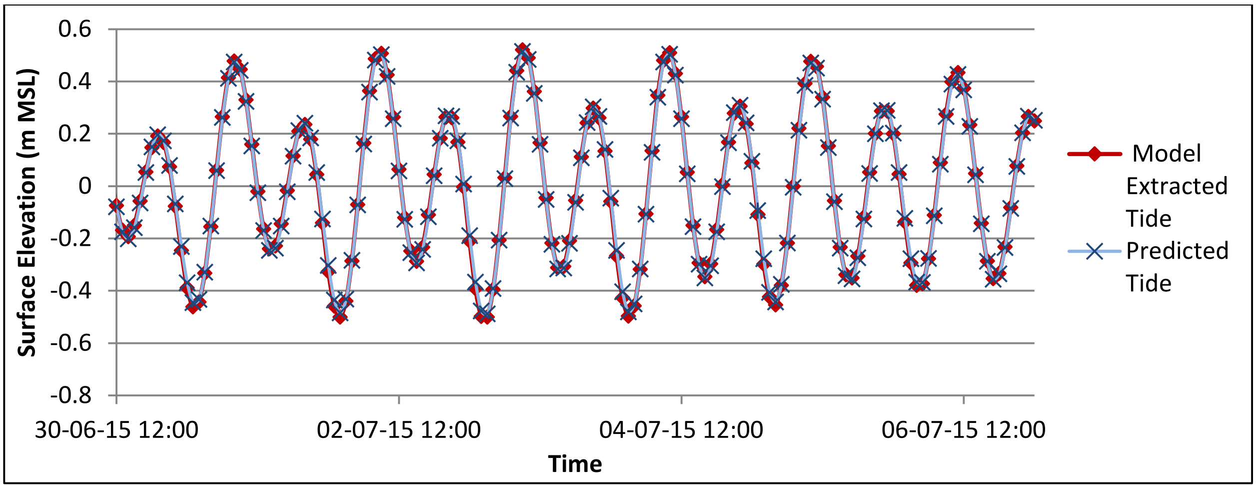


Figure 4.5: Calibration with Predicted Tide at Male

4.4 MIKE 21 HD Results

The main objective of the HD modelling is to observe the flow pattern in the site area and find out the effective current flow for thermal dispersion at outfall. Hence current speeds and directions were extracted at the outfall location (Figure 4.6) for both monsoon periods and spring and neap tidal conditions. The average current speed and direction for different conditions are given in Table 4.2.

According to the results, it can be observed that the wave condition is not significantly affected for the current at outfall location; it is basically tide dominant. The direction of current varies almost 180 degree with ebb and flood conditions, but Table 4.2 gives direction values only considering westward current flow condition.

