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Joseph Mario Ray

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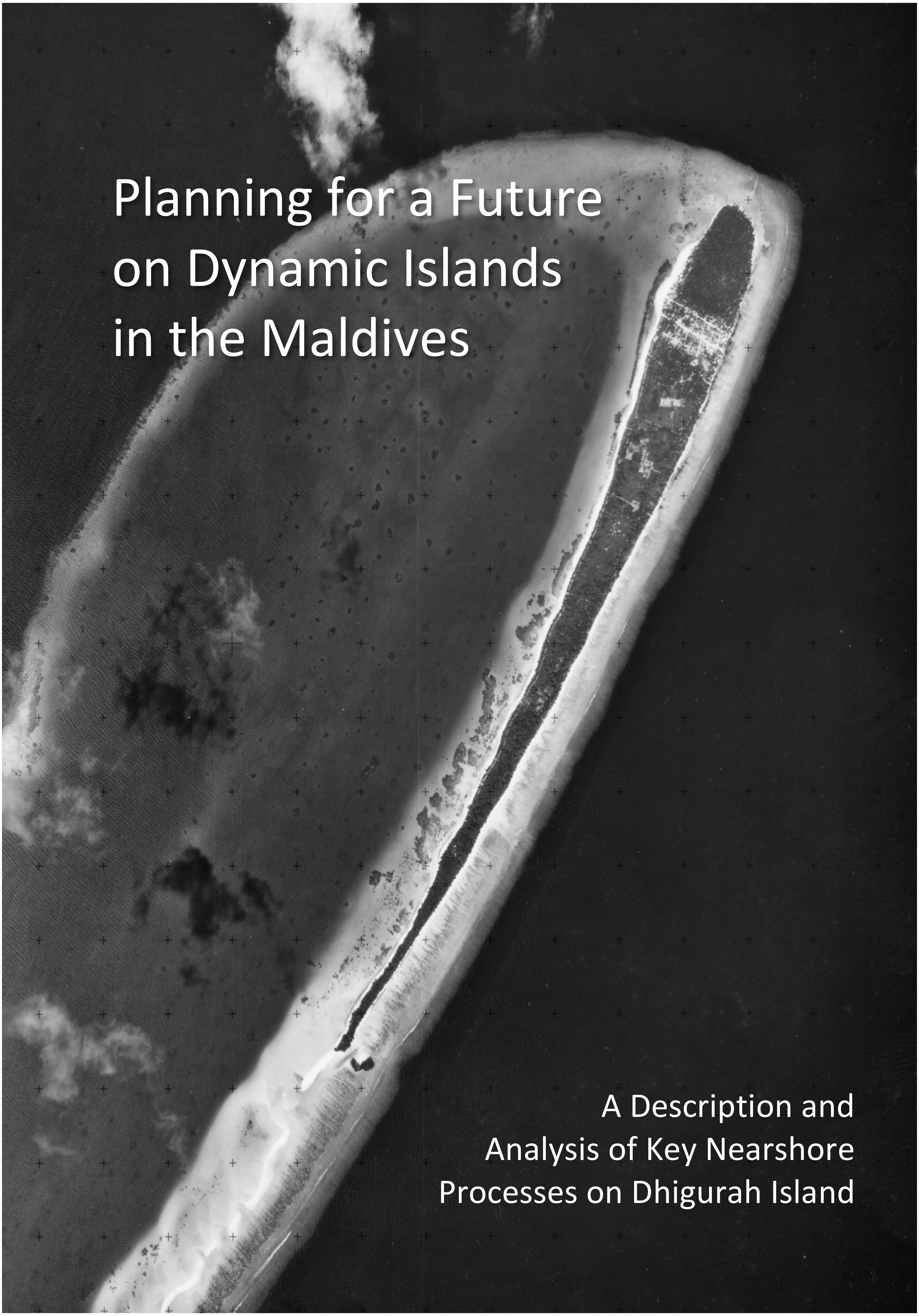

Planning for a Future on Dynamic Islands in the Maldives

A Description and Analysis of Key Nearshore Processes on Dhigurah Island

THE UNIVERSITY OF EDINBURGH

ABSTRACT OF THESIS

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Name of Candidate **Joseph Mario Ray**

Address **20 Thirlestane Road, Edinburgh, EH9 1AW**

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Low-lying atoll states are commonly portrayed as the most vulnerable to the impacts of sea-level rise. However, many studies now contradict this notion by showing atoll islands to be dynamic morphological landforms that adjust their shape, size and position in response to changes in boundary conditions.

A common response to shoreline instability and the needs of the tourist industry has been to construct hard-engineering structures, which degrade natural habitat and undermine the inherent ability of islands to adapt to environmental changes. Coastal infrastructure is known to constrain nearshore processes and yet it is often designed without information on, or proper consideration of, its effect on nearshore processes.

If island communities are to allow their islands to be dynamic and to live with natural nearshore processes, they need a better site-specific understanding of these processes. To address part of this gap in understanding, this study examines two key nearshore processes on Dhigurah Island, the Maldives – sediment supply and seagrass. It finds that there is an active sediment supply of *Halimeda* and coralline red algae from the inner reef flat to the oceanward shoreline. It also concludes that seagrass beds are significantly higher than surrounding substrates and they provide important coastal protection. With understanding of these processes, island planners will be able to protect and incorporate them in any future development of coastal infrastructure.

This study also carries wider significance, as Dhigurah Island is representative of many islands in the Maldives that are beginning to embrace tourism. Current provisions for planners to gain understanding of the nearshore processes on all the islands in the Maldives expecting development are deficient. Therefore, this study presents the principles behind, and the scope of, a rapid study that could be conducted on any island within a reasonable timescale. Through community ownership of this rapid study and lifelong learning, communities will be able develop an understanding of nearshore processes. This will give them the skill and motivation to work with the natural processes by which their islands adapt to environmental changes.

Acknowledgements

To Dad, the adventurer.
Thank you for taking me on so many adventures, from the Red Sea to Fiji, Suakin and Zanzibar.

To Mum, the artist.
You inspired me with stories of Jacques Cousteau, sharks and by painting the walls of our house with tropical fish.

To Prof. Sandy Tudhope, thank you for the time you invested in guiding me through this dissertation. I have thoroughly enjoyed learning from you and have been inspired by your teaching. I look forward to putting my new skill set to use and exploring more islands in the future.

To Dr. Meriwether Wilson, thank you for a brilliant programme. I am so grateful to have been given the opportunity to pursue so many interesting things, from octopus fisheries, to deep sea corals, migrating tuna, and, of course, Parrotfish. I look forward to sharing these ecosystem stories with others.

And finally, thanks to Dan, for what has been a grand year full of fun and plenty of Camembert.

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Abbreviations

CRA	Coralline Red Algae
EIA	Environmental Impact Assessment
Halimeda spp.	*Halimeda* species
H. micronesica	*Halimeda micronescia*
H. macrophysa	*Halimeda macrophysa*
ICCR	Integrating Climate Change Risks into Resilient Island Planning
IUCN	International Union for Conservation of Nature
MWSRP	Maldives Whaleshark Research Programme
RNPS	Rapid Nearshore Processes Study

1. Introduction

Low-lying atoll states are commonly portrayed as the most vulnerable to the impacts of sea-level rise [1,2,3,4,5]. However, many studies now contradict the notion that sea-level rise will cause widespread destabilisation, by showing islands to be dynamic morphological landforms that adjust their shape, size and position in response to changes in boundary conditions [6,7,8]. Atoll islands, it is argued, have an inherent ability to adapt to threats such as sea-level rise, if natural processes are allowed to continue. These findings mean that it is possible to be cautiously optimistic about the prospects of a proportion of low-lying atolls.

In the context of rapid population growth, the development of tourism and limited land area on many atoll islands [9,10], a common response to perceived island instability and perceived erosion has been to maintain the integrity of shorelines and reclaim land through hard-engineering structures [11,12]. But coastal infrastructure is known to constrain nearshore processes and force them along a trajectory which otherwise they would not take [13,14]. Furthermore, coastal infrastructure is often designed without information on nearshore processes and the ad hoc replication of these designs has resulted in a high rate of failure.

If island communities are to allow their islands to be dynamic and they are to live with natural nearshore processes, they need a better understanding of these processes, an understanding that is site-specific [14,15]. This study addresses part of this need by describing two of the key nearshore processes, sediment supply and the influence of seagrass, on Dhigurah Island, the Maldives. This study is unique because there are currently no studies that describe and analyse Dhigurah Island's nearshore processes. It will provide decision makers with information that can help them ensure that future development does not undermine the key nearshore processes described, thereby helping to maintain the ability of the island to respond dynamically to threats to its stability. The timing of this study is particularly important because it comes at a time that pre-empts an expected boom in development on Dhigurah Island [16].

This study also carries greater significance; Dhigurah Island is representative of many islands in the Maldives that are beginning to embrace tourism. And while every island is different, there are similarities in nearshore processes that govern island maintenance and construction.

Current provisions for planners to gain understanding of the nearshore processes on all the islands in the Maldives expecting development within the necessary timescale are seriously deficient [17]. Therefore, this study proposes a way forward. Drawing on the findings and insights of the nearshore processes studied on Dhigurah Island, and a review of relevant literature, this study proposes the scope of a ‘rapid nearshore processes study’ (RNPS) that could be used to assess the nearshore processes on any island in the Maldives.

2. Literature Review

This chapter provides a review of existing literature relevant to this study's line of enquiry and will be referred to throughout subsequent chapters. It demonstrates how this study addresses a particular gap in the literature, as well as highlighting why it is unique, important and carries wider significance beyond the study site.

Vulnerability of Low-Lying Atoll Islands

The long-term persistence of low-lying atoll islands is widely debated. A popular view, based on anticipated acceleration of sea-level rise, is that low-lying atoll islands will be subject to coastal erosion, flooding, saline intrusion of fresh ground-water and finally inundation [1,2]. The Maldives, the Marshall Islands, Kiribati and Tuvalu, are perceived to be particularly vulnerable due to their low elevation, constrained resource base, and high population densities [3,4,5]. It is expected that many of these states' islands will become uninhabitable during the 21st century [2]. According to Yamamoto and Esteban [18], if the most extreme predictions of climate change are realised, then it is highly probable that entire island states will physically disappear due to submergence by the sea. In this scenario, island states would need to evacuate their entire populations. While this is a hypothetical situation, mass relocation forms part of several island states' adaptation plans. The government of Kiribati, for example, has purchased land in Fiji and is trying to equip its population with higher level qualifications as part of its 'Migration with Dignity' policy [19]. Likewise, the Tuvaluan government is also discussing potential relocation options [20].

Dynamic Islands

However, numerous other studies now contradict the notion that sea-level rise will cause widespread destabilisation and inundation of low-lying atoll islands in the 21st century and offer a cautiously optimistic outlook instead [11,21]. Islands, it is argued, are not inert landforms that will remain static as sea-level rises [21]. Rather, they are dynamic morphological landforms that adjust their shape, size and position in response to changes in boundary conditions; this ability to adapt has been observed on a decadal time scale [8] as well as a multi-centinial time scale [6,7] (Figure 2.1).

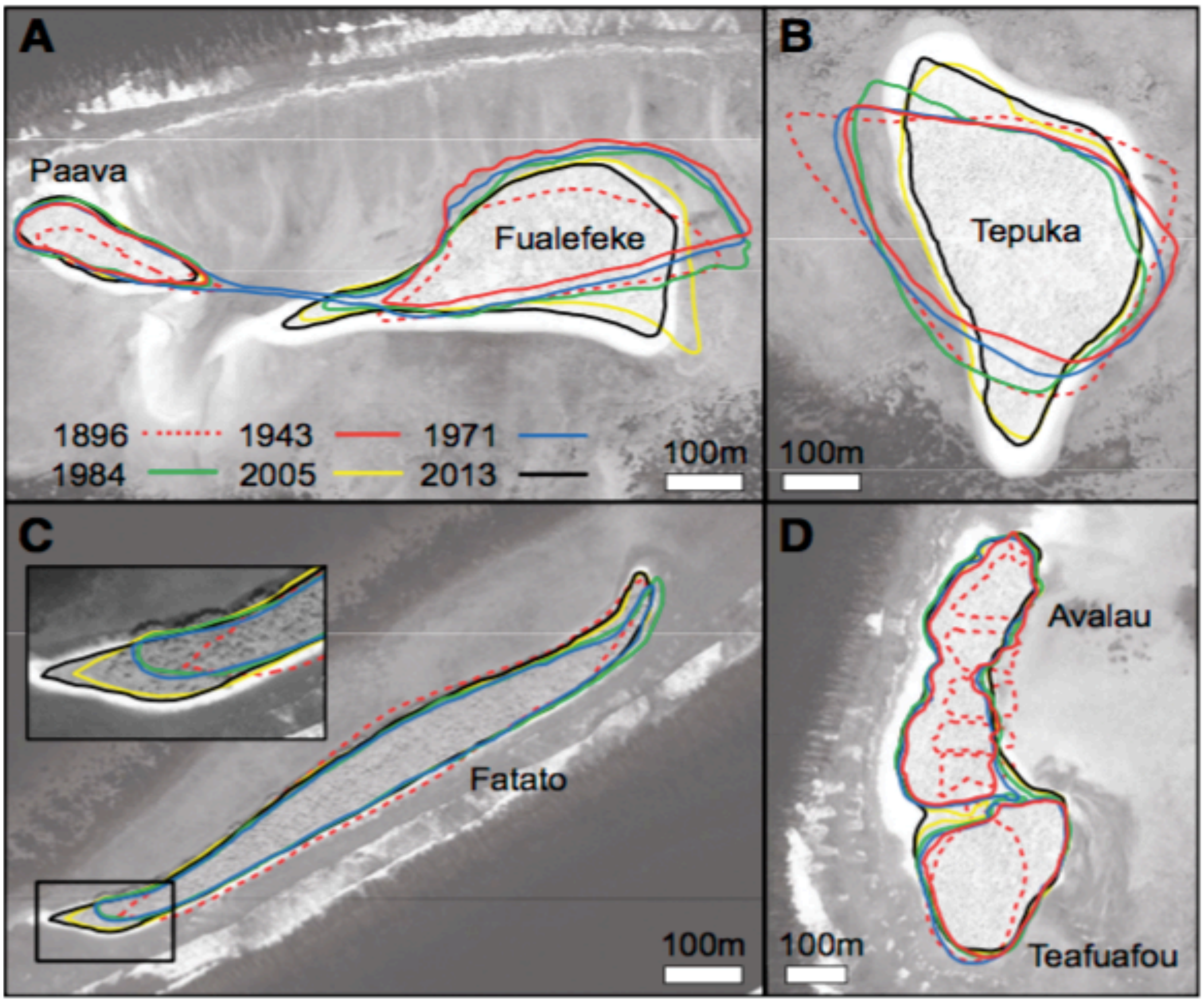


Figure 2.1: Image taken from Kench et al. [7] which shows how four different islands on Funafuti Atoll, Tuvalu, have changed between 1896 and 2013.

Atoll islands also have the ability to grow or build upwards with several studies showing evidence of islands experiencing net accretion rather than long-term erosion [6,7,11,22,23]. In Funafuti, a Central Pacific atoll, it was found that despite experiencing some of the highest rates of sea-level rise over the past 60 years, no islands have physically disappeared due to submergence by the sea [7]. Instead, the majority of islands have enlarged with a 7.3% increase in net island area during the 20th century [7]. Likewise, results from a study of Wotje Atoll (Figure 2.2), the Marshall Islands, suggest that between 1945 and 2010 there has been net accretion rather than erosion [6].

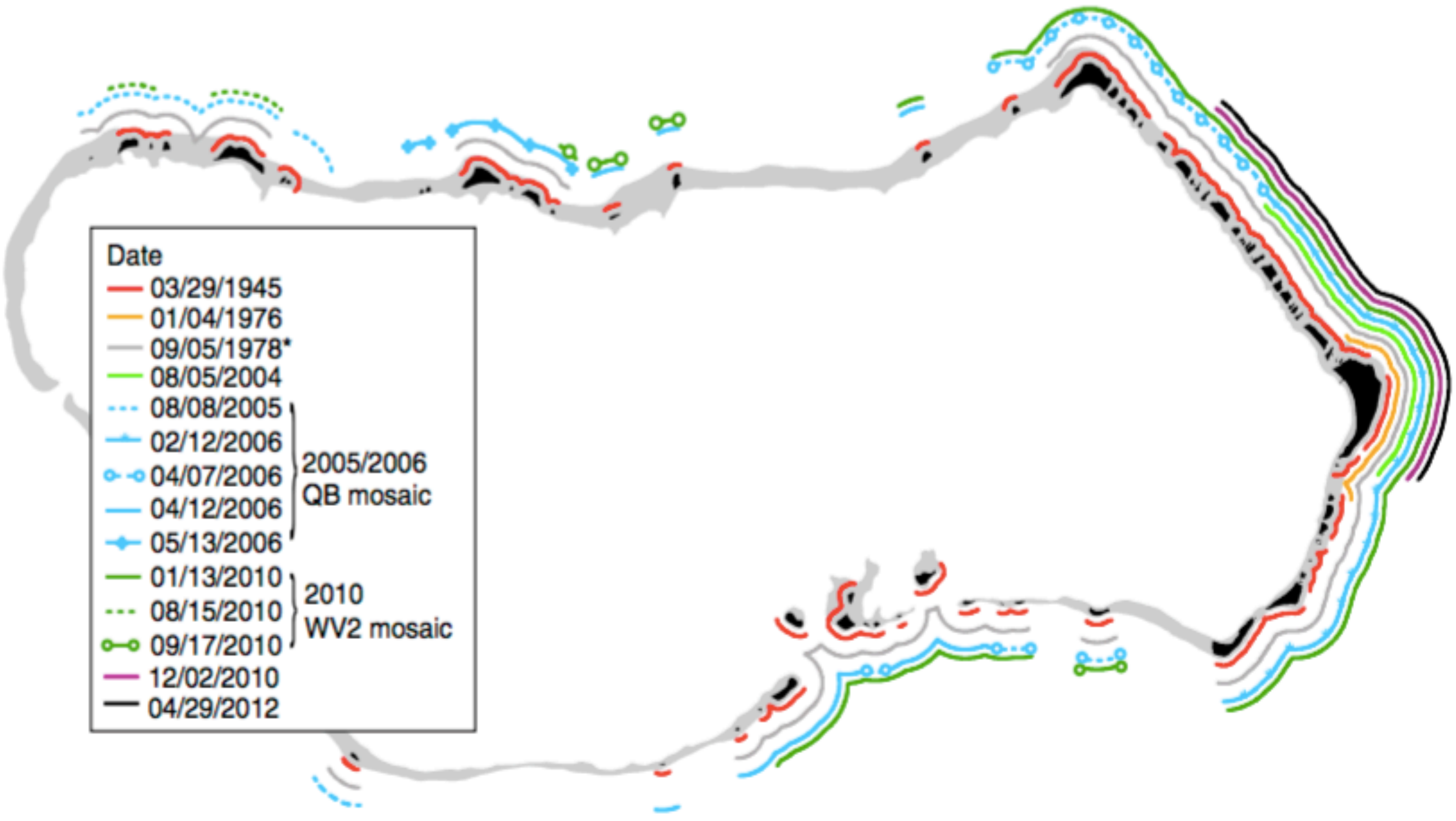


Figure 2.2: Image taken from Ford [6] which shows changes in shoreline position of Wotje Atoll, Marshall Islands.

These findings offer hope for a proportion of low-lying atoll nations. If islands are to maintain their inherent capacity to adapt to changes in boundary conditions, then they must be allowed to be dynamic, to erode and accrete, as they constantly change shape, position, and size [14]. For island communities, co-existing with dynamic islands requires understanding of nearshore processes and flexibility.

Co-existing with Dynamic Islands

In the context of rapid population growth, the development of tourism and limited land area on many atoll islands [9,10] a common response to perceived island instability and erosion has been to maintain the integrity of shorelines and reclaim land through hard-engineering structures [11,12]. In Tarawa Atoll, Kiribati, for example, 29% of the shoreline has seawalls [24] and there have also been land reclamations [11].

The discrete nature of the Maldives' island morphology has seen communities develop a much longer dependence on hard-engineering structures than many other atolls with more semi-continuous islands [25]. Francois Pyrad de Laval, a French navigator who visited the Maldives from 1602 – 1607, describes an already long-standing tradition of coral masonry [26]. British civil servant Harry Bell, who spent time in the Maldives as an archaeologist in the early 20th century, describes how key buildings such as the mosque, royal palace and seawall protecting the harbour were constructed of coral [27]. Today, Malé has heavily armoured shorelines all around the perimeter of the island (see Figure 2.3). These structures have enabled Malé to support a population of more than 153,000 in just 5.8 square kilometres [28]. The extent to which the surrounding coral reef habitats and nearshore processes have been disrupted and degraded, as well as the amount of investment in infrastructure, means that Malé's long-term persistence is reliant on the maintenance of hard-engineering structures [29]. It is locked into a 'hard path.'

Figure 2.3: Photo taken by author in Malé, showing heavily armoured shoreline.

Hard-engineering solutions are also an extremely expensive solution. According to Donner and Webber [30], protecting South Tarawa, one of 32 atolls in Kiribati, for 25 years would cost approximately USD 100 million, without taking into account maintenance costs, sourcing of materials and reconstruction after storm events. In response to the 2004 Boxing Day Tsunami, the Maldivian government tried to pursue a more cost effective hard-engineering strategy called the 'Safer Islands Strategy' [29]. Several islands were identified which would become regional centres where best practices learnt from Malé and Hulhumalé could be applied [29] (see Figure 2.4). By selecting only 10 – 14 islands to follow a similar development path as Malé, and coupling this with a population consolidation programme already under way, a more cost effective way of providing physical and livelihood security was hoped to be achieved [29].

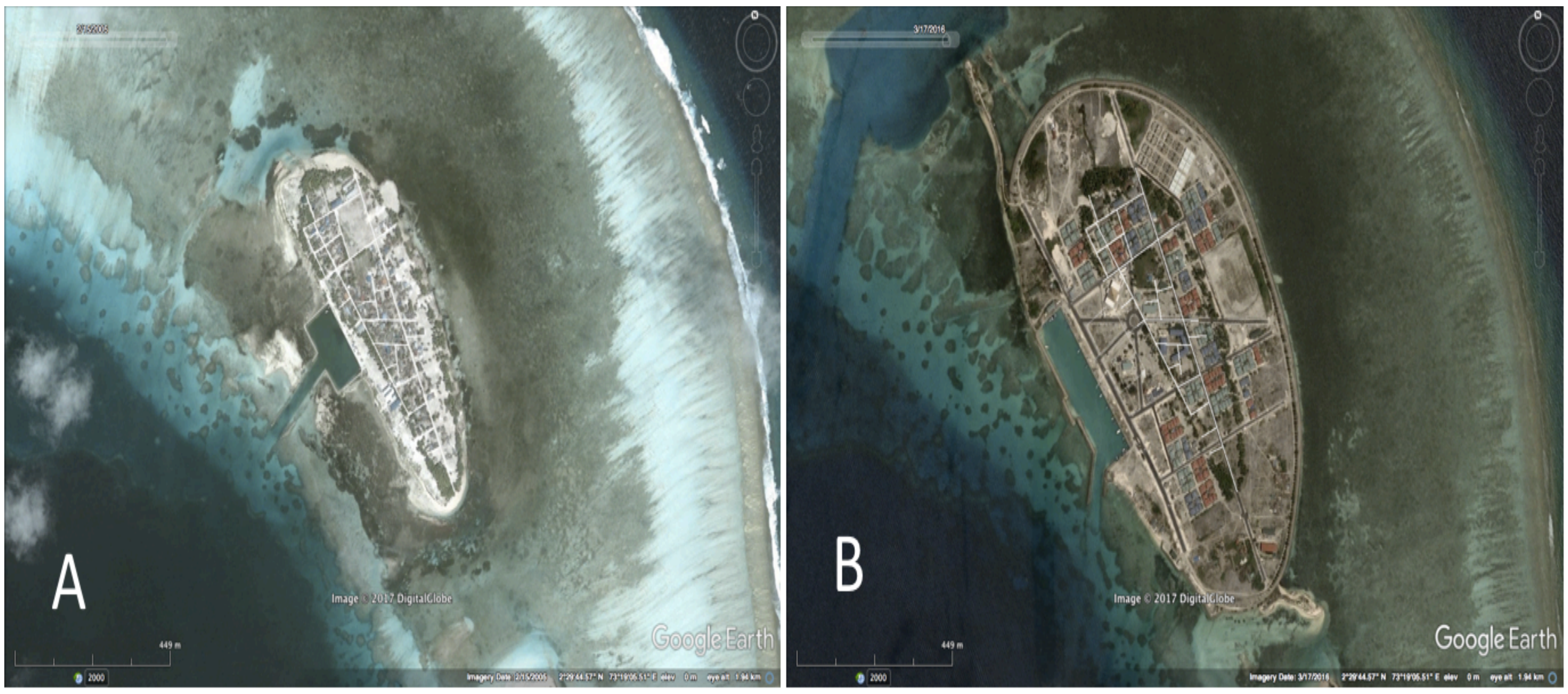


Figure 2.4: The island of Vilufushi was selected as a 'Safe island.' These historical images, which are at the same scale, from Google Earth show that a significant amount of development, land reclamation and construction has taken place in the space of 11 years: A) Vilufushi in 2005 B) Vilufushi in 2016.

The 'Safer Islands Strategy', however, was abandoned in 2010 in favour of the 'Integrating Climate Change Risks into Resilient Island Planning' (ICCR) programme [29,31]. With a total project budget of USD 9.3 million, key benefits of the ICCR were said to be lower costs, as well as greater local involvement [31]. This strategy would promote "soft adaptation" measures. The term "soft adaptation" used by Sovacool (2011) refers to climate change adaptation measures that "prioritise natural capital, community control, simplicity and appropriateness." Hard measures, include "capital-intensive, large, complex, inflexible technology and infrastructure" [32]. In the context of island stability, soft adaptation includes activities such as mangrove planting and reef conservation [30], whereas hard measures refer to hard-engineering structures as mentioned above, large-scale dredging, reclamation, excavation and blasting.

Adverse Effects of Hard-Engineering on Nearshore Processes

There has also been a growing recognition of the adverse effects of coastal infrastructure on nearshore processes [13,14]. In a study of Majuro, the capital of the Marshall Islands, it was found that coastal infrastructure not only removed sediment during the construction phase, but also disrupted long-shore sediment transport leading to erosion [12]. In a study of the Maldives, Kench [14] shows how engineered structures “directly compromise the natural processes of island dynamics” and ultimately force islands along a spatial trajectory which otherwise they would not take. Figure 2.5 shows how coastal processes and coastal infrastructure might interact [14]. Figure 2.5 shows the natural shoreline dynamics of a small elongated island without (a-c) and with (d-f) a harbour constructed on one side. Introducing a structure perpendicular to an island deflects currents from the updrift side of the structure and forms eddies on the downdrift side causing accelerated rates of deposition and erosion respectively. It also prevents sediment transport with accretion of sediment on the updrift side and reduction on the downdrift side. Perpendicular structures, argues Kench [14], can “unevenly partition the sediment reservoir into discrete cells,” which can encourage erosion by “reducing the volume of sediment in one part of the shoreline sediment budget.”

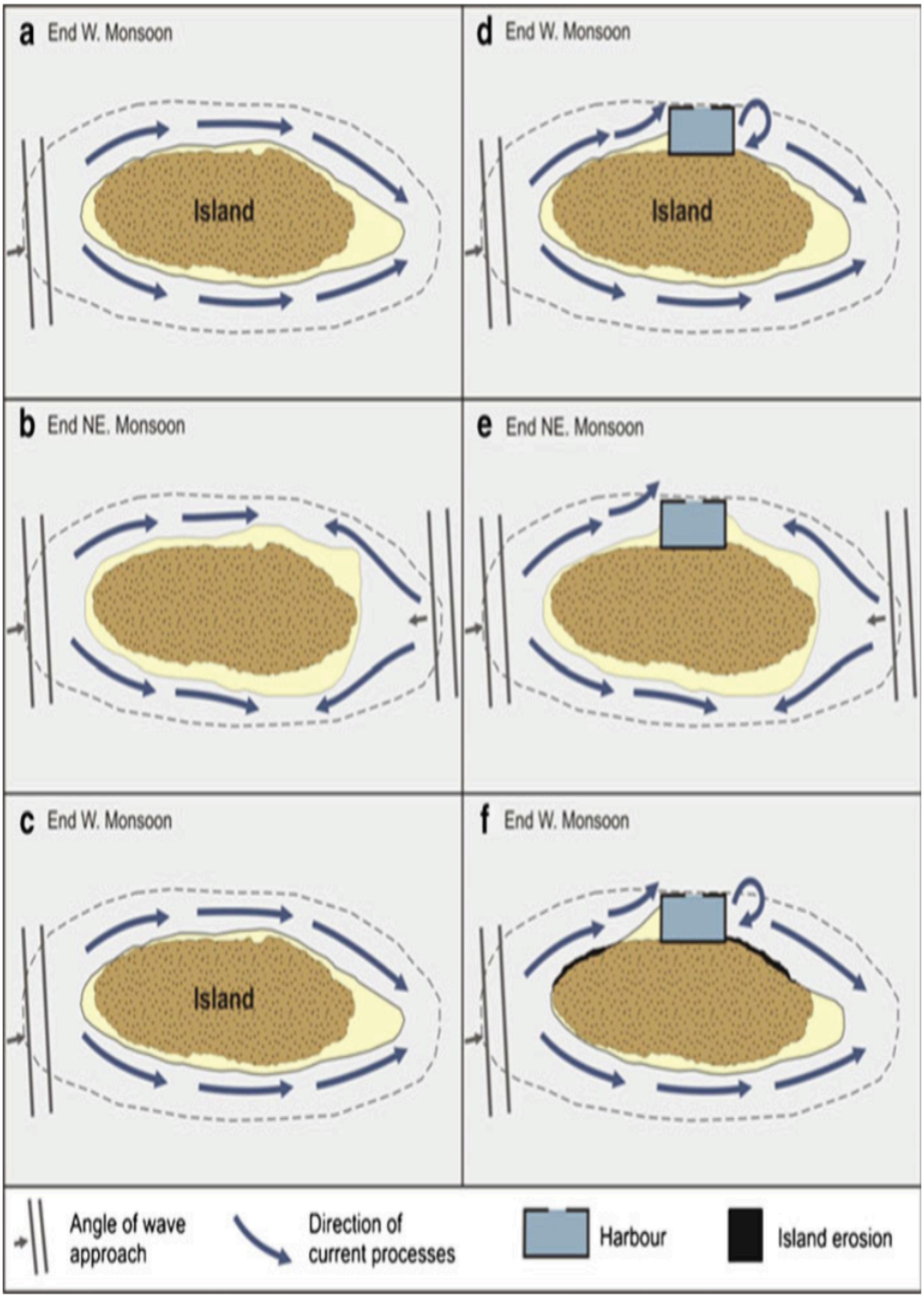


Figure 2.5: a) b) and c): Natural shoreline dynamics of a small elongate island in the Maldives. d) e) and f): the potential impacts that a harbour might have on natural shoreline dynamics.

Despite evidence of hard-engineering structures exacerbating erosion [13,14,30], they are still popular on smaller islands [29]. They were particularly favoured in the aftermath of the 2004 Boxing Day Tsunami [29]. In a survey of 30 inhabited islands in the Maldives, it was found that 73% of the islands had constructed seawalls and 90% had infrastructure associated with harbours [33]. One of the difficulties for implementing soft measures is that they are often viewed as temporary solutions and are not as well received as the more tangible hard structures [31]. A similar perception of hard measures has been seen in Kiribati where, despite the evidence of seawalls exacerbating erosion [30], they remain a popular adaptation measure and continue to carry status and demonstrate public spending [30].

Failure of Hard-Engineering

Frustration has been growing amongst local communities and resort owners as the rate of failure of hard-engineering structures in the Maldives is high [33,34,35]. A key reason for this, Owen et al. [15] argue, is that assertions of island vulnerability, and subsequent responses, often use a 'fixed template' in which islands are represented as homogenous, both in terms of their "biophysical and social characteristics and how they are impacted by environmental change." Broad-scale national assessments of vulnerability operate at a scale which is not appropriate for understanding local variances in vulnerability [36]. Recent studies have documented considerable differences in nearshore process even between islands within the same region [7,11,37]. Therefore, while a particular design of a hard engineering structure may be appropriate for one island, due to the differences in coastal nearshore processes it may be inappropriate for another [33,34].

A second reason for the high rate of failure of hard engineering structures in the Maldives is due to the ad hoc replication of structures by communities who do not have the technical capacity [33,34]. In response to the 2004 Boxing Day Tsunami, many smaller islands copied Malé by building hard engineering structures [29]. But while Malé's defenses were contracted to professional construction firms, construction of defences on rural islands often breaches best practices [33,34].

Understanding Nearshore Processes

Kench [14] and Owen et al. [15] argue that there is a major gap in “site-specific” and “ground-truthed” understanding of local nearshore processes. A better understanding of nearshore processes at this scale would enable more robust assessments of island vulnerability and better inform future development and adaptation strategies [15]. Rather than relying on spatial analysis tools, Owen et al. [15] argue that using simple geographic tools and supporting this with community observations is more effective in providing information at an appropriate scale that can be used more effectively to inform development and monitor future change.

While there are many processes that govern the maintenance and construction of atoll islands, including sediment supply, exposure to wave regimes, storm events, seasonal variability and establishment of vegetation, this study focuses on two nearshore processes: 1) sediment supply and 2) seagrass. The reasons for choosing these two processes are explained below and literature on both processes is examined.

Sediment Supply

The long-term persistence of atoll islands is dependent on the production and transport of sediment towards the shoreline [22]. Islands in the Maldives are composed of sediment produced on surrounding coral reef habitats. The primary source of sediment is through the conversion of reef framework to sediment by Parrotfish [38,39,40]. Parrotfish graze on algae but will also ingest pieces of rock and coral which is later excreted as fine sand. Sand is then exported off the reef or transported towards the shoreline. Over time, the transportation of sand can create entire new islands that are sometimes colonised by animals and plants [39]. Figure 2.6 shows the major sedimentary processes observed by Perry et al. [39] on Vakkaru, the Maldives.

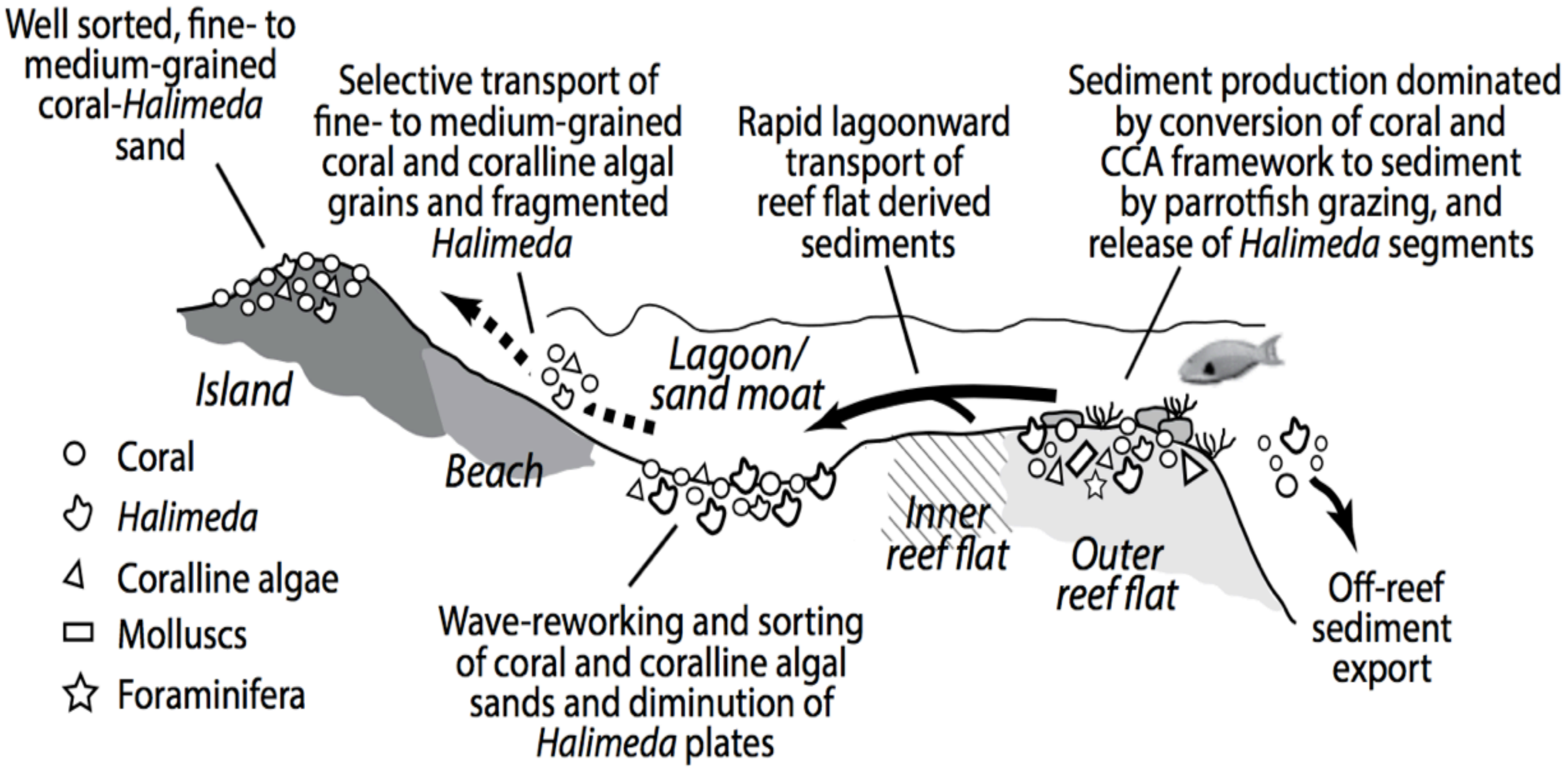
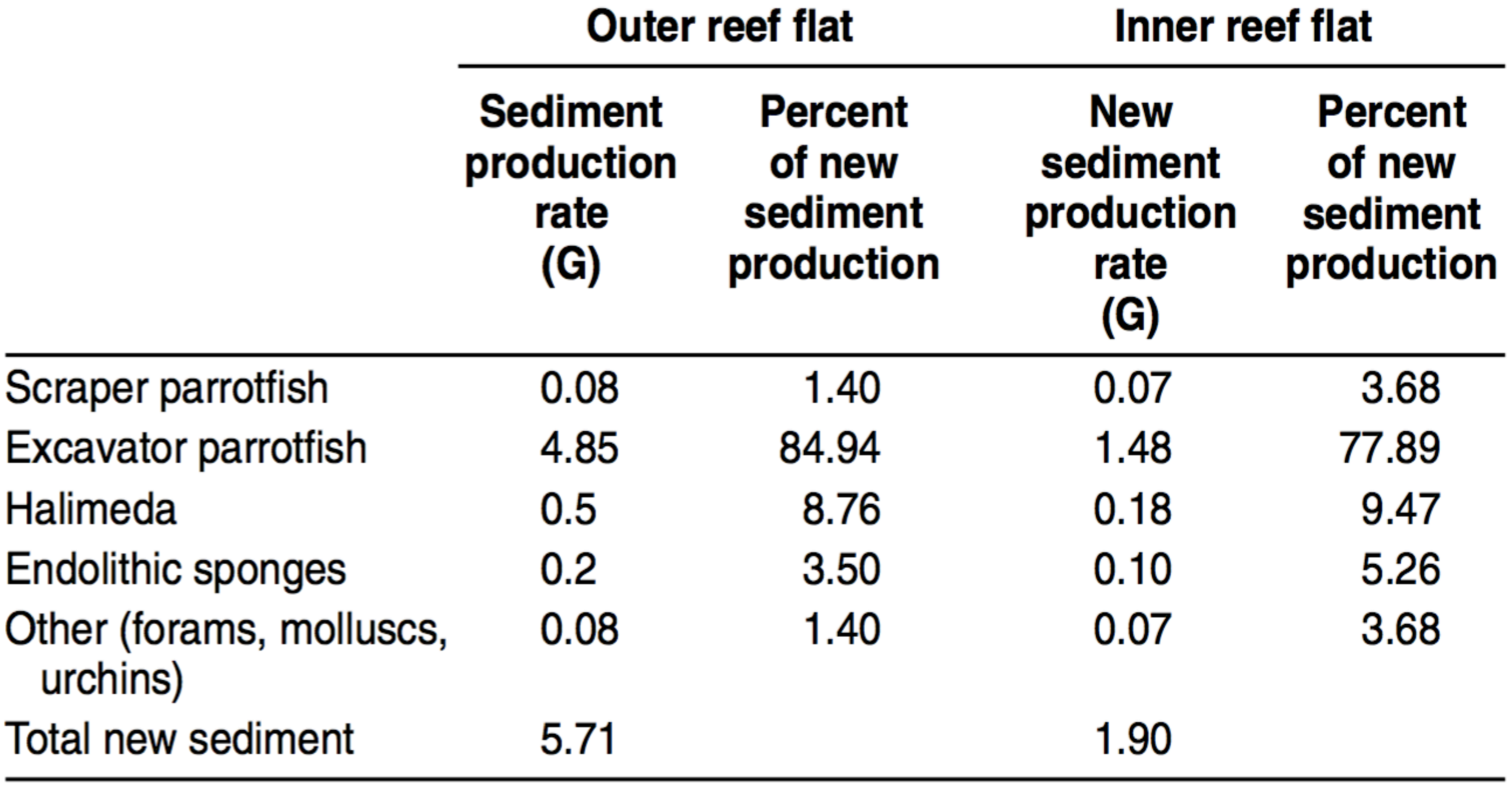


Figure 2.6: Schematic summarising the major sedimentary processes around the island of Vakkaru, the Maldives [39].

