

Coastal Monitoring, Reef Island Shoreline Dynamics and Management Implications

Final Report

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CONTENTS

	Page
1. INTRODUCTION	2
2. METHOD	3
3. SUMMARY OF BASELINE COASTAL MONITORING	3
3.1 Data Capture	5
3.2 Data Reduction	5
4. REVIEW OF COASTAL STRUCTURES	6
4.1 Types of Coastal Structures	6
4.2 Design and Construction of Coastal Structures	15
4.3 Environmental Effects of Coastal Structures	22
4.4 Coastal Process Characteristics of Maldivian Reef Islands	24
4.5 Interaction Between Coastal Processes and Structures on Maldivian Reef Islands	32
5. DECISION SUPPORT FOR COASTAL MANAGEMENT	41
5.1 Guiding Principles	42
5.2 Major Infrastructure Development at the Coast	43
5.3 Managing Erosion	47
6. REFERENCES	54

1. INTRODUCTION

This project is funded by the Maldives Environmental Management Project (IDA Credit 4427-MV) to improve the information basis for coastal erosion management in the Maldives. Coastal erosion is prevalent on many islands in the Maldives and local communities have been coping with unstable island shorelines throughout the history of their occupation. Recent extreme events (the 2004 tsunami and swell event in 2007) are believed to have exacerbated erosion on many islands and future sea level rise is thought to further accelerate shoreline instability. As a consequence coastal erosion has been identified as a major environmental problem by local communities and the government.

This project will strengthen the approach to managing shoreline erosion and flooding in the Maldives. Specific objectives of the project are to:

- Investigate the capacity of natural and engineered structures to defend against coastal erosion/storm surges.
- Develop appropriate ‘soft engineering’ (and/or other design alternatives) for typical coastal development and coastal defence works.

Underpinning these objectives is a synthesis of information on the oceanographic processes governing island shoreline change and evidence of island change at short to medium timescales (the timescales over which erosion management are most relevant). Information on these processes is scarce and elements of the work programme are aimed specifically at synthesizing and generating new data on island shoreline dynamics to support informed decision making.

This interim report has a number of objectives:

1. To summarise the outcomes of initial field surveys.
2. To review the designs of typical shoreline structures adopted in the Maldives.
3. To examine the environmental impact on coastal processes and shoreline stability of coastal structures adopted in the Maldives.
4. Examine alternative approaches to shoreline management in the Maldives.

2. METHOD

The methodology used to address the objectives of the Interim Report involved a mix of field data collection and review of existing technical information. The summary of initial surveys is based on coastal monitoring data collected in the field in conjunction with the EPA coastal monitoring group. The review of existing coastal structures adopted in the Maldives was undertaken through analysis of technical information collated by Mr Shaig under his contract to the project.

Assessment of the impacts of structures on coastal processes was achieved through a review and analysis of the dynamics and process regime of island shorelines and their interaction with shoreline structures. Lastly, proposed alternatives are discussed in light of ways to avoid impacts of structures on coastal processes and erosion.

3. SUMMARY OF BASELINE COASTAL MONITORING SURVEYS

A major element of this project is to monitor island shoreline dynamics to assist in the support of coastal management decision making. In the context of the Maldives, shorelines are known to change between seasons driven by oscillations in monsoonal wind and wave conditions (Kench and Brander, 2006; Kench, 2009). Consequently, it is important to document the position and change in morphology of island shorelines at the end of each season (October and February).

As identified in the inception report (Kench, 2009) there has been little coastal monitoring undertaken in the Maldives to examine island change at short to medium timescales. Therefore, a major component of the inception mission was to design and implement an expanded coastal monitoring programme of reef islands in the atolls of Noonu, Raa, Baa and Lhaviyani. The monitoring programme and selection of islands was guided by the following design criteria:

- The position of islands in the atoll and their exposure to wind and waves. In most atolls, islands are found on all sides of the atoll and on reef platforms located in the atoll lagoon. Existing evidence suggests that island shoreline change varies in response to differences in relative location in an atoll. For this project islands were selected along a west to east energy gradient across the atoll and included lagoonal reef islands where they existed.
- The shape of islands, which influences wave refraction and diffraction patterns that control shoreline change. In this study the range of islands selected encompasses a large range of island shapes.
- Whether islands are inhabited or uninhabited. The aim of this project is to support management of shorelines on inhabited islands. However, understanding of shoreline dynamics is best captured on uninhabited islands, where shorelines are unaffected by anthropogenic effects. This project selected a mix of inhabited and uninhabited islands for comparative analysis.

Based on these factors Table 3.1 contains the complete list of islands selected for analysis as part of extended coastal monitoring. Of note, the number of islands selected is considerably greater than

the 16 identified in the briefing document. This increase in number of monitored islands reflects the need to increase the diversity of islands examined and generate a larger dataset for comparative analysis of island dynamics. Furthermore, the islands of Baa atoll that have previously been monitored were included in the monitoring network.

Table 3.1 Complete list of islands included in coastal monitoring surveys in atolls of Noonu, Raa, Baa and Lhaviyani, Northern Province, October 2009.

Atoll	Island	Location	Inhabited/ Uninhabited	Start Date	Custodian	Survey No.	Survey Type	
							Profiles	GPS
Noonu								
	Holhudhoo	SW - internal	I	Oct 2009	EPA	1	Y	Y
	Manadhoo	E – peripheral	I	Oct 2009	EPA	1	Y	Y
	Maalhendhoo	E – peripheral	I	Oct 2009	EPA	1	Y	Y
	Kuramaadhoo	W – peripheral	U	Oct 2009	EPA	1	Y	Y
	Dhigurah	SE – internal	U	Oct 2009	EPA	1	Y	Y
	Iguraidhoo	S central	U	Oct 2009	EPA	1	Y	Y
	Maafunafaru	Central	U	Oct 2009	EPA	1	Y	Y
	Burehifasdhoo	NE - peripheral	U	Oct 2009	EPA	1	Y	Y
	Fushivelavaru	W – internal	U	Oct 2009	EPA	1	Y	Y
Raa								
	Alifushi	peripheral	I	Oct 2009	EPA	1	Y	Y
	Hulhudhuffaaruu	E - peripheral	I	Oct 2009	EPA	1	Y	Y
	Meedhoo	S – central	I	Oct 2009	EPA	1	Y	Y
	Maashigiri	W - peripheral	U	Oct 2009	EPA	1	Y	Y
	Fasmendhoo	SW - internal	U	Oct 2009	EPA	1	Y	Y
	Bodufushi	S – central	U	Oct 2009	EPA	1	Y	Y
	Lun'boakandhoo	N – central	U	Oct 2009	EPA	1	Y	Y
	Vandhoo	E – peripheral	U	Oct 2009	EPA	1	Y	Y
Lhaviyani								
	Naifaru	W – peripheral	I	Oct 2009	EPA	1	Y	Y
	Felivaru	W – peripheral	I	Oct 2009	EPA	1	Y	Y
	Kurendhoo	SW – peripheral	I	Oct 2009	EPA	1	Y	Y
	Huravalhi	NW – peripheral	U	Oct 2009	EPA	1	Y	Y
	Vavvaru	W - peripheral	U	Oct 2009	EPA	1	Y	Y
	Lhossalafushi	SW - peripheral	U	Oct 2009	EPA	1	Y	Y
	Thilamaafushi	SE - peripheral	U	Oct 2009	EPA	1	Y	Y
	Maabinhuraa	E - peripheral	U	Oct 2009	EPA	1	Y	Y
South Maalhosmadulu								
	Eydhafushi	E - peripheral	I	Oct 2009	EPA	6	Y	Y
	Dhonfaru	E - internal	I	Oct 2009	EPA	7	Y	Y
	Dhakandhoo	W – peripheral	U	Jan 2002	EPA/UoA	7	Y	Y
	Keyodhoo	Central	U	Jan 2002	EPA/UoA	7	Y	Y
	Hulhudhoo	Central	U	Jan 2002	EPA/UoA	7	Y	Y
	Madhirivaadhoo	E – peripheral	U	Jan 2002	EPA/UoA	7	Y	Y
	Thiladhoo	E – peripheral	U	Jan 2002	EPA/UoA	7	Y	Y
	Aidhoo	E – peripheral	U	Jun 2002	EPA/UoA	5	Y	Y

3.1 Data Capture

A total of 34 islands were surveyed during a two week field programme from October 12 to 26th, 2009. On each island, the following survey activities were undertaken:

- Insertion of a minimum of 4 benchmarks (cemented pegs).
- Global Positioning System (GPS) measurements of the benchmark positions.
- Topographic surveys of island and beach from each benchmark.
- GPS survey of the toe of beach surrounding the island.
- GPS survey of the edge of vegetation.

3.2 Data Reduction, Analysis and Reporting

Since the inception of this project surveys have been undertaken in October 2009 and February 2010. The analysis and reporting of these surveys is contained in a comprehensive companion report (Kench, 2010).

4. REVIEW OF COASTAL STRUCTURES

The purpose of this review is to examine the type and design of structures or management strategies used on the coastline of Maldivian reef islands. Structures are typically inserted to provide improved infrastructure and transport linkages (e.g. boat harbours and channels) and to mitigate perceived coastal erosion. This review is divided into a number of parts. *First*, the range and purpose of structures inserted at the coast are identified. This section highlights the placement of structures at the coast, their planform configuration and relationship to the shoreline and reef flat. This provides a basis to discuss the impact of structures on reef island coastal processes. *Second*, the designs of coastal structures are examined. However, it should be noted that the designs accessed and provided by Shaig (2009) are limited to those coastal structures designed by the Construction Section of the Ministry of Housing Transport and Environment (MHTE). In general, these designs are limited to structures associated with harbours, which include quay walls, breakwaters and seawalls. These projects also often involve dredging. Importantly few, if any, designs have been viewed of small-scale community interventions at the coast. However, visual observations of some attempts to arrest shoreline erosion were observed in the field. *Third*, the impact of structures on coastal processes are examined. This section focuses on the interaction of structures and coastal modifications with nearshore processes.

4.1 Types of Coastal Structures

Examination of reports collated by Shaig (2009) and field observations indicate that a wide range of management solutions have been adopted on or adjacent to the shorelines of Maldivian reef islands. Almost all inhabited islands in the atolls of Lhaviyani, Noonu, Raa and Baa have undergone significant coastal modifications (as summarised in Table 4.1). Most of the inhabited islands have been inhabited for a considerable time period. There are a number of exceptions. Hulhudhuffaru is a new settlement created in the 1990s. Dhuvaafaru has also only recently been populated following the 2004 tsunami. Most of the resort islands in the study atolls, except Sonevaafushi, have also undertaken major coastal developments albeit at a smaller scale than the inhabited islands. The most significant coastal modifications are the construction of harbours, dredged channels and land reclamation.

4.1.1 Harbours

Many (most) inhabited islands possess artificial harbours that provide safe anchorage and facilities to transfer goods. There is strong demand for harbours from island communities. Figure 4.1 shows a number of recent boat harbour designs produced by the Construction Section (MHTE). Figure 4.2 shows the configuration of boat harbours with respect to the natural island shoreline. It is clear from the examples examined that boat harbours have been sited on all exposures of reef islands. There are some common aspects of these designs which are of relevance to this review:

Table 4.1 Summary of structural modifications to island coastlines and adjacent reefs on inhabited islands of Noonu, Raa, Baa and Lhaviyani, Northern Province.

Island Name	Land Use	Reef entrance	Harbour basin	Quay wall	Harbour breakwater	Jetty (on stilts)	Foreshore protection	Nearshore protection	Over water structures	Land reclamation	Beach replenishment
Manadhoo	Settlement	Y	Y	Y	Y		Y			Y	
Velidhoo	Settlement	Y	Y	Y	Y	Y	Y			Y	
Kendhikolhudhoo	Settlement	Y	Y	Y	Y	Y	Y			Y	
Holhudhoo	Settlement	Y	Y	Y	Y		Y			Y	
Irufushi	Resort	Y				Y	Y	Y	Y		Y
Ungoofaaru	Settlement	Y	Y	Y	Y		Y			Y	
Meedhoo	Settlement	Y	Y	Y	Y		Y			Y	
Vaadhoo	Settlement	Y	Y	Y	Y		Y			Y	
Hulhudhuffaaru	Settlement	Y				Y					
Alifushi	Settlement	Y	Y	Y	Y		Y			Y	
Eydhafushi	Settlement	Y	Y	Y	Y		Y			Y	
Kamadhoo	Settlement	Y	Y	Y	Y		Y			Y	
Kudarikilu	Settlement	Y	Y	Y	Y		Y			Y	
Sonevaafushi	Resort	Y				Y					
Royal Island	Resort	Y	(dredged area)			Y	Y	Y	Y		Y
Hithaadhoo	Settlement	Y	Y	Y	Y		Y			Y	
Naifaru	Settlement	Y	Y	Y	Y		Y			Y	
Hinnavaru	Settlement	Y	Y	Y	Y		Y			Y	
Kurendhoo	Settlement	Y	Y	Y	Y		Y			Y	
Kanuhuraa	Resort	Y	Y	Y	Y	Y	Y		Y		

Source: Shaig, A., 2009. Coastal Erosion Data Synthesis Report.

- Most harbours have been constructed in a way that modifies the planform configuration of the island shoreline. For example, most protrude from the shoreline across the adjacent reef flat by up to 50 m (Fig. 4.1A; Fig. 4.2).
- Land reclamation is common on either side of the harbour basin (Fig. 4.1A, B; Fig. 4.2).
- All have hard shore-parallel structures at the shoreline (quaywall; Fig. 4.1).
- Most have structures that extend perpendicular from the shoreline (Fig. 4.2).
- The majority of harbours have dredged basins in close proximity to the island shoreline.
- Many harbours also have dredged channels that bisect the adjacent reef flat allowing safe passage of boats at all tidal stages.

Until recently boat harbours tended to conform to a single design in terms of the dimensions of the basin and structural design of quaywalls, etc. However, it should also be noted that there has been a more recent shift away from a ‘one-design’ boat harbour to consider alternative options to provide safe anchorage. In part, this reflects growing awareness of the environmental impacts of harbours (discussed in detail in Section 5). More recent designs have been characterised by shoreline detached breakwaters with the aim of allowing currents to flow through the harbour (Fig. 4.1C, D; Fig. 4.3). Of note, the proposed reconstruction of the Kurendhoo harbour (Lhaviyani, Fig. 4.1D) involves removal of the seawall at the southern end of the basin (shown in Fig. 4.2F).