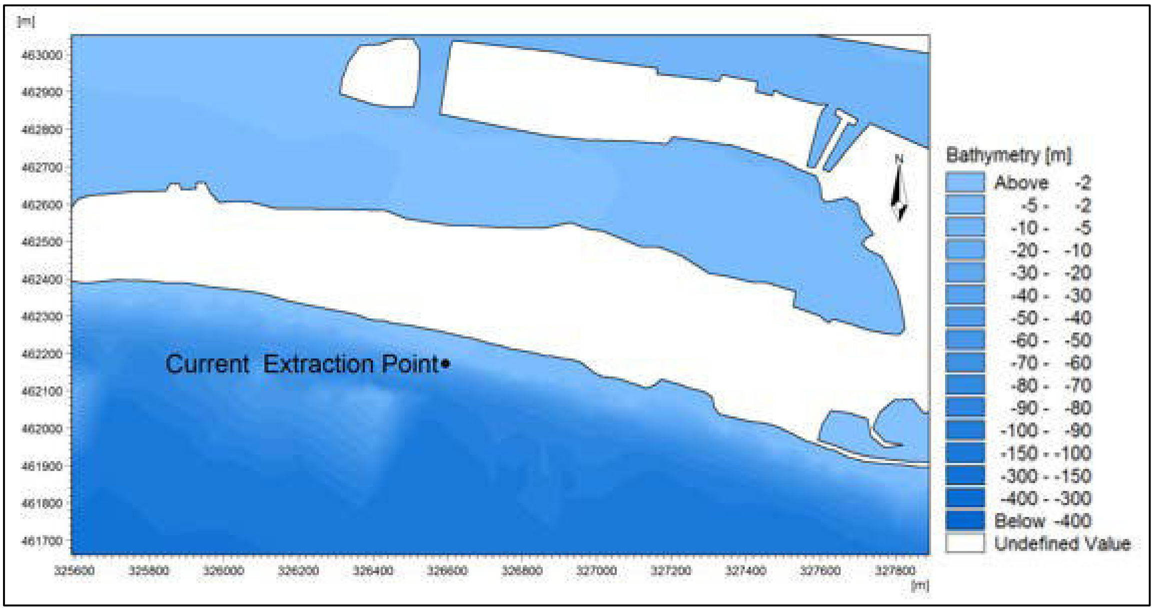


Figure 4.6: Current Extracted Points

Table 4.2: Average Current Condition at Extracted Point

Monsoon	Tidal Condition	Current Speed (m/s)	Direction (deg)
SW	Neap Tide	0.10	277
	Spring Tide	0.22	280
NE	Neap Tide	0.10	280
	Spring Tide	0.20	271

5 THERMAL DISPERSION MODELLING

5.1 Introduction

The proposed incinerator will use sea water as the coolant and discharge hot water back to the sea. Inevitably, the temperature of water discharged is above the ambient. As temperature is one of the most important environmental variables, discharging water of such temperature will have significant impact to the aquatic organisms and to the local biological and biogeochemistry of the ocean. Impacts of high water temperature discharge are such as:

- Coral bleaching
- Reduction of dissolved oxygen level
- Stimulation of phytoplankton and benthic algal growth
- Alteration in ecosystem which affects the mortality and reproduction
- Alteration of thermal structure of the ocean, current patterns, surface wave patterns

In this modelling process, initial dilution is estimated using a near field model (CORMIX). Thereafter using its results depth average diluted thermal factors are obtained and fed them to a far field model (MIKE 21 HD Thermal Dispersion). Finally spreading of thermal plume in 2D plain can be obtained.

5.2 Simulation Scenarios

Three single port outfalls, each consists of 1.1 m diameter pipe in which discharges effluent having 3 K excess temperature relative to the ambient temperature at 2 m/s flow velocity were considered in simulations. These outfalls release the hot water plume at 30 m depth. These scenarios have been selected based on indicative model runs from the previous study taking all possible monsoonal and tidal conditions into account. Therefore all together four number of scenarios were simulated as given in the following table.

Table 5.1: Simulation Scenarios

Sc. ID	Monsoon	Tide	Current Condition	
			Speed (m/s)	Direction (Deg. N)
NE_S	North-East	Spring	0.2	271
NE_N		Neap	0.1	280
SW_S	South-West	Spring	0.22	280
SW_N		Neap	0.1	277

In addition, single outfall which releases total discharge of above mentioned three outfalls was also simulated in near field model to check the effect compared to three outfalls. Thus, this single outfall discharges 19,880 m^3/h hot water plume through a 1.9 m diameter pipe at 2 m/s velocity.

5.3 Near Field Modelling

Three outfalls place in a 20m interval distance to each other in a straight line. This outfall line is parallel to the shoreline and around 75m away from the shore as shown in the **Figure 5.1**.

