Affordable coastal protection

in the Pacific islands

DESKTOP REVIEW

Tonkin + Taylor, in association with the University of New South Wales Water Research Laboratory (WRL), was engaged by the Pacific Region Infrastructure Facility (PRIF) to undertake an engineering study of affordable options for coastal protection. The objective is to build on existing knowledge in an effort to develop innovative solutions to protect coastlines in such a way that will maximise the use of local materials and labour while, at the same time, minimising the need for imported goods and equipment.

This report not only catalogues the existing approaches to shoreline protection in the Pacific region, based on technical, social and environmental criteria; it also provides an evaluation of each.

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Abbreviations

ARI	Annual Recurrence Interval
BoM	Bureau of Meteorology
ENSO	El Niño-Southern Oscillation
km	kilometre
m3	Cubic metre
MSL	Mean sea level
PIC	Pacific island country
PRIF	Pacific Region Infrastructure Facility
PVC	Polyvinyl chloride

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Executive Summary

Overview

Erosion and recession of shorelines is of significant concern to Pacific island countries (PICs). Coastal erosion is caused by a number of factors that include storms and high water levels, reduced sediment production on coral reefs, removal of coastal sands by mining of beaches and the trapping of sediment by rivers and structures. Projected climate change effects, such as the rise in sea levels and changes in storm frequency and intensity, may also increase the risk of erosion.

Erosion and accretion are natural processes. However, when they affect road, maritime or aviation infrastructure, these high value assets are placed at risk, significantly impacting costs and services. While it is possible to adopt a range of measures to mitigate hazardous coastal erosion, including avoidance of vulnerable locations or relocating assets, it is often not possible when confronted with limited land availability or prohibitively high relocation costs. As such, land and assets must be protected by other means.

The Pacific Region Infrastructure Facility (PRIF) commissioned Tonkin + Taylor and the University of New South Wales Water Research Laboratory to undertake a coastal engineering study of various affordable coastal protection options. A further analysis was made of local materials and labour in an effort to minimise the importation of goods and equipment.

Chapter 4 of this study classifies and evaluates the application of various approaches to protect shorelines in the Pacific region, based on technical, social and environmental criteria. An economic analysis of the designs is made in Chapter 5, taking into account wave height, material and its availability, transportation and expected design life, so as to provide an annualised costing in relation to various locations, based on their wave regimes. Chapter 6 provides recommendations of preferred approaches, and it provides various existing approach modifications to improve performance. In addition, it includes additional hydraulic model testing to facilitate the creation of generic design guidelines.

Protection methods used in the Pacific region

The application of rock riprap seawalls is widespread in the Pacific region's volcanic and coral islands, as are vertical concrete walls; grouted stone and coral walls; sand- and grout-filled bags; and gabion baskets. Other types of protection include pneumatic tyres, tree trunks, scrap metal and machinery and drums that are filled with concrete and coral rubble or gravel revetments. While concrete armour units have been used, they are generally limited to port or other areas of higher value. The major challenges that have been identified from the most common solutions in PICs include the following:

- use of local beach material exacerbates shore sediment deficit;
- use of low-strength and lightweight concrete leads to structural failure;
- failure of structural components, such as gabion wire and low-cost sandbags;
- extension of walls are not sufficiently deep to prevent scouring of the base of the wall and the loss of material from behind;
- use of geotextile (or other filter) behind the wall is absent, resulting in the loss of material when the wall cracks or is undermined;
- walls are insufficient in height or lack an upstand wall, thus allowing waves to overtop; and
- lack of backshore protection results in land damage.

Results of technical analysis

Results of the technical analysis in Chapter 4 demonstrate that revetments built from conventional materials are the most effective in protecting land. They also have a typically long design life. They are moderately complex to design and build, depending on the construction methodology—unless geosynthetic containers and Seabee armour units are used. Revetments also require a substantial construction plant, are moderately resilient to climate change, and can often be raised, although it is essential to ensure that units are adequately designed for increased wave climate and height. The social effects of the structures are typically average to poor, with no specific design consideration given to access, although some methods (e.g. geotextile containers) do provide reasonable coastal access. Environmental impacts are, likewise, average to poor, since the natural system is interrupted by a fixed structure that occupies a large area.

Conventional, vertical structures are moderately effective in protecting land, although they dissipate less wave energy, are more vulnerable to toe scour and overtopping and have limited resilience to climate change. It is also a challenge to raise or otherwise upgrade them. Since they restrict access to the shore, they are socially and environmentally limited unless stairs or ramps are integrated at the design stage. Furthermore, through wave reflection, they may increase end-effect erosion, although they occupy a smaller area than revetment structures.

Low-cost solutions, using local materials, are usually simple and scalable, and offer good opportunities for the local labour market. Usually, however, the design has a short life cycle and they are limited in effectively protecting land. Low-cost options are not environmentally effective and may release material (e.g. sandbags, rock, tyres) into the marine habitat as they deteriorate, or will fail if inadequately designed. Some options relevant to lower energy environments, nevertheless, have been identified. These require easily available materials, such as concrete Besser blocks, and should be placed in alternative configurations.

Ecologically based approaches, such as coastal planting and restoration, tend to have superior environmental outcomes. Beach replenishment, for example, is highly site-specific and is dependent on a supply of specific materials to prevent continuous erosion. The protection of land, however, is not guaranteed, given that water levels are often high and erosion of the backshore can occur. Replenishment is often combined with harder backstop structures to improve effectiveness, while maintaining the environmental benefits.

Coastal planting is somewhat beneficial in the long term as the plants mature, particularly in dissipating infrequent overtopping flows and reducing wind-blown sand. The prevention of erosion and loss of beach material, however, is more limited, especially as a result of frequent wave force. Furthermore, planting may restrict access to and views of the coast by the local population and tourists, thereby creating a disconnection from the coast.

Results of cost analysis

Results of the cost analysis are presented in Appendix B wherein the coastal protection costs are presented for each option—including transport—with wave conditions taken into account. Factored in the annual costs of protection is the typical design life. Options considered unsuitable for particular wave climates, however, are excluded from the analysis. Table 12 to Table 14 present a summary of the relative annual costs, proportional to a locally constructed rock revetment.

The conclusions of the study are as follows:

- Hand-placed sandbags have the lowest initial capital cost; however, they have a limited design life and wave height. Nevertheless, the use of alternative bag materials may provide a longer design life, as do alternative placement configurations which have the potential to improve stability under wave attack, making them more attractive options for temporary works and remote locations.
- Rock, depending on local availability, has the lowest annual cost. The high-density volcanic rock requires smaller rocks, translating into lower seawall volumes and cost compared to lower-density limestone and coronus materials.

- Where rock is locally unavailable and must be transported, the initial capital cost of rock revetments increases substantially, although the annual cost remains lower than many shorter design-life options that are locally available.
- Solutions that use locally and inexpensively available materials often have a low to moderate initial capital cost. The fact that the designs have a short life (usually 2–10 years), however, substantially increases the annual and whole-life costs.
- Small, hand-placed, concrete armour units, such as Seabees, are typically two to three times more expensive than locally available rock, although by being less in volume, they become more cost-efficient as transport costs increase. Furthermore, the larger the design wave height, the lower the transport cost will be and, therefore, the more cost effective.
- Large geosynthetic containers are more expensive on islands where rock is available; however, due to the relatively low transport cost from remote locations, these containers are comparable to the single-layer armour units, despite the fact that their shorter design life will increase the annual cost.
- Beach replenishment costs depend significantly on the availability of material, affecting the capital cost and ongoing material loss, the latter of which affects the design life. Where a low-cost supply of sand or gravel is used and ongoing losses are likely to be low, such an approach may prove to be more cost effective than other methods, particularly in remote locations. This would also apply should control structures be used to extend the life of replenishment.

Regional analysis of material availability

The selection of the most appropriate coastal protection method is highly dependent on the local availability of material. The geology of Pacific islands comprises a mix of dense volcanic rock and less dense coral and coronus (i.e. uplifted coral) rocks. Gray (2015) has reviewed the aggregate availability in PICs (Table 2) of material and has found that most countries have volcanic and coronus rock, although Kiribati, the Republic of the Marshall Islands, and Tuvalu have only coral. On the one hand, islands with volcanic material of sufficiently large size tend to have rock revetments that are the most technically robust and cost-efficient solution. On the other hand, islands without such rock (i.e. including some that form part of countries where there is some volcanic material present) tend to have other protection materials that are potentially more efficient.

Recommendations

Based on the findings of this study, the following recommendations are made:

1. Avoid or retreat from hazardous coastline areas to ensure a more robust, long-term solution compared to shoreline armouring, although this may not be socially, economically or politically feasible.
2. Maintain and improve local sediment budgets to potentially reduce the impact of coastal erosion, thus reducing the need for and reliance on coastal protection structures.
3. Determine whether coastal planting of appropriate plant species can assist in reducing overtopping flows and wind-blown transport.
4. Consider conventional structures and lower-cost local approaches where coastal protection structures are required. Technical, environmental and social factors also should be taken into account. The financial assessment should include material availability and transport costs, which may vary substantially based on location.
5. Improve local approaches through the use of alternative materials, as well as design and construction methodologies in an effort to increase the design life and improve hydraulic performance. Examples include:
    a. higher quality ultraviolet, stabilised polyester geotextile bags rather than the low-cost woven polypropylene bags that are in use;
    b. alternative bag placement and bonding patterns to improve hydraulic performance, which would require additional hydraulic testing to extend guidelines;

   c. pre-cast blocks rather than bags in grouted seawalls to improve the unit material quality and the bond between units;
   d. more durable and robust gabion basket materials, subject to cost and affirmation of design life by manufacturers;
   e. extension of structure toe to a firm substrate or below expected scour depth to prevent undermining and toe failure;
   f. suitable geotextile behind structures to retain backshore soils, including in the event of the partial failure of a rigid structure; and
   g. extension of structures to sufficiently high levels to prevent frequent overtopping occurrences, or placement of stabilising materials, such as natural vegetation or armouring, within the overtopping zone.

6. Compare the manufacture of single-layer concrete armour units (e.g. Seabees) at a central location, as well as the transportation feasibility to the site, against local manufacture. The cost to produce, transport and place, as well as structure integrity and design life, should be compared for the two options, followed by a recommendation.
7. Undertake an assessment of commonly available materials for low-energy environments, such as concrete masonry (Besser) blocks, using alternative placement configurations..
8. Undertake hydraulic model testing of two coastal protection options to enable development of design guidance
   a. **geosynthetic containers**

      Test alternative placement and bonding orientations of geosynthetic containers to extend current design guidance. Given the viable application of geosynthetic containers in remote locations where transport costs dominate, increasing the tolerable wave climate, particularly for smaller, hand-placed units (i.e. with good high-quality geotextile), would substantially improve their use. Current placement orientation is with the long bag axis along the coastline due to easier construction and precedent. Alternative bag orientations (e.g. long axis offshore and/or alternating courses) are likely to have increased stability, but this has not yet been quantified.

   b. **concrete masonry block revetment**

      Testing of a revetment constructed using innovative placement of commonly available concrete masonry or Besser blocks. Testing should be undertaken to determine threshold wave conditions (i.e. height and period) for hand-placed concrete blocks, using a range of placement configurations and revetment slopes.

9. Produce a guidance document including:
   a. guidance on assessing design conditions;
   b. guidance on comparing options for shoreline protection, including non-structural options and selection of the most appropriate, to include:
      - design conditions
      - required design life
      - availability of materials, construction plant and local expertise
      - transport costs
   c. Concept-level designs and drawings of:
      - coastal planting
      - rock revetments
      - single layer, hand placed armour units, such as Seabees, or concrete blocks (i.e. depending on model testing results)
      - geotextile containers
      - beach replenishment
      - applicability for a range of wave height conditions.

1 Introduction

Tonkin + Taylor, in association with the Water Research Laboratory of the University of New South Wales, Australia, was engaged by the Pacific Region Infrastructure Facility (PRIF) to undertake specialist coastal engineering research on affordable options for coastal protection.

1.1 Background and study objective

The recession of shorelines due to coastal erosion is an ever-present concern for Pacific Island countries (PICs) (Figure 1). Coastal erosion may be the result of a number of causes, including storms and high water levels, reduced sediment production on coral reefs, removal of coastal sands by mining of beaches and rivers and structures trapping sediment. Climate change effects, such as sea level rise and the increased frequency and intensity of storms, also increase the risk of erosion.

Figure 1: Pacific Island Location Image

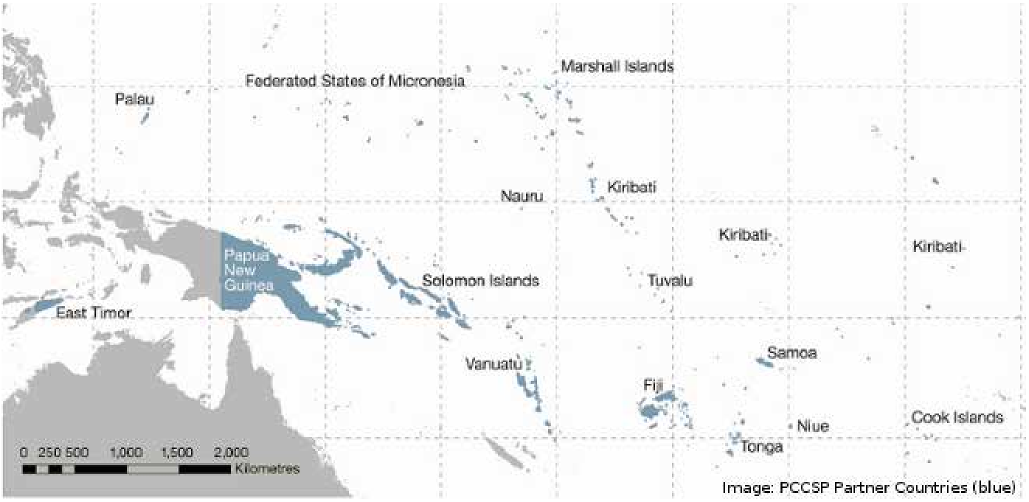


Image: PCCSP Partner Countries (blue)

Source: Pacificclimatefutures.net.