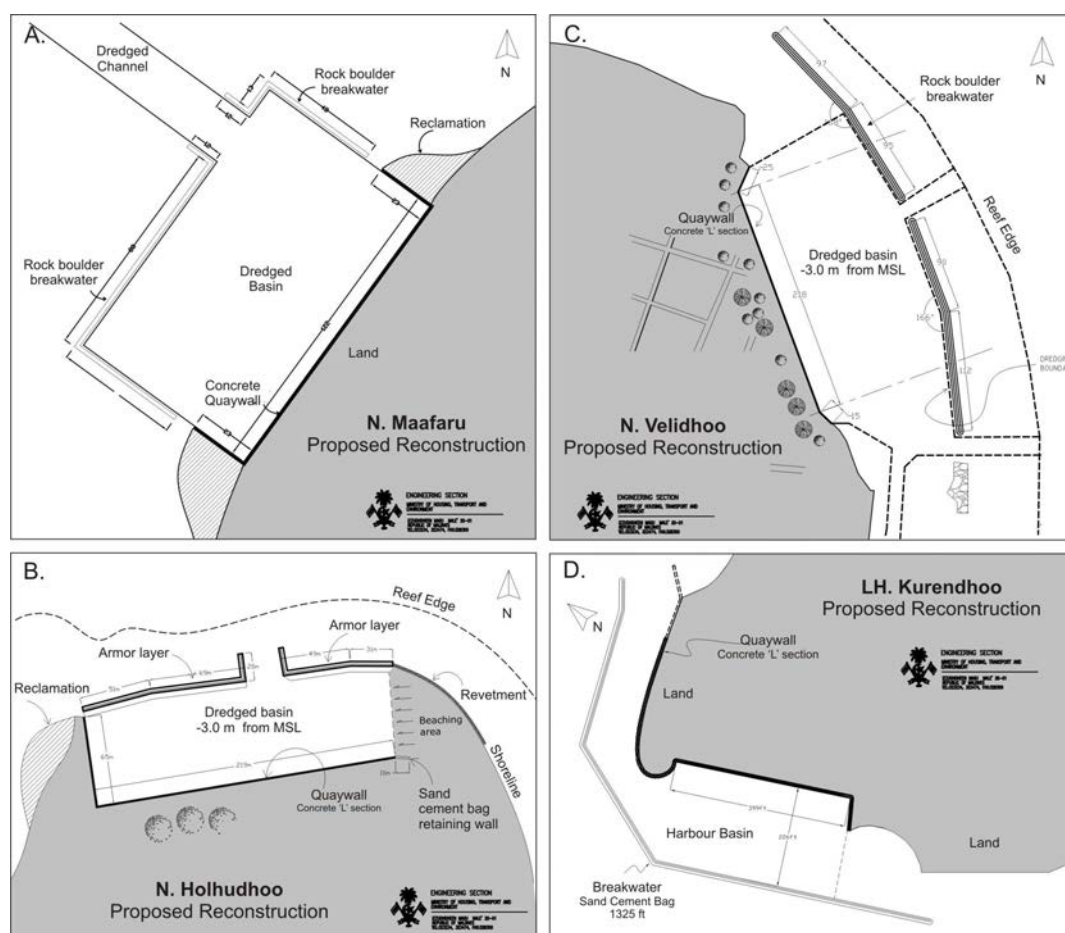


Figure 4.1. Construction plans for boat harbours on four atoll islands in the Maldives. Construction plans obtained from Construction Section MHTE.



Figure 4.2. Aerial photographs of six atoll islands showing the location and configuration of boat harbours. Note physical structures and dredged areas (harbour basins and channels). Source: Google images.



Figure 4.3. Aerial photographs of two atoll islands showing the location and configuration of boat harbours with disconnected breakwaters allowing greater alongshore flow. Source: Google images.

4.1.2 Reclamation

Reclamation has occurred at different scales on many inhabited islands. As noted above, reclamation has commonly been associated with harbour development in order to protect shore perpendicular structures at the ends of the harbour basin (Fig. 4.1A, B), or to reclaim small areas of land adjacent to harbours for boat landing, storage or recreational space (Fig. 4.2A-F). In general, these are small scale reclamations that directly affect small areas of island shorelines and reef.

However, on a number of inhabited islands major reclamations have entirely transformed the footprint of the island. In the study atolls, Hithadhoo (Baa) and Naifaru (Lhaviyani) have undergone significant reclamation. Figure 4.4 shows the changes in planform configuration of Naifaru since 1969. The figure shows significant shoreline modifications between 1969 and 1997 (groynes, small reclamations, seawalls, etc). However, recently large-scale reclamation took place increasing the island area by approximately 200% (Fig. 4.4) and occupying a large proportion of the reef flat surface. Reclamation of islands on vacant reef platforms is also undertaken to form and build new resorts. Large-scale reclamation was also undertaken on the Hulumalé (200 hectares) to create a large island for human occupation as part of the Government planning processes.



Figure 4.4. Changes in planform configuration of Naifaru (Lhaviyani) 1969 to 2009. The 1969 and 2009 shorelines are projected on the 1998 aerial photograph. Note the rapid expansion in island area between 1998 and 2009 as a consequence of dredging and reclamation.

4.1.3 Erosion mitigation strategies

In addition to the structures associated with development and planning initiatives there are a range of other structures inserted at the shoreline that are aimed at mitigating erosion (Figure 4.5). The types of structures, their typical construction and their underlying principles are outlined below.

Seawalls: Seawalls are hard structures that are inserted parallel with the shoreline (Fig. 4.5A, 4.6A-D). A seawall is a self-supporting structure (unlike revetments) and does not rely on land to support the structure. The basic purpose of a seawall is to hold the position of the coastline and prevent further erosion. Seawalls can also be used to offset flooding if built to a suitable elevation to avoid wave overtopping. Seawalls do not protect a beach. The environmental effects of seawalls will be discussed in Section 5.

Revetments: A revetment is also a shore parallel structure (Fig. 4.5B). However, a revetment is not self-supporting. It requires support from the land that it is designed to protect. The purpose of revetments is identical to a seawall and they can cause similar environmental effects.

Groynes: A groyne is a structure anchored at the shoreline that extends across the beach and reef flat perpendicular to the shoreline (Fig. 4.5C, 4.6E). The purpose of a groyne is to interrupt normal longshore current and sediment transport processes in order to preferentially trap and retain sand on the updrift side of the structure. These have typically been constructed to retain beaches on resort islands (Fig. 4.6E), but have also been inserted as a consequence of harbour developments.

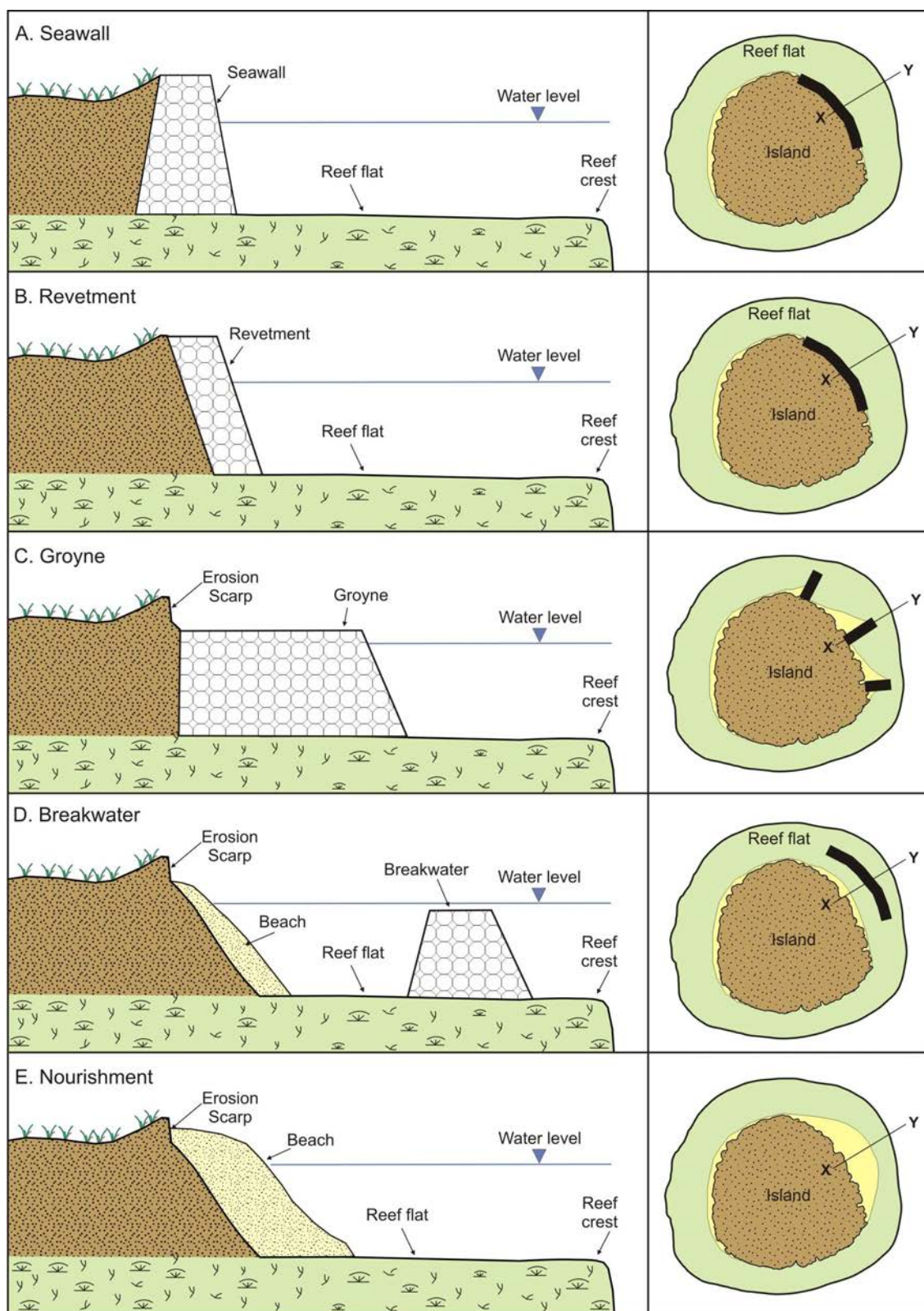


Figure 4.5. Types of erosion mitigation strategies adopted in the Maldives. Each panel indicates the position of each mitigation approach relative to the shoreline. Panels on right show configuration of mitigation strategy in planform.

Breakwaters: Breakwaters are typically shore parallel structures that are detached from the shoreline (Fig. 4.5D, 4.6F, G). In the Maldives they are commonly found on the central reef flat where their elevation can reach above or below mean sea level. The purpose of a breakwater is to break incident wave energy offshore so that the island shoreline is protected from direct wave attack. The aim is to reduce erosion of the island shoreline. Furthermore, breakwaters alter wave refraction and alongshore current processes and can promote the deposition of sediment at the shoreline in the lee of the breakwater (Fig. 4.5D).

Nourishment: Artificial placement of sand and gravel has gained global acceptance in order to replenish (nourish) the volume of sand stored at the coastline. Nourishment does not require hard structures and is widely considered as an environmentally benign strategy as it simply adds more sediment to the shoreline.

A number of resorts adopt beach nourishment in order to provide amenity value for tourists (Fig. 4.5 H). However, the design of nourishment projects is critical to the viability and success of nourishment programmes. Critical design considerations include:

- **Sediment grade and durability:** In general, the grade (size) and durability of sediment placed at the shoreline should be equal to or greater than the native sediment.
- **Nourishment volume:** It is necessary to identify the volume of nourishment required to replenish the beach. This must be based on a sound understanding of the rate of sediment loss from the coast in order to evaluate the life expectancy of the nourished volume. Once the nourishment volume has been established a borrow site must be identified. Commonly lagoon or deeper water supplies of material are targeted for nourishment. However, the grade of deeper water sediment reservoirs is often finer than the host sediment and this is unsuitable. Furthermore, it is important to assess the impacts of dredging of this borrow material.
- **Placement:** Placement of the nourished volume is also of paramount importance with regard to longevity of the replenishment.

It is important to stress that the purpose of nourishment is to restock the amount of sand at the shoreline. Nourishment, like the range of hard structural solutions, does not solve the cause of erosion or island instability.

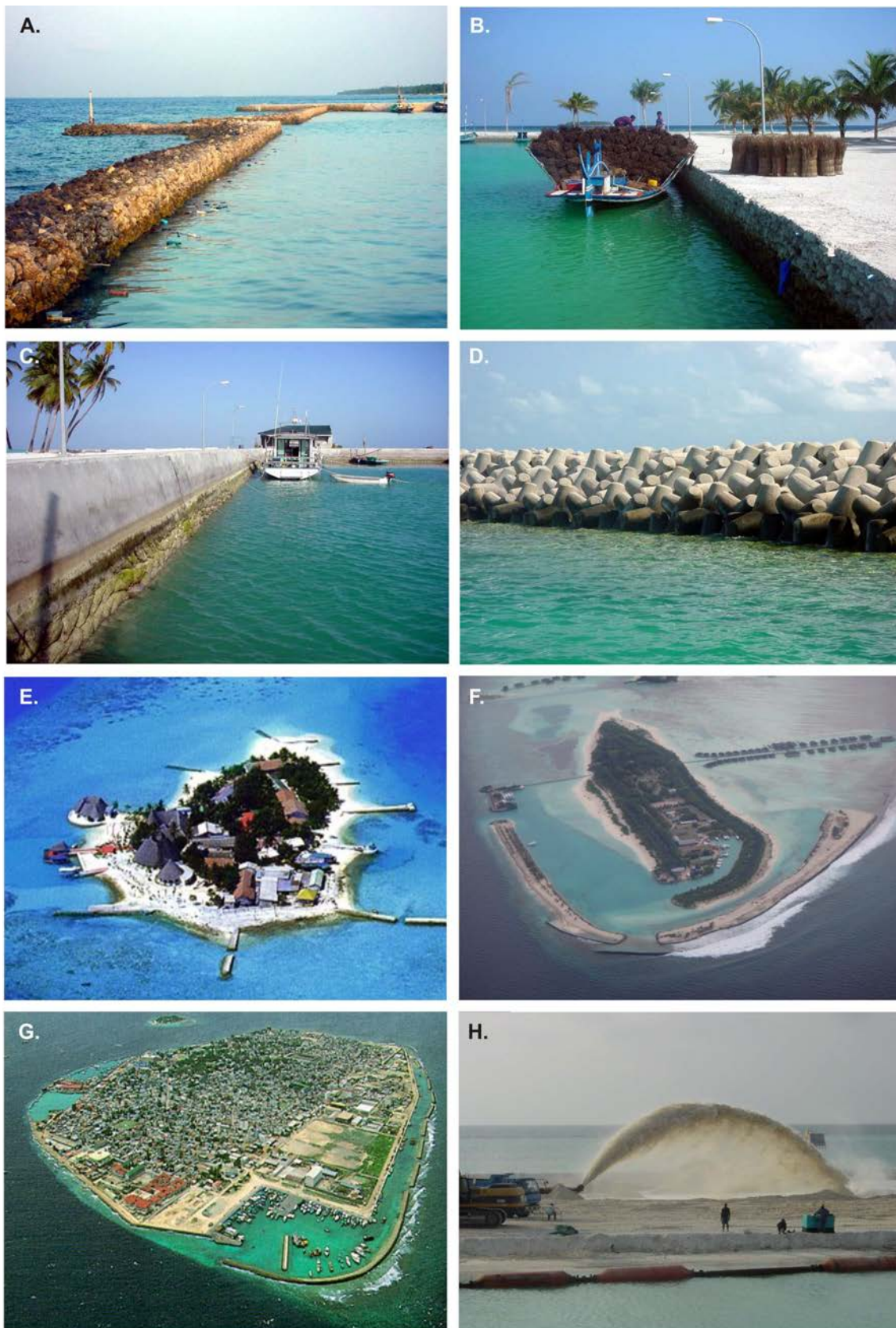


Figure 4.6. Range of structures to mitigate shoreline erosion. A) Coral block seawall used as breakwater for harbour. B) Coral block quay wall in harbour. C) Concrete wall over stacked sandbag seawall. D) Tetrapod seawall. E) Arrangement of groynes on island shoreline. F) and G) Breakwaters on reef edge. H) Sand pumping to reclaim land. A similar technique is adopted to nourish beaches.