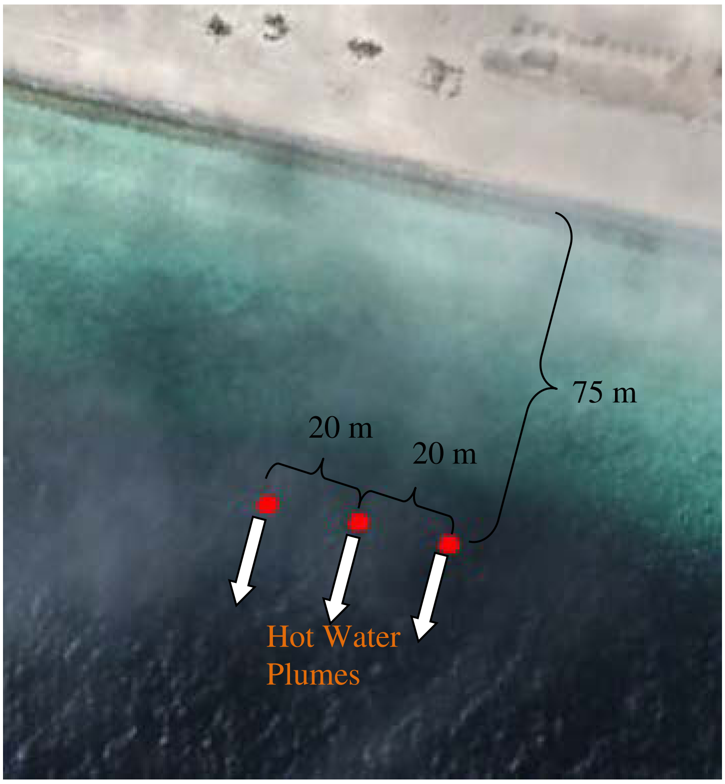


Figure 5.1: Locations of Outfalls

The outfalls are set perpendicular to the shore in which the outlets are arranged to release the hot water jet parallel to the centre line of their ports at a depth of 30 m towards the deep sea. It releases horizontally close to the sea bottom. Since the density of the heated plume is less it acts as negatively buoyant discharges and tends to move upwards. The initial dispersion is very important and generally reduces the excess temperature by a factor of 2 to 3 over a distance of a few meters. Once the discharge momentum reduced below a certain limit due to the dilution, the mixing is cease to be the dominant factor and the discharge transforms into what is generally known as a plume. After this, the discharge enters the far field. To examine the near field behaviour of the heated plume CORMIX mixing zone model is used.

5.3.1 CORMIX Modelling System

The CORMIX is a mixing zone model and decision support system for environmental impact assessment of regulatory mixing zones resulting from continuous point source discharges (Doneker & Jirka 2007). It is a computer-aided-design (CAD) developed by the Defrees Hydraulic Laboratory at Cornell University, Ithaca, New York, in cooperation of USEPA for studying aqueous pollutant discharges into a range of water bodies, design and mixing zone analysis (Doneker & Jirka 2007). The role of boundary interaction is the emphasis of the system for predicting steady-state mixing behaviour and plume geometry (Doneker & Jirka 2007).

Simulation model selection in CORMIX is controlled by the Graphical user interface (GUI) and mixing zone rule-based expert systems technology. Description of discharge and ambient conditions are specified as input data in the GUI. Based on the inputs, the most appropriate hydrodynamic simulation model is determined. CORMIX employs the length-scaled rule-based system for classification of flow regimes and uses the length scale for predicting the initial dilution. CORMIX simplifies the characteristics of each stage in the steady-state condition and predicts the plume dilution by using some empirical equations (Etemad-Shahidi & Azimi 2007).

CORMIX is applicable to wide range of problems from a simple single submerge pipe discharge into a small stream with rapid cross-sectional mixing to a complicated multiport diffuser installation in deeply-stratified coastal water. However, there is lack of applicability in highly unsteady ambient flow conditions that are prone to locally recirculating flows (Doneker & Jirka 2007).

The main aim is to obtain an estimation of spreading of heated plume around the discharge. The model set up used the excess temperature as a tool to access the change in temperature level.

5.3.2 Model Simulations

As discussed earlier dilution process can be divided into a primary jet dilution in the so-called **near-field** and a subsequent natural dilution in the **far-field**. The natural dilution (far field) is influenced by waves, currents and environment conditions.

In general near field of an outfall is governed by the initial jet characteristics of the plume, current flow acting on the outfall location, and outfall geometry. In this case, horizontal single port discharge is considered in the modelling simulations. The density of effluent is 1021.4m^3/kg according to its temperature 31 ^{0}C and the ambient density of the sea water is considered as 1025m^3/kg. Ambient temperature level is assumed as 28 ^{0}C. Simulations were carried out for a list of scenarios given in Table 5.1.