Coral reef framework is also converted to sediment as a result of abrasion from high-magnitude events that can wash up large amounts of coral rubble towards the shore [40]. One recent event that will have contributed to the conversion of reef framework to sediment is the 2004 Boxing Day Tsunami. However, given that the Maldives do not typically experience severe storms, rubble is not be expected to be a prominent part of island substrates [22].



	Outer reef flat		Inner reef flat	
	Sediment production rate (G)	Percent of new sediment production	New sediment production rate (G)	Percent of new sediment production
Scraper parrotfish	0.08	1.40	0.07	3.68
Excavator parrotfish	4.85	84.94	1.48	77.89
Halimeda	0.5	8.76	0.18	9.47
Endolithic sponges	0.2	3.50	0.10	5.26
Other (forams, molluscs, urchins)	0.08	1.40	0.07	3.68
Total new sediment	5.71		1.90	

Figure 2.7: Total new sediment, and the proportion of contributors, produced on the reef surrounding Vakkaru Island, the Maldives [39]. Note: G = kg $CaCO_3$ m^2 yr^{-1}.

The next most abundant contributor of sediment to islands in the Maldives is most commonly *Halimeda* [39] (see Figure 2.7), a green macro algae that produces a calcium carbonate skeleton [41]. Once *Halimeda* segments are released, they tend to either be exported off-reef, or transported towards the island (see Figure 2.6). Although different species of *Halimeda* produce varying quantities of sediment, they are known to be able to produce more than 2 kg $CaCO_3$ m^{-2} yr^{-1} [42,43]. In Perry et al. [39] study of Vakkaru Island, *Halimeda* produced more than 8% and 9% of the sediment produced on the outer reef flat and inner reef flat respectively.

Coralline red algae (CRA), while not a major source in Perry et al.'s [39] study of Vakkaru Island, are another producer of carbonate sediment that have been shown to play an important part in the sediment budget of Indo-Pacific atolls [44,45]. CRA are known to thrive in shallow subtidal and intertidal habitats [46,47]. Unlike *Halimeda*, they can photosynthesise under very low light [48]. Assessing the calcium carbonate production rates of coralline red algae is a priority for future research, however, studies have recorded rates between 23.38g $CaCO_3$ m^{-2} yr^{-1} and 81.09g $CaCO_3$ m^{-2} yr^{-1} [45]. CRA are extremely vulnerable to ocean acidification and rising temperatures showing "decreased net calcification, decreased growth and reproduction, as well as reduced abundance and diversity" [45,49]. Unfavourable conditions give an advantage to non-calcifying algae which can result in an ecological shift as CRA are outcompeted for light and space [50]. The Maldives experienced three mass-bleaching events in recent history: 1998, 2010 and 2016 [51], which is likely to have had a significant effect on the abundance of CRA and the sediment budget of many islands in the Maldives.

Yet despite these fundamental links between island stability and sediment production, sediment production regimes remain poorly quantified [39]. The Reef Budget Methodology, pioneered by Perry et al. [52], attempts to quantify the geomorphic performance of an island by determining the abundance of the most significant carbonate producing and eroding taxa and then applying known carbonate production rates [52]. The results provide an indication as to whether the island is in a net accretionary, net erosional, or static budgetary state [52].

Nevertheless, without information on the transport of sediment from the reef to the shoreline, sediment production budgets only provide a partial picture of sediment supply to an island. A recent study by Perry et al. [53], found that an abundance of *Halimeda* on the reefs surrounding Kadahalagalaa Island, Huvadhoo Atoll, did not result in an abundance of island building sediment on adjacent beaches [53]. *Halimeda* segments can rapidly degrade into silt and clay size fragments (<63µm) which are "volumetrically unimportant" for island building [53]. Studying sediment transport pathways between production zones and deposition zones provides a more complete picture which will help to inform the management of shorelines. In discussing the mismatch between the abundance of *Halimeda* as a reef colonising taxa and a beach contributing sediment on the island of Kandahalagala, Perry et al. [53] highlight the transport of sediment as an important area which needs more investigation.

The Maldives has been the site of several sedimentary studies in recent years, with studies being conducted in Huvadhoo Atoll [40,53], North Male Atoll [54,55] and North Mallhosmadulu Atoll [39]. Dhigurah Island, located in South Ari Atoll, has not been studied. This study, therefore, contributes to a growing literature that is continually improving understanding of sediment supply in the Maldives.

Seagrass

Seagrass plays an important role in the formation of islands as well as their persistence. Sediment accumulation, driven by wave processes, will often create sand cays on the surface of reef platorms. While unvegetated sand cays have some capacity to persist [56], greater stability is produced with the establishment of vegetation [22]. Where seagrass becomes established, below the ground, a tightly knit mat of roots and rhizomes holds the seabed in place [57]. Above the ground, friction from leaves reduces current velocities and attenuates wave energy [58,59,60,61]. The ability of seagrass to trap sediment is usually attributed to different properties of seagrasses, including species type, biomass and the percentage of the water column it occupies [62,63,64]. The ability of seagrass to reduce hydrodynamic energy has led to the concept of seagrass beds as sediment deposition zones [65,66]. The low energy environment created by the presence of seagrass increases sediment accretion rates [64,67,68,69] and reduces resuspension rates [70], which encourages faster growth of seagrass by decreasing turbidity and improving light availability [59]. Thus, the presence of seagrass promotes conditions that are favourable to seagrass in the same or adjacent areas. Due to this ‘positive feedback,’ areas that were previously unsuitable for seagrass are more likely to become conlonised by seagrass [71].

Another reason for deciding to focus on seagrass as a key nearshore process is because intial observations on Dhigurah Island found seagrass beds to be significantly higher than the surrounding substrate (approximately 25 centimetres). This feature of seagrass beds was regarded as signifcant and warrented investigation given that nearshore bathymetry plays an important role in an island’s ability to persist and adapt to the impact of sea-level rise [59,73]. According to the literature, this feature of seagrass has been observed elsewhere, and over long temporal scales, the difference between areas with and without seagrass is “expected to seriously affect the form of the cross-shore height profile” [69]. In a study by Christianen et al. [69], seagrass beds off Derawan Island, Indonesia, were 13 centimetres higher than unvegetated patches. In another study conducted in Rhode Island, USA, seagrass beds were approximately 18 centimetres higher than the surrounding sea bed [73]. As seagrass beds build upwards, they change the bathymetry of the seabed, reducing water depth, which further attenuates wave energy and increases shoreline stability [59,73]. If the accretion process continues so that seagrasses are exposed at low tide, intertidal vegetation, such as mangroves, may take over [59]. On the other hand, if intertidal vegetation does not take over, then faster currents travelling over shallow seagrass beds may act to resuspend sediment and erode the seagrass bed [59]. In turn, slower currents in deeper water will allow the accretion process to resume in an accretion-erosion cycle [59].

Just as studies show that the presence of seagrass prevents erosion and provides coastal protection [76,77,78], the opposite, increased erosion and shoreline instability, can also occur in areas in which seagrass has disappeared or diminished [79,80]. It follows, therefore, that understanding more about the factors affecting the distribution and location of seagrass around Dhigurah Island will help inform future planning. The primary factor controlloing the distribution of seagrass is wave energy [81,71]. Excessive exposure to waves can limit seagrass growth by physical disturbance [82,83]. High wave energy and faster currents also increase sediment resuspension and therefore reduce light availability [84,85]. High energy environments, tend to limit growth and diversity of seagrasses [59]. As seagrass beds become more patchy they will be able to attenuate less wave energy, which will destroy more seagrasses [59]. Despite the importance of wave energy on seagrass being widely recognised, very few studies have managed to quantify a direct correlation due to the variation in hydrodynamic processes [71]. In a study of Puget Sound, Washington, USA, Stevens and Lacy [71] speculate that grain-size may be a key factor affecting the distribution of seagrass with no seagrass present in areas with coarse substrates (gravel and cobble). Examination of seagrass sediment cores in Shark Bay, Australia, showed that CRA was an important contributor of sediment suitable for seagrass growth [84]. *Halimeda* produce gravel size sediment fragments which are not suitable for growth of seagrass [87,71].

Literature therefore shows that seagrasses provide a number of important coastal protection services [74,75] and therefore they are a key nearshore process for the inherent ability of Dhigurah Island to adapt to changes in boundary conditions.

3. Study Site

This chapter introduces the study site, starting with an overview of the Maldives and key physical and anthropogenic threats to atoll islands in the region. Dhigurah Island, the site of this study, is then introduced with a description of its location within the Maldives, the state of tourism on the island, coastal infrastructure and the local community's perceptions of island vulnerability.

The Maldives

The Maldives is an archipelago of coral atolls and reef platforms located in the Indian Ocean, stretching approximately 886 km north to south (6°57'N - 0°34'S) (see Figure 3.1). The atolls and reef platforms host more than 1,200 islands, with 80 percent of land less than 1 metre above mean high water sea-level [88]. The size of the islands range from less than 1 ha to 595 ha, though the modal size is 2.5 ha [14].

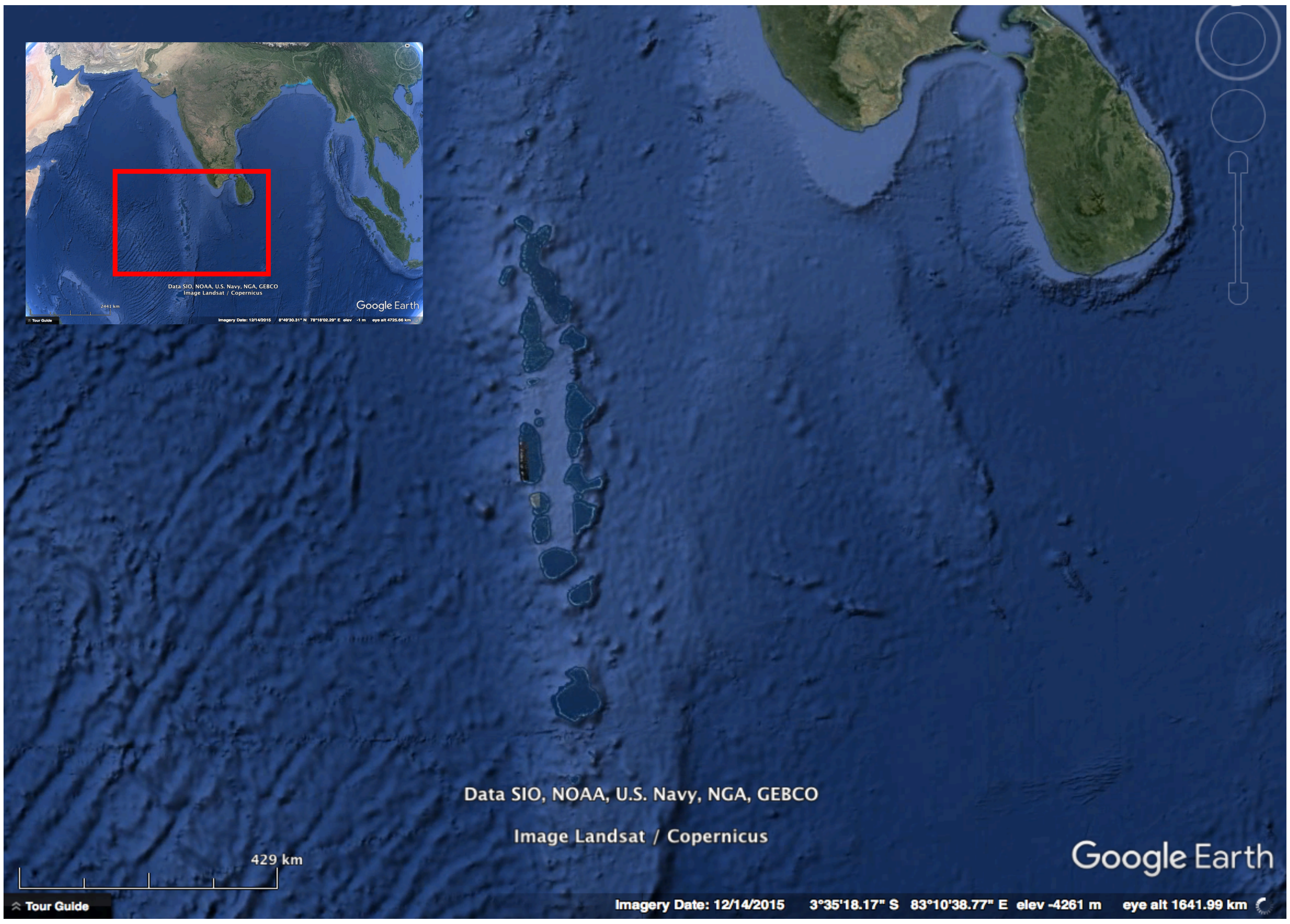


Figure 3.1: Google Earth images showing the location of the Maldives in the Indian Ocean

Two types of island are found in the Maldives: interior islands, which are reef platforms within the lagoon of an atoll, and rim islands, which form the perimeter of atolls. Atoll rim islands are of particular socioeconomic importance to the Maldives as they host 89% of the population and account for 82% of the land area [40]. The population, according to the 2014 census, is 341,256 [28]. More than a third of Maldivians live in the capital city of Malé; only three other islands have a population over 5,000 meaning that the majority of the population is made up of smaller island communities [88].

Due to its proximity to the equator, the Maldives does not tend to experience severe storms [22]. Rubble, dislodged by storms, therefore, is not a prominent feature on islands throughout the Maldives [22]. However, there have been two major events in recent history which have had a major impact on the Maldives [29]. In 1987, a storm in the Indian Ocean resulted in waves 5 metres above mean sea level reaching Malé and inundating much of the capital for two days [29], while in 2004 the Boxing Day Tsunami killed over 70 people [22]. While the Maldives has only a moderate tidal range of between 1 – 2 metres [22], one feature that has a significant effect on the geomorphology of the islands is the reversal of monsoons [89]. 'Iruvai,' is the north-east monsoon which occurs from January through April. 'Halhangu,' the south-west monsoon, usually occurs from May through November. Annual rainfall is approximately 2,124mm.

A study by Kench et al. [90], provides evidence of a late Holocene sea-level highstand of 0.5 ± 0.1 m above 2009 levels. Kench et al. [90] argue that their findings show that the Maldives is capable of adapting to sea level rise at rates comparable to those predicted for this century. However, there was no unequivocal evidence of past higher sea levels on Dhigurah Island.

In 1972, the Maldives received 1000 tourists [91]. The number of tourists now arriving each year exceeds one million [91]. The Maldives has been very successful in branding itself as a luxury destination [92]. To manage its growing popularity and safeguard its local customs and traditions, in 1984 "inhabited" islands were prevented from engaging in tourism. Only on islands designated as "resort" islands was tourism allowed [14]. Nearshore processes have been dramatically affected on resort islands where a variety of infrastructure has been constructed including jetties, harbours, causeways and private villas and bungalows built out into the subtidal zone (see Figure 3.2). In 2009, President Nasheed changed the law, allowing "inhabited" islands to receive tourists [93]. As a result, there has been a proliferation of guesthouses built by local Maldivians on "inhabited" islands [94]. For example, the island of Maamagili, has seen dramatic change with the construction of a domestic airport in order to meet the needs of increased tourism in South Ari Atoll [95] (see Figure 3.3).

Figure 3.2: Google Earth images of Vonmuli Island, Dhaalu Atoll. A) 2011 B) 2016.

While there has been much construction, many inhabited islands still appear to have a relatively undeveloped tourism industry [94]. A possible explanation for this is the limited funds available in small communities to invest in tourist infrastructure. Many families are saving up in order to be able to afford to build a guesthouse; others are looking to set up business ventures with third parties [94].

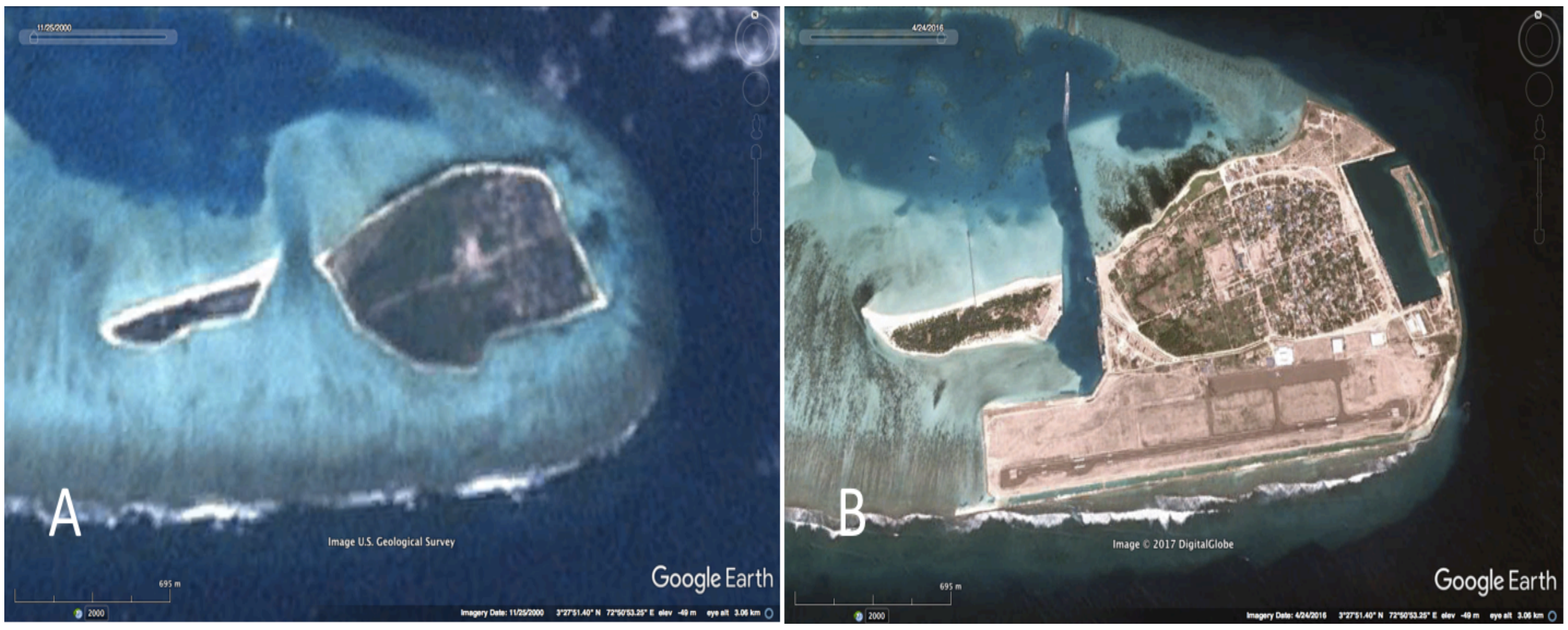


Figure 3.3: Google Earth images of Maamagili Island, South Ari Atoll. A) 2001 B) 2016.

In addition to its status as a luxury destination, the Maldives is often used as a symbol for climate change, gaining considerable media attention under President Mohammed Nasheed [96]. Prior to the United Nations Climate Change Conference in Copenhagen, 2009, President Nasheed held an underwater cabinet meeting in order to highlight the plight of low-lying atoll nations (see Figure 3.4).

Figure 3.4: A photo of the underwater cabinet meeting held by President Nasheed of the Maldives [96].

Dhigurah Island

Dhigurah Island is located in South Ari Atoll (see Figure 3.5). Located on the south-east side of the atoll (see Figure 3.6), it is sheltered by Faafu Atoll to the south, Vaavu Atoll to the east, and the rest of the North and South Ari Atoll to the North and West (see Figure 3.5).

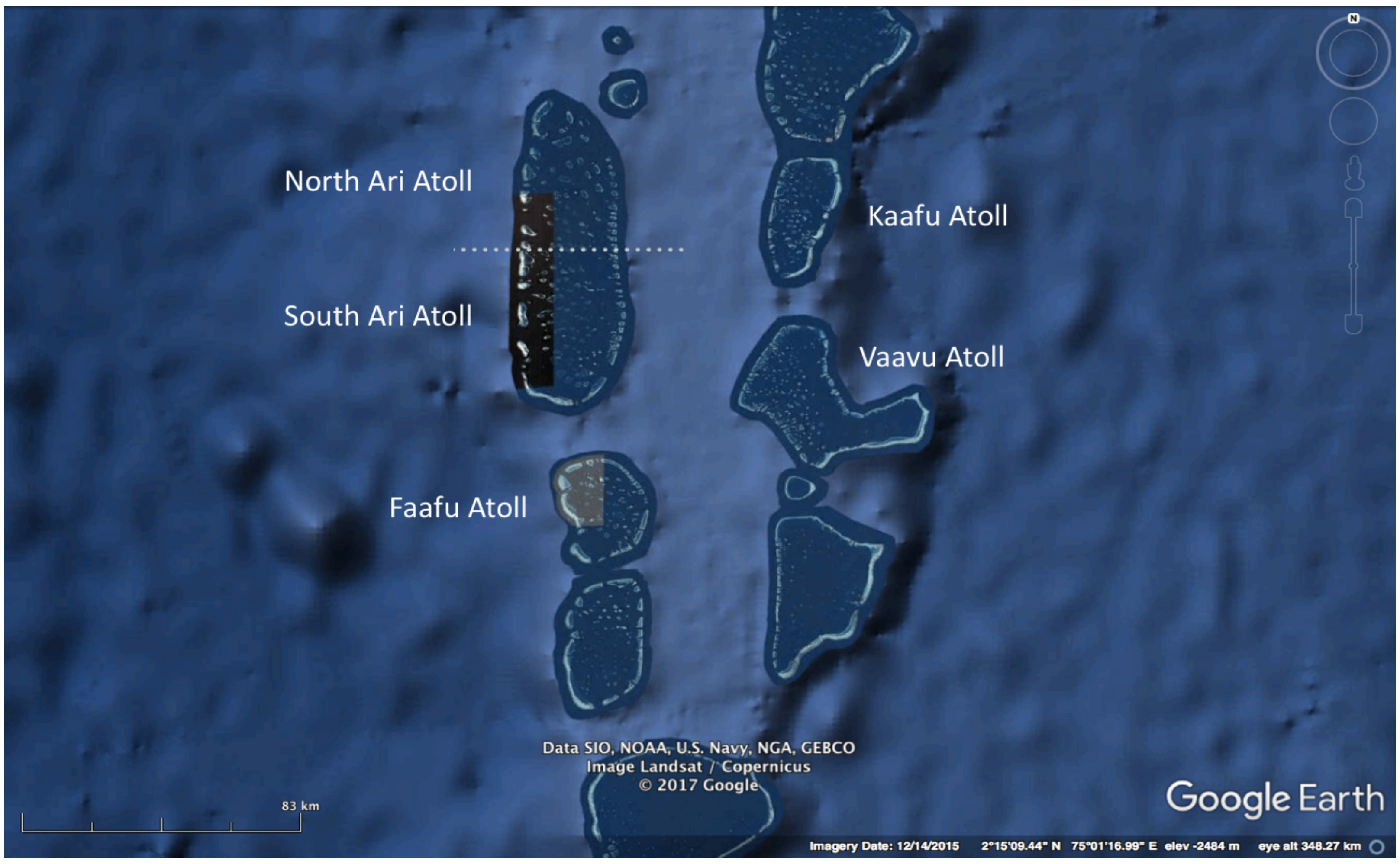


Figure 3.5: Location of South Ari Atoll and surrounding Atolls.

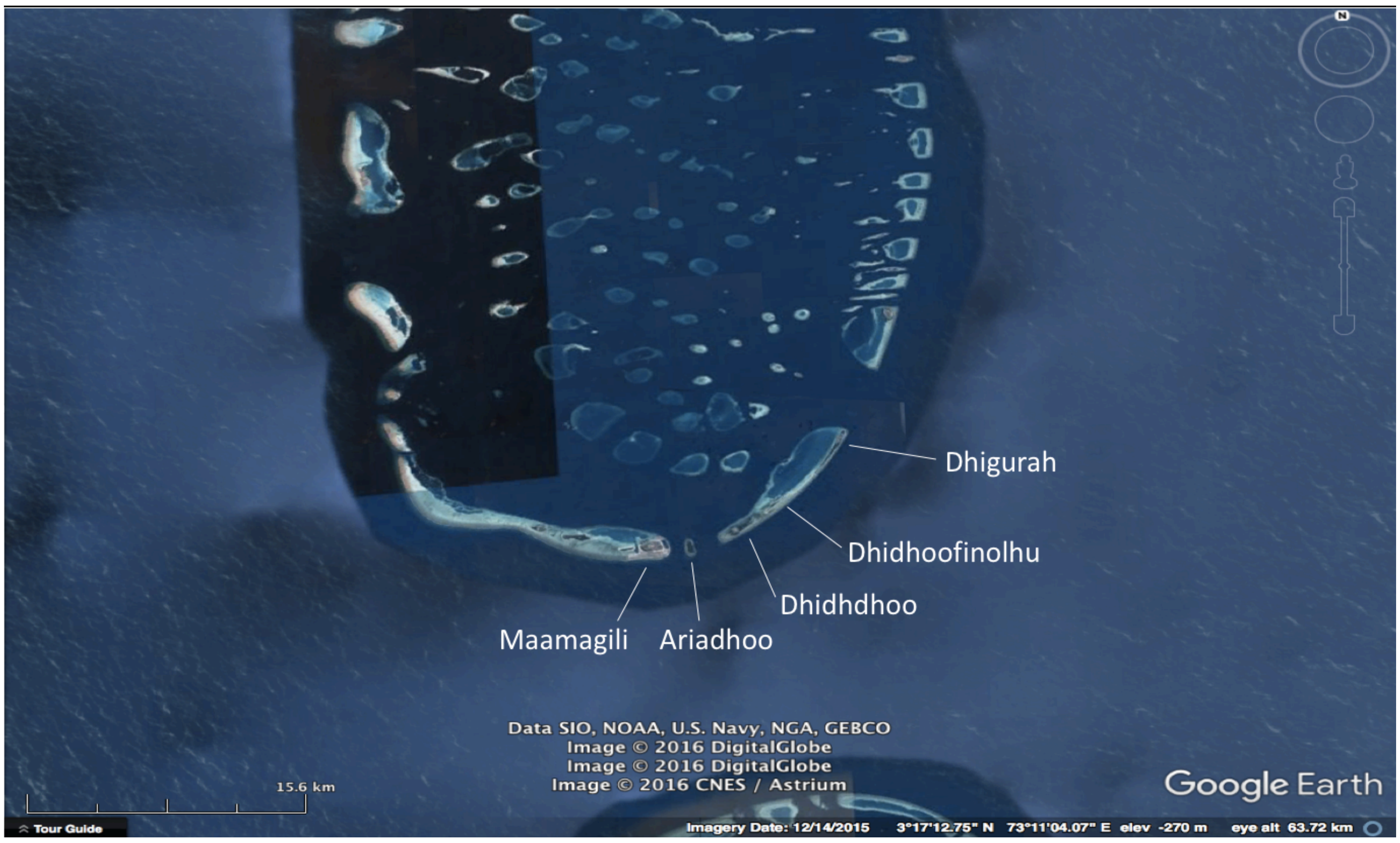


Figure 3.6: Location of Dhigurah Island within South Ari Atoll and neighbouring islands.

Figure 3.7: Google Earth image showing Dhigurah Island.

Dhigurah Island, long and slender in shape, is an atoll rim island. The island's 600 inhabitants are concentrated around the northern end with the rest of the island covered with mature vegetation and vegetable plantations [16,94] (see Figure 3.7).

Tourism on Dhigurah Island

Since 2009, when laws were changed to allow "inhabited" islands to engage in tourism [93], there has been a significant amount of investment in tourism on Dhigurah [98]. Dhigurah has five resorts, a state of the art diving centre, water sports facilities, several tourist shops and a café [97]. It is also home to the Maldives Whaleshark Research Programme (MWSRP) [99] who regularly host international volunteers (see Figure 3.8).

Figure 3.8: Images showing A) TME Retreats Hotel [100] B) Boutique Beach Hotel [101] C) Tourists enjoying activities with Adventure Watersports [102] D) MWSRP volunteers [99] E) Island Divers' PADI Dive Centre [103].

All the residents of Dhigurah Island that were interviewed in this study had a generally positive view of tourism [104]. Tourism brings in revenue for the local council who have plans to revamp facilities; Mohammed is particularly excited about plans to build an artificial football pitch [104]. Tourism also offers individuals a greater income opportunity. Many residents of Dhigurah are following a nationwide trend and setting up their own guesthouses [94]. Mohammed, who has many years of experience working for a luxury resort, will soon quit his job to help run the family guesthouse which is currently under construction [104]. He believes that the change to regulations in 2009 have made the Maldives more accessible and affordable, that small-scale ventures can fill a gap in the market and perhaps even compete with resorts by providing a much more affordable option: "people are paying huge prices to go diving with resorts, but we can take them diving to the same place, at a much cheaper price!" [104]. Ibrahim, another local resident, has had a long career in shipping, but now works as a security guard as well as renting out a room in his house to tourists whenever the opportunity arises. He is eager for more business [105]. The shift from traditional occupations to a reliance on tourism on Dhigurah is exemplified by Ahusam, who used to hunt

Whalesharks as a boy but now earns his living by protecting them [106]. The younger generation no longer view fishing as a desirable occupation, but look to tourism as their best hope of making a good income [106].

Current Coastal Infrastructure

Government policy in the Maldives is to have a safe harbour on each of the 200 inhabited islands [107]. Prior to the construction of the harbour on Dhigurah in 2004, there was a jetty on the lagoonward side of the island [106]. It appears that the material dug up during the construction of the harbour was deposited primarily on the northern most tip of the island, as well as along a short section of the lagoonward shoreline and the oceanward shoreline (see Figure 3.9) suggested by the marked difference in vegetation height (see Figures 3.10 and 3.11). These observations were later confirmed by Hassan [16].


Indicative location of where island was extended with material from the construction of the harbour in 2004

Figure 3.9: Harbour excavation material deposits. A and B refer to the location of photos shown in figures 3.10 and 3.11. Arrows next to A and B indicate the direction in which the photos were taken.

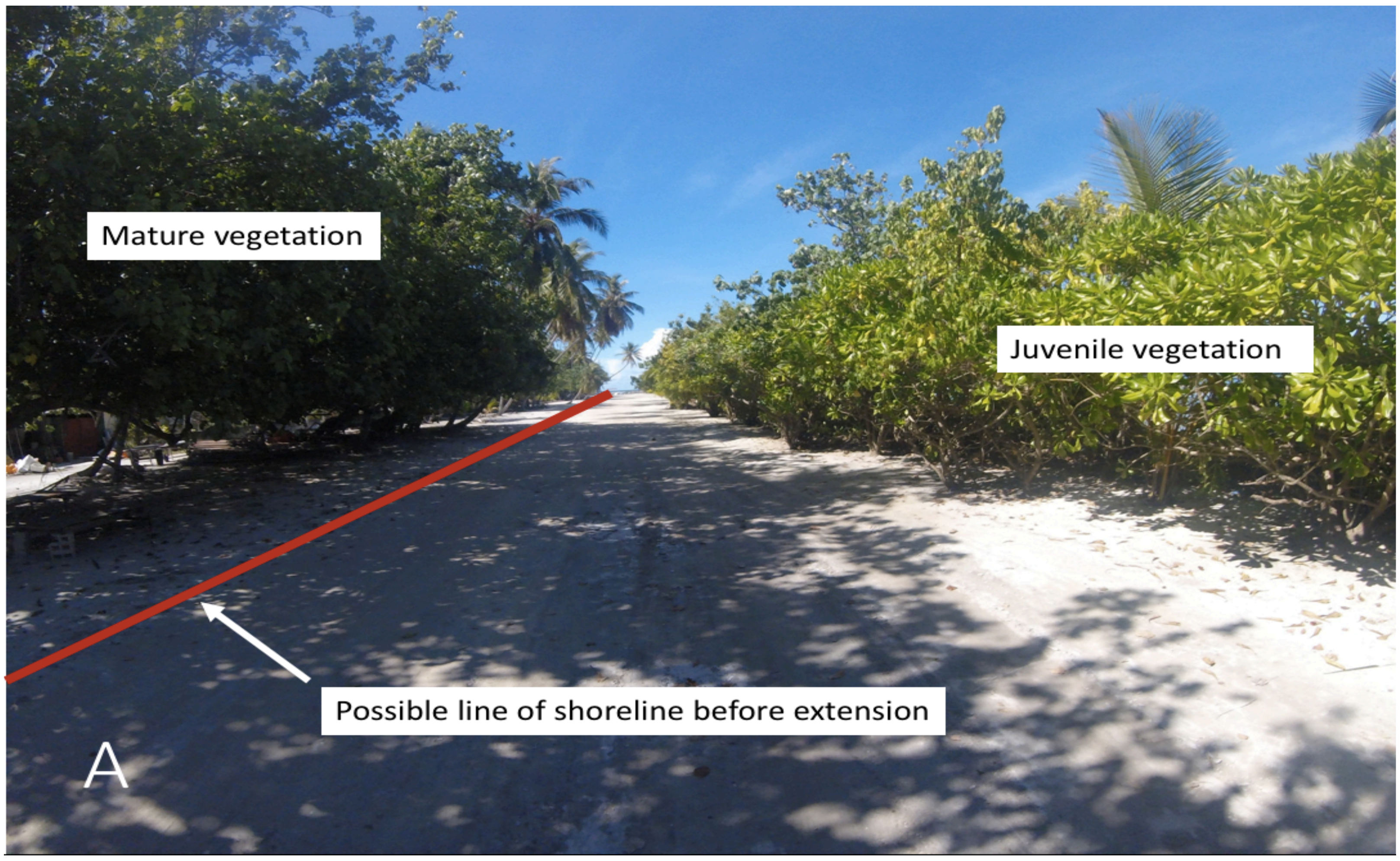


Figure 3.10: Photo taken at location A (refer to Figure 3.9 for location). Using methods outlined in chapter 4, the height of vegetation was used to make observations about recent apparent shoreline stability. The juvenile vegetation on the right suggests this land has not been there as long as land with mature vegetation.

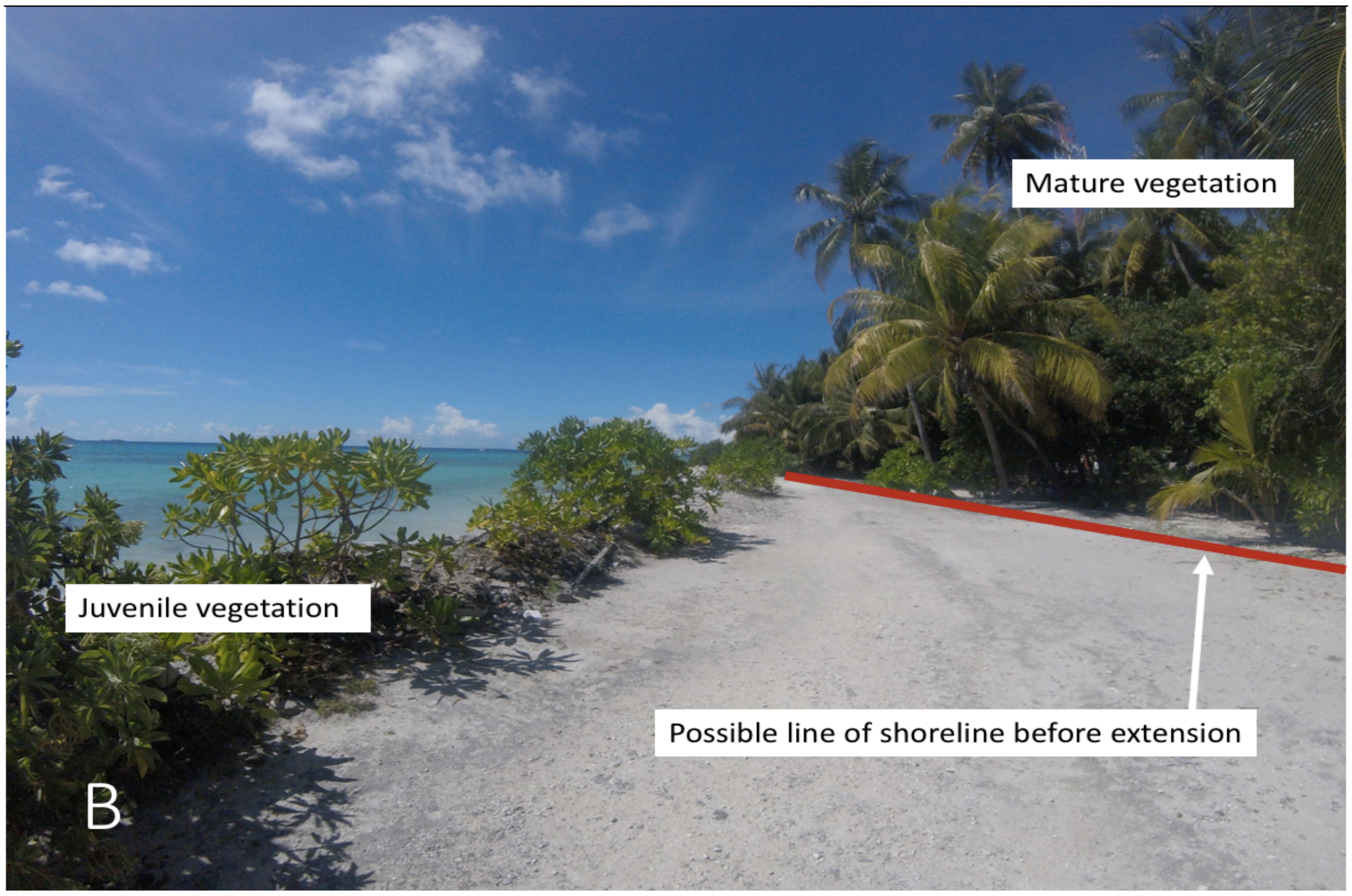


Figure 3.11: Photo taken at location B (refer to Figure 3.9 for location). The juvenile vegetation on the left suggests this land has not been there as long as land with mature vegetation.

Currently, there are several new hotels under construction (see Figure 3.12), and due to lack of space elsewhere, these are all found on the fringe between the populated north-east of the island and the south-west which has mature vegetation (see Figure 3.12). Future development, therefore, looks to be expanding south-west along Dhigurah. Yet this poses a potential problem: as new hotels are built further away from the harbour's facilities, it is foreseeable that there will be a demand for easier access to the ocean.