4.2 Design and Construction of Coastal Structures

The formal design of coastal engineering structures in the Maldives occurs primarily through the Construction Section of the Ministry of Housing Transport and Environment (MHTE). Such designs are associated with major infrastructure projects such as boat harbours (which involve dredging and construction of seawalls, quaywalls, breakwaters, etc.) and reclamation.

In contrast, the design of structures to combat erosion on outer islands, as part of community concerns regarding shoreline stability, appears to be less formalized. In a review of erosion management processes in the Maldives, Kench (2001) found that few structures followed formal design guidelines. Consequently, the choice of structure, its physical dimensions and construction materials were selected without knowledge of detailed coastal processes and in particular extreme energies at the shoreline. Discussions with Government officials indicate that the management of shoreline erosion, its assessment and development of erosion solutions is administered through the Environment Section and associated environmental impact processes. Importantly, this is undertaken without specific coastal engineering expertise. Typically, designs are recycled from the Construction Section (MHTE) or formulated based on techniques used in non-reef environments without regard to the unique process characteristics of reef islands.

It should be re-emphasised that designs accessed and provided by Shaig (2009) are limited to those coastal structures designed by the Construction Section. No formal designs have been viewed of small-scale community interventions at the coast. However, visual observations of some attempts to arrest shoreline erosion were observed in the field.

4.2.1 Design considerations for coastal structures

In order to evaluate the design and performance of coastal structures it is instructive to overview key design criteria that contribute to successful performance of coastal structures (principally seawalls). Importantly, failure to follow these criteria is a primary reason for the failure of structures and promotion of adverse environmental effects.

<p>1. Foundation Conditions and 2. Toe Protection</p> <p>1. Structure foundations must be positioned at sufficient depth to avoid scour and undermining. 2. Structures must also have adequate toe protection to prevent structure being undermined.</p> <p>Where structures are located directly on hard reef surfaces undermining is of less concern. Where structures are located on soft sediments (e.g. in backreef or lagoon settings) toe protection is necessary and foundations will need to be excavated.</p>	
<p>3. Drainage</p> <p>Structures should provide for adequate land drainage.</p> <p>One of the biggest reasons seawalls fail is the inability to drain water from the land. Water ponded behind walls places pressure on structures and can promote toppling.</p>	
<p>4. Height of Structure</p> <p>Structures should be built high enough to avoid wave overtopping and flooding of the island surface.</p> <p>In the Maldives many structures have been overtopped leading to slumping of the island surface and structure and ultimately leading to the collapse of some structures.</p>	
<p>5. Secure Terminal Ends of Structure</p> <p>The ends of structures must be securely fixed to the island to avoid erosion at the ends of structures and accelerated erosion. This type of erosion is known as 'flanking'.</p>	
<p>6. Size of Aggregate</p> <p>The size of material used in structures should be of sufficient size to withstand wave energy.</p> <p>In the Maldives limited supplies of aggregate have led to the use of cement sand bags and coral boulders. These materials have low wave thresholds (~0.5 m). Consequently, structures are susceptible to rapid degradation and failure.</p>	
<p>7. Minimise Void Spaces</p> <p>In block structures it is important to ensure void spaces between blocks (coral, cement bags) cannot allow island sediments to be washed through. This can be achieved using graded fill on the landward side and or geotextile matting that prevents the movement of sediment through the structure.</p> <p>Where sediment can leak through the structure the land surface subsides promoting erosion and eventual collapse of structures.</p>	

Figure 4.7. Design considerations for the insertion of shore parallel structures. Contravention of these considerations is the most common cause of the failure of coastal structures.

4.2.2 Engineering designs in the Maldives

Figure 4.8 presents examples of engineering designs, which are typical and currently adopted by the Construction section. This report is unable to professionally critique the technical engineering detail of each design. However, there are features of the designs that have specific implications for the geomorphic processes and likely longevity of structures.

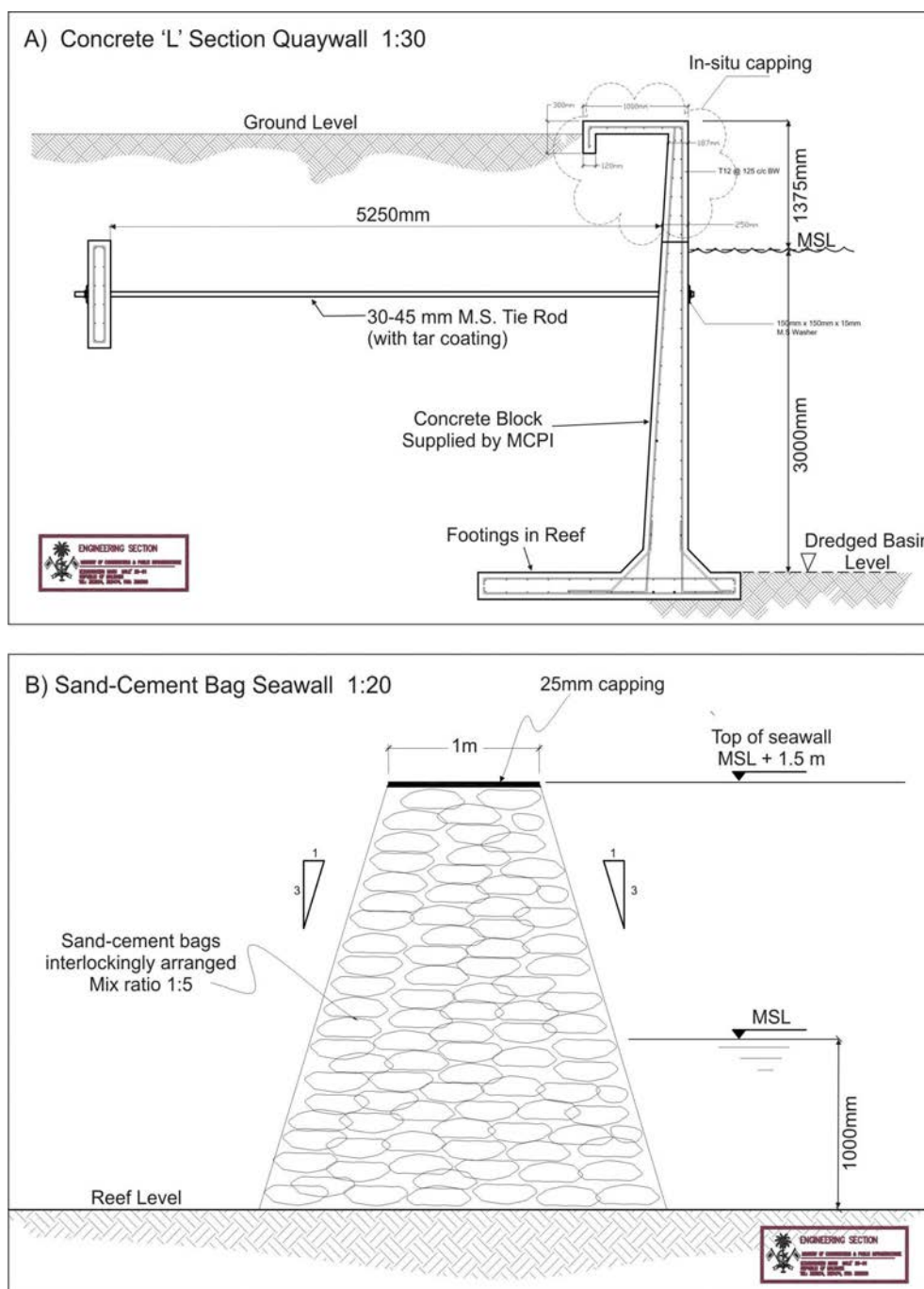


Figure 4.8. Examples of engineering designs for a quaywall (A) and seawall/breakwater (B).

- i) *Design height of structures (Fig. 4.7).* Structures are designed with a minimum freeboard above mean sea level (msl). For example the quaywall and seawall designs presented in Figure 4.8 provide for a 1.37 and 1.5 m clearance above msl. Understanding extreme water levels at the coastline is a critical element of coastal structures designed to mitigate erosion and flooding. However, throughout the Maldives there is little wave and storm surge information on which to base design heights. Despite this lack of records, recent extreme events and the fragmentary wave records that do exist provide an indication of potential extreme water levels.

Tidal range: The tidal range in the Maldives reaches a maximum of ~1.2 m. This suggests that there is a maximum clearance of structures of 0.9 m above maximum tidal limit.

Wave heights: Measurements of shoreline wave heights indicate that waves can reach in excess of 1.0 m on the outer reef and close to the shoreline, under westerly monsoon and exposed island shoreline conditions (Kench et al., 2006, 2009a,b).

Extreme events: Instrumental records show that during the Indian Ocean tsunami shoreline surges reached 2.5 m above msl (Kench et al., 2006, 2008). Such water levels overtopped and inundated island surfaces.

Collectively, these water levels indicate that current designs do not provide sufficient elevation to protect island surfaces from overtopping. Overtopping of structures is a major factor in the longevity and deterioration of structures.

- ii) *Lack of Environmental Parameters.* Following discussions with staff of the Construction Section (MHTE) and examination of designs (Section 4.1), it is apparent that coastal management solutions (including engineered designs) are developed in a vacuum of environmental information on wave conditions, currents, beach dynamics and sediment flux (as also highlighted by Kench, 2001). This system has evolved due to the lack of coastal process information. Consequently, the choice of structure, its physical dimensions and construction materials were selected without knowledge of detailed coastal processes and in particular extreme energies at the shoreline. In part this Technical Assistance Project begins to rectify this lack of information and synthesise environmental information to better support engineering designs.
- iii) *Construction materials.* In the Maldives coastal structures (seawalls, revetments, groynes and breakwaters) have been built from a wide variety of materials. In general, more robust materials have been employed in major Government infrastructure projects and resort developments. Recent structures have been built using concrete slab, cement sand bags or large cast engineering units (CEUs) such as tetrapods (e.g. Fig. 4.6D). However, older structures have been constructed from

coral block (e.g. Fig. 4.6A). Structures sponsored or constructed by local communities consist of a more diverse array of materials which include concrete, cement sand bags, coral rock, metal drums and in isolated instances, wooden structures.

Size of Engineering Units. The size of individual rock units is a critical design consideration of seawalls and coastal structures (Fig. 4.7). In cases of major infrastructure projects the size of CEU's is conservative (e.g. use of tetrapods, Fig. 4.6D). However, at smaller scales the size of engineering units is constrained by available aggregate supplies. The access to aggregates is a major constraint in atoll countries which lack access to rock quarries or other high grade materials. In lieu of such resources reef rock, coral blocks and cement sand bags have been employed. While some dredging projects have been able to access large reef blocks in general, aggregates are small in size (sand and gravel). To overcome this difficulty the use of cement sand bags has become common. Furthermore, during the construction process cement bags are placed in an interlocking arrangement. However, there are a number of design issues with the use of cement sand bags. First sand bag structures are only as strong as the weakest component of the seawall. Consequently, one poorly mixed bag of cement may provide the structural weakness for deterioration of a wall (Fig. 4.7, 4.9A). Second, the maximum size and weight of bags (~0.5x0.3x0.15m) is limited. A typical cement sand bag is physically stable under wave height conditions up to 0.5 m. While some shorelines do receive low wave energy, most would experience wave energy conditions greater than 0.5 m for periods in each year. Collectively, these constraints suggest that the use of cement sandbag structures should only be adopted in the lowest energy environments; and, that sand bag structures in higher energy settings will require ongoing maintenance over the short- to medium-term.

It should be noted that in some structures coral blocks and sand bags are rendered with cement. This provides a measure of protection to the individual units. However, such protection is a temporary measure only. As soon as the rendered cap deteriorates the engineering units are exposed to degradation.

- iv) *Use of geotextile filter cloth.* Notably the use of geotextile filter cloth is not specified in engineering designs (e.g. Fig. 4.7). Field observations indicate that filter cloth is used in some instances. However, its use does not appear to be consistent and is lacking in older structures. Geotextile filter cloth is used to back structures and provides an impermeable membrane to prevent the movement of sediment from the land through the coastal structure. Without this barrier loss of land through coastal structures can occur leading to further erosion and collapse of structures.
- v) *Drainage.* One of the most significant reasons for the failure of coastal structures is inadequate consideration of drainage from the land. However, the inability to direct water from behind structures can cause pressure from the land to topple structures (Fig. 4.9C, D). This poses a particular problem in low-lying atoll islands

where the land elevation with respect to water level is small and drainage options are limited. It is not apparent from design that drainage is given explicit consideration. The problem of water ponding and drainage can be reduced through appropriate design height considerations that prevent wave overtopping.

4.2.2. Condition of engineered structures

Field inspection of numerous structures indicates that their life span is short, they often do not stop the erosion problem, and they often exacerbate island erosion and can impact on reef productivity (Kench et al., 2003). Coastal structures typically fail for a range of reasons which are summarised in Figure 4.7. These factors relate to the design of structures with respect to the coastal geology. As outlined in the previous section many structures in the Maldives do not comply with the basic conditions for seawall design and construction. In particular, elevation, end effects and aggregate size are common elements that can compromise the structural integrity of structures and potentially exacerbate environmental problems.

Outside of the capital island (Male) coastal protection structures are commonly composed of coral rock (e.g. Fig. 4.6A), coral sand cement and blocks, or any other solid debris that can be sourced by local communities (e.g. 44 gallon drums). Coral fragment shape and density mean that individual clasts are frequently too small to remain immobile under even relatively low energy conditions, and cements are either of poor quality or not used. Appropriate grading of material used in construction is rare. Except where erected on beach rock, toe protection is rarely considered and appropriate foundation materials are rarely used. The absence of suitable natural structures to which seawalls and groynes can be fixed, leads to structures liable to flanking at the lateral extent of seawalls or on the inshore end of groynes. Construction methods and materials mean that in many cases water and sediments can move freely around, and occasionally over and through seawalls. The net effect of failed structures in many cases is exacerbation of erosion problems. This leads to promulgation of engineering structures with examples of entire shorelines being armored.