Since all three outfalls have the same conditions in discharge effluent and all are single port outfalls, one outfall discharge was considered in near field modelling, but the combine effect of all three outfalls was interpreted using excess temperature isolines (refer Section 5.3.3). However, the resultant condition of all three discharges was applied in the far field model (HD model) through extracting the near field model results.

5.3.3 CORMIX Model Results

Visualization of the effluent discharged from the port and rising to the surface in a cross flow at near-field region is given in below 3D plots for all simulations. Both plan view and the elevation of the plume for these scenarios are given in Annex A. In addition, the graphs which show variation of excess temperature with downstream distance are also given in Annex A.

The apparent 'discontinuity' effects in the Excess temperature vs. Downstream distance graphs (refer Annex A) are due to a transition in the plume profile that were assumed to cover highly complex flow characteristics in that distance of the discharge point. Owing to the so called "Coanda effect" in the near field, the bottom of the sea limits ambient entrainment into the jet. Most of the near field mixing is due to the buoyancy differences between ambient water and discharge. Though the CORMIX model visualisation may appear as a discontinuity, the results of the model rather indicate the user of the presence of these highly complex flow conditions whose tendency is in line with the expected results, i.e. the neap tide conditions reveal that the Coanda effect occurs closer to the discharge point.

If the Coanda effect occurs, it reduces the initial dilution and causes to reduce the dissipation of excess temperature. However, the existing bathymetry at the vicinity of proposed outfall locations indicates a steep sloping bed profile and heat plume releases towards slope further into the deep sea. Hence heat plume tends to flow without having a bottom attachment (Coanda effect), then high initial dispersion and further reduction of excess temperature could be expected. Therefore this considered case is more conservative.

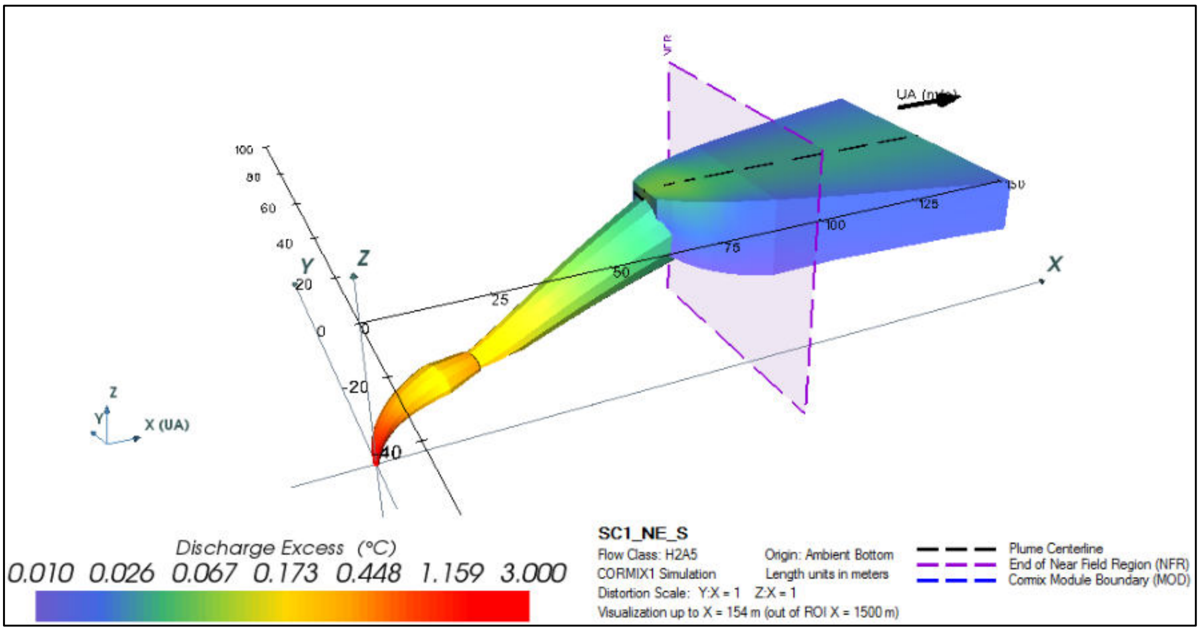


Figure 5.2: Effluent Discharged at Near-Field Region (NE Monsoon – Spring Tide)

