Coastal vulnerability, adaptation & resilience in local communities of North Ari Atoll

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SUMMARY

This study supports coastal component of the Resilience-Based Management (RBM) Framework developed for North Ari Atoll under the project REGENERATE. Project Regenerate is working to establish a Resilience-Based Management (RBM) Framework to improve the ability of policy makers and stakeholders in the Maldives to understand and address the risks from global, regional and local-scale pressures on the environment.

This aim of this study is to contribute to the coastal resilience component of the RBM framework. This component is useful for the RBM framework due to the inherent links between physiographic conditions of a coral island and its surrounding reef, and due to the nature of impacts on the coral reef environment from coastal modifications and erosion mitigation efforts.

The project areas of this study are 23 islands and their reefs in North Ari Atoll. The methodology used to address the objectives of this report involved a mix of field data collection, digital remote sensing imagery processing, questionnaire surveys and review of existing technical information. Field assessments were undertaken in nine islands.

North Ari Atoll is an administrative unit comprising three natural atolls: the northern half of Ari Atoll, Rasdhoo Atoll and Thoddoo Atoll. There are 80 reef systems and 56 islands, comprising 460 Ha within the administrative unit. Thoddoo Island is the largest island in the atoll, comprising 38% of the total land. Inhabited islands have a mean land area 43 Ha, while the resorts islands are generally small with a mean land area of 6.7 Ha. The islands in the atoll have been classified into four categories: atoll lagoon islands, oceanic islands, oceanward rim-perpendicular islands and oceanward rim-parallel islands. The coastal processes operating in these islands are different from one another and have implications on coastal management.

The two main coastal vulnerabilities for the islands of North Ari Atoll are beach erosion and flooding. Beach erosion is considered a high frequency hazard for all the islands as it affects inhabitants on a regular basis. Based on the interviews, erosion is considered an issue in inhabited islands if it occurs close to the settlement or if any structures are at risk. Erosion in resort islands is considered a major hazard if it affects the facilities constructed near the beach or if there is no beach to support the tourism product offered on the island. The resort islands in the Atoll are particularly vulnerable to erosion due to their physiographic features, particularly their small size. According to the Disaster Risk Profile of Maldives (UNDP, 2006), North Ari Atoll islands are exposed to Tsunami and storm surge flooding. The report notes that, tsunami risk is moderate with predicted maximum wave height between 2.5 m to 3.2 m on the eastern half of the atoll and 0.8 to 2.5 m on the western half of the atoll. Most islands in the Atoll, with the exception of a few large islands are prone to flooding. The reasons are mainly the low elevation and small size of islands.

Coastal erosion conditions on the islands have been analyzed in detail using remote sensing technology for all islands. The key finding is that most islands have been relatively stable in the medium-term. However, substantial shoreline changes were observed in the last 45 years in Ukulhas, Mathiveri and Himandhoo. The smaller islands have also shown proportionally substantial changes. Most of these changes have been natural. The coastal processes operating around the different types of islands noted above also differ based on their location within the atoll, orientation, shape, size, coastal process characteristics and intensity of the monsoon.

Almost all islands in the Atoll have had some form of coastal modification. There two broad types of coastal infrastructure: island access and erosion mitigation infrastructure. Access infrastructure includes harbors, reef entrances and access jetties. Harbours usually come as a suite of structures such as breakwaters, quay walls, harbour basins, reef entrances and land reclamation. Land reclamation is usually undertaken from dredge waste. All inhabited islands, except Himandhoo Island, have a harbour. All resort islands have access jetties and two resorts islands have a harbour basin and a quay wall. The harbours are constructed based on a standard design replicated across all islands. None of these structures seem to be built with long-term natural resilience in mind.

Erosion mitigation has been undertaken in all resort islands and to some extent in inhabited islands. A range of options have been used in the resorts including soft and hard engineering options. Soft engineering options mainly include beach replenishment and hard engineering options include groynes, nearshore breakwater, foreshore breakwater and revetments. Most of these structures, except for a few resorts, seem to have been implemented on a piece-meal basis rather than an overall management plan. As a result, a lot more structures than what may have been required have been constructed. Erosion mitigation in inhabited islands has been undertaken mainly as part of harbour development projects. The main method for general erosion management in the inhabited island is to dump construction waste.

There are also some practices traditionally used in inhabited islands to improve resilience. These include voluntarily enforced land use setbacks depending on the coastal conditions, retention of a coastal vegetation belt, preservation of coastal ridges and banning of sand mining activities from the beach.

The present coastal structures, except in a few resorts, have been constructed without due importance to the prevalent coastal process operating around them. As a result, most of the inhabited islands have had unintended erosion and changes to medium-term island

shoreline positions. In resort islands, the use of shore protection measures on a piece-meal basis has led to unintended effects on the shoreline, resulting in more structures. The coastal processes in some of these islands have been altered severely, forcing the complete reliance on human intervention to manage the shoreline. The scale of these issues could have been reduced if a long-term resilience based approach was used for coastal management.

A number of current poor practices may have also resulted in reduced natural resilience. These include sand mining, coral mining, overfishing from the house reef, waste dumping to the beach, coastal vegetation removal and settlement encroachment closer to the beach.

Projected sea level rise raises some concerns in relation to the current practices in coastal infrastructure development. Coral islands are known to be morphologically resilient over time but for this resilience to work, it needs the coastal processes to function properly. The current practices will force continuous human intervention to adapt to sea level rise and at a higher cost that what would have been possible with natural resilience.

A conceptual model has been proposed to show links and interaction between the dominant forces that operate around a coral island. Island shoreline dynamics are the result of complex interactions between many natural processes. These include the long-term climate, monsoonal variations, hydrodynamics, reef and island morphology, and coral reef biological and physical processes. In islands inhabited or influenced by man, human activities add a new dimension that may alter the natural processes further. The links between the coral reef and the island shoreline is also a process that involves constant feedback between natural forces and human activities. Based on the above, there are three major natural components influencing shoreline dynamics: (i) climate and hydrodynamics; (ii) morphology and (iii); coral reef processes. The model provides an understanding of how these key components interact and the likely result of changing any of these components naturally or artificially.

Based on these assessments, the study provides a set of guiding principles and recommendations for coastal infrastructure development in North Ari Atoll. The aim of these guidelines is to provide decision support for coastal infrastructure development with a focus on preserving long-term resilience. Specific guidance has also been provided for existing infrastructure on the island.

This study is intended to support the RBM proposed for North Ari Atoll. The report provides decision support guidance for infrastructure development but for more specific guidance on the structures themselves, it should be used in conjunction with other publications on the subject, namely, Survey on Climate Change Adaptation Measures (Shaig, 2011) and Formulation of Guidelines for Climate Risk Resilient Coastal Protection in the Maldives (Ministry of Environment and Energy, 2013).

1. INTRODUCTION

This study looks into the existing coastal vulnerabilities and coastal management challenges in the islands of North Ari Atoll and how the communities have adapted to these vulnerabilities and challenges. Focus is placed on understanding how the man-made adaptations effect or complement natural resilience and how the present practices could be enhanced to improve resilience. A conceptual model has been presented to describe the natural processes operating around a coral island of Maldives and how man-made changes to these processes could alter natural resilience.

This study is funded by Project REGENERATE. Project REGENERATE is working to establish a Resilience-Based Management (RBM) Framework to improve the ability of policy makers and stakeholders in the Maldives to understand and address the risks from global, regional and local-scale pressures on the environment.

This aim of this study is to contribute to the coastal resilience component of the RBM framework. This component is useful for the RBM framework due to the inherent links between physiographic conditions of a coral island and its surrounding reef, and due to the nature of impacts on coral reef environment from coastal modifications and erosion mitigation efforts. A model of coastal development on the islands is also useful to understand how infrastructure development can affect and erode ecological resilience to climate change and other threats.

The specific objectives of this project are:

1. To document the variety of adaptation measures currently being taken to address coastal erosion, flooding and other climate related risks.
2. To document coastal modifications undertaken on the islands.
3. To examine the shoreline dynamics of the islands based on multi-decadal remote sensing data, onsite interviews, and field surveys.
4. To assess the potential effects of past coastal modifications and resource extraction practices on the present coastal processes.
5. To model the interactions between physical and biological processes on the reef and their links with island dynamics. Specific focus is to be given to examine the relationship between coral reef resilience and island dynamics.
6. To identify recommendations for local erosion management and infrastructure development that could reduce stress on coral reef resilience and growth.

This report is organized into five sections. The first section describes the existing physiographic conditions of the study atoll and its islands and examines beach dynamics in detail. This section also summarizes known coastal vulnerabilities of the islands. The second section examines some of the man-made changes to the coastal and marine environment including coastal infrastructure and erosion mitigation measures. The third section explores the implications of existing coastal modifications and erosion mitigation practices. The final section provides recommendations for developing coastal infrastructure and erosion mitigation measures in view of facilitating natural resilience.

2. METHODOLOGY

The methodology used to address the objectives of this report involved a mix of field data collection, digital remote sensing imagery processing, questionnaire surveys and review of existing technical information.

2.1 Study Area

The project study area is the islands and their surrounding reefs in North Ari Atoll. The selection of islands was designed to include as many islands as possible. The following factors were considered in island selection:

i. Availability of historical imagery and satellite imagery.
ii. iIsland accessibility (approvals and support) for surveying needs
iii. Physical variation in reef characteristics and climatic forcing across the atoll. These include differences in wave regimes.
iv. Geomorphological variations in the location of islands within an atoll
v. Variations in (geomorphological) types of islands

Table 2.1 below provides the study islands shortlisted for this project. *Figure 2.1* shows the study area map

Note: F = islands where field assessments were undertaken specifically for this project

No.	Island	Land use status	Survey
1	Thoddoo	Inhabited	F
2	Rasdhoo	Inhabited	F
3	Ukulhas	Inhabited	F
4	Bodufolhudhoo	Inhabited	F
5	Mathiveri	Inhabited	F
6	Feridhoo	Inhabited	F
7	Maalhos	Inhabited	F
8	Himandhoo	Inhabited	F
9	Veligandu	Resort	F
10	Kuramathi	Resort	
11	Gangehi	Resort	
12	Velidhoo	Resort	
13	Kudafolhudhoo	Resort	
14	Madoogali	Resort	
15	Etheremadivaru	Resort	
16	Mayyaafushi	Resort	
17	Bathalaa	Resort	
18	Halaveli	Resort	
19	Ellaidhoo	Resort	
20	Fesdhoo	Resort	
21	Mushimasmigili	Resort	
22	Madivaru	Uninhabited	
23	Vihamaafaru	Uninhabited	

Note: F = islands where field assessments were undertaken specifically for this project

Table 2.1 List of islands shortlisted for the study

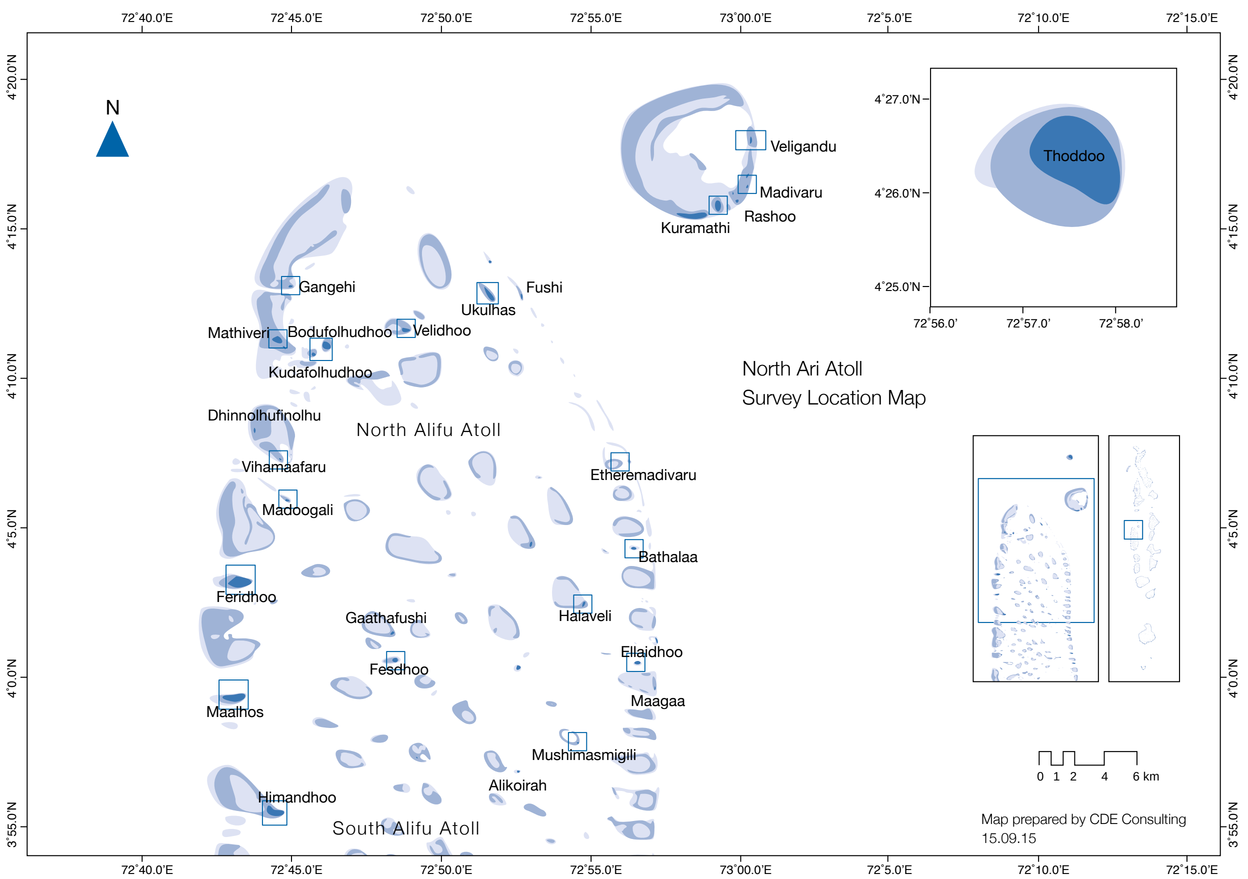


Figure 2.1 Map showing the distribution of survey islands

2.2 Field Assessments

Field assessments were undertaken in nine islands. Although all islands were targeted for field assessments only nine islands were accessible during the study period. Most of the remaining islands were not accessible due to limited contact with the management and the unavailability of the Engineering Departments of the contacted resorts during the survey period. Weather was also a limiting factor as the survey coincided with a rainy period.

The following assessments were undertaken during field visits.

1. Documenting and inventory of the coastal modifications. A questionnaire and a checklist were used to collate data. Pictures and measurements were taken from the structures to build the database. Additional information on the structure was obtained from the council to fill the questionnaire.
2. Documenting present and past adaptation measures against erosion and flooding. A questionnaire (see Appendix B) was used to document the existing structures and interviews with the elderly and the Island Council was used to record the past practices, events and opinions on erosion.
3. Visits to the erosion sites were undertaken in many islands with the interviewees to verify and document exact locations.
4. Ground-truthing remote sensing data to geo-correct existing images and to aid coastal infrastructure mapping.
5. Shoreline surveys using high resolution GPS in islands with no data for 2014.
6. An attempt was made to map and ground-truth the all coastal infrastructure in the islands surveyed. GPS coordinates of the structures and their measurements were recorded using high resolution Trimble Geoexplorer Geo7x DGPS. A tape measure was used to measure elevation and width of the structures. Photographic evidence of each structure was also recorded.

2.3 Analysis and Reporting

Results from the assessment were compiled and analyzed in Male', generally parallel to the survey activities, where possible. Delays in the completion of field assessment led to postponement of the analysis stage.

Past shoreline data was extracted using historical aerial imagery and satellite imagery. Aerial photographs from 1969 were scanned at a resolution of 600 dpi and geo-corrected in ArcGIS software by using the most recent satellite imagery as the basis. Images of intermediate years were extracted from Google Earth and geo-corrected with an accuracy of <+/- 3 m. Vector lines representing vegetation extent and low tide level were extracted from the raster images. Additional data on coastal infrastructure was also extracted from the images after cross-checking with ground truth data.

Assessments on potential effects of the structures and recommendations were derived based on reviews of existing studies and results from the field assessments.

3. PHYSIOGRAPHY OF NORTH ARI ATOLL AND ITS ISLANDS

3.1 Atoll Physiography

Ari Atoll is located in central Maldives along the western line of the double chain of atolls that comprise the Maldives (See *Figure 3.1*). There are three natural atolls that comprise Ari Atoll: the main Ari Atoll, Rasdhoo Atoll and Thoddoo Atoll. Among these, Thoddoo is a small oceanic platform and Rasdhoo is a small circular atoll. Thoddoo and Rasdhoo Atolls are located northeast of the main atoll at 26 km and 9 km respectively and are separated by deep channels. These three atolls were originally managed as one administrative unit but were subdivided into North Ari Atoll and South Ari Atoll in the 1990s. The term "North Ari Atoll" is used to define an administrative unit comprising the northern half of North Ari Atoll, Thoddoo Atoll and Rasdhoo Atoll.

Ari Atoll could be described as an open atoll comprising of numerous shallow reef systems separated by deeper reef passes. Rasdhoo Atoll is could be considered a closed atoll with three narrow reef passes and rim reefs covering the rest of the atoll perimeter. Thoddoo Atoll is an oceanic platform which rises to the surface from a depth of around 1000 m.

Ari Atoll proper is about 90 km long and 32 km wide at its widest point (along east-west axis). It covers a surface area of 2,300 sq km and is the third largest atoll in the Maldives. It comprises of about 255 reef platforms with a total area of 430 sq km[1]. The total shallow reef area is estimated at 180 sq km. The atoll comprises of numerous shallow reefs flats on the atoll rim, shallow reef flats within the atoll lagoon usually enclosing a deep lagoon, subtidal reefs (haa), atoll lagoon pinnacles (giri) and submerged reefs. There are 53 reef passes in the atoll with widths ranging between 0.25 km and 11.7 km. There are about 122 islands in the atoll including vegetated islands, sand banks and rubble islands.

The administrative subdivision of North Ari Atoll covers a surface area of 960 sq km. It comprises of about 80 reef systems covering 170 sq km. Among these there are about 23 rim reef platforms and 28 atoll lagoon reefs with deep inner lagoons. There are 28 reef passes in the atoll. The widest reef passes are located on the northeastern quadrant of the atoll where two 10 km wide reef passes can be found. There are numerous submerged reefs in North Ari atoll and most of them are located on reef passes. The most notable are those located east of Ukulhas Island.