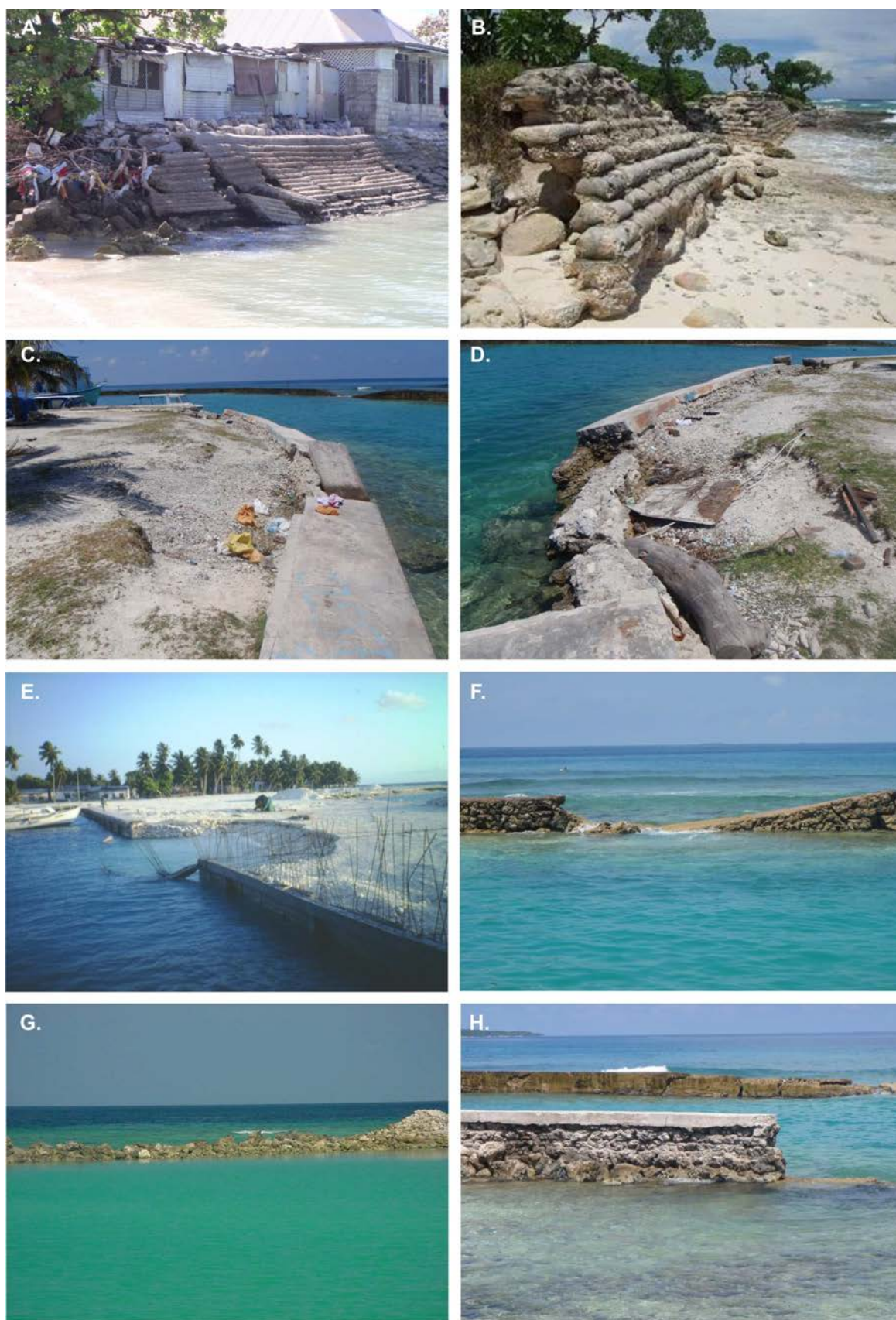


Figure 4.9. Examples of common failings of coastal structures in reef island settings. In most cases structures do not comply with the design considerations for structures (Figure 4.8). A) and B) Undermining and collapse of cement sand bag seawall due to overtopping and lack of geotextile. C) and D) Slumping of land behind seawall and collapse of structure. E) – G) Overtopping, breaching and failure of walls.

4.3 Environmental Effects of Coastal Structures

This section provides an overview of the potential environmental effects of coastal structures. It is based on an examination of the potential impacts of structures on coastal processes and geomorphology reported in the literature from continental coastlines.

4.3.1 Local scale impacts of coastal structures at the coast

As a basis to consider the impacts of coastal structures it is pertinent to restate the purpose of using coastal protection structures. In general, the use of seawalls (or groynes) is to prevent landward retreat, inundation and loss of land through wave action. Structures fix the land/sea boundary and are inserted where erosion is currently an existing problem. Seawalls do not promote accretion nor reduce the regional trend of erosion. Furthermore, structures do not protect the beach fronting the wall or adjoining unprotected sections of shoreline. Indeed, on an eroding coast the beach in front of a seawall may narrow and eventually disappear if there is an inadequate sediment supply (Kraus, 1988).

An issue in the insertion of hard structures at the coast is whether the presence of shore parallel (seawalls) or shore perpendicular structures (e.g. groynes) promotes changes in processes that adversely affect the persistence of beaches and geomorphology of the beach and nearshore. Weggel (1988) notes that the degree of structure/process interaction is dependent on the position at which structures are inserted. For example, a wall inserted well above high tide mark cannot interact with the process regime and, therefore, cannot alter the morphology of the nearshore. However, structures inserted directly below high tide mark will interact with processes for part or all of a tidal cycle, which may produce morphological changes in the beach and nearshore system. Many of the structures in the Maldives fall into this second category.

Numerous studies have been undertaken examining the interaction between coastal structures and physical processes and their consequent impacts on coastal geomorphology (as expressed in beach morphology and erosion). Commonly these studies have been undertaken on open coast beach systems in continental coastal settings and have looked at individual structures. Most of these studies have previously been reviewed by Kraus (1988) and Kraus and McDougall (1996) and their findings are summarised in Table 4.2.

Table 4.2. Summary of impacts of coastal structures at the coast

Impact

Beach Scour: Lowering of bed level at toe of structure

Depth of scour: Kraus (1988) concluded that scour was related to wave height duration and reflectivity of a structure. In particular, that the significant deepwater wave height provided a good estimate of scour (e.g. Sawaragi and Kawasaki, 1960). Furthermore, increasing slope angle of structures reduced the magnitude of scour (e.g. Sawaragi, 1967). However, Kraus and McDougall (1996) refined their conclusion to note that scour is not produced by wave reflection. Rather, wave reflection may suspend sediment at the toe of cliff and alongshore gradients of transport are most likely the cause of bed lowering at the toe of structures.

Beach profile change:

Sand volume: Numerous studies show that during storms the beach profile in front of a wall retains the same amount of sand as a beach without a wall. The main observed difference was a downward displacement (lowering) of the beach slope near the wall (Kraus and McDougall, 1996).

Beaches have been shown to become progressively narrower in the presence of structures (Wood, 1988; Pilkey and Wright, 1988).

Beach recovery is similar for beaches with and without seawalls: As noted by Morton (1988) if sufficient sediment supplies exist, a beach in front of a seawall will recover. However, if sediment supplies are depleted long-term beach lowering and narrowing will occur.

Accelerated erosion:

Three mechanisms were identified by which seawalls may contribute to erosion:

- Retention of sediment behind walls (placement loss erosion). Erosion from ‘placement loss’ refers to the fact that structures lock sediment behind them which is unable to interact with the coastline. Consequently, there is a depleted volume of sediment available for coastal change to occur. This can promote additional erosion.
- Structure acting as a groyne by disrupting alongshore sediment transport promoting downdrift erosion.
- Flanking at the terminal ends of walls.

Three other mechanisms of erosion were raised but remain speculative:

- Increased turbulence due to wave reflection
- Offshore transport by rip currents
- Enhanced transport by a short-crested wave system composed of incident and reflected waves

Beach planform effects:

Numerous field observations show that erosion at the terminal ends of structures can occur (termed flanking) which can focus erosion and cause disruption to the planform configuration of coastlines.

Insertion of groynes (harbours) purposely impedes sediment transport alongshore. Consequently, alongshore (downdrift) sectors of shoreline are deprived of sediment and can promote erosion.

Waves and water level interaction:

Studies indicate that nearshore processes can be altered in the presence of structures. The following responses have been identified: wave reflection, increases in surge level and increased setup which raises water level against the shoreline.

Circulation effects in nearshore:

Weight of evidence indicates that seawalls have little effect on alongshore current processes and sediment transport. However, the presence of shore perpendicular structures does interfere with both alongshore current patterns and sediment fluxes. Currents and sediment can be impeded in their alongshore transport forming cusped beaches and current eddies. The outcome is a current shadow and depletion of sediment flux on downdrift shorelines.

Beach dynamics

Disruptions to sediment fluxes and currents (above) can compromise the normal dynamic behavior (erosion and accretion cycles) of shorelines.

Source: based on Krauss (1988)

4.4 Coastal Process Characteristics of Maldivian Reef Islands

As indicated in Section 4.3 the scientific understanding of the impacts of coastal structures on coastal processes and geomorphology emanates from studies on continental coastlines. Therefore, it is necessary to consider the relevance of these impacts in coral reef settings which have some unique differences in the coastal process regime and to the way that coastlines change over event (storm) to seasonal and decadal timeframes. These differences are summarized in the context of the Maldives before consideration is given to the potential interaction of structures with reef island process systems and potential environmental impacts.

Erosion or change in island shorelines is controlled by a combination of wave and current processes that transport sediment (sand) around island shorelines. Understanding of the controls on island erosion, therefore, must consider the wave processes and the influence of climate in modifying nearshore wave and current processes.

In general, very little research has been undertaken on the process controls on reef island change in the Maldives. The most detailed work has been undertaken in a set of experiments in South Maalhosmadulu atoll that was specifically established to examine both island change and the processes (wave and current conditions) driving coastal change. A summary of the relevant scientific literature on Maldivian reef island development and change is contained in Appendix 1.

4.4.1 Climate and Wave Regime

Climate control on processes: Wind speed and direction are the primary controls on wave processes. The Maldives has three climate stations that straddle the archipelago and which provide standard wind strength, wind direction, temperature rainfall and other climatic parameters. These climate stations are located in Addu, Hulule and Hanimaadhoo and historical datasets extend back approximately 40 years (Department of Meteorology, 1995). In addition climate data can also be identified from airport islands.

With respect to island shoreline change, the influence of the climate on reef platform processes in the Maldives can be divided into the two principle monsoon periods, which are characterised by strong reversals in wind direction that are confined to a narrow range of wind angles. Analysis of 30-years of wind data from the Hulule since 1964 (Fig. 4.10) indicates that the Maldives experience southwest to northwest winds ($\sim 225\text{--}315^\circ$) from April to November during the *Hulhangu* monsoon, with a mean wind speed of 5.0 ms^{-1} . This is also known as the westerly monsoon. In contrast, the *Iruvai* monsoon, from December to March is characterized by winds from the northeast-east ($\sim 45\text{--}90^\circ$) with a mean wind speed of 4.8 ms^{-1} (Fig. 4.10). This period is also known as the northeast monsoon. Wind strength is most variable during the cross-over between northeast and westerly monsoons with mean wind speed falling to 3.5 ms^{-1} in March.

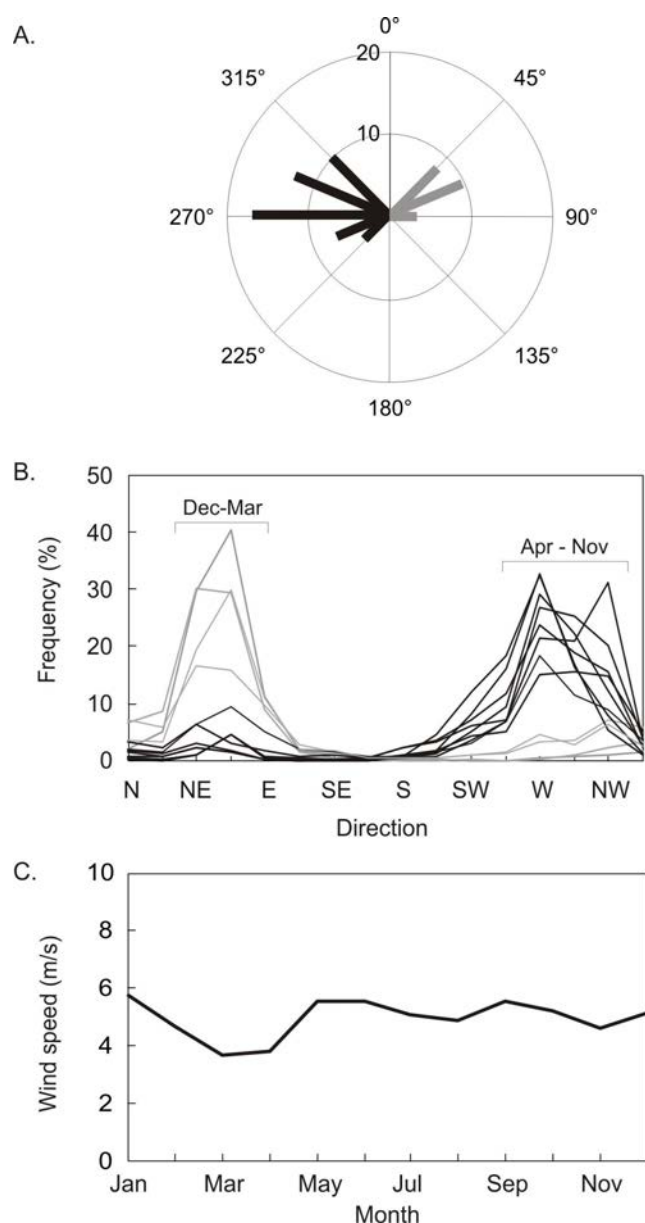


Figure 4.10. Summary wind data for the Maldives. A) Wind rose of the 36-year record of mean wind direction and strength (1964-2000). B) 36-year monthly wind direction. In both A) and B) April – November denoted by black lines and December to March indicated by gray lines. C) Mean monthly wind speed. Data from the Hulule climate station. Source: Department of Meteorology, Maldives.

Wave Climate: Information on the deepwater wave climate is limited, but satellite altimetry wave climate data (for a ten-year period) for the region (Young 1999) indicates the dominant swell approaches from a southerly direction (Fig. 4.11). On a seasonal basis, swell is from the south-southwest from April to November, with a peak significant wave height (H_s) of 1.8 m in June, and from the south to southeast directions from November to March with a minimum H_s of 0.75 m in March (Fig. 11B-D). The estimates and seasonality in wave height conditions are consistent with independent analysis of a shorter three-year record of satellite altimetry data by Harangozo (1992).

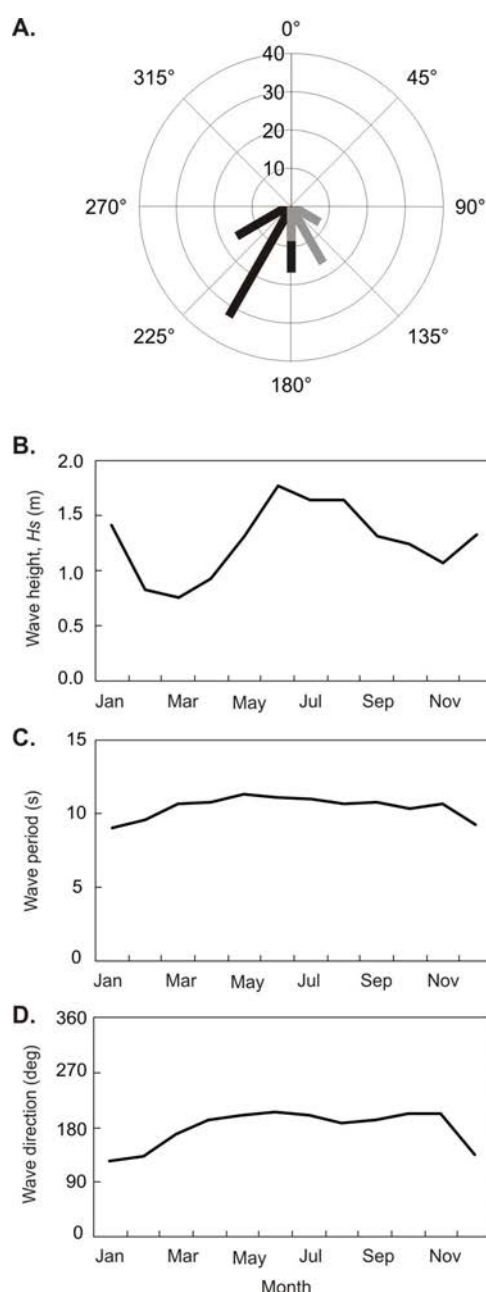


Figure 4.11. Summary wave data for the Maldives. A) Directional wave rose of 10-year mean percent frequency showing swell direction for April – November (black line) and December–March (gray line). B) Mean monthly significant wave height. C) Mean monthly significant wave period. D) Mean monthly wave direction. Source: global wave climate data of Young (1999).