While erosion and accretion are natural processes, when they affect road, maritime or aviation infrastructure, these high value assets are put at risk with significant potential cost implications. Erosion is of particular concern for the transport infrastructure that provides critical lifelines for these geographically-dispersed nations.

While a range of measures may be used to mitigate the erosion hazard, including the avoidance of hazardous locations or relocation of assets, these are often not feasible options when land availability is limited or infrastructure is expensive to relocate. In these cases, the land and assets must be protected.

Traditional responses to coastal erosion include rock or concrete revetments and seawalls. These structures are typically engineered to withstand scour, wave impact and overtopping, and formal design guidance is available. Major obstacles for the construction of coastal protection in PICs include the lack of suitably experienced designers and contractors, construction plant, suitable local materials—especially rock of sufficient size and quality—and the high cost of importing materials.

A range of "non-engineered" methods for coastal (land) protection have been trialled throughout the region with varying levels of success. These have included gabion baskets, sandbags, grout-filled bags, stacked coral rock, grouted coral rock, concrete-filled pipes and other materials of opportunity. Major issues with these methods have included the use of local beach sand, exacerbating coastal erosion; the use of coral sand aggregate that produces lightweight and low-strength concrete; undermining of walls; and damage of the backshore due to overtopping of walls and loss of material from within the wall. Many of these issues can be addressed by modifying the design or materials.

The objective of this study is to build on existing knowledge, in order to develop an innovative solution for coastal protection that maximises the use of local materials and labour. This will minimise the requirement for imported materials and equipment.

1.2 Scope of works

The objectives will be achieved through the following scope of works:

Phase 1: Desktop review (this report):

- identify PICs which suffer from issues with supply of competent material;
- cataloging existing approaches to shoreline protection (both engineered and non-engineered, hard and soft)
- critically evaluate such approaches by using a multi-criteria analysis that considers technical, financial and material supply constraints; and
- provide recommendations for preferred approaches as a function of location and/or improvement of existing solutions.

Phase 2: Development of guidance document:

- Develop a guidance around the preferred approach(s), including the use of physical hydraulic model testing (where necessary) to confirm design parameters.

1.3 Report outline

This desktop review report is structured as follows:

Section 1

Introduction and overview.

Section 2

Pacific environmental context, including aspects that influence coastal protection works that incorporate wind, waves and material availability.

Section 3

Discussion of coastal protection principals and existing approaches to coastal protection in PICs. See Appendix A for further specific details, including a catalogue of approaches tested.

Section 4

Presentation of the framework and results of the technical analysis of coastal protection methods, including engineering, social and environmental aspects. These are evaluated for each approach in Appendix A.

Section 5

Presentation of the framework and results of an economic analysis of technically viable coastal protection methods, including the effect of location and material supply.

Section 6

Presentation of conclusions and recommendations for production of guidance document for preferred coastal protection methods.

2 Pacific environmental context

2.1 Introduction

The Pacific Ocean is the largest ocean body in the world, extending from the Antarctic to the Arctic and between the Americas in the East and Asia and Australia in the West. This study focusses on the Pacific island countries (PICs) shown in Source: Pacificclimatefutures.net.

Table 1 provides an overview of statistics for the relevant PICs.

Up to 30,000 islands are located within the Pacific Ocean, with a total coastline length of over 50,532 kilometres (Paeniu et al., 2015). Because the islands in the Pacific region are surrounded by water and the majority of Pacific Islanders live within 10 kilometres of the coast (Ram Bidesi et al., 2011), the coast is an important and valuable feature. Pacific coasts are dominated by coral reefs, beaches and mangroves, among others, and are constantly changing as a result of natural processes (Paeniu et al., 2015). Relevant natural processes affecting the coast are tides, strong currents, storm surges, sea level rise, strong wind, waves, tropical cyclones and coral reef growth and degradation. Human activities, such as coastal protection structures, reef mining or beach sand extractions affect the coastal processes and may exacerbate the rate of change of coastlines. Human activities and the changing natural processes induce coastal hazards, such as coastal erosion. The gross domestic product of PICs is typically low, below the global average of US$10,700 per capita (World Bank, 2016), which limits their capacity to adapt to coastal hazards and ongoing climate change.

Table 1: Overview of Pacific Island Countries

Country	Area[1] (kilometres[2)]	No. Islands[1]	Population[1]	GDP[1] (Per Capita, US$)	Coastline[2] (kilometres)	Maximum height above sea level[3] (metres)
Cook Islands	237	15	10,900	16,002	120	652
Micronesia, Federated States of	700	607	103,549	3,200	6,112	791
Fiji (and islands)	18,270	332	881,065	4,870	1,129	1,300
Kiribati	810	33	102,351	2,950	1,143	83*
Marshal Islands, Republic of	180	34	52,634	4,390	370	3
Niue	260	1	1,190	5,800	64	69
Palau, Republic of	460	>300	20,918	11,110	1,519	214
Papua New Guinea	452,860	≈600	7,321,000	2,240	20,197	4,697
Samoa	2830	10	190,372	4,060	403	1,860
Solomon Islands	27990	≈80	561,231	1,830	9,880	2,447
Timor-Leste	14870	2	1,212,107	2,680	735	2,963
Tonga	720	177	105,586	4,260	419	1,030
Tuvalu, Republic of	30	9	9,893	5,720	24	5
Vanuatu	12190	82	258,883	3,160	2,528	1,877

Sources: [1]World Bank (2016); [2]Paeniu et al. (2015); [3]PCCSP (2011).

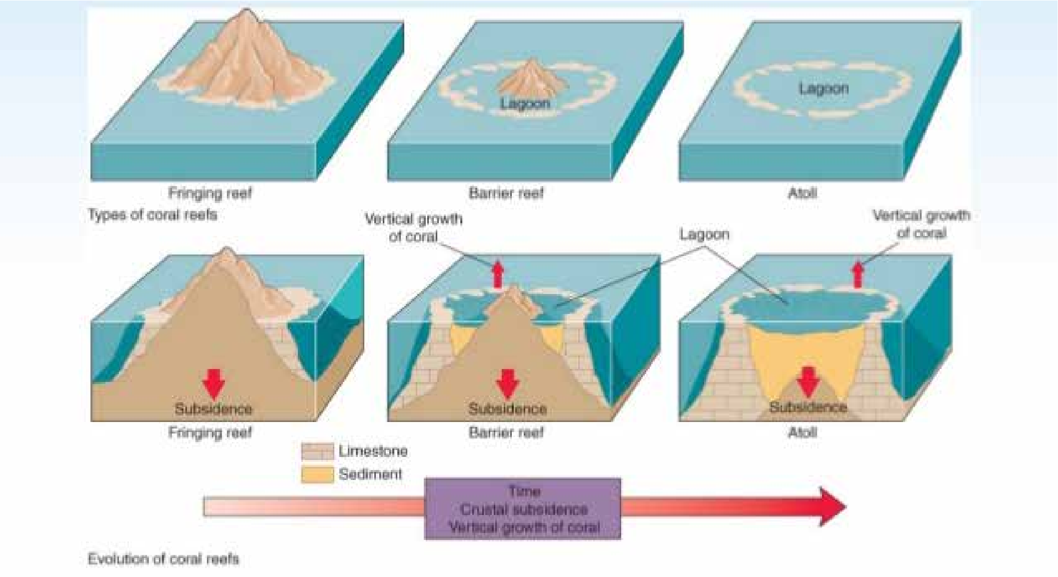
** Apart from a volcanic island, Banaba, the majority of Kiribati is composed of coral atolls at an elevation of less than three metres.*

2.2 Geology

The geology of Pacific islands comprises a mixture of dense volcanic rock and less dense sedimentary and coronus rocks. Neall and Trewick (2008) suggest five major processes involved in island formation:

- basaltic magmas rise through the lithosphere to the surface, forming active large shield volcanoes;
- growth of coral around the volcano, forms fringing reefs;
- gradual subsidence of the volcano as it moves away from its area of generation, with reefs moving progressively offshore to become barrier reefs;
- complete subsidence leading to development of atolls built on subsided volcanoes; and
- further subsidence leading to submerged seamounts.

Figure 2: Development Sequence of Coral Reefs



Source: Sumich and Morrissey (2009).

Gray (2015) describes the geology of Pacific island countries (PIC) and indicates available aggregate resources (Table 2). Most PICs comprise volcanoes or a central volcanic core where volcanic rock can be found. This rock is a hard, well-cemented, massive volcanic breccia/rock strata (Gray, 2015). Coronus and coral aggregates are coralline material that is procured from live or dead reef. Coronus is coralline material that originates from uplifted coralline deposits (Gray, 2015). Coral rock originates from live or dead material and is a result of either fringing, barrier or atoll reef formation (Bullen, 1989). These coral-based aggregates are generally less dense. Kiribati, the Republic of the Marshall Islands and Tuvalu only have coral. It should be noted that in countries where certain material is present, not every island will contain such material (i.e. remote atolls in the northern Cooks Islands will not contain volcanic rock, while the southern islands do), and the actual availability of material will be dependent on social, technical and regulatory criteria.

Table 2: Geological Description and Material Types Present in Pacific Island Countries[1]

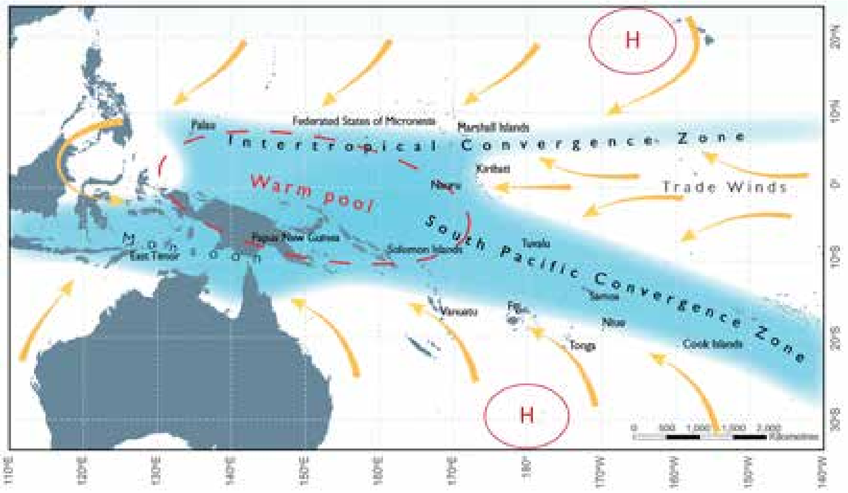
Country	Material type			Geological description
	Coral	Coronus	Volcanic	
Cook Islands	✓	✓	✓	Located in the Central-southern Pacific, the Cook Islands form two distinct geographic groups. In the North are six coral atolls, while the South has islands that are mostly of volcanic origin, usually with distinct central cores. Most have an elevated coral reef platform adjacent to the coast, as well as recent coral reefs.
Micronesia, Federated States of	✓	✓	✓	Located in the west central Pacific, the Federated States of Micronesia comprise more than 600 tiny islands and atolls. There is a mixture of mountainous islands of volcanic origin, low coral atolls and isolated reefs.
Fiji (and islands)	✓	✓	✓	Located in the central Pacific, the Fiji islands comprise more than 320 islands, islets and reefs. The two main islands—and many of the others—are of volcanic origin. They are ruggedly mountainous with limited alluvial plains, uplifted limestone and raised shorelines and extensive coral reefs in shallow areas.
Kiribati	✓	×	×	Kiribati comprises three island groups which lie across the equator. Apart from Banaba, which rises to 80 metres above sea level, the islands are low-lying coral atolls, often enclosing a central lagoon. The thin layer of sandy coral supports only sparse vegetation.
Marshall Islands, Republic of	✓	×	×	The Republic of the Marshall Islands represents islands that are scattered, low-lying coral atolls that form the easternmost group of the Micronesian archipelago. Some atolls enclose very large lagoons.
Niue	✓	✓	✓	Niue is a raised atoll, southeast of Samoa, with its former reef and lagoon uplifted to about 60 metres above sea level. The central plateau in the middle of the island is edged with steep slopes. A coral reef fringes parts of the coastline.
Palau	✓	×	✓	Palau is an archipelago of about 340 islands in the Northwest Pacific. Only nine of them are inhabited. There are two volcanic islands with high centres, although most of the remaining islands are raised coral atolls.
Papua New Guinea	✓	✓	✓	Located just below the Equator in the western South Pacific, Papua New Guinea has 600 islands and coral atolls that are mostly of younger volcanic origin, although the mainland is a massive rugged cordillera (the Central Highlands) with wide and very fertile alpine valleys, as well as ice-capped peaks.
Samoa	✓	✓	✓	Located to the west of American Samoa, Samoa has two large islands and six smaller islets formed from volcanic cones, with several peaks and deeply eroded canyons. Coastal beaches ring the main islands.
Solomon Islands	✓	✓	✓	Located southeast of Bougainville (in Papua New Guinea), the Solomon Islands are a series of high, rugged islands that are located along a northwest/southeast trending fault system with some raised coral reefs. Soils range from extremely rich volcanic to relatively infertile coral limestone.
Timor-Leste	✓	×	✓	Timor-Leste is part of the island of Timor, the largest and easternmost of the Lesser Sunda Islands. Most of the country is mountainous.
Tonga	✓	✓	✓	Tonga comprises 169 islands in an archipelago in two almost parallel chains. The eastern islands consist of low coral islands with a covering of volcanic ash. The western islands consist of tall, recently formed volcanic islands.
Tuvalu	✓	×	×	Located north of Fiji and south of the Equator, the islands and atolls of Tuvalu are of coral formation and they are very low lying.
Vanuatu	✓	✓	✓	The young volcanic islands of Vanuatu, some of which are still active, were formed from belts of older sedimentary rock which were repeatedly uplifted.