The west side of the atoll faces the Indian Ocean with depths of over -4000 m, while the eastern side faces the inner sea of Maldives (Hatharu atholhu medhu) with average depths

1 Calculation includes shallow reefs, deep reef lagoons and visible reef slopes.

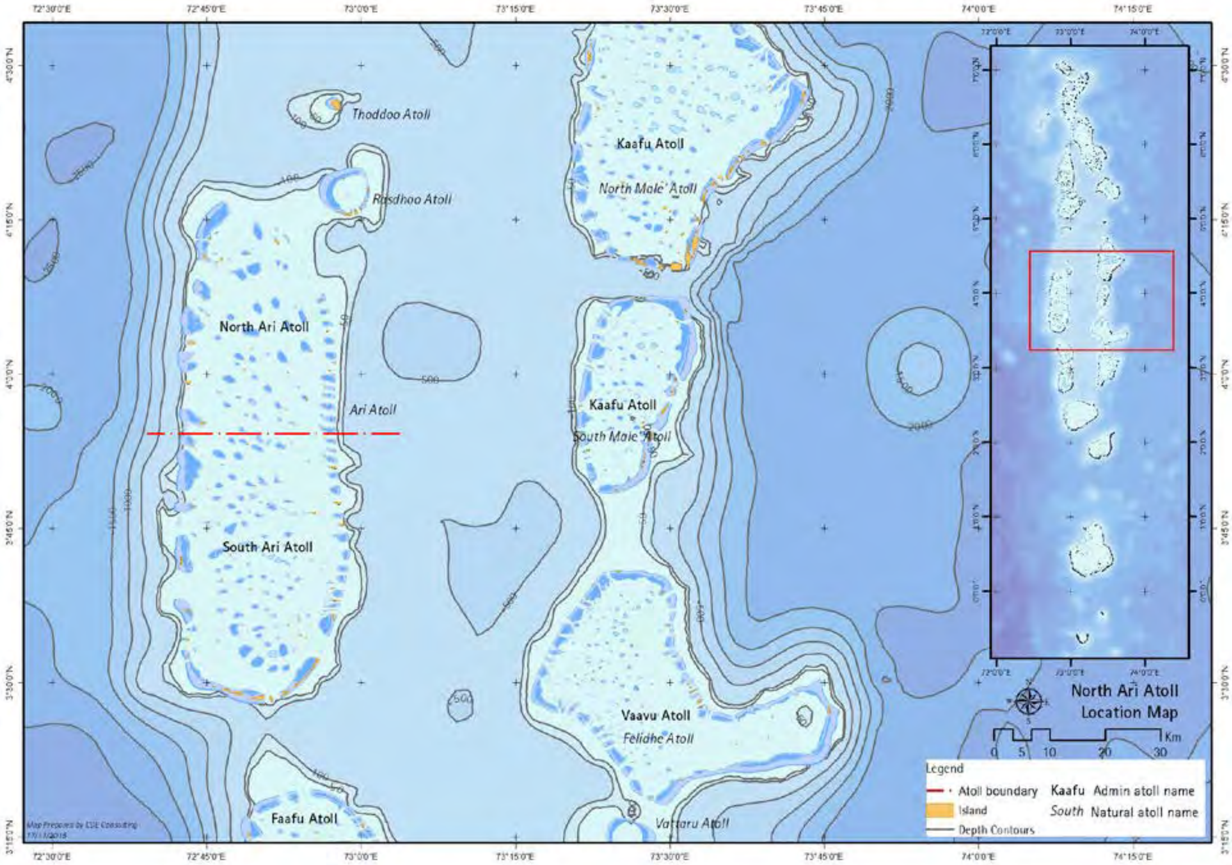


Figure 3.1 Location Map of North Ari Atoll

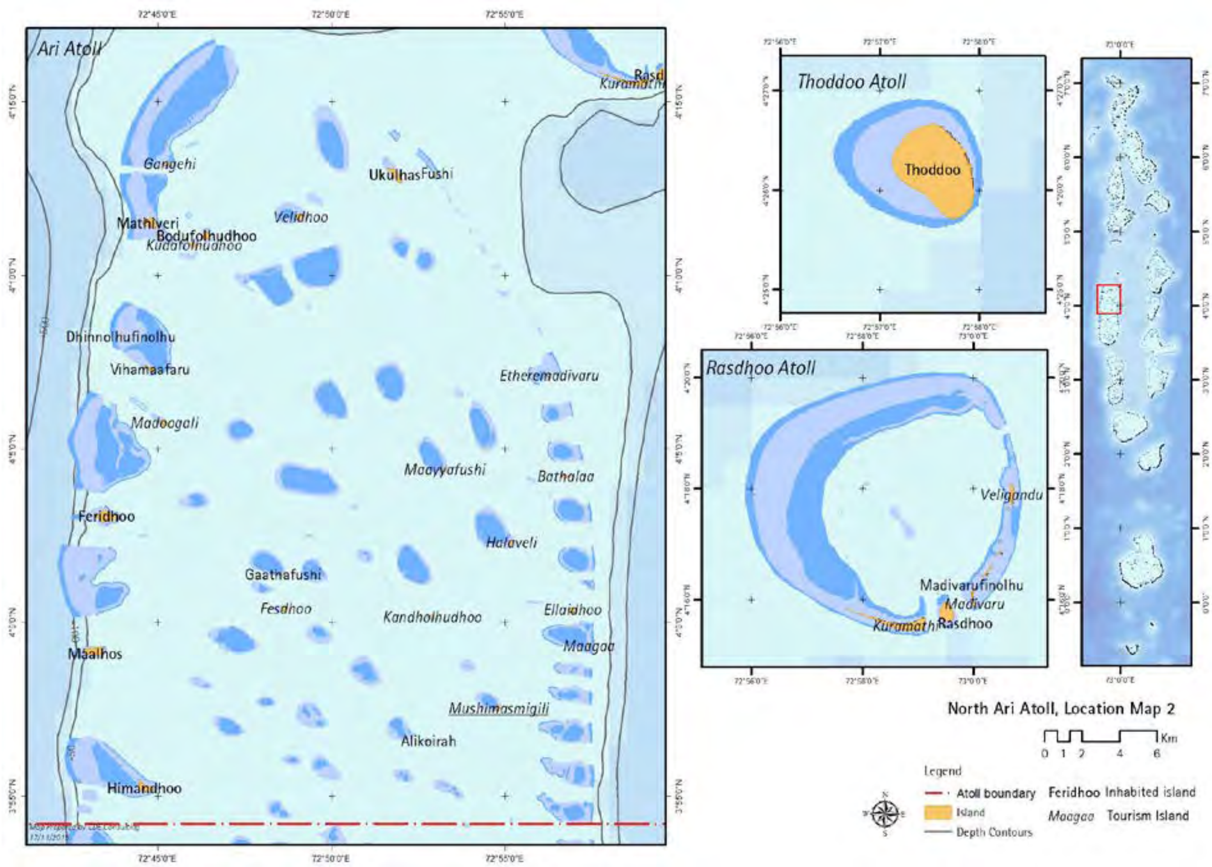


Figure 3.2 North Ari Atoll detailed map

of around -300 m. The deep channel separating Ari Atoll and Rasdhoo Atoll is shallow with depths between less than -50 m. The channel separating Thoddoo and Rasdhoo Atoll is relatively deeper with depths of over -150 m. The western rim reefs slope steeply reaching 1000 m within a space of 5 km. The Atoll lagoon has average depths over 50 m. The reef passes on average have depths less than -50 m.

Thoddoo Atoll is an oceanic island separated from the main atoll. The reef system is about 5 sq km and comprise of a single island on the reef platform. The western side of the reef slopes to -100 m within a space of 7 km while the southeastern side slopes to -100 m within 0.35 km. The island is located on the eastern half of the reef flat.

Rasdhoo Atoll is a ring-shaped enclosed atoll with a maximum diameter of 9.25 km and a surface area of 62 sq km. The rim reefs surround the atoll, with one continuous reef covering the western and northern rim. There are three reef passes on the atoll and the widest reef pass is about 450 m wide. A separate reef platform covers the eastern rim. There are only 5 islands in the atoll and all of them are located on the Southeast quadrant.

3.1.1 Atoll Climate and Oceanographic Regime

The climate of Maldives is characterized by the monsoons of the Indian Ocean. Monsoon wind reversal significantly affects weather patterns. Two monsoon seasons are observed in Maldives: the Northeast (Iruvai) and the Southwest (Hulhangu) monsoon. The parameters that best distinguish the two monsoons are wind and rainfall patterns. The southwest monsoon is the rainy season while the northeast monsoon is the dry season. The southwest monsoon occurs from May to September and the northeast monsoon is from December to February. The transition period of southwest monsoon occurs between March and April while that of northeast monsoon occurs from October to November.

The winds that occur across Maldives are mostly determined by the monsoon seasons. The two monsoons are considered mild given that Maldives is located close to the equator. As a result, strong winds and gales are infrequent although storms and line squalls can occur, usually in the period May to July. During stormy conditions gusts of up to 60 knots have been recorded at Male' (Department of Meteorology, 2014).

Wind has been uniform in speed and direction over the monsoon seasons since the 1970s in the Maldives (Naseer, 2003). Wind speed is usually higher in central region of Maldives during both monsoons, with a maximum wind speed recorded at 17.5 ms-1 for the period 1975 to 2014 (Department of Meteorology, 2014). Mean wind speed is highest during the months May and October in the central region. Wind analysis indicates that the monsoon is considerably stronger in central and northern region of Maldives compared to the south (Department of Meteorology, 2014).

There are two major types of waves observed along the islands of Maldives. The first type is wave generated by local monsoon wind with a period of 3-8 seconds and the second type is swells generated by distance storms with a period of 14-20 seconds (Kench et. al (2006), DHI (1999), Binnie Black & Veatch (2000), Lanka Hydraulics (1988a & 1998b)). The local monsoon predominantly generates wind waves, which are typically strongest during April-July in the southwest monsoon period. Wave data for Male and Hulhulé between June 1988 and January 1990 (Lanka Hydraulics 1988a & 1998b) show that the maximum significant wave height (Hs) recorded for June was 1.23 m with a mean period (Tm) of 7.53s. The maximum recorded Hs for July was 1.51 m with a Tm of 7.74s. The mean wave periods were 5.0 – 9.0s and the peak wave periods were within 8.0 – 13.0s.

Information on the deep-water wave climate is limited, but studies based on satellite altimetry wave climate data have identified the presence of swell waves approaching predominantly from a southwest to a southerly direction Young (1999) . In addition wave hind cast assessments (Naseer (2003)) and localized wave studies also confirm these patterns (Kench et. al (2006a), DHI (1999), Binnie Black & Veatch (2000)).

Tides in the Maldives are mixed and semi-diurnal/diurnal. Water levels at the site vary mainly in response to tides, storm surge or tsunamis. Tidal variations are referred to the standard station at Hulhulé Island. Typical spring and neap tidal ranges are approximately 1.0 m and 0.3 m, respectively (Ministry of Environment and Construction, 2004). Maximum spring tidal range in Hulhulé is approximately 1.1 m. There is also a 0.2 m seasonal fluctuation in regional mean sea level, with an increase of about 0.1 m during February to April and a decrease of 0.1 m during September to November.

Ari Atoll should be considered an open atoll due to the numerous reef passes on the atoll rim that allow both waves and currents to flow through them. This allows flushing within the atoll lagoon, a crucial factor for the formation of patch reefs and islands within the atoll lagoon.

Detailed assessment of wave propagation patterns through an atoll was undertaken by Kench et al. (2006). The results showed that that wave energy was strongest during the SW monsoon and that there is a wave energy gradient across the atoll particularly during the SW monsoon. The western reefs received the strongest wave energy while the openness of the atoll allows waves to propagate up to the eastern rim, albeit with limited energy. The wave decay was only observed for the SW monsoon.

3.1.2 Reef Island Physical Characteristics

North Ari Atoll comprises of about 56 islands of which 34 are vegetated, 16 are sand banks (finolhu) and 7 are coral rubble accumulations (huraa). Among these, Thoddoo Atoll comprises of only Thoddoo Island. Rasdhoo Atoll comprises of 12 islands of which six islands are vegetated (Shaig, 2007). There are also about 4 man-made islands created either for tourism purposes or as dredge disposal sites during dredging projects. Reef islands are found distributed across North Ari Atoll in various reef settings. These include rim reefs, atoll lagoon reefs and oceanic platforms.

Almost all islands in the atoll are currently being used for some activity. There are 8 inhabited islands and 13 resorts with major developments. Among the remaining small islands and sand banks, almost all of them are being used for tourism related activities (see Table 3.2). The high level of island use is characteristic of tourism dominated central atolls of Maldives.

The total land area at low tide level in North Ari Atoll is about 460 Ha and within vegetated area is 380 Ha (Shaig, 2007). *Table 3.1* summarizes the land area of islands in the Atoll. The largest island is Thoddoo Island with 173 Ha (at low tide level). Mean island size is 8 Ha. The average size of inhabited islands is 43 Ha and they comprise the largest islands in the atoll, except for the Kuramathi Island (30 Ha) that has been developed as a resort.

The mean size of resort islands is 4.8 Ha within vegetated area and 6.7 within low tide area. The figure drops to 3.1 Ha if Kuramathi is excluded. Most of the islands in the atoll (75%) are smaller than 5 Ha and only 8 islands are larger than 10 Ha.

The largest islands are found on the atoll rim (mean land area = 11.6 Ha). The islands in the atoll lagoon are generally smaller (mean land area = 4.7 Ha). Most of the sand banks are found in the Atoll lagoon while most rubble dominated islands (huraa) are found on the atoll rims. The absence of large islands in the atoll lagoon is an interesting phenomena observed in the central Maldives. The reasons are yet unclear but this could be related to the moderate wave activity in central Maldives compared to South Indian Ocean swell affected south and storm prone north Maldives.

Reef islands are distributed unevenly throughout North Ari Atoll. Islands in Rasdhoo Atoll are clustered on the SE quadrant of the atoll. Islands in the main atoll are distributed on the atoll rim and atoll lagoon. The highest concentration of land is found on the western rim. A key feature of the islands in the atoll is the location of islands close to the southern and eastern end of the reef system. All islands accept 5 islands are located between the south and east quadrant. The reasons for this pattern are also unclear but as indicated by Naseer (2003), it could be related to wave propagation patterns within the atoll and reef system during SW monsoon.

3.1.3 Reef Island Geomorphic Characteristics

Visual observations were undertaken in the islands of North Ari Atoll to determine the general geomorphic characteristics of the islands. The following observations were made:

a. The beach areas of the islands observed had fine to moderately coarse coral sand.
b. Island ocean side beach elevations on the western rim were generally higher than atoll lagoon and those on the eastern rim.
c. Islands on the western rim contained lithified beach rocks and coral conglomerates, particularly on its ocean side or swell wave exposed sides. Islands such as Feridhoo, Maalhos and Mathiveri had well-developed beach rock pavement covering most of the ocean side shoreline. The northern shoreline of Thoddoo Island contains the longest continuous stretch of exposed beach rock in the atoll. When formed on existing beach, these structures help to protect the beach from wave abrasion (Stoddart and Steers, 1973) and could help prevent erosion particularly during storm events.

Island Size (Ha)	No of islands	Total Area (Ha)	Percent of total islands	Percent of total island area
< 1	26	5.3	46%	1%
1.0 - 4.99	16	43.5	29%	10%
5.0 - 9.99	5	32.1	9%	7%
10.0 - 19.99	1	11.2	2%	2%
20.0 - 29.99	5	115.8	9%	25%
30.0 - 39.99	1	31.7	2%	7%
> 40	2	217.7	4%	48%

Source: (Shaig, 2007)

Table 3.1 Summary of land area in North Ari Atoll

d. The atoll lagoon islands do not have major beach rock pavements.
e. The beach sediment composition of the wave exposed beaches of some of the atoll rim islands, particularly western rim islands, showed very coarse to boulder sized material. This is likely due to the prevalence of strong wave energy in these zones and the inability of fine sand to stabilize under those conditions (Stoddart and Steers, 1973).
f. Only Ellaidhoo Island was known to have low lying area within the island. The island contained mangrove vegetation.
g. Most of the inhabited islands have gone through major coastal changes due to land reclamation.
h. The resort islands have also modified the island's geomorphology through beach replenishment and erosion mitigation structures.

3.1.3.1 Island Types

Kench (2010) proposed three categories of islands based on location, coastal process characteristics and shoreline dynamics. These were (i) Type A - circular and smaller islands located within atoll lagoon; (ii) Type B - east-west oriented islands located on the atoll rim; and (iii) Type C - north-south or reef edge parallel islands located on the rim. Among these, the type A and Type B islands undergo significant seasonal movement of sand along most of its shoreline. Type C islands predominantly have changes occurring on the northern and southern and of the island.

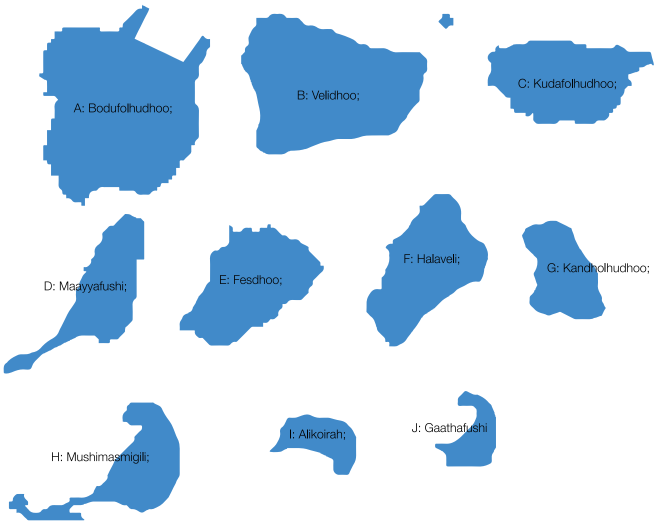
Based on the assessment in North Ari Atoll, this study has classified islands to four main groups. These categories are largely based on Kench (2010) but have been modified to place emphasis on physiographic features of North Ari Atoll. The categories are:

1. Atoll lagoon islands
2. Oceanward rim-perpendicular islands on the atoll rim
3. Oceanward rim-parallel islands on the atoll rim
4. Oceanic islands

An outline of the island types their shapes and islands belonging to those groups are summarized in *Table 3.2* below.

The coastal processes and geomorphological characteristics differ between these island types. Some of the notable features deduced from field assessments and from studies in other atolls could be summarized as follows:

a. Atoll Lagoon Islands: The island shapes are moderately uniform. They are mostly oriented either east-west or northeast-southwest. The islands in the northern half of the atoll, exposed to wave activity approaching through the northern reef passes, are oriented east-west. Islands in the inner atoll lagoon further south have a northeast-southwest orientation. The inner lagoon islands are likely to be more exposed to monsoonal climate oscillations, resulting in more substantial seasonal changes to the beach (Kench et al., 2009b). The islands are also generally smaller and vulnerable to medium- to long-term island shifts (see Section 4.2). These islands generally have lower elevations. Beach rock is usually non-existent.
b. Oceanward rim-perpendicular islands: These islands are formed perpendicular to the reef edge along its length. In most cases the reef itself is shaped and oriented in the same direction. Waves approach at an angle to these reefs. Most islands are oriented in an East-west direction and occur on the eastern and western rim of the main Ari Atoll. The ocean side beach ridges are higher. The western rim islands in this category

Island Type	Description	Sketch	Islands in North Ari Atoll
A	Atoll lagoon island		A: Bodufolhudhoo; B: Velidhoo; C: Kudafolhudhoo; D: Maayyafushi; E: Fesdhoo; F: Halaveli; G: Kandholhudhoo; H: Mushimasmigili; I: Alikoirah; J: Gaathafushi

Continued on next page

Table 3.2. Summary of island types

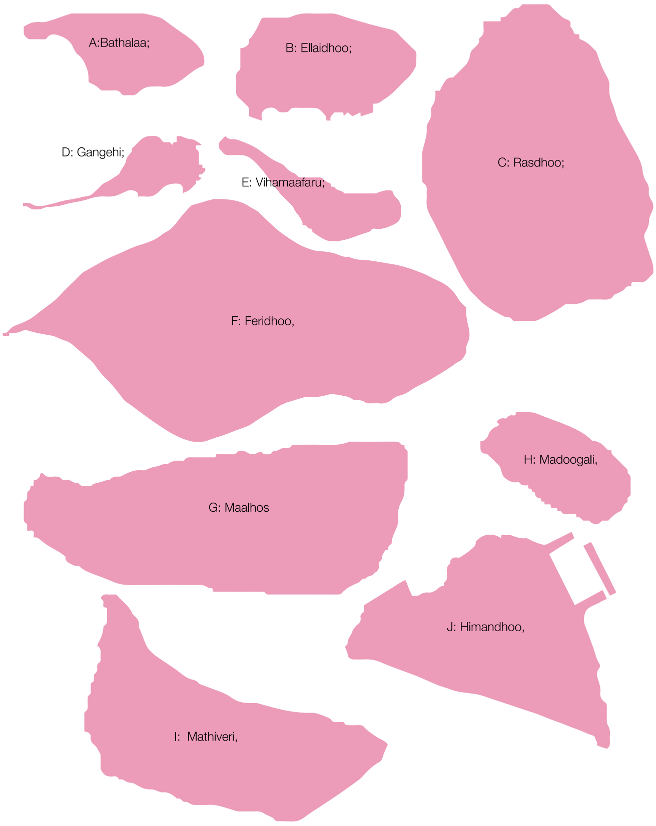
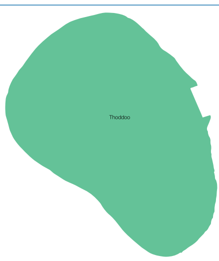
<table>
<tr><th>Island Type</th><th>Description</th><th>Sketch</th><th>Islands in North Ari Atoll</th></tr>
<tr><td>B</td><td>Oceanward rim-perpendicular island</td><td>
</td><td>A:Bathalaa;
B: Ellaidhoo;
C: Rasdhoo;
D: Gangehi;
E: Vihamaafaru;
F: Feridhoo,
G: Maalhos
H: Madoogali,
I: Mathiveri,
J: Himandhoo,</td></tr>
<tr><td>C</td><td>Oceanward rim- parallel islands</td><td>
</td><td>A: Ukulhas;
B: Veligandu;
C: Etheremadivaru
D: Maagau,
E: Kuramathi</td></tr>
<tr><td>D</td><td>Oceanic Island</td><td></td><td>Thoddoo</td></tr>
</table>

Table 3.2. Summary of island types

usually contain very coarse sediments and beach rock formations. Wave driven currents approaching from the ocean side dominates hydrodynamics and as a result the effects of seasonal oscillations may be comparatively less prominent than atoll lagoon islands.

c. Oceanward rim-parallel islands: These islands form parallel to the reef rim along its length. There are only a limited number of island in this group and they only occur on the atoll eastern rim and the southern rim of Rasdhoo Atoll. The most prominent islands are Kuramathi and Ukulhas Island. Island orientation is generally north-south, except Kuramathi which is east-west oriented. All these islands follow the orientation of the reef. Beach rock can be observed on the ocean side in two islands. Coral rubble zones were observed on the ocean side reef rim on all of these islands, except Veligandu Island. The ocean side beach is generally higher than the lagoonward side. The effects of northeast monsoon are expected to be stronger on these islands, compared to the southwest monsoon.
d. Oceanic island: Thoddoo Island is unique as it sits in the middle of the ocean on a single reef, unlike Rasdhoo and Ari Atoll. The effects of monsoonal climate oscillation are more pronounced on the western side of Thoddoo due to direct exposure to swells and monsoonal waves. Thoddoo also contains the highest elevation in the atoll due to the swell waves.

3.2 Coastal Vulnerabilities

The two main coastal vulnerabilities for the islands of North Ari Atoll are beach erosion and flooding. Beach erosion is considered a high frequency hazard for all the islands as it affects inhabitants on a regular basis. Interviews with the locals showed that, in inhabited islands, erosion is considered a serious hazard only if it affects the built up area, particularly property. In this regard, erosion is considered severe in Ukulhas, Mathiveri, Rasdhoo and Bodufolhudhoo. A key feature of all these four islands is that they have comparatively higher population densities in the atoll. Limited land often forces the settlement close to the coastal areas and as a result, even seasonal changes are considered serious.

Erosion in resort islands is considered a major hazard if it affects the facilities constructed near the beach or if there is no beach to support the tourism product offered on the island (Shaig, 2011). Quite often seasonal beach changes are also not acceptable as it may result in one section of the island completely lacking a beach for a given tourist season. The resort islands of North Ari Atoll are particularly vulnerable to erosion due to their physiographic features, particularly their small size. A more detailed assessment of the erosional vulnerability of islands in the atoll is provided in *Section 3.3*.