4.4.2 Influence of monsoons and wave climate on reef platform processes

In 2002 a detailed set of experiments were undertaken to measure wave processes incident at reef platforms across South Maalhosmadulu atoll. Experiments focused on two scales. First, wave recorders were placed on the outer reef edge of reef platforms located on the western atoll periphery, central lagoon and eastern atoll periphery. This experiment was designed to establish whether wave energy gradients existed across the atoll. Second, wave recorders and current meters were deployed around the island shoreline of three islands to establish the

nature of wave processes on reefs and the current patterns that influence shorelines. Both experiments were conducted in the westerly and northeast monsoon periods (June and February) in order to establish whether the monsoons had a measurable impact on nearshore circulation. Key findings of these experiments are summarized below.

Atoll scale wave characteristics

- There is a general reduction in wave energy across the atoll (windward to leeward) in each season. Therefore, there is a wave energy gradient across atolls.
- There is a shift in dominance from swell to wind-generated wave energy across the atoll.
- The direction of wind-generated wave energy switches between monsoon periods although oceanic swell propagates from the southern ocean throughout the year.
- The wave energy gradient across the atoll reverses between the west and northeast monsoons.

Based on these findings Kench et al. (2006) argue that spatial difference in gross wave energetics and net balance of wave energy on reef platforms can be used to account for the presence and location of reef islands on reef platforms.

Reef platform wave characteristics

Individual platform scale experiments measuring wave processes around the perimeter of reef islands showed that:

- Windward shorelines receive greater input of energy through a combination of swell and wind-wave energy.
- Leeward shorelines receive lower total energy input in each season as wind-wave energy is effectively dissipated on windward reef surfaces.
- Swell wave energy is of equal height around reef island shorelines as it refracts around island shorelines.
- Tides act to modulate the amount of wave energy that leaks onto reef surfaces. Greatest wave energy accesses reef island shorelines at higher tidal stages.
- Monsoon seasons promote changes in the areas of a reef island shoreline that receive greatest wave energy.
- Velocities under waves are sufficient to entrain sediment in the nearshore and beach environment under normal energy conditions.

An example of recorded wave heights around an island shoreline is presented in Table 4.3. Such data can be used to assist in the design of structures.

Table 4.3. Summary significant and maximum wave height values recorded at Dhakandhoo Island, Baa atoll, June 2002. Measurements recorded at the windward and leeward reef edge and four shoreline locations around the island.

Location		<i>H_s</i>		<i>H_{max}</i>		<i>T_s</i>	<i>T_z</i>
		Mean (m)	Peak (m)	Mean (m)	Peak (m)	(s)	(s)
Windward RF	W	0.21	0.43	0.36	0.71	8.2	5.5
Leeward RF	E	0.24	0.44	0.38	0.63	10.4	8.2
Shoreline	N	0.24	0.43	0.35	0.66	11.4	7.2
	E	0.29	0.47	0.43	0.73	10.8	7.9
	S	0.25	0.42	0.37	0.58	9.9	7.1
	W	0.22	0.38	0.37	0.65	7.8	5.3

H_s = significant wave height (average of the top one third of highest waves). *H_{max}* = maximum recorded wave height. From Kench et al. (2009a).

Reef platform circulation

Changes in incident wave conditions between seasons modulate reef platform circulation patterns between seasons.

- Nearshore currents were found to be unidirectional in most instances and, therefore, their direction is not influenced by tides.
- Circulation patterns showed distinct changes between monsoon seasons. In general, flows are toward the east under westerly monsoon conditions and toward the south-southwest under northeast monsoon conditions (Fig. 4.12).
- No relationship was identified between the magnitude of wave energy and current processes. For example, the windward exposed reefs did not exhibit significantly greater currents than centrally located and leeward reefs.
- The precise nature of current patterns on reefs differed between reef islands. Differences reflect a number of factors: the shape of each platform, which controls localised wave refraction patterns; and, direction and character of waves impacting reefs (swell versus wind waves), which is a function of the boundary wave climate, position of each reef platform within the atoll and their proximity to neighbouring reefs and gaps in the atoll periphery (Kench et al., 2009a).

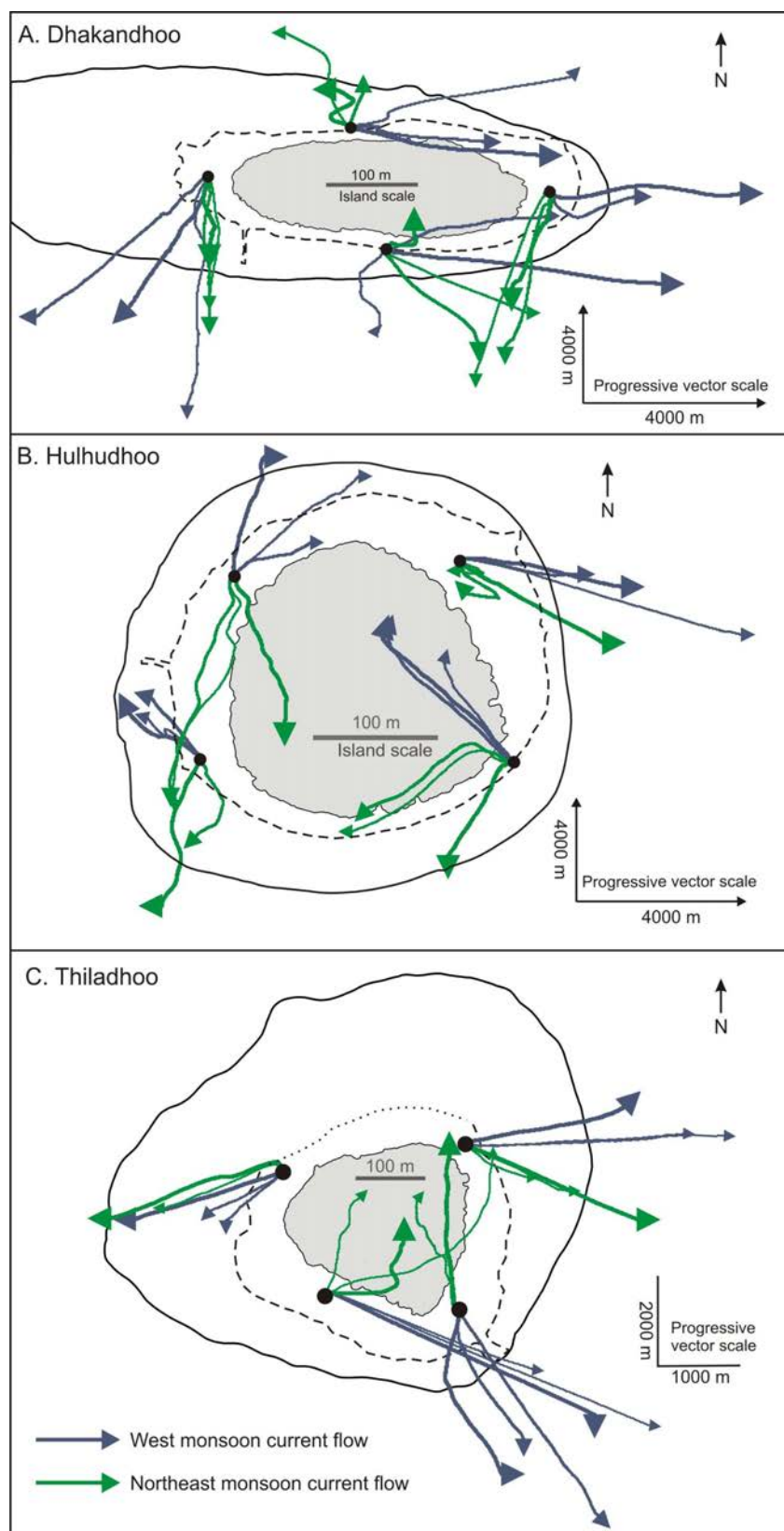


Figure 4.12. Summary nearshore current patterns around three reef islands in South Maalhosmadulu atoll. Each coloured arrow represents 12.5 hours of continuous current flow. Source: Kench et al. (2009b).

4.4.3 Coastal monitoring and shoreline dynamics

The seasonal morphological behaviour of beaches that fringe eight islands in South Maalhosmadulu atoll was documented by Kench and Brander (2006) based on repeat global positioning system surveys (Fig. 4.13). In summary, they found:

- i) Large seasonal adjustments in beach position around island shorelines. On circular islands the entire perimeter of the island experienced shoreline change.
- ii) Beach changes were correlated with different monsoon seasons.
- iii) Both the magnitude and planform adjustments in beach position varied between islands of differing shape. For example, beach change was constrained to a smaller proportion of the shoreline on elongate islands. These findings were summarised by the reef island oscillation index in which circular and elongate islands were shown to exhibit the most and least dynamic shoreline behaviour respectively (Fig. 4.14).

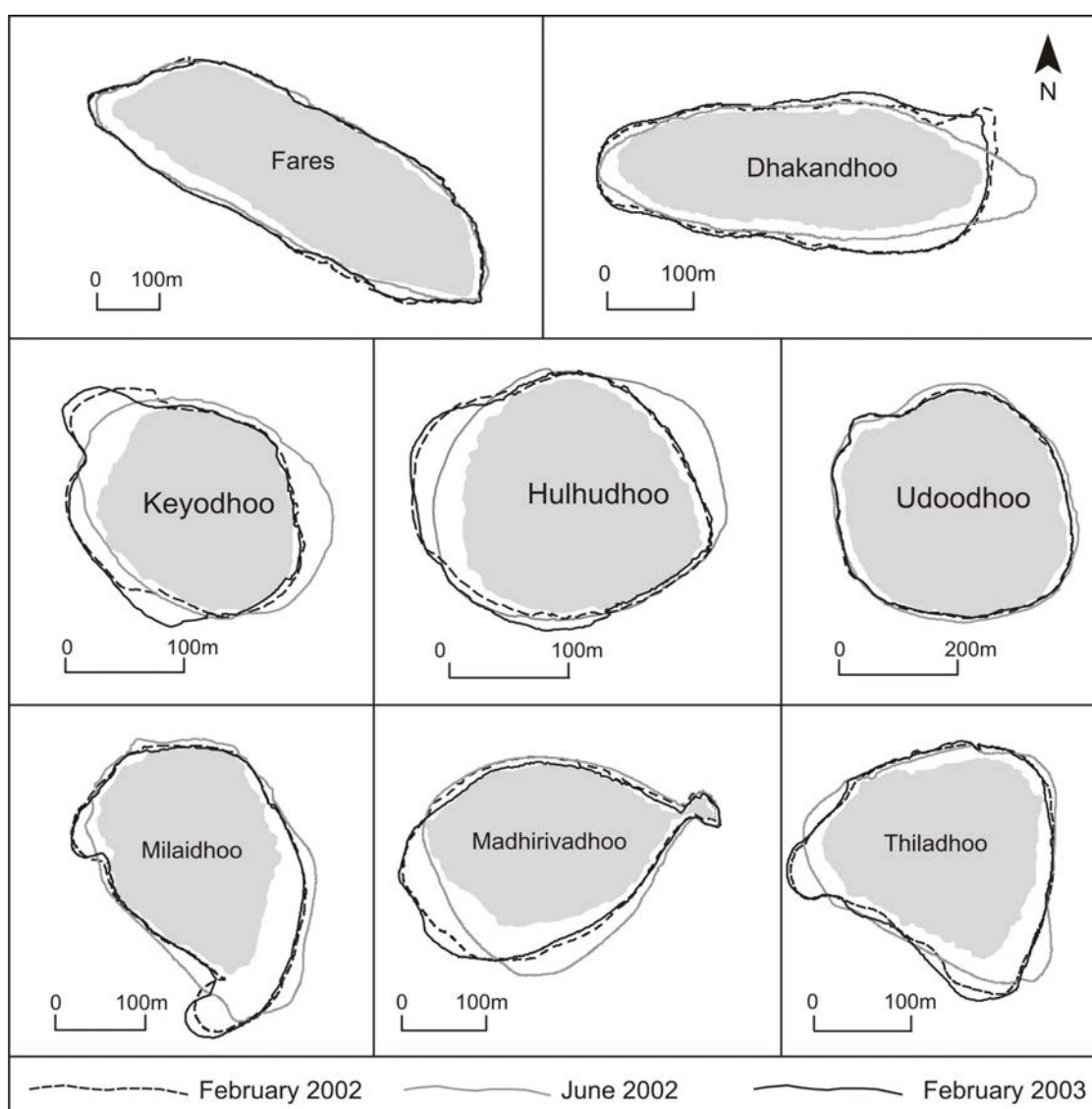


Figure 4.13. Seasonal change in eight reef island shorelines, South Maalhosmadulu atoll. Surveys undertaken using GPS. Source: Kench and Brander (2006).

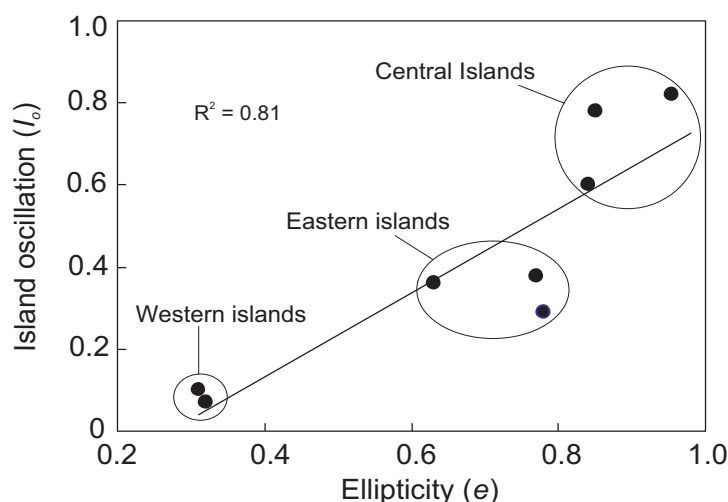


Figure 4.14. Degree of island oscillation versus ellipticity of reef islands in Baa atoll, Maldives. Island oscillation refers to the proportion of shoreline along which shoreline change takes place between seasons. Ellipticity signifies the circularity of reef islands. An ellipticity value of 1.0 = a perfect circle. Results indicate that as islands become more circular the alongshore movement of the beach is greater between seasons. From Kench and Brander (2006).