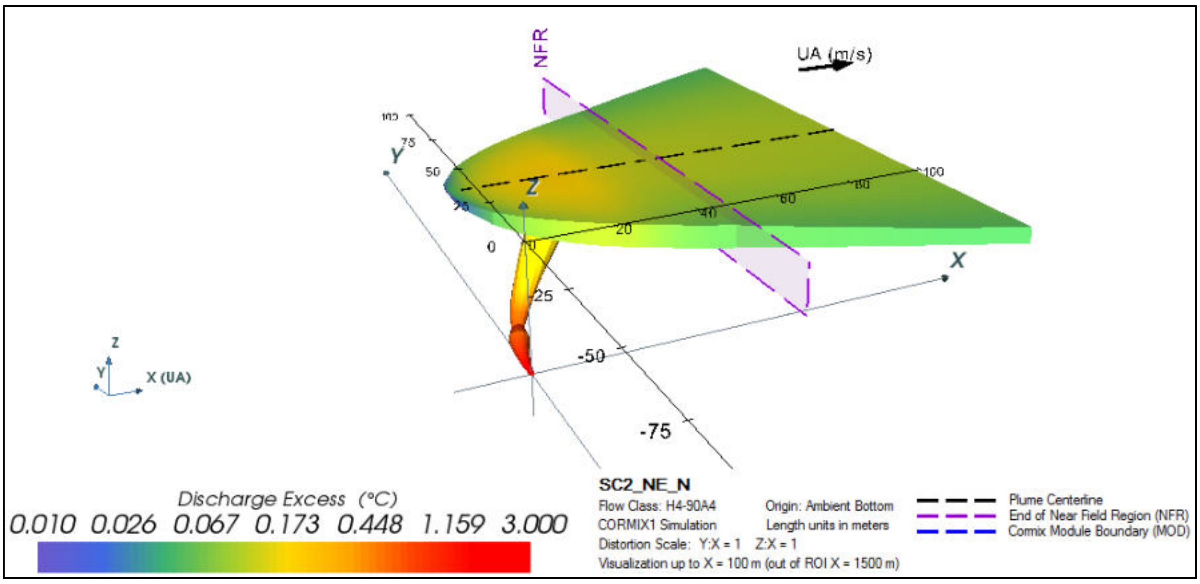


Figure 5.3: Effluent Discharged at Near-Field Region (NE Monsoon – Neap Tide)