Figure 3.12: Map with the locations of new hotels under construction in April 2017. A) B) C) and D) photos of new hotels under construction.

Another important observation that was made by the University of Edinburgh in April 2017 was that sand had been loaded into bags at the spit on Dhigurah's south-western point and transported elsewhere. Where it had been transported was not clear, but it may have been used to cover the streets for the upcoming visit of the Minister of Education.

Perceptions of Island Vulnerability

On Dhigurah Island the local community generally dismisses sea-level rise as being insignificant [16]. While inhabitants identified areas that show recent signs of accretion or erosion, they were noted as being fairly insignificant in terms of overall island stability [16]. A comparison of the latest Google Earth image (see Figure 3.7), with an historical image from 1969 (see Figure 3.13), explains this confidence. The island appears to be maintaining a distinctive elongate shape. The key difference in shoreline is on the north-east tip with the construction of the harbour expanding the area of the island.

Low-frequency and high-magnitude events, such as the 2004 Boxing Day Tsunami, seem to have left little impression on the vulnerability of Dhigurah Island perceived by residents. Local resident Hassan recalls seeing a “below knee-height” wave reaching Dhigurah but said there was no damage done to the island. Some damage was recorded at Lux Resort on the neighbouring island of Dhidhoofinolhu [16]. Issues of greater concern to inhabitants include health facilities, sporting facilities, and air pollution, due to the increase in motorbikes on the island [104].

Figure 3.13: An historical aerial photograph of Dhigurah Island taken by the British Royal Airforce on 25 February 1969 [108].

4. Methods

This study uses a mixed methods approach that comprises simple field techniques, satellite imagery and aerial photographs, and community knowledge to explore sediment supply and seagrass.

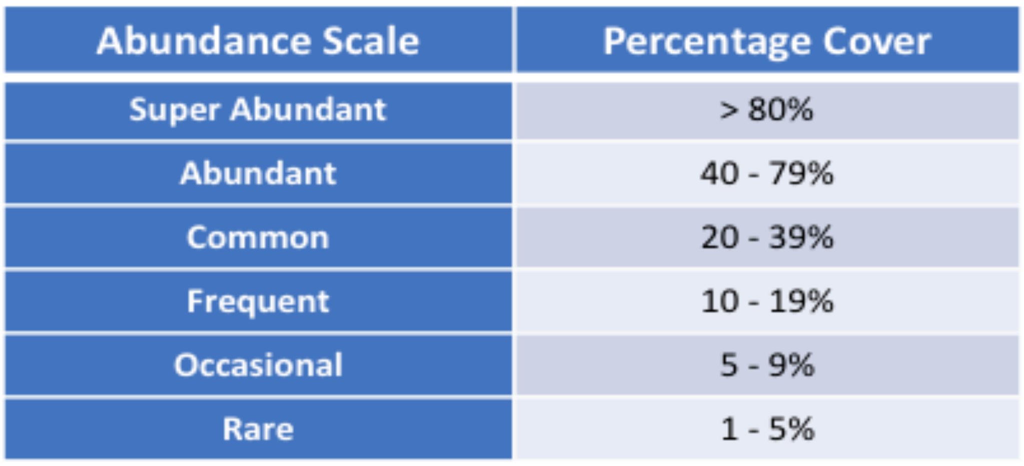
Site Selection

Twenty-two sites were chosen along the oceanward side of the island. Sites were limited to the oceanward side for the following reasons: first, it is more exposed and therefore subject to higher wave energies. Given the complex interactions between wave energy, sediment supply and marine vegetation, the oceanward side presents a more interesting study site [59]. Second, the variation in habitat on the oceanward side with seagrass at sites 1 – 12, but no seagrass at sites 13 – 22, presents an opportunity to explore the effect of different habitats. Their locations were recorded using a GPS and can be seen in Figure 4.1 below. As the presence of seagrass is a key variation along the oceanward side of Dhigurah Island, all maps in each chapter will distinguish between these sites by using green map pointers to represent sites with seagrass, and blue map pointers to represent sites without seagrass.

Figure 4.1: GPS locations of research sites.

Distribution of Sediment Producing Algae

All 22 sites were surveyed for the presence of *Halimeda* and CRA using 1 m x 1 m quadrats as reference frames for counting. The abundance of *Halimeda* and CRA was calculated using the SACFOR abundance scale in Figure 4.2 below.



Abundance Scale	Percentage Cover
Super Abundant	> 80%
Abundant	40 - 79%
Common	20 - 39%
Frequent	10 - 19%
Occasional	5 - 9%
Rare	1 - 5%

Figure 4.2: SACFOR Abundance Scale used to calculate the abundance of *Halimeda* and CRA.

The database, Algaebase, was used to identify the major *Halimeda* species present on the inner reef flats surrounding Dhigurah Island [108] (see Figure 4.3). Two major species were identified: 1) *Halimeda micronesica* and 2) *Halimeda macrophysa*. These findings are consistent with Perry et al.'s [53] study of sediment production by *Halimeda* spp. in the Huvadhu Atoll, which also identified these two species as the major shallow water species.

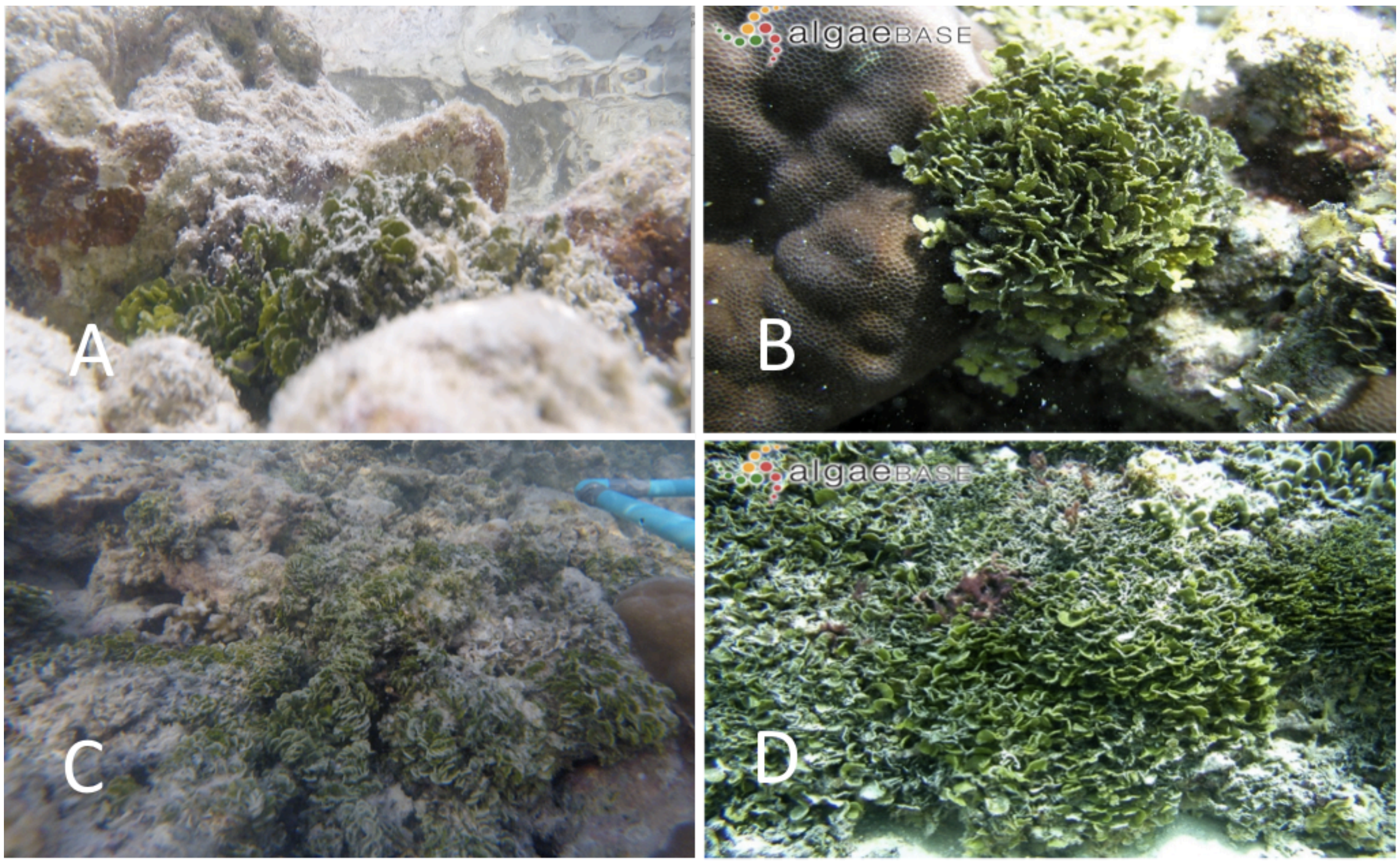


Figure 4.3: A) Photo taken of *H. micronesica* on Dhigurah Island B) Photo of *H. micronesica* from Algaebase [108] C) Photo taken of *H. macrophysa* on Dhigurah Island D) Photo of *H. macrophysa* from Algaebase [108]

Algaebase was also used to try and identify the genus of CRA on the inner reef flat surrounding Dhigurah Island. *Lithothamnion* is described as "bright pink to purplish, minutely white-speckled calcareous crust, becoming very thick, usually with abundant regular or irregular branches, free or attached to substratum." While this description matches observation from the field (see Figure 4.4), other studies conducted in the same atoll as this study's area only refer to CRA, in the order of Corallinales, but do not specify the genus [109] [110]. Thus, in the absence of literature that confirms *lithothamnion* as the predominant species, and the knowledge to identify this algae beyond its order, this study will follow the literature and refer to them as CRA.

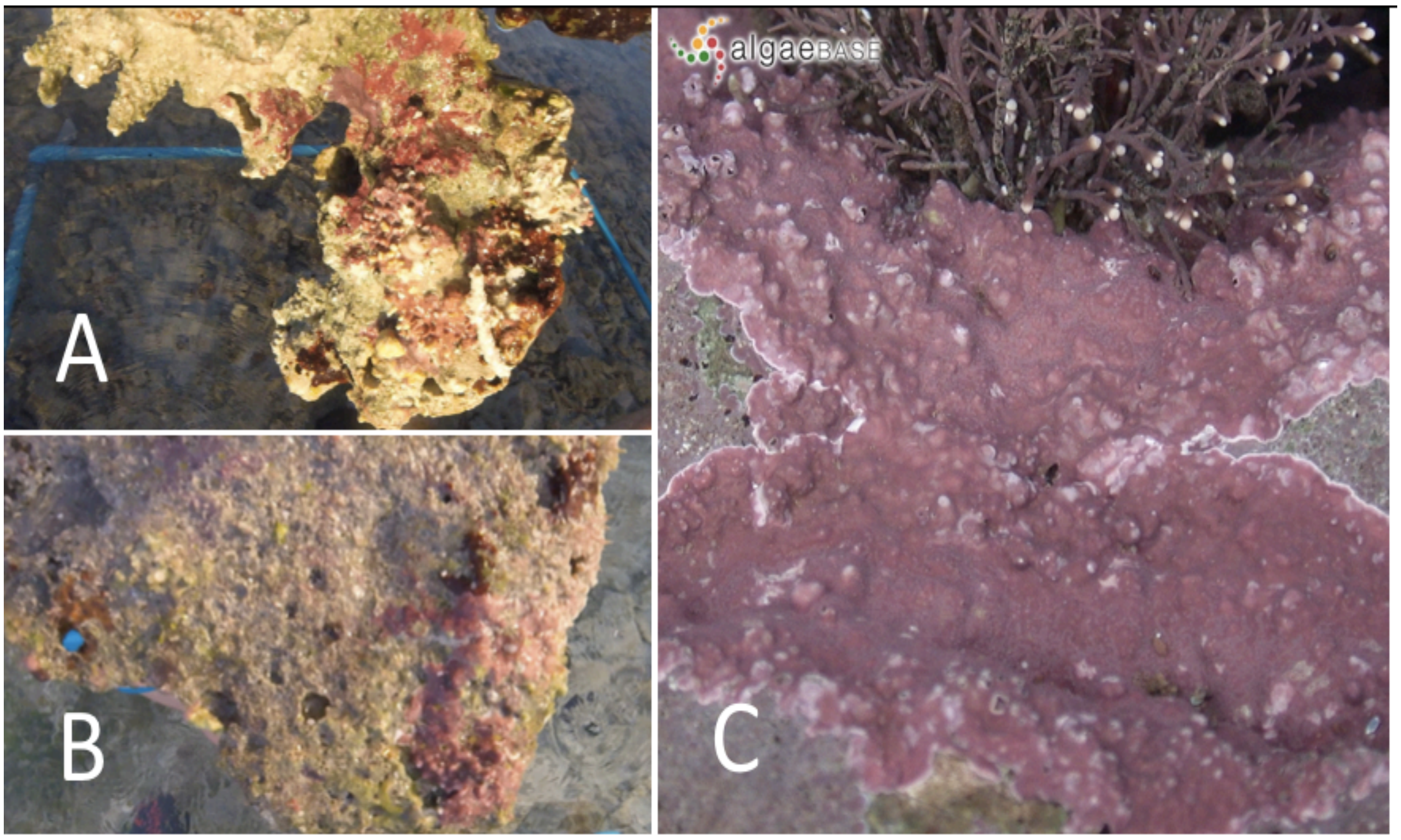


Figure 4.4: A) and B) Photos of CRA on Dhigurah Island C) Photo of *lithothamnion* from Algaebase [108]

The method for distributing quadrats when surveying the inner reef flat for the presence of *H. micronesica, H. macrophysa* and CRA was informed by literature [43,45,53], as well as a pilot study on sediment supply carried out by students from the University of Edinburgh, in May 2017, on Dhigurah Island's oceanward inner reef flat [111]. According to Perry et al. [53] *H. micronescia* and *H. macrophysa* "grow semi-cryptically within crevices, between coral rubble, or under semi-protected areas of reef framework." For CRA, substrate type, rather than water depth or distance from shore, appeared to be the most important factor affecting its distribution [111]. This is confirmed by Basso [45], who states that CRA are known to be widespread in sub-tidal areas in tropical oceans, and Hillis-Colinvaux [43], who describes the extensive habitat of CRA which can be found as deep as 150 metres. Although CRA is an important contributor of sediment to seagrass beds [84], according to the pilot study conducted by students from the University of Edinburgh [111], CRA was not observed growing in seagrass beds or living unattached in sandy substrate. Rather, CRA were most commonly found attached to broken pieces of dead coral and rubble [111]. Similarly, *Halimeda* spp. were not observed growing in seagrass beds or living unattached in sandy substrate [111]. Quadrats were therefore only placed in areas that were identified as having suitable habitat. Quadrats were placed in a grid shape (10 x 15m) that began just short of the reef crest and ended where there was no longer any suitable habitat closer to shore. Quadrats were typically placed 5 metres centre to centre, but distances between each quadrat, and therefore the size of the grid, varied slightly due to differences in the width of suitable habitat.

To compare the results of the survey for sediment production between sites 1 – 12 and sites 13 – 22, the Mann-Whitney U-test, a simple non-parametric test was used [112].

Sediment Deposition

In order to ascertain whether there was an active sediment supply from the inner reef flat to adjacent shores, empirical observations about the composition of sediment on beaches were made along the oceanward shoreline. Four samples, were collected from different parts of the beach at each site (the vegetation line, the beach berm, sea-level and below the water line). The samples, approximately 1 kg of sediment altogether, were then put together into one container and analysed on site. Only sediment that was at least 2 mm in diameter was examined. Whenever *Halimeda spp.* or CRA were observed to be at least 20% of the all the sediment collected at a site it was recorded as being present.

When larger than 2mm in diameter, *H. micronesica* forms distinctive segments (see figures 4.5 and 4.6) that can be told apart from other sediment types. *H. macrophysa*'s calcium carbonate skeleton is not as strong and breaks down more easily making it more difficult to identify [41] (see Figure 4.7). Sediment from CRA has distinctive branches (see Figure 4.8).

Prof. Tudhope of the University of Edinburgh helped with familiarisation of sediment identification prior to this research being conducted.

Figure 4.5: *H. micronesica* sediment.

Figure 4.6: *H. micronesica* sediment.

Figure 4.7: *H. macrophysa* sediment.

Figure 4.8: CRA *lithothamnion* sediment.

Bathymetric and Topographic Profiles

Bathymetric profiles were measured along transects perpendicular to the shoreline at each site (see Figure 4.9). Two topographic profiles of the island were measured by the University of Edinburgh [113], at sites 7 and 16, and are displayed together with the results of the bathymetric profiles. Each of the bathymetric profiles extends from the vegetation line to the reef crest. Water depth was measured every 2 metres along each transect and the time of the measurements was recorded. The water depth measurements were then tied to the vegetation line by using a laser level to measure the difference in height between sea-level at that time, and the vegetation line.

Figure 4.9: Indicative location of bathymetric and topographic profiles at sites 1 - 22

Bathymetric data was later adjusted to heights below and above mean sea level using tide tables supplied by the Maldives Meteorological Service for Hulhulé Island. There will be some difference between tides in Hulhulé Island, which is located approximately 80 miles north east of Dhigurah Island, and Dhigurah Island. Hulhulé’s tide predictions were compared with tide data collected by the University of Edinburgh on Dhigurah Island during April 2017. By plotting both sets of tide data on a graph it is evident that the tides at Hulhulé and Dhigurah

Island are within 10 centimetres of each other (see Figure 4.10). This margin of error was deemed as being appropriate for the purposes, and duration (21 April – 12 May), of this study.

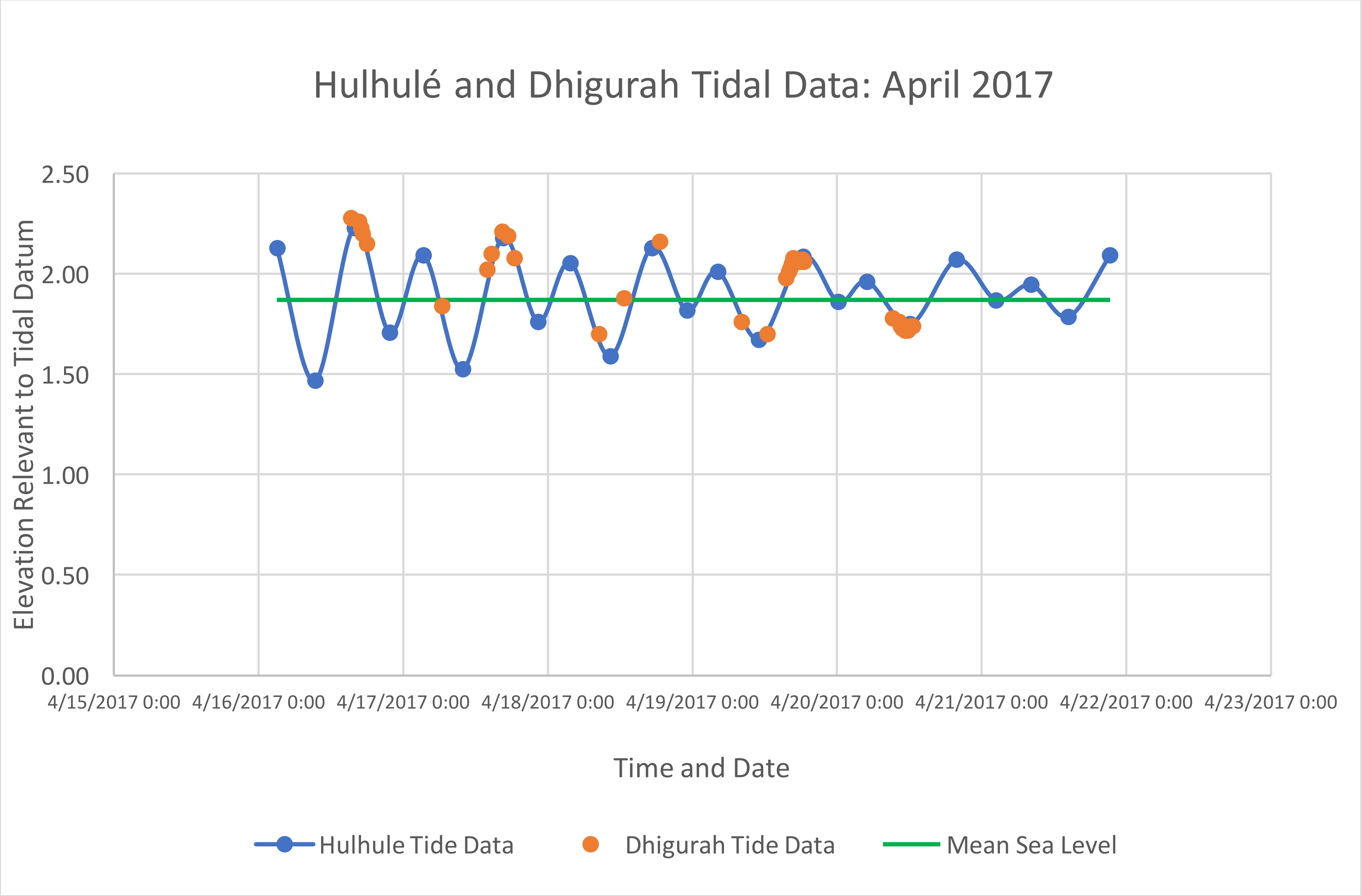


Figure 4.10: A comparison of tide data from Hulhulé Island and Dhigurah Island during April 2017.

Shoreline Stability

Results of the bathymetric profiles, which are discussed in chapter 6, show that sites with seagrass have profiles that are significantly shallower than sites without seagrass. As has been discussed in chapter 2, the amount of wave energy attenuated by nearshore habitats increases as water depths decrease [59,72]. Therefore, a plausible hypothesis, is that there will be a positive correlation between the presence of seagrass and shoreline stability. In order to test this hypothesis, each site was examined for evidence of apparent recent erosion and accretion.

Several indicators of erosion and accretion were used in order to define the status of each site as either eroding, stable or accreting. The first indicator was the relative volume of sediment at the beach at each site. As Kench [14] and Kench et al. [89] show, the reversal of monsoons has a significant effect on the movement of sediment and is capable of dramatically changing the abundance of sediment at a beach. Therefore, these observations only represent one point in time in a cycle that may include erosion and re-deposition [22]. A second indicator, which can be used to make observations about shoreline stability on a decadal time scale is the maturity of vegetation along the shoreline. Cocos *nucifera*, a common coconut palm on Dhigurah Island and the Maldives in general, grows at a rate of 30 – 50 centimetres per year during the first 40 years of growth [114]. Using a laser level the height of vegetation was recorded at each site. This could be used to make certain deductions about shoreline events. For example, an 8 metre high coconut palm could be approximately 20 years old. If it was being undercut and overhanging the water then it could be inferred that the shoreline had not receded as far in approximately 20 years. On the other hand, the presence of 2 metre coconut palms on the shoreline suggests that the shoreline has only been in place long enough for that vegetation to establish itself, in this case, approximately 5 years.

The presence of beach rock is also useful in reconstructing trends in coastal history [115]. Beach rock is indurated sediment, that forms rapidly as a result of the interaction between seawater and freshwater in the phreatic zone under the beach face [115]. Visible outcrops of beach rock indicate the "former occurrence of this interaction and can therefore be used to delineate the location of former shorelines" [115].

In order to document all these observations, photos and hand drawn sketches were made at each of the 22 sites in order to assess the state of the shoreline. Photos and shoreline stability assessments are included in chapter 6.

Historical Imagery

Historical images from Google Earth, were used to make observations on island change and shoreline stability within the last decade. In order to acquire images further back in time, an image search was undertaken by the National Collection of Aerial Photography. The image search found a photograph of Dhigurah Island taken on 25 February 1969 (see chapter 3, Figure 3.13).

Community Knowledge

To enhance the data collected, this study integrates community knowledge, believing it to be an important source of information [116]. Information was gained through observations and informal interviews and discussions. These discussions usually happened during everyday events such as eating at the local café, sharing a meal in a local family's home, playing football and whilst conducting research. All those talked to were aware of the research being done, and while this is likely to have affected their answers to questions, it provided a good conversation topic that provided many useful observations. Local residents appeared to be very comfortable talking and were happy to discuss issues of geomorphology and historical change that were raised. The only ethical issue is that of anonymity. This will be resolved by using pseudonyms when referencing conversations with community members.

5. Sediment

This chapter presents the results for the surveys for *Halimeda spp.* and CRA, and for the samples of sediment taken from adjacent beaches. The results are then discussed. Please refer to chapters 2 and 4 for a review of relevant literature and a description of the methods used, respectively.

Results

H. micronesica and *H. macrophysa*: abundance on the inner reef flat

Results from surveys for *H. micronesica* and *H. macrophysa* are displayed below (see figures 5.1 and 5.2). Using the Mann-Whitney U test, it was found that the amount of *Halimeda spp.* at sites 13 – 22 was statistically significantly higher than the amount of *Halimeda spp.* at sites 1 – 12 (*p-value* < 0.01).

Within sites 1 – 12 there is evident variation in the abundance of *Halimeda spp*. At sites 1 – 4 every single quadrat recorded *Halimeda spp.* as 'Rare'. Whereas at sites 5 – 12, not only are *Halimeda spp.* more abundant, but there is greater variation with every site recording at least three different values on the SACFOR abundance scale. The Mann-Whitney U test was repeated, this time, comparing sites 5 – 12 with sites 13 – 22 (see figures 5.1 and 5.2). It was found that the amount of *Halimeda spp.* at sites 13 – 22 was statistically significantly higher than the amount of *Halimeda spp.* at sites 5 – 12 (*p-value* < 0.01).

CRA: abundance on the inner reef flat

Results from surveys for CRA are displayed below (see figures 5.3 and 5.4). Using the Mann-Whitney U test it was found that the amount of CRA at sites 1 – 12 was statistically significantly higher than the amount of CRA at sites 13 – 22 (*p-value* < 0.01).

Figure 5.1: Results of surveys for *Halimeda* spp. at sites 1 – 12. Each square represents a quadrat. Locations of quadrats are indicative of real location.

Figure 5.2: Results of surveys for *Halimeda spp.* at sites 13 – 22.

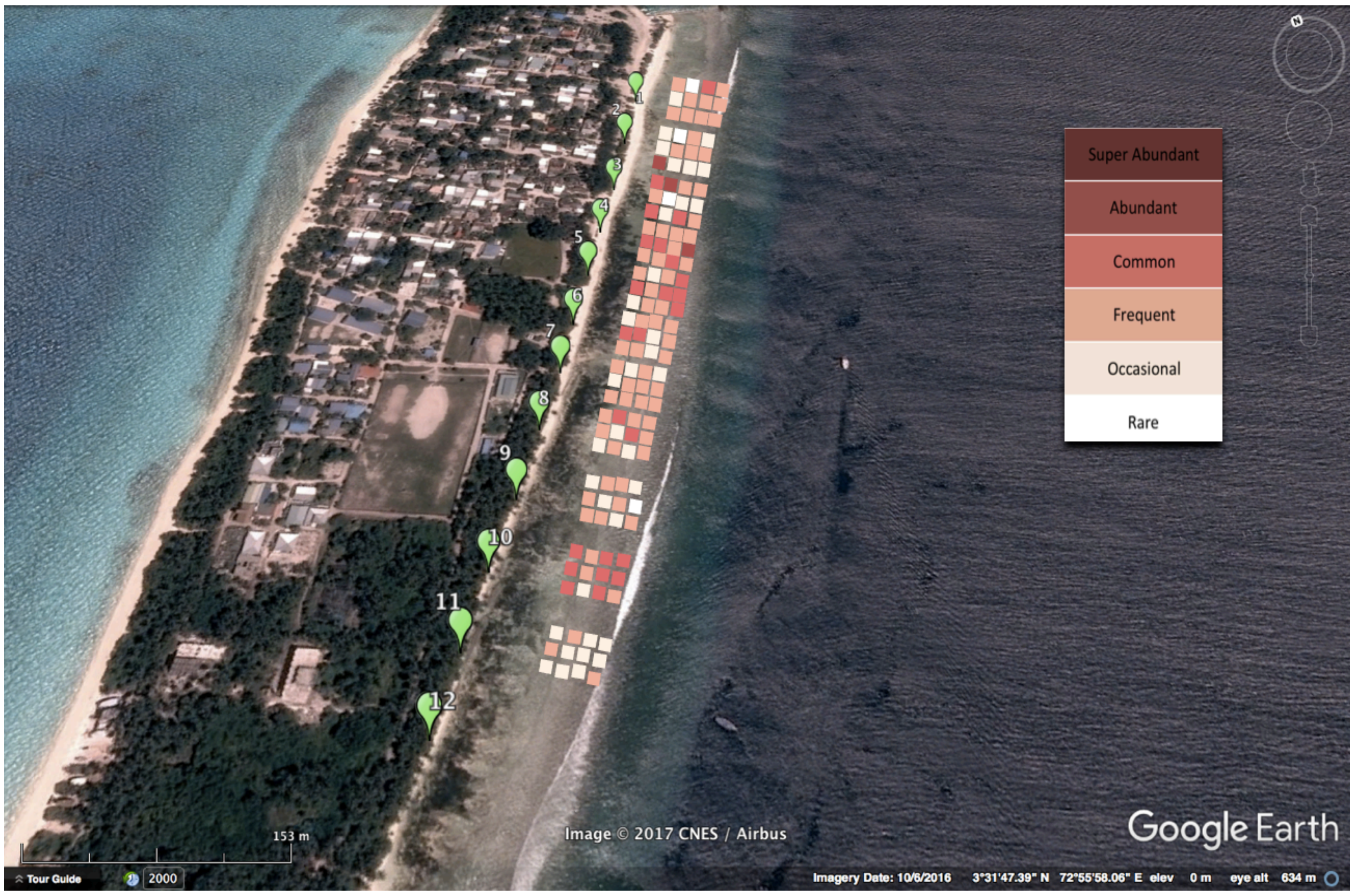


Figure 5.3: Results of surveys for CRA at sites 1 – 12.

Figure 5.4: Results of surveys for CRA at sites 13 – 22.

Beach Sediment Samples

Results from empirical observations of sediment on the beaches of Dhigurah Island's oceanward side are shown below in figures 5.5 and 5.6. Sediment from *H. micronesica* was observed as making up a minimum of 20% of sediment with diameters larger than 2 mm on beaches close to sites 1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 14, 15, 18 and 20 (see figures 5.5 and 5.6). As explained in chapter 4, sediment from *H. macrophysa's* calcium carbonate skeleton breaks down easily making it too difficult to identify. CRA was observed as making up a minimum of 20% of sediment on beaches close to sites 1, 3, 5, 6, 11, 12 and 19 (see figures 5.5 and 5.6).

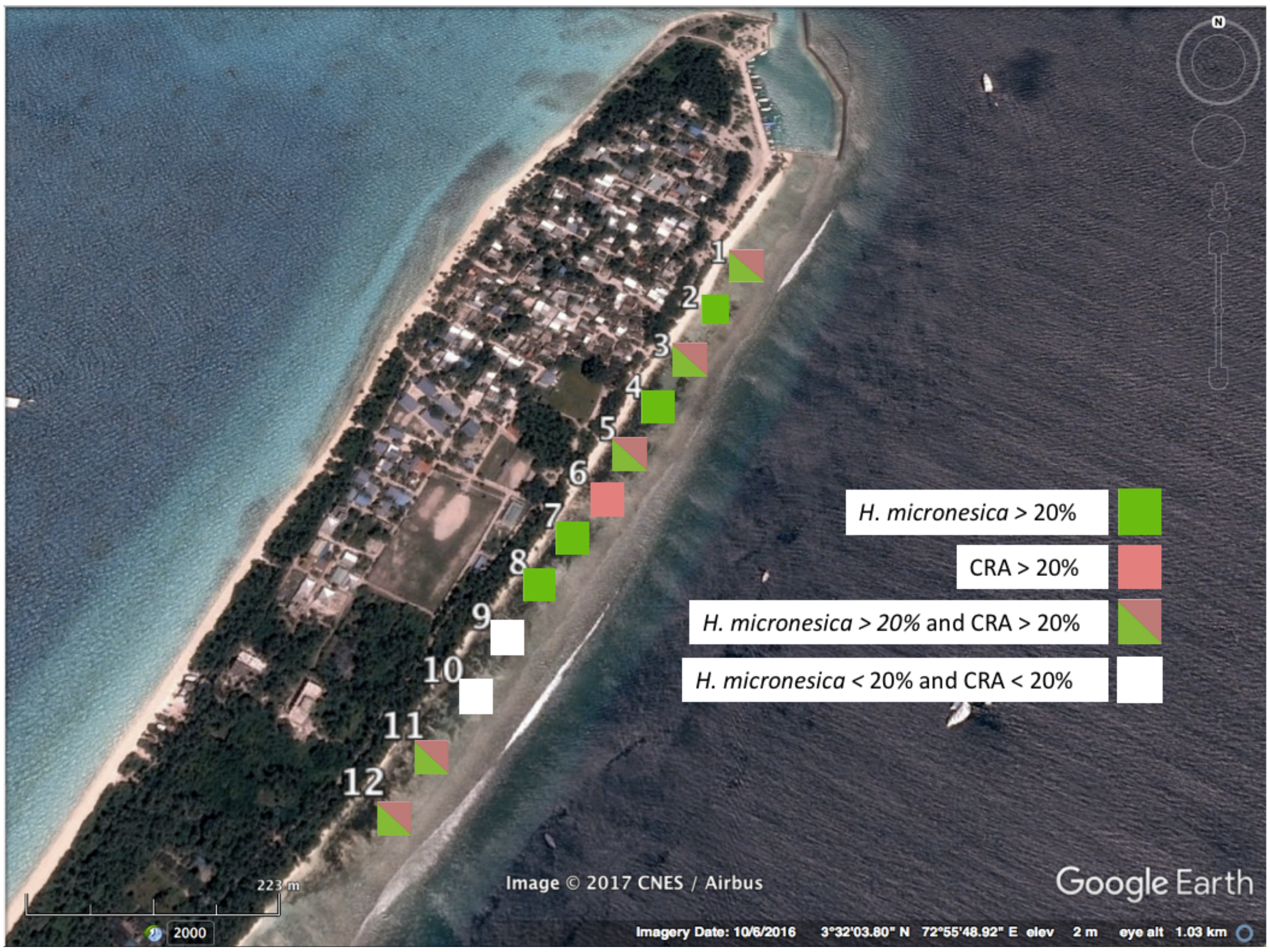


Figure 5.5: Results of empirical observations of sediment type on beaches at sites 1 – 12 for sediment with a diameter > 2 mm.

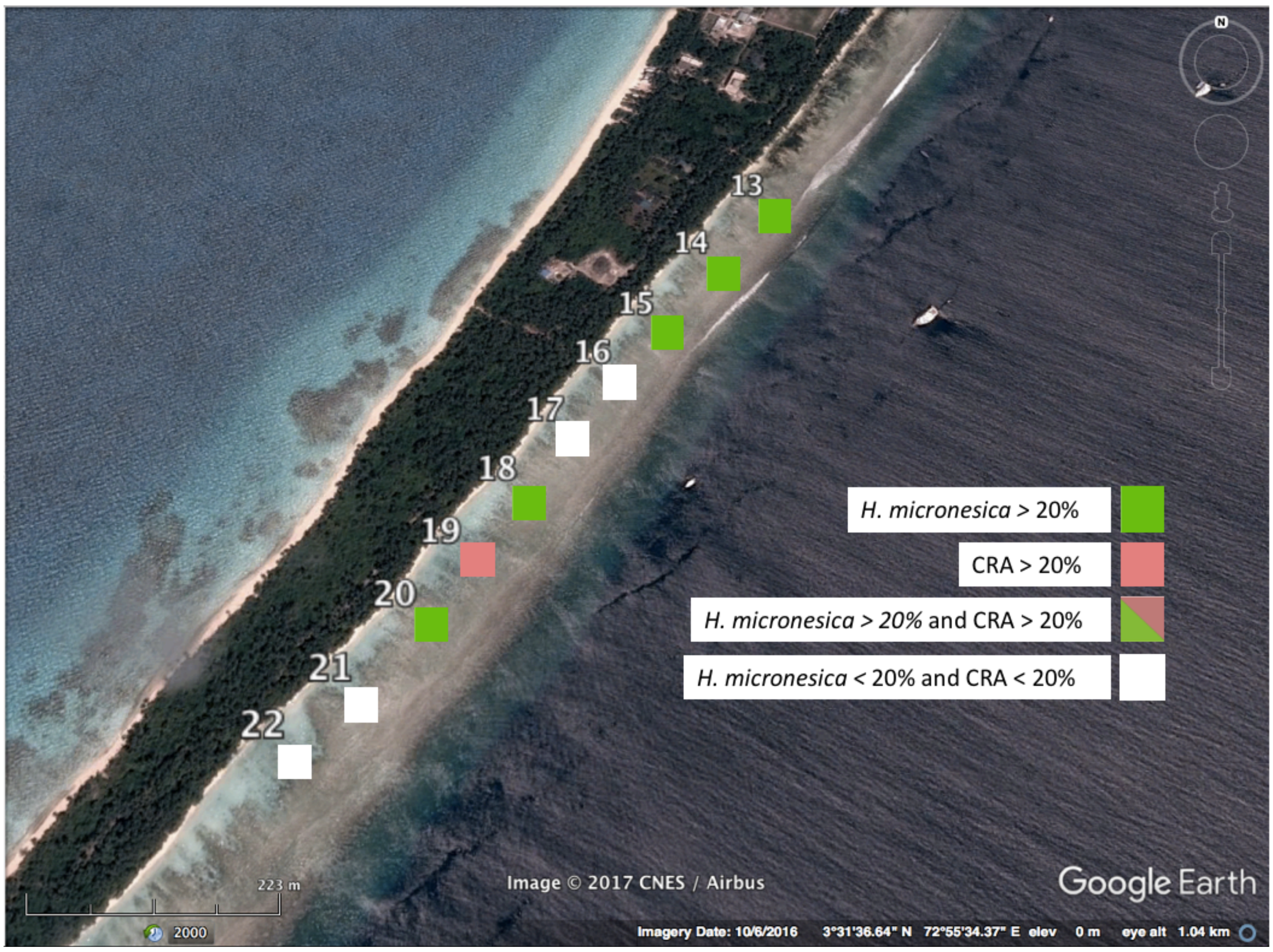


Figure 5.6: Results of empirical observations of sediment type on beaches at sites 13 – 22 for sediment with a diameter > 2 mm.

Neither *H. micronesica* nor CRA made up a minimum of 20% of sediment at sites 9, 10, 16, 17, 21 and 22. Sediment was too fine (< 0.5 mm) to be able to distinguish sediment type at sites 16, 17, 21 and 22. A plausible explanation for this is as follows. The bathymetric profiles at sites 13 – 22 are deepest very close to shore; it may be that sediment larger than 2 mm settles in these areas and finer sediment higher up the beach due to their relative weight and the wave energy required for transport. While observations and photos were taken of the substrate at sites 1 – 12 and 13 – 22, they did not include a record of sediment grain size. Therefore, testing this hypothesis would require further research.

Discussion

In this section, the discussion of the results is framed around the following questions:

1) Why are there significantly more *Halimeda spp.* at sites 13 - 22 than at sites 1 – 12, and why are they so rare at sites 1 - 4?

2) Why is CRA more abundant at sites 1 – 12 with seagrass?

3) If an active sediment supply is to be maintained what are the implications for future development on Dhigurah Island?

Why are there significantly more *Halimeda spp.* at sites 13 – 22 than at sites 1 – 12, and why are they so rare at sites 1 - 4?

A plausible explanation for this difference in abundance could be due to the variation in substrate structure and complexity that can be observed between sites. As Perry et al. [53] show, *H. micronesica* and *H. macrophysa* have a preference for "semi-cryptic habitats and most commonly grow from crevices in the framework or from between branched coral rubble." Photos taken at sites without seagrass (13 – 22), and data collected by McDowell [117] show that the habitat is similar to that described by Perry et al. [53]. Figure 5.7 shows the sea bottom was scattered with coral colonies (the most common species being *Acropora*, *Fungia*, *Porites*, and *Platygyra*).