4.4.4 Process controls on dynamics of reef island shoreline change

Monsoonally-forced changes in nearshore wave and current patterns control seasonal morphological responses of island beaches. Waves and currents provide the process mechanism that drives change in shoreline position between seasons. Analysis of high frequency current records indicates that velocities in the nearshore commonly exceed the threshold condition for medium-sized carbonate sediments ($\sim 0.20 \text{ ms}^{-1}$, Kench and McLean, 1996). Furthermore, sediment was observed to be highly mobile in the swash zone of all beaches. Once entrained, unidirectional shoreline currents transfer sediment alongshore to leeward depocentres and govern the reorganisation of mobile beach materials around the study islands (Fig. 4.13). Of note, beaches show the greatest degree of morphological change at locations where current patterns exhibit the largest changes between monsoon seasons.

Collectively the process and morphological observations of recent research in Baa atoll provides the first detailed process linkages between waves, currents and consequent shoreline dynamics on three reef platform islands in the Maldives. The findings provide insights into the morphodynamic behaviour of reef islands that are likely to have implications in other reef platform settings and which can be synthesised to improve the information base with which to make better informed coastal management decisions. A conceptual model of coastal processes and island behaviour can be constructed which has the following characteristics:

- Island shorelines are dominated by alongshore current processes.
- Alongshore process and morphological change signatures are likely to dominate on reef platforms where wave refraction around the reef structure

can take place, but is not likely to occur on islands situated on extensive linear atoll reef rims where wave refraction is precluded by the reef extent and/or presence of a backing lagoon.

- Alongshore currents promote alongshore reorganisation of sediments around island shorelines.
- The nearshore current patterns that control sediment transport are influenced by seasonal variations in wind and wave patterns which can lead to total reversal in circulation around islands.
- Island shorelines are morphologically very dynamic and exhibit large changes in position in response to changes in wave energy and current energy.
- The dynamics of island shoreline change is dependent upon the shape of the reef platform, position in the atoll and magnitude of change in wave energy between seasons.
- Shoreline dynamics indicate there are sectors of island shorelines that act as deposition zones and other sectors that act as sediment transfer zones.
- Reef platform current patterns and island morphodynamics are not sensitive to the magnitude or changes in magnitude of wave energy incident on reef platforms. Rather than change in gross energy, it is the magnitude of change in direction of wave approach that is the most important control on island morphodynamics.

4.5 Interactions of Coastal Processes and Structures on Maldivian Reef Islands

Observational insights into the coastal processes and shoreline dynamics of reef islands (summarised in previous sections) have important implications for how coastal structures may interact with processes and potentially promote adverse environmental impacts.

4.5.1 Interaction with shore perpendicular structures

Figures 4.15 and 4.16 illustrate the interaction of island shoreline processes with structures that extend perpendicular to the shoreline (e.g. groynes or boat harbours). In both examples a number of impacts are predicted:

- i) Direct interference with alongshore currents patterns. In particular, currents are deflected away from the shoreline on the updrift side of structures and current shadows (eddies) can form on the downdrift side of groynes.
- ii) Change in current velocity. On the updrift side of shore perpendicular structures currents decelerate near the shoreline, which can induce deposition of sediment.
- iii) Change in sediment transport and deposition. Key impacts of shore perpendicular structures on sediment transport are:

- the trapping of sediment on the updrift side of structures promoting shoreline accretion;
 - reduction in transfer of sediment to the downdrift side of structures depleting the sediment volume on this shoreline and potentially promoting erosion.
- iv) Alterations to shoreline sediment budget and breakdown of shoreline dynamics. Perpendicular structures partition the sediment volume into discrete cells. This can promote shoreline erosion by reducing the volume of sediment in one part of the shoreline sediment budget. As shown in Figure 4.15 if shore perpendicular structures are located in the transfer pathway of the alongshore reorganisation of sediment, the downdrift sector of the island shoreline is depleted of sediment. In the subsequent monsoon period the small volume of sediment, trapped on this downdrift coast, is rapidly remobilized and transport away from the shoreline exposing the vegetated shoreline to prolonged wave attack during the remainder of the seasonal cycle. This can exacerbate shoreline erosion on the sector of the island which has a net sediment deficit. This outcome is expected on islands where the shoreline undergoes significant movement between seasons.
- v) Partitioning of sediment supply to downdrift shorelines. On some islands the degree of shoreline change is constrained to one end (or a limited range) of the shoreline (e.g. elongate islands). This occurs where the energy input remains constant throughout the year (e.g. islands on atoll periphery). Consequently, impacts on shoreline dynamics may be less of a concern. However, in such locations the ocean reef flat is commonly the primary area in which new sediment is generated from the reef platforms and transported to the island. In such instances new sediment may not reach the downdrift shoreline. Over time this may lead to reduction in the total volume of sediment on the downdrift shoreline and degradation of the beach leading to shoreline erosion.

In summary the insertion of shore perpendicular structures is likely to have significant impacts that compromise nearshore current processes, sediment transport and shoreline change.

Recently, designs for shore detached harbours have been proposed. Features of these designs include a piled jetty that connects the shoreline to a harbour basin that is located on the reef flat surface. Such structures behave like offshore breakwaters. Potential effects of such structures are indicated in Section 4.5.3.

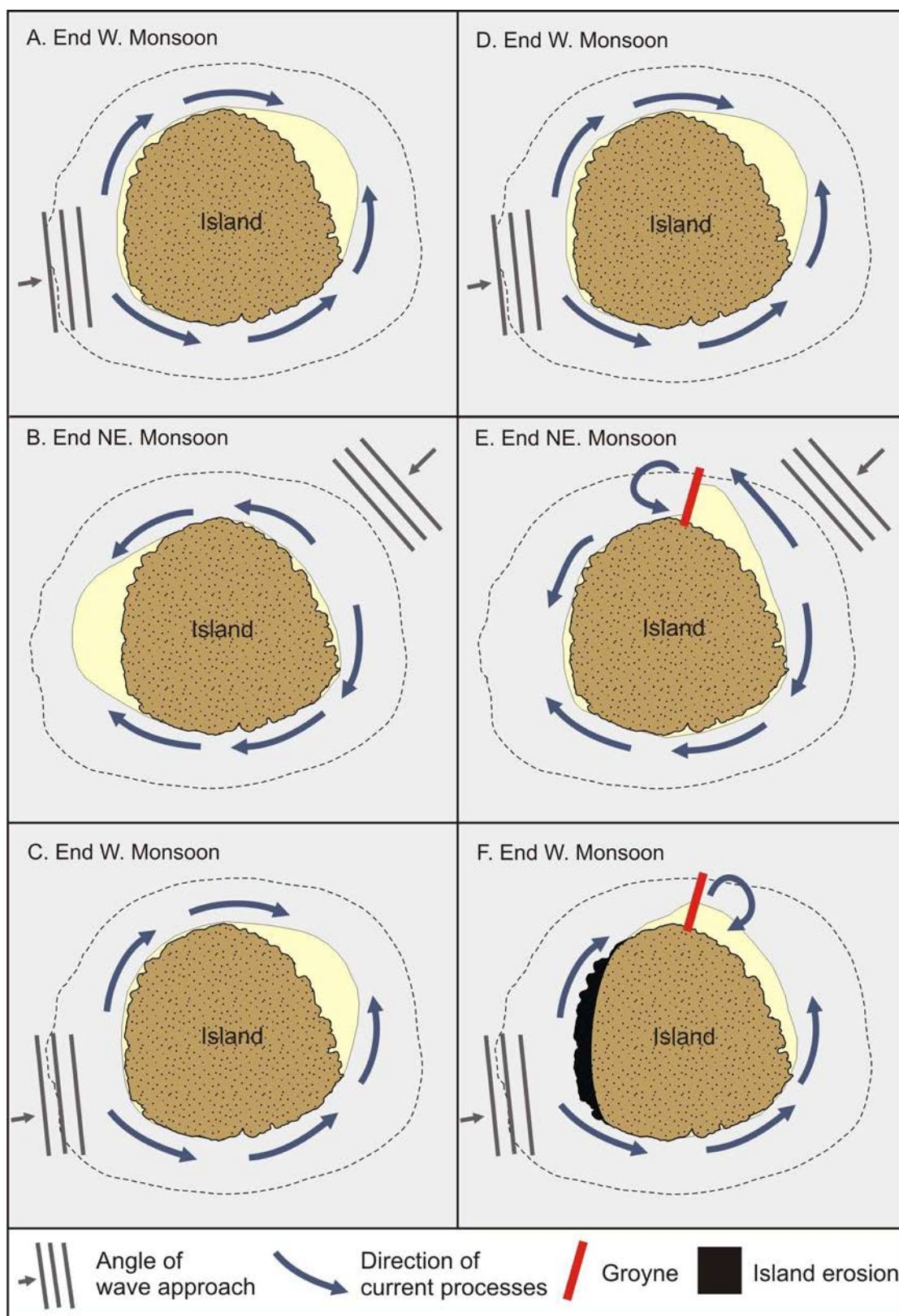


Figure 4.15. Natural seasonal shoreline dynamics on circular reef platforms (A-C). Potential impacts on shoreline dynamics following insertion of a shore perpendicular structure (groyne, D-E).

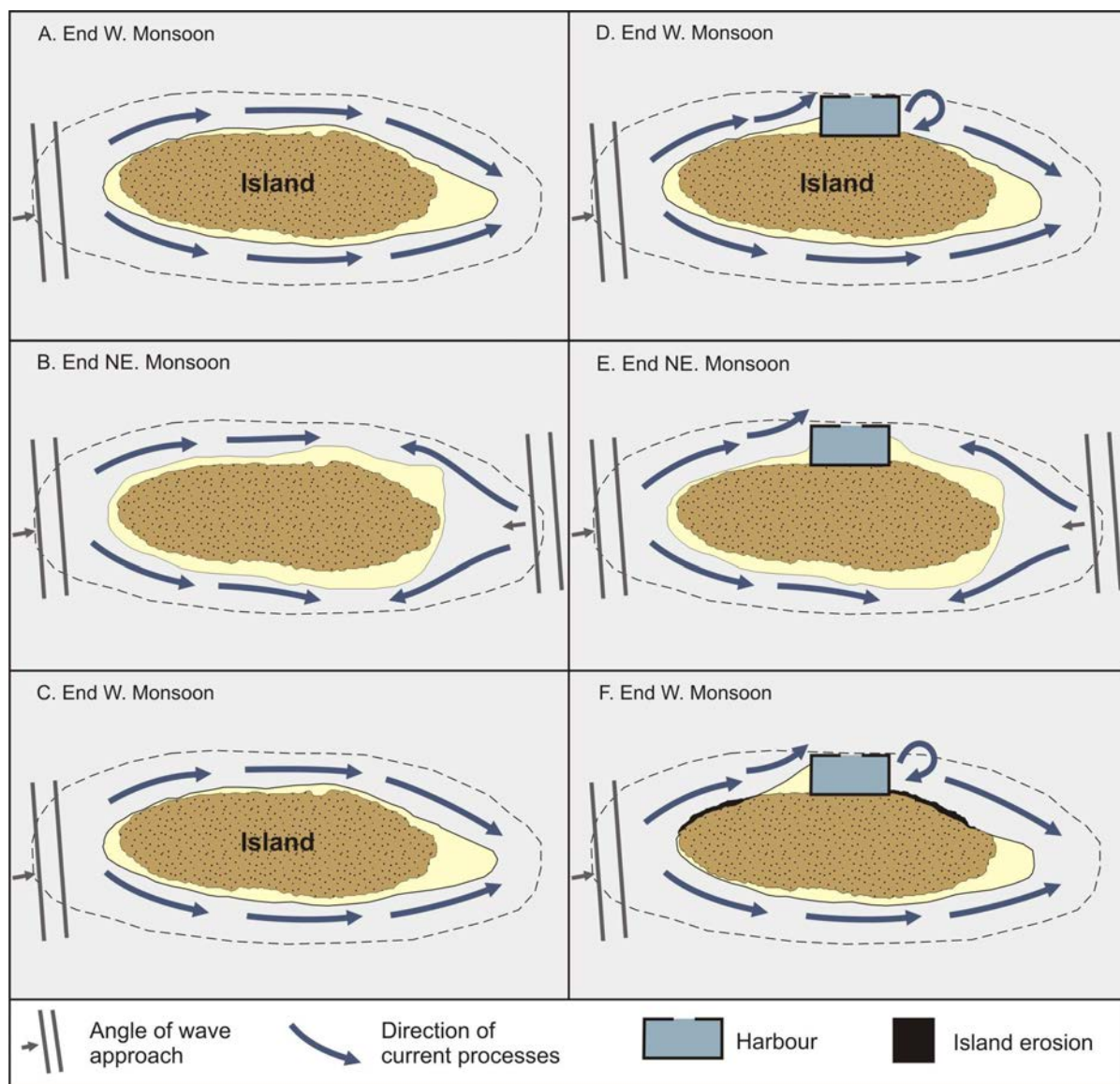


Figure 4.16. Natural seasonal shoreline dynamics on an elongate reef island (A-C). Potential impacts on shoreline dynamics following insertion of boat harbour (D-E).

4.5.2 Interaction of processes with shore parallel structures (seawalls)

In the presence of an ample sediment supply beaches will form in front of rock structures. Indeed, on many reef island shorelines, beachrock (a naturally occurring rock that forms through cementation of beach sand) parallels the shoreline. In such cases this rock can be seasonally covered and uncovered with beach material. Therefore, given a sufficient supply of sediment and assuming a shore parallel structure does not protrude from the shoreline it is possible that such structures have minimal impact on nearshore processes and on sediment transport and deposition.

However, there are a number of instances in which seawalls can interfere with natural processes and sediment transport, and promote shoreline erosion.

- i) Poor design and construction. Sections 4.2 and 4.3 outline a number of reasons why seawalls fail which are primarily related to design criteria and construction methods. Due to the dynamic nature of island shorelines and alongshore dominance of processes it is expected that a similar range of impacts can be expected as found in other coastal settings. Many of these impacts can be prevented if walls are constructed to high design standards.
- ii) Accelerated erosion at terminal ends of structures. As documented in a number of examples beaches can migrate substantial distances alongshore (and around island shorelines) between seasons. However, it should be recognized that the magnitude of the beach excursion distance varies between islands of different shape and exposure (Figs. 4.13, 4.14). However, such dynamism implies that island shorelines and structures can be seasonally exposed to wave action. During periods when structures are exposed turbulence at the terminal ends of structures and strong alongshore current gradients can accelerate shoreline erosion of unprotected coastlines (Fig. 4.17) and can promote a crenulate shoreline configuration.
- iii) Passive erosion. As noted in Section 4.2 the insertion of structures does not address the underlying cause of the erosion problem. Seawalls lock sediment behind them, which is unable to contribute to the normal range of seasonal beach dynamics. However, each season natural processes require a finite volume of sediment to satisfy the balance of energy and capacity of currents to transport sediment. If sediment is locked behind a seawall other sectors of the island shoreline can erode to compensate for losses elsewhere in the shoreline. As reef islands are small this leads to self cannibalisation of shorelines and accelerated shoreline erosion.