Coastal flooding has long been considered the main natural hazard facing Maldives due to its rapid-onset and potential for substantial damage (UNDP, 2006, UNDP, 2009). In most severe cases these events occur without warning and have caused loss of human life and property (Fujima et al., 2005).

According to the Disaster Risk Profile of Maldives (UNDP, 2006), North Ari Atoll islands are exposed to Tsunami and storm surge flooding. The report notes that, tsunami risk is moderate with predicted maximum wave height between 2.5 m to 3.2 m on the eastern half of the atoll and 0.8 to 2.5 m on the western half of the atoll.

Storm surges may also affect North Ari Atoll. The predicted maximum storm tide for the atoll for a 500 year return period is 1.38 m (UNDP, 2006). The location of the atoll on the western line of the double chain of atolls protects the island from the severest storm surges.

The islands of North Ari Atoll are also exposed to a seasonal flooding event known as Southwest Monsoon Udha. Usually these events reach less than 50 meters from the beach ridge (UNDP, 2009). They are known as low impact events but in some low lying islands it could cause damage to personal property.

Coastal vulnerabilities to flooding in the islands of Maldives are the result of a number of physiographic as well as human factors (UNDP, 2009). Natural factors include low elevation, small size, reef morphology, beach morphology, swell propagation patterns in the South Indian Ocean and exposure to tsunami prone Sumatran subduction zone (Shaig, 2009). Human factors include development closer to flood prone shorelines, land reclamation and inappropriate coastal modifications (UNDP, 2009).

The islands of North Ari Atoll, with the exception of a few large islands, are prone to flooding. The reasons are mainly the low elevation and small size of islands. The islands most naturally resilient to severe flooding are Thoddoo, Feridhoo and Maalhos Island. These islands have higher coastal ridges and a wider coastal vegetation belt to minimize the effects of flooding. The most exposed islands in the atoll are the resort islands: almost their entire infrastructure is located within 100 m of the shoreline. As noted above the, atoll is comparatively less exposed to the most severe flooding events such as tsunamis and storm surges. Nonetheless, human modifications to the coastal environment and the low elevations will continue to keep the islands at risk to flooding.

While coastal flooding in a given island is linked strongly to physiographic features of the atoll and the island (UNDP, 2009), coastal erosion and accretion is more strongly linked to the physical and biological aspects of its underlying reef. The next section will explore the erosion and island dynamics in more detail.

3.3 Coastal Erosion – A review of reef island beach dynamics

Coral reef islands are low-lying accumulations of unconsolidated, or poorly lithified, carbonate sand and gravel deposited on coral reef platforms by the focusing effect of waves and currents (Stoddart and Steers, 1977). The islands remains in a balance between a number of forces such as waves, currents, water level, reef sediment production and human activities (Woodroffe, 1993, Kench, 2010, Kench et al., 2009b, Wiens, 1962, Kench et al., 2003). Changes to these parameters can result in a response from the island to adjust to the new conditions. These changes can be often visible as erosion.

This section explores the erosion and accretion patterns in the inhabited islands of North Ari Atoll in the medium-term (between 1969 and present day).

3.3.1 Coastal Erosion

Beach erosion could be described as the loss of sediments from a section of the beach at a speed faster than it receives new sediments. Beach erosion can be seasonal, temporary due to a storm or long-term. Reasons for erosion are varied and are the result of interaction between a number of natural processes and human interventions (Kench and Brander, 2006, Shaig, 2011, Kench et al., 2003).

There are three types of erosion observed in the islands of North Ari Atoll: (1) seasonal erosion; (2) medium-term erosion, and (3) long-term island shifts. Seasonal erosion is the changes that occur on an island due to the monsoonal changes in winds, waves and currents within in given year. These changes may involve shifting significant volumes of sand from one side of the island to another. These changes often revert and vegetated areas aren't usually eroded. The medium-term erosion may occur in cycles (cycles of 5-6 years have been observed in many islands) and can involve erosion of vegetated land. These changes may also revert back within the change cycle. The long-term erosion usually involves island shifting its position within the reef to adjust to a change in the above discussed parameters. These events can last more than 10 years. This type of erosion is more disruptive and can involve shoreline, or in cases of small islands, the whole island shifting up to 200 m within a span of 40 years.

3.3.1.1 Seasonal changes to shoreline

As noted above, seasonal changes to the shoreline are the result of seasonal oscillations in the monsoon. During the SW monsoon, when the wind blows from the west for about 8 months, the beach in most islands shifts eastward. This process is related to the general west-to-east current flow and the presence of wind waves from the west. The process reverses during the NE monsoon when the wind blows from

Island Type	NE Monsoon	SW Monsoon
A: Atoll lagoon island	Sand accumulated on the eastern side shifts to the western side via both the northern and southern shoreline. Volume of sand shifted is substantial.	Sand accumulated on the eastern side during the NE monsoon shifts to the western side via both the northern and southern shoreline. Volume of sand shifted is substantial.
B: Oceanward rim-perpendicular island	Sand accumulated on the eastern side shifts and is spread along the northern and southern shoreline. On the western atoll rim islands, sand may not travel up to the western end due to the prevalence of wave driven currents from the west. However, on the eastern rim, material will travel up to and extend the western end. Volume of sand shifted is substantial.	The process reverses and sand located along the northern and southern shoreline is transported to the eastern side, extending the beach. On the eastern rim islands, this movement is somewhat controlled due to the presence of wave driven currents flowing westward.
C: Oceanward rim-parallel islands	Sand located on both ends of the island (in north-south oriented islands) move westward. There is limited change on the Oceanside. Usually sand spits extend out of both ends of the island.	Sand located on both ends of the island (in north-south oriented islands) move eastward. There is limited change on the lagoon side on larger islands. Usually sand spits extend out of both ends of the island.
D: Oceanic Island	Sand movement occurs mainly between the NW and the SE Quadrant. During the NE monsoon sand travel further south. The northern side is unable to retain sand and the area is dominated by beach rock.	Sand moves northward along the western shoreline but does not reach the northern shoreline. Wave driven currents dominate the western side throughout the year.

Table 3.3 Summary of generalized sediment movement patterns in North Ari Atoll islands

the North to East quadrant. Currents during this period are mainly from east-to-west.

The pattern of seasonal shoreline shifts vary between islands based on their location within the atoll, orientation, shape, size, coastal process characteristics and intensity of the monsoon (Kench, 2010). Table below summarizes the generalized sediment movement patterns for the island categories defined in *section 4.1.3.1*.

Among the above described types of islands, Types A, B and D islands have substantial seasonal movement of sand along much of its shoreline. In particular, Type A islands have a larger percentage of its beach seasonally mobile due to their exposure to monsoonal oscillations and smaller island size. Type B islands also tend to involve significant seasonal shifts, although these shifts are most prominent in smaller islands. Type C islands mainly involve seasonal changes on the northern and southern end of the island. However, smaller islands tend to have a larger section of their ocean facing shoreline mobile.

These patterns of seasonal sediment movement play an important role in keeping the island shoreline balanced against the prevailing hydrodynamic conditions. Alterations to these patterns due to coastal developments may result in substantial changes to the erosion and accretion patterns around the island (Kench et al., 2003). This aspect is explored in more detail in Chapter 4.

3.3.1.2 Medium- to long-term changes to shoreline

As noted above, the island shoreline may response to changes in hydrodynamic conditions, climate or changes to reef health and morphology by adjusting the position of the shoreline or the whole island. This is often a good indicator of the natural processes occurring on the reef and how volatile the shoreline is on a given island.

One of the methods to detect these changes is to analyze historical patterns in shoreline change. This study has undertaken an atoll level assessment of island morphological stability in the medium-term by analyzing muti-decadal shoreline data. As explained in Chapter 3 this was achieved by comparing shoreline changes between 1969 and present day using geo-corrected aerial and satellite imagery. A total of 19 islands were analyzed including all inhabited islands. A focus was placed to analyzing a sample of islands within the above described island types such as the rim islands, atoll lagoon islands and oceanic islands.

The results showed that all islands have undergone changes to the shoreline over the last 45 years. A summary of the changes are presented in *Table 3.4*.

Overall the net natural change between 1969 and present day vegetated land is low with an average change <±5%. Larger islands represented the smallest change. All substantial changes were observed on smaller islands. Thoddoo Island had the highest net accretion with a total of 3 ha of vegetated land. The biggest net erosion was observed on Madivaru Island (an uninhabited island). It had lost 48% of its vegetated land (0.46 Ha). Most of the eroded material from Madivaru has been responsible for expanding the Madivaru Finolhu sand bank, which is now established as a separate vegetated island.

Bigger changes were observed in Veligandu (23%), Kudafolhudhoo (15%), Ellaidhoo (22%) and Vihamaafaru (17%). Among these islands Kudafolhudhoo and Ellaidhoo had expanded its vegetated area by planting trees and building on its previous beach area. Ellaidhoo represents an extreme case of this practice. The entire reef perimeter is now protected using a breakwater and beach is only present on the SW corner of the island. The rest of the areas had very narrow beach. Similarly Kudafolhudhoo Island had its beach volume significantly reduced and the island appears to have expanded southward. Based on the findings from the neighboring islands, it appears that beach areas might have been intentionally or unintentionally stabilized to expand the vegetated area.

The results from inhabited islands have to be viewed with caution as all these islands have had land reclamation. The final results have excluded the reclaimed area but the material transported naturally to other parts of the island through coastal processes, have not been accounted. Thus, it is possible that the net change also include some of these materials, albeit, representing a smaller volume.

Similarly, the results from resort islands may also have been affected due to constant beach replenishment activities. Again, the volume of sand in vegetated areas from replenished material is expected to be small.

In terms of the land lost due to erosion, Ukulhas Island's northern beach retreated about 160 m. The eroded materials were placed on the NW side of the island. Similar big movements were observed on the western side of Himandhoo Island. Despite these changes, the overall land area remains fairly constant in most islands, as the materials are reworked around the island.

No	Island	Island use	Location within Atoll	Initial Vegetated Area (Ha)	Final Vegetated Area (Ha)	Reclamation (Ha)	Net Natural change	% Natural change	Ocean side	Lagoonside	Maximum shoreline shift (m)	Maximum Accretion (m)	Description of predominant pattern
1	Thoddoo	Inhabited	Oceanic	152.2	157.22	1.95	3.07	2%	NA	NA	NA	NA	Northwestern shoreline expanding; NW contracting
2	Rasdhoo	Inhabited	South rim	17.67	20.21	1.63	0.91	5%	Accretion	Stable	20	50	Slow ocean side migration
3	Ukulhas	Inhabited	Atoll lagoon	16.42	19.65	3.2	0.03	0%	Erosion	Accretion	160	75	Northside orientation shifted slightly westward
4	Bodufolhudhoo	Inhabited	Atoll lagoon	7.45	10.6	2.78	0.37	5%	NA	NA	NA	NA	Not applicable due to extensive reclamation
5	Mathiveri	Inhabited	West rim	18.02	20.62	3.1	-0.5	-3%	Erosion/ accretion	Erosion	47	23	SE corner eroding; orientation shifted slightly west
6	Feridhoo	Inhabited	West rim	39.5	41.75	1.41	0.84	2%	Erosion/ Accretion	Stable	55	22	Western half migrating northward
7	Maalhos	Inhabited	West rim	28.98	29.93	1.68	-0.73	-3%	Erosion	Erosion	35	9	Stable overall west side migrating southward
8	Himandhoo	Inhabited	West rim	19.13	18.95	0.14	-0.32	-2%	Erosion	Accretion	80	33	Migrating south east
9	Veligandu	Resort	East rim	2.15	3.52	0.87	0.5	23%	Accretion	Erosion	10	26	Stabilized through shore protection measures
10	Gangehi	Resort	West rim	1.92	1.94		0.02	1%	Erosion	Accretion	25	21	Shoreline contracting SE and SW; expanding NE
11	Velidhoo	Resort	Atoll lagoon	7.04	7.58		0.54	8%	NA	NA	42	47	Migration east ward
12	Kudafolhudhoo	Resort	Atoll lagoon	3.51	4.31	0.29	0.51	15%	NA	NA	9	20	Migration southward
13	Madoogali	Resort	West rim	4.68	4.82		0.14	3%	Accretion	Eroding	14	30	Ocean side migration
14	Etheremadivaru	Resort	East rim	1.48	1.44		-0.04	-3%	Erosion	Erosion	30	18	Eroding from east and west and expanding north to south
15	Halaveli	Resort	Atoll lagoon	2.58	4.34	1.24	0.52	20%	NA	NA	NA	NA	Not applicable due to reclamation
16	Ellaidhoo	Resort	East rim	3.97	4.95	0.12	0.86	22%	NA	NA	40	0	Beach areas protected and vegetation grown on them
17	Fesdhoo	Resort	Atoll lagoon	3.05	3.4		0.35	11%	NA	NA	25	30	Migration Northwest ward
18	Madivaru	Uninhabited	East rim	0.95	0.49		-0.46	-48%	Accretion	Erosion	65	24	Ocean side migration
19	Vihamaafaru	Uninhabited	West rim	1.49	1.75		0.26	17%	Accretion	Erosion	15	58	Reorienting island shape slightly towards NW

Table 3.4 Summary of island change characteristics

" Island shoreline may response to changes in hydrodynamic conditions, climate or changes to reef health and morphology by adjusting the position of the shoreline or the whole island. This is often a good indicator of the natural processes occurring on the reef and how volatile the shoreline is on a given island."

The following table summarizes the findings from medium-term erosion (between 1969 and 2011) in inhabited islands. Maps showing the shoreline comparison are attached in *Figures 3.6* to *3.12*.

Island	Summary of historical changes
Thoddoo	Overall the island has grown in size. Sediment produced from the reef rim is transported and added to the island sediment budget. The SW corner of the island accreted gradually. Shoreline in this areas expanded by 25 m (See Figure3.6). Newly stabilized areas grew vegetation and became permanent land. Erosion was experienced on the SW section of the shoreline, which retreated 20 m. At present erosion is being experienced on the SE corner of the island. The effects of harbour development were observed to be moderate on the island, based on available data.
Rasdhoo	Changes to the shoreline were minimal but the settlement's proximity to the shoreline led these changes to be considered as serious. Overall the island shape on the southern side was altered naturally. The eastern side eroded at a slow pace since 1969 and eroded material was deposited on the southern side (See Figure 3.7). The southern side has expanded consistently. The present processes around the island have changed considerably since the harbor construction project.
Ukulhas	Substantial changes occurred on the northern end of the island. Overall the ocean exposed northern end has adjusted by migrating 0.9 Ha of land westward. The shoreline shifted 150 m between 1969 and 2005 before stabilizing due to reclamation and revetments. This was the largest shoreline migration observed in the Atoll. The area continues to erode even after reclamation. The southern end of the island has also expanded slightly while the rest of the island remained intact (See Figure 3.3 and Figure 3.8).
Bodufolhudhoo	Reclamation makes it unsuitable long-term shoreline change assessment.
Mathiveri	The island has undergone severe erosion on the SE and NE corner of the island (See Figure 3.9). The SE corner shifted westward by about 50 m between 1969 and 2001. There was some stabilization in between, particularly between 2008 and 2010 but has since been eroding severely. The NE corner had retreated 30 m and could be linked to the construction of a harbor.
Feridhoo	Island has been fairly stable between 1969 and 2013. The most significant changes occurred on the Northwest corner where the shoreline expanded by 50 m and is still expanding (See Figure 3.4, 3.5 and 3.10). Erosion has been observed on the SW side of the island, particularly over the last 10 years. Here shoreline has retreated 10-15 m. Additional changes are taking place on the island following the construction of a harbor. At present the areas east of the harbor are experiencing erosion.
Maalhos	Severe erosion has occurred on the NE corner where the beach retreated 35 m between 1969 and 2013 (See Figure 3.11). The area continues to erode. Shoreline retreat was also observed on the eastern end. The rest of the island has been stable.
Himandhoo	Himandhoo has the most mobile beach among the western rim islands. Its NW corner has been particularly active with 1 Ha of land shifting in the last 45 years. (See Figure 3.12). The western shoreline has retreated consistently particularly after 2001. Severe erosion is being experienced on the eastern end and parts of the south side beach. The NE end of the island is accreting but remains a volatile zone.