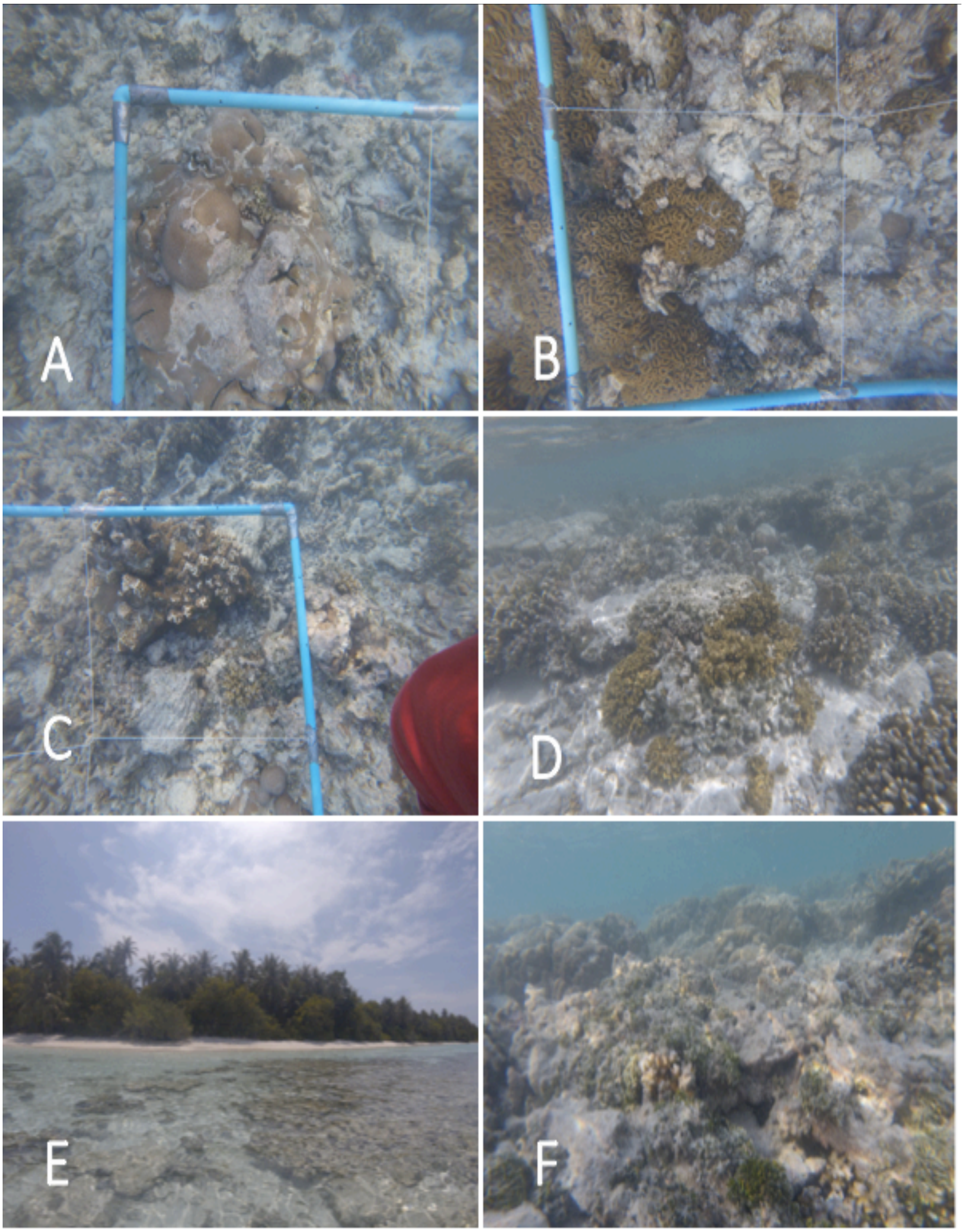


Figure 5.7: a collection of photos representative of the type of habitat found at sites 13 – 22. A) Photo showing the coral *Porites* [117] B) Photo showing the coral *Favia* [117] C) Photo showing the coral *Platygyra* [117] D) Photo taken by author at site 19 showing substrate with scattered coral colonies E) Photo taken at site 17 showing scattered coral colonies F) Photo taken at site 15 showing *H. micronesica*.

At sites 1 - 12, the inner reef flat, located beyond seagrass beds, was predominantly dead coral, with some sand and live coral [111] (see Figure 5.8). Therefore, one plausible explanation as to why there are more *Halimeda spp.* at sites 13 – 22 is due to there being more suitable habitat.

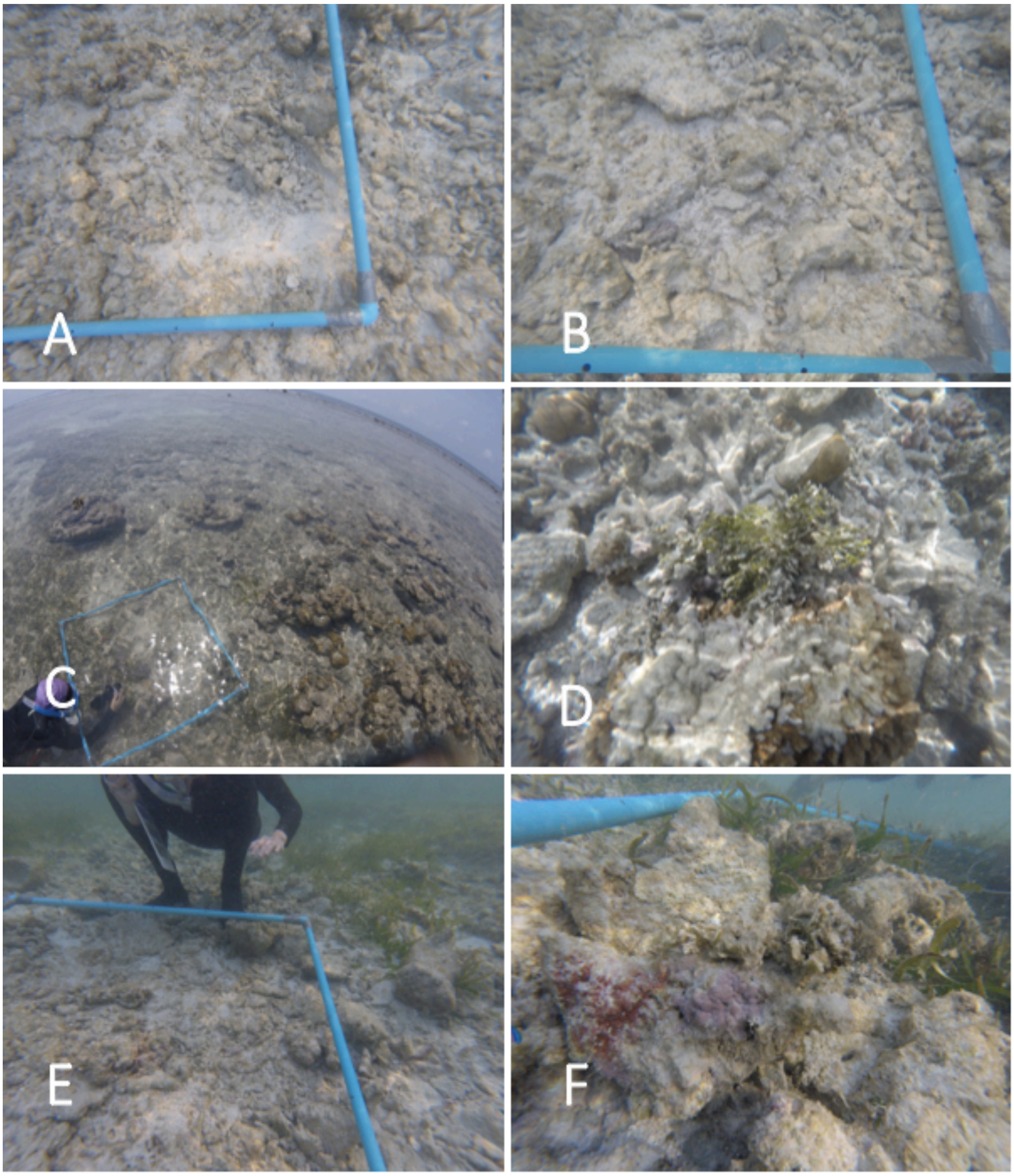


Figure 5.8: Collection of photos taken by author at sites 1 – 12. A) sand and rubble at site 1 B) sand and rubble at site 2 C) scattered coral colonies at site 6 D) *H. micronesica* at site 6 E) sand and rubble at site 8 F) evidence of CRA at site 11.

Another plausible explanation as to why there are less *Halimeda spp.* at sites 1 – 12, and particularly at sites 1 – 4, could be their relative proximity to the harbour and its adverse effects upon *Halimeda* spp. *Halimeda* spp*.* have a marked ability to withstand disturbance, one reason for their widespread distribution, however, they require sunlight to grow and therefore are vulnerable to sedimentation and less likely to grow well in turbid conditions [41]. The harbour, which was built in 2004, according to local resident Hassan [16], has a wall that runs perpendicular to the shoreline (see Figure 5.9).

Figure 5.9: Photo showing the harbour wall. To the right of the wall is the harbour. To the left of the wall is the location of sites 1 – 22 stretching into the distance.

Dhigurah Island lies along a north-east to south-west axis. The Halhangu and Iruvai monsoons see prevailing winds switch between south-west and north-east respectively. The construction of the harbour, a structure perpendicular to shore, therefore, is likely to have had significant effects on the natural shoreline dynamics of Dhigurah Island. During the Halhangu monsoon (see Figure 5.10), on the updrift side of the structure there will likely be accretion as sediment is prevented from travelling further north-east by the harbour wall. As a consequence, there will also be a reduction in the volume of sediment transported to the downdrift side of the harbour.

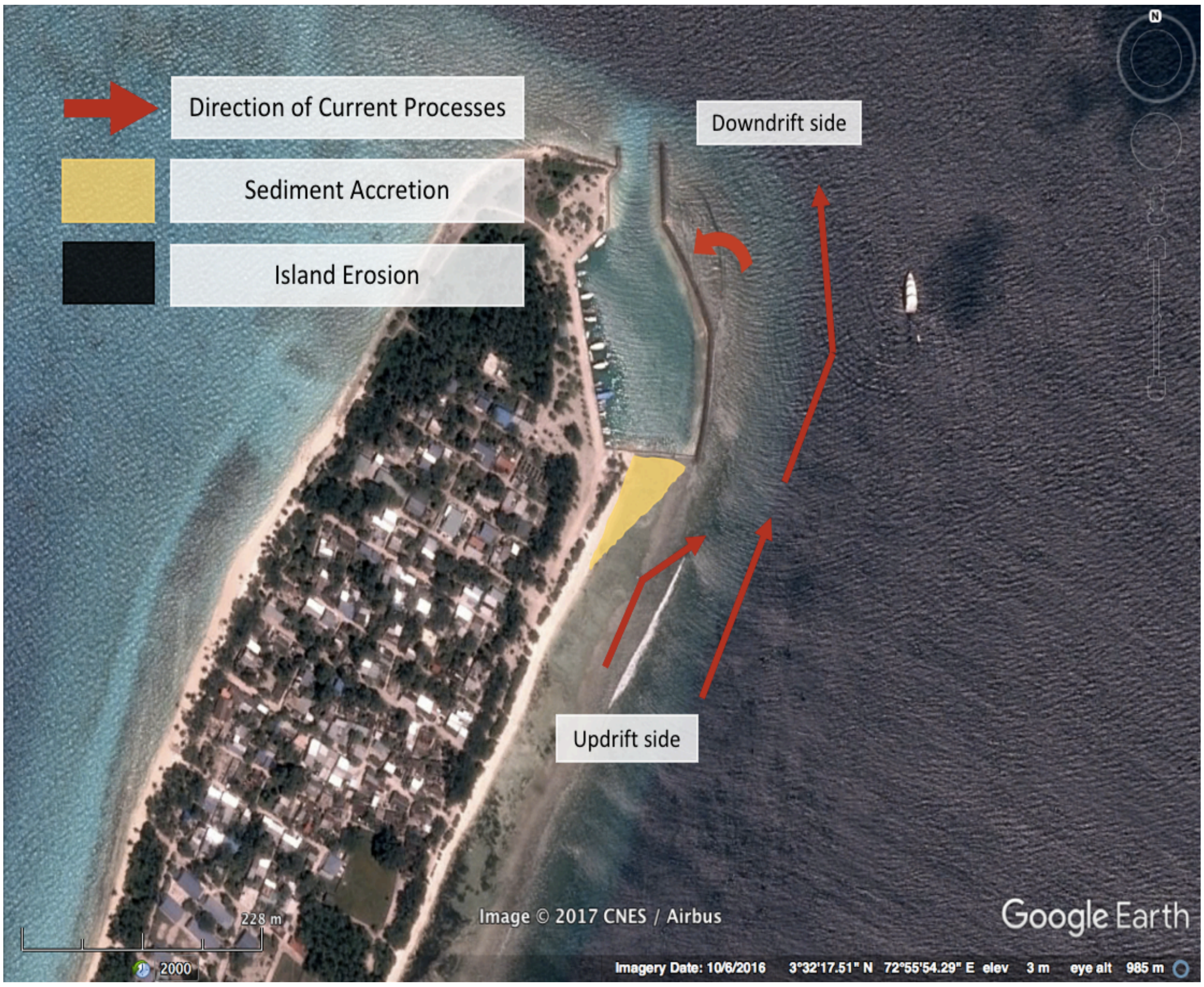


Figure 5.10: Google Earth Image with potential impacts of the habour on current dynamics and sediment transport during the Halhangu monsoon.

During the Iruvai monsoon, with prevailing winds from the north-east, the harbour is likely to deflect currents from the updrift side of the structure and form eddies on the downdrift side creating turbidity [14] (see Figure 5.11). The reduction in volume of sediment on the north-east tip of the island during the Halhangu monsoon, will be further reduced during the Iruvai monsoon as it is exposed to prevailing winds.

Figure 5.11: Google Earth image with potential impacts of the habour on current dynamics and sediment transport during the Iruvai monsoon.

As Kench [14] argues, perpendicular structures can "unevenly partition the sediment reservoir into discrete cells" causing shoreline erosion. While sediment will be transported back along the coast in a south-west direction during the Iruvai monsoon, the net effect will be sediment accumulation south west of and close to the harbour wall. This will likely result in turbid conditions, therefore, adversely affecting the ability of *H. micronesica* to grow.

As well as the construction of the harbour, it is also necessary to evaluate the effect of harbour maintenance activities on *Halimeda spp*. According to local resident Hassan, the harbour was dredged only a few weeks before this study was conducted [16]. The sediment that was removed was deposited on the south-west side of the harbour wall [16] (see Figure 5.12). This is likely to further discourage growth of *Halimeda spp.* by causing sedimentation and turbidity. While this was the first time that the harbour has been dredged since it was built, it will be an activity that will be repeated. Therefore, the decision about where to deposit sediment in future might take into consideration the findings of this study.

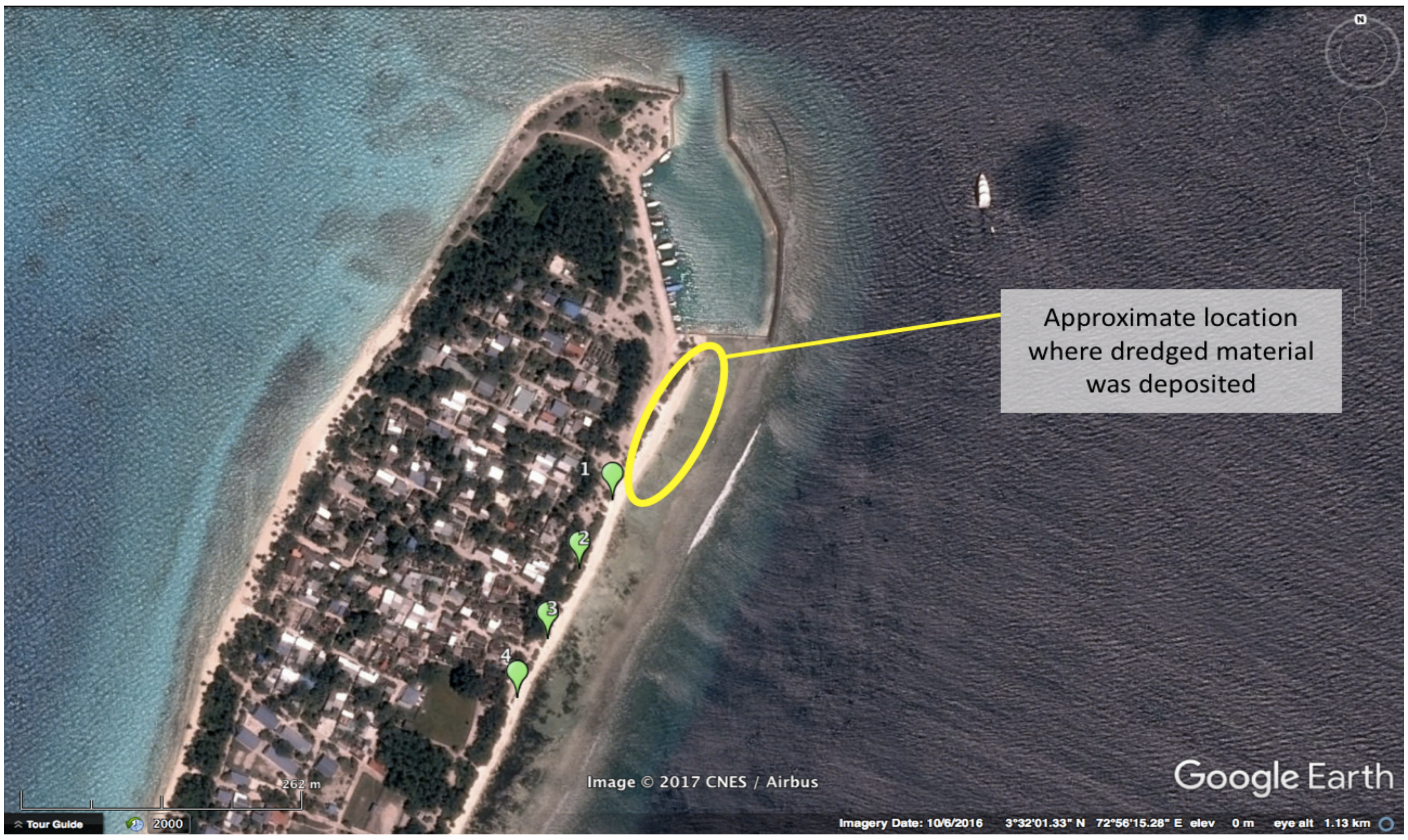


Figure 5.12: An annotated map from Google Earth showing the location of sites 1 – 4 and the location where the dredged material was deposited.

Why is there significantly more CRA at sites 1 – 12?

Interestingly, where *Halimeda spp.* are more abundant there is less CRA, and vice versa. CRA are known to grow in shallow subtidal and intertidal rocky habitats [46,47]. While it was not possible to identify the genus of CRA and therefore comment further upon its preferred habitat, it is possible to infer that habitat type is once again a plausible explanation for the difference in abundance. As shown in chapter 4, CRA was most commonly found attached to the underside of rocks and pieces of dead coral [111]. According to these observations, sites

1 - 12 show more suitable habitat with the substrate being predominantly dead coral, with some sand and live coral [111] (see Figure 5.8). Sites 13 – 22 are less suitable with the sea bottom scattered with coral colonies [117] (see Figure 5.7).

Another plausible explanation for the inverse correlation between *Halimeda spp.* and CRA that was considered, was whether they compete against each other. No studies could be found that described the interaction between *Halimeda spp.* and Red Coralline Algae, but this could be an area of future research in the Maldives.

A characteristic of CRA that may explain why they are present at sites 1 – 4 when *Halimeda spp.* are only recorded as 'rare', is that they can photosynthesize under very low light conditions [45]. *Halimeda spp.*, on the other hand, are vulnerable to sedimentation and less likely to grow well in turbid conditions [41]. Therefore, CRA will be more resilient to the effects of the harbour wall and harbour maintenance activities.

If an active sediment supply is to be maintained, what are the implications for future development on Dhigurah Island?

Atoll islands rely on the transport of sediment from production zones to deposition zones. The fact that *H. micronesica* and CRA are found growing on the inner reef flat and found as sediment on several of the adjacent beaches suggests that there is an active supply of sediment. What, then, are the implications for future development along Dhigurah's oceanward side? Dhigurah Island is an elongate island with the main access point for boats being the harbour at the north-eastern tip. Future developments look likely to occur further south-west, further away from the harbour, and as a result may increase demand for more access points. In neighbouring islands Dhidhoofinolhu (see Figure 5.13) and Dhidhdhoo (see Figure 5.14) channels have been dug through reefs on both the oceanward and lagoonward side in order to create easier access to deeper water [118].

Figure 5.13: Google Earth Image of a boat channel dug by Lux resort on Dhidhoofinolhu Island.

Figure 5.14: Google Earth Image showing boat channels dug on inhabited island of Dhidhdhoo.

Building such channels requires the removal of reef framework, and therefore a reduction in the amount of suitable habitat for *Halimeda spp.* and CRA. A 20 metre wide and 100 metre long boat channel, as seen in Figure 5.14 above, would remove aproximately 2000 m^2 of reef framework. In Perry et al.'s [53] study of Kandahalagala Island, it was calculated that *H. micronesica* produced an average of 41.91g $CaCO_3$ m^{-2} yr^{-1} and *H. macrophysa* produced an average of 25.08g $CaCO_3$ m^{-2} yr^{-1} on the reef flat surrounding the island. CRA have been found to produce a similar amount of calcium carbonate, with studies recording production rates between 20 and 90g $CaCO_3$ m^{-2} yr^{-1} [45,118].

Applying these rates, an area of 2000 m^2 could produce 160 kg of sediment per year if *H. micronesica, H. macrophysa* and CRA are all present. Applying known production rates for areas that are planned for development present an easily communicable opportunity cost for decision makers. Losing 160 kg of sediment per year in favour of the construction of a boat channel might be considered a small cost given the anticipated profits from improved tourism services which would more than pay for sediment to be transported to the island. However, to this amount of sediment should be added other major sources of sediment such as the conversion of reef framework from Parrotfish grazing. On Vakkaru Island Perry et al. [53] found that Parrotfish produced 1.55 kg m^{-2} of sediment per year on the inner reef flat and 4.93 kg m^{-2} sediment per year on the outer reef flat. Establishing whether Dhigurah Island maintained healthy populations of Parrotfish would be an important subject to investigate. They are not targeted by Dhigurah's fishermen [106] and observations by MWSRP and the author on three different occassions suggest that Parrotfish populations are thriving around Dhigurah Island [111] (see Figure 5.15).

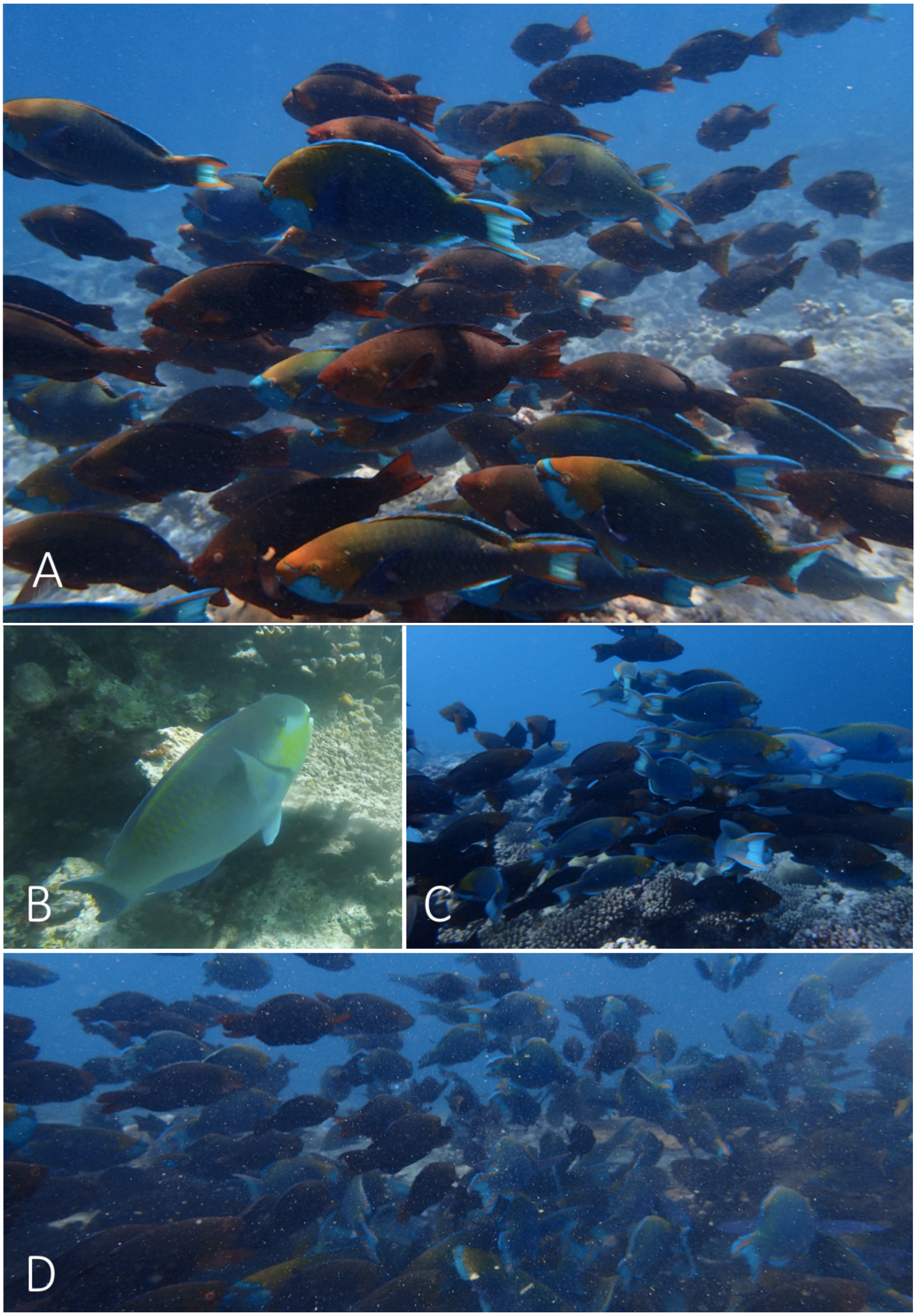


Figure 5.15: Collection of photos taken on the outer reef flat of Dhigurah's oceanward side on three different outings. A) a shoal of Parrotfish [99]. B) an adult Parrotfish, photo taken by author. C) and D) photos of a shoal of Parrotfish taken by MWSRP during a single outing [99].

The alternative of importing dredged sediment can cause destabilisation and damage at the source locations. In addition, unless nearshore coastal processes are clearly understood, it may be deposited in a location that will not provide any long term benefit. At the same time, when island planners appreciate how natural sediment production carries on day after day, year after year without any cost or input needed, they might decide that keeping reef framework in place and finding alternative solutions for tourist infrastructure is more beneficial after all. Since the Safer Islands Policy and population consolidation strategy now appears to have been abandoned [29], expensive dredging operations indeed seem to be less in favour than softer engineering strategies and working with existing coastal processes.

6. Seagrass

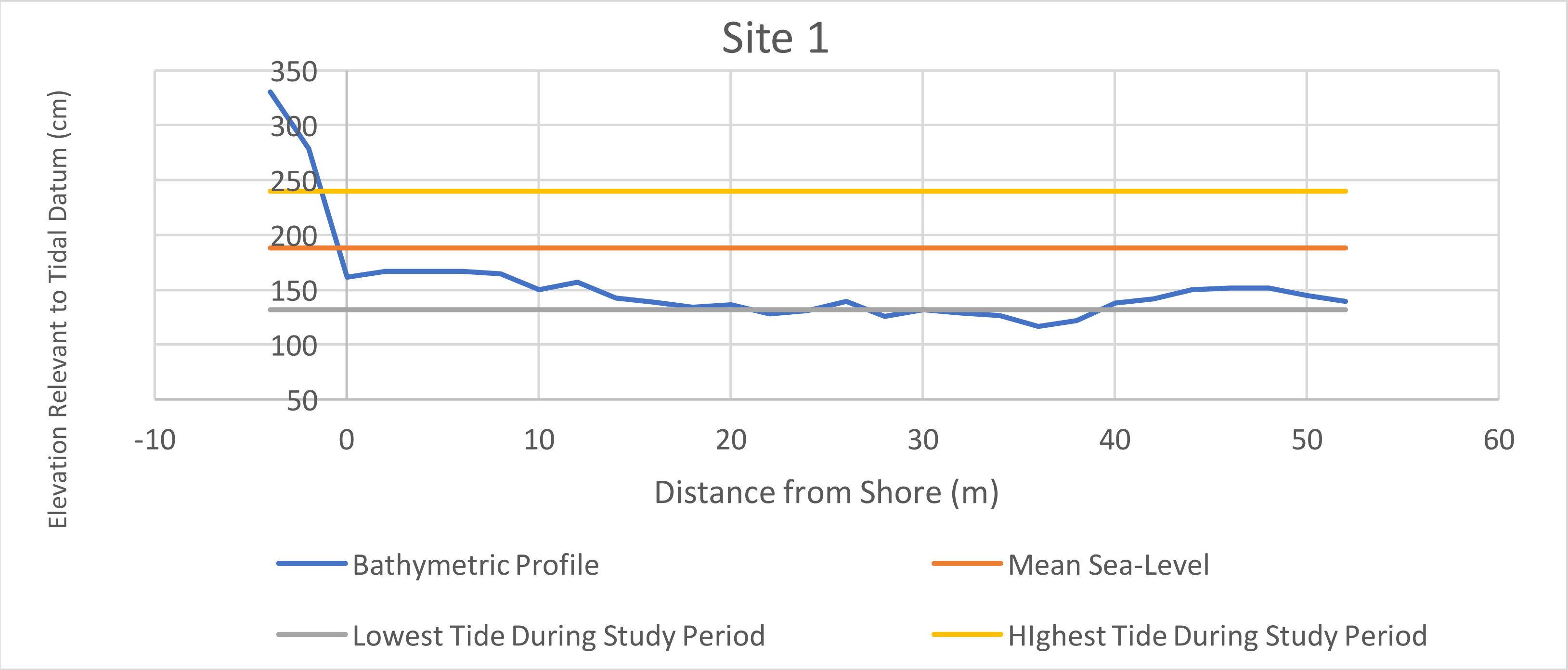
This chapter presents the results for the bathymetric profiles and shoreline stability surveys. The results are then discussed. Please refer to chapters 2 and 4 for a review of relevant literature and a description of the methods used, respectively.

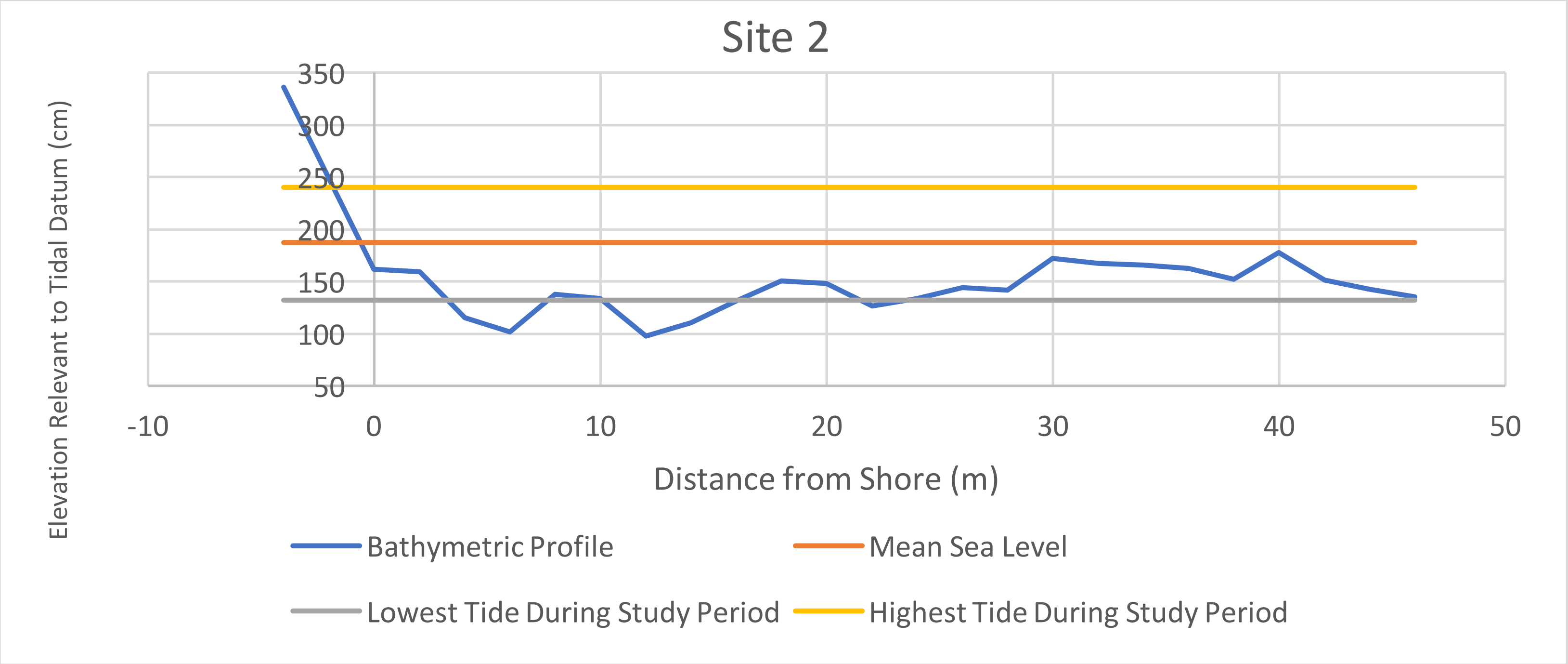
Results

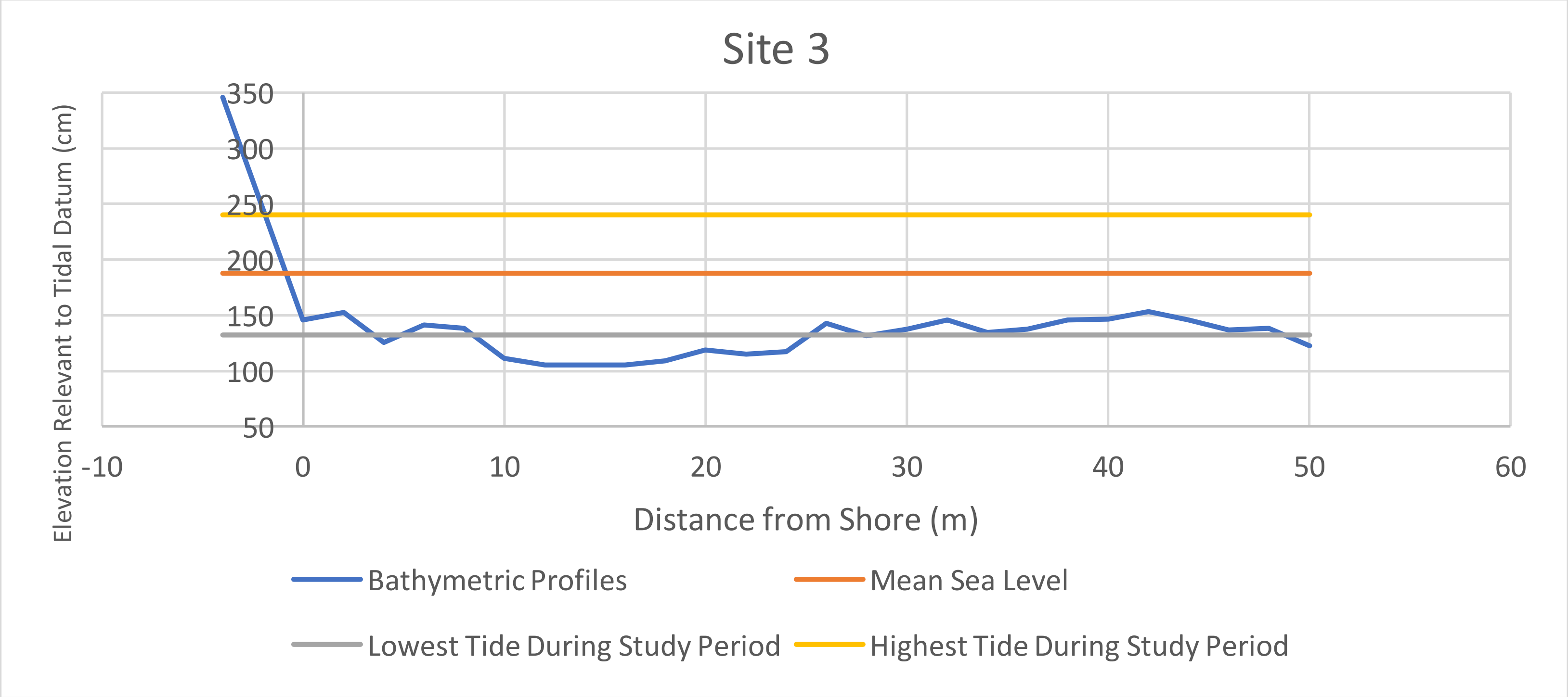
Profiles at Sites 1 – 12

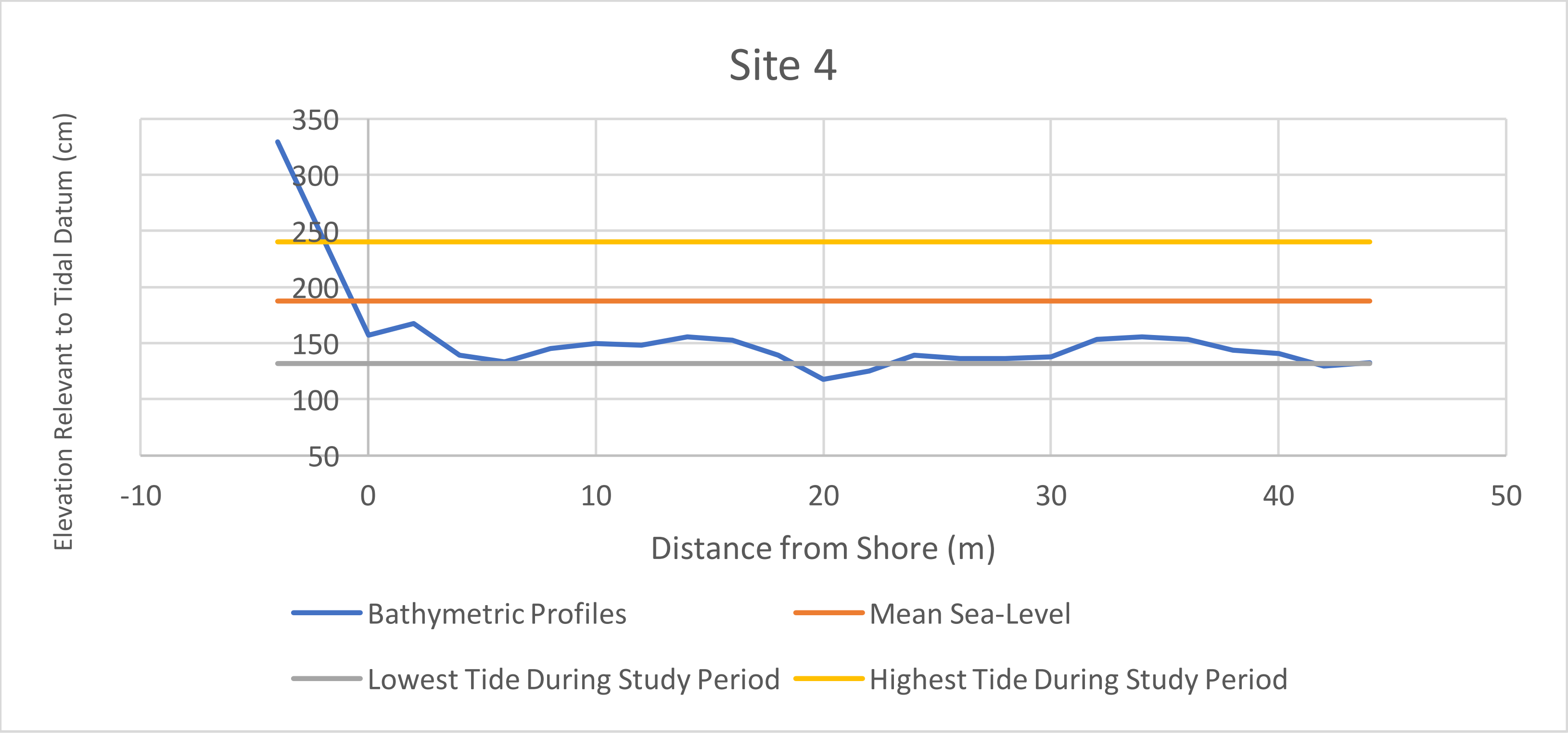
Figure 6.1: Indicative location of bathymetric profiles at sites 1 – 12 and topographic profile extending across the island from site 7.