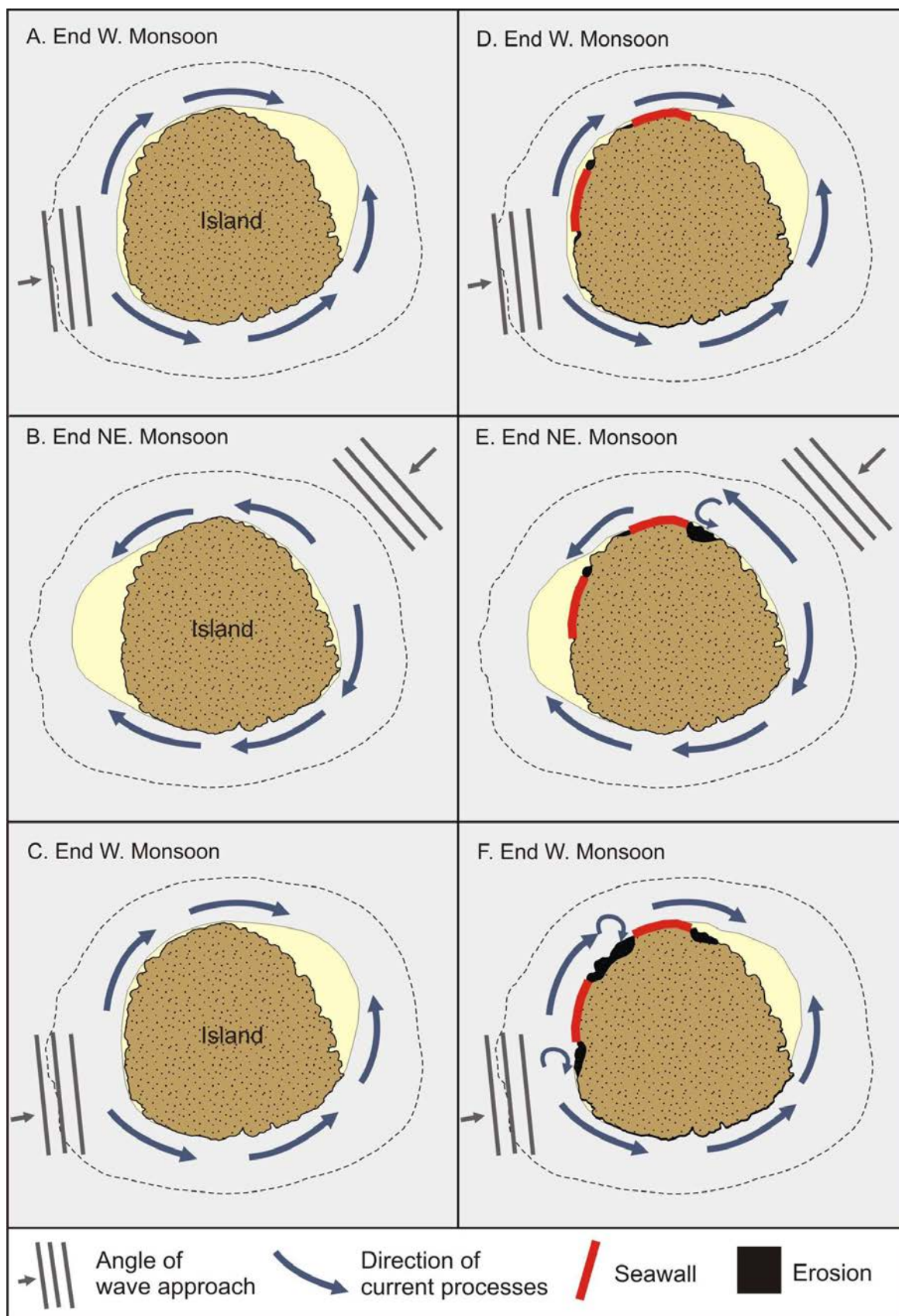


Figure 4.17. Natural seasonal shoreline dynamics on a circular reef island (A-C). Potential impacts on shoreline dynamics following insertion of shore parallel structure (D-E).

4.5.3 Interaction of processes with offshore breakwaters

Recently the use of offshore breakwater has been proposed as an alternative to shoreline structures to protect shorelines from wave attack and erosion. The principle of offshore breakwaters is to present a structure (Figs. 4.5D, 4.6F,G) that breaks waves offshore and refracts waves across the reef surface (Fig. 4.18), in such a manner that opposing nearshore currents are generated that transport sand to the lee of the breakwater forming a beach. In extreme cases breakwaters built above high tide level can filter all wave energy from a shoreline (e.g. tetrapod walls surrounding Malé). As noted earlier, there are proposals to construct detached harbours located on reef surfaces. The location of such harbours would act in a similar fashion to breakwaters.

There have been no studied examples of breakwaters on the reef platform of reef islands that document whether manipulation of processes in this manner does occur. However, observational evidence indicates that where breakwaters have been inserted shoreline instability and erosion continue to be a problem. Based on the conceptual models of island shoreline processes (developed in Section 4.4) there are a number of factors that are likely to contribute to the ineffectiveness of breakwaters and exacerbate coastline instability.

- i) *Island shorelines are integrated current and sediment transport systems.* The insertion of a breakwater on one sector of an island shoreline implies that the structure is able to partition the shoreline into discrete process zones that do not interact. Furthermore, this suggests nearshore currents and beach dynamics can be manipulated on one part of the island shoreline in isolation of the remaining shoreline. However, reef island shorelines are integrated process sediment systems. Consequently, modification of processes on one sector will have alongshore impacts on the island shoreline. In particular, if beach accretion is able to be manipulated in the lee of a breakwater this sand is most likely to be drawn from alongshore zones which will deplete the sediment reserves, disrupt natural shoreline dynamics and promote erosion (Fig. 4.18).
- ii) *Island shorelines are dominated by alongshore processes.* Most applications of breakwaters have occurred on linear continental shorelines where cross-shore processes dominate. However, reef islands are dominated by alongshore current processes. To be locally effective in contributing to shoreline deposition the breakwater must overcome the normal nearshore process regime and replace it with a localized counter current (Fig. 4.18). Given the wave environment of reef surfaces (see following paragraph) such an outcome is doubtful and undesirable. However, if such a change is achieved the nearshore process regime of the entire shoreline will be affected promoting island instability.
- iii) *Wave processes* on coral reef flats are characterized by a noisy surfzone environment consisting of a combination of broken swell, reformed waves and short period waves. It is unclear whether the refraction that is necessary to alter shoreline current patterns can be achieved.
- iv) *Seasonal shifts in process characteristics.* The wave and current characteristics of reef platforms can alter between seasons. In extreme cases the nearshore current

processes reverse and sectors of the reef platform undergo marked changes in the magnitude of incident wave energy. Consequently, a breakwater can be seasonally ineffective and will only modify processes during those periods when waves propagate onto the reef platform and interact with the breakwater.

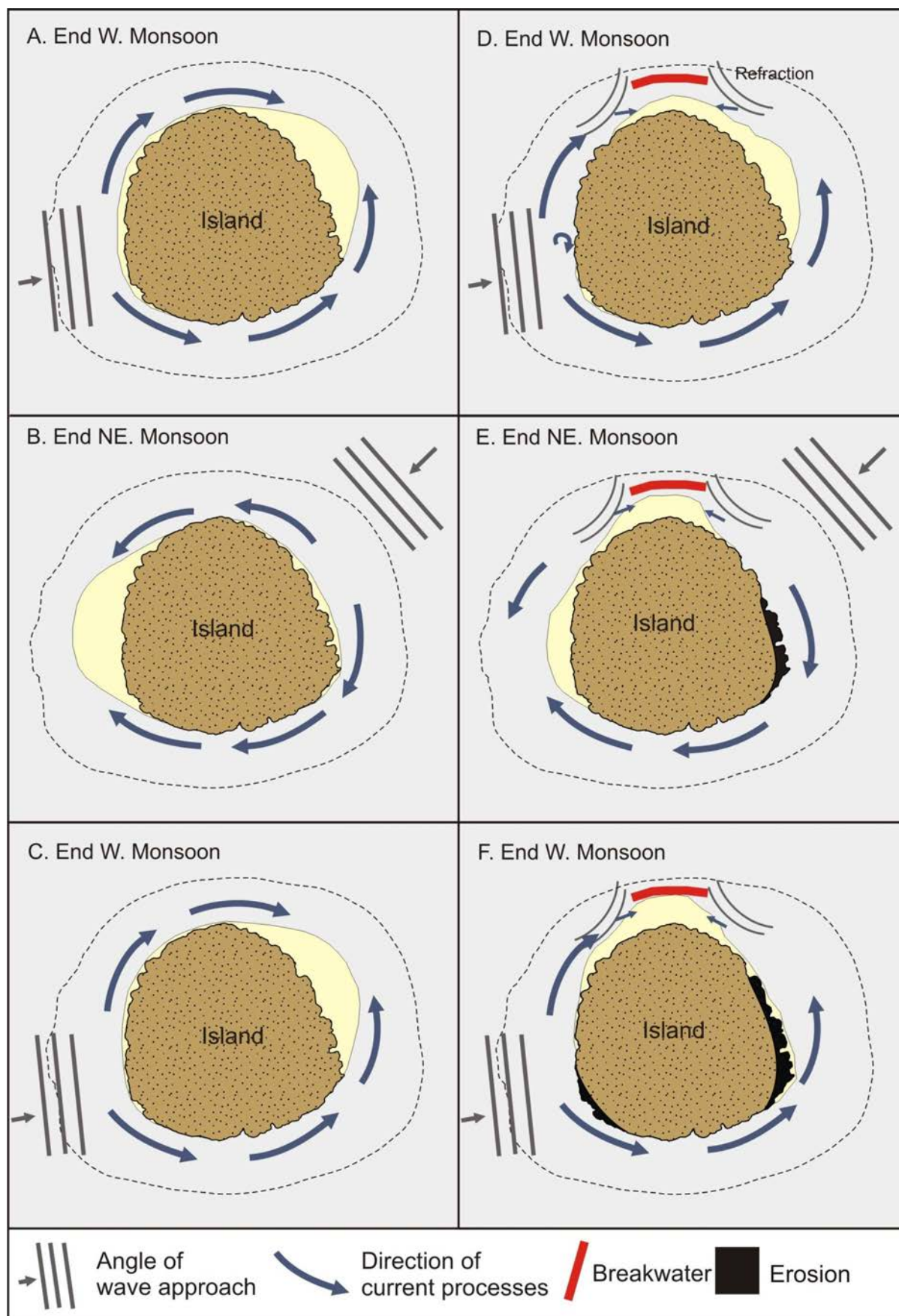


Figure 4.18. Natural seasonal shoreline dynamics on a circular reef island (A-C). Potential impacts on shoreline dynamics following insertion of shore parallel structure (D-E).

5. DECISION SUPPORT FOR COASTAL MANAGEMENT

This report has examined the use, design, construction and potential effects of coastal structures on reef islands in the Maldives. Through analysis of available information on coastal processes and shoreline dynamics it has developed a conceptual understanding (based on field research) of the controls on coastal processes and shoreline dynamics of reef islands. This conceptual understanding has provided the context to examine the likely impacts of structures on the nearshore coastal process regime of reef islands and the potential consequences for shoreline stability (Section 4.5). An issue for management is how this improved understanding of coastal processes and interaction with structures can enhance the approach to coastal management decision-making in the Maldives. This section proposes an alternate approach to the evaluation of coastal management strategies to support improved decision making concerning coastal erosion and development activities at the coast. The emphasis is on the adoption of appropriate tools to combat or prevent shoreline instability. Consideration of approaches to management are underpinned by some guiding principles based on island geomorphic behaviour and coastal processes. Consideration of management approaches are then divided into two: those that deal with large-scale infrastructure development of island shorelines; and, consideration of local-scale erosion mitigation works.

5.1 Guiding Principles

It is recommended that a number of guiding principles underpin the approach to coastal management decision making. These principles are founded on the understanding that:

- **Reef islands in the Maldives are physically sensitive landforms.**
- **The presence of islands on reef surfaces reflects the balance between sediment supply from reefs, the size and shape of the reef platforms, and wave, tide and current processes that transport sediment onto and around island shorelines.**
- **Reef island shorelines are in continual adjustment to changes in sediment supply, wave processes and nearshore current processes.**
- **As islands provide the only habitable land in the Maldives, maintaining the integrity of island landforms is of paramount importance to island communities.**

In light of the above understanding of the natural dynamics of reef islands it is recommended that:

- **Management decisions should preserve the natural functioning of:**
 - **Coral reef ecological processes.**
 - **Reef island coastal processes (nearshore current and wave processes).**
 - **Shoreline change (beach) dynamics.**
- **Management decisions should avoid actions that alter or interfere with:**
 - **Nearshore current processes.**
 - **Nearshore sediment transport processes.**
 - **Beach change.**
- **Placement of structures on island shorelines that promote adverse effects on the coastal environment should be avoided.**
- **Engineered structures are not compatible with the natural dynamics of reef islands and should be avoided where possible.**

5.2 Major Infrastructure Development at the Coast

Many of the largest infrastructure projects located at the coast are Government supported transport and communication projects which include harbours and associated dredged channels.

To date the majority of harbours have been attached to island shorelines and have compromised nearshore processes and shoreline dynamics (Section 4.2).

The selection of sights for harbours and the configuration of boat harbours can take advantage of improved understanding of reef island coastal processes and shoreline dynamics and should involve an evaluation of the latter.

5.2.1 Assessment of shoreline dynamics

Through coastal monitoring it has been established that the magnitude of shoreline dynamics of reef islands can vary depending on the size, shape and location of reef islands as shown in Figs. 4.13, 4.14). It is possible to categorize islands based on the process regime and degree to which shorelines change (Fig. 5.1). These differences can be used to inform the strategic placement and configuration of harbours and other coastal management strategies.