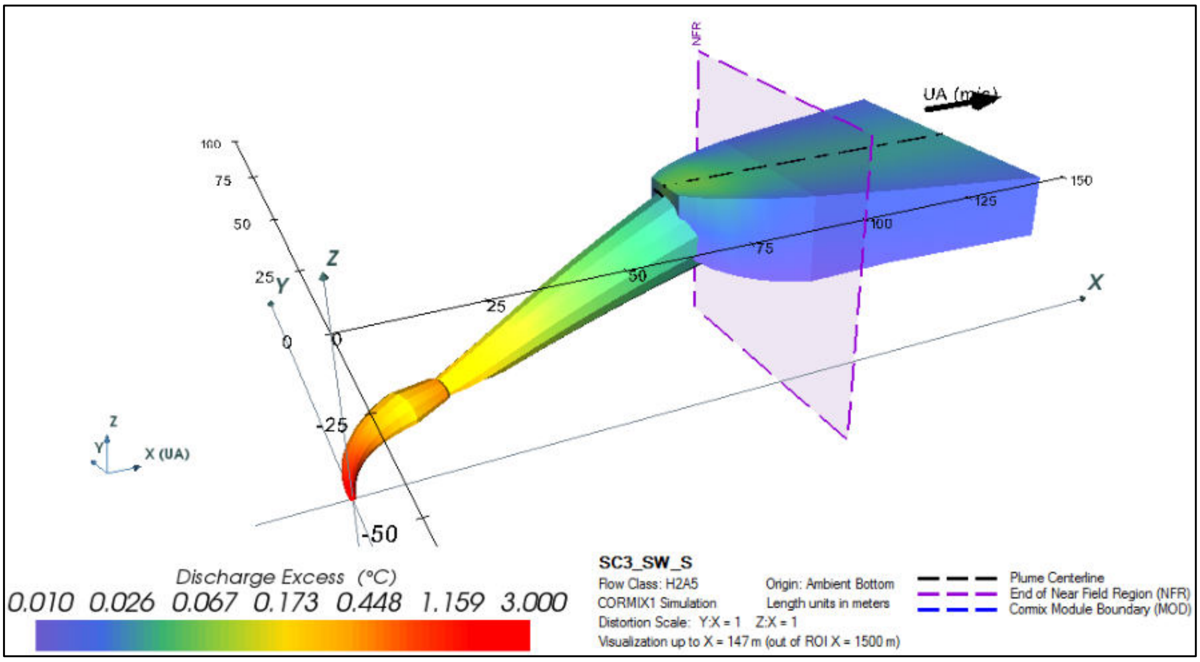


Figure 5.4: Effluent Discharged at Near-Field Region (SW Monsoon – Spring Tide)

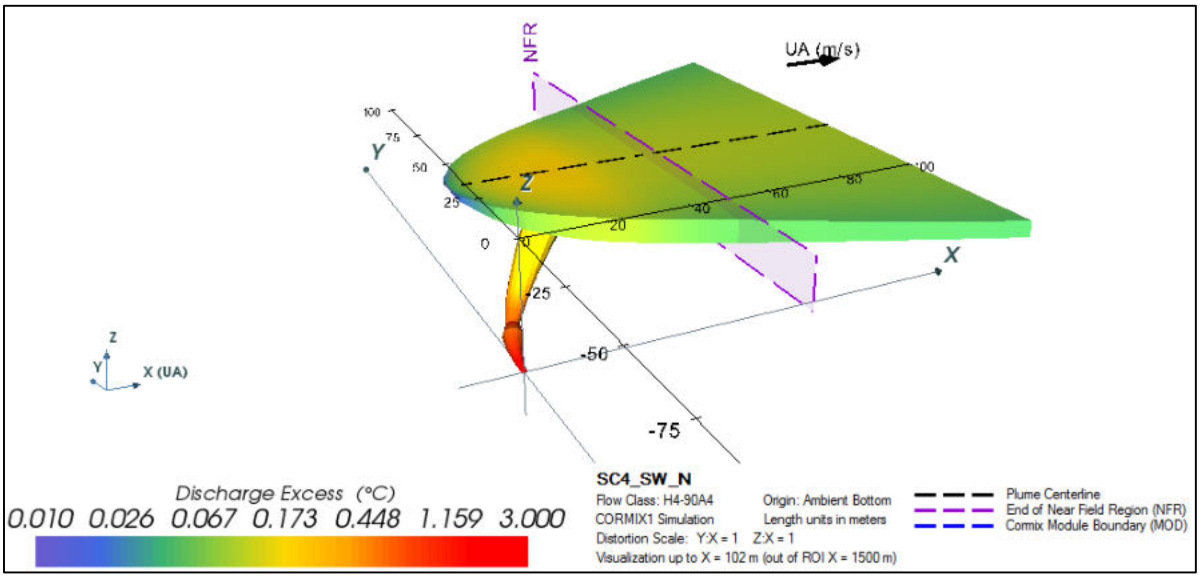


Figure 5.5: Effluent Discharged at Near-Field Region (SW Monsoon – Neap Tide)

The excess temperatures at the boundary of the near field were extracted from the model results for every scenario and they are presented in the table below.

Table 5.2: Excess Temperatures at Near Field Boundary

Sc. ID	Monsoon	Tide	Current Condition		Excess Temperature at Edge of Near Field (K)
			Speed (m/s)	Direction (Deg. N)	
NE_S	North-East	Spring	0.2	271	0.039
NE_N		Neap	0.1	280	0.114
SW_S	South-West	Spring	0.22	280	0.036
SW_N		Neap	0.1	277	0.112

Effect of Three Outfalls

As mentioned above, the heat plume discharge of only one outfall was considered in the near field simulation, but to visualize the combine effect of heat dispersion from all the three outfalls within the Near Field region, the same result obtained for the single outfall for a particular scenario was repeated considering the geographical locations of the outfalls in terms of the downstream distances. Since the outfalls are located in 20 m interval in general downstream direction, the same result was overlaid by 20 m interval.