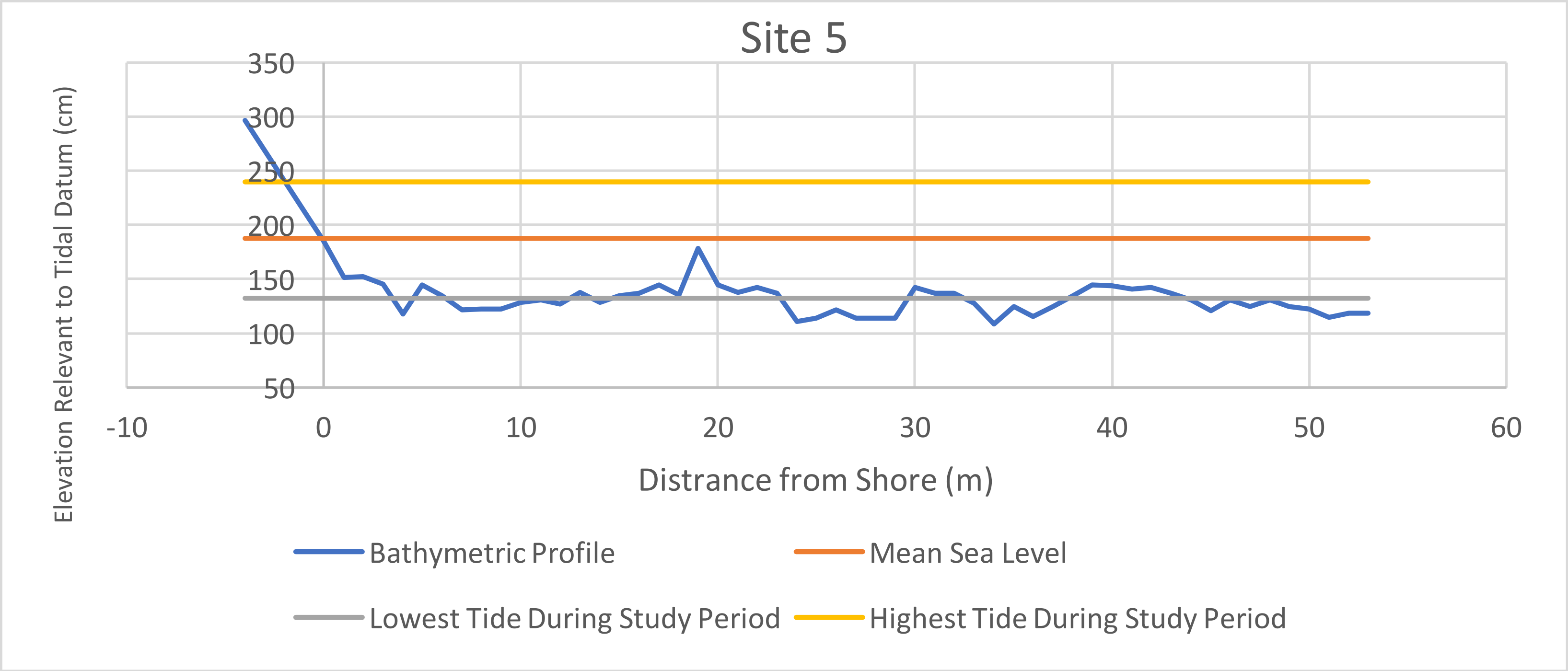
The results for the bathymetric profiles at sites 1 – 12 and the topographic profile that extends across the island from site 7 (see Figure 6.1 for indicative location) are displayed on the following pages. The bathymetric profiles at sites 6 and 7 have areas that are above mean sea level. Site 6 had the greatest area above mean sea level with 43 % of the transect, and site 7 had 18%. The majority of profiles, however, are situated between mean sea level and the lowest tide during the study period (21 April – 12 May). Site 12 was the flattest profile, with all measurements falling within a 31 cm range. Site 2 showed the greatest variation in level with all measurements falling within a range of 90 cm. The mean length of the transects at sites 1 – 12 was 58 metres. The width of the island at sites 1 – 12 ranged between 200 – 260 metres.

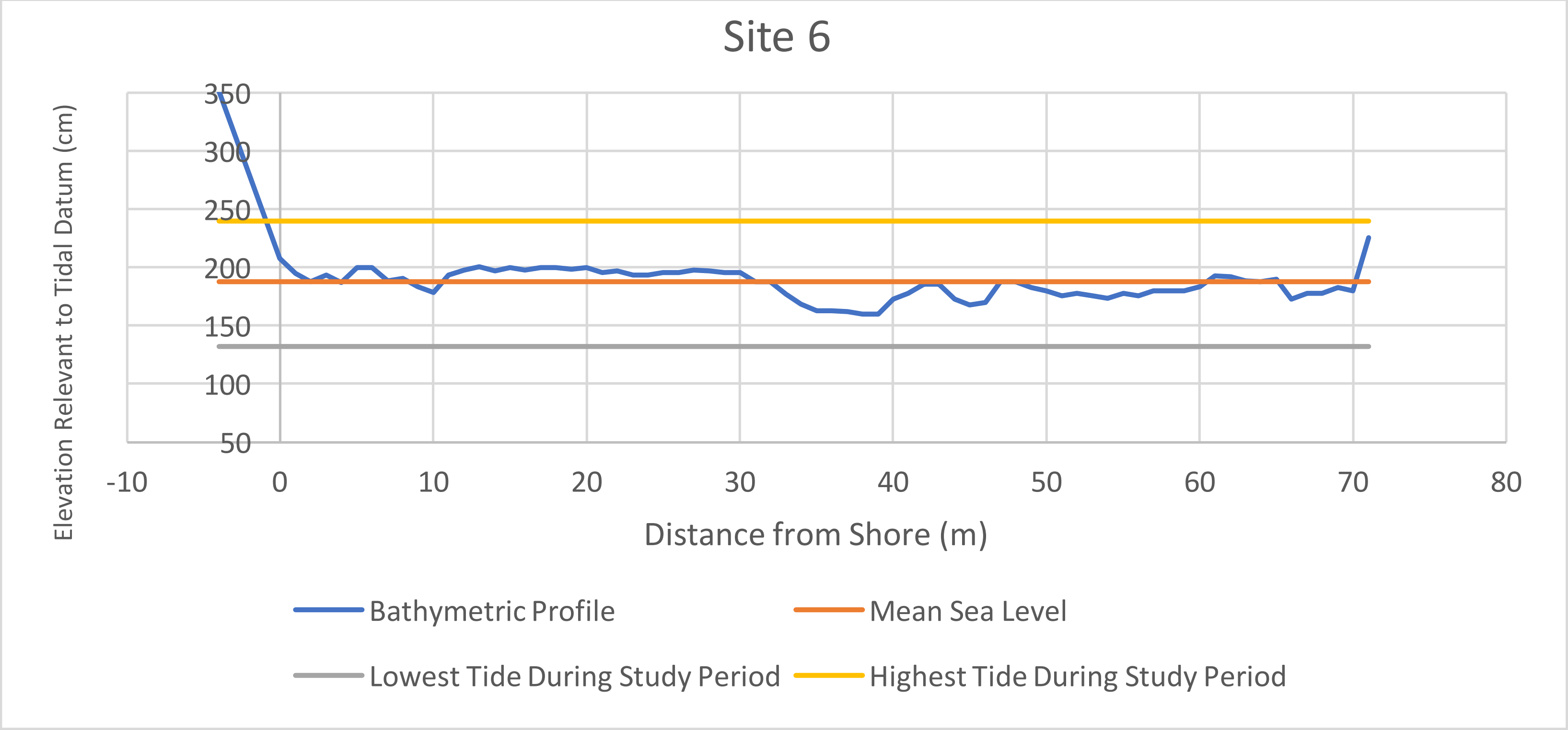


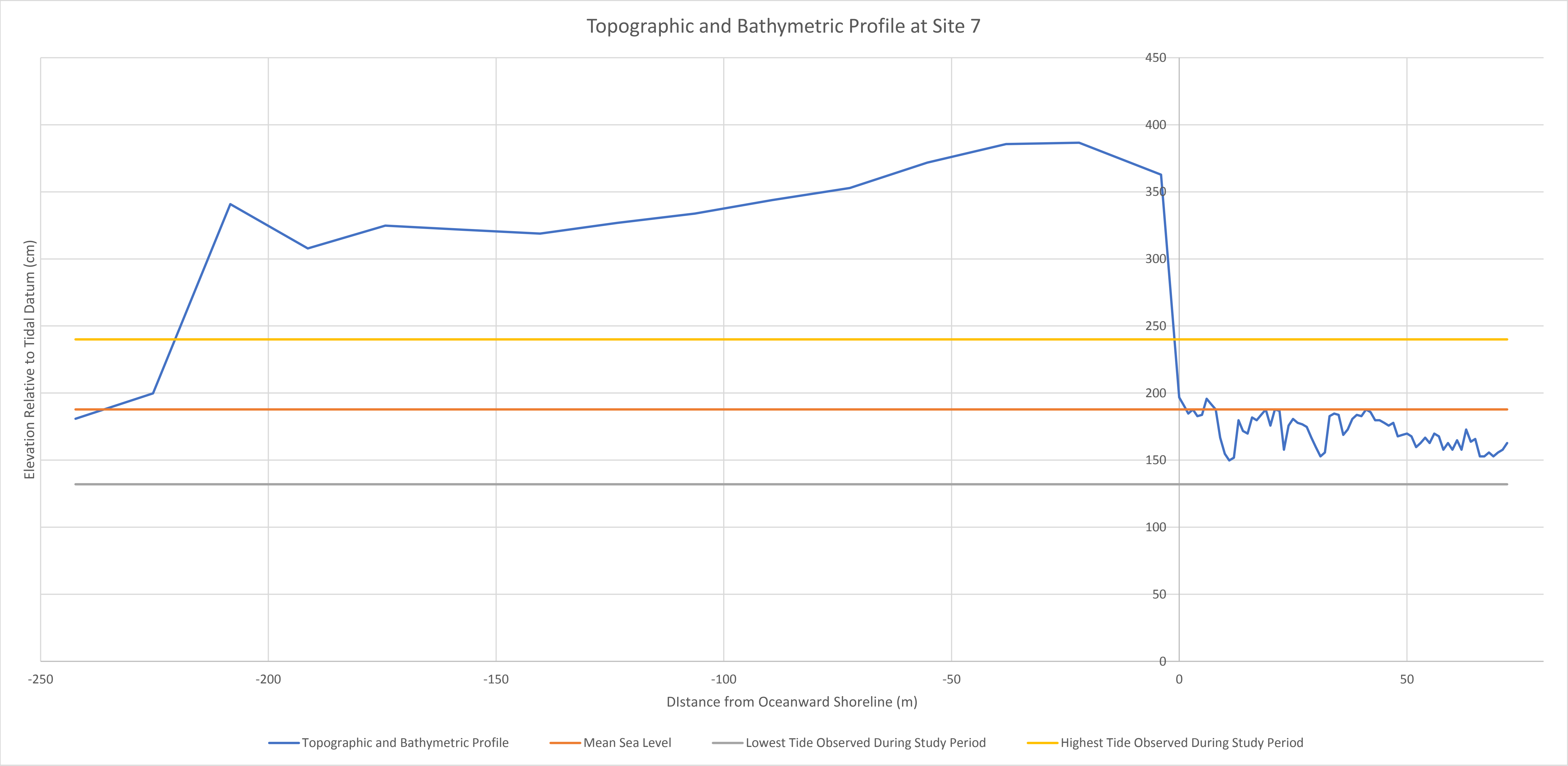




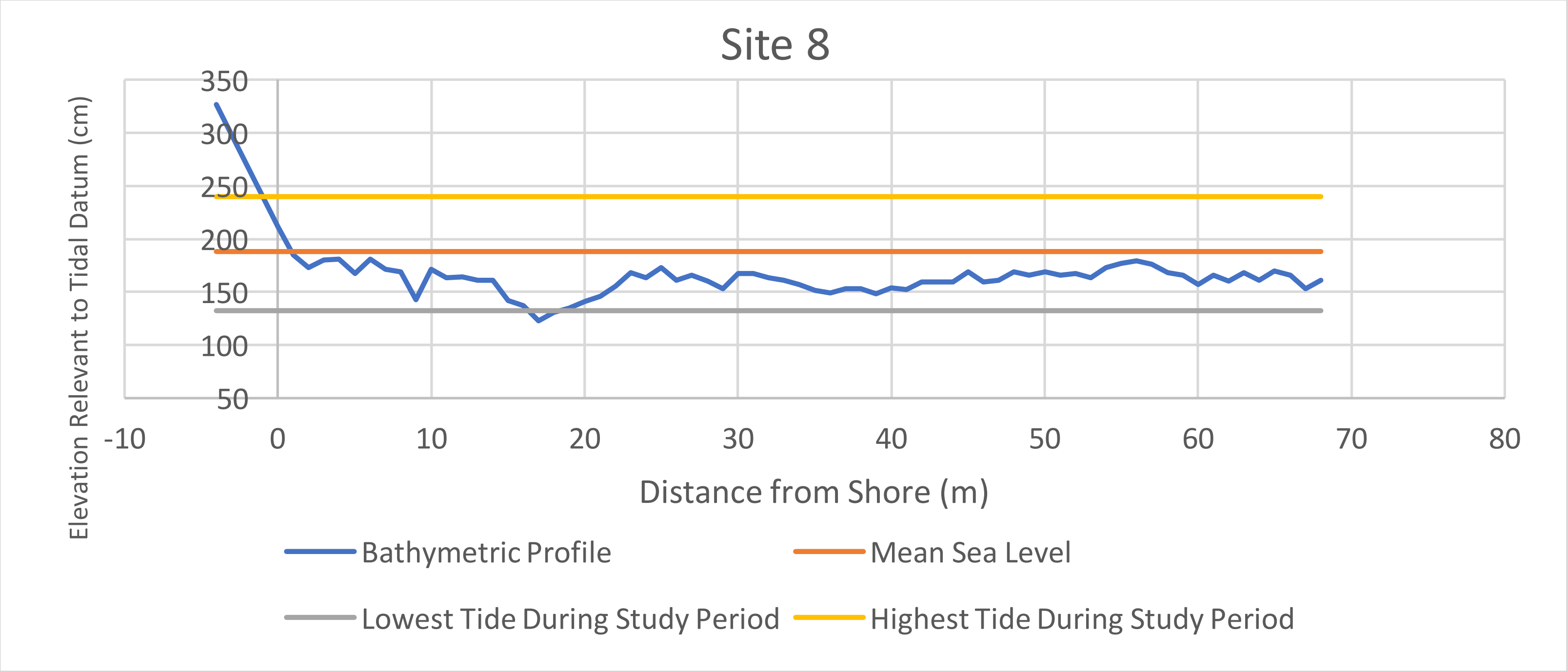

Site 4
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
Distance from Shore (m)
Bathymetric Profiles
Mean Sea-Level
Lowest Tide During Study Period
Highest Tide During Study Period

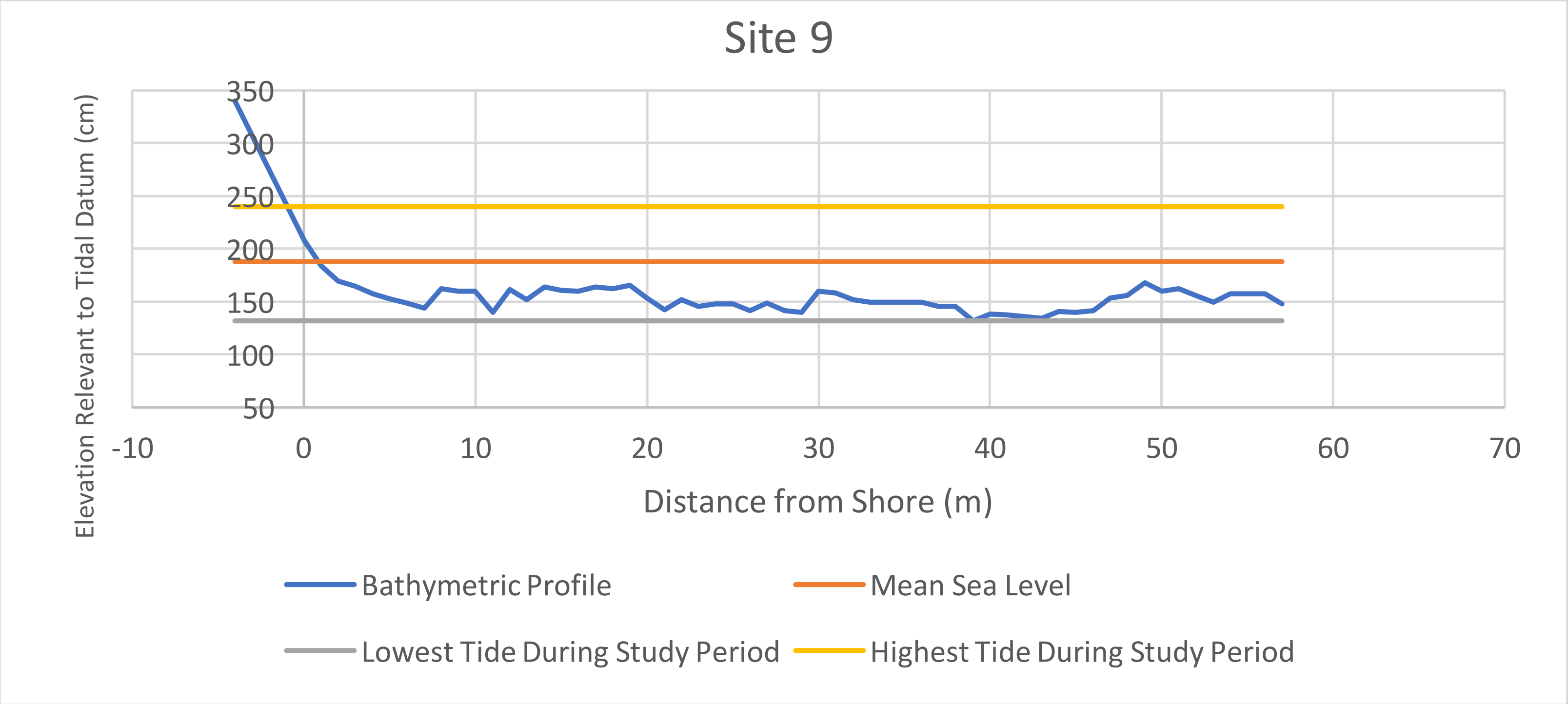

Site 5
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
Distrance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period

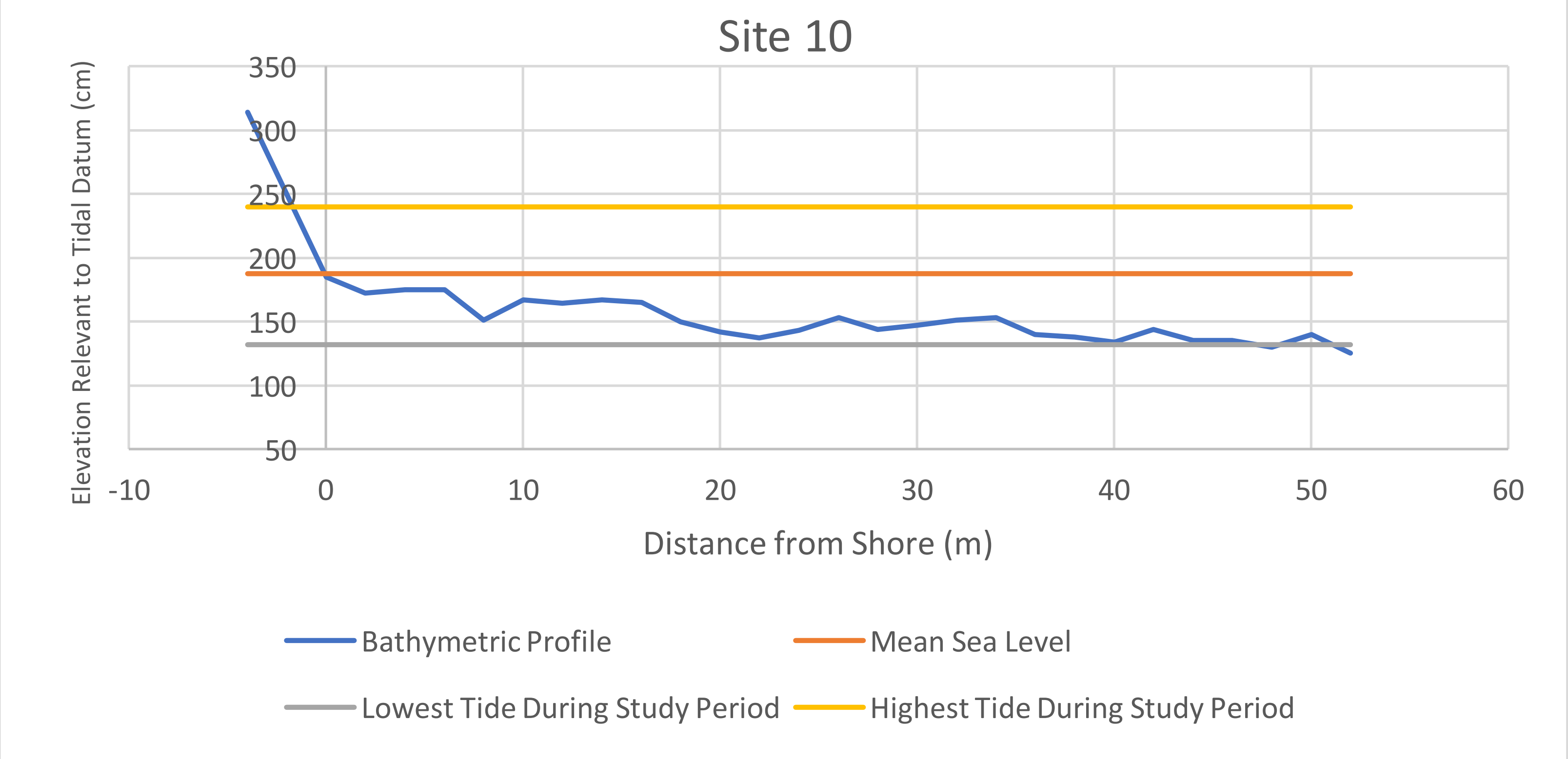

Site 6
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
70
80
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period

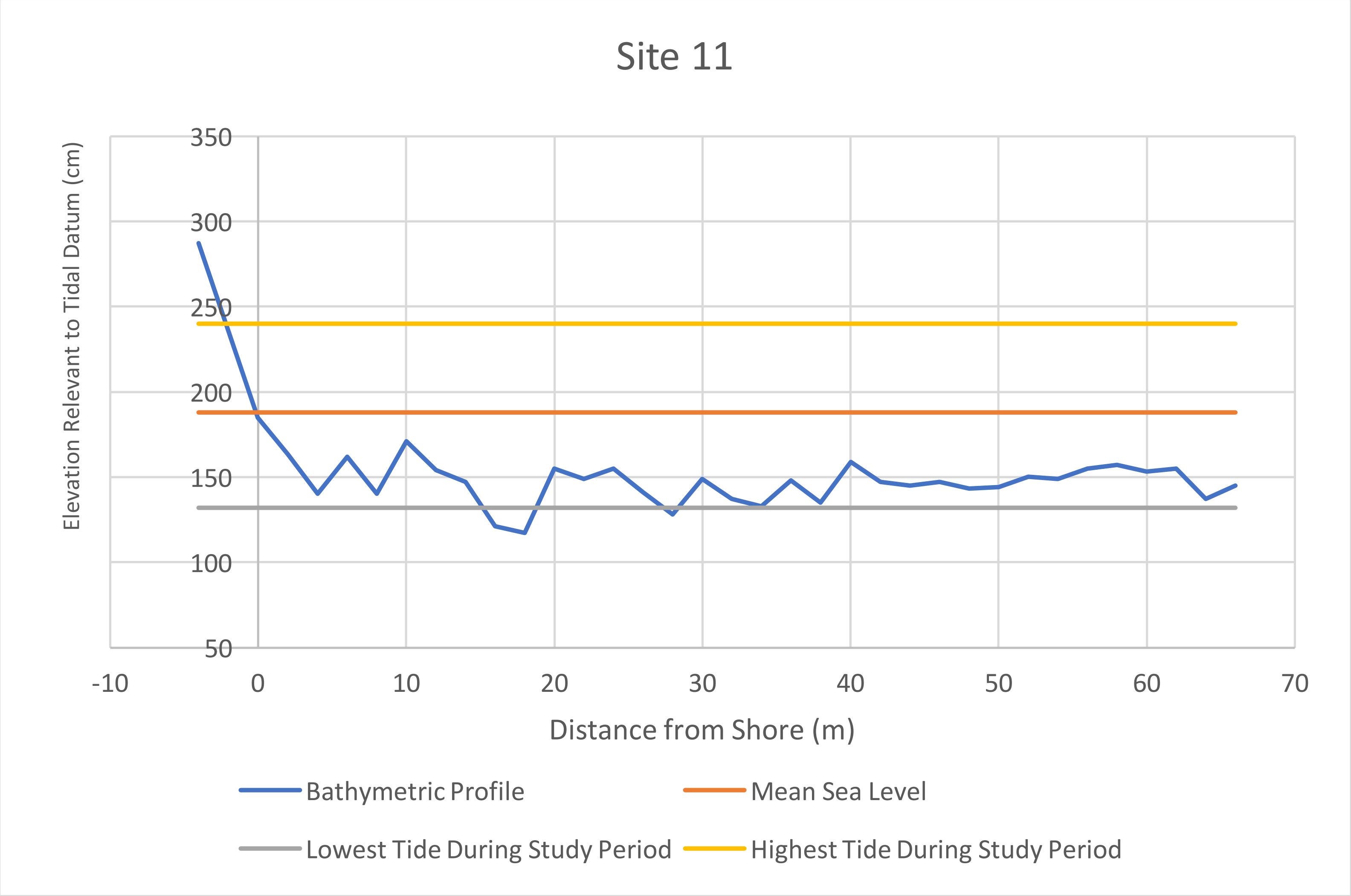


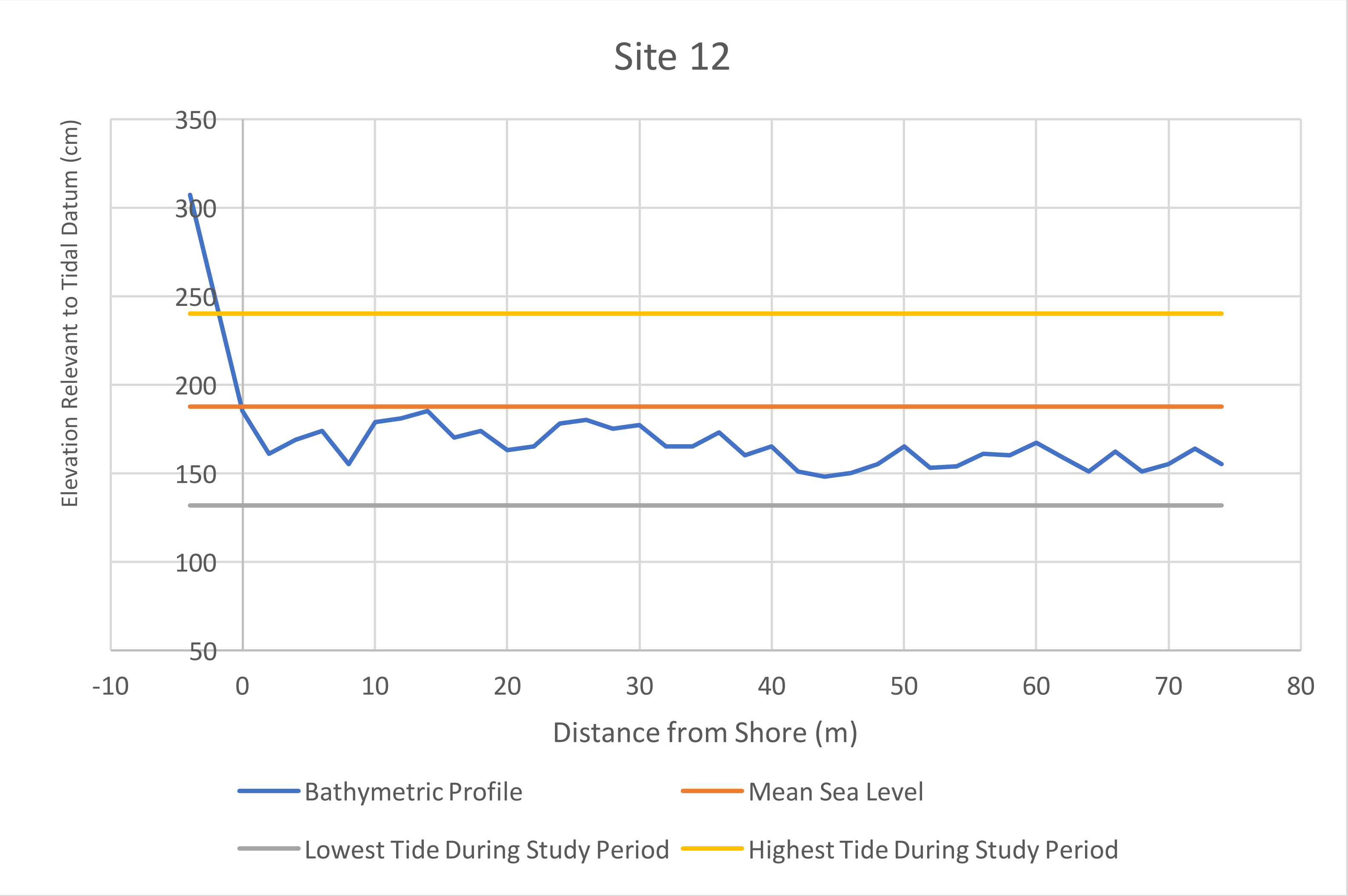
The topographic profile at site 7 shows that the highest point is 147 cm above the highest tide observed during the study period.


Site 8
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
70
80
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period


Site 9
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
70
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period


Site 10
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period


Site 11
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
70
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period


Site 12
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
70
80
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period

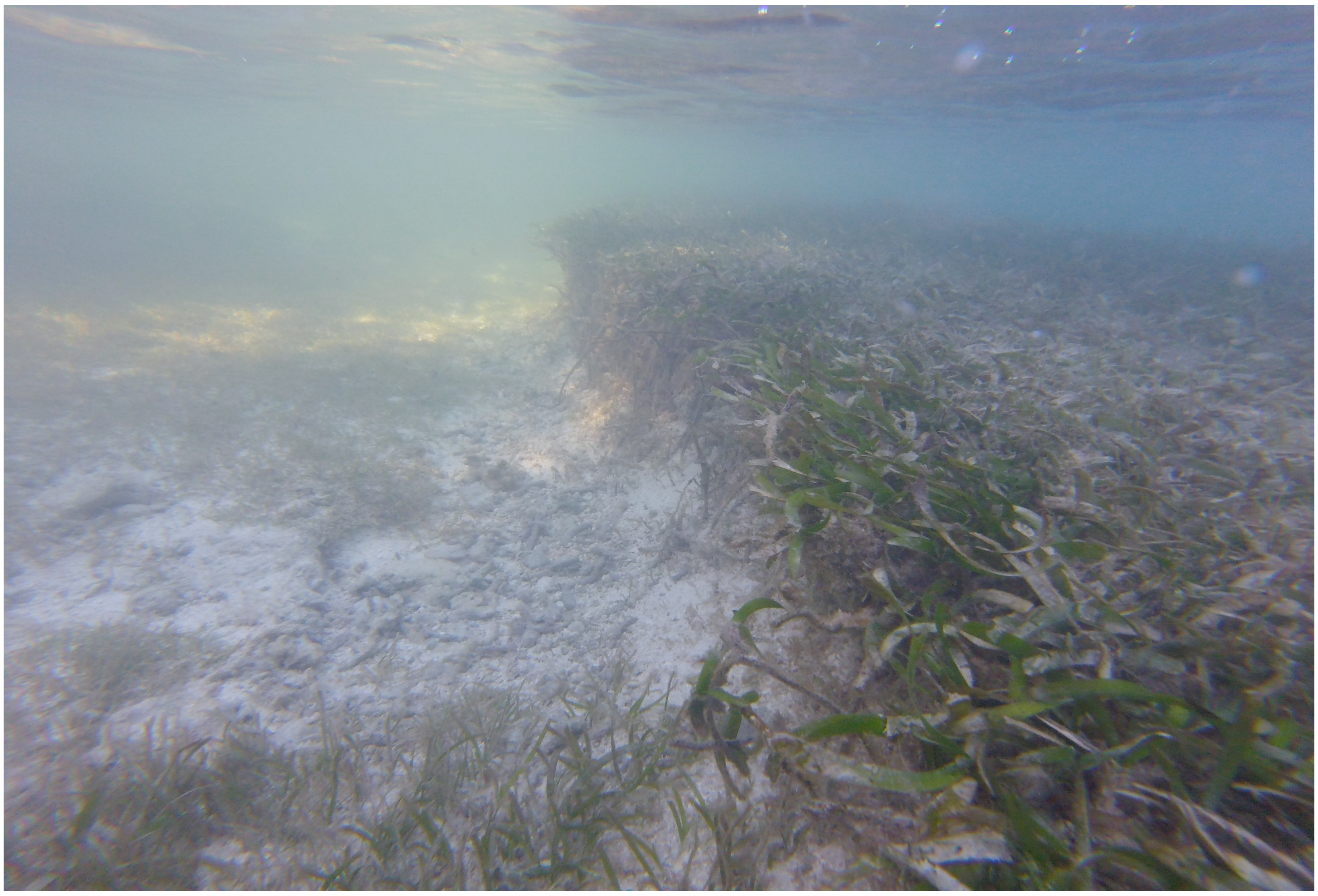


Figure 6.2: Photo taken at site 7 showing seagrass bed higher than surrounding substrate.

Figure 6.3: Photo taken at site 12 showing seagrass beds from above.

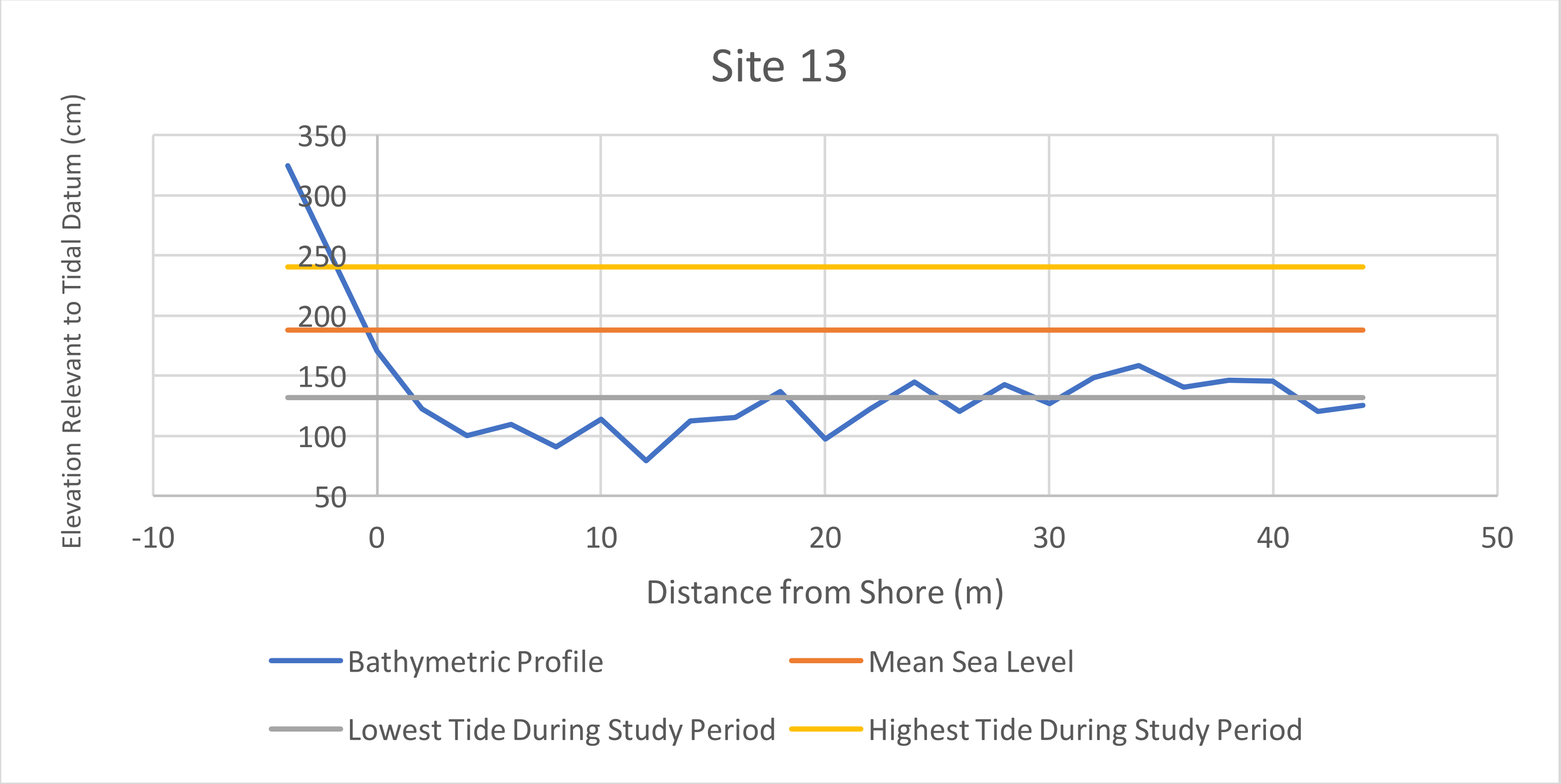
Figure 6.4: Photo taken at site 8 showing seagrass beds higher than surrounding substrate.