[1] *Adapted from Gray (2015).*

2.3 Climate

The climatic system in the Southwest Pacific is influenced by several major climate features. Some of these features exist throughout the year while others have pronounced and regular seasonal cycles. (BoM and CSIRO, 2011). Figure 3 shows the average positions of the major climate features in the Southwest Pacific between November and April. The arrows indicate surface winds and the blue shading, rainfall convergence zones.

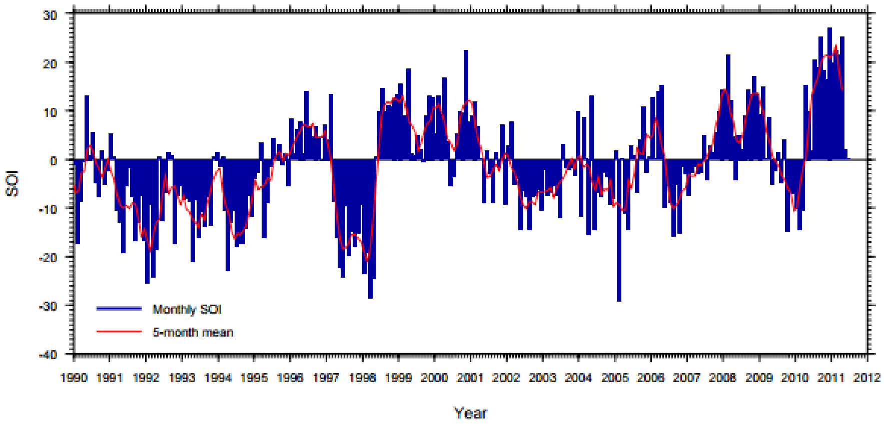
Figure 3: Average Positions of the Major Climate Features in the Southwest Pacific between November and April



Source: PCCSP (2011:8).

The Southern Oscillation is a major natural climate oscillation influencing the climate in the Pacific. It has an irregular cycle of periods between two to seven years. Source: BoM (2011). Figure 4 shows the Southern Oscillation Index since 1900. A strong persistent negative Southern Oscillation is typical of El Niño conditions, which cause an unstable tropical climate system by moving the South Pacific Convergence Zone north and east. A strong and persistent positive Southern Oscillation Index is indicative of La Niña, which pushes the South Pacific Convergence Zone south and west. Other natural climate oscillations, apart from the El Niño/Southern Oscillation (ENSO) are the Pacific Decadal Oscillation, the Interdecadal Pacific Oscillation, Southern Annular Mode and the Indian Ocean Dipole (BoM and CSIRO, 2011). These oscillations affect the mean level of the sea, the strength and extents of trade winds and the formation and tracks of cyclones.

Figure 4: Southern Oscillation Index Values since 1900



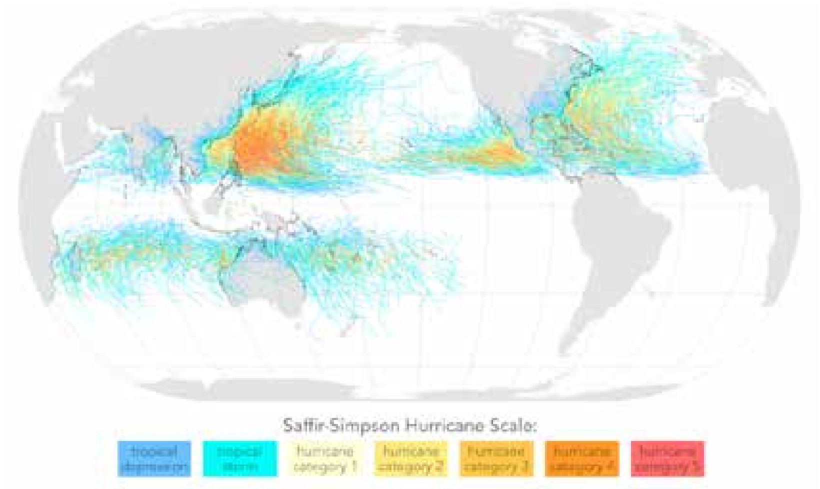
Source: BoM (2011).

2.3.1 Tropical cyclones

Tropical cyclones are prominent weather systems that disturb the mean climate system and are characterised by a low pressure centre, strong winds, heavy rainfall, storm surges and large waves. They occur from December to March and, in general, more cyclones occur during El Niño periods than La Niña. Most tropical cyclones originate between 5º (degrees) and 30º latitude in the Northern and Southern Hemispheres. Cyclones rarely penetrate within ±5° latitude due to the weakness of Coriolis acceleration near the Equator (Forbes and Hosoi, 1995).

Figure 5 shows the tropical cyclone tracks and intensity from 1945 to 2006. It can be seen from this figure that cyclones tend not to occur between 0º and 5º and infrequently extend south to about 30º latitude across the Southwest Pacific. It can also be seen that they do not occur in the Eastern Pacific or South Atlantic.

Figure 5: Tropical Cyclone Track and Intensity, 1945-2006



Source: NASA Earth Observatory.

The majority of PICs relevant to this study are located within the tropical cyclone hazard zone. Strong onshore or alongshore winds and low atmospheric pressure result in elevating the water level above the predicted tide (storm surge). Tropical cyclone-induced storm surge is likely to affect the design of coastal structures. The return periods for the cyclonic wind hazard (metres per second, or m/s) are shown in Table 3. It is evident from this table that no cyclonic wind hazard is present for Kiribati and Nauru which are located around the Equator. While no information on wind strength relating to direction is provided, cyclones can produce high wind speeds from any direction due to their small size and circular wind field, although winds are generally strongest on the leading quadrant. The column headed, Standard, is the three-second gust value adopted in national building/engineering codes for that nation.

Table 3: Cyclonic Wind Strength for Pacific Island Countries
(metres per second)

Return period wind hazard m/s				Country	Standard
25yr	50yr	100yr	500yr		500yr
68	77	84	95	**Cook Islands**	-
44	55	62	75	**East Timor**	-
50	58	64	74	**Federated States of Micronesia**	-
58	64	69	76	**Fiji**	66
-	-	-	-	**Kiribati**	-
54	64	71	82	**Marshall Islands**	-
-	-	-	-	**Nauru**	-
63	71	77	86	**Niue**	-
57	65	71	80	**Palau**	-
33	42	48	58	**Papua New Guinea**	45
62	69	75	84	**Samoa**	66
34	41	46	53	**Solomon Islands**	45
64	70	75	82	**Tonga**	66
35	41	46	53	**Tuvalu**	-
69	75	79	86	**Vanuatu**	66

Sources: BoM and CSIRO (2011).
Note: Values are taken as the median wind gust speed found in a 2° x 2° region, centred on each country's capital city.

2.4 Water levels

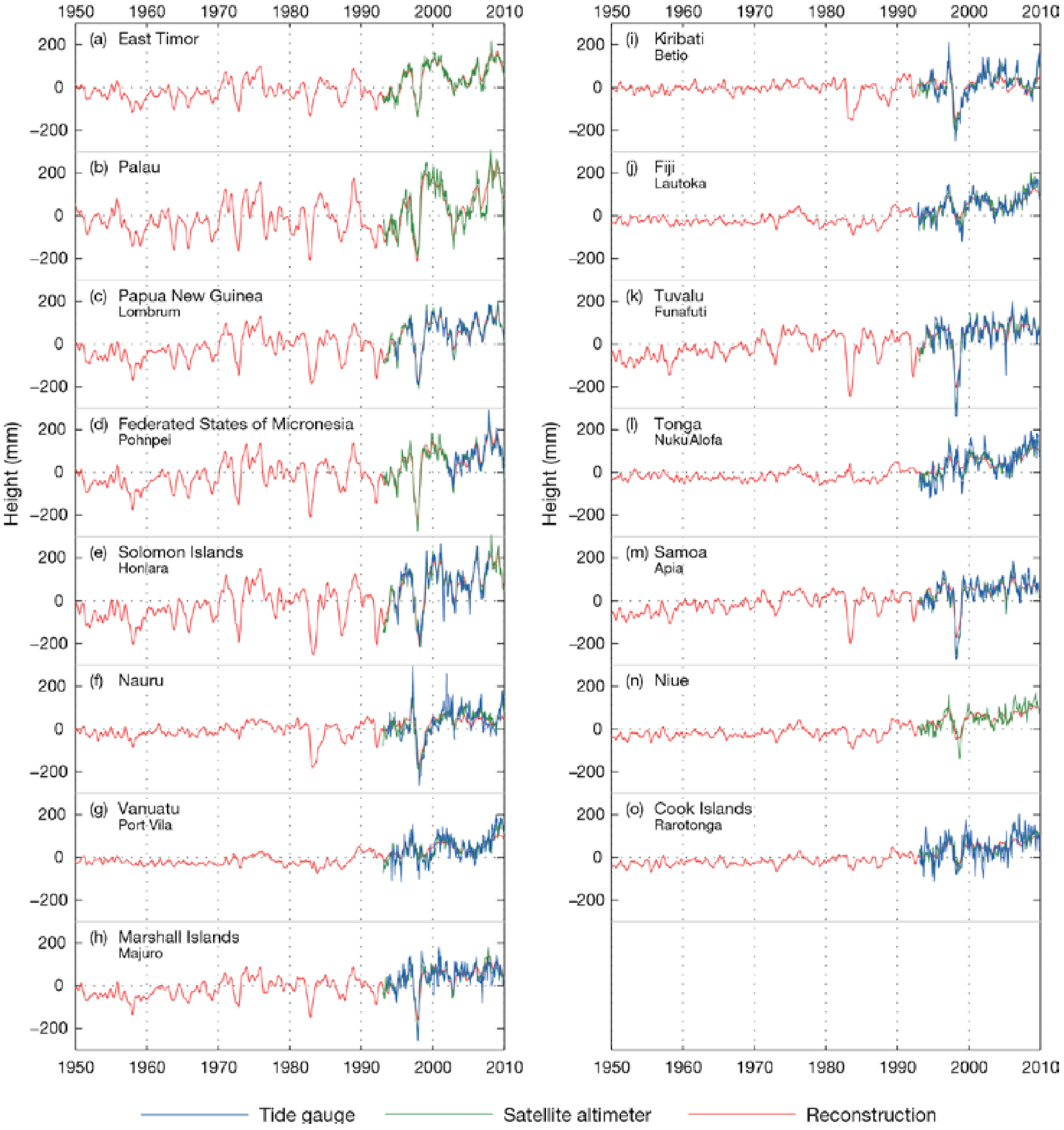
Water levels observed at a particular location fluctuate due to a range of astronomical, meteorological, climatic and tectonic processes. These fluctuations occur at a range of time scales from hours to days for meteorological processes (i.e. storm surge); hours to weeks for astronomical processes (tides); months to years for cyclical climatic processes, such as ENSO and Interdecadal Pacific Oscillation cycles; and years to millennia for long-term climate change and gradual tectonic movement.

2.4.1 Mean water levels

Shorter period fluctuations, such as tides and meteorological effects, fluctuate around a mean water level. As described above, this mean water level is also likely to change over time, and its exact value will depend on the time period over which the level is averaged. The mean sea level (MSL) at a certain given time is often adopted as a land datum although, over time, this datum is likely to deviate from the existing mean level.

Since 1993, sea level measurements have been continuously recorded by the SEAFRAME tide gauges on PICs. Figure 6 shows a time series of monthly tide gauge data (blue) with satellite altimeter data (green) and reconstructed sea levels (red) for every PIC (BoM and CSIRO, 2011). The tide gauge and satellite altimeter data show an increasing trend of the mean water level, from 1993 to 2010 for the majority of PICs.

Figure 6: Time Series of Monthly Tide Gauge Data with Satellite Altimeter Data and Reconstructed Sea Levels

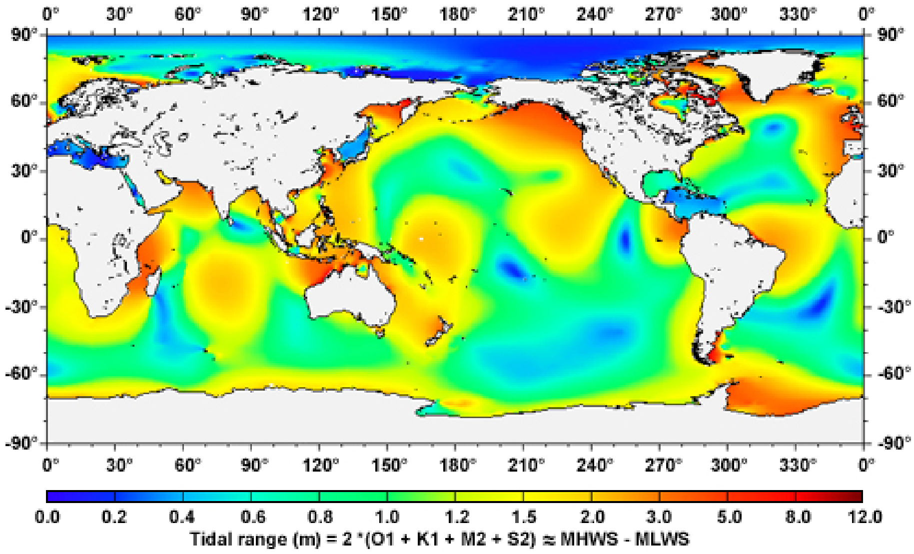


Sources: BoM and CSIRO (2011).
Note: Monthly tide gauge data (blue); satellite altimeter data (green); reconstructed sea levels (red).