Figures 5.6 to 5.9 show the overall results of the vertical profile of heat plume dispersion in the near field region while Figures 5.10 to 5.13 show the same in the plan view. In this case, the results were interpreted using excess temperature isolines.

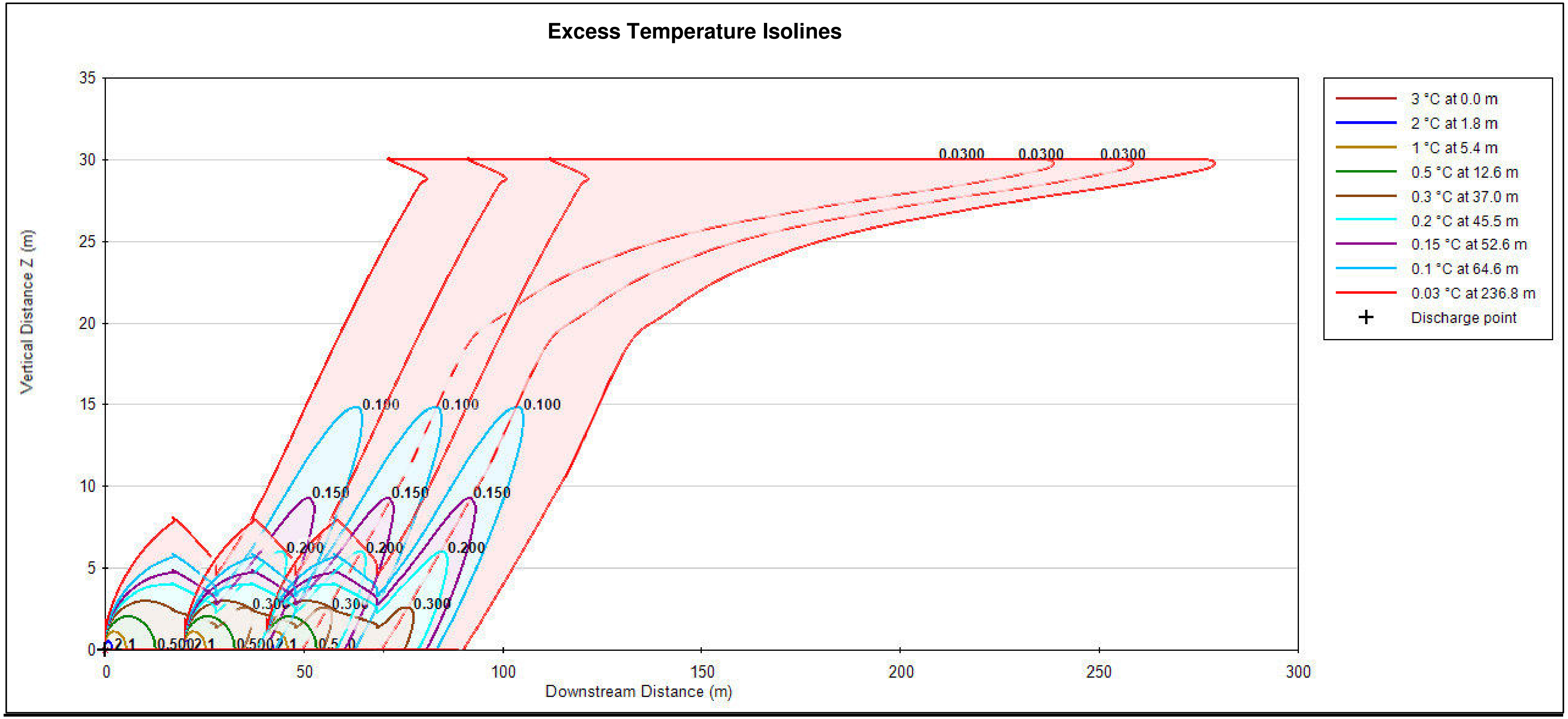


Figure 5.6: Interpreted Overall Results for Vertical Profile of Heat Plume for NE Monsoon – Spring Tide