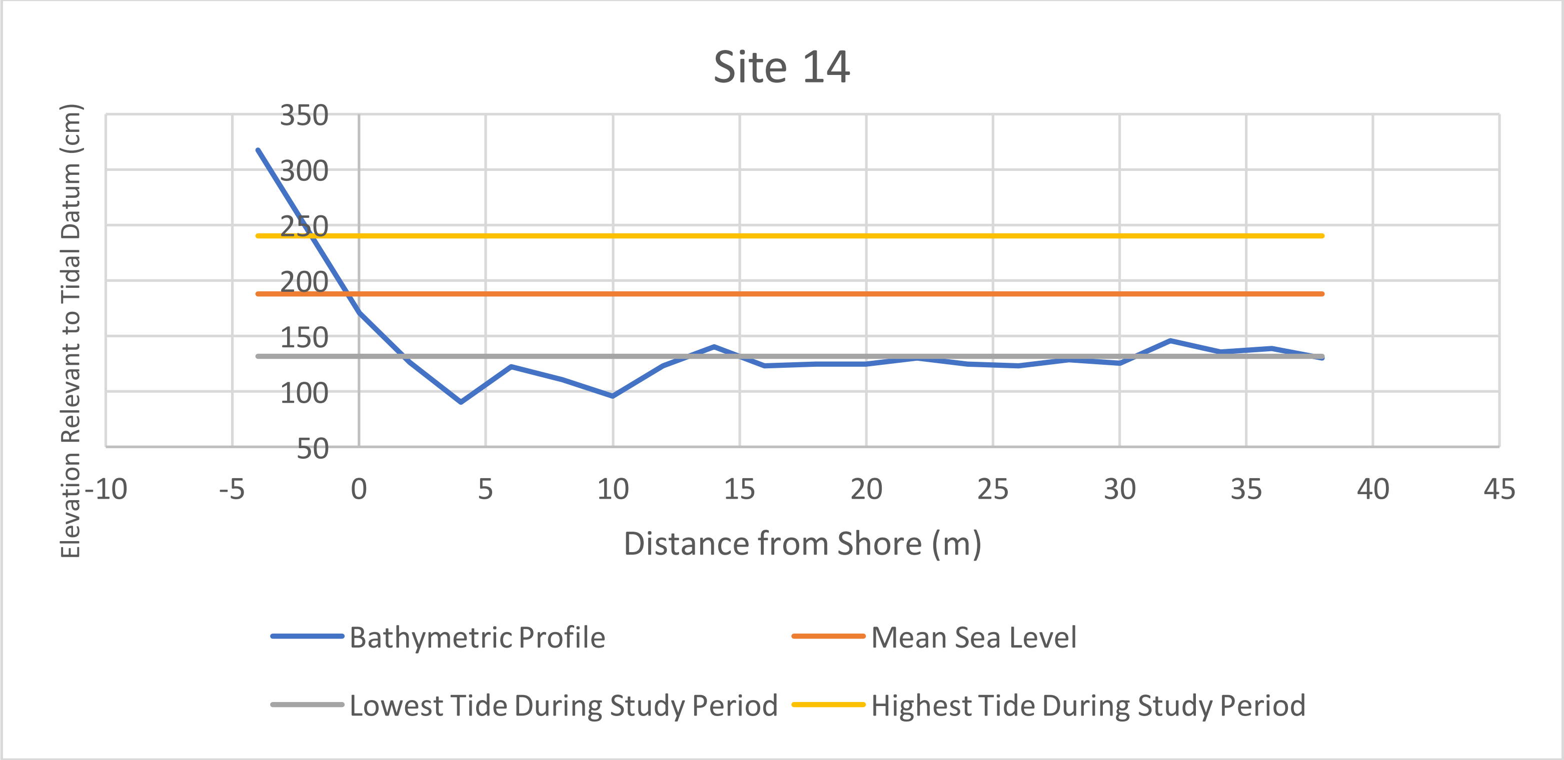
Figure 6.5: Photo taken at site 12 showing seagrass beds exposed during low tide.

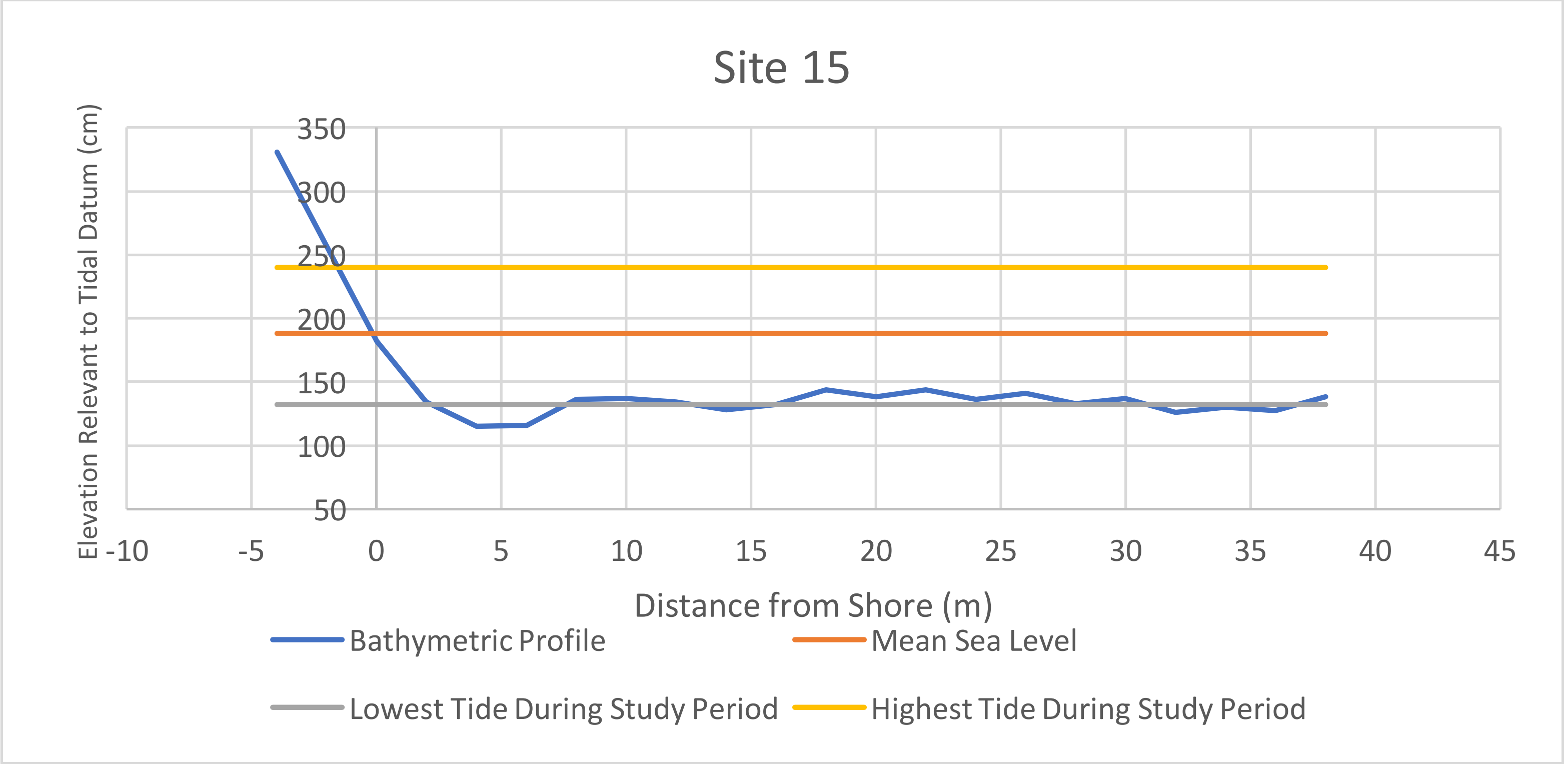
Profiles at Sites 13 – 22

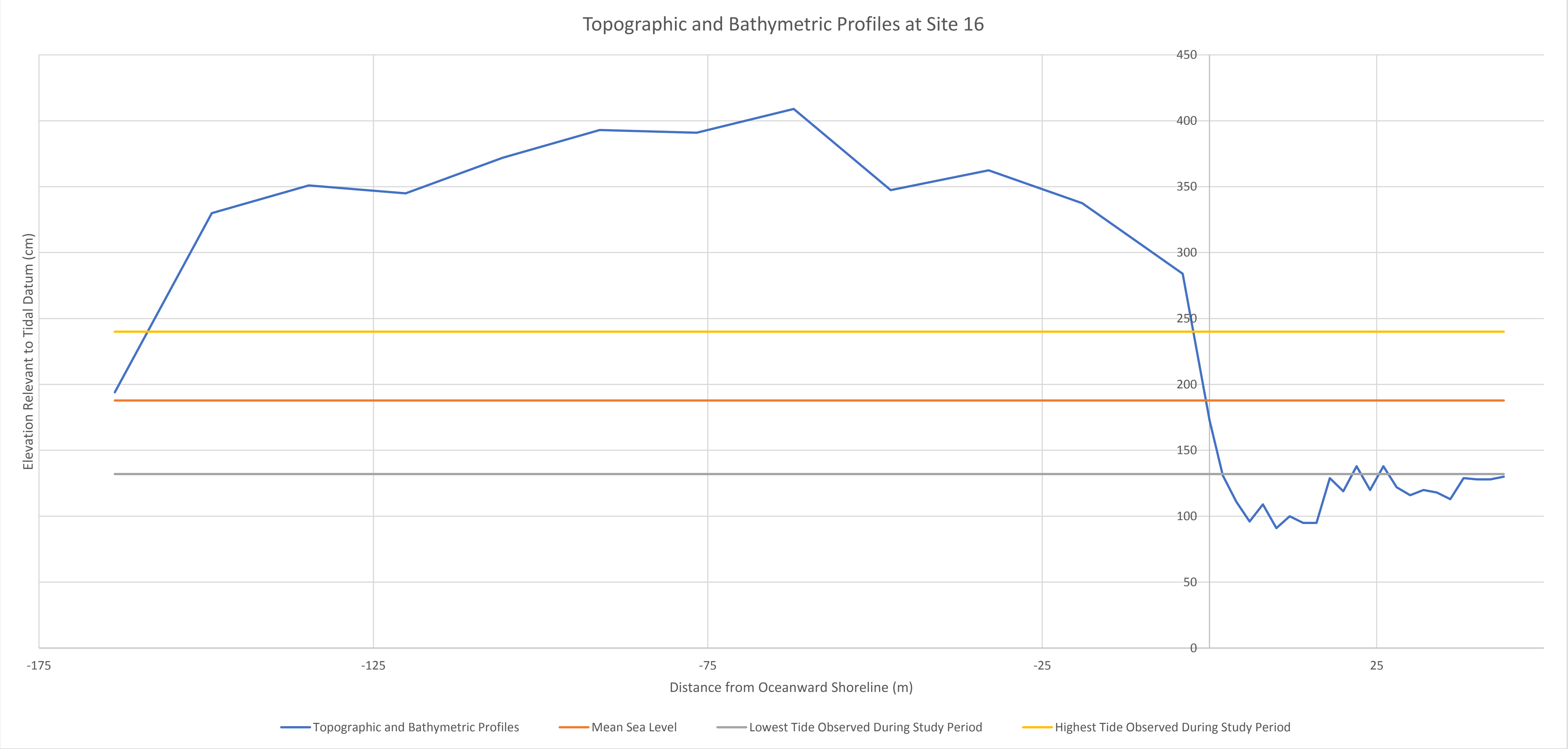
Figure 6.6: Indicative location of bathymetric profiles at sites 13 – 22 and topographic profile extending across the island from site 16.

Graphs showing the bathymetric profiles at sites 13 – 22 and the topographic profile that extends across the island from site 16 (see Figure 6.6 above for indicative location) are displayed on the following pages. Unlike profiles at sites 1 – 12, no profiles at sites 13 – 22 had any measurements above mean sea level. Instead, the majority were below the lowest tide observed during the study period (21 April – 12 May). Another difference between profiles at sites 1 – 12 and 13 – 22 is that profiles at sites 13 – 22 show a greater range in water depth measurements with measurements at the flattest profile falling within a range of 69 cm and measurements at the most uneven profile falling within a range of 123 cm. The deepest part of the profiles at sites 13 – 22 tends to be situated close to shore. As the profile extends towards the reef crest the profile becomes shallower (see profiles for sites 14 and 15 for example). The mean length of the profiles at sites 13 – 22 was 43 metres. The width of the island at sites 13 – 22 ranged between 120 – 190 metres.

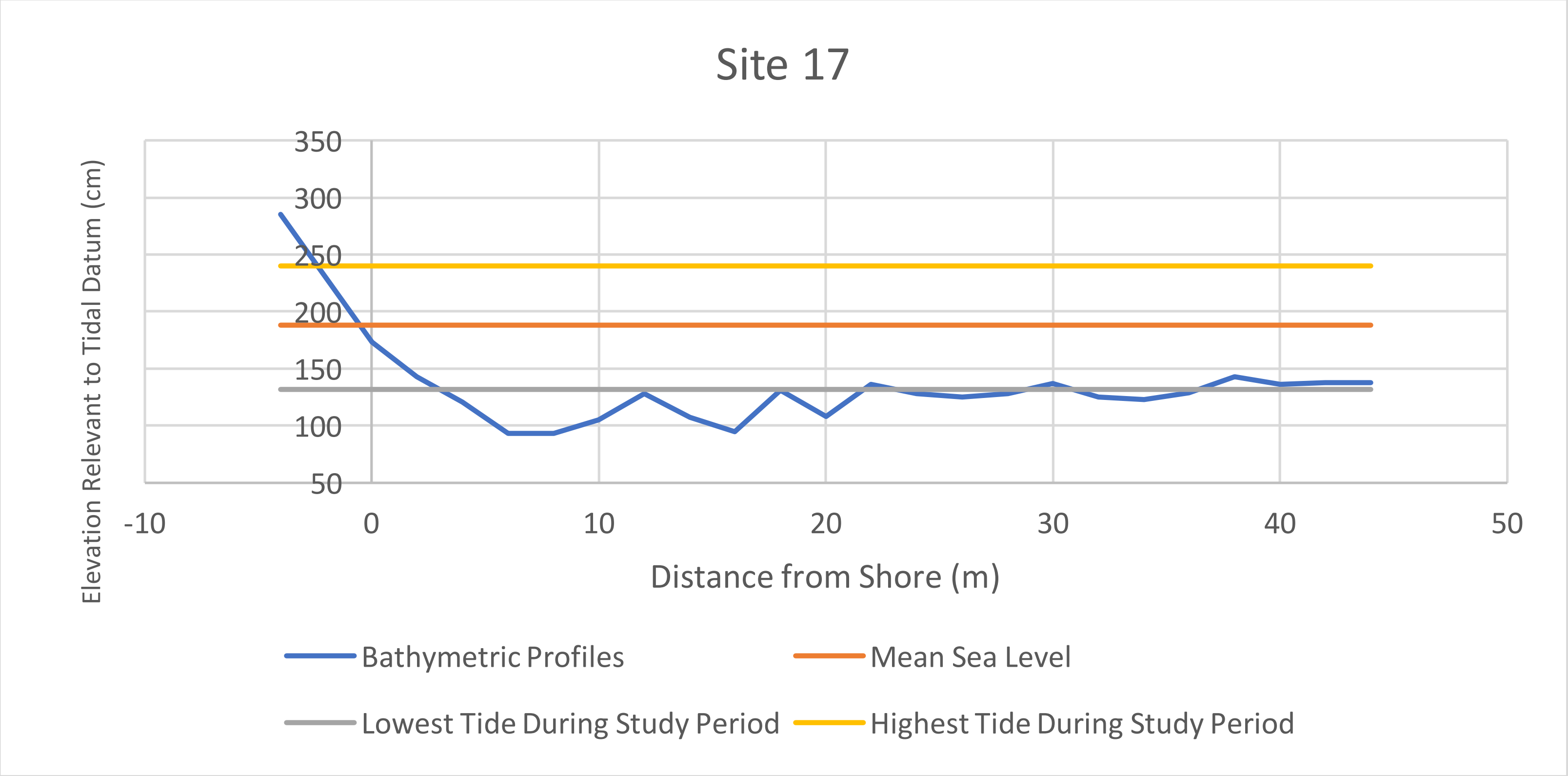

Site 13
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period

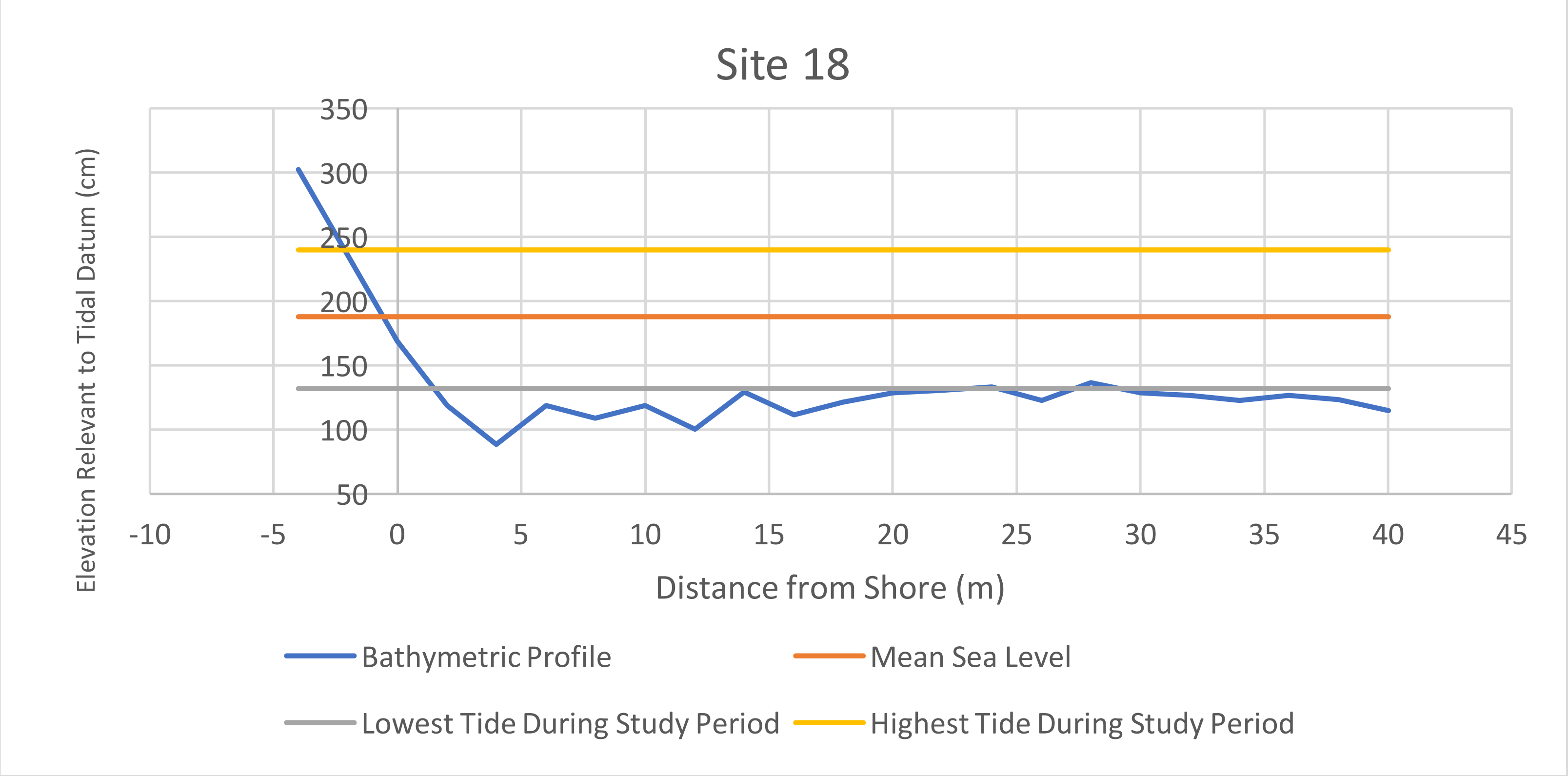

Site 14
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
-5
0
5
10
15
20
25
30
35
40
45
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period

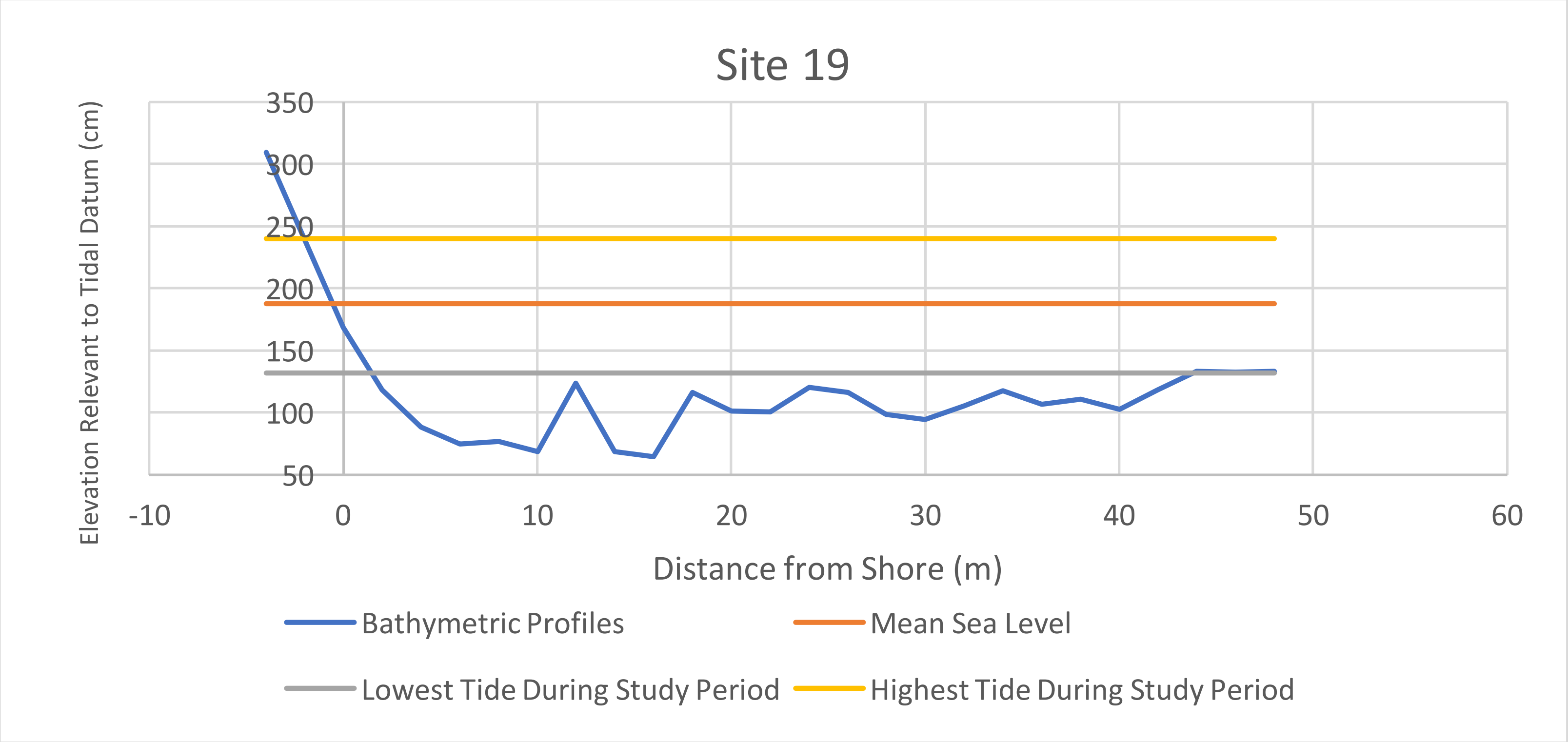

Site 15
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
-5
0
5
10
15
20
25
30
35
40
45
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period

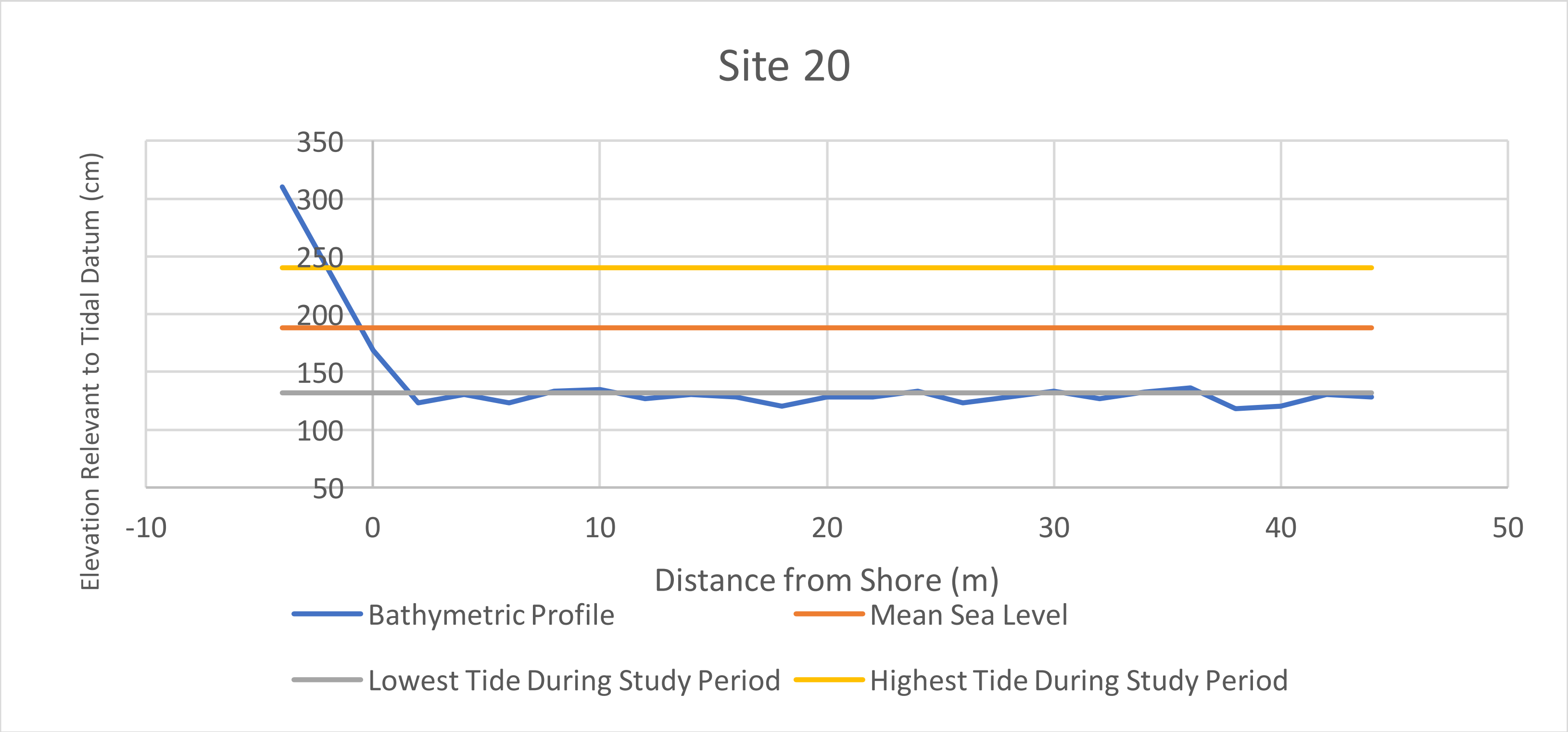


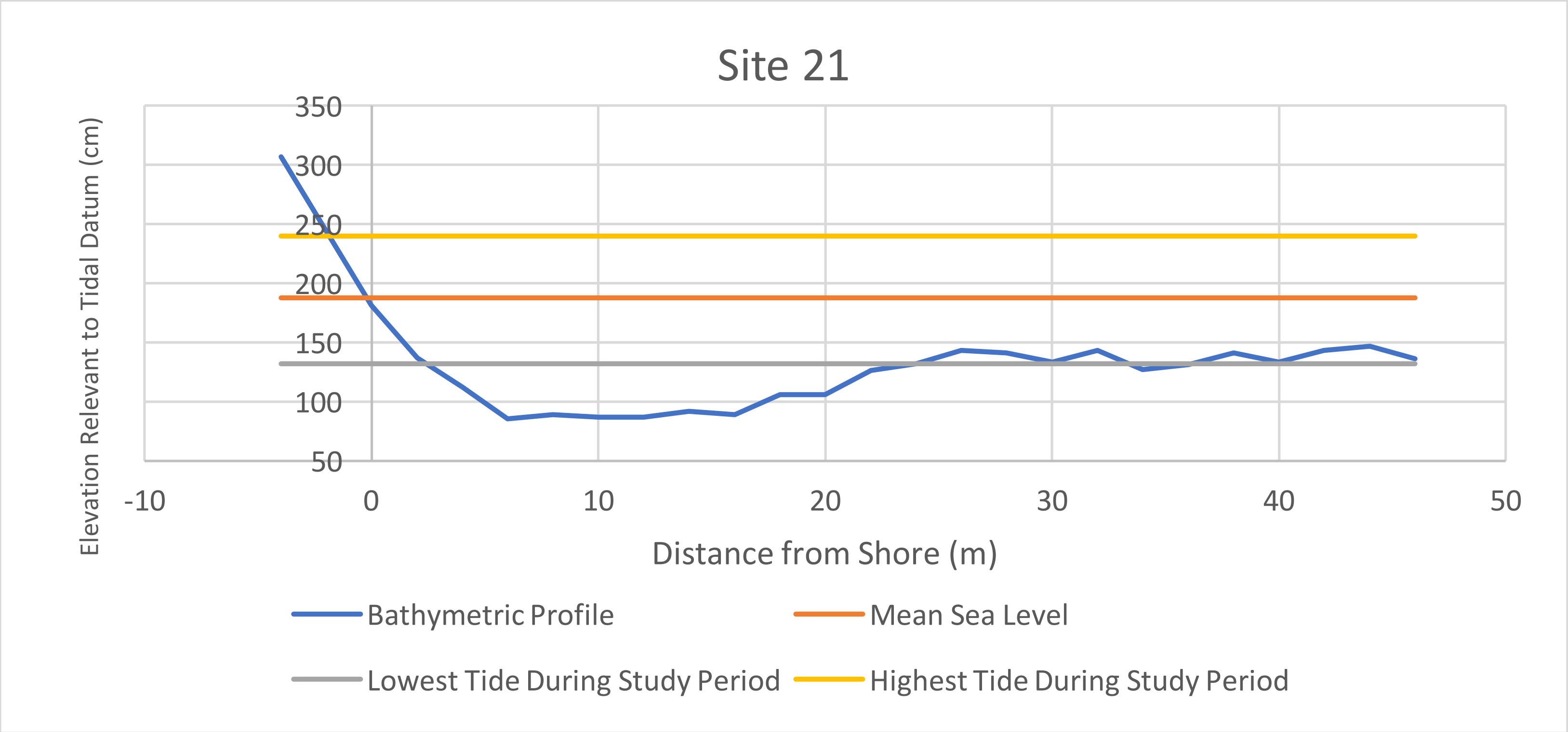
The topographic profile at site 16 shows that the highest point is 169 cm above the highest tide observed during the study period.


Site 17
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
Distance from Shore (m)
Bathymetric Profiles
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period


Site 18
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
-5
0
5
10
15
20
25
30
35
40
45
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period


Site 19
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
Distance from Shore (m)
Bathymetric Profiles
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period


Site 20
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period


Site 21
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period

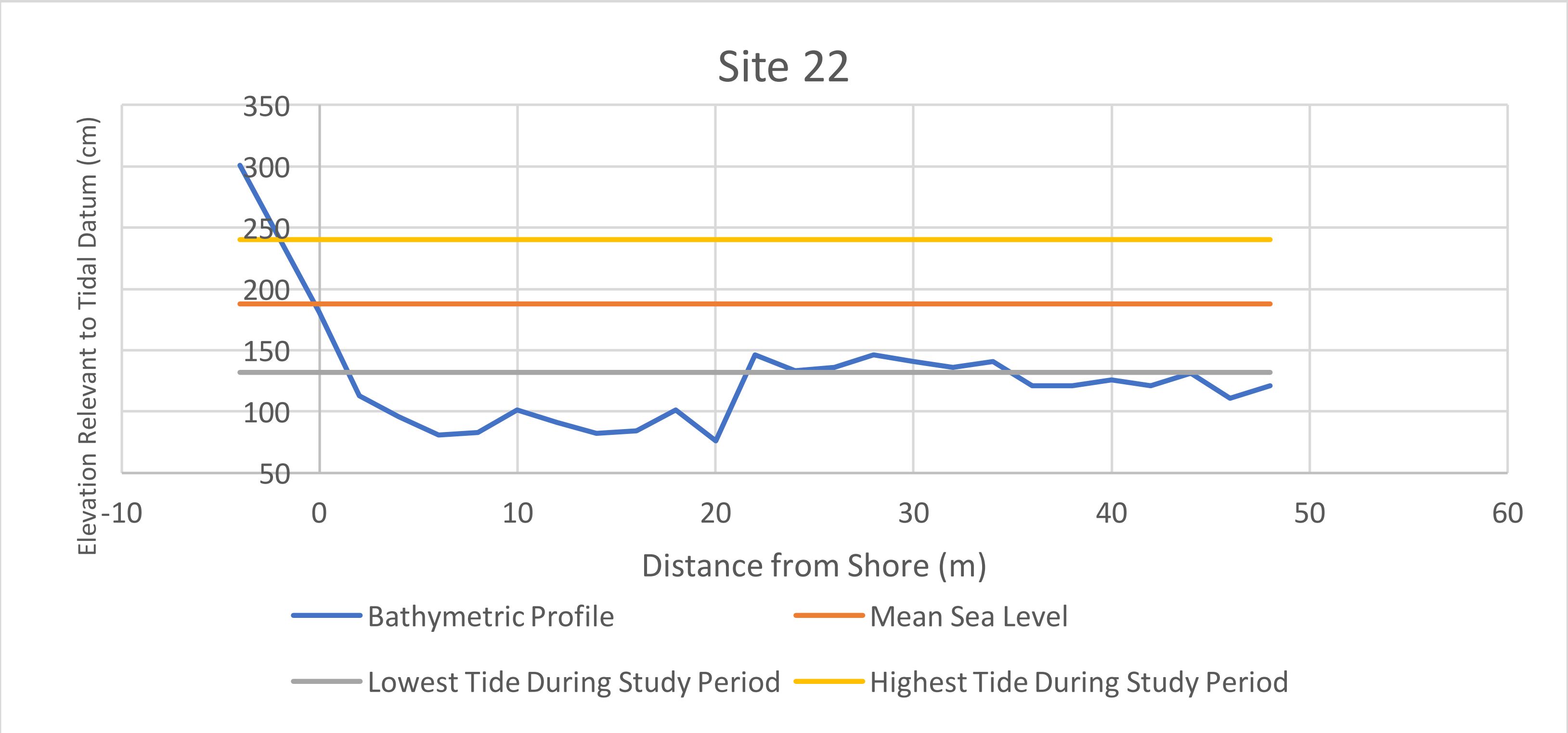

Site 22
Elevation Relevant to Tidal Datum (cm)
350
300
250
200
150
100
50
-10
0
10
20
30
40
50
60
Distance from Shore (m)
Bathymetric Profile
Mean Sea Level
Lowest Tide During Study Period
Highest Tide During Study Period

Figure 6.7: Photo taken at site 14 showing sandy substrate close to shore.

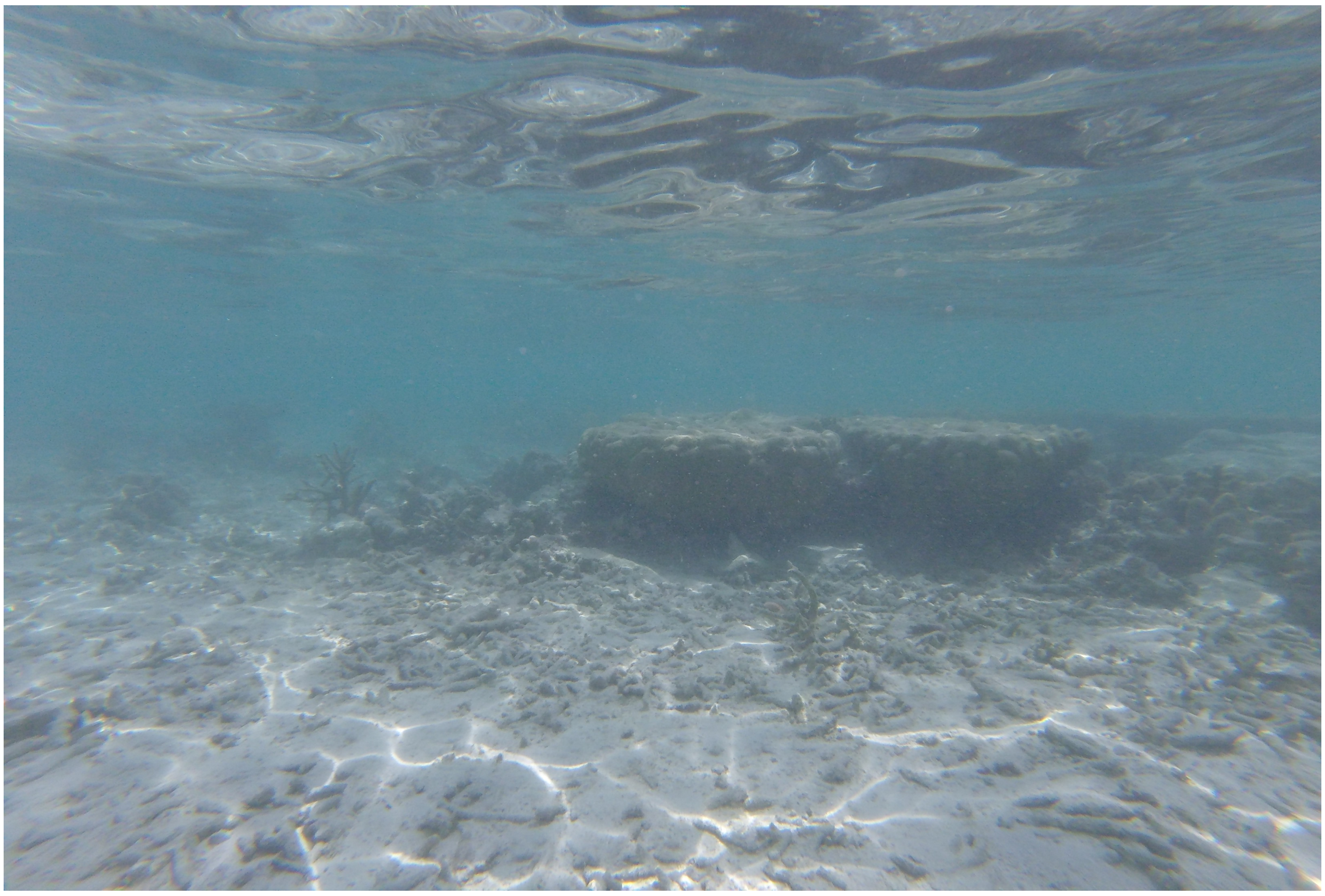


Figure 6.8: Photo taken at site 13 showing deeper water close to shore and the beginning of the inner reef flat on the right hand side.

Figure 6.9: Photo taken at site 15 showing the reef flat.