Table 3.5 Summary of medium- to long-term shoreline changes in inhabited islands

Figure 3.3 Beach pioneers and halophytes growing in stabilizing areas - Ukulhas

Figure 3.4 Accretion in Feridhoo

Figure 3.5 Severe erosion in Feridhoo

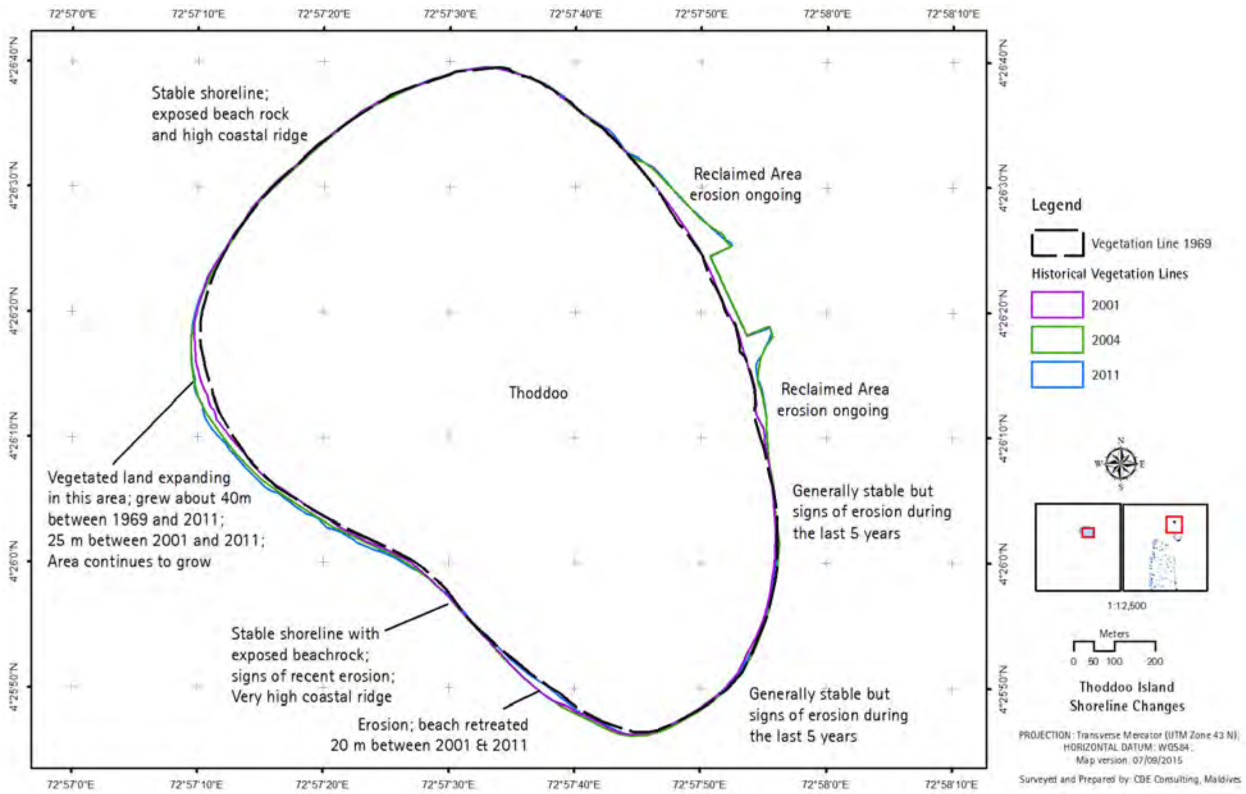


Figure 3.6 Thoddoo medium-term shoreline changes

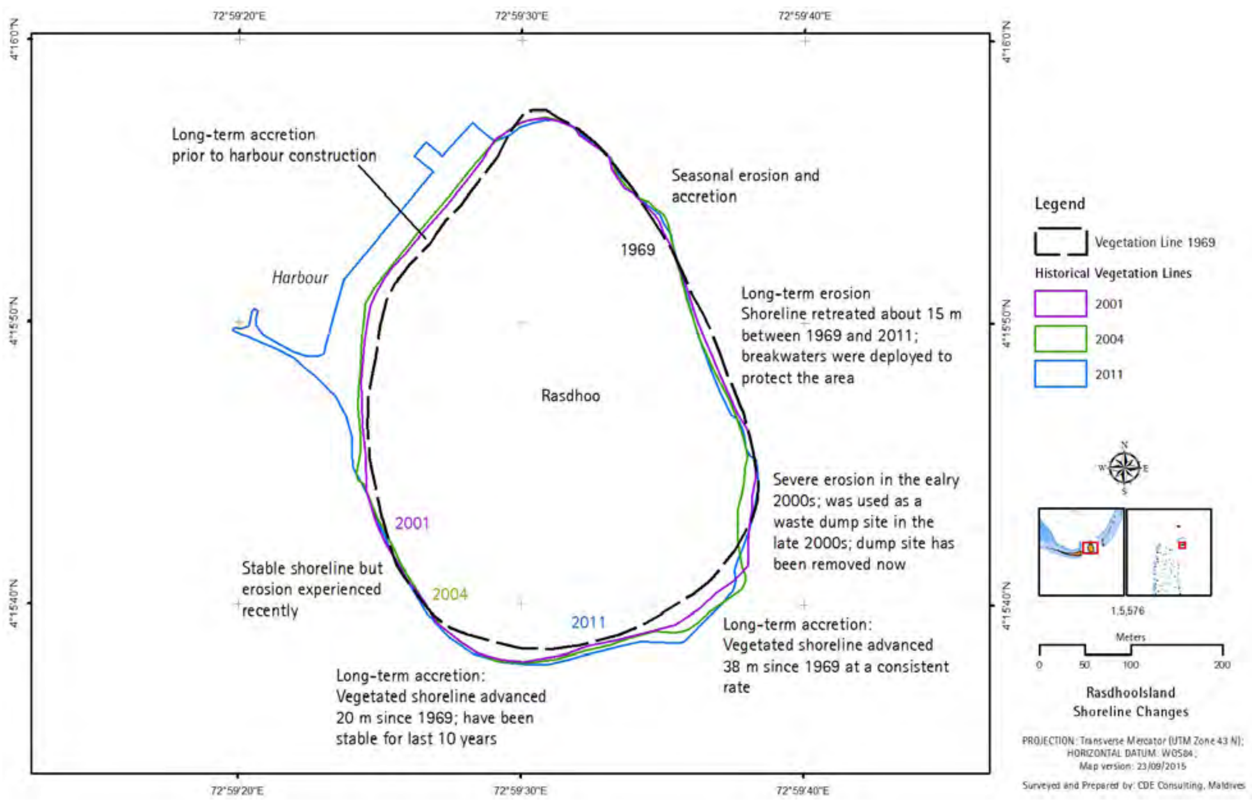


Figure 3.7 Rasdhoo medium-term shoreline changes

Figure 3.8 Ukulhas medium-term shoreline changes

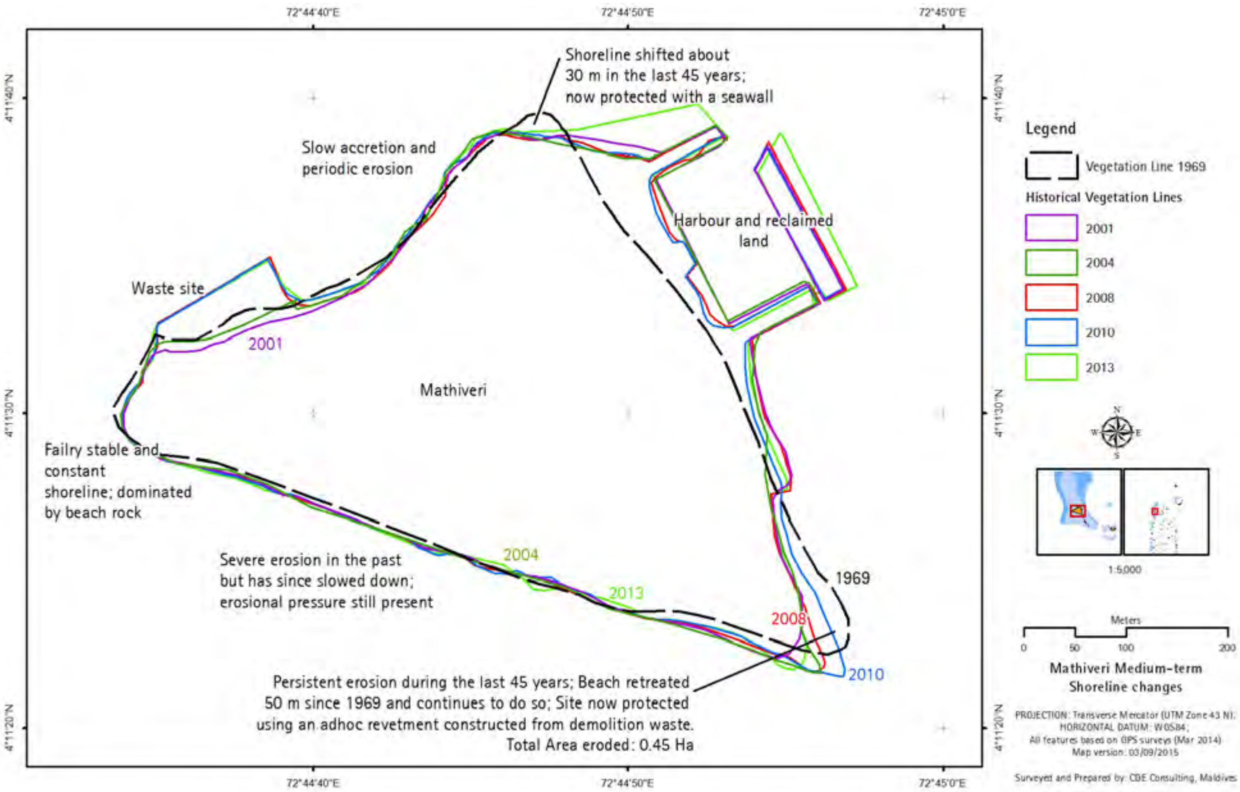


Figure 3.9 Mathiveri medium-term shoreline changes

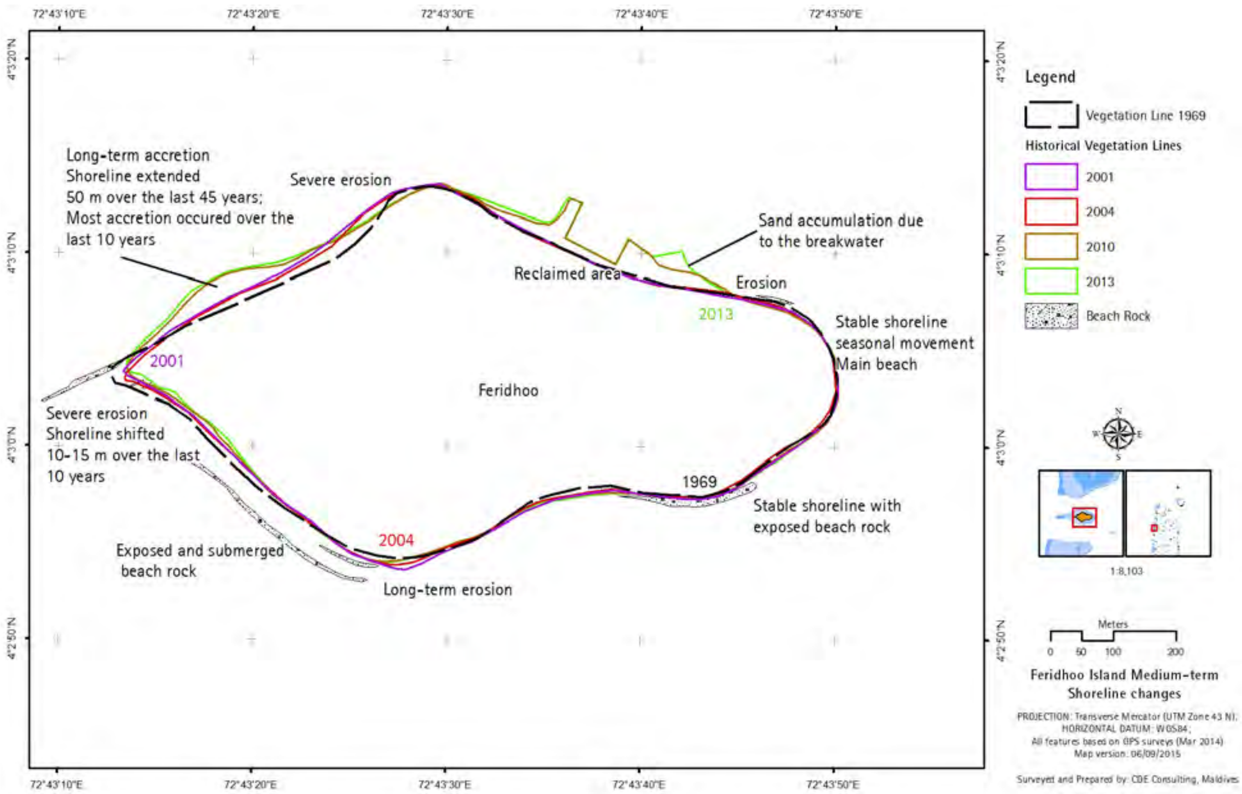


Figure 3.10 Feridhoo medium-term shoreline changes

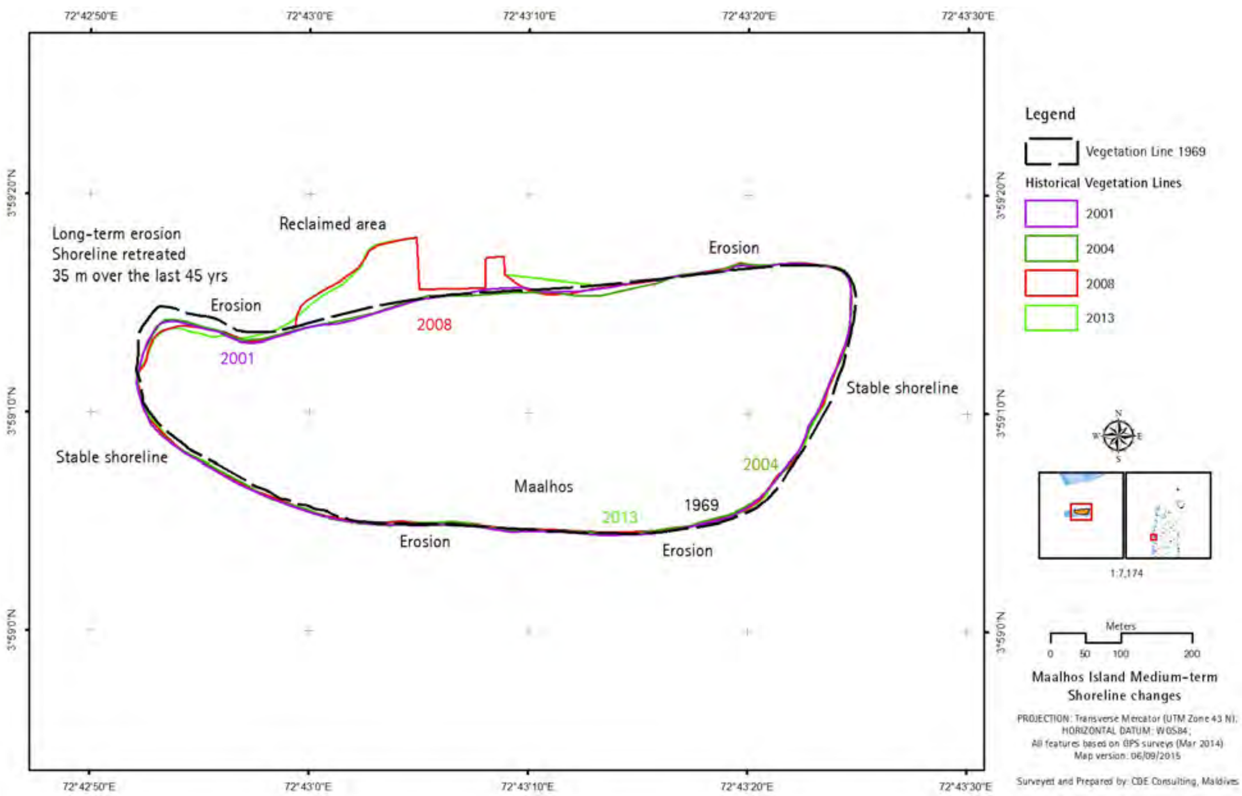


Figure 3.11 Maalhos medium-term shoreline changes

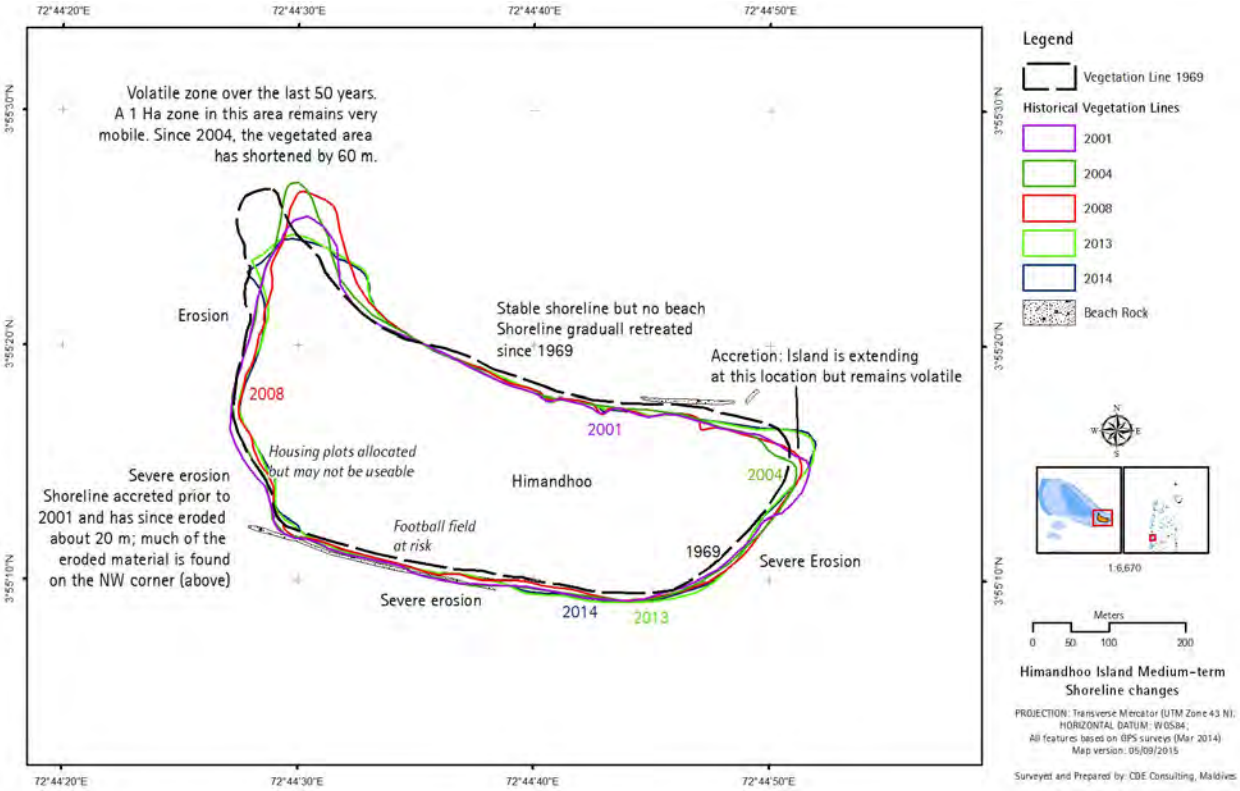


Figure 3.12 Himandhoo medium-term shoreline changes

3.3.1.3 Atoll Level Observations

The western rim islands showed surprisingly limited growth in the sediment budget and three of the largest islands on the western rim (Mathiveri, Maalhos and Himandhoo) showed a net loss while the others added fairly limited new land. Islands on the western rim of Maldives are known to produce excessive amount of the sand and often enlarging the island manifold. For example the Island of Bileffahi on the western rim of Shaviyani Atoll had added 5 Ha of new land within 45 years. Rangali Island in South Ari Atoll added 4 Ha (50 %) of the present island size naturally during the same period. Thoddoo Island also had 3 Ha of new land added to it during the same period.

It is not clear why the above noted islands have net higher production rate compared to the islands in North Ari Atoll. However, given that the wave exposure is similar in Rangali and Thoddoo, other parameters such as reef size, coral species and fish species may be playing a role in sediment production rate.

There was no clear pattern in island migration within the atoll lagoon. The general island migration patterns were either to NW or to the east.

Islands on the eastern rim of Rasdhoo Atoll tended to migrate ocean side. This could be related to the formation of rubble ramparts on the reef edge. Some of these ramparts were known to have been formed during a series of storm events that occurred around the late 1980s. Most reefs on the eastern rim of Ari Atoll have similar features.

The island of Gangehi has been remarkably stable even though it is very small and located on western rim. It stability may be related to the wave refraction patterns in the area.

3.3.1.4 Reasons for coastal erosion in North Ari Atoll

Natural causes

Much of the major long-term erosion and depositional changes that have occurred in North Ari Atoll are most likely the result of natural causes. Some of the possible reasons are:

- Changes to wind/wave dynamics – There are known changes to monsoonal intensity and oceanographic conditions that may be responsible for periodic shifts in the erosion and accretion patterns. Usually such changes affect an entire region and may be visible in the neighbouring islands. Such changes may be associated with periodic or yearly variations in wind speeds, direction, angle of wave approach and the intensity of storm events.
- An aging reef flat – the reef flat is clearly not as productive of carbonate sediments as it was >3000 years ago. Any sand loss from the island is not likely to be balanced by influx of new sediment. The island mass is thus

a finite reserve of sand, that needs careful management. The quality of reef has observably declined even over last 45 years based on the old aerial photographs. Number of coral colonies has disappeared, particularly from the southern and south eastern side either through natural causes or mining.

- Recent perturbations – The central Maldives is known to experience strong storm events and the specific location of eastern and western rim island exposes them to abnormal well wave events which could change the coastal conditions abruptly. The coastal system may also have been affected by the 2004 Indian Ocean tsunami, although there is no direct evidence to support this yet (Kench et al., 2006b).
- Changes to offshore bathymetry are known to affect the shoreline response as they can change the hydrodynamics. There are some visible changes to the coral rubble rampart on the eastern rim reefs that may play a role in stabilizing or destabilizing the islands within them.

Human causes

Human activities are also known to have played a major role in recent changes to shoreline dynamics due to the introduction of island access infrastructure or due to the introduction of erosion control measures. Alternation of shoreline dynamics results in the island responding to the changes by adjusting the shoreline (as observed in Mathiveri). We may see these changes as severe erosion. Often, human activities can exacerbate an ongoing natural change as observed in Ukulhas Island. These aspects are explored in more detail in Chapter 4.

3.3.2 Natural resilience features

The islands of Maldives are known to have mechanisms to adapt to prevailing conditions and natural hazards (UNDP, 2009). These mechanisms are manifested as identifiable geophysical features. The following table presents a summary of natural resilience features observed from the islands of North Ari Atoll.

4. COASTAL INFRASTRUCTURE AND EROSION ADAPTATION MEASURES

The natural conditions on most islands of North Ari Atoll have been changed over the years, particularly after the 1980s due to the extensive coastal modifications. These changes were mostly necessitated for infrastructure development or erosion mitigation. Some activities are undertaken due to existing resource (sand and coral) extraction practices. These changes have implications on the coastal processes operating around the island. This section compiles and presents the coastal infrastructure and coastal adaptation measures against erosion and flooding used in North Ari Atoll.

Feature	Description
Coastal Ridges	Coastal ridges are formed in response to the prevailing wave conditions at a given site (Woodroffe, 1993). Island in the northern and southern Maldives are known to have the highest coastal ridges, which may have been developed naturally as response against strong waves. Island is the central Maldives are generally known to have lower ridges due to limited exposure to stronger waves (UNDP, 2009). Islands closer to the oceanward reef edge are also known to have higher coastal ridges compared to those located within the atoll (UNDP, 2009) In general, the islands of North Ari Atoll were observed to be low lying. Coastal ridges were observed in Thoddoo, Feridhoo and Maalhos Island. All these islands are exposed to swells while Feridhoo and Maalhos had their shoreline very close to the oceanward rim. An exception to this pattern was observed in Mathiveri Island.
Healthy coral reefs	The coral reefs of Ari Atoll are generally known to be in healthy condition compared to other parts of the Maldives. A healthier reef in terms of coral cover and fish life may assist in higher sediment production. Growth of coral colonies within the shallow lagoon or reef flat are also known to stabilize the beach behind it due to the ability of the shallow reefs to mitigate wave energy. This pattern was observed on the northwestern corner of Feridhoo Island.
Beach Rock	Beach rocks are consolidated sand and coral which forms where groundwater and seawater meets on the beach. Once the shoreline is eroded it is exposed and visible. Beach rocks are known to play a role in controlling beach erosion especially in high energy zones. There are well developed beach rock systems in Thoddoo, Mathiveri, Bodufolhudhoo, Feridhoo, Ethermadivaru, Maalhos and Himandhoo. All of these islands, except Bodufolhudhoo and Etheremadivaru are exposed to SW monsoon swells.

Table 3.6 Summary of medium- to long-term shoreline changes in inhabited islands

Figure 3.13 Beach rock plays a role in holding the sediments in place in Feridhoo

Figure 3.14 Beach rock as a natural revetment in strong wave conditions: (a) Maalhos; (b) Mathiveri (c)Thoddoo and (d) Himandhoo

4.1 Coastal Infrastructure and modifications

A wide range of coastal infrastructure has been constructed on the islands of North Ari Atoll (see *Table 4.1*). All inhabited islands and resort islands have undergone coastal modifications. The most common infrastructure is those related to island access. This is considered a basic necessity for socio-economic development. The extent of changes on the inhabited islands depends on the amount of public investments undertaken by the Government. The access infrastructure on resorts islands have been kept to a bare minimum in most islands.

4.1.1 Harbours

Harbours are most common type of island access infrastructure in North Ari Atoll. They usually comprise of a suite of developments including a reef entrance, harbour basin, quay wall, breakwater and revetment or seawall (as summarized in *Figure 4.1*). Harbours are generally designed as protruding structure from the island shoreline (See *figure 4.2*). The dredged material is generally placed on either side of the harbor providing protection for its quay wall and space to develop support facilities of the harbor. Access infrastructure generally occupies 10% of the shoreline.

All inhabited islands except Himandhoo have a harbour. A new harbour is planned and budgeted (according to the Island Council) for 2015. The earliest harbours were constructed in Mathiveri, and Ukulhas followed by Bodufolhudhoo and Thoddoo. Recent projects include Feridhoo, Maalhos and Rasdhoo. The designs for Feridhoo and Maalhos are different from that of the earlier harbours, particularly in relation to the material used for construction. Ukulhas and Mathiveri have been renovated recently to meet with the new harbour design standards. Among the older harbours, only Thoddoo has not been renovated.