2.4.2 Tides

Astronomical tide is the periodic rising and falling of the level of the sea surface, caused by the gravitational interaction of the earth, sun and moon on the earth's waters. Tides within the Pacific southwest basin are semi-diurnal, with a typical tidal range (difference between high and low waters) ranging from 1 m to 2.5 m (based on the Source: National *Tidal Centre,*).

Figure 7: Global Tidal Range

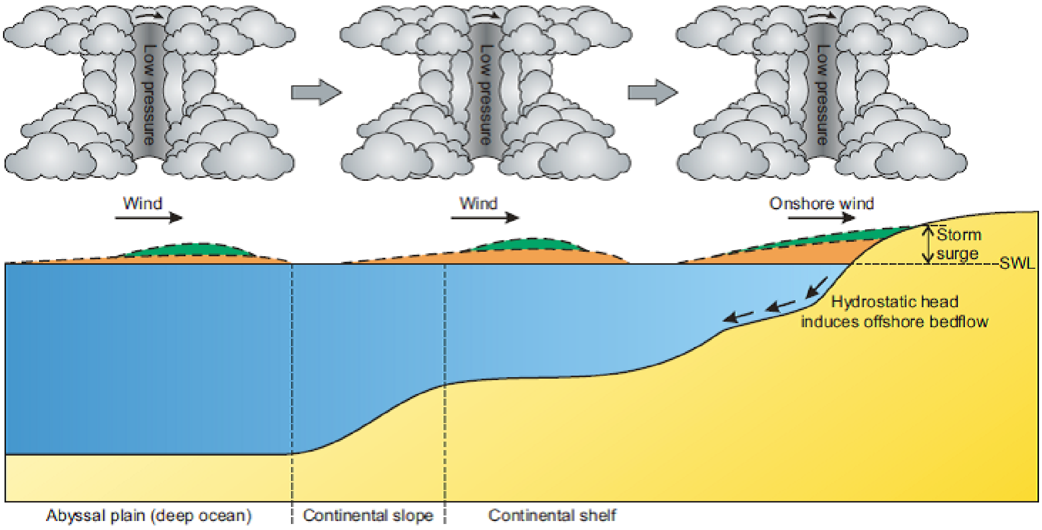


Source: *National Tidal Centre, Australian Bureau of Meteorology*.

2.4.3 Storm surge

Storm surge results from the combination of barometric setup from low atmospheric pressure and wind stress from winds blowing along or onshore, which elevates the water level above the predicted tide (Source: Adapted from Shand et al. (2010).). The combined elevation of the predicted tide, climatic cycles and storm surge is known as storm tide. Cyclones are particularly effective at generating storm surge due to their very low central pressure and high winds; however, their small size means that the cyclone must pass very close to the observation point for the surge to be significant. Additionally, storm surge is amplified in shallow coastal waters and within embayments, implying that islands surrounded by relatively deep water are less vulnerable to large surge heights.

Figure 8: Processes Contributing to Storm Surge

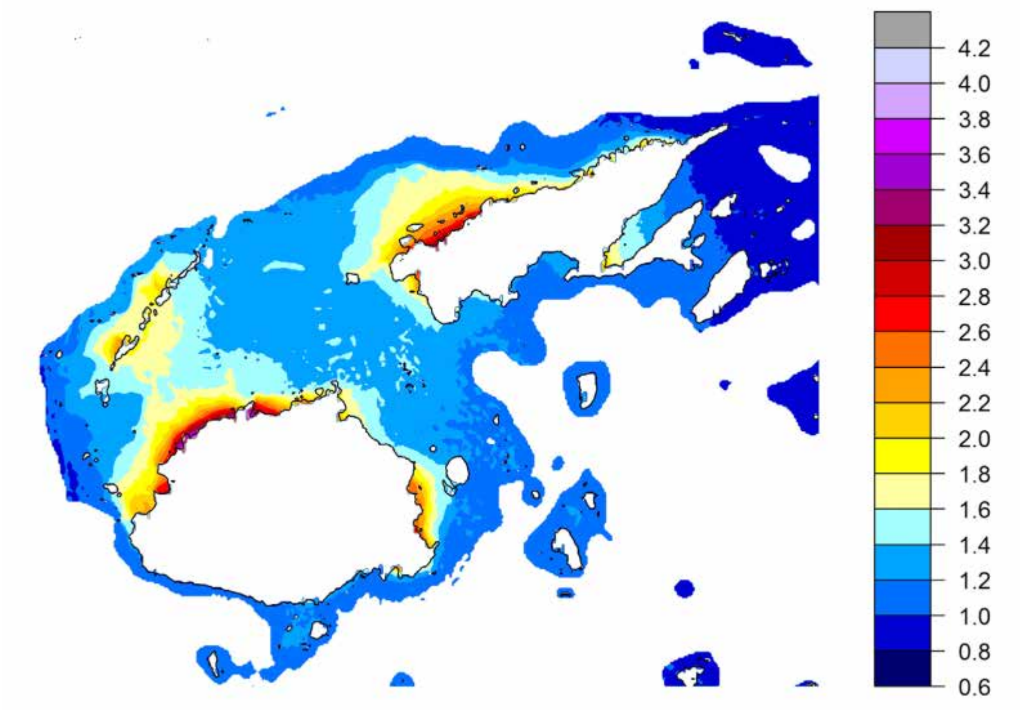


Source: Adapted from Shand et al. (2010).

The elevation of the storm tide at any particular island group will depend on the mean water level at the time, the astronomical tidal level, the magnitude and proximity of a cyclonic system and the strength and direction of cyclonic winds. McInnes et al. (2014) recently quantified storm tide risk in Fiji using a probabilistic approach. They found that storm surge is typically greatest on the northwest-facing coasts and coasts with shallow coastal waters (Figure 9). Findings showed the 200-year Annual Recurrence Interval (ARI) storm tides to range from 1.2 m above MSL at southeast-facing and deeper coastlines to over 3 m along northwest-facing coastlines. While equivalent data is not available across all PICs, it can be inferred from cyclone strength and tidal range that 200-year ARI storm surge levels are likely to range from 1 m to 3 m above MSL.

Figure 9: Maximum Modelled Storm Tide Heights in Fiji for 200-Year Annual Recurrence Interval Events

(metres above MSL)



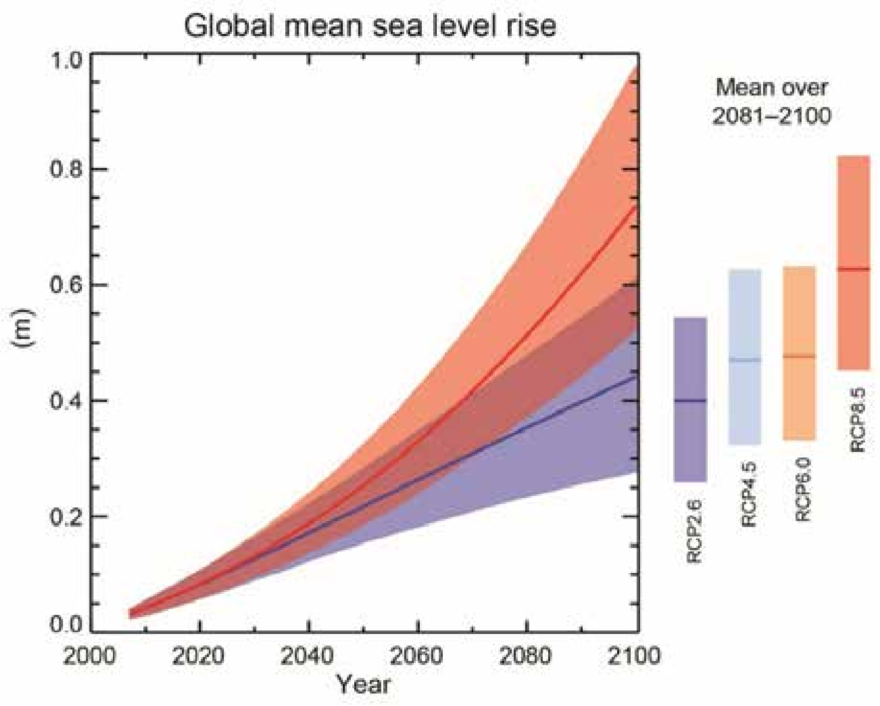
Source: McInnes et al., 2014.

2.4.4 Sea level rise

The MSL has been rising over the last decades, with the Australian Bureau of Meteorology observing trends of relative sea levels ranging from 3.6 millimetres a year (mm/yr) to 17 mm/yr between 1993 and 2010 across the southwest Pacific, based on SEAFRAME tide gauge data. This is higher than the global average of sea level rise of 3.3 mm/yr over the same time period (Cazenave and Llovel, 2010) and indicates a likely tectonic movement, as well as a rise in the actual MSL.

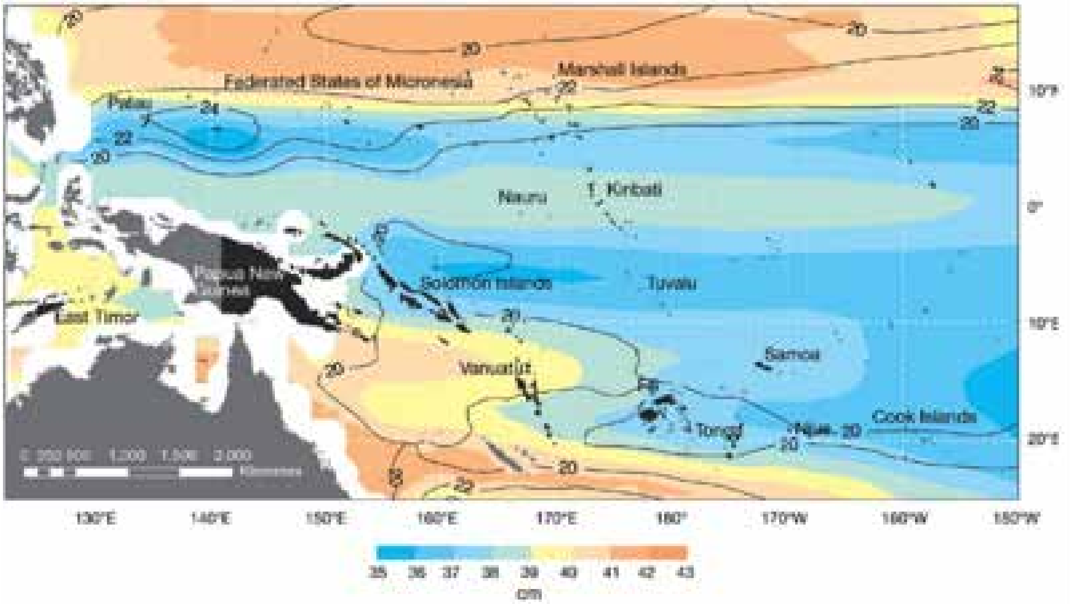
Modelling presented within the most recent Intergovernmental Panel on Climate Change report (IPCC, 2014) shows projected global sea level rise values by 2100 to range from 0.27 m to 1 m, depending on the emission scenario adopted (Figure 10). Based on recent rates of sea level rise, rates within the Pacific could be higher than this global average projection. Within the Pacific region, projections of sea level rise also vary, with Figure 11 showing sea level projections for the "A1B" scenario (based on IPCC's Fourth Assessment Report modelling) for 2081-2100 to vary by up to 10 centimetres.

Figure 10: Projections of Potential Future Sea Level Rise Presented within the Fifth Assessment Report of the Intergovernmental Panel on Climate Change



Source: IPCC (2014).

Figure 11: The Sea-Level Projections for the A1B (Medium) Emissions Scenario in the Pacific Climate Change Science Program Region for 2081-2100, Relative to 1981-2000[1]



Source: Aus BoM and CSIRO (2011).

[1] *Based on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*

2.5 Waves

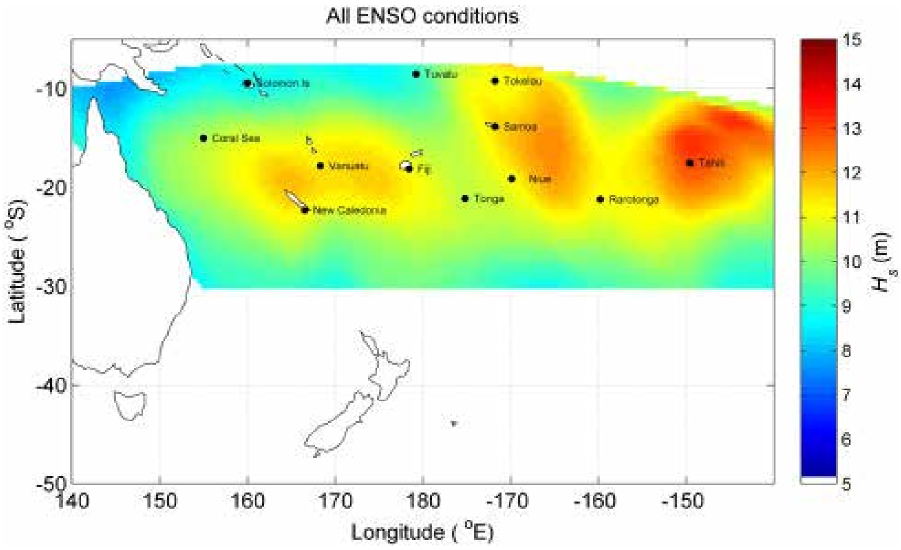
As winds blow over a water surface, energy is transferred into the water column to form waves. There are typically four sources of waves in the Pacific region:

- Waves generated locally within lagoons: These waves may be up to 1 m high with periods of three to four seconds in larger lagoons (i.e. Tarawa, Kiribati), although they are typically less than 0.5 m with periods of one to two seconds.
- Wind sea waves associated with local trade winds: Waves are typically less than 2 m with less than 10-second periods. These waves affect Pacific islands between +30º and -30°.
- Swell waves generated by large extratropical storms in the 40º-50° belt of the southern and northern Pacific Oceans. These waves typically affect Pacific island coasts facing them, with waves up to 5 m (or more) and long periods between 13 and 20 seconds (Kruger et al., 2011). However, swell may propagate through the entire Pacific with swells from the southern Pacific Ocean, reaching Hawaii in the North and swells generated in the northern Pacific reaching Tonga in the South.
- Tropical cyclone and storm-induced waves are generated locally: These waves are generally responsible for the largest waves and can be combined with significant storm surge, as described in Section 2.4.3.