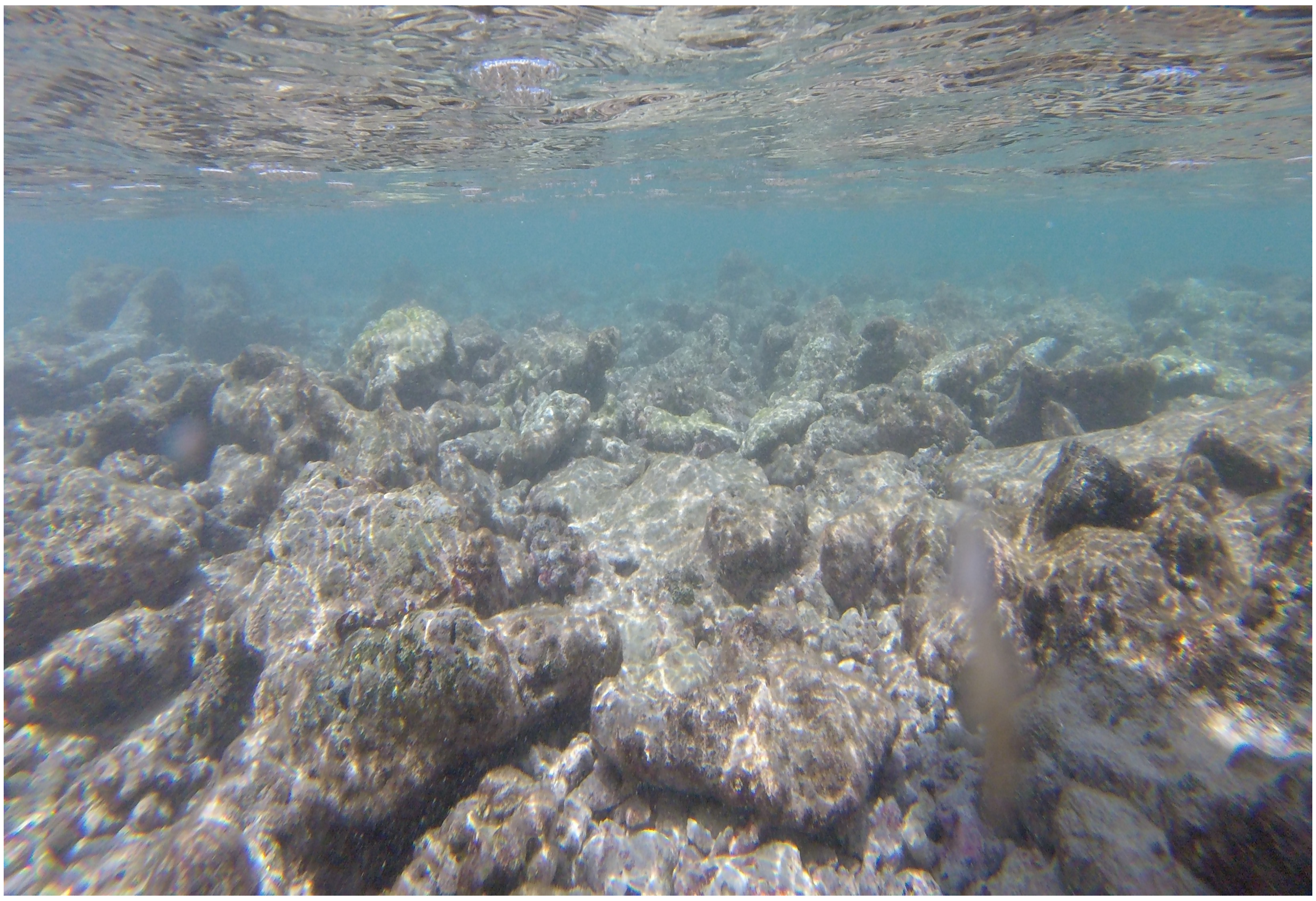


Figure 6.10: Photo taken at site 13 showing the reef crest.

In order to help visualize the bathymetric profiles, a three-dimensional model has been created and is displayed below in Figure 6.11. Sites 6 and 7 show area above the water level, which is set at mean sea level.

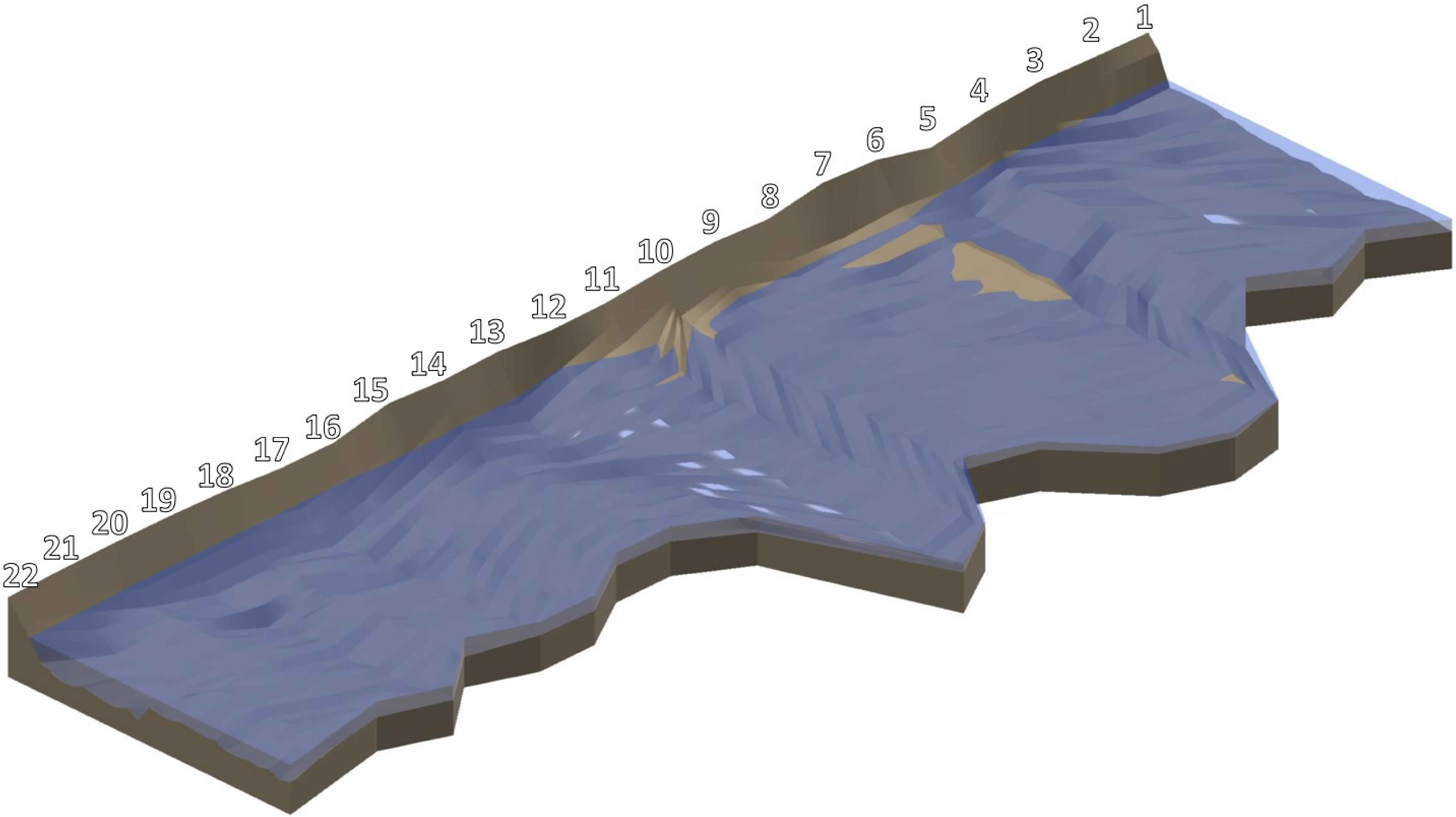


Figure 6.11: 3D model of the bathymetric profiles at sites 1 - 22.

Shoreline Stability

According to the criteria described in chapter 4, sites 1 – 12 show variation in apparent recent shoreline stability with 5 sites described as stable, 4 as accreting, and 3 as eroding (see figures 6.12 – 6.16). While the location of sites described as 'stable' or 'eroding' appears to be random, sites that were 'accreting' are grouped together, occurring at sites 1, 2, 3, and 4, and in close proximity to the harbour.

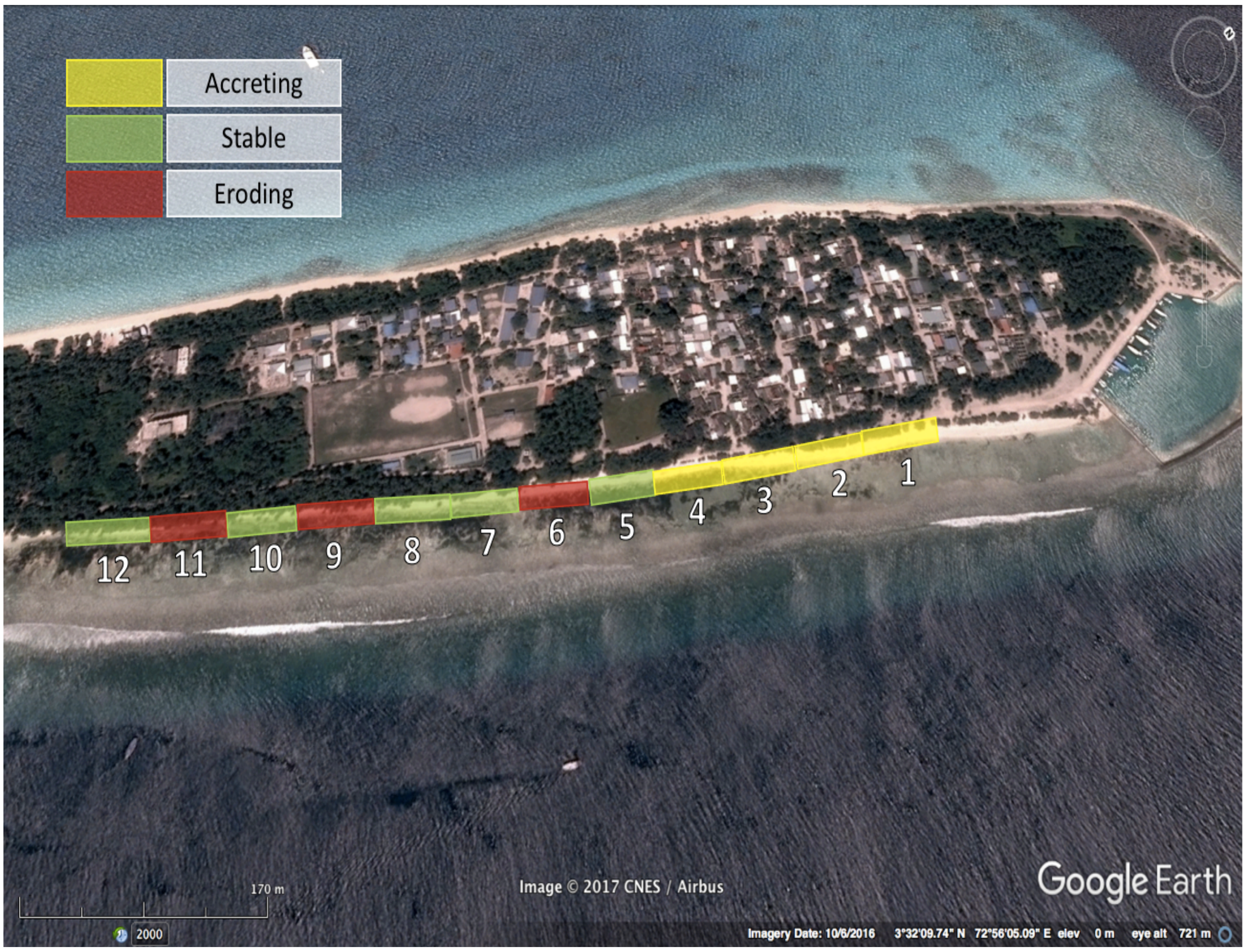


Figure 6.12: Google Earth image with the results of the shoreline stability survey at sites 1 – 12.

Figure 6.13: Photo taken at site 2 showing young vegetation indicating an accreting shoreline according to methods described in chapter 4.

Figure 6.14: photo taken at site 11 showing overhanging vegetation indicating an eroding shoreline.

Figure 6.15: photo taken at site 8 showing a mix of young and mature vegetation close to shore indicating a stabe shoreline.

Figure 6.16: photo taken at site 9 showing beach rock indicating an eroding shoreline.

Sites 13 – 22 show variation in recent apparent shoreline stability with 5 sites described as stable, 3 as eroding and 2 as accreting. Site 20 showed the most explicit signs of accretion with young vegetation, approximately 1.5 metres high close to shore with more mature vegetation further inshore. Site 22 appeared to have the most severe erosion as roots of mature vegetation were exposed.

Figure 6.17: Google Earth image with the results of the shoreline stability survey at sites 13 – 22.

Figure 6.18: photo taken at site 22 showing roots of mature vegetation exposed indicating an eroding shoreline according to methods outlined in chapter 4.

Figure 6.19: photo taken at site 17 showing young vegetation indicating an accreting shoreline.

Figure 6.20: photo taken at site 14 showing beach rock and vegetation being undercut indicating an eroding shoreline.

Figure 6.21: photo taken at site 19 showing both young and more mature vegetation close to the shoreline indicating a stable shoreline.

Discussion

Results suggest that seagrass reduces water depth. Given the effect that water depth has on attenuating wave energy, it was hypothesised that there would be a positive correlation between the presence of seagrass and greater apparent recent shoreline stability. While the results did not support this hypothesis, the literature argues that seagrass provides coastal protection services that can play an important role in the stability and long term persistence of low-lying atoll islands. Therefore the discussion in this section is framed around the following questions: 1) why is seagrass present at sites 1 – 12 but not at sites 13 – 22 and what determines its location around the island? 2) Why is there no correlation between the presence of seagrass and shoreline stability? 3) If seagrass is to be protected, what are the implications for future development on Dhigurah Island?

Why is seagrass present at sites 1 – 12 but not at sites 13 – 22 and what determines its location around the island?

Results from surveys of sediment (see chapter 5) show that at sites with seagrass (1 – 12), there is significantly more CRA than at sites without seagrass (13 – 22). As Logan et al. [84] show, CRA is an important contributor to sediment accumulation in seagrass beds. While CRA was not observed growing in seagrass beds, it is likely that seagrass cores would reveal CRA as a major contributor given their abundance on the inner reef flat just beyond the seagrass beds at sites 1 – 12.

Halimeda spp. are less abundant at sites with seagrass (1 – 12) than at sites without seagrass (13 – 22). *Halimeda* produce gravel size sediment fragments which are not suitable for growth of seagrass [87,71]. Has the relative abundance of *Halimeda* spp. at sites 13 – 22 discouraged the growth of seagrass? While observations and photos were taken of the substrate at sites 1 – 12 and 13 – 22, and from these it appeared that there was a variety of grain sizes present at all sites, a comprehensive record of sediment grain size was not taken. Therefore, testing this hypothesis would require further research.

Figure 6.22: Location of seagrass beds surrounding Dhigurah Island. Before travelling to Dhigurah Island, Google Earth images were used to identify possible locations of seagrass beds. Once on site, these initial observations were ground-truthed by snorkelling and walking in shallow sub-tidal areas.

Another factor that needs considering is wave energy. High energy environments tend to limit growth and diversity of seagrasses [59]. Despite the importance of wave energy on seagrass being widely recognised [71,81], it is difficult to quantify a direct correlation due to the variation in hydrodynamic processes. A common feature of the other two locations of seagrass beds found around Dhigurah Island is that they appear to be close to sheltered environments (see Figure 6.22). One bed is found on the lagoonward side, another is found next to storm deposits of rubble that have now been vegetated. The largest bed (found at sites 1 – 12) is not located in a sheltered environment being on the oceanward side and is therefore subject to higher wave energy. Could seagrass have established itself near the harbour before colonising further south-west? The reason behind this hypothesis is that seagrass beds create positive feedbacks that can lead to colonisation of adjacent areas that were previously unsuitable for seagrass [71]. However, an examination of historical imagery (see figures 6.23 and 6.24), appears to show that seagrass was already established, albeit less abundantly, along Dhigurah's oceanward side in 1969.

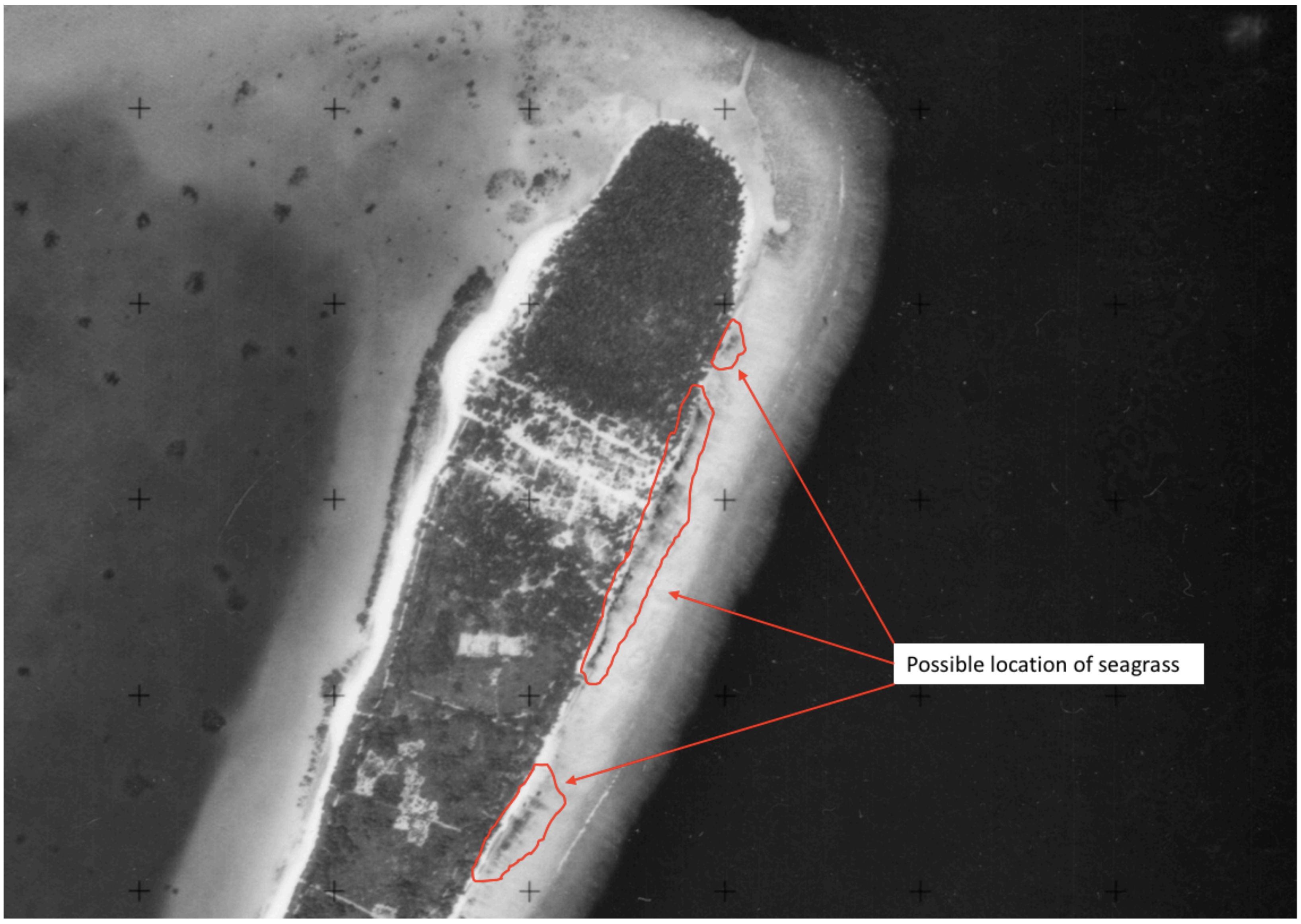


Figure 6.23: Historical image from 1969 appearing to show patches of seagrass close to Dhigurah Island's oceanward shoreline.

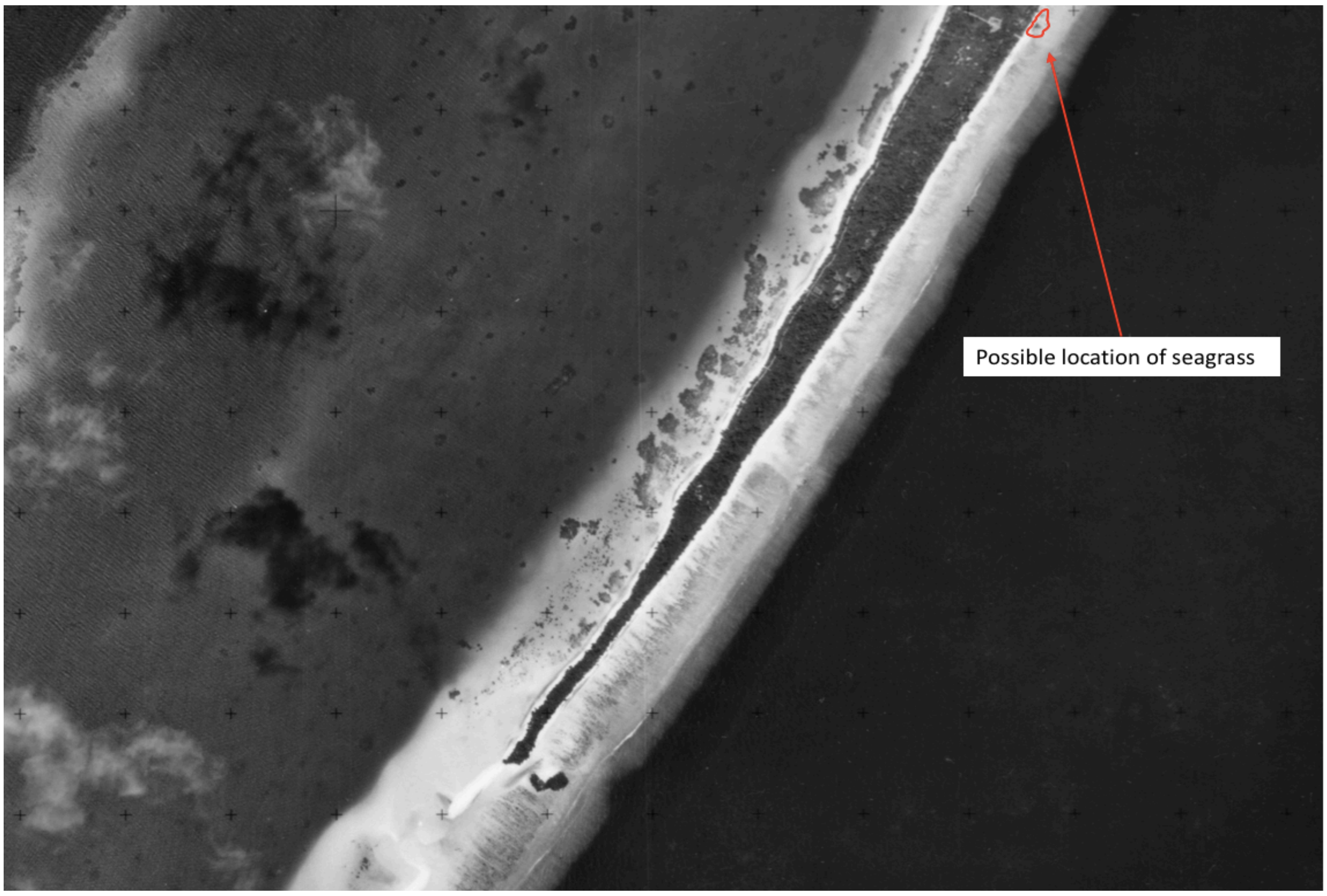


Figure 6.24: Historical image from 1969 appearing to show patches of seagrass close to Dhigurah Island's oceanward shoreline.

A series of images from the second largest current-day seagrass bed located next to the storm deposits on the oceanward side (see Figure 6.25 for location) show that while there appears to be no seagrass in this particular location in 1969, there was in 2010, and it appears to have almost doubled in area in the space of 6 years.

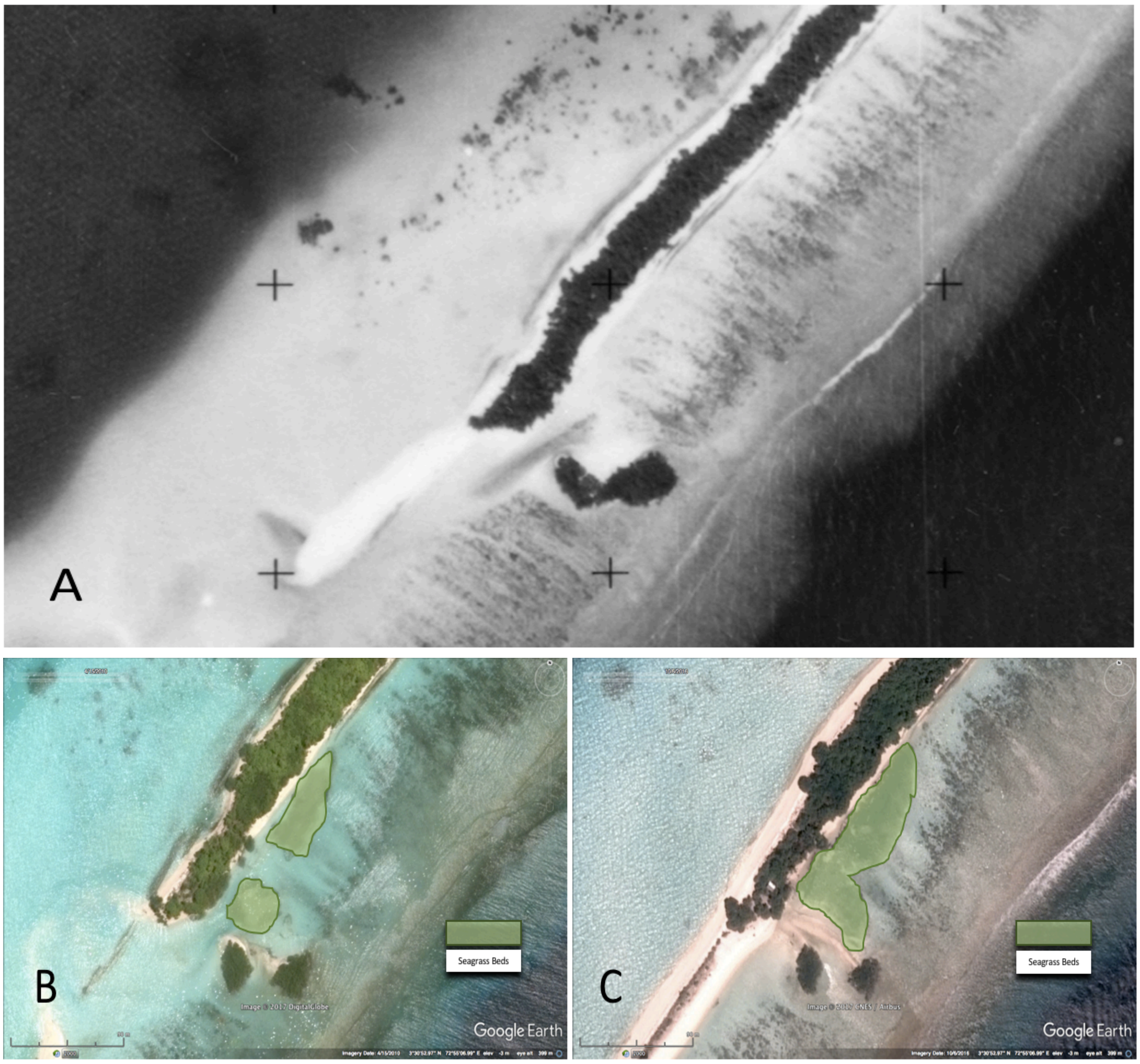


Figure 6.25: A) Historical image taken in 1969 showing storm deposits but no seagrass. B) Google Earth image showing seagrass bed in 2010. B) Google Earth image showing seagrass bed in 2016.

It is difficult to know whether seagrass has established itself because the conditions were suitable, or whether the conditions are suitable as a result of the presence of seagrass. While this study presents plausible hypotheses to explain the distribution of seagrass surrounding Dhigurah Island, further research over greater temporal scales that ties local historical knowledge together with analysis of historical imagery would provide a better understanding of the key factors affecting seagrass distribution. This information could then be used to inform the maintenance of seagrass beds.

Why is there no correlation between the presence of seagrass and shoreline stability?

While the literature argues that seagrass provides important coastal protection services, the results show no correlation between the presence of seagrass and apparent recent stability at adjacent shorelines. Given that the bathymetry of sites with seagrass was characterised by significantly shallower water depths, it was hypothesised that shorelines at sites with seagrass would show more evidence of apparent recent stability. A few plausible explanations are given for the actual results.

One plausible explanation is that while seagrass attenuates wave energy at sites 1 – 12, the lack of seagrass at sites 13 – 22 is offset by the presence of live coral on the inner reef flat, which is shown by McDowell [117] to be more abundant at sites 13 – 22. While seagrass is present at sites 1 – 12, the absence of live coral is concerning for the long-term maintenance of the largest seagrass bed. The crumbling of dead coral can result in a 'pseudo sea-level rise' as water depths increase on the reef flat [120].

Another consideration is the variation in distance from reef crest to shoreline. The further waves travel over shallow environments the more wave energy is attenuated [61]. The mean distance from the vegetation line to the reef crest was measured as 58 metres at sites 1 – 12 and 43 metres at sites 13 – 22. Observations from aerial images, however, suggest that distances between the vegetation line and the reef crest are slightly greater at sites 13 – 22. A limitation of measurements taken is that it is difficult to observe the exact location of the reef crest when taking measurements in the water, and it may have extended for some distance beyond its apparent location.

As Guannel et al. [61] argue, if a fringing reef, like that on Dhigurah Island's oceanward side, can keep up with sea-level, then it will be more effective at attenuating waves than seagrass.

While sites 13 – 22 have live coral, their ability to attenuate waves is also threatened. The Maldives experienced several recent mass bleaching events in 1998, 2010 and 2016 as a result of increased water temperatures and ocean acidification brought about by climate change [121]. The effect these disturbance events have had on coral reefs surrounding Dhigurah is currently being researched as part of the IUCN's 'Project Regenerate' [121]. Differences in anthropogenic activities at a local scale have either compounded or dulled the effects of climate change [121,122]. Local stressors, such as siltation from harbour construction, which Dhigurah has experienced, may have contributed to the death of coral at sites 1 - 12 [107]. Fortunately, coral reefs in the Maldives have shown a marked ability to recover in comparison to other reefs in the Indian Ocean [124]. There is concern, however, that the cumulative effects of global disturbances and local disturbances may be eroding reef resilience [124]. The stability of Dhigurah's oceanward shoreline will be greatly affected by the health of coral reefs. All these factors mean there will be no certain correlation between the presence of seagrass or coral reefs and shoreline stability.

Sites 1, 2, 3 and 4 were all described as showing evidence of accretion. Furthermore, as has been discussed in chapter 3, when the harbour was constructed, material was used to extend parts of the island [16]. As the harbour was built in 2004, vegetation has only had 13 years to establish itself which explains the lack of coconut palms taller than 5 metres. Harbour maintenance recently saw the harbour dredged with the material deposited just south-west of the harbour (see Figure 6.26). This explains why sites 1, 2, 3, 4 appeared to have significantly more sediment than other beaches.

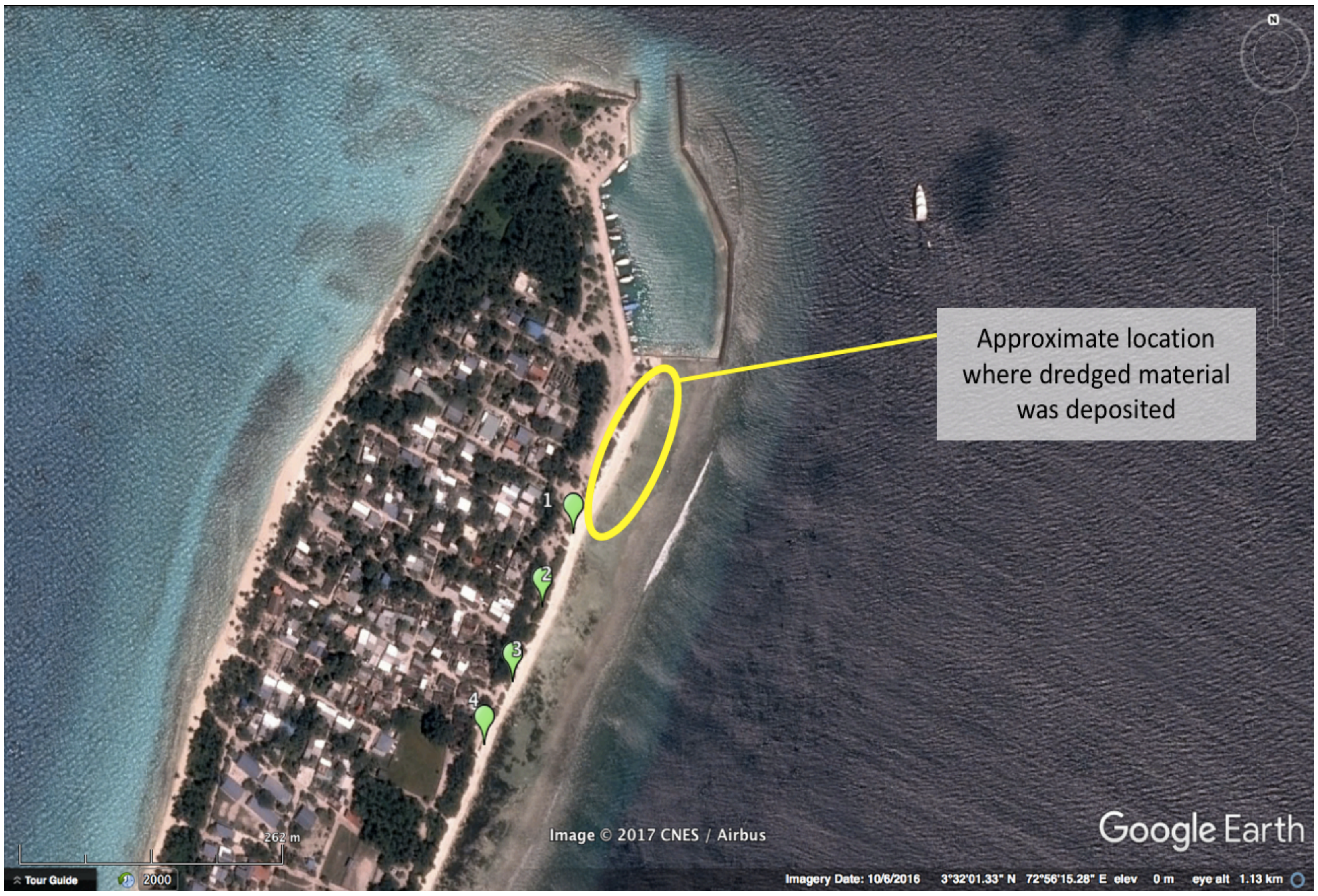


Figure 6.26: Google Earth image showing approximate location where dredged material was deposited.

If seagrass is to be protected, what are the implications for future development on Dhigurah Island?

While some future development might help to create sheltered conditions in which seagrass thrives, it can also have adverse effects. During storms or due to high wave energy, seagrass is often washed ashore. As the Maldives is marketed as a luxury destination with pristine beaches, tourists have complained about seagrass spoiling beaches and are disappointed when their expectations are not met [125]. Consequently, seagrass beds are undesirable for the tourism industry [125]. Comparing historical images of the island of Dhidhdhoofinolhu, South Ari Atoll, it is evident that seagrass beds have been systematically cleared (see Figure 6.27).

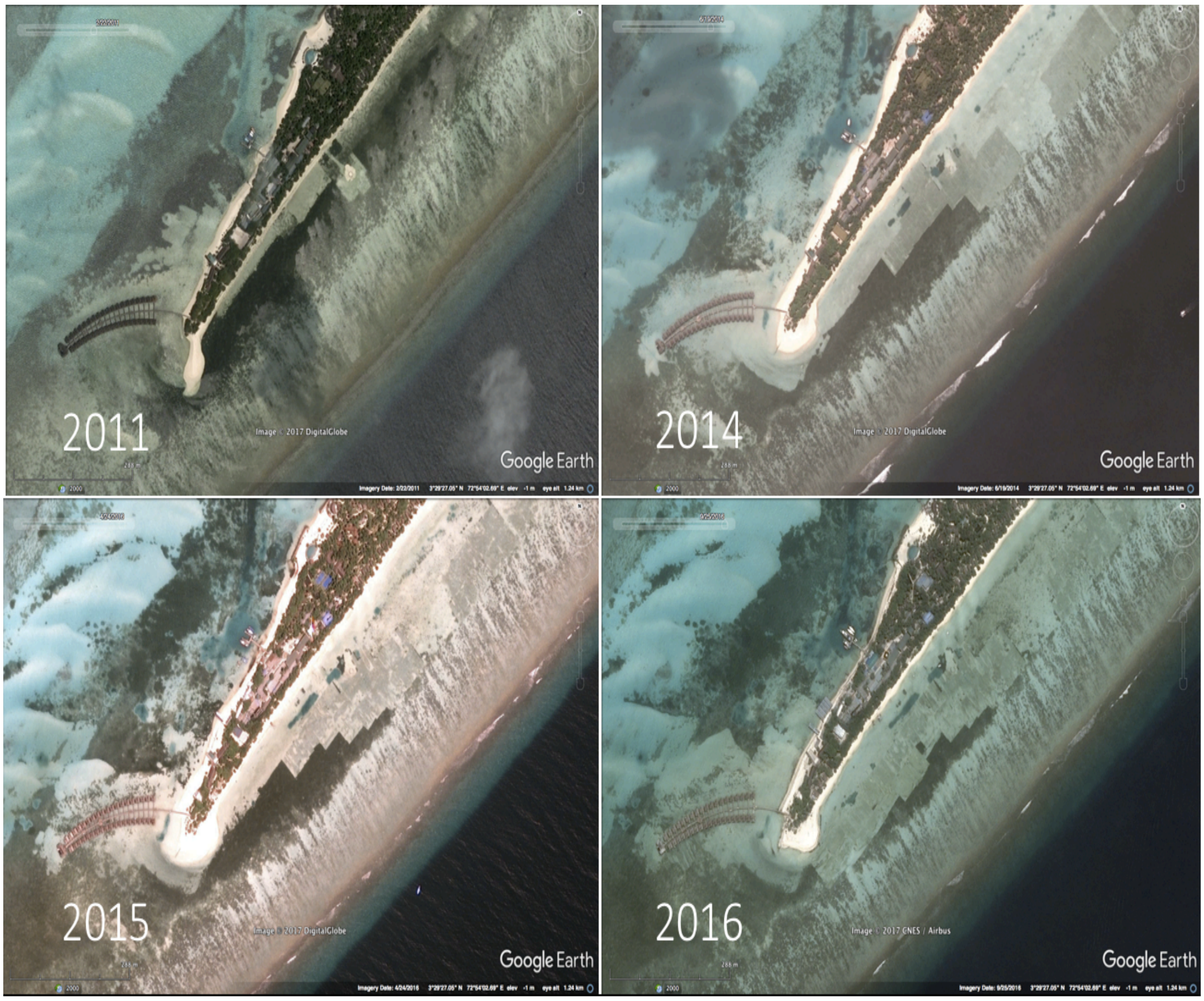


Figure 6.27: Historical images from Google Earth showing change to seagrass beds from 2011 to 2016 on Dhidhdhoofinolhu, South Ari Atoll.

Like Meeru Island, Dhigurah Island also experiences seagrass being washed ashore (see Figure 6.28). While current measures to create ‘pristine’ beaches include clearing seagrass from the beaches (see Figure 6.28), increased tourism could result in pressure for the complete removal of seagrass beds on Dhigurah’s oceanward side. Another effect that future development could have is to increase nutrient influx which has been shown to cause a decrease in seagrass meadows [126].

Figure 6.28: A) photo taken by author showing seagrass washed ashore on Dhigurah’s oceanward side.
B) photo taken by the local council showing a group of people clearing the beach [127].

However, for the long-term persistence of the island, the tourism industry will have to tolerate seagrass beds and designs of coastal infrastructure may need to be modified or curtailed in order to protect seagrass, as well as coral reefs.

7. Rapid Nearshore Processes Study

In the Maldives, any project that is likely to have an impact on the environment must submit an Environmental Impact Assessment (EIA), a tool to help planning and decision making by examining the environmental impact of a project before it goes ahead, to the Ministry of Environment and Energy [128].

However, a review of literature shows that the current provisions for planners to gain understanding of the nearshore processes on the islands expecting development within the necessary timescale are seriously deficient [17,128,129,130,131,132].

EIAs are often viewed as a “perfunctory requirement” [17], as the resources, trained personnel and technical capacity are not sufficient to follow up the outcome of an EIA. Furthermore, development has often occurred without any information of baseline conditions, adequate consideration of nearshore processes, cumulative effects of developments, and often without consulting local communities who are left feeling disenfranchised [17].

By drawing on the literature mentioned above and the findings of this study, a way forward is proposed, responding to the call by Zubair et al. [17] for suggestions of “practical remedies through locally adapted general frameworks.”

This study proposes the scope of a rapid nearshore processes study (RNPS) that addresses many of the problems with the current provisions. Five areas of investigation are recommended as key components of an RNPS in the Maldives. Before outlining the components that form the basis of the RNPS, a few key principles are explained.