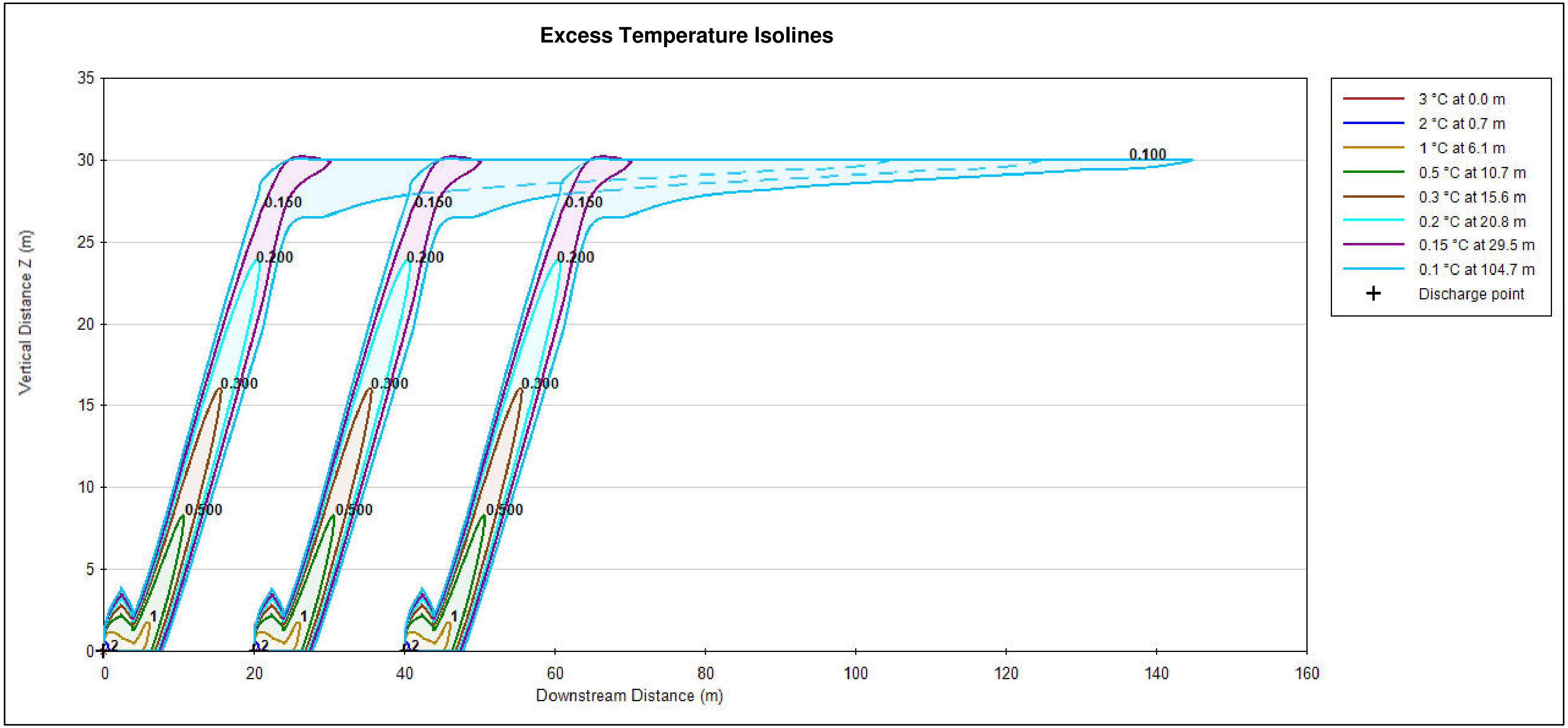


Figure 5.7: Interpreted Overall Results for Vertical Profile of Heat Plume for NE Monsoon – Neap Tide