Stephens and Ramsay (2014) have assessed tropical cyclones in the South Pacific and found deep-water significant wave heights of 6-9 m, 8-12 m, and 10-14 m, respectively, for the 10-year, 50-year, and 100-year ARI cyclonic events. An example of the significant wave height, associated with 50-year ARI tropical cyclones in the southwest Pacific area, is shown in Figure 12.

The actual wave height, reaching a particular coastline, is highly affected by local bathymetry and the presence of offshore fringing reefs, which cause breaking and refraction of incoming wave energy. Local nearshore wave modelling is typically required to resolve nearshore wave processes.

Figure 12: Significant Wave Height Associated with 50-Year Annual Recurrent Interval Tropical Cyclones



Source: *Stephens and Ramsay (2014).*

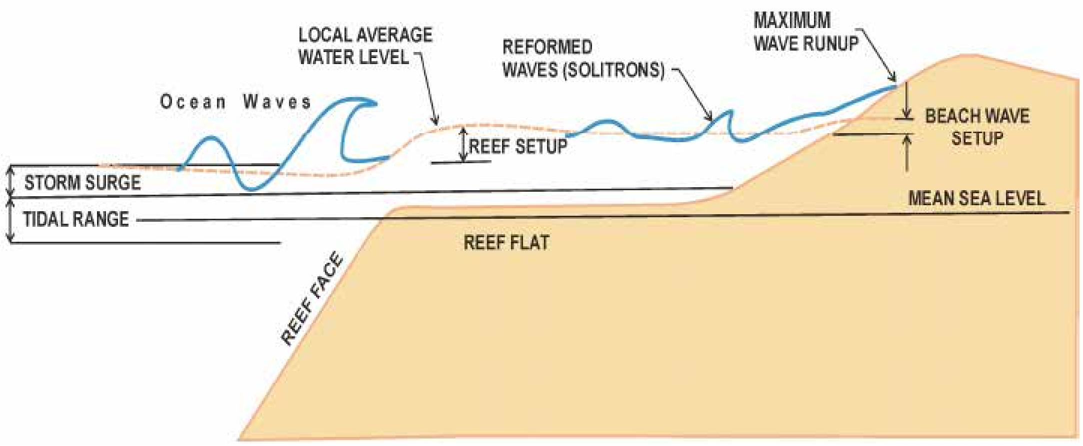
2.6 Reef-top processes

As waves approach a coral reef, they shoal and change in height and direction before breaking on the reef crest. They then decay as they move across the reef flat due to dissipative breaking processes and bed friction. Studies have shown that the maximum size of waves on reef flats is controlled by water depth, with the maximum wave height approximately 0.6 times the water depth (Gourlay, 1994; Kench and Brander, 2006). On a fringing reef where the reef crest is shallower than the backing lagoon, a broken wave may reform into an oscillatory (unbroken) wave and propagate across the lagoon before breaking again—at a reduced height—on the backing shoreline.

Nearshore water level can also be modified by wave processes. Wave setup occurs due to onshore momentum flux that occurs during wave breaking. Without breaks in the reef, to allow the seaward escape of elevated water within the lagoon, setup can be significant. Empirical models derived by Gourlay (1994) suggest that wave setup may be up to 15% of offshore breaking wave height. Where the elevated water flows out through reef passes, fast currents occur which may have complex interactions with incoming waves.

An associated process is wave runup, which varies with breaking wave characteristics and beach and backshore slope and composition. Wave runup causes periodic wave swash above the inundation level and may contribute to flooding and cause risks to public safety and impact damage to structures. Kruger et al. (2011) noted wave runup of 2-5 m above MSL on Fiji's south coast, associated with a distant swell event. Callaghan et al. (2006) reported building damage due to wave runup 25 m above MSL on a cliff coast in Niue during Tropical Cyclone Heta. Components which may elevate water levels, resulting in inundation of land, are shown in Figure 13.

Figure 13: Schematic Diagram Showing Components of Wave Setup and Runup Level



Source: Jones et al. (2003).

2.7 Sediment transport

Natural sediment transport occurs (i.e. when sediment is available) in the cross-shore and longshore directions due to the effects of wind, waves and longshore currents. Where more sediment arrives at a location than is removed, the sediment budget is positive, accumulation occurs and the shoreline is likely to accrete seaward. Where more sediment moves away from a site than arrives, the sediment budget is negative, erosion occurs and the shoreline is likely to move landward (i.e. recession). The removal of sediment by people (i.e. sand mining), either from the beach face or from offshore and/or coastal structures, may negatively affect this natural sediment budget.

Factors that affect sediment transport—and as a result, sediment budgets—are changes in wave direction and height, as well as changes in the mean and extreme water level. Increases in water level can potentially allow more sediment to be transported by allowing greater wave energy to reach the backshore. Furthermore, relatively small changes in wave direction may either increase or decrease transport. Medium-term cycles, such as ENSO and Interdecadal Pacific Oscillation cycles, have been shown to affect water levels (SPSLCMP, 2010), wind direction and strength (Webb, 2005,) and beach platform alignment.

Anthropogenic changes, such as causeway construction, have the potential to increase extreme water levels at the shoreline. This occurs as flow paths for the onshore momentum flux, associated with wave breaking, are removed by the infilling of channels between the islands. The static water level, known as setup, must then increase to compensate this momentum flux imbalance. This removes sediment transport from the ocean to the lagoon side and may also increase sediment transport along the ocean coastline by allowing greater wave energy to reach higher on the beach face.

Structures, such as seawalls, groynes and breakwaters, may trap sand or alter waves. This can cause altered local patterns of erosion and accretion.

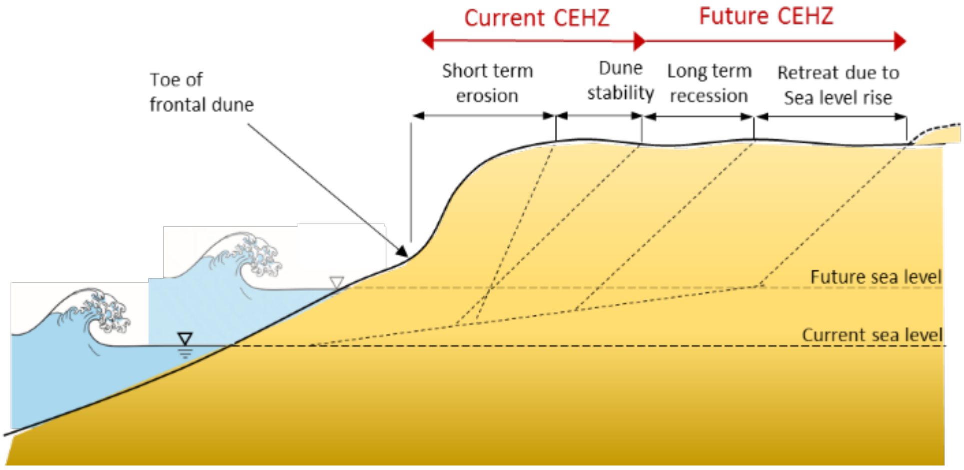
2.8 Shoreline processes

Coastal recession occurs when more sediment leaves the seaward edge of a shoreline than arrives; that is, the process of erosion exceeds the process of accretion over the long term. Recession can occur on all coastal types, including unconsolidated beaches, soft estuarine shorelines and harder cliffed coastline, although the mechanism responsible for recession and the rate of recession will vary. On unconsolidated beaches, shoreline change can occur due to short-term fluctuations in the beach profile and from long-term trends of recession or accretion that are a function of sediment supply and demand. Short-term fluctuations can occur at different time scales. The most readily apparent is the change in beach profile due to onshore storms, with sand generally removed from the upper parts of the beach and deposited offshore, and rebuilding after the storm has passed. However, there are also seasonal and decadal variations. Beach recession is typically defined as a long-term landward translation of the beach profile and is typically influenced either by sediment supply not being sufficient to replace sediment transported away by wave action, or due to increased exposure to wave energy as the sea level rises or offshore reefs and structures are removed or lowered.

The sediment available on a beach greatly influences long-term recession rates and the potential for short-term erosion. This sediment volume is affected by the removal of sediment directly (i.e., by sand mining) or by affecting sediment supply.

Sea levels are projected to rise at an increased rate in the future. As the sea level rises, the morphology of the beach profile at the land-sea intersection is expected to respond. The most widely known model for this beach response is that of Bruun (1962). The Bruun model assumes that as the sea level is raised, the equilibrium profile is moved upward and landward, conserving mass and the original shape (Bruun, 1962, 1983). This profile translation effectively results in a recession of the coastline. While some recent studies have observed increases in total land area on PICs over the past decades (Webb and Kench, 2010), they have generally occurred on more mobile reef-top islands where there is biogenic sand production (Figure 14). Coupled with this, Hoegh-Guldberg et al. (2007) suggest that ocean acidification over the twenty-first century will compromise carbonate accretion, with corals becoming increasingly rare on reef systems and thus reducing an important source of sediment for Pacific beaches. The only offset to this may be a projected increased rainfall (BoM, 2012), bringing more volcanic sediments from the catchment.

Figure 14: Definition Sketch for Current and Future Coastal Erosion Hazard Zones



Source: Shand et al. (2013)

3 Coastal protection in Pacific island countries

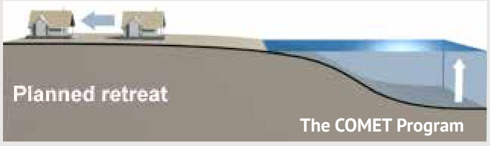
3.1 Introduction

While erosion and accretion are natural processes, when they affect road, maritime or aviation infrastructure, these high value assets are put at risk with significant potential cost implications. Erosion is of particular concern for transport infrastructure which provides critical lifelines for these geographically-dispersed nations.

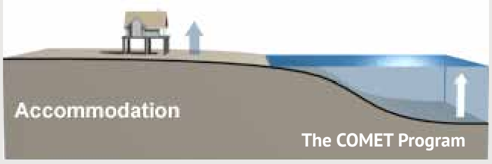
A range of measures may be used to mitigate the erosion hazard, including avoidance of hazardous locations or relocation of assets. These options often are not feasible when land availability is limited or infrastructure is expensive to relocate. In these cases, the land and assets must be protected.

The principles of coastal protection are described in Figure 15. These include examples of specific protection measures that have been trialled within the Pacific.

Figure 15: Principles of Coastal Protection

Avoidance/ Retreat	***Avoidance*** **or** ***Retreat*** **from the hazard, through either planning restrictions or by relocating assets out of the hazard-affected area, will eliminate the likelihood and therefore the risk.**	
	Examples	Development restrictions Relocation out of hazard zone 
	Benefits	Long-term security No/low maintenance requirements and future costs No risk of immediate failure of protection system Reduction of risk to ecosystems and the environment Potential increase in public space in high-use amenity areas (i.e. beaches) Potential Increase in tourism Low regrets
	Barriers	Perceived (or real) loss of land or use of land Land unavailability for relocation or high purchase cost Services required to relocation areas Potentially noneconomically viable or compensation required Legacy issues; community, social and political inertia

Continued next page

<table>
<tr><td rowspan="4">Accommodate</td><td colspan="2"><i>Accommodate</i> the hazard by reducing the likelihood or magnitude of the hazard or reducing the consequence of the hazard. Use in combination with hazard <i>Avoidance</i>.</td></tr>
<tr><td>Examples</td><td>Structure maintenance
Higher building platform levels
Early warning systems plus disaster risk reduction, reducing loss of life
Ecosystem-based approaches
 </td></tr>
<tr><td>Benefits</td><td>Typically lower capital costs than protection
Less regrets than protection
Generally lower impact on ecosystems and environment than protection (or improvement in case of ecosystem-based approaches)
Minimal social disruption</td></tr>
<tr><td>Barriers</td><td>May not be sustainable in the long term (i.e. seawall repairs)
May take time to become effective (i.e. ecosystem-based approaches)
Risk may be reduced but not eliminated</td></tr>
<tr><td rowspan="4">Protect</td><td colspan="2">Construction of physical works to <i>Protect</i> against a particular threat or range of threats. Options may be “hard” such as a revetment or seawall; or “soft”, including beach nourishment or a combination of the two. Protection options should be used in combination with <i>Accommodation</i> options, such as ecosysem-based approaches to widen benefits and minimise adverse effects, and with <i>Avoidance</i> options to ensure long-term resilience.</td></tr>
<tr><td>Examples</td><td>Beach nourishment
Offshore structure
Groyne
Revetment
Seawall
 </td></tr>
<tr><td>Benefits</td><td>Immediately beneficial for intended purpose (i.e. protection of land from erosion)
If adequately designed, effective against intended hazard
If adequately designed, benefits for years to decades
Will incorporate ecologically beneficial aspects or minimise damage
Will improve amenity (i.e. beach nourishment or walkway on concrete capped seawall)</td></tr>
<tr><td>Barriers</td><td>High regrets if it fails (i.e. seawall collapse)
Perceived level of protection may encourage development, increasing consequence and, therefore, risk after the works’ protective lifespan has passed
High ongoing maintenance and replacement costs
May adversely affect ecology and the environment
May adversely affect recreation amenity or other uses of the area</td></tr>
</table>

3.2 Alternatives to hard protection

A range of alternatives to hard coastal protection may be considered to provide more economic or long-term solutions to coastal erosion. These are discussed in the sections below.