Key Principles

Replicable at Low Cost

First, given the number of islands that lack information on nearshore proccesses and that are expecting development, the RNPS must be replicable at low cost. Like this study, and as Owen et al. [15] recommends, the methods in an RNPS should rely on simple geographic tools that can be sourced locally, be supported by community observations, and should not require significant technical or financial capacity.

Community Collaboration

Second, an RNPS must encourage community collaboration in order to achieve local buy-in. Given that the study may recommend forgoing or modifying development opportunities in favour of maintaining nearshore processes, and given the insignificance of sea-level rise as a local concern [16], the recommendations of an RNPS may not be well received. The attitude of the community to risks will vary between islands. As Owen et al. [15] argue, "notions of risk and exposure are complex and embedded in both the biophysical and social contexts of each island community." Community participation will necessarily form part of an RNPS, as local knowledge is an important source of data [116], especially in the Maldives where documentation of marine ecosystems is lacking [88]. Yet with only this degree of community participation, local buy-in is still unlikely to be achieved. As Sillitoe [134], Marshall [135], Thornton and Scheer [116], and Kittinger [130] all suggest, actively involving the community in every step of a project, so that they become collaborators, not just participants, can result in better understanding of the project's goals and a sense of stewardship. This approach may see communities conclude that the maintenance of nearshore processes is desirable [133,134]. The study methods chosen must therefore be suitable for use by the community.

Flexible

Third, an RNPS would need to be flexible. An RNPS is possible because there are similarities in nearshore processes common to all islands in the Maldives [22]. Yet, as this study has emphasised**,** every island is different, which is why there is a call for improved understanding of nearshore processes at a "site-specific" scale [15]. Therefore, an RNPS should describe and make observations about key nearshore processes that are most important to islands in the Maldives, but also remain flexible enough to examine features of individual islands that appear significant.

Communication

Fourth, the communication of the results so that they are understandable by local communities is important [17,136,137,138]. The results should be non-technical and easy to understand so that island inhabitants and resort planners can apply what they have learnt and the process can move beyond what Arnstein [140] describes as ‘tokenism’. Although this might require input from outside the community, a study by Leon et al. [139] shows how incorporating scientific knowledge with 3D modelling, as this study has done, created a forum for discussion, with interest from groups who would not usually be involved in decision making.

An Ongoing Process

Fifth, the proposed RNPS is only a starting point and it should be able to be continuously upgraded by further information and studies. In the Marshall Islands, barriers to improving understanding of nearshore processes among local communities included a lack of resources, funds, on ground capacity and institutional constraints [15]. On Dhigurah Island, however, there are clear opportunities for island communities to learn. This can start with education at the local school. Most schools use the Cambridge Syllabus with Marine Science an option which students can study. The Cambridge Syllabus is “sensitive to the needs of different countries” and consequently provides flexibility so that island in the Maldives can make the content more relevant to their situation [141].

Another resource for Dhigurah Island is that it hosts MWSRP. While there are only a few islands that host environmental NGOs, there is an opportunity to develop relationships between the NGOs and local schools, with the NGOs acting as providers of relevant and even island specific education as well as offering an informed opinion on the impact of future development on the environment.

Key Components

Sediment Supply

The stability of islands in the Maldives is dependent on the production and transport of sediment towards the shoreline [22]. While several studies have used the Reef Budget Methodology to carry out detailed sedimentary studies of islands in the Maldives [52], doing so would not align with the principles of being replicable at a low cost and rapid to carry out. This RNPS suggests a very simplified 'Reef Budget' that entails a description of the distribution of most significant producers of sediment surrounding an island. These would be likely to include Parrotfish [38,39], *Halimeda spp.* [39], and CRA [44,45]. This would then be followed by a description of sediment (larger than 2 mm) found on the beach in order to infer whether there might be an active sediment supply. Key questions to investigate, therefore, would include:

- Are Parrotfish visibly abundant? Is there any reason to believe they are under threat? Are they being targetted by fishermen?
- Where are *Halimeda spp.* most abundant? Where are they least abundant? And why?
- Where is CRA most abundant? Where is it least abundant? And why?
- Are there any other significant sediment producers?
- Are there signs of *Halimeda spp*. or CRA or other sediments on adjacent beaches?
- Are there evident sediment pathways and how are these affected by the reversal of monsoons? Is there an evident erosion-accretion cycle?
- How can any development plans be adapted to protect sediment producers and sediment transport pathways?

Marine Vegetation

As has also been discussed in chapter 2, greater stability is produced with the establishment of vegetation [22]. Seagrass is prevalent throughout the Maldives. Mangroves are less common but can be found in some parts of the country [142]. Mapping out the locations of marine vegetation and investigating how they have changed over time can provide important information about long-term trends in the stability of an island [22]. Given the lack of documentation of marine ecosystems in the Maldives [88], the acquisition of this information will be reliant on local knowledge and, if available, historical imagery. Key questions to investigate, therefore, would include:

- How is marine vegetation distributed? How has this changed over time?
- How might future development threaten marine vegetation and how can any development plans be adapted to mitigate or prevent this altogether?
- Are historical images of the area of interest available from easily accessible sources such as Google Earth?

Profiles

In this study, bathymetric profiles were used to explore observations about the effect of seagrass on water depths. Profiles, both bathymetric and topographic, provide important information about the morphodynamic development of reef islands and can help to predict the vulnerability of islands to future extreme events such as storms and flooding [22].

Shoreline Stability

Observations about recent apparent changes to shoreline stability can be made using methods identified in chapter 4. Reconstructing trends in coastal history provide information about the stability of an island and how it might adjust to future changes in boundary conditions. Key questions to investigate include:

- What vegetation is on the shoreline and what is its height and condition? Does this change moving inland?
- Are there visible outcrops of beach rock?
- What can be inferred from the above about how the shoreline has changed over time?

Coastal Infrastructure

Historical images and local knowledge may help provide some information about baseline conditions prior to the construction of harbours and other coastal infrastructure. Observations about the possible effect of coastal infrastructure already in place can be made with key questions including:

- Has coastal infrastructure been constructed and what effect has it had?
- Are structures affecting currents and wave regimes?
- Are structures affecting sediment transport? Where is the island accreting and eroding?
- Is material being dredged for harbours or construction, or is it being deposited? Are channels being excavated or blasted for boat access? How is all this affecting coastal processes?

8. Conclusion

This study has presented arguments and evidence that low-lying atoll islands are dynamic morphological landforms that have an ability to adapt to changes in boundary conditions. This inherent resilience means there is reason to be cautiously optimistic about their long-term persistence.

The common response to threats such as sea level rise, shoreline instability and the desires of the tourist industry has been to construct hard-engineering structures which degrade natural habitat and inhibit the natural nearshore processes whereby islands adapt to changes.

A cost-effective way by which island communities can safeguard and even enhance the inherent resilience of their island is to ensure that development does not undermine key nearshore processes that contribute to the maintenance and construction of their island. This requires greater understanding of key nearshore processes at a site-specific scale.

To contribute to this understanding, this study has conducted field research on two key nearshore processes on Dhigurah Island, the Maldives. It has been found that there is an active sediment supply of *H. micronesica*, *H. macrophysa* and CRA from the inner reef flat to the oceanward shoreline. While CRA is particularly vulnerable to global stressors, which cannot be tackled by Dhigurah's community, the community can take steps to better protect *Halimeda* spp. *Halimeda* spp. are particularly vulnerable to sedimentation and turbidity, so dredged harbour material should not be deposited near sites where it is found to be present, and alternative locations should be considered.

It was also concluded that seagrass beds provide important coastal protection to Dhigurah Island's oceanward shoreline. By reducing water depths they attenuate more wave energy thereby reducing erosion. Loss of seagrass could result in significantly more erosion on the oceanward shoreline as sediment becomes unconsolidated and less wave energy is attenuated. Seagrass therefore needs to be protected despite the desire of the tourist industry to remove it in order to maintain pristine beaches. All nearshore processes need to be protected from pollution, eutrophication, and the construction of coastal infrastructure that impedes their functioning.

This study carries wider significance than its use by decision makers on Dhigurah Island. Dhigurah Island is representative of many islands in the Maldives that are beginning to embrace tourism [106]. Therefore, the lack of information on nearshore processes on many other islands remains an urgent need to address. It is evident that conducting a detailed study of all the nearshore processes on all the islands in the Maldives that are expecting development would be too time and resource consuming [142,143].

Given that current provisions for planners to gain understanding of the nearshore processes on all the islands in the Maldives expecting development are deficient, this study has suggested that what is needed is to develop the scope of a rapid study of nearshore processes (RNPS). Key principles of an RNPS, presented in chapter 7, are that it should be easily replicable at low cost, that it should benefit from local knowledge and be undertaken in collaboration with the local community, that it should be flexible enough to recognise particular local features, that the results should be easily communicable and that understanding of nearshore processes should be seen as an ongoing educational process for island residents of all ages. Items studied should include sediment production, transport and deposition, marine vegetation, bathymetric and topographic profiles, shoreline stability and coastal infrastructure.

With such understanding, island communities will be better prepared and motivated to work with the natural processes by which their islands adapt to environmental changes.

9. Bibliography

[1] W. R. Dickinson, ‘Holocene Sea-Level Record on Funafuti and Potential Impact of Global Warming on Central Pacific Atolls’, *Quat. Res.*, vol. 51, no. 2, pp. 124–132, 1999.

[2] T. M. A. Khan, D. A. Quadir, T. S. Murty, A. Kabir, F. Aktar, and M. A. Sarker, ‘Relative Sea Level Changes in Maldives and Vulnerability of Land Due to Abnormal Coastal Inundation’, *Mar. Geod.*, vol. 25, no. 1–2, pp. 133–143, 2002.

[3] J. Barnett and W. Adger, ‘Climate Dangers and Atoll Countries’, *Clim. Change*, vol. 61, no. 3, pp. 321–337, 2003.

[4] J. Hay and N. Mimura, ‘Supporting climate change vulnerability and adaptation assessments in the Asia-Pacific region: an example of sustainability science’, *Sustain. Sci.*, vol. 1, no. 1, pp. 23–35, 2006.

[5] C. B. Field, V. R. Barros, and Intergovernmental Panel on Climate Change. Working Group II, *Climate change 2014: impacts, adaptation, and vulnerability : Working Group II contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press, 2014.

[6] M. Ford, ‘Shoreline changes interpreted from multi-temporal aerial photographs and high resolution satellite images: Wotje Atoll, Marshall Islands’, *Remote Sens. Environ.*, vol. 135, p. 130, 2013.

[7] P. S. Kench, D. Thompson, M. R. Ford, H. Ogawa, and R. F. Mclean, ‘Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll’, *Geology*, vol. 43, no. 6, pp. 515–518, 2015.

[8] P. Kench and R. W. Brander, ‘Response of reef island shorelines to seasonal climate oscillations: South Maalhosmadulu atoll, Maldives’, 2006.

[9] D. Storey and S. Hunter, ‘Kiribati: an environmental “perfect storm”’, *Aust. Geogr.*, vol. 41, no. 2, pp. 167–181, Jun. 2010.

[10] P. Jones and J. P. Lea, ‘What Has Happened to Urban Reform in the Island Pacific? Some Lessons from Kiribati and Samoa’, *Pac. Aff.*, vol. 80, no. 3, pp. 473–491, 2007.

[11] A. P. Webb and P. S. Kench, ‘The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific’, *Glob. Planet. Change*, vol. 72, no. 3, pp. 234–246, 2010.

[12] M. Ford, ‘Shoreline changes on an urban atoll in the central Pacific Ocean: Majuro atoll, Marshall Islands’, *J. Coast. Res.*, vol. 28, no. 1, pp. 11–22, 2012.

[13] F. Bulleri and M. G. Chapman, ‘The introduction of coastal infrastructure as a driver of change in marine environments’, *J. Appl. Ecol.*, vol. 47, no. 1, pp. 26–35, 2010.

[14] P. S. Kench, ‘Compromising Reef Island Shoreline Dynamics: Legacies of the Engineering Paradigm in the Maldives’, in *Pitfalls of Shoreline Stabilization*, vol. 3, J. A. G. Cooper and O. H. Pilkey, Eds. Dordrecht: Springer Netherlands, 2012, pp. 165–186.

[15] S. D. Owen, P. S. Kench, and M. Ford, ‘Improving understanding of the spatial dimensions of biophysical change in atoll island countries and implications for island communities: A Marshall Islands’ case study’, *Appl. Geogr.*, vol. 72, pp. 55–64, Jul. 2016.

[16] M. Ray, ‘Interview with Hassan’, Dhigurah Island, 06-May-2017.

[17] S. Zubair, D. Bowen, and J. Elwin, ‘Not quite paradise: Inadequacies of environmental impact assessment in the Maldives’, *Tour. Manag.*, vol. 32, no. 2, pp. 225–234, 2011.

[18] L. Yamamoto and M. Esteban, ‘Vanishing Island States and sovereignty’, *Ocean Coast. Manag.*, vol. 53, no. 1, pp. 1–9, Jan. 2010.

[19] Karen E Mcnamara, ‘Cross-border migration with dignity in Kiribati’, *Forced Migr. Rev.*, no. 49, pp. 52–53, 2015.

[20] L. Yamamoto and M. Esteban, ‘Migration as an Adaptation Strategy for Atoll Island States’, *Int. Migr.*, 2017.

[21] M. L. Yates, G. Le Cozannet, M. Garcin, E. Salai, and P. Walker, ‘Multidecadal Atoll Shoreline Change on Manihi and Manuae, French Polynesia’, *J. Coast. Res.*, vol. 29, no. 4, pp. 870–882, 2013.

[22] C. D. Woodroffe, ‘Reef-island topography and the vulnerability of atolls to sea-level rise’, *Glob. Planet. Change*, vol. 62, no. 1, pp. 77–96, 2008.

[23] N. Biribo and C. Woodroffe, ‘Historical area and shoreline change of reef islands around Tarawa Atoll, Kiribati’, *Sustain. Sci.*, vol. 8, no. 3, pp. 345–362, 2013.

[24] V. Duvat, ‘Coastal protection structures in Tarawa Atoll, Republic of Kiribati’, *Sustain. Sci.*, vol. 8, no. 3, pp. 363–379, 2013.

[25] C. Cocklin and M. Keen, ‘Urbanization in the Pacific: environmental change, vulnerability and human security’, *Environmental Conservation*, Dec-2000. [Online]. Available: /core/journals/environmental-conservation/article/urbanization-in-the-pacific-environmental-change-vulnerability-and-human-security/96C33EC73CBA006602E28D2A3B6C2575. [Accessed: 08-Jul-2017].

[26] F. Pyrard, P. de Bergeron, and J. Bignon, *The voyage of François Pyrard of Laval to the East Indies, the Maldives, the Moluccas and Brazil*. London : Printed for the Hakluyt Society, 1887.

[27] H. C. P. Bell, *The Máldive Islands : monograph on the history, archaeology, and epigraphy*. Colombo : Ceylon Government Press, 1940.

[28] ‘National Bureau of Statistics > Census 2014’. .

[29] A. K. Naylor, ‘Island morphology, reef resources, and development paths in the Maldives’, *Prog. Phys. Geogr.*, vol. 39, no. 6, pp. 728–749, 2015.

[30] S. D. Donner and S. Webber, ‘Obstacles to climate change adaptation decisions: a case study of sea-level rise and coastal protection measures in Kiribati’, *Sustain. Sci.*, vol. 9, no. 3, pp. 331–345, Jul. 2014.

[31] UNDP and GEF, ‘Integrating Climate Change Risks into Resilient Island Planning in the Maldives, Mid-Term Evaluation Report.’ Dec-2012.

[32] B. K. Sovacool, ‘Hard and soft paths for climate change adaptation’, *Clim. Policy*, vol. 11, no. 4, pp. 1177–1183, Jul. 2011.

[33] A. Shaig, ‘Survey of climate change adaptation measures in Maldives: integration of climate change risks into resilient Island planning in the Maldives project’. Ministry of Housing and Environment, Government of Maldives, 2011.

[34] P. S. Kench, ‘South Tarawa Coastal Condition Assessment’, 2010.

[35] Andrew Cooper and Orrin H. Pilkey, *Pitfalls of Shoreline Stabilization: Selected Case Studies*, vol. 3. Dordrecht: Springer Netherlands, 2012.

[36] B. H. MacGillivray, ‘The position of place in governing global problems: A mechanistic account of place-as-context, and analysis of transitions towards spatially explicit approaches to climate science and policy’, *Environ. Sci. Policy*, vol. 53, pp. 8–17, Nov. 2015.

[37] L. A. Nurse *et al.*, ‘2014: Small Islands’, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the*

Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom: Cambridge University Press, 2014, pp. 1613–1654.

[38] A. Hoey and D. Bellwood, ‘Cross-shelf variation in the role of parrotfishes on the Great Barrier Reef’, *Coral Reefs*, vol. 27, no. 1, pp. 37–47, 2008.

[39] C. T. Perry, P. S. Kench, M. J. O’Leary, K. M. Morgan, and F. Januchowski-Hartley, ‘Linking reef ecology to island building: Parrotfish identified as major producers of island-building sediment in the Maldives’, *Geology*, vol. 43, no. 6, pp. 503–506, Jun. 2015.

[40] H. K. East, C. T. Perry, P. S. Kench, and Y. Liang, ‘Atoll-scale comparisons of the sedimentary structure of coral reef rim islands, Huvadhu Atoll, Maldives’, *J. Coast. Res.*, vol. 75, no. sp1, pp. 577–581, 2016.

[41] H. G. Multer and I. Clavijo, ‘Halimeda investigations: progress and problems’, *NOAA/RSMAS*, 2004.

[42] E. Drew, ‘Halimeda biomass, growth rates and sediment generation on reefs in the central great barrier reef province’, *Coral Reefs*, vol. 2, no. 2, pp. 101–110, 1983.

[43] L. Hillis-Colinvaux, ‘Halimeda growth and diversity on the deep fore-reef of Enewetak Atoll’, *Coral Reefs*, vol. 5, no. 1, pp. 19–21, 1986.

[44] J. A. Marsh, ‘Primary Productivity of Reef-Building Calcareous Red Algae’, *Ecology*, vol. 51, no. 2, pp. 255–263, 1970.

[45] D. Basso, ‘Carbonate production by calcareous red algae and global change’, *Geodiversitas*, vol. 34, no. 1, pp. 13–33, 2012.

[46] A. J. Melville and S. D. Connell, ‘Experimental effects of kelp canopies on subtidal coralline algae’, *Austral Ecol.*, vol. 26, no. 1, pp. 102–108, Feb. 2001.

[47] A. B. Villas-Boas, R. Riosmena-Rodriguez, and M. A. de O. Figueiredo, ‘Community structure of rhodolith-forming beds on the central Brazilian continental shelf’, *Helgol. Mar. Res.*, vol. 68, no. 1, pp. 27–35, Mar. 2014.

[48] M. Björk, S. M. Mohammed, M. Björklund, and A. Semesi, ‘Coralline Algae, Important Coral-Reef Builders Threatened by Pollution’, *Ambio*, vol. 24, no. 7/8, pp. 502–505, 1995.

[49] K. Kuffner and I. B. Kuffner, ‘Decreased abundance of crustose coralline algae due to ocean acidification’, *Nat. Geosci.*, vol. 1, no. 2, pp. 114–117, 200802.

[50] P. Porzio and L. Porzio, ‘Effects of ocean acidification on macroalgal communities’, *J. Exp. Mar. Biol. Ecol.*, vol. 400, no. 1, pp. 278–287, 2011.

[51] ‘USAID Project Regenerate in Maldives’, *IUCN*, 07-Dec-2016. [Online]. Available: https://www.iucn.org/regions/asia/countries/maldives/usaid-project-regenerate-maldives. [Accessed: 01-Mar-2017].

[52] C. T. Perry, T. Spencer, and P. S. Kench, ‘Carbonate budgets and reef production states: a geomorphic perspective on the ecological phase-shift concept’, *Coral Reefs*, vol. 27, no. 4, pp. 853–866, 2008.

[53] C. T. Perry, K. M. Morgan, and M. A. Salter, ‘Sediment generation by Halimeda on atoll interior coral reefs of the southern Maldives: A census-based approach for estimating carbonate production by calcareous green algae’, *Sediment. Geol.*, vol. 346, pp. 17–24, 2016.

[54] K. M. Morgan and P. S. Kench, ‘Parrotfish erosion underpins reef growth, sand talus development and island building in the Maldives’, *Sediment. Geol.*, vol. 341, pp. 50–57, Jul. 2016.

[55] K. M. Morgan and P. S. Kench, ‘Reef to island sediment connections on a Maldivian carbonate platform: using benthic ecology and biosedimentary depositional facies to examine island-building potential’, *Earth Surf. Process. Landf.*, vol. 41, no. 13, pp. 1815–1825, Oct. 2016.

[56] S. G. Smithers, N. Harvey, D. Hopley, and C. D. Woodroffe, ‘Vulnerability of geomorphological features in the Great Barrier Reef to climate change’, in *Climate Change and the Great Barrier Reef: a vulnerability assessment*, J. E. Johnson and P. A. Marshall, Eds. Townsville, QLD, Australia: Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, 2007, pp. 667–716.

[57] J. Borg, A. Rowden, M. Attrill, P. Schembri, and M. Jones, ‘Wanted dead or alive: high diversity of macroinvertebrates associated with living and “dead” Posidonia oceanica matte’, *Mar. Biol.*, vol. 149, no. 3, pp. 667–677, 2006.

[58] M. S. Fonseca and J. A. Cahalan, ‘A preliminary evaluation of wave attenuation by four species of seagrass’, *Estuar. Coast. Shelf Sci.*, vol. 35, no. 6, pp. 565–576, 1992.

[59] J. Madsen, P. Chambers, W. James, E. Koch, and D. Westlake, ‘The interaction between water movement, sediment dynamics and submersed macrophytes’, *Hydrobiologia*, vol. 444, no. 1, pp. 71–84, 2001.

[60] T. J. Bouma *et al.*, ‘Trade-Offs Related to Ecosystem Engineering: A Case Study on Stiffness of Emerging Macrophytes', *Ecology*, vol. 86, no. 8, pp. 2187–2199, 2005.

[61] G. Guannel, K. Arkema, P. Ruggiero, and G. Verutes, ‘The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience’, *PloS One*, vol. 11, no. 7, p. e0158094, 2016.

[62] M. S. Fonseca and J. Fisher, ‘A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration’, *Mar. Ecol. Prog. Ser.*, vol. 29, pp. 15–22, 1986.

[63] J. Mellors, H. Marsh, T. J. B. Carruthers, and M. Waycott, ‘Testing the sediment-trapping paradigm of seagrass: Do seagrasses influence nutrient status and sediment structure in tropical intertidal environments?’, *Bull. Mar. Sci.*, vol. 71, no. 3, pp. 1215–1226, 2002.

[64] K. Fujita, R. Asami, H. Takayanagi, and Y. Iryu, ‘Carbonate sedimentation in seagrass beds on Ishigaki-jima, Ryukyu Islands, southwestern Japan’, *Isl. Arc*, vol. 24, no. 2, pp. 263–279, 2015.

[65] J. R. Grady, ‘Properties of Sea Grass and Sand Flat Sediments from the Intertidal Zone of St. Andrew Bay, Florida’, *Estuaries*, vol. 4, no. 4, pp. 335–344, 1981.

[66] M. N. Almasi, C. M. Hoskin, J. K. Reed, and J. Milo, ‘Effects of natural and artificial Thalassia on rates of sedimentation’, *J. Sediment. Res.*, vol. 57, no. 5, pp. 901–906, Sep. 1987.

[67] E. Gacia, T. C. Granata, and C. M. Duarte, ‘An approach to measurement of particle flux and sediment retention within seagrass (Posidonia oceanica) meadows’, *Aquat. Bot.*, vol. 65, no. 1, pp. 255–268, 1999.

[68] E. Gacia *et al.*, ‘Sediment deposition and production in SE-Asia seagrass meadows’, *Estuar. Coast. Shelf Sci.*, vol. 56, no. 5, pp. 909–919, 2003.

[69] M. J. A. Christianen *et al.*, ‘Low-Canopy Seagrass Beds Still Provide Important Coastal Protection Services’, *PLOS ONE*, vol. 8, no. 5, p. e62413, May 2013.

[70] E. W. Koch, J. D. Ackerman, J. Verduin, and M. van Keulen, ‘Fluid Dynamics in Seagrass Ecology—from Molecules to Ecosystems’, pp. 193–225, 2007.

[71] A. Stevens and J. Lacy, ‘The Influence of Wave Energy and Sediment Transport on Seagrass Distribution’, *Estuaries Coasts*, vol. 35, no. 1, pp. 92–108, 2012.

[72] A. R. Bos, T. J. Bouma, G. L. J. de Kort, and M. M. van Katwijk, ‘Ecosystem engineering by annual intertidal seagrass beds: Sediment accretion and modification’, *Estuar. Coast. Shelf Sci.*, vol. 74, no. 1, pp. 344–348, 2007.

[73] M. M. Harlin, B. Thorne-Miller, and J. C. Boothroyd, ‘Seagrass-sediment dynamics of a flood-tidal delta in Rhode Island (U.S.A.)’, *Aquat. Bot.*, vol. 14, no. C, pp. 127–138, 1982.

[74] C. L. Amos *et al.*, ‘The stability of tidal flats in Venice Lagoon—the results of in-situ measurements using two benthic, annular flumes’, *J. Mar. Syst.*, vol. 51, no. 1, pp. 211–241, 2004.

[75] C. E. L. Thompson, C. L. Amos, and G. Umgiesser, ‘A comparison between fluid shear stress reduction by halophytic plants in Venice Lagoon, Italy and Rustico Bay, Canada—analyses of in situ measurements’, *J. Mar. Syst.*, vol. 51, no. 1, pp. 293–308, Nov. 2004.

[76] S. Adriano, F. Chiara, and M. Antonio, ‘Sedimentation rates and erosion processes in the lagoon of Venice’, *Environ. Int.*, vol. 31, no. 7, pp. 983–992, Sep. 2005.

[77] D. L. Ramage and D. R. Schiel, ‘Patch dynamics and response to disturbance of the seagrass Zostera novazelandica on intertidal platforms in southern New Zealand’, *Mar. Ecol. Prog. Ser.*, vol. 189, pp. 275–288, Nov. 1999.

[78] G. De Falco, S. Ferrari, G. Cancemi, and M. Baroli, ‘Relationship between sediment distribution and Posidonia oceanica seagrass’, *Geo-Mar. Lett.*, vol. 20, no. 1, pp. 50–57, 2000.

[79] W. F. de Boer, ‘Seagrass–sediment interactions, positive feedbacks and critical thresholds for occurrence: a review’, *Hydrobiologia*, vol. 591, no. 1, pp. 5–24, Oct. 2007.

[80] C. M. Duarte, J. Terrados, N. S. Agawin, M. D. Fortes, S. Bach, and W. J. Kenworthy, ‘Response of a mixed Philippine seagrass meadow to experimental burial’, *Mar. Ecol. Prog. Ser.*, pp. 285–294, 1997.

[81] M. S. Fonseca and S. S. Bell, ‘Influence of physical setting on seagrass landscapes near Beaufort, North Carolina, USA’, *Mar. Ecol. Prog. Ser.*, pp. 109–121, 1998.

[82] E. W. Koch, ‘Beyond Light: Physical, Geological, and Geochemical Parameters as Possible Submersed Aquatic Vegetation Habitat Requirements’, *Estuaries*, vol. 24, no. 1, pp. 1–17, 2001.

[83] S. E. Lawson, P. L. Wiberg, K. J. McGlathery, and D. C. Fugate, ‘Wind-driven sediment suspension controls light availability in a shallow coastal lagoon’, *Estuaries Coasts*, vol. 30, no. 1, pp. 102–112, Feb. 2007.

[84] B. W. D. Logan Graham R.Read, James F.Cebulski, Donald E., *Carbonate Sedimentation and Environments, Shark Bay, Western Australia*. American Association of Petroleum Geologists, 1970.

[85] E. W. Koch, J. D. Ackerman, J. Verduin, and M. van Keulen, ‘Fluid Dynamics in Seagrass Ecology—from Molecules to Ecosystems’, pp. 193–225, 2007.

[86] M. M. van Katwijk and D. Hermus, ‘Effects of water dynamics on Zostera marina: Transplantation experiments in the intertidal Dutch Wadden Sea’, *Mar. Ecol. Prog. Ser.*, vol. 208, pp. 107–118, 2000.

[87] S.-N. Chen, L. Sanford, E. Koch, F. Shi, and E. North, ‘A nearshore model to investigate the effects of seagrass bed geometry on wave attenuation and suspended sediment transport’, *Estuaries Coasts*, vol. 30, no. 2, pp. 296–310, 2007.

[88] Maldives Government: Ministry of Energy and Environment, ‘Fifth National Report of the Maldives to the Convention on Biological Diversity’, *Ministry of Energy and Environment*. 2015.

[89] P. S. Kench, R. W. Brander, K. E. Parnell, and R. F. Mclean, ‘Wave energy gradients across a Maldivian atoll: Implications for island geomorphology’, *Geomorphology*, vol. 81, no. 1, pp. 1–17, 2006.

[90] P. S. Kench, S. G. Smithers, R. F. McLean, and S. L. Nichol, ‘Holocene reef growth in the Maldives: Evidence of a mid-Holocene sea-level highstand in the central Indian Ocean’, *Geology*, vol. 37, no. 5, pp. 455–458, May 2009.

[91] Maldives Government: Ministry of Tourism, ‘Annual Publications’, *Ministry of Tourism*. 2016.

[92] M. Domroes, ‘Conceptualising State-Controlled Resort Islands for an Environment-Friendly Development of Tourism: The Maldivian Experience’, *Singap. J. Trop. Geogr.*, vol. 22, no. 2, pp. 122–137, Jul. 2001.

[93] Maldives Government: Ministry of Tourism, ‘Regulations’, *Ministry of Tourism.* 2016.

[94] Tom Chesshyre, ‘Guesthouses in paradise: Maldives on the cheap; After years of restrictions, inexpensive B&Bs are opening up on smaller islands and there isn’t a luxury resort in sight. Tom Chesshyre goes island hopping.(Features)’, *The Times (London, England)*, p. 24, 2014.

[95] Maldives Government: Ministry of Tourism, ‘News & Events’, *Ministry of Tourism*. 2016.

[96] C. Booker, ‘Maldives’ underwater cabinet meeting was a sorry stunt’, 24-Oct-2009.

[97] SAMPA, ‘Communities’, *sampamaldives*, [Online]. Available: https://sampamaldives.wordpress.com [Accessed: 22-Jul-2017].

[98] M. Ray, ‘Interview with Raisha’, Dhigurah Island, 08-May-2017.

[99] ‘Maldives Whale Shark Research Programme | Conservation through Research and Community Mobilisation’. [Online]. Available: https://maldiveswhalesharkresearch.org [Accessed: 13-June-2017].

[100] ‘TME Retreats Dhigurah (Dhigurah Island, Maldives) - Hotel Reviews, Photos & Price Comparison - TripAdvisor’. [Online]. Available: https://www.tripadvisor.co.uk/Hotel_Review-g6852341-d4237095-Reviews-TME_Retreats_Dhigurah-Dhigurah_Island.html. [Accessed: 22-Jul-2017].

[101] ‘Boutique Beach’. [Online]. Available: http://boutiquebeach.club/. [Accessed: 22-Jul-2017].

[102] ‘Adventure Watersports Dhigurah (Dhigurah Island, Maldives): Top Tips Before You Go - TripAdvisor’. [Online]. Available: https://www.tripadvisor.co.uk/Attraction_Review-g6852341-d10065779-Reviews-Adventure_Watersports_Dhigurah-Dhigurah_Island.html. [Accessed: 22-Jul-2017].

[103] ‘Island Divers’, *Island Divers*, 2017. [Online]. Available: https://islanddivers.mv. [Accessed 20-July-2017].

[104] M. Ray, ‘Interview with Mohammed’, Dhigurah Island, 02-May-2017.

[105] M. Ray, ‘Interview with Ibrahim’, Dhigurah Island, 29-Apr-2017.

[106] M. Ray, ‘Interview with Ahusam’, Dhigurah Island, 30-Apr-2017.

[107] A. Jaleel, 'The status of the coral reefs and the management approaches: The case of the Maldives', *Ocean Coast. Manag.*, vol. 82, pp. 104–118, Sep. 2013.

[108] 'Algaebase :: Listing the World's Algae'. [Online]. Available: http://www.algaebase.org/. [Accessed: 09-Jun-2017].

[109] E. Gischler, 'Sedimentation on Rasdhoo and Ari Atolls, Maldives, Indian Ocean', *Facies*, vol. 52, no. 3, pp. 341–360, 2006.

[110] K. Klostermann and L. Klostermann, 'Sedimentary record of late Holocene event beds in a mid-ocean atoll lagoon, Maldives, Indian Ocean: Potential for deposition by tsunamis', *Mar. Geol.*, vol. 348, pp. 37–43, 20140201.

[111] L. Enthoven, N. Gebruk, M. Ray, and R. Sinclair, 'Pilot Study of Dhigurah Island's Subtidal Habitats', Dhigurah Island, TME Resort, 21-Apr-2017.

[112] J. Fowler, *Practical statistics for field biology*, Second edition.. Chichester: Wiley, 1998.

[113] University of Edinburgh Marine Systems and Policies Field Trip to the Maldives 2017, 'University of Edinburgh - Pilot Study of Dhigurah Island's Geomorphology'. Apr-2017.

[114] A. Factor and F. Shafeega, 'Common Plants of the Maldives'. Nov-2010.

[115] V. Semeniuk and D. J. Searle, 'Beach Rock Ridges/Bands along a High-Energy Coast in Southwestern Australia: Their Significance and Use in Coastal History', *J. Coast. Res.*, vol. 3, no. 3, pp. 331–342, 1987.

[116] Adela Maciejewski . Scheer and Thomas F. Thornton, 'Collaborative Engagement of Local and Traditional Knowledge and Science in Marine Environments: A Review', *Ecol. Soc.*, vol. 17, no. 3, p. 8, 2012.

[117] J. McDowell, 'Ground Truthing: Do Coral Reefs in Close Proximity to Seagrass Beds Show Greater Resilience to Climate Change?' May-2017.

[118] 'Reef frequented by whale sharks "destroyed" by resort's excavation work | Maldives Independent'. .

[119] P. Schäfer, H. Fortunato, B. Bader, V. Liebetrau, T. Bauch, and J. J. G. Reijmer, 'Growth Rates and Carbonate Production By Coralline Red Algae in Upwelling and Non-Upwelling Settings Along the Pacific Coast of Panama', *Palaios*, vol. 26, no. 7/8, pp. 420–432, 2011.

[120] C. Sheppard, D. J. Dixon, M. Gourlay, A. Sheppard, and R. Payet, 'Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles', *Estuar. Coast. Shelf Sci.*, vol. 64, no. 2, pp. 223–234, 2005.

[121] 'USAID Project Regenerate in Maldives', *IUCN*, 07-Dec-2016. [Online]. Available: https://www.iucn.org/regions/asia/countries/maldives/usaid-project-regenerate-maldives. [Accessed: 01-Mar-2017].

[122] J. Maynard, P. Marshall, J. Johnson, and S. Harman, 'Building resilience into practical conservation: identifying local management responses to global climate change in the southern Great Barrier Reef', *Coral Reefs*, vol. 29, no. 2, pp. 381–391, 2010.

[123] M. Ateweberhan, D. A. Feary, S. Keshavmurthy, A. Chen, M. H. Schleyer, and C. R. C. Sheppard, 'Climate change impacts on coral reefs: Synergies with local effects, possibilities for acclimation, and management implications', *Mar. Pollut. Bull.*, vol. 74, no. 2, pp. 526–539, 2013.

[124] C. Pisapia, D. Burn, R. Yoosuf, A. Najeeb, K. D. Anderson, and M. S. Pratchett, 'Coral recovery in the central Maldives archipelago since the last major mass-bleaching, in 1998', *Sci. Rep.*, vol. 6, 2016.

[125] 'Meeru - Big problem with seagrass on the beaches - Maldives Message Board - TripAdvisor'. [Online]. Available: https://www.tripadvisor.co.uk/ShowTopic-g293953-i7445-k6637507-Meeru_Big_problem_with_seagrass_on_the_beaches-Maldives.html. [Accessed: 12-Jul-2017].

[126] O. T. Magoon, L. L. Robbins, and L. Ewing, 'Carbonate Beach Sediment Composition at a Tourist Beach, Negril, Jamaica', Reston, VA, 2002, pp. 204–217.

[127] 'Secretariat of Dhigurah Council', *Government Organisation*. [Online]. Available: https://www.facebook.com/pg/Secretariat-of-Dhigurah-Council-215512571976521/posts/?ref=page_internal. [Accessed: 11-Jul-2017].

[128] S. Saeed and M. Khaleel, 'Paper 8: environmental changes in the Maldives: current issues for management Male.', 1998. [Online]. Available: http://www.fao.org/docrep/X5623E/x5623e0r.htm. [Accessed: 03-Aug-2017].

[129] Asian Development Bank, 'Environmental Management of the Republic of the Maldives'. Asian Development Bank, 1999.

[130] R. Dowling, 'The Maldives', in *Tourism in South and Southeast Asia: Issues and cases*, Butterworth-Heinemann, 2000, pp. 248–255.

[131] Maldives Government: Ministry of Housing and Infrastructure, 'Maldives Third Tourism Master Plan', *Ministry of Housing and Infrastructure* (2007 - 2011)'.

[132] Ministry of Planning and National Development, 'Maldives - Key Indicators.' 2007.

[133] J. Glasson, R. Therivel, and A. Chadwick, *Introduction To Environmental Impact Assessment*. Routledge, 2013.

[134] P. Sillitoe, 'The Development of Indigenous Knowledge: A New Applied Anthropology', *Curr. Anthropol.*, vol. 39, no. 2, pp. 223–252, 1998.

[135] P. Marshall, A. Lyons, C. Luder, J. Maynard, and R. Beeden, 'A Reef Manager's Guide to Fostering Community Stewardship'.

[136] J. Kittinger *et al.*, 'Restoring ecosystems, restoring community: socioeconomic and cultural dimensions of a community-based coral reef restoration project', *Reg. Environ. Change*, vol. 16, no. 2, pp. 301–313, 2016.

[137] W. R. Sheate, 'Public Participation: The Key to Effective Environmental Assessment National Affairs', *Environ. Policy Law*, vol. 21, pp. 156–160, 1991.

[138] J. Weston, 'From Poole to Fulham: A Changing Culture in UK Environmental Impact Assessment Decision Making?', *J. Environ. Plan. Manag.*, vol. 45, no. 3, pp. 425–443, May 2002.

[139] J. X. Leon, J. Hardcastle, R. James, S. Albert, J. Kereseka, and C. D. Woodroffe, 'Supporting Local and Traditional Knowledge with Science for Adaptation to Climate Change: Lessons Learned from Participatory Three-Dimensional Modeling in BoeBoe, Solomon Islands', *Coast. Manag.*, vol. 43, no. 4, pp. 424–438, Jul. 2015.

[140] S. Arnstein, 'A ladder of citizen participation', *35*, 1969.

[141] Cambridge International Examinations, 'Syllabus Cambridge O Level Marine Science 5180'. 2015.

[142] 'Enhancing the appreciation of Mangroves and its benefits for the local communities'. [Online]. Available: https://www.mangrovesforthefuture.org/grants/small-grant-facilities/maldives/enhancing-the-appreciation-of-mangroves-and-its-benefits-for-the-local-communities/. [Accessed: 26-Jul-2017].

[143] G. McDowell, J. Ford, and J. Jones, 'Community-level climate change vulnerability research: trends, progress, and future directions', *Environ. Res. Lett.*, vol. 11, no. 3, p. 33001, Mar. 2016.

[144] V. Reyes-García *et al.*, ‘Local indicators of climate change: the potential contribution of local knowledge to climate research’, *Wiley Interdiscip. Rev. Clim. Change*, vol. 7, no. 1, pp. 109–124, 2016.