Some resorts islands, namely Madoogali, Maayyafushi, Ellaidhoo and Kudafolhudhoo have elements of a harbour with a dredged basin, reef entrance or a quay wall (see *table 4.1*) but none of these islands have harbours constructed to the extent of those in inhabited islands. Perhaps the main reason is the need to maximize beach space. The average length of shoreline dedicated for access infrastructure in resort islands in North Ari Atoll is about 3.5% compared to 13% in inhabited islands.

Figure 4.1 Basic elements of harbor infrastructure

4.1.2 Access Jetties

All resort islands have jetties for island access. All islands except Ellaidhoo and Kudafolhudhoo have piled structures that allow water and sand flow underneath them. The main jetty head is generally located away from the island. These structures seem to have minimal impact on coastal processes.

Most islands have a single jetty but Velidhoo and Bathalaa have two jetties which they alternate during the two seasons for access. Sometime they alternate them as service and guest jetty.

4.1.3 Over water structures

Over water structures are mainly constructed on resort islands. These mainly come in the form of guest accommodation (water bungalows), access jetties or guest service outlets like restaurants and spas. Some structures are constructed as semi-water villas with part of the structure on land and water. These structures are built partly on the beach.

The land tenure system in the Maldives does not allow private properties to be built overwater in inhabited islands.

4.1.4 Reef Entrance

Dredging reef entrances is part of the suite of facilities constructed with a harbor. It is also done separately to access the deep lagoon of a reef, to access a boat yard or as a separate access to the island which does not have a harbour. In North Ari Atoll, all inhabited islands, except Himandhoo have their reef entrances as part of the harbour. Himandhoo has two reef entrances – one on the south and one the north. Bodufolhudhoo also retains two channels with one for the existing harbour and one for the old access point on the western side of the island. Bodufolhudhoo was also forced to close down one of its dredged channels due to strong wave refraction within the harbour.

Figure 4.2 Harbour designs used in the inhabited islands of North Ari Atoll

Reef entrances for resort islands are most commonly dredged to access the deep lagoon. All resorts with large lagoons (Etheremadivaru, Maayyaafushi, Halaveli, Fesdhoo and Mushimasmigili) have them. These channels are usually located away from the island. Dredge waste from the channel is usually used to create a small island next to the channel.

Ukulhas contains two additional channels which are regarded as unnecessary dredging undertaken mainly to unload material to the island during harbor construction projects.

4.1.5 Land Reclamation

There have been no major land reclamation projects in North Ari Atoll, except for a recently reclaimed Madivaru Finolhu (next to Mathiveri Island), which is being planned as a resort island. All land reclamation activities in inhabited islands have been undertaken as part of dredge waste disposal from the harbor basin and reef entrance dredging project. The reclamation activities were a relief for the smaller and congested islands such as Bodufolhudhoo, Rasdhoo, Mathiveri and Ukulhas. Other islands such as Thoddoo, Feridhoo and Maalhos may not have gained much benefit in terms of additional land, but the reclaimed areas are being used for harbour auxiliary services. Dredged waste disposal has been a method for erosion mitigation (explained in next section) for smaller and severely eroding islands.

4.2 Erosion Mitigation Infrastructure and Measures

Erosion mitigation has been undertaken as part of harbour construction projects or independently as a separate project. In inhabited islands these structures are usually constructed by locals using local resources rather than using Government funding. As a result there are no formal designs for the structures and maintenance requirement is high. The high cost has also prevented wide spread use of shore protection structures in inhabited islands.

In resort islands, erosion mitigation is the most dominant coastal feature as retaining a beach is essential for the tourism product. The rest of this section explains the types of erosion mitigation infrastructure used in the islands of North Ari Atoll.

4.2.1 Historical Perspective

Interviews were conducted with elderly and knowledgeable members of the public to establish when erosion became a concern for the surveyed islands. It revealed that the erosion has been an issue since the 1980s. The common characteristics of islands reporting severe erosion were their small size, high density and proximity of settlement edge to high tide line. These islands include Bodufolhudhoo, Rasdhoo and Mathiveri. Ukulhas and Mathiveri also identified erosion as a problem after their respective harbor construction projects were completed. None of the islands were able to specify the exact year in which erosion became a problem indicating that it was a gradual and an ever present hazard.

Coastal protection emerged in most islands after the 1990s, particularly in Mathiveri, Rasdhoo and Bodufolhudhoo. Erosion in larger inhabited islands like Feridhoo, Maalhos and Thoddoo were not identified as a problem and thus no substantial measures were used. Issues in these large islands coincided mainly with coastal developments like harbor and particularly around the newly reclaimed areas. In resort islands erosion appears to have been a significant issue since they opened.

" The common characteristics of islands reporting severe erosion were their small size, high density and proximity of settlement edge to high tide line."

A summary of the hard engineered adaptation measures in the survey islands are present in *Table 4.2*. The most common hard engineered adaptation measure for erosion prevention is foreshore breakwaters or seawalls, followed by near shore breakwater and groynes. Details of these adaptation measures are presented in the following sections.

No	Island	Island use	Harbour Basin	Dredged reef entrance	Manually cleared reef entrance	Groyne (Harbor protection)	Revetment (Harbor protection)	Quay wall	Harbour Breakwater	Entrance Channel Protection	Jetty	Land reclamation	Overwater structures
1	Thoddoo	Inhabited	Y	Y				Y	Y			Y	
2	Rasdhoo	Inhabited	Y	Y		Y		Y	Y			Y	
3	Ukulhas	Inhabited	Y	Y			Y	Y	Y	Y		Y	
4	Bodufolhudhoo	Inhabited	Y	Y	Y	Y		Y	Y	Y		Y	
5	Mathiveri	Inhabited	Y	Y			Y	Y	Y	Y		Y	
6	Feridhoo	Inhabited	Y	Y		Y	Y	Y	Y	Y		Y	
7	Maalhos	Inhabited	Y	Y		Y		Y	Y			Y	
8	Himandhoo	Inhabited	Y	Y	Y						Y		
9	Veligandu	Resort	Y	Y					Y		Y	Y	Y
10	Kuramathi	Resort	Y	Y							Y		Y
11	Gangehi	Resort									Y		Y
12	Velidhoo	Resort		Y		Y		Y			Y	Y	Y
13	Kudafolhudhoo	Resort		Y	Y							Y	
14	Madoogali	Resort	Y	Y	Y				Y		Y		
15	Etheremadivaru	Resort		Y							Y	Y	
16	Mayyaafushi	Resort		Y	Y			Y			Y		
17	Bathalaa	Resort			Y						Y		
18	Halaveli	Resort	Y		Y						Y		
19	Ellaidhoo	Resort	Y	Y		Y		Y	Y	Y	Y	Y	
20	Fesdhoo	Resort	Y	Y	Y						Y		
21	Mushimasmigili	Resort	Y	Y							Y	Y	

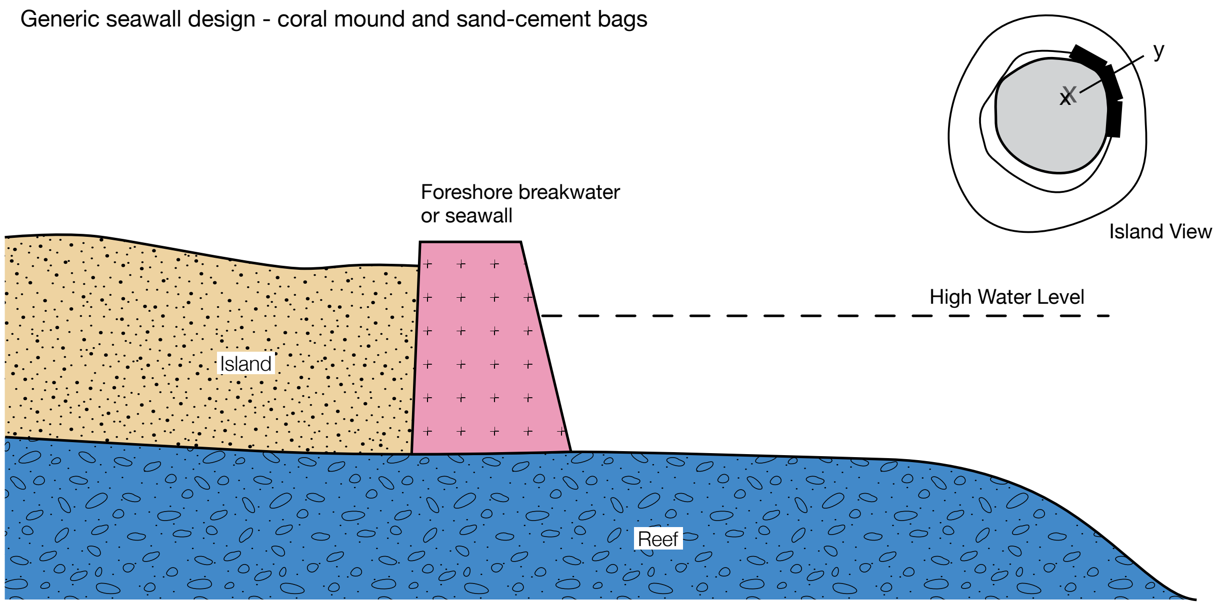
Table 4.1 Summary of coastal infrastructure in North Ari Atoll

4.2.2 Foreshore Breakwaters or Seawall

Foreshore breakwaters or seawalls are the most common type of coastal erosion mitigation measure used in the inhabited islands. They are commonly used to hold the island shoreline in place, rather than retain a beach. This serves the dual purposes of preventing any further erosion of the island and preventing wave overtopping or flooding. It is used as a last resort against island erosion in most islands. It does not resolve the causes of erosion. Its implementation can be found in both inhabited and resort islands. This is also the most commonly used erosion prevention measure in community financed coastal adaptation projects.

The structure is generally self-supporting and does not require land to retain its strength (see *Figure 4.3* below). The design heights of the structures were uniform with about 0.5 to 1 m above high tide. The seaward slope of the structures varies from island to island particularly between resorts and inhabited islands. It has been constructed using a number of materials ranging from coral mound, sand cement bags, sheet piles, wooden piles and jumbo bags (Shaig, 2011). In the surveyed islands, the materials used for construction include coral mound (plastered and unplastered), gabion type with coral mounds (unplastered with netting) and sand cement bags (plastered and unplastered). Bodufolhudhoo Island had a unique seawall constructed by placing concrete in reused plastic barrels (See *Figure 4.4*).

Foreshore breakwaters or seawalls have been effectively deployed to control shoreline retreat in the resort islands of North Ari Atoll. In inhabited islands, it's mostly been deployed as part of land reclamation following harbour dredging (for example: Mathiveri, Maalhos and Bodufolhudhoo) or as retaining walls (See *Figure 4.6*) to enclose waste sites (for example, Bodufolhudhoo, Mathiveri and Rasdhoo – See *Figure 4.5*). In resort islands, they are deployed to halt shoreline retreat at severe erosion zones (for example: Gangehi). It is not used to retain a beach. In fact, it neither addresses the causes of erosion nor does it assist in rejuvenating the beach around the seawall area.



Source: Coastal Adaptation Study (Shaig, 2011)

Figure 4.3 Standard sea wall design for coral mound and sand-cement bags

Figure 4.4 Example of improvised Sewall structures: concrete filled barrels in AA Bodufolhudhoo

Figure 4.5 Examples of Seawall structures: semi-plastered coral mound seawall in Bodufolhudhoo and Mathiveri

Figure 4.6 Examples of Seawall structures: plastered sand-cement bag seawalls in Maalhos and Mathiveri

Table 4.2 Summary of erosion mitigation infrastructure in North Ari Atoll

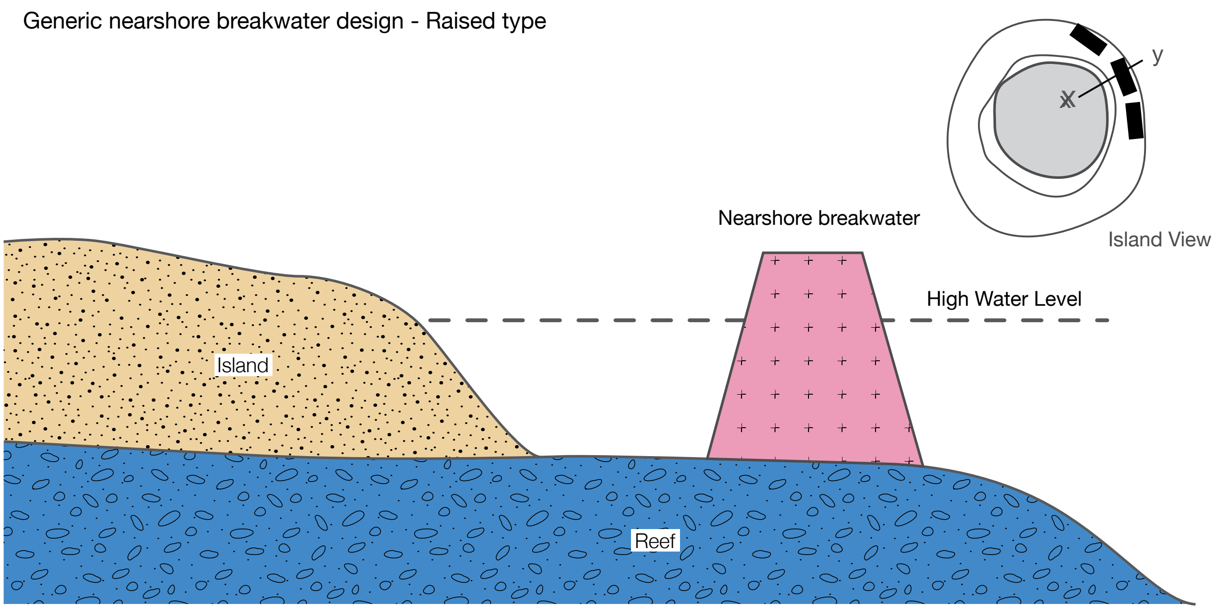
No	Island	Island use	Foreshore Breakwater (Seawall)	Near shore raised breakwater	Near shore submerged breakwater	Revetment	Groynes	Replenishment / reclamation	Ad hoc construction waste dumping	Other
1	Thoddoo	Inhabited							Y	
2	Rasdhoo	Inhabited	Y		Y	Y	Y	Y	Y	
3	Ukulhas	Inhabited				Y		Y	Y	
4	Bodufolhudhoo	Inhabited	Y					Y	Y	Y
5	Mathiveri	Inhabited	Y	Y	Y	Y		Y	Y	Y
6	Feridhoo	Inhabited	Y			Y	Y		Y	Y
7	Maalhos	Inhabited	Y	Y		Y	Y		Y	
8	Himandhoo	Inhabited	Y						Y	Y
9	Veligandu	Resort	Y					Y		
10	Kuramathi	Resort		Y	Y		Y	Y		
11	Gangehi	Resort	Y	Y			Y	Y		
12	Velidhoo	Resort	Y	Y			Y			
13	Kudafolhudhoo	Resort	Y				Y	Y		
14	Madoogali	Resort	Y						Y	Y
15	Etheremadivaru	Resort	Y	Y			Y			
16	Mayyaafushi	Resort	Y	Y				Y	Y	Y
17	Bathalaa	Resort							Y	Y
18	Halaveli	Resort	Y	Y			Y			
19	Ellaidhoo	Resort	Y	Y			Y			
20	Fesdhoo	Resort	Y			Y	Y	Y	Y	Y
21	Mushimasmigili	Resort	Y				Y		Y	

4.2.3 Nearshore breakwater

Nearshore breakwaters are generally constructed detached and parallel to the island shoreline. They are commonly used in inhabited islands to protect harbours. They have also been deployed as an erosion mitigation measure in a limited number of inhabited islands. They are the most common erosion mitigation structure used in the resort islands of North Ari Atoll. The purpose of a breakwater is stop or reduce the wave energy within the reef flat before it reaches the shoreline, thereby creating a zone of calm conditions behind the structure and the beach. These structures are specifically used to prevent erosion and to create calm condition in harbor basin.

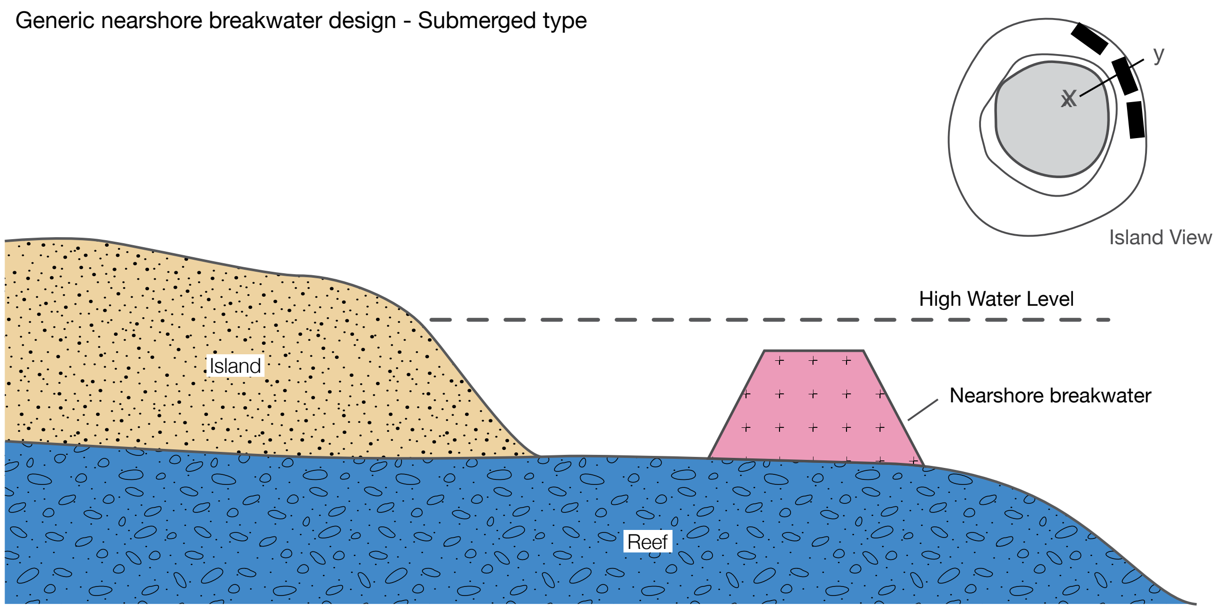
There are two types of breakwaters: i) raised above high tide level or; ii) below high tide or mean sea level (Shaig, 2011). Breakwaters in inhabited islands are generally constructed overwater, but over time it can become submerged structure due to damage to the original structure (For example: Rasdhoo, Mathiveri and Mayyafushi). The most common construction material is coral mound or sand-cement bag structures.

Breakwaters have been used successfully in Veligandu, Kuramathi, Velidhoo, Gangehi, Madoogali, Halaveli and Ellaidhoo. Among these, the entire reef perimeter of Ellaidhoo is covered with breakwaters and a large proportion of the reef perimeter in Velidhoo, Halaveli and Gangehi are protected by breakwaters. Among inhabited islands, it was implemented in Mathiveri and Bodufolhudhoo but in both of these islands the structures collapsed and failed to serve its intended purpose. The failure could be attributed to poor design, construction and lack of maintenance.



Source: Coastal Adaptation Study (Shaig, 2011)

Figure 4.7 Near shore break water design - raised type



Source: Coastal Adaptation Study (Shaig, 2011)

Figure 4.8 Near shore break water design - Submerged type

Figure 4.9 Break water design used prior to 2010s – sand cement bags from Thoddoo Island

Figure 4.10 Current break water design for harbours – Raised rock boulder breakwater in Rasdhoo and Maalhos

4.2.4 Revetment

Revetments are shore parallel structures constructed on the beach. It requires the support of the beach and is usually constructed to the same or similar slope as the beach. It performs a similar function to a seawall in that it prevents further erosion of the shoreline.

Revetment has been used mainly to protect newly reclaimed areas after harbour dredging. It has also been used to prevent erosion in Ukulhas Island. It does not appear to have been used in a resort island.

Revetments in North Ari Atoll have been constructed mainly using armour rock. There is only one instance of the use of sand-cement bag revetments.

Figure 4.11 Revetment – Armor rock structures in Mathiveri and Rasdhoo

4.2.5 Groynes

Groynes are shore perpendicular structures constructed along the beach. Their main purpose is to minimize erosion by controlling the sediment movement around the island. The groynes trap sand behind the structure and are usually implemented as a groyne field with a series of units spaced at the required intervals. This allows retaining sand between them. They are most commonly used in resort islands where retention of beach is a key priority. They are used in inhabited islands to prevent sedimentation of the harbour basin.

The basic design includes a structure extending into the lagoon above high water level. The length of the structures varies depending on the island used. The seaward end may be designed as a circular shaped structure for aesthetic purposes. It is usually constructed using sand-cement bags or coral mounds.

Photo by: Oxana Amelchenko

Figure 4.12 Groynes used for erosion mitigation in Velidhoo and Mayyafushi

Figure 4.13 Groyne constructed in Feridhoo to prevent sedimentation in harbor basin and to prevent erosion

4.2.6 Construction Waste

Ad hoc dumping of construction waste is a common practice for erosion mitigation in inhabited islands across Maldives. In the North Ari Atoll, all inhabited islands had a section of the island shoreline protected using this method. It is most commonly found around the newly reclaimed areas around a harbour.

Waste is not dumped in a planned manner and in some islands it has become a major aesthetic issue. It also contains dangerous material such as sharp objects that are a hazard to anyone using the area.

Its effectiveness is poor. In areas of heavy erosion, despite the presence of the debris, erosion tends to continue leaving behind the debris in the lagoon.

Construction debris has been used as a breakwater, particularly in Mathiveri Island. They used the debris from the old harbour demolition to create a makeshift structure.

Figure 4.14: Ad hoc dumping of construction waste to mitigate erosion in Mathiveri Island. A range of measures including groynes, revetments and nearshore breakwater have been constructed using harbour demolition waste.

Figure 4.15 Construction waste used for erosion mitigation in (a, b) Thoddoo, (c) Ukulhas and (d) Bodufolhudhoo

4.2.7 Beach replenishment

Beach replenishment is the most common method of erosion mitigation in the resort islands of Maldives. It is considered a soft engineering method where no permanent structures are constructed. Its main goal is to replace the eroded areas with sand so as to return the beach to its original state before erosion. It is considered a more effective solution than solid structures for islands undergoing moderate levels of erosion. Beach replenishment is a temporary solution and does not address the causes of erosion. The natural processes operating around the island dictates the stability of the fill material and beach profile in the post replenishment stage.

Beach replenishment requires dredging sand from the lagoon and dumping on the beach. A sand pump is usually used to dredge sand from the lagoon and to dump it directly on to the beach. The beach is profiled manually as the use of heavy machinery is not an option in operating resorts.

This method of erosion mitigation is not used in inhabited islands. Perhaps this is because the objective of the erosion mitigation in inhabited island is to prevent shoreline retreat affecting the settlement physically. In resort islands, the primary objective is to retain a beach as well as control the beach retreat.

This activity is known to have significant impacts in sensitive marine environments due to suspended sediments, turbidity and lagoon benthos disturbance.

4.3 Other practices related coastal vulnerability reduction

4.3.1 Land-use setbacks

Land-use setbacks from beach have traditionally been used as the one of the main measures against impacts from severe erosion. The traditional land use setbacks are being sacrificed as the island becomes densely populated. Islands such as Bodufolhudhoo and Rasdhoo struggle to maintain the buffer. At times of erosion, these two islands are most at risk. Bigger islands like Thoddoo, Feridhoo and Maalhos tend to have wider setbacks.

There is a regulatory requirement of 15 m setback between the shoreline and settlement for inhabited islands. Islands with land use plans follow this requirement strictly. In other islands, the local authorities themselves control the allocation of plots close to the beach.

Resort islands have a regulatory requirement of 5 m set back from the beach and this regulation is strictly enforced. However, for resorts, it becomes a necessity for the beach accommodations to be kept within close proximity to the beach. In cases of erosion prone islands, the 5 m setback is not enough and often leads to construction of erosion mitigation measures.

Land-use setbacks provide the most environment friendly option against medium term-erosion. This method recognizes that certain areas of the island are volatile and exposed to periodic erosion and provision is given to facilitate these natural processes by avoiding construction in these zones.

Figure 4.16 Building in close proximity to an eroding shoreline in Rasdhoo Island

4.3.2 Sand mining

Sand mining is banned in the Maldives from within 100 ft from the island shoreline. This has helped to reduce the negative effects on the sediment budget of the islands. Unfortunately, inhabited islands with limited space on the reef and larger islands still tend to mine sand from their own beach for development needs. Active sand mining was observed on Thoddoo and Feridhoo Island during the field visit. Extraction of sand from the beach may reduce the sediment budget faster than it can replenish and lead to erosion in the long-term.

4.3.3 Retention of coastal vegetation

Coastal vegetation is known to play a major role in reducing the exposure and impacts of natural hazards in the Maldives. Coastal vegetation belt retention is a traditional adaptation measure against strong wind, resulting salt spray, occasional coastal flooding and coastal erosion (Shaig, 2011). The following observations were made in North Ari Atoll.

a. The western rim islands, exposed to strong winds and salt spray during Southwest Monsoon, have a wider coastal vegetation system. These include Feridhoo, Maalhos, Himandhoo and Mathiveri. The exceptions to this rule are the resorts on the western rim for which there is no link between exposure patterns and vegetation belt.
b. In the central parts of the atoll and in Rasdhoo, vegetation belt is uniformly maintained suggesting the limited effects of salt spray on these islands.
c. All inhabited islands surveyed had a strong vegetation belt except for Bodufolhudhoo Island, which had undergone significant reclamation.

4.3.4 Preservation of coastal ridges

Similar to the vegetation belt, the coastal ridges on islands play an important role in mitigating the effects of waves. Strong ridges were observed on western rim islands (Feridhoo, Maalhos and Himandhoo) due to their exposure to SW monsoon winds and swells. Mathiveri and Gangehi was an exception to this observation. Thoddoo Island had the highest ridges, perhaps due to its constant exposure to swells. These ridges have so far been retained in the islands studied.

4.4 Perceptions towards coastal erosion and mitigation measures

Since the physical survey was possible only in inhabited islands and only one resort island, the perceptions of the inhabited islands are presented here. The key perceptions of the locals were:

a. Erosion is always the result of coastal infrastructure, particularly harbour construction and channel dredging. This was the case in Ukulhas, Mathiveri, Bodufolhudhoo, Maalhos and Thoddoo Island. (However, this may not always be the case: see Next chapter). Among these Ukulhas and Mathiveri strongly believe that their erosion problems are related to the harbor construction.
b. Erosion is only reported as a problem if houses or infrastructure are within close proximity to eroding areas. In larger islands (like Thoddoo, Feridhoo and Maalhos) erosion was not reported as a serious problem, mainly because it occurs in uninhabited areas of the island. Analysis of shoreline data showed that some of these islands were indeed eroding.
c. Harbour projects are also seen as a solution for erosion problems as they see that material dredged as a source of sand to fill the eroded areas. This opinion was strongest in Himandhoo Island, which had used dredge material to replenish eroding areas before.
d. There is a general feeling that it is the responsibility of the Government to provide coastal adaptation. Community expenditure on coastal protection is considered only when properties are at risk.
e. Both Government and community expenditure on coastal protection is considered only when erosion reaches a critical level, by which time options available are costly.
f. Failure of structures such as quay wall and breakwaters are generally seen as a fault with workmanship. However, most failures are equally related to poor design.
g. They do not consider soft engineering measures such as beach replenishment, setbacks or planting vegetation as options for erosion control. They only consider hard engineered solution as the erosion mitigation measures.
h. They do not consider climate change as the cause of erosion on their island.

5. IMPLICATIONS OF COASTAL MODIFICATIONS AND CURRENT PRACTICES ON ISLAND RESILIENCE

This chapter provides an overview of observed implications on geophysical resilience of the study islands from the coastal infrastructure and erosion mitigation measures discussed in the previous section. Information is largely based on existing literature on the subject and observed changes.

5.1 Effects of coastal modifications

5.1.1 Dredging and constructing harbours

As noted in the previous section, harbours are the most common and prominent coastal infrastructure developed on the inhabited islands of Maldives. Their effects have been examined in studies such as Kench et. al (2003), Kench (2010) and numerous Environmental Impact Assessments (see www.epa.gov.mv). The suite of structures constructed for a harbour (breakwater, quay wall, and harbour basin and reef entrance) combine to bring about the impacts on islands.

As noted in chapter 4, there are four main types of islands in North Ari Atoll: east-west oriented elongated islands on western rim; circular islands, north-south elongated islands, and odd shaped island.

The observed effects on each of these types of island differ and are summarized below.

East-west oriented islands

Harbours constructed on east-west oriented islands on the western rim of the atoll (Maalhos and Feridhoo) had similar types of impacts. *Figure 5.1* and *Figure 5.2* shows the effects on sediment transport patterns due to harbor construction in Maalhos Island as an example. A summary of the changes is provided below:

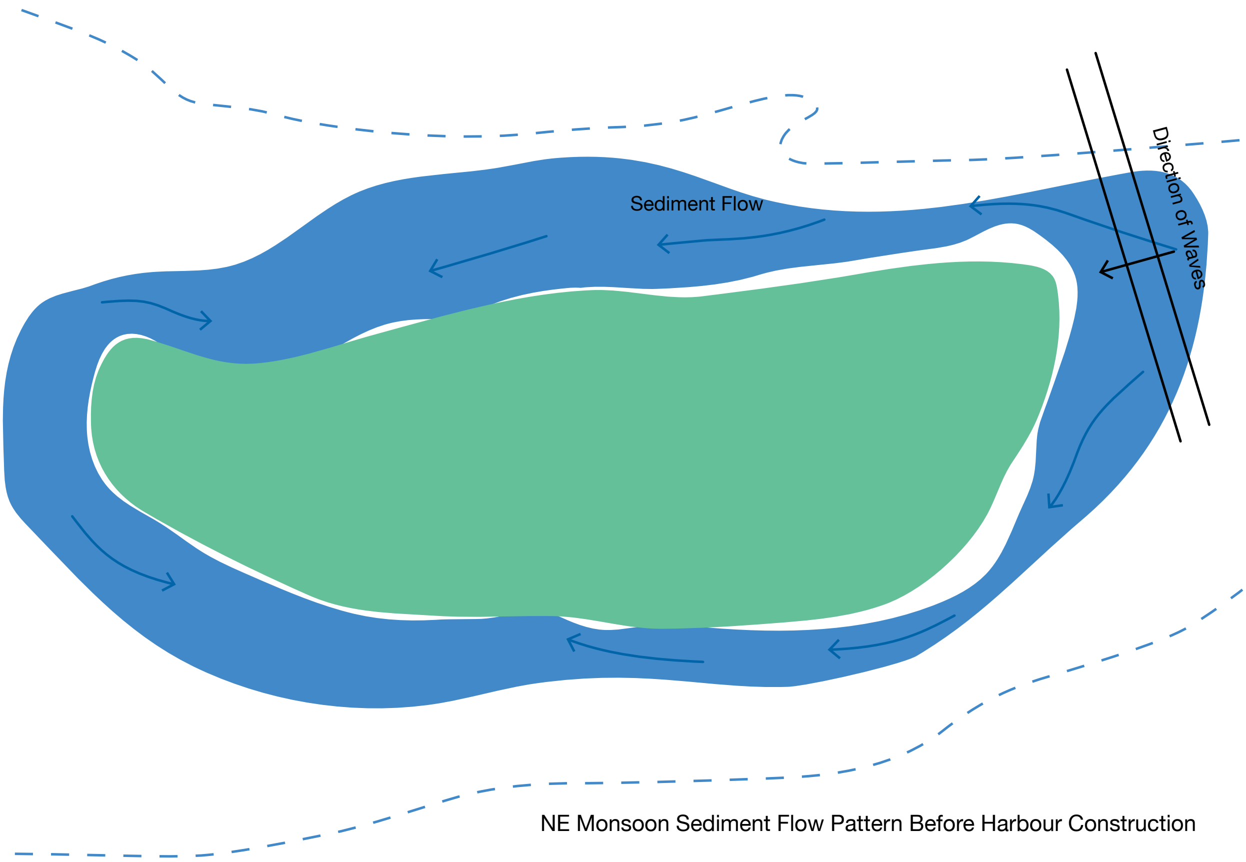
a. Along-shore currents are directly altered due the harbors protruding from the island shoreline. Eddies are formed on the downwind side of the harbor facilitating scouring on one side.

b. Sediments transported along the shoreline are trapped on the updrift side of the harbor and the down drift side experiences erosion due to lack of sediments (See *Figure 5.4*). The process is reversed seasonally. During SW monsoon updrift occurs on the western side of the harbor and down drift occurs on the eastern side. The pattern is reversed again during the NE monsoon (See *Figure 5.3*). During the initial seasons after construction, this process can create net erosion on the down drift side.

c. The dredged channels and harbor basins can act as sediment sinks for sediment transported along the shoreline. Overtime this leads to a shallow reef entrance or harbor basin. It also leads to a net loss of sediments from the sediment budget leading to overall erosion around the island. It is estimated that the longer the process continues, the higher the net loss. Some islands have used a groyne to prevent sediments seeping into the channel.

d. Present day sediment production occurs predominantly on the oceanward side reef (Gischler, 2006). When sediment transport is cut-off between west and east, a net loss is expected on the eastern side overtime, while more sand is retained on the western side.

" Coastal vegetation is known to play a major role in reducing the exposure and impacts of natural hazards in the Maldives. Coastal vegetation belt retention is a traditional adaptation measure against strong wind, resulting salt spray, occasional coastal flooding and coastal erosion. "



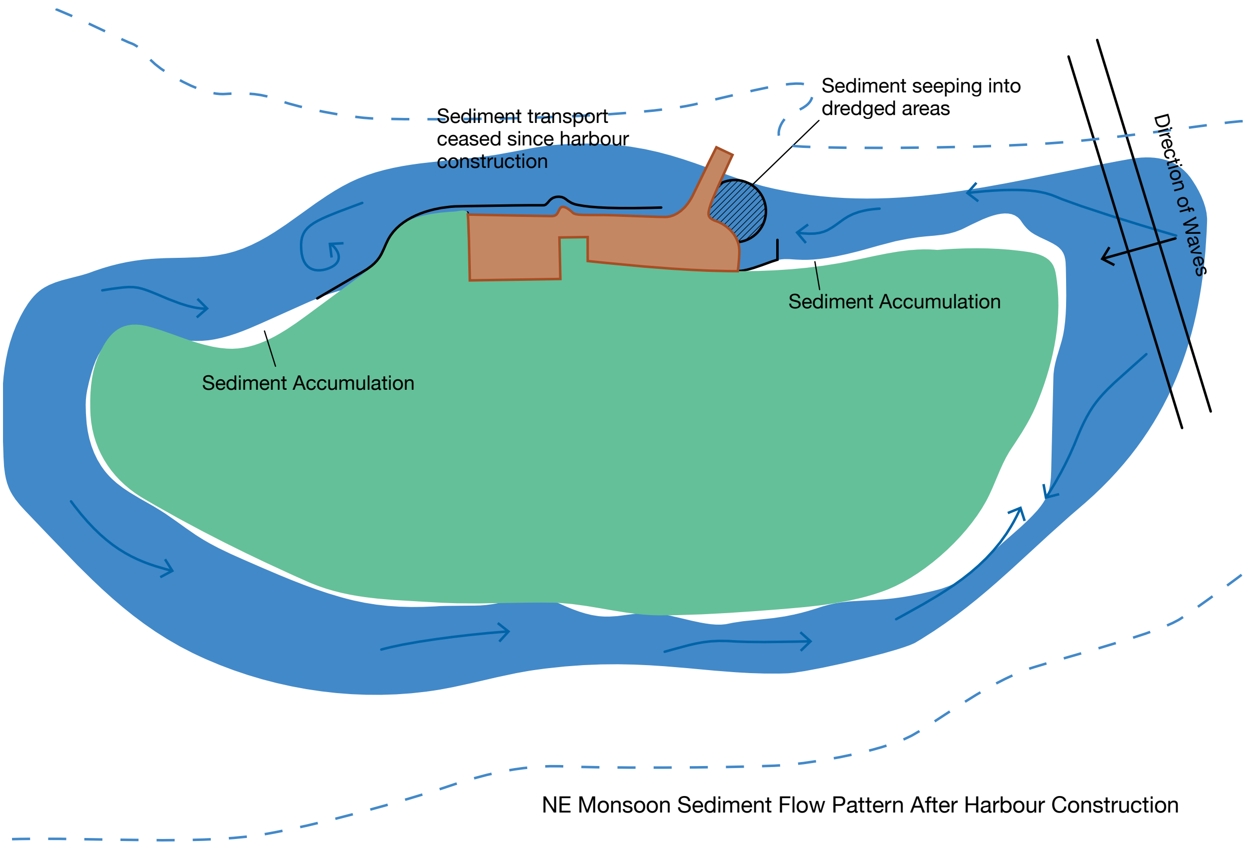


Figure 5.1 Effects of harbor construction on sediment transport around Maalhos Island during NE monsoon

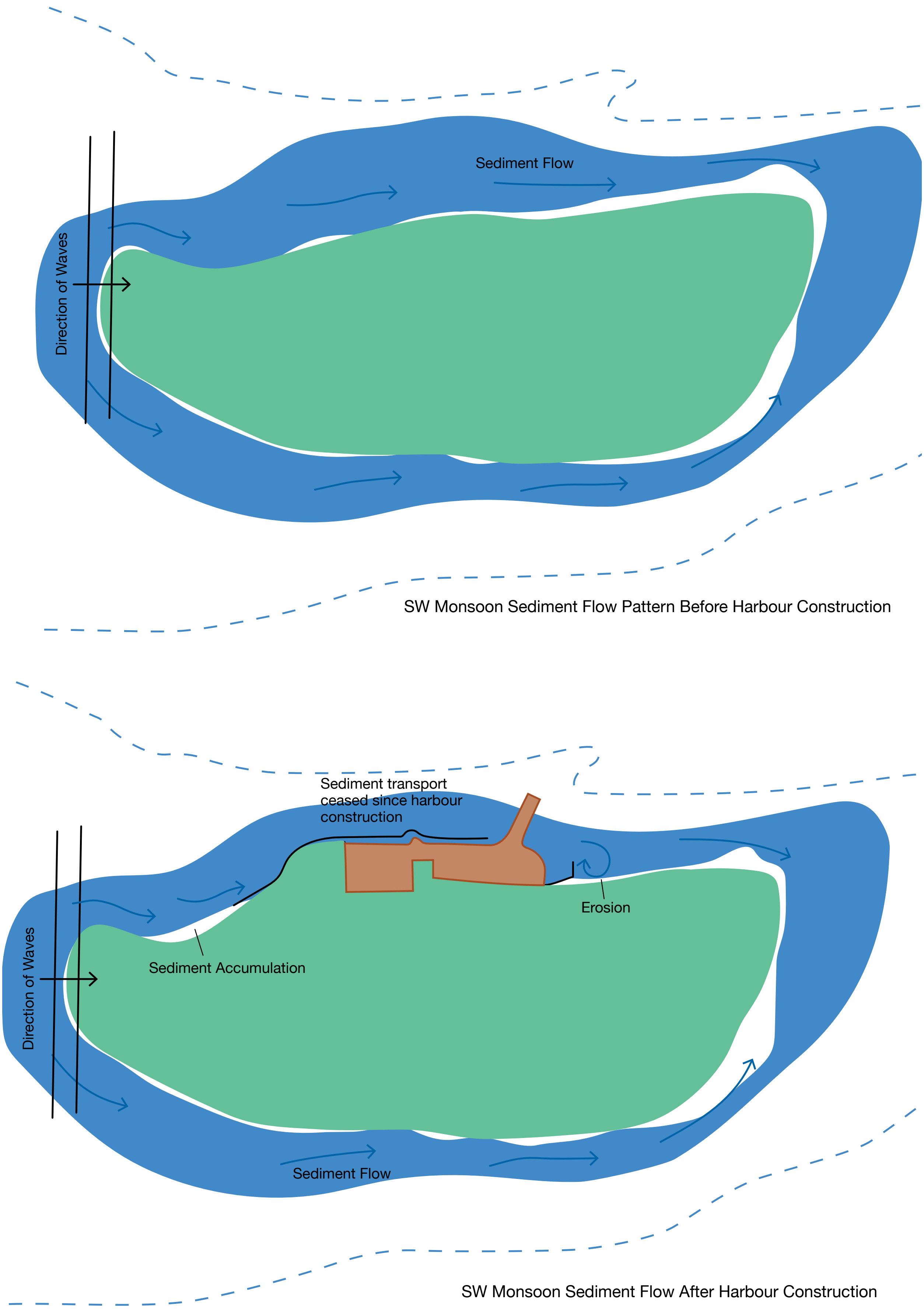


Figure 5.2 Effects of harbor construction on sediment transport around Maalhos Island during SW monsoon

Figure 5.3 Accretion during NE monsoon on the eastern side of the harbour

Figure 5.4 Erosion on the western side of the harbor

Circular Islands

The patterns of erosion and accretion in circular islands (namely Rasdhoo, Bodufolhudhoo and Thoddoo) were not uniform, perhaps due to their different locations and wave regimes. Bodufolhudhoo is an island located inside the atoll lagoon and Rasdhoo is located on an atoll rim. Thoddoo Island is a separate atoll in itself exposed to stronger waves regularly. All these islands have harbours constructed on them.

In general, circular islands located within atoll lagoons tend to have a very mobile beach system, moving large volumes of sand seasonally (Kench, 2010, Kench and Brander, 2006, Kench et al., 2009b). This pattern applies to Bodufolhudhoo Island and to some extent Thoddoo Island. It does not seem to apply to Rasdhoo as it is considered an atoll rim island which usually has a dominant flow from the ocean side to lagoon side but not vice versa.

The effect of harbour construction on Bodufolhudhoo has been the complete blockage of sediment movement around the island. The actual effects are hard to quantify due to extensive reclamation. Nonetheless its impacts could be summarized as follows:

a. Seasonal sand movement has ceased and only occurs as two pockets: one on the eastern side and one on the western side. There seems to be no connection between them.
b. The use of solid jetties on the western side further limits sand movement.
c. Sand production seems to occur primarily on the northern side. However, this material may only be transported to the western side. Sand flowing towards the eastern side may end up in the dredged channels. The eastern side is therefore permanently deprived of new sand.
d. Similarly the dredged areas on the west may restrict new sediments from reaching the beach.
e. All in all, Bodufolhudhoo is now dependent on human intervention to mitigate erosion. Its natural adaptive capacity seems to be limited due to the numerous restrictions posed on littoral sediment transport.

The development of a harbour on the northern end of Rasdhoo has also separated the sediment flow into two separate cells: one on the east and one on the west. The following impacts were observed:

a. The western side is more active due to the presence of a larger volume of sand, while the eastern side has a narrower beach with limited sand.
b. Sediment seems to unusually accumulate on the oceanward side behind the protection offered by shallow reef and very shallow coral rubble zones on the reef flat.
c. Any further sediment flow northward during stormy periods may end up in the dredged basin

Elongated north-south oriented islands

The only inhabited island falling into this category is Ukulhas Island located on the eastern rim. There was no data on the shoreline position just before the construction of the harbor and it was therefore difficult to draw conclusion on the actual impacts of harbor construction on the sediment flow pattern. Historical images taken in 1969 and its comparison with images taken few years after the completion of harbour indicates severe erosion on the northern side of the island had existed before construction. Thus, we cannot attribute the severe long-term shoreline shifts observed on the northern side of Ukulhas entirely to harbor construction. Nonetheless, we can observe that the issues on the northern side are now compounded due to harbour construction. Sediment flowing from the south during the NE monsoon no longer reaches the northern ends due to obstruction created by the harbor. Similarly not enough new sediment is received to the south, possibly leading to a gradual loss of beach on the eastern side. The western side, with limited coastal developments appears to remains stable.

5.1.2 Constructing erosion Mitigation Measures

Foreshore breakwaters or Seawall

As noted in the previous chapter, seawalls are not designed to maintain a beach. It is designed to halt erosion by preventing interaction between sand and the coastal processes.

In principle, the shore parallel structures may not have a major negative impact on coastal processes if there is a sufficient supply of sediments (Kench, 2010). However, if there is a deficiency in sediment supply either through natural causes or due to obstruction of coastal process, a poorly designed structure can become a hindrance to coastal processes.

The following issues were identified with the existing seawalls in inhabited islands:

a. The design parameters sometimes do not match the wave conditions on the site. As a result, there is wave overtopping leading to back scour and eventual collapse of the structure (For example Maalhos, Mathiveri and Rasdhoo). Once a section of the structure is damaged, it seems to disintegrate easily as it is usually constructed from sand-cement bags or corals. Eventually the shoreline is exposed to erosion or in the case of Rasdhoo, the waste site was exposed to waves.
b. The ends of the seawall structure are sometimes not completed properly leading to erosion around the seawall edges.
c. Locking sediment behind a seawall reduces the sediment budget as it is not allowed to migrate freely. This may lead to eventual erosion in another section of the shoreline.
d. The vertical nature of the seawalls helps to creating 'standing waves' in the lagoon from the waves deflected off the structure. This may prevent the formation of beach in front of the seawall or restrict sediment transport in front of it.
e. In summary, seawalls may not necessarily restrict the island's ability to naturally adapt and in some cases could be considered a complementary structure for natural adaptation.

Revetment

As noted in previous chapter, revetments are similar to seawalls in their function in relation to erosion mitigation. Their primary benefit is their sloped nature allowing better energy dissipation and for sand to flow around it. Revetments themselves are not a hindrance to natural adaptation but locking large amounts of the sediment budget behind a revetment deprives the rest of the beach enough sediments to naturally adapt to changing coastal processes.

Breakwater

Breakwaters are designed to alter the wave conditions and eventually the nearshore currents to provide a positive influence on the sediment stability at a given point. Their use as an erosion mitigation measure at present has been restricted in North Ari Atoll to resort islands. The following issues were identified in the North Ari resorts that have implemented them. It has to be noted this assessment is based on remote sensing technology rather than onsite observations.

a. Breakwater units as individual arrangements or widely spaced arrangements appear to be only partially successful as observed in Kuramathi Island. However, if the structure is placed within 15-30 m of an area which already as a beach, it tends to assist the formation of 'tombolos' or protruding sections on the beach.
b. If only a section of the beach is protected by a closely spaced breakwater system, the area behind it usually retains sand, but the rest of the island is deprived of sand (For example Kuramthi and Velidhoo Island). This is due to the significant seasonal change in the wind and wave patterns between the two monsoons. This effect is more prominent in circular islands within the atoll lagoon.
c. Large-scale implementations with structure above high tide line and with

closely spaced units are generally expected to cease interaction between the coastal processes and the beach (Kench, 2010). However, this is not always the case as observed in Ellaidhoo and Halaveli.

d. Breakwaters also appear to be ineffective in a number of islands, namely Veligandu and sections of Velidhoo. While they appear to be playing some role in mitigating erosion, at some points along the shoreline, it is completely ineffective in other sections. There are a number of potential reasons for this:
    a. Island shorelines are generally dominated by along shore processes (Kench and Brander, 2006). It may be that in areas where they are ineffective are areas where along shore processes are more dominant.
    a. There are known periodic seasonal variations in wind (Department of Meteorology, 2014) and by inference wave activity, and intensity which may render these structures effective during some years but ineffective during others. During those times, the presence of a breakwater may be more of a hindrance than an advantage.
e. All in all, a breakwater may actually reduce the ability of a coral island to naturally adapt to changes in coastal process and climatic patterns.

Groynes

The use of groynes primarily target controlling coastal processes to retain beach at specific sections of an island which otherwise might move seasonally. Groynes directly control the alongshore current patterns. They usually work by retaining sand on the unpdrift side but may also lose sand on the downwind side (Kench, 2010, Kench and Brander, 2006).

As noted in the previous chapter, groynes are used in inhabited islands mainly to prevent sediment flow into dredged basins or reef entrances. These structures (for example Maalhos) have seasonal impacts where during one seasons they perform the function intended by retaining sand on the updrift side. However, during the next season, they becomes more of a negative impact on the beach as the downdrift side starts to recede due to wave refraction. Depending on the intensity of the seasons, these groynes may also be ineffective in preventing some material to seep into the dredged areas.

Groynes are a popular choice for erosion mitigation in resort islands of North Ari Atoll (for example Kudafolhudhoo, Fesdhoo, Veligandu, Velidhoo and Halaveli). However, their effectiveness is questionable in most of these properties. Among the properties investigated, Fesdhoo appears to be the most successful. It has managed to retain sand within reasonably spaced cells without overcrowding the beach with structures.

Kudafolhudhoo appears to be a poor example of groyne use and a site that shows the likely consequences of getting the design parameters for groynes wrong. On average the island has a groyne every 30 m and comes at varying lengths, shapes and elevations. It appears that these structures are ad hoc responses rather than a planned implementation. The island still has most if its beach eroded.

Similarly islands like Velidhoo and Halaveli seem to have groynes placed in a similar manner indicating ‘trial and error’ implementations.

The main issue with groynes seems to be that once a single groyne or a small groyne field is constructed, the island ends up implementing groynes all around it. This is most likely due to the deprivation of sediments to other sections of the island and downdrift erosion which forces additional structure to mitigate them.

It was noted that once a groyne is constructed, it usually does not get removed even if the erosion problem goes away temporarily. This may be due to the costs involved in constructing them in the first place.

Groynes significantly alter the coastal processes and therefore hinder the ability of the islands to adapt naturally.

5.2 Effects of poor practices on beach environment

In addition to the coastal modifications, some poor practices may also be leading to severe erosion in some of these islands. The most notable issues are summarized in this section.

Sand mining

Sand mining from an island beach or within 100ft of any inhabited islands has been banned in the Maldives. Unfortunately, some of the larger islands surveyed, or at least a section of the population of these islands, still practice mining sand from the beach. Large amounts can be mined at a given time and are used mainly for construction and landscaping purposes. Taking sand from the beach creates a net loss of sediments if that rate of extraction is greater than the rate of sand production from the reef and accumulation around the island. Thus, a net loss in the sediment budget is likely in the long run.

Sand mining has been a common practice in the Maldives. Extraction volumes may have been smaller in the past but with a boom in population the volume of sand extracted may be unsustainable now.

Sand mining is usually done above the high tide water mark. When large holes are left behind after mining, spring tides may flood these holes forcing the high tide water mark to retreat. This process also reduces the elevation of natural ridges or dunes.

Over fishing

Overfishing from within the house reef may reduce the population fish species that are responsible for the breakdown of coral into sand. Sediment production through the activities of fish is a critical part of short-term sediment production (Bellwood et al., 2011). Declining fish populations responsible for this process (for example, parrotfish) may reduce the sediment supply to the island. Over time, this may lead to net losses in the sediment budget.

Waste dumping

Dumping solid waste on the beach is still practiced in some of the islands surveyed. This waste eventually ends up being transported on to the lagoon or reef slope. It also breaks down, is mixed with the beach sand and is transported around the island. Most common materials found are plastic, glass, construction waste (such as aggregate and concrete pieces).

Dumping waste, particularly construction waste, prevents sediments from flowing around the island efficiently.

Coastal vegetation removal

Removing coastal vegetation exposes the beach dunes to wind erosion. The roots of the trees, particularly coconut trees, help to keep the beach sand intact for longer periods than a beach without any trees. Thus, clearing large areas of coastal vegetation may negatively affects the beach processes.

Development encroachment to coastal area

Erosion becomes a problem when it affects property. Encroaching coastal areas that require space for natural processes to operate will eventually result in erosion. This is the case in most of the resort islands developed in North Ari Atoll. The need to build closer to the beach especially in smaller islands within atoll lagoon have resulted the need for extensive shore protection measures in all the resorts of North Ari Atoll.

5.3 Future projections against sea level rise

Sea level rise has been regarded as a serious concern for the islands of Maldives. There is observed inter-annual variability in sea level as well as a long-term trend of increasing relative sea level (Figure 4.5). The observed long-term trend in sea level is 1.7 mm/yr (Hay, 2006). This value is towards the upper end of the predicted global sea level rise values as described in the IPCC report (IPCC, 2007). Extreme sea levels are also present in the mean hourly sea-level data from Hulhulé' which shows a long term trend of 7 mm/yr (Hay, 2006). These values suggest abnormal storm or swell activities which has the potential to cause flooding in low lying islands.

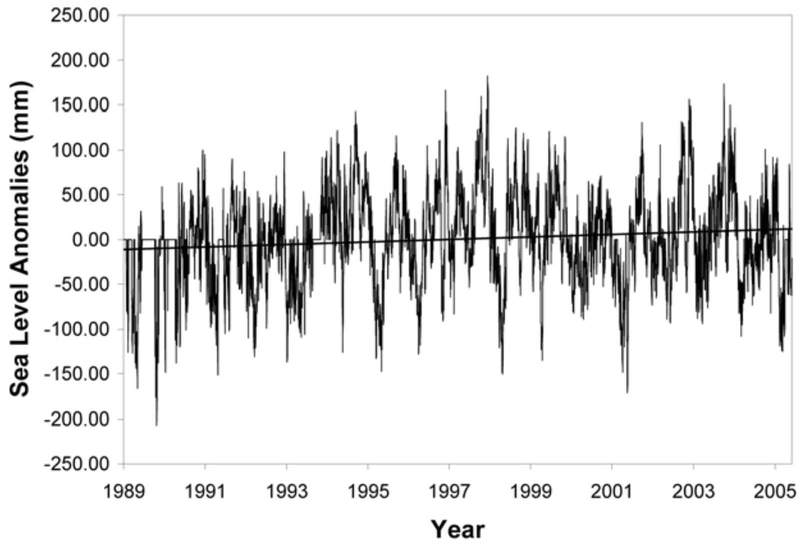
There are two scenarios presented for coral island states: (1) the reefs keep up with the rising sea level and the island geophysical setup continues with minimal changes, and; (2) reefs fail to keep up and island geophysical setup undergoes substantial changes (Shaig, 2006a). Under the first scenario, there may be changes to hydrodynamics around the island but the assumption is that these changes will be something closer to the status quo.

The second scenario poses a more serious threat. Islands in the Maldives could be considered loosely consolidated sediment sitting on top of a reef based on a balance of hydrodynamic conditions such as waves, currents, water level and coral cover. Changes to any one of these conditions may result in a geophysical response from the island, usually in the form of shoreline erosion and accretion. A higher water level will invariably mean an adjustment to higher tide levels, higher wave run-ups, raised water table and possibly stronger currents (Yamano, 2000). All these changes may combine to erode the island from higher energy zones and accrete around the lower energy zones.

It is also predicted that beach in the coral islands will respond to changes in water level by adjusting the shoreline vertically and horizontally (Kench and Cowell, 2001, Woodroffe, 2008, Woodroffe et al., 1999). The Shoreface Translation Model is used to model and describe these changes. Evaluations undertaken by Kench and Cowell (2001) predicted stronger vertical adjustment to coastal ridges. The process is also accommodated by a retreating shoreline and more sand from the sediment budget is borrowed to elevate the shoreline. Such adjustments are already visible in various parts of the Maldives where island in high energy zones have comparatively higher ridges than those that receive lower energy (Shaig, 2011, UNDP, 2009). It is also known that the southern and northern islands have higher oceanward ridges compared to central islands (UNDP, 2009). The islands of North Ari Atoll fall to the latter category.

As explained in Chapter 3, another response from the island against changes in hydrodynamic condition is to shift its position on the reef to the areas where wave and current energy is least intense. These changes are highly likely with increasing sea level.

Smaller islands are more mobile and physically most at risk from sea level rise (Shaig, 2009). Moreover, smaller islands with developments closer to shoreline are likely to experience more challenges (Shaig, 2006b). Most of the islands North Ari Atoll fall into the latter category. Almost all resort islands, except Kuramathi are small, located within atoll lagoon, have a circular shapes and have 90% of their infrastructure within 100 m of the shoreline. Among inhabited islands, Rasdhoo, Bodufolhudhoo, Ukulhas and Mathiveri are most at risk due to the small islands and proximity of structures to shoreline. The islands most resilient are expected to be Thoddoo, Feridhoo and Maalhos, which are already adapted to stronger wave conditions and have a larger land area to accommodate natural shoreline adjustments.



(Source: Hay, 2006)

Figure 5.5 Daily mean values of sea level for Hulhulé (1989 to 2005), relative to mean sea level. Also shown is the linear trend in sea level over the same period

6. RESILIENCE-BASED COASTAL MANAGEMENT

This report has briefly examined the underlying natural conditions on the islands of North Ari Atoll that make it resilient or vulnerable and how man-made changes may alter these conditions. The existing knowledge on coastal processes, island dynamics and links to the underlying coral reef allows us to form a conceptual understanding of how they interact to make the island and its coastal environment naturally resilient. It also allows us to understand the potential consequences of coastal modifications and how it may alter the prevailing conditions.

This section attempts to simplify this understanding using a conceptual model. The focus here is to identify processes that may make an island resilient or vulnerable, particularly in relation to its underlying reef. Based on the model, a set of guiding principles is suggested for resilience based management. Specific suggestions have also been provided for coastal development activities in the atoll.

6.1 A model for island dynamics, reef growth and reef resilience

Coral islands in Maldives are unconsolidated sediments placed on the reef flat by hydrodynamic and biological processes. The island may be resting at specific position on the reef in a balance between climate, hydrodynamic and biological processes of the coral reef. Changes to these processes are known to result in the island responding by modifying beach characteristics and in some cases by shifting the island.

As explored in this report, island shoreline dynamics is the result of complex interactions between a number of these natural processes. These include the long term climate, monsoonal variations, hydrodynamics, reef and island morphology, and coral reef biological and physical processes. In islands inhabited or influenced by man, human activities add a new dimension, which may alter the natural processes further. The links between coral reef and the island shoreline is also a process that involves constant feedback between the natural forces and human activities.

There are three major natural components influencing shoreline dynamics: (i) climate and hydrodynamics; (ii) morphology and (iii); coral reef processes. Figure 6.1 presents a conceptual model for island shoreline dynamics and how it interacts with these processes.

Reef and Island morphology

The foundation of any existing island could be described as its underlying reef morphology. During the Halocene reef growth, the present reefs would have arrived at a specific morphology influenced by hydrodynamics and biological processes (Kench et al., 2009a). Morphological features of the reef include the shape, size, orientation, depth or elevation and location within the atoll. These features will in turn remain linked to the climate and hydrodynamic conditions (Gischler et al., 2014). For example, reefs receiving strong waves and on the atoll rim have shallow well-developed coral rubble zones on the ocean side reef flat and the reef flat tend to be generally shallower.

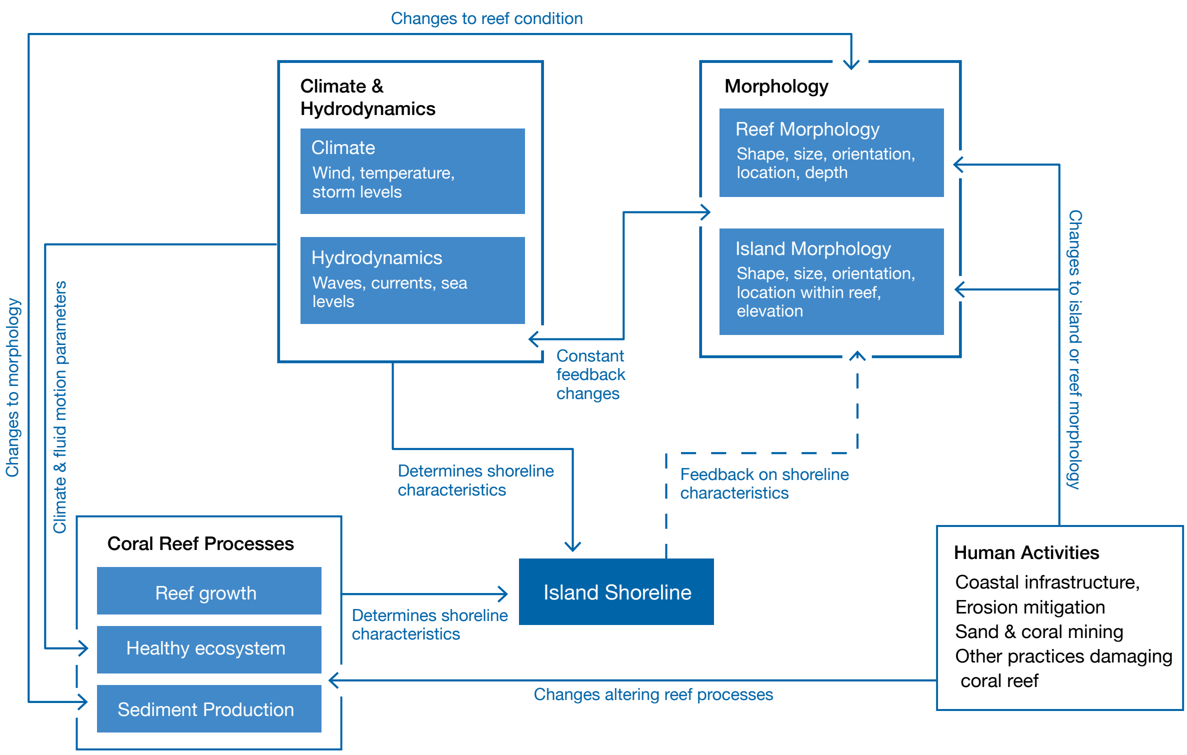


Figure 7.1 A conceptual model of relationship between natural processes, human intervention, coral reef and island shoreline

Similarly, east-west oriented reefs on the atoll rim experience stronger wave activity on a larger proportion of the reef perimeter compared to north-south oriented reefs.

Once the reef is established, the island formation is known to be strongly influenced by the reef morphology (Ali, 2000). Often the island takes the shape of the reef, influenced largely by the hydrodynamic patterns in and around the reef (Mandlier and Kench, 2012). Examples of this link could be observed in Feridhoo, Maalhos, Ellaidhoo, Ukulhas and Rasdhoo Island. Once the island is established the link is maintained. Changes to the morphology of reef, particularly depth (in the short- to medium-term) and reef shape (in the long-term) may result in an equivalent natural response in island morphology. For example, growth of large coral reef colonies in the shallow waters of reef flat is known to stabilize beach areas behind them, facilitating accretion of shoreline causing potential medium term shifts in the island. This pattern has been observed in islands in Noonu Atoll and Raa Atoll (for example N. Raafushi and R. Kothaifaru). Similarly, natural deepening of the lagoon either through death of coral colonies or due to increase in water level can lead to a response from shoreline (see the explanation later under climate and hydrodynamics).

Climate and Hydrodynamics

The island morphology is also inherently linked to climate and hydrodynamics around the reef. Climatic conditions such as wind, temperature, tide and storm events coupled with existing reef morphology determines the hydrodynamic conditions around and on a reef system. Hydrodynamic conditions such as waves, currents and water level are driven by the climate features, primarily wind and tides. Hydrodynamics in return affects the island morphology (Mandlier and Kench, 2012, Kench et al., 2009b). In the central Maldives, the stronger the waves, the less likely that natural islands occur close to the reef edge (Shaig, 2009). In places where they do occur (for example, Maalhos and Feridhoo) the shoreline has specific characteristics such as a high beach berm, extensive beach rock outcrops and coral boulder or rubble beaches. Usually these types of islands occur on the northern and southern parts of Maldives where wave or storm conditions are stronger (UNDP, 2009). The atoll rim islands also do have more resilient shorelines against strong waves on its ocean side due to their constant exposures to stronger wave conditions (UNDP, 2009). Islands within the atoll, which are less exposed to stronger waves, have more volatile beaches against any strong wave activity, particularly abnormal storm events.

There is constant feedback between climate, hydrodynamics, and morphology. Changes to hydrodynamics, monsoonal patterns, temperature or increase in storms may result in changes to the island and reef morphology. Reef morphology generally requires a longer period to change (Gischler et al., 2014). Occasionally, storm events can change sections of reef morphology as observed in coral rubble zones formed on the eastern reefs of Ari Atoll. A change in reef morphology provides feedback to the hydrodynamic patterns (such as waves and currents) which in turn will adjust to the changes.

The beach morphology is to a large extent determined by climate and hydrodynamics (Ali, 2000). Beach morphological factors such as beach elevation or profile, and sediment size are determined largely by the prevailing wave conditions (Stoddart and Steers, 1973). Changes to reef morphology are provided as feedback to the island morphology.

Coral Reef Processes

Coral reef processes is the third major component affecting the island shoreline. Coral reef processes include both biological and physical processes. The biological process involves the reef growth and maintenance of the coral reef ecosystem. The reef growth process has been largely responsible for the modern day islands in Maldives by keeping pace with rising sea level during the Halocene period (Kench et al., 2009a). A healthy ecosystem helps to keep the outer reefs healthy and thereby having a positive effect on the hydrodynamics and island morphology (Gischler, 2006). Changes to live coral cover especially on the reef rim and within shallow lagoon may increase the water depth and have negative effects on the reef morphology and subsequently on the island morphology. Coral cover and fish life may also assist in the production of sand through physical processes (Bellwood, 1996).

Physical processes on the reef are partly responsible for the production of sand (Stoddart and Steers, 1973, Woodroffe, 1993). Sediment input from the reef may be crucial to maintain a net positive balance in the sediment budget around the island in the medium- to long-term. Sediment production may also be responsible for having positive effects on hydrodynamics by filling the deep lagoons in the long-term (Schlager and Purkis, 2013). The shallower the reef, the more energy it is likely to dissipated before they reach the shoreline. Physical processes are dependent on the health of the reef and the ecosystem. A dead reef may continue to produce sand but there may eventually be a point where no new sediment could be produced. A healthy ecosystem and fish community also helps to maintain the fish population necessary to break coral pieces and produce sand (for example parrotfishes).

There is constant feedback between the coral reef processes and the reef and island morphology and occurs over a longer period. Changes to coral cover may alter the reef depth while changes to reef morphology could also affect coral cover.

The physical and biological processes on the reef also partly determine the shoreline characteristics (Stoddart and Steers, 1973). The type of corals, algae, foraminifera, for example, determines the composition of sand on the beach. The production of sediment though mechanical or from fish feeding determines if the island receives enough sand to maintain a positive balance in the sediment budget, particularly in shorelines experiencing sediment loss to deeper waters. It is known that the reefs are not as productive as they were 5000 years ago, when the sea level stabilized (Montaggioni and Braithwaite, 2009, Gischler, 2006). However, they may still play a role in the long-term maintenance of island morphology and shoreline.

Human Activities

Human activities form a new dimension for island beach dynamics. Modifications to the reef and shoreline can have both short- and long-term effects on island stability. Direct modification of the shoreline through construction of coastal structures can alter the island morphology (Kench et al., 2003). These include the construction of harbour breakwaters, seawalls, shore protection measures and other erosion mitigation activities (Kench, 2010). Direct modification of the reef or lagoon due to construction of access infrastructure such as as reef entrances, harbour basins or other dredged areas is an alternation to the reef morphology. These changes will be provided as feedback to the hydrodynamic characteristics (waves, currents and water level). Activities such as dredging and breakwaters often have immediate effects on hydrodynamics. As described above, due to the feedback between morphology, hydrodynamics and island shoreline, these changes will trigger a response from the island coastal system. In the short-term these changes could be visible as erosion and accretion. In the long-term, depending on the scale of changes, these man-made alterations could result in a shoreline or island shift, which is often associated with large scale erosion at a certain section of the island.

Other practices which exploit the reef resources such as sand mining, coral mining, reef fishing and waste dumping on the beach degrade the coral reef quality in the medium- to long-term. Coral mining may increase the water depth, reduce the biological diversity of a reef (Brown and Dunne, 1988) and reduce its sediment production capacity. Similarly, sand mining from within the lagoon may change the lagoon depths depending on the scale of mining activities. Waste dumping on the beach results in waste to be transported on to the reef, suffocating or killing them. Plastics are known as a significant risk in this regard. Cumulative effects of these practices may lead to long-term degradation of the reef and subsequent adjustment to coral reef processes and morphology. Thus, the feedback between coral reef processes, morphology and hydrodynamics results in the island shoreline responding to these changes.

6.1.1 Opportunities and Challenges

The above discussed model helps to provide an understanding of the opportunities and challenges in managing the coastal environments of coral islands in North Ari Atoll and in general to the Maldives. The key challenges could be summarized as follows:

a. The interactions between morphology, climate, hydrodynamics and coastal processes coupled with the unconsolidated nature of the coral islands means that natural changes can affect the erosion risks faced by the island at any given time. If these changes involve a higher magnitude of natural change, the subsequent erosion on the island may be substantial and will require shore protection.

b. These interactions can be altered significantly due to man-made coastal development activities. These changes can be abrupt or may occur over long-term based on the scale of changes. If developments are undertaken without taking the prevailing natural balance into account, the subsequent impacts on the island coastal environment may be significant.

c. Some of the man-made changes may not result in immediate impacts. Instead, it may take a longer period for the effects to become apparent. Effects can also be cumulative from a number of man-made alterations. Identifying exactly the cause of coastal issues at a given point in time may be difficult for these long-term changes.

d. The anticipated sea-level rise will be a substantial change to the boundary conditions on any reef. An increase in water level can trigger changes to hydrodynamics and, in the short-term, island morphology. Island beaches are likely to retreat and elevate, while substantial sections of the beach may migrate to less exposed areas. On inhabited and resort islands, these movements can damage property and livelihood.

e. The anticipated climate change, particularly global warming and increase in sea surface temperatures can reduce the efficiency of coral reef processes. Increase temperature and ocean acidity could reduce the productive capacity of coral reefs. Subsequently, changes in coral reef process could trigger a change in reef and island morphology, and hydrodynamics.

The geophysical and biological processes also provide opportunities for coastal management.

a. The model provides a basis to plan for natural resilience in coral islands. An understanding of how the unique natural processes operate on an island provides guidance on how coastal modifications should be approached. Structures that may alter the status quo in natural processes could be assessed to determine the scale of changes and subsequent effects.

b. The links between the long-term coral reef processes such as coral reef health, sand production and island's coastal stability are not immediately visible and are hard to quantify. However, given the present knowledge, planning for long-term coastal resilience on coral islands will require starting with making the surrounding reef resilient. As described in the above model, coral reef processes play a vital role in morphology and hydrodynamics and is directly related to long-term shoreline characteristics and stability.

c. Erosion mitigation could target the nature of erosional problem facing the island. Seasonal or medium-term erosional pressures could be targeted with soft engineering options while long-term island shifts could be addressed with hard engineering options.

6.2 Guiding Principles for resilience based management

As noted in Chapter 5, almost all islands in North Ari Atoll have undergone some form of coastal modification either as island access infrastructure or as erosion mitigation measures. All inhabited islands, except Himandhoo have a harbor, which includes a standard suite of infrastructure such as a harbor basin, seawalls, reef entrance and breakwater. Himandhoo is planning to construct a harbour in 2015 or 2016. Hence, recommendations for harbor infrastructure for inhabited islands may be of little practical use. Nonetheless, the present coastal environment conditions on the islands on North Ari Atoll provide lessons for undertaking coastal modification projects in similar settings across Maldives and in the remaining islands.

Almost all the resort islands in the atoll have undertaken erosion mitigation measures. Some of these measures have been forced on them due to natural changes while most of the measures appear to be the result of human practices. The current measures also provide lessons for undertaking erosion mitigation in other islands.

This section provides a set of guiding principles for future coastal developments in North Ari Atoll, with a focus on maintain or enhancing natural resilience, particularly to the predicted sea level rise.

The following factors form the basis of guiding principles:

a. Coral island coastal environments are highly volatile and remain in a balance between a number of physical and biological forces. Any man-made changes to prevailing conditions are likely to result in a response from the natural system, and may manifest itself as unintended erosion.

b. Conditions vary between islands and different types of islands. Alterations to the process should consider that what worked in one type may not work in the other.

" There is constant feedback between the coral reef processes and the reef and island morphology and occurs over a longer period. Changes to coral cover may alter the reef depth while changes to reef morphology could also affect coral cover. "

c. The underlying coral reef both in its physical and biological form plays a key role in the long-term resilience of island morphology. Any activity or practice that could be detrimental to the long-term health of reef ecosystem or the reef morphology may reduce the ability of the island to be resilient.

d. Larger corals islands are morphologically resilient in the long-term. The resilience may require substantial changes to the coastline over the long-term. The more humans encroach the volatile areas, the higher the likelihood impacts on property and livelihood.

Based on the above, the following guiding principles are recommended:

a. All coastal infrastructure should first consider the scale of disruption to coastal processes. If the scale of change is substantial and is likely to lead to major changes to the shoreline, it should consider alternative designs that could minimize the change or avoid construction. The following changes are considered the most significant:
   ii. Changes that interfere with sediment transport along the beach
   iii. Changes that alter nearshore currents

b. Structures should be designed specifically for the island after taking the prevailing physical processes around the island into account. Structures that may hinder the natural dynamics of the island should be redesigned or avoided.

c. Erosion mitigation measures should consider a management plan for the entire beach before designing structures. Piece-meal solutions for dealing with erosion hotspots may result in the problem moving elsewhere, unless the solutions anticipate the overall changes.

d. Islands are morphologically resilient and they display certain morphological characteristics which are representative of the prevailing conditions. When considering local artificial structures, these characteristics should be taken as a guide during design. For example, the beach on the ocean ward side is generally steeper, higher and contains coarse material. Activities such as reclamation should consider these features if no shore protection is proposed or even if structures are considered.

e. Shore perpendicular structures that alter the sediment transport process should be avoided where possible. Temporary activities such as shore perpendicular sand bunds should also be placed for the shortest duration possible.

f. Soft engineering should be considered as the first option for erosion mitigation. Soft engineering options include land use set back, coastal vegetation retention and beach replenishment. Erosion mitigation measures should be considered before it becomes a serious issue. This will provide time to consider soft adaptation measures.

g. Avoid erosion mitigation needs in resorts where practical. When planning resort islands, long term beach movement should be considered before placing facilities close to the beach line. Placing facility in an erosion prone zone would otherwise force the developer to undertake mitigation measures in the near future.

h. Coral reef resilience should be considered as a primary line of defense for island stability. Activities that damage coral reef ecosystem should be avoided or mitigated as much as possible. This includes all coastal construction activities, particularly those involving dredging activities such as land reclamation, harbor and reef entrance dredging, and beach replenishment. Suspended sediment containment during dredging should be made compulsory when working within 1 km of live coral zones.

In addition to the above guidelines, more specific design guidelines could be referred in Manual on Climate Risk Resilient Coastal Protection (Ministry of Environment and Energy, 2013).

6.3 Recommendations for local infrastructure

This section provides recommendations for access infrastructure and erosion mitigation measures based on the findings from the experiences of North Ari Atoll islands. The recommendations are based on how the changes have fared in relation to the conceptual model described in the previous section and the guiding principles above.

6.3.1 Recommendations for Harbour infrastructure

a. It is common practice to use the same design template for harbor infrastructure in all islands of Maldives. This practice stems from the designs prepared by Ministry of Housing and Infrastructure and insistence of the local community to establish a design that is tried and tested. Unfortunately a standard design can never be applicable to the multiple types of islands that exist in the Maldives. The communities should insist on developing a design that is most suitable for the conditions on the island with long-term coastal resilience in mind.

b. The east-west oriented islands on the western and eastern rim require a detached harbour rather than the standard design of attaching the quay wall to the island shoreline. A detached harbour has its basin located away from the shoreline and closer to the reef edge. The basin can be connected to the island using a piled jetty. This allows the sediment to flow along the beach, which is crucial for these types of islands. The present erosional pressures on either side of the harbor on Maalhos, Feridhoo and Ellaidhoo could have been avoided with this design.

c. Islands in the atoll lagoon, particularly with a circular shape, also involve substantial sand movement around the island. Such islands also require a detached harbor.

d. The designs should not only consider the present conditions on the reef and the shoreline but the long-term trends as well. Developing harbour infrastructure in a way that alters the prevailing processes reduces the ability of the islands to adapt to natural changes as described in the model above. These islands will eventually require human intervention to respond every major natural change. Such islands could be described as highly vulnerable to the effects of climate change, particularly the effects of sea level rise.

e. Coastal infrastructure development projects appear to be responsible for altering the coral reef environment at least in the short- to medium-term. Dredging projects, particularly with the current practice of not using a sediment containment measures, are known to have severely damaged coral reefs in the vicinity of the dredging and reclamation projects. As described in the conceptual model, a change in the coral reef processes and ability of the coral reef ecology to function properly will have consequences for the long-term shoreline stability and resilience.

6.3.2 Recommendations for erosion mitigation infrastructure

a. Extensive use of shore protection measures were observed in the resort islands of North Ari Atoll. Based on long-term shoreline change assessments, it was apparent that most of these measures weren't deployed for major shifts in the island shoreline but rather to periodic erosion and seasonal changes. The need for such structures primarily arose due to the proximity of the facilities developed on the island to the shoreline line and the small size of the islands. In principle, beach villas of resorts are meant to be located close to the beach line. However, simply placing the rooms close to the shoreline based on the shoreline at the time of planning was main cause for treating seasonal or periodic erosion as severe erosion. Thus, areas that are prone to long-term shifts and periodic erosion should be identified during planning and adequate setbacks or preemptive beach restoration measures need to be undertaken in such areas.

b. Occasionally, the protection measures did not match the processes existing around the island. This has resulted in 'patch-work' structures where subsequent structures were placed to compensate for the errors from the initial structure. The extensive use of groynes in some resort islands, particularly circular and elongated islands, bears evidence of this practice. It is recommended that structures be deployed in small islands after a comprehensive assessment of the processes operating around the island.

c. The growth of shallow water reef colonies, particularly Acropora colonies, is known to provide stability to beach areas. This is due to the effects of wave energy reduction as the waves propagate over it. It is possible to replicate this process artificially by planting Acropora colonies on the reef flat. However, this practice will need to be studied further to establish the right depth, water conditions and wave conditions to deploy them.

7. CONCLUSION

This study has examined the coastal vulnerabilities and management challenges in the islands of North Ari Atoll and presented a conceptual model for understanding the interactions between the natural processes and human intervention. Based on these findings, it has contributed to enhance the coastal management component of the Resilience-Based Management Framework (RBM) and provided decision support guidance on coastal management.

Coastal management is a crucial component of any coral reef management programmes as it is usually the most visible and concerning issue related to marine environment for the general public. Quite often coral reef and coastal erosion issues are treated separately leading the public to understand them as two unrelated matters. In reality, as explored in this report, the underling reef, both in its physical and biological form, is largely responsible for the physiographic and morphological features of an island. In the long-term, the morphological and biological characteristics may well determine the natural resilience of coral islands.

Coral islands have a highly active and sensitive coastal environment. It sits in a balance between climate, hydrodynamic and biological processes of the coral reef. Changes to parameters within these processes may lead to equivalent responses in the island morphology and beach position. We may see these changes as coastal erosion. Most changes occurring on islands of North Ari Atoll are natural. However, human activities have helped to exacerbate the problems by speeding up the changes or by introducing new changes.

All inhabited islands, except Himandhoo Island, have major coastal infrastructure. These have not been designed with long-term natural resilience in mind. Many resorts have numerous erosion mitigation measures developed on them. Some of them appear to be piece-meal implementations rather than based on an overall erosion management plan. While harbor infrastructure on inhabited islands are immovable, erosion mitigation measures could still be corrected. New erosion mitigation measures will still be required.

This report provides a framework for understanding coastal process interactions and decision-making guidance for future resilience based coastal management. Hopefully, this document will contribute to a better understanding of the coastal processes and better coastal management practices in North Ari Atoll.

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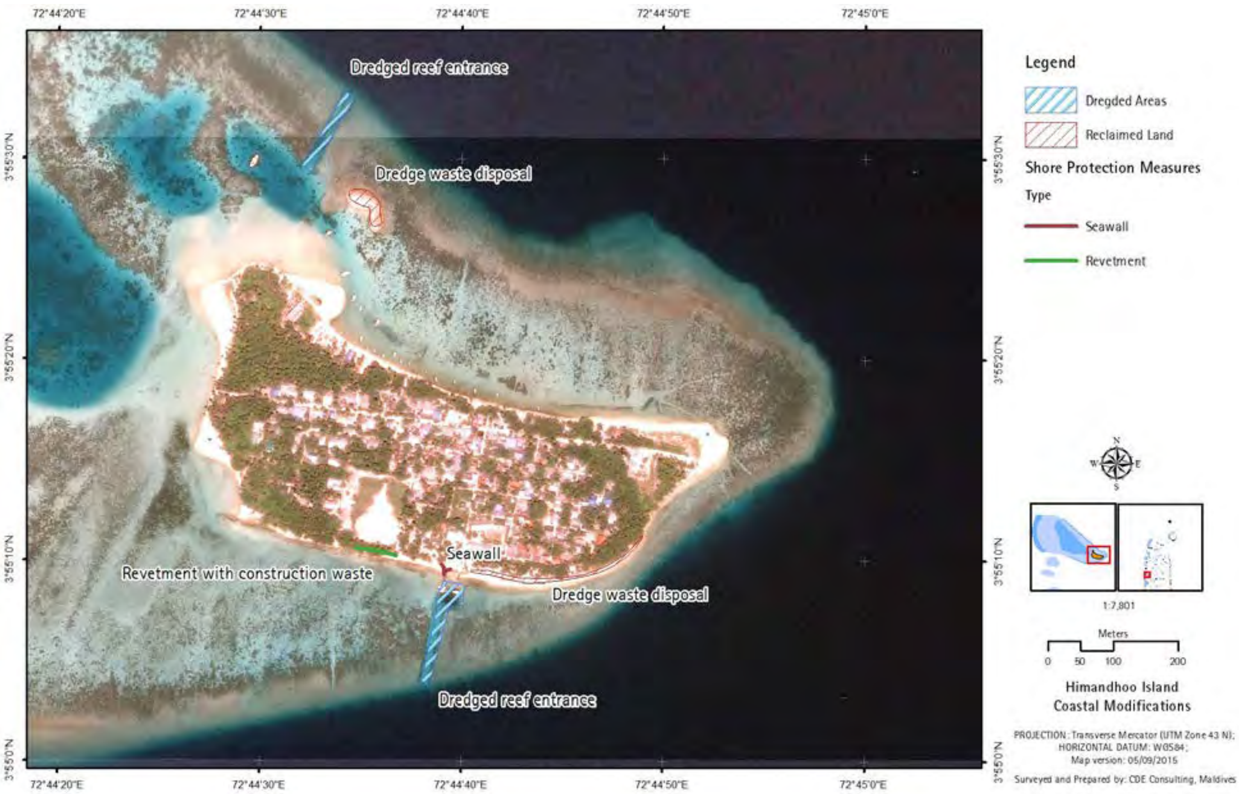
APPENDIX A: COASTAL MODIFICATIONS MAP OF INHABITED ISLANDS

Revetment with construction debris
Rock boulder revetment
Seawall
Old revetment now dmaged
Harbour Breakwater
Harbour
Dredged reef entrance
Rock boulder revetment
Coral boulders
Legend
Dregded Areas
Reclaimed Land
Shore Protection Measures
Type
Quaywall
Breakwater
Groyne
Seawall
Revetment
1:8,875
Meters
0 50 100 200
Ukulhas Island
Coastal Modifications
PROJECTION: Transverse Mercator (UTM Zone 43 N);
HORIZONTAL DATUM: WGS84;
Map version: 06/09/2015
Surveyed and Prepared by: CDE Consulting, Maldives

Revetment with construction debris
Dredged area
Harbour Breakwater
Harbour
Dredged reef entrance
Seawall/groyne to block sand movement
Seawall
breakwater constructed over beach rock; now damaged
Legend
Dregded Areas
Reclaimed Land
Shore Protection Measures
Type
Quaywall
Breakwater
Seawall
Revetment
Beach Rock
1:7,690
Meters
0 50 100 200
Feridhoo Island Medium-term
Coastal Modifications
PROJECTION: Transverse Mercator (UTM Zone 43 N);
HORIZONTAL DATUM: WGS84;
All features based on GPS surveys (Mar 2014)
Map version: 06/09/2015
Surveyed and Prepared by: CDE Consulting, Maldives

72°42'50"E
72°43'0"E
72°43'10"E
72°43'20"E
3°59'20"N
3°59'10"N
3°59'0"N
Dredged reef entrance
Harbour Breakwater
Revetment with construction debris
Harbour
Seawall
Legend
Dregded Areas
Reclaimed Land
Shore Protection Measures
Type
Quaywall
Breakwater
Groyne
Seawall
Revetment
1:7,239
Meters
0 50 100 200
Maalhos Island
Coastal Modifications
PROJECTION: Transverse Mercator (UTM Zone 43 N);
HORIZONTAL DATUM: WGS84;
Map version: 05-Sep-15
Surveyed and Prepared by: CDE Consulting, Maldives



72°44'20"E
72°44'30"E
72°44'40"E
72°44'50"E
72°45'0"E
3°55'30"N
3°55'20"N
3°55'10"N
3°55'0"N
Dredged reef entrance
Dredge waste disposal
Seawall
Revetment with construction waste
Dredge waste disposal
Dredged reef entrance
Legend
Dregded Areas
Reclaimed Land
Shore Protection Measures
Type
Seawall
Revetment
1:7,801
Meters
0 50 100 200
Himandhoo Island
Coastal Modifications
PROJECTION: Transverse Mercator (UTM Zone 43 N);
HORIZONTAL DATUM: WGS84;
Map version: 05/09/2015
Surveyed and Prepared by: CDE Consulting, Maldives

APPENDIX B: DATA CD

This report is accompanied by a data CD. It contains the following:

1. ArcGIS database of coastal protection measures inventory of North Ari Atoll
2. ArcGIS database of shoreline data
3. Survey forms used in the assessment

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