3.2.1 Avoidance of or retreat from hazard

The most effective way to manage the risk from a hazard, where feasible, is to avoid the hazard altogether. Development restrictions place limits on the development that may occur in locations deemed to be hazardous or they infer requirements for measures to be undertaken to avoid the hazard. These restrictions may apply to new development only or may include modifications to existing development. Restrictions on development in one area require alternative sites, with infrastructure such as roads, power and water in place to minimise the negative social impacts.

Asset relocation involves the progressive abandonment or movement of assets, located in hazardous zones or not built to withstand hazardous events to nonhazardous areas. Such relocation may be required immediately when the hazard is high and protection or accommodation is not feasible, or may only occur in the future when climate change increases the hazard to a point where retaining the asset is not sustainable. The site-specific negative social impacts relating to involuntary resettlement losses must be considered.

3.2.2 Maintaining sediment budgets

A sediment budget refers to the sediments entering and leaving a coastal system. Where more material leaves the system than enters, the system is in deficit, and erosion/recession of the backshore occurs. Changes in the sediment budget may be due to natural changes in the environment or due to human activities such as degradation of the reef, trapping of sediment by structures or direct removal of material from the coastal zone through sand mining.

Sand mining has historically occurred throughout the Pacific region on a commercial and a domestic scale. Sand can be derived from river systems, lagoons and fringing coral reefs. Some of these sources are naturally replenished and sustainable, although excessive removal of material or removal from the wrong locations may lead to an eventual deficit of sand on the beach and increase the potential of erosion. While much of commercial mining has ceased in recent years, observation by the authors suggests smaller-scale domestic mining continues in many Pacific island countries (PIC).

Alternatives to coastal sand mining are to mine on land where sands have been historically deposited or at sediment sinks where material has left the coastal system. An example of this is the EU-funded Environmentally Safe Aggregates for Tarawa project at South Tarawa in Kiribati, where offshore lagoon material is dredged and sorted to provide a sustainable aggregate source.

Reducing sand mining in some locations may reduce the potential for shoreline erosion and the requirement for coastal protection works. It also improves the amenity value of the coastline for the local community, as well as for tourist operations. In some locations, however, reduction of sand mining could lead to reduced navigability and the infill of ports.

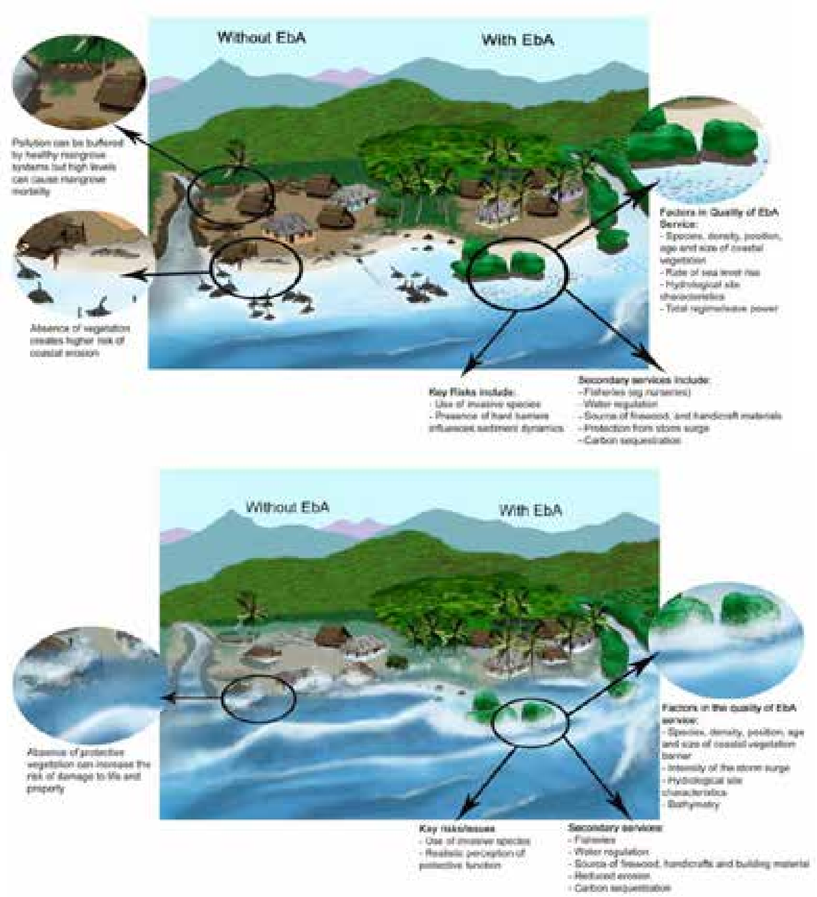
3.2.3 Ecological-based approaches

Ecosystem-based approaches aim to protect the shoreline from wave-induced erosion by maintaining healthy ecosystems. These may include:

- establishment of offshore vegetation, such as mangroves, to dissipate wave energy before it reaches the shoreline and to trap fine sediment while maintaining habitats for juvenile fish and marine species;
- establishment of backshore vegetation to reduce wave runup extent and damage potential, trap wind-blown sand and improve ecological connectivity between the land and sea; or
- improvement of coral reef health to ensure coral production is maintained.

The use of ecosystem-based approaches for coastal protection (Figure 16) and as a method of offsetting the impacts of climate are described extensively through the literature (World Bank, 2010; Hills et al., 2011), including techniques for combining ecosystem-based approaches with conventional protection structures (DECCW, 2009). Although economic analyses of ecological approaches often identify high benefit-cost ratios compared to coastal protection structures, this is generally a function of low implementation costs, with modest improvements in the protection provided. Such improvements would not likely achieve the desired outcomes when erosion is directly and immediately threatening coastal infrastructure or assets.

Figure 16: Concept Sketches of the Use of Ecosystem-Based Approaches to Reduce the Effects of Coastal Erosion and Flooding



Source: Hills et al. (2011).

3.3 Coastal protection structures

Coastal protection structures have a principal function of protecting the shoreline from erosion caused by wave, current or tidal effects. These may include structures that are built on and directly armour the shoreline, or they may be structures that are located offshore and indirectly protect the land by reducing wave heights. Coastal protection structures are varied in their form and construction material, and they are vulnerable to different failure mechanisms that exert varying pressures on the environment.

Key design factors considered in coastal protection include:

- structure along shore length
- structure cross-shore location (backstop wall or in active beach)
- required height of structure to limit overtopping to desired levels
- slope of structure

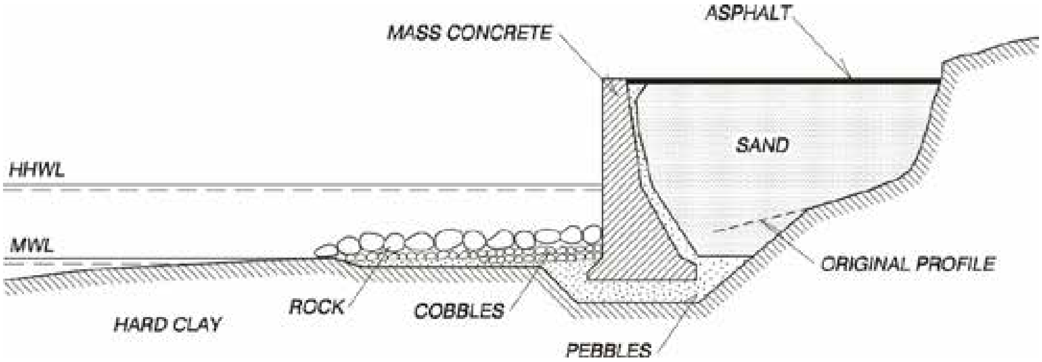
- seawall toe detail
- seawall end detail
- material size and density
- filter material and geotextile
- crest width
- allowance for settlement and later crest raising
- backshore protection.

3.3.1 Structural type

3.3.1.1 Rigid structures

Rigid structures protect the land by resisting coastal processes. They may be vertical, sloping or stepped, and are traditionally constructed of mass concrete or reinforced concrete, grouted rock or blocks, timber or steel sheet piling or timber posts. They require a well-founded toe, preferably on hard substrate or should be deeply piled to avoid scour and undermining. Additional toe protection may be required when using a semi-rigid structure to prevent scour and undermining (Figure 17). The structures must be robust due to the high wave loading and, therefore, be either massive structures or those better suited to low-to-medium wave environments where wave loading is moderate. Runup and overtopping is similarly high, as rigid structures do not tend to effectively dissipate wave energy. Backshore protection is often required to limit damage by wave overtopping.

Figure 17: Example of a Vertical Fronted Seawall



Source: USACE (2006).

3.3.1.2 Semi-rigid structures

Semi-rigid structures are able to move under wave loading, allowing some energy to be dissipated and for the structure to settle as the seabed or backshore changes form due to erosion or settlement. Semi-rigid structures, therefore, are often better suited to higher wave environments and to such dynamic environments as sandy beaches rather than rigid structures. Semi-rigid structures are generally sloped revetments and, therefore, they use more space than rigid structures. Examples of semi-rigid structures include:

- rock revetments (Photo 2)
- concrete armour unit revetments
- articulated blocks and blanket structures
- cut and stacked blocks
- sand-filled geotextile bags held under gravity (Photo 1).

Due to the flexibility of the outer layer, a filter layer is required to contain the fine land material behind. This filter may be a smaller aggregate or a geotextile fabric. This filter essentially forms the barrier between land and sea, with the armour providing protection to the filter from wave attack.

Photo 1: Semi-rigid geotextile container (Maccaferri NZ Ltd.)

Photo 2: Rock revetments (Shand) in Kiribati

3.3.1.3 Dynamic shoreline protection

Dynamic structures respond to incoming waves, altering in shape to effectively absorb energy without compromising the integrity of the structure. Examples of dynamic protection include:

- reshaping revetments, whereby rocks are mobile under wave attack and form a more stable profile (i.e. Photo 3 and Photo 4); and
- sand replenishment (known as beach nourishment), the artificial addition of sand or gravel to the coast to improve the capacity of a beach to act as a buffer against storm erosion, coastal recession or tidal inundation to protect the land behind.

Dynamic materials may continue to be moved over time, with some losses from the system expected. Coastal protection, using dynamic materials, therefore must include sufficient material to protect against wave attack and gradual material loss over time. Rock and gravels are generally less mobile than sands and require less ongoing maintenance and replenishment. Control structures, such as groynes and offshore structures, also are used to limit material loss from the system.

Photo 3: Gravel replenishment at Funafuti, Tuvalu (Taiwanembassy.org)

Photo 4: Stacked coral block wall in Kiribati collapses forming a 'dynamically stable revetment' *(Credit: Shand)*

3.3.1.4 Offshore structures

Offshore structures protect the shoreline by reducing the wave energy arriving at the shore and rotating incoming wave crests. On a sandy coast, this can reduce longshore drift gradients and encourage sand deposition in the lee of the structure (Photo 5 and Photo 6). Offshore structures may be emergent, partially-emergent, or submerged. Submerged and semi-submerged structures act by breaking or refracting the waves rather than absorbing or reflecting them to dissipate energy. While less visually intrusive, they are less effective than emergent structures, particularly during high water level and wave conditions that can result in beach erosion. Structures may be constructed from rock, pre-cast concrete armour units or geotextile containers, and must be stable under wave attack. They should have the capacity to reduce transmitted wave energy to a desirable level.

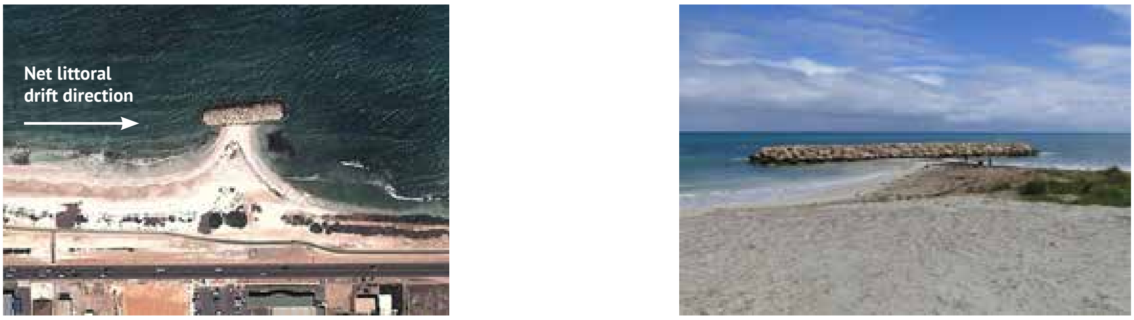


Photo 5 and Photo 6: Beach Tombolo created in lee of an offshore breakwater in Geraldton, Western Australia *(Credit: Shand)*

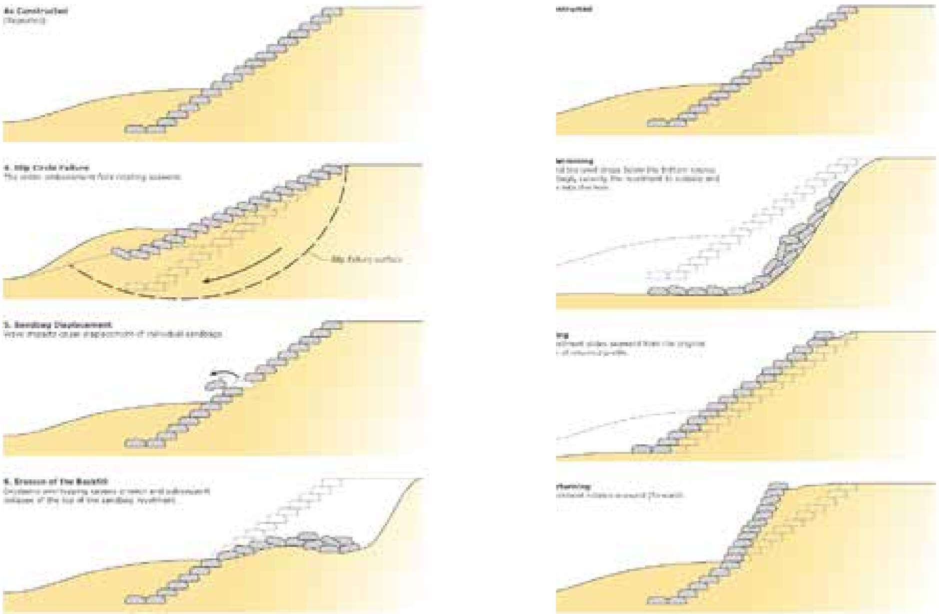
3.3.2 Failure mechanisms

Typical failure mechanisms, as defined within USACE (2006), include:

- undermining, in which the sand or rubble toe level drops below the footing of the wall, causing the wall to subside and collapse in the hole;
- sliding, in which the wall moves away from the retained profile;
- overturning, in which the wall topples over;
- slip circle failure, in which the entire embankment fails;
- loss of structural integrity, due to wave impact;
- erosion of the backfill, caused by wave overtopping, high water table levels or leaching through the seawall;
- corrosion, abrasion and impact damage; or
- outflanking and end scour.

Failure mechanisms (Figure 18) can differ for coastal protection types with rigid structures. They tend to be more vulnerable to catastrophic failure, while semi-rigid and flexible structures tend to fail with progressive actions.

Figure 18: Examples of Seawall Failure Mechanisms



Source: WRL. (2015).

3.3.3 Effects of seawalls on beaches

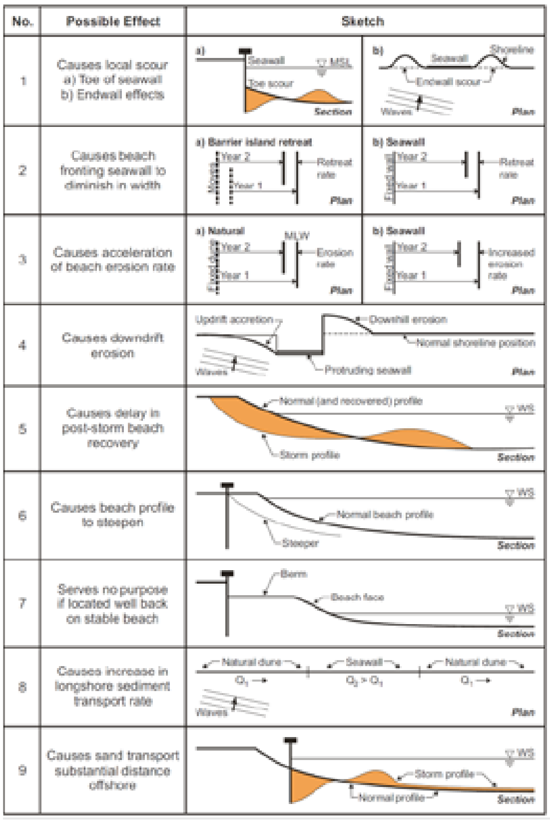
It is important to note that coastal protection structures, such as seawalls and revetments, are intended to protect the land behind the structure only. They do not protect the fronting beach and, if the coast is in a state of recession, the beach will gradually be lost in front of a wall. Similarly, they will not protect adjacent land from ongoing erosion/recession. If recession is ongoing, the problems of erosion will continue adjacent to any constructed wall. This land must be monitored and, if erosion persists alongshore into other high-value areas, the seawall may need to be extended and/or additional management options considered.

Kraus and McDougal (1996) attributed much of the controversy about the potential adverse effects of seawalls on beaches to a lack of distinguishing between “passive erosion” and “active erosion” (Pilkey and Wright, 1988; Griggs et al. 1991, 1994). Passive erosion is defined as being caused by “*tendencies which existed before the wall was in place*” and active erosion as being “*due to the interaction of the wall with local coastal processes*.” Of passive erosion, Griggs et al. (1994) stated that whenever a seawall is built along a shoreline undergoing long-term net erosion/recession, the shoreline will eventually migrate landward behind the structure, resulting in the gradual loss of beach in front of the seawall as the water deepens and the shore face profile migrates landward.

Dean (1986) presented a list of nine possible and often suggested effects of seawalls on adjacent shorelines and beaches. He then critically examined these postulations and concluded (Basco, 2006) the following (numbers in parentheses reflect the potential effect from Figure 19):

- Dean found that armouring of a beach does **not** cause profile steepening (6); delayed beach recovery after storms (5); increased longshore transport (8); sand transport further offshore (9) and increased long-term average rate of erosion (3).
- Dean found that armouring of the beach **will** contribute to frontal effects (toe scour, depth increases, 1a); end-of-wall effects (flanking; 1b); blockage of littoral drift when projecting in surf zone (groyne effect; 4) and a reduced beach width fronting armouring (2).

Figure 19: Commonly Stated Effects of Seawalls on Adjacent Shorelines and Beaches



No.	Possible Effect
1	Causes local scour a) Toe of seawall b) Endwall effects
2	Causes beach fronting seawall to diminish in width
3	Causes acceleration of beach erosion rate
4	Causes downdrift erosion
5	Causes delay in post-storm beach recovery
6	Causes beach profile to steepen
7	Serves no purpose if located well back on stable beach
8	Causes increase in longshore sediment transport rate
9	Causes sand transport substantial distance offshore

Source: Adapted from Dean (1986).

3.4 Overview of coastal protection in Pacific island countries

SOPAC (1994, 1999) reviewed and discussed coastal protection measures in the South Pacific. It found that beach mining and reclamation of shorefront land exacerbated natural erosion processes. SOPAC also discovered that conventional rubble mound structures have been widely used throughout the Pacific. These have consisted of basalt and granite, where available (e.g. Samoa and Cook Islands), coral boulders in other locations and some concrete armour units where deepwater protection is required. Some standard designs have been used, such as to protect coastal roads in Western Samoa, although many walls are based on rock availability rather than formally designed.

Hand-placed rocks are widely used due to the ease of construction, although they often fail through undermining, overtopping or the rock being undersized. Gabion baskets are similarly popular due to the relative ease of construction and availability of small rock. These have been relatively successful, especially when placed at the back of the beach where they are not frequently exposed to wave action, although once the wire coating is damaged and corrosion occurs, failure is rapid. Likewise, sand- and cement-filled bags are popular; however, degradation of the fabric from ultraviolet exposure, abrasion from coral and vandalism may occur, so it is suggested that use is restricted to temporary works.

While no results have been reported, small-pattern placed armour units, such as Seabees, have reportedly been trialled on Onotoa, Kiribati. These units are deemed effective and economic. Care, however, is needed with the preparation of the foundation, toe detailing and placement of units to ensure satisfactory interlocking. Larger concrete armour units have been used, although these are restricted to deepwater locations where design waves are large.

SOPAC (1994) cited the lack of suitably sized materials as a major limitation in constructing conventional coastal protection structures and, where coral boulders or concrete units are used, physical modelling is generally required. SOPAC provided indicative cost estimates for coastal protection materials (excluding transport) at that time, ranging from A$15/cubic metre ($m^3$) for hand pitched walls, A$40/$m^3$ for rubble mound walls, A$200 m^3 for mass concrete walls or units to A$500/$m^3$ for reinforced concrete units or walls. It stressed that these are indicative due to the large numbers of factors influencing construction, including project size, contractor experience, type of equipment available, remoteness of site and materials, influence of water and level of international expertise and supervision required. They recommended that a coastal protection manual be drafted that focusses on the design conditions, available material resources and skills in PICs.

Paeniu et al. (2015) presents a review of the typical coastal protection works used within different PICs, based on information provided by local stakeholders. A summary of these are presented within Table 4. These show that rock riprap seawalls are widespread in volcanic and coral islands, together with vertical concrete walls; grouted stone and sandbag walls; and gabion baskets. Other types of protection include rubber tyres, tree trunks, scrap metal and machinery and drums filled with concrete. Concrete armour units have been used, although these are generally limited to ports or areas of high value. Examples of failed interventions are presented and these are mostly collapsed seawalls with apparent undermining, structural failure and overtopping.

Table 4: Identified Coastal Protection Works in Pacific Island Countries

Country	Reported coastal protection works	Guidance documents available
Cook Islands	concrete sea walls, rock boulder revetments, groynes, rock breakwater, beach replenishment	
Micronesia, Federal States of	Grouted coral seawalls, stacked coral	
Fiji (and islands)	Mass concrete seawall, reinforced concrete seawall, rock revetment, rubber tyres, gabion baskets, mangrove planting	
Kiribati	Small stacked sandbags, grout-filled and mortared sandbags, reinforced concrete, grout mattress, tetrapod armour units, rock revetment, gabion baskets, stacked coral, grouted coral, planted mangroves	Shoreline protection guidelines[1]
Nauru	Coral boulders, concrete seawalls, rock seawalls	
Niue	Minimal—one concrete seawall at Avatele Bay	
Palau	Rock riprap, grouted rock, vertical concrete	
Papua New Guinea	Stacked rock, bricks, sandbags, tree trunks, gabion baskets, concrete-filled tyres	
Marshall Islands, Republic of	Rock rip-rap revetment sandbags, vertical concrete block or cemented coral walls, concrete armour units, gabion baskets filled with coral gravel, stacked tyres, scrap metal and old heavy machinery	Landowner's Guide to Coastal Protection
Samoa	Grouted stone walls, rock revetments, groynes, beach replenishments, mangrove planting	Public Works Department standard rock revetment design
Solomon Islands	Rock revetments, stacked rock behind wooden piles, mangrove planting, vertical concrete wall, concrete armour units (tetrapods), gabion baskets	
Timor-Leste	Rock revetments, concrete armour units, mangrove planting, coastal and marine protected areas	
Tonga	Limestone/coral boulders, mangrove planting, grout-filled bags	
Tuvalu	Vertical concrete wall, gabion baskets, concrete cubes, steel drums filled with concrete	
Vanuatu	Vertical concrete wall, stacked coral, grouted coral, gabion baskets, revegetation	

Sources: Paeniu et al. (2015) and others.
[1]BECA (2011).

A selection of coastal protection works are shown in Photo 7 through Photo 14, and individual methods are described in further detail in Appendix A (Catalogue of coastal protection methods).

Photo 7: Grout-filled sandbags *(Credit: Shand 2015)*

Photo 8: Stacked coral blocks

Photo 9: Bitumen

Photo 10: Gabion baskets

Photo 11: Concrete filled drums

Photo 12: Rock revetment

Photo 13: Rock filled timber wall

Photo 14: Geotextile containers

3.4.1 Observed failure mechanisms

Major issues (Photo 15 through Photo 18), identified with the commonly used solutions in PICs, include:

- use of local beach sand, exacerbating shore sediment deficit;
- use of low strength and lightweight concrete leading to structural failure;
- failure of structural members, such as gabion wire;
- insufficient extension of wall depth to prevent scouring of the base of the wall and loss of material from behind;
- lack of geotextile (or other filter) use behind the wall, resulting in loss of material when the wall cracks or is undermined;
- walls under-height or lacking an upstand wall to allow waves to overtop; and
- lack of backshore protection, resulting in land damage, among others.

Photo 15: Outflanking *(Credit: Shand)*

Photo 16: Overtopping *(Credit: Shand)*

Photo 17: Undermining *(Credit: Shand)*

Photo 18: Structural failure *(Credit: Shand)*

3.4.2 Use of concrete in Pacific island countries

3.4.2.1 Use of coral aggregates

In many PICs, the dense and durable volcanic aggregates, typically used in concrete, are not available, other than only coral and coronus materials (Table 2). The latter are typically less dense and durable.

Howdyshell (1974) has reviewed concrete methods and examples since World War II and has discovered that coral has been used successfully as an aggregate for concrete, providing the coral is uniform and of high quality and the mix design is carefully prepared and complied with. The only significant type of deterioration observed was the cracking and spalling that is associated with corroding reinforcing steel.

This may be attributable to the salts present in unwashed coral aggregates, which destroy the passivity of embedded steel and lead to corrosion. Similar corrosion, however, occurs in many conventional concrete structures that are situated in the marine environment, particularly where the reinforcement is close to the surface and/or where cracks are present.

Yodsudjai et al (2002) found that while the strength and durability of concrete is influenced by the quality, strength and durability of the low-quality and coarse aggregate that is used, the use of low cement-water ratios (i.e. increasing the amount of cement in the mix) lessens the negative effect of the coral aggregate. Moreover, a reasonable compressive strength can still be achieved.

3.4.2.2 Use of salt water

A number of experimental investigations have been carried out on concrete, using sea water for mixing and/or curing. Kaushik and Islam (1998) report that seawater, used as mixing water in concrete, will decrease the setting time and increase early strength by approximately seven days. A decrease in strength of 5-10%, however, was observed after 18 months. Mixing and curing in salt water had a minimal effect on concrete alkalinity. Mbadike and Elinwa (2011) report an 8% strength decrease and Islam et al. (2012) report a 10% loss in strength when concrete was mixed and cured with sea water.

Mohammed, Hamada and Yamaji (2004) report an earlier strength gain and no difference in long-term strength when sea water was used for mixing. There was no indication that seawater-mixed concrete is less durable. Maniyal and Patil (2005) found no major difference in compressive strength when sea water was used for mixing and curing. They suggest that sea water is safe to use for mass concreting without any change of the concrete strength properties.

Nishida et al. (2014) carried out a literature review and an experimental test. They found 50% of papers reviewed had a positive opinion of using sea water in concrete mixing, with the addition of minimal additives such as blast furnace slag or fly ash. They also indicated the possibility of using sea water in reinforced concrete.

Literature on the effect of sea water on concrete, reinforced with alternative materials such as glass fibres or basalt reinforcing, is limited. Information from manufacturers suggests that this may be feasible, although it would require further investigation.

Photo 19 and Photo 20: Local coral aggregates being supplied and mixed by hand in Kiribati, 2015 *(Credit: Shand)*

3.4.3 Review of alternative materials

3.4.3.1 Gabion basket materials

Maccaferri gabions are now available with a polymer coating (i.e. conventional steel wire), called "PA6". According to Maccaferri, this coating offers significant environmental benefits over traditional polyvinyl chloride-(PVC)coated wire mesh products, as it neither contains heavy metals, phthalates nor ozone-depleting chemicals (Maccaferri, 2012).[1] Used over "Galmac" (or "Galfan", a 95% zinc + 5% aluminium alloy that coats the steel wire) (Galvinfo, 2011; Maccaferri 2004), PA6 coating has greater durability, strength, resistance to erosion and a longer design life than a PVC coating. While it is not a PVC replacement, it is suggested for use when a PVC coating does not provide the required environmental or technical performance or design life.

Welded gabions are popular for architectural applications or low-height structures with minimal risk of differential settlement.[2] Permathane Pty. Ltd. supplies stainless steel welded mesh for gabions, more suited to marine applications than coated-steel wire gabions.[3] These are available in grade 316 and 316L (i.e. low carbon) stainless steel, commonly known as marine-grade stainless steel (Permethane, 2016).

Triton gabions and Triton gabion mats are constructed from Tensar geogrid plastic and are an alternative to steel wire gabions in environments where there is a high potential for corrosion, such as in coastal applications.[4] They are available either in prefabricated units or in roll form.

3.4.3.2 Geotextile fabrics

Secondary microplastics (i.e. plastic particles smaller than 5 millimetres) can originate from the breakdown of larger plastic debris through physical, biological and chemical processes (Cole et al., 2011). The primary outdoor cause of degradation of plastics is solar ultraviolet radiation, causing plastic to become weak and brittle, where it can be broken into fragments by any mechanical source (GESAMP, 2015).

Geotextiles and geogrids are most commonly made from polyester (i.e. usually polyethylene-terephthalate), polypropylene or polyethylene.[5] Polyethylene-terephthalate may be hydrolysed in the presence of water, which is accelerated by alkaline conditions (Geofabrics, 2009). There does not appear to be any research suggesting that synthetic geotextile or geogrid products have an adverse environmental impact; however, this is a potential through degradation and fragmentation of the product.

Alternative natural geotextiles have been used for erosion control and slope stabilisation. Due to their biodegradability and significantly shorter lifespan (i.e. compared to synthetic materials), natural geotextiles are used in conjunction with revegetation.

Coir is a natural fibre extracted from the husk of coconuts and is resistant to microbial attacks and salt water (Jayasekara and Amarasinghe, 2010). Coir geotextiles or matting and coir logs (i.e. coir geotextile filled with coir fibre) are used for soil erosion control and slope stabilisation, in combination with vegetation, to stabilise the slope when the coir has disintegrated (Vaighai Agro, 2015; Energy and Environmental Affairs, 2016).[6] Coir geotextiles and logs have a lifespan of one to five years, depending on the product and application.[7]

Jute is a vegetable fibre that can be spun into coarse, strong threads. The source of the fibre is mostly *Corchorus olitorius* and *Corchorus capsularis*, grown predominantly in India and Bangladesh. Jute is used to make burlap and hessian. It is also manufactured into a geotextile, used for erosion control in combination with planting. Jute geotextile has a shorter lifespan than coir, ranging from one to four years, depending on the product and application (Ghosh, Bhattacharyya and Mondal, 2014).[8]

4 Technical analysis

4.1 Introduction

This assessment has focussed on coastal protection measures—intended to directly protect land or assets—that have been reported as being used within the Pacific or further afield. Sources of information have included published literature, reports, anecdotal information and first-hand observation by the authors. This assessment has not focussed on methods of hazard avoidance or accommodation, the benefits of which are well covered in the literature.

Technical criteria for coastal protection structures have been established, including engineering, social and environmental criteria. These criteria are described below and are evaluated for each coastal protection approach in Appendix A. Results are summarised at the end of this section.

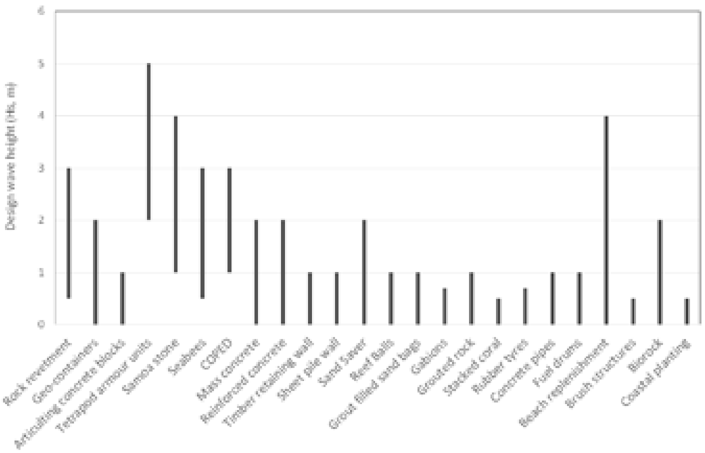
4.2 Engineering considerations

Engineering considerations determine the ability of the protection measure to provide shoreline protection, including the conditions under which it may be used (Table 5; Figure 20), design life, ability to resist scour and overtopping and resilience to climate change. The availability of design guidance, construction complexity, plant required and scalability influences how easily the structure may be designed and constructed. Typical results, corresponding to low, medium and high ratings, are presented below.

Table 5: Technical Analysis: Engineering Considerations

Technical Criteria		Rating		
		1	3	5
Engineering	**Design wave characteristics**	Single wave height/period	Range of heights	All heights and periods up to design level
	Design life	<2yrs	5-20 years	>50 years
	Time period to become effective	>2 years	Within 2 years	Immediate
	Effectiveness at protecting land	Limited protection of backing land or often fails	Moderate protection or sometimes fails	High level of protection of backing land reported in all cases
	Effect on overtopping	Large overtopping volumes or runup level high	Moderate overtopping volumes	Low overtopping volumes or decreases runup
	Toe scour	High toe scour occurs	Moderate toe scour	Low levels of toe scour occur
	Design guidance available	None	Some	Complete
	Resilience to climate change	No adaptation—replacement required	Modification required	Provision for a specified level of climate change
	Construction complexity	Requires international contractor	Requires local contractor	Semi-skilled or unskilled local labour
	Construction plant required	Large and/or expensive plant required	Some construction plant required	No construction plant required
	Scalability	Highly site-specific	Site-specific modification required	Very generic

Figure 20: Design Wave Height under which Each Option Is Generally Considered Effective



Notes: Hs = Significant wave height; m = metre.

4.3 Social considerations

Social criteria assesses the degree to which the protection method affects the local population in terms of utilising local labour during construction, affecting public access to the marine area, modifying the aesthetics of the area and the overall cultural acceptability of the option. These are highly site-specific and can only be answered in general terms, particularly cultural acceptability which, for this study, has been defined based on previous usage within the Pacific.

Table 6: Technical Analysis: Social Considerations

Technical Criteria		Rating		
		1	3	5
Social	**Use of local labour**	Local labour cannot be used	Use of some local labour	May be completed using local labour
	Beach access	Prohibits access	Access unchanged or still possible	Enhances access
	Aesthetic	Significantly differs from existing	Slightly differs from existing	In keeping with existing environment
	Cultural acceptability	Never used	Occasionally	Widely used

4.4 Environmental considerations

Environmental considerations include occupation of the marine area and seabed; effect of the protection structure on adjacent land by causing "end effect" erosion; effect on the overall sediment budget; effect on ecosystems; and impact of construction activities on the environment. As most coastal protection structures are intended to protect land, they therefore prevent this erodible material from being added to the sediment budget. Structures with better dissipation characteristics tend to cause smaller end effects than do reflective structures.

Ecosystems are often adversely affected where connectivity between the land and marine area is broken; however, some structures may provide additional opportunity for habitat through voids and irregular surfaces (Table 7). While construction activities are generally short term, longer-term effects may occur where a structure rapidly deteriorates, spilling material into the marine environment.

Table 7: Technical Analysis: Environmental Considerations

Technical Criteria		Rating		
		1	3	5
Environmental	**Seabed occupation**	Large occupation area (<3 x design wave height)	Moderate occupation area (1-2 x design wave height)	Small occupation area (less than 1 x design wave height)
	End effects	Enhances erosion of adjacent land	Rates of background erosion remain constant	Reduces erosion of adjacent land
	Effect on sediment budget	Depletes sediment budget	Not effect on sediment budget	Enhances sediment budget
	Effect on ecosystems	Significant adverse effect	Neutral or both positive and negative effects	Significantly improves ecosystems
	Impact of construction activities	Significant and/or long-term adverse effects	Some and/or short-medium term effects	Negligible adverse impacts

4.5 Results

An analysis of each method has been undertaken with a description of results, presented in Appendix A. A summary of assessed ratings is presented in Table 8.

The results demonstrate that revetments constructed of conventional materials are the most effective at protecting land and have typically long design lives. They are moderately complex to design and construct with all materials, except geocontainers and Seabees, depending on construction methodology, thus requiring substantial construction plant. They are moderately resilient to climate change and can often be raised, although care needs to be taken that the units are adequately designed for any increased wave climate. Social effects are typically average to poor without specific design consideration for access, although some methods, such as geotextile containers, provide reasonable coastal access. Environmental impacts, likewise, are average to poor as the natural system is being interrupted by a fixed structure with, generally, a large occupation area.

Conventional vertical structures are also moderately effective at protecting land, although they dissipate less wave energy and are more vulnerable to toe scour and overtopping. They also have limited resilience to climate change, being difficult to raise or otherwise upgrade. These structures have poor social and environmental effects, restricting access to the shore (i.e. unless stairs or ramps are integrated) and promoting end effects through wave reflection, although they occupy a smaller area than revetment structures.

Low-cost solutions, using local materials, are typically simple and scalable with good opportunity for local labour. However, they typically have short design lives and limited effectiveness at protecting land. They have poor environmental effects and often spill material (e.g. sandbags, rock, tyres) across the coast as they deteriorate and fail.

Ecosystem-based approaches, such as coastal planting and replenishment, tend to have the best environmental outcomes; however, replenishment is highly site-specific and a detailed study and design are required in each case. Furthermore, design life can be short if erosion is ongoing and replenishment material is rapidly lost. Protection of land is not guaranteed with high water levels, often causing continuing erosion of the backshore despite replenishment. Replenishment is often combined with harder “backstop” protection structures to improve effectiveness while maintaining environmental benefits. Coastal planting can be moderately beneficial in the long term as plants mature although, again, it does not provide complete protection. Furthermore, planting can restrict access and views of the coast for locals and tourists, thereby disconnecting people from the coast.

As the weighting of each criterion is dependent on project and stakeholder values, no attempt at such weighting has been undertaken. Instead, options most and least preferred, from a technical viewpoint, are presented in Table 9.

Table 8: Results of Technical Analysis

Technical Criteria		Rating			Revetments							Vertical Seawalls				Offshore		Low cost or local materials							EbA			
		1	3	5	Rock revetment	Geocontainers	Articulating concrete blocks	Tetrapod armour units	Samoa Stone	Seabees	COPED	Mass concrete	Reinforced concrete	Timber retaining wall	Sheet pile wall	SandSaver	Reef Balls	Grout-filled sandbags	Gabion baskets and mattresses	Grouted rock	Stacked coral	Rubber tyres	Concrete pipes	Filled drums	Beach replenishment	Brush structures	Biorock	Planting mangroves and vegetation
Engineering	**Design wave characteristics**	Single wave height/ period	Range of heights	All heights and periods up to design height	5	3	2	3	4	4	3	4	3	2	2	1	3	1	1	2	1	1	2	1	4	1	3	1
	Design life	<2yrs	5-20 years	>50 years	5	3	3	4	4	4	4	4	4	3	3	3	3	2	2	2	1	1	2	1	2	1	3	4
	Time period to become effective	>2 years	Within 2 years	Immediate	5	5	5	5	4	4	5	5	5	5	5	3	2	5	5	5	5	5	5	5	4	2	1	1
	Effectiveness at protecting land	Limited protection of backing land or often fails	Moderate protection or sometimes fails	High level of protection of backing land reported in all cases	5	4	4	5	5	5	3	4	4	3	3	2	2	2	3	2	1	1	1	1	3	1	1	2
	Effect on overtopping	Large overtopping volumes or runup level high	Moderate overtopping volumes	Low overtopping volumes or decreases runup	4	2	3	5	4	3	3	1	1	1	1	1	3	1	3	2	3	3	1	1	5	3	3	4
	Toe scour	High toe scour occurs	Moderate toe scour	Low levels of toe scour occur	3	2	3	3	3	3	3	1	1	1	1	3	5	1	2	1	3	2	1	1	5	3	3	4
	Design guidance available	None	Some	Complete	5	4	3	4	4	5	2	4	4	4	3	3	2	2	3	2	1	1	1	1	4	1	3	2
	Resilience to climate change	No adaptation - replacement required	Modification required	Provision for a specified level of climate change	3	2	2	3	2	3	3	1	1	1	1	2	2	1	1	1	1	1	2	2	4	4	5	4
	Construction complexity	Requires international contractor	Requires local contractor	Semi-skilled or unskilled local labour	3	3	3	2	2	3	2	3	2	3	3	4	2	4	4	4	5	4	3	4	3	5	2	5
	Construction plant required