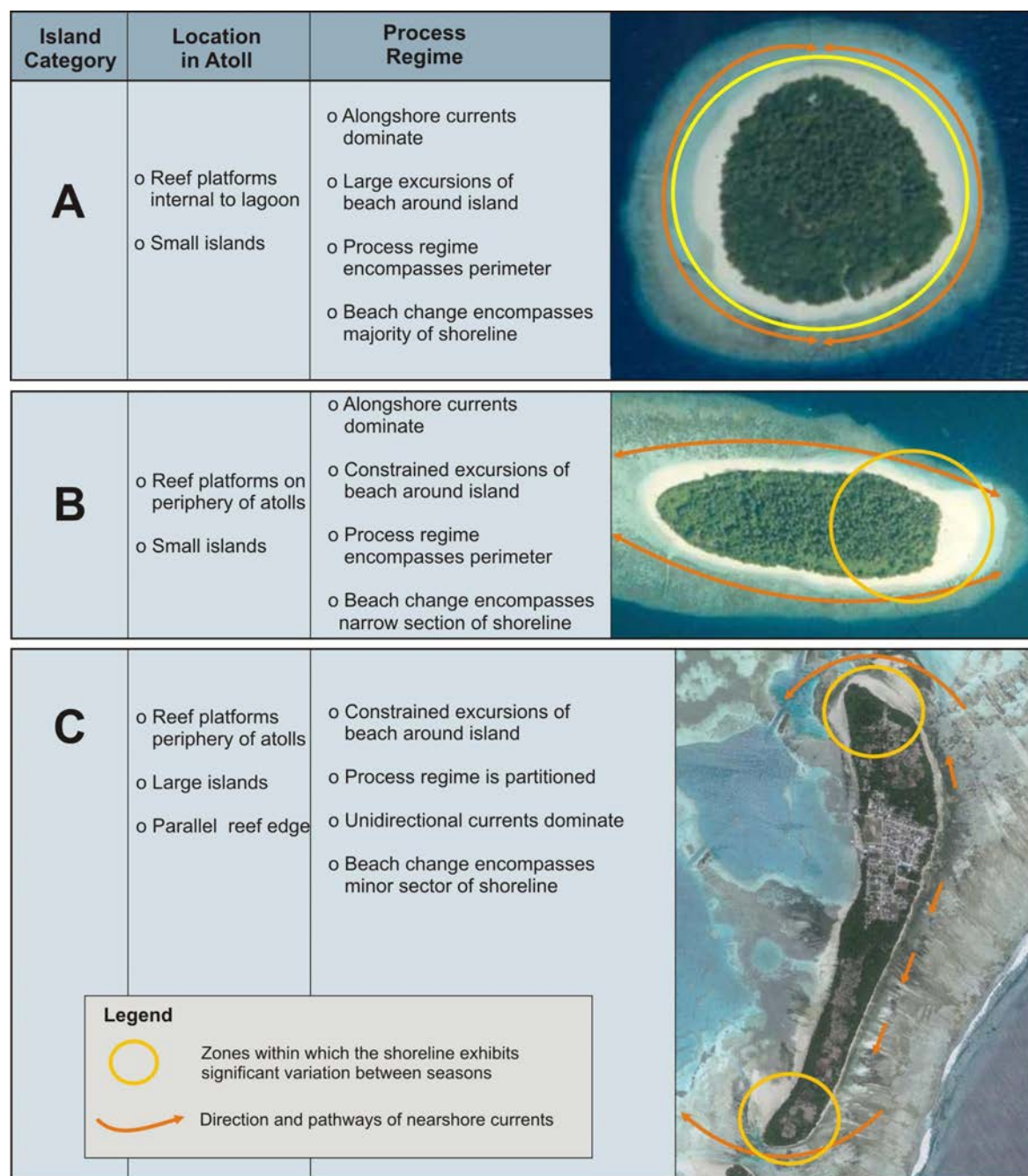


Figure 5.1. Division of reef island types in the Maldives based on location, coastal process characteristics and shoreline dynamics. Ongoing monitoring can develop further island categories.

5.2.2 Recommended management strategies: Type A and B Islands

Type A and B islands are small reef platform islands that can be located either in atoll lagoons (A) or on the periphery of the atoll rim (B). These islands exhibit a high degree of shoreline dynamism and shorelines are sensitive to changes in nearshore processes. On such islands it is recommended that:

i) Permanent and solid shoreline attached structures are prohibited.

Such structures alter nearshore processes and sediment transport and can destabilize island shorelines (see section 4.5).

ii) Harbours should be detached from island shorelines.

Harbour basins should ideally be located off the edge of the reef platform. Location of harbours off the reef edge would reduce impacts on reef platforms wave and current processes and minimize impacts on island shoreline dynamics. Piled jetties should connect the harbour basin and shoreline.

If harbour basins are detached and located on a reef flat it is expected that environmental impacts will be similar to those predicted with breakwaters (Section 4.5.3).

iii) Detached harbours should be connected to the island via piled structures (jetties).

Piled structures allow maintenance of nearshore current processes and sediment transport alongshore.

5.2.2 Recommended management strategies: Type C Islands

Type C islands are larger, located on the periphery of atolls and are oriented parallel to the reef edge. These islands exhibit a high degree of shoreline dynamism at their terminal flanks but due to the extended size, circulatory flow patterns are not apparent and shoreline sediment movements do not encompass the entire shoreline. Indeed some sectors of these shorelines are relatively stable and adjoin extensive shallow lagoon environments. In such settings it is imperative to document the dynamic and stable sectors of shorelines.

On such islands it is recommended that:

iv) Permanent and solid shoreline attached structures are prohibited at terminal ends of islands.

Such structures alter nearshore processes and sediment transport and can destabilize island shorelines (see section 4.5).

v) Harbours should be detached from islands and located in proximity to the most stable sections of lagoon island shorelines.

Harbour basins should be located away from the island shoreline with a minimum separation of 30 m.

vi) Detached Harbours should be connected to the island via piled structures (jetties).

Piled structures allow maintenance of nearshore current processes and sediment transport alongshore.

vii) Permanent and solid shoreline-attached structures may be permitted where it can be demonstrated that the shoreline is stable over decadal timeframes and is not an important sediment bypass zone that connects dynamic sectors of islands.

5.3 Managing Erosion

Effective management of shoreline erosion of reef islands requires the following steps.

5.3.1 Confirmation of the erosion problem

Shoreline and island erosion refer to the long-term (permanent) loss of the shoreline. For islands in the Maldives this can either mean retreat of the shoreline causing loss in total area of islands (and habitable land) or alternatively, migration of islands on their reef platform. In the latter case the position of a shoreline is permanently lost (which may pose particular management problems for inhabitants) while the total island area may remain stable, through deposition of shoreline material on another part of the island.

For coastal management purposes it is useful to distinguish between *short-term* and *long-term* movements of the coast. Observations presented in Section 4.4 indicate island shorelines experience large short-term (seasonal and inter-annual) changes. These changes are seasonally balanced and do not represent erosion. Shoreline monitoring such as that which has been instigated as part of this TA Programme is essential to provide a rigorous understanding of short-term variability in shoreline position. Currently there is little information to assess long-term (decadal scale) movements in island shorelines. However, it should be highlighted that analysis of aerial photographs as advocated in this TA programme will generate information on long-term shoreline change.

Assessment of short-term versus long-term shoreline change is necessary to establish the magnitude and rate of shoreline change (erosion).

5.3.2 Diagnosis of the cause of erosion

Effective management of erosion must identify the cause of erosion. Erosion is triggered by alterations in natural processes and can be caused by changes in natural processes or anthropogenic actions (summarised in Table 4.4).

While the causes outlined in Table 4.4 undoubtedly promote erosion, few studies have quantitatively established the link between a specific cause and the magnitude of erosion. Further, studies have not attempted to tease apart the relative importance of natural versus human-induced causes of erosion and the cumulative effects of human actions at the coast. Such a distinction is of more than academic importance. Management of specific erosion issues is most effective when based on a complete understanding of how each process has been affected to promote erosion. Identifying the cause of erosion is essential if an erosion problem is to be successfully managed to minimise its effect. For example, beach sand mining has been attributed to causing erosion problems on many islands. To validate this assumption actual quantities mined need to be evaluated in the context of the net sediment deficit in the shoreline sediment budget. If proven to be the cause, management actions can be designed to rectify the problem. This may include restrictions on volumes extracted or replenishment of the sediment volume.

Once the cause of erosion has been established an appropriate strategy to combat the cause can be developed.

Table 4.4. Potential causes of island erosion in the Maldives.

Alterations to Processes leading to Island Erosion	NATURAL CAUSES	HUMAN ACTIVITY
Increasing wave energy at shoreline promoting shoreline instability	<ul style="list-style-type: none"> • Long-term sea level change increasing water depth over reef allowing greater wave energy to propagate across reef • Change in wave regime associated with climate change (e.g. larger waves or change in angle of approach) • Change in frequency/intensity of storms 	<ul style="list-style-type: none"> • Artificially increasing water depth over reef through: <ul style="list-style-type: none"> • Channel dredging (e.g. Fuammulah) • Reef blasting • Coral mining (removing protective buffer of reef) • Re-focusing of wave energy by diffraction/ refraction (e.g. at offshore breakwaters, boat harbours, groynes) • Boat wakes of faster modern craft
Reduction of sediment supply generated on reef	<ul style="list-style-type: none"> • Reduction in reef productivity (e.g. through sea-level stabilisation) 	<ul style="list-style-type: none"> • Pollution of reef - decreasing productivity • Coral mining
Interruption or removal of sediment from the littoral transport budget	<ul style="list-style-type: none"> • Formation of updrift littoral barriers (e.g. through beachrock development) 	<ul style="list-style-type: none"> • Sand extraction or dredging • Coral mining • Insertion of shore perpendicular structures (groynes, rubbish, land reclamation) limiting downstream sediment sources
Increase in sediment transport out of island sediment budget	<ul style="list-style-type: none"> • Increased longshore drift due to change in medium term wave climate • Increase in offshore sediment transport due to increase in sea conditions • Increase in lagoonward sediment transport due to increase in currents 	<ul style="list-style-type: none"> • Scouring of beach due to stormwater discharge • Removal of vegetation • Beach nourishment (add more sediment to transport system that is transported away)

5.3.3 Assessment of coastal processes and shoreline dynamics

Before management strategies can be evaluated the character of coastal processes and shoreline dynamics must be assessed. It is proposed that simple categorization of islands as presented in Figure 5.1 provides the minimum level of analysis. Such categorization can be updated as new information on the range of different island types emerges.

5.3.4 Assessment of assets at risk

The decision to intervene at the coast and mitigate erosion is most commonly exercised when assets are under threat. However, too frequently erosion management strategies are adopted based on physical considerations of land loss, rather than whether the land loss is affecting a community asset. Consequently, it is recommended that:

- i) **Erosion mitigation strategies are only pursued where the width of the island between the upper beach and infrastructure is less than 5 m.**
- ii) **Where the width of the vegetated backshore is greater than 5 m erosion mitigation strategies are not pursued. Rather monitoring should be established to better resolve the rate of shoreline change. Monitoring should occur at 6 month intervals. Periodic review of monitoring data will allow the rate of change to be established and provide a timeframe against which management strategies may need to be taken.**

5.3.5 Selection of management strategy

A range of erosion management strategies have been used and can be considered to combat island erosion. These can be divided into medium and short-term interventions.

Medium-term strategies: Where the width of vegetated backshore is greater than 5 m it is advocated that shoreline monitoring occur to provide improved resolution of the rate of shoreline change. This approach also provides time to consider and evaluate the best approach to mitigate erosion. Such strategies should consider:

- i) *Zoning and Relocation of Asset.* Analysis of the rate of shoreline change and lifetime of the asset at risk should allow for an informed decision as to whether the asset can be relocated landward away from the active shoreline.
- ii) *Soft Engineering Measures:* a number of non-structural solutions can be evaluated including:
 - Beach nourishment: where material is placed on the beach to add sediment to the coastal system.
 - Nourishment of the island ridge: in this approach sediment is placed on the island margin and is vegetated to add sediment volume to the island surface.

Both approaches rely on replenishing the sediment reservoir of the coastal/island system. Importantly such measures are only temporary if the cause of erosion is not solved.

Short-term strategies: Where it is decided that interventions are an urgent priority a range of engineering options can be evaluated. The following sections outline key considerations for the use of different structures.

SHORE PERPENDICULAR STRUCTURES

When considering the use of a shore parallel structure it should be recognized that:

- **A shore perpendicular structure does not solve the cause of erosion.**
- **A shore perpendicular structure alters coastal processes.**
- **A shore perpendicular structure alters natural shoreline dynamics.**
- **A shore parallel structure is likely to transfer the erosion problem to unprotected sections of coastline.**

When considering the use of shore parallel structures It is recommended that:

- i) Permanent shore perpendicular structures (groynes) are prohibited from Type A and B island shorelines.**

Such structures compromise natural processes and shoreline movements and should not be permitted.

- ii) The use of temporary shore perpendicular structures (groynes) is permitted.**

- Such structures should only be permitted following examination and quantification of the shoreline processes and sediment fluxes.
- Structures should be designed (length and height) to trap less than 20 % of the annual alongshore flux of sediment.
- Structures should be made from materials that are able to be relocated (e.g. sand bags or small CEUs).
- Where such structures are permitted, monitoring of island shorelines should occur to assess whether the structure is exacerbating island erosion.

- iii) Permanent shore perpendicular structures (groynes) are permitted on Type C island shorelines.**

Structures should be kept away from the terminal ends (or most dynamic parts) of island shorelines.

SHORE PARALLEL STRUCTURES

When considering the use of a shore parallel structure (seawall) it should be recognized that:

- **A shore parallel structure does not solve the cause of erosion.**
- **A shore parallel structure protects the land and assets behind the structure.**
- **A shore parallel structure is likely to transfer the erosion problem to unprotected sections of coastline.**

When adopting the use of a shore parallel structure it is recommended that:

- i) Shore parallel structures (seawalls) are permitted on island shorelines where:**
 - a. The width of vegetated backshore from island edge to asset is less than 5.0 m
 - b. Where the asset is a critical public lifeline or service structure.

- ii) Shore parallel structures should not be sited on sectors of shoreline that act as major transfer pathways for sediment movement.**

- iii) The design of shore parallel structures must adhere to the design criteria for seawalls (as presented in Figure 4.7). In particular designs must:**
 - a. Have suitable foundations.
 - b. Have suitable toe protection.
 - c. Have a design elevation to prevent wave overtopping.
 - d. Be composed of engineering units able to withstand waves of 1.0 m in height.
 - e. Allow suitable drainage of surface water.
 - f. Ensure void spaces are avoided to prevent slumping and collapse.
 - g. Be securely fixed to the island.

- iv) Shore parallel structures must not protrude from the planform configuration of the coastline.**

- v) Where such structures are permitted, monitoring of island shorelines should occur to assess whether the structure is exacerbating island erosion.**

BREAKWATERS

When considering the use of offshore breakwaters it should be recognized that:

- **A breakwater does not solve the cause of erosion.**
- **A breakwater modifies reef top wave and current processes.**
- **A breakwater can fundamentally alter the nearshore coastal process regime of an island.**
- **A breakwater can alter the natural shoreline dynamics of an island and is likely to promote island instability.**
- **There is no convincing evidence that breakwaters stabilize and build reef island shorelines.**

When adopting the use of a breakwater it is recommended that:

i) Breakwaters are prohibited on Type A islands.

On Type A islands (Fig. 5.1) the process regime affects the entire shoreline. Therefore, interferences with the processes regime will promote alongshore instability.

ii) Breakwaters are permitted in Type B and C islands on sectors of shoreline which do not show a high degree of seasonal change (Fig. 5.1).

NOURISHMENT

When considering the use of nourishment it should be recognised that:

- **Nourishment does not solve the cause of erosion.**
- **Nourishment replaces sediment in the coastal system.**
- **Renourishment will be necessary in the medium-term.**

When adopting the use of nourishment it is recommended that:

- i) **The shoreline sediment budget is estimated.**

- ii) **The estimated volume of sediment required to replenish the shoreline sediment reservoir is identified.**

It is important not to overfill the sediment system as this could also lead to adverse environmental effects.

- iii) **Nourishment material is equivalent or larger than the native beach sediment.**

- iv) **An available source of sediment is identified.**

- v) **Placement occurs during calm weather conditions to avoid adverse impacts on the reef system.**

Avoid nourishing the shoreline under the most active sediment transport period in any season.

- vi) **Sediment placement occurs either on the land surface or beach system, within the dynamic envelope of beach change.**

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APPENDIX 1: REVIEW OF PROCESS CONTROLS ON ISLAND CHANGE

Table 2. Summary of research on Maldivian reef island formation and processes

Articles related to reef island development and process controls on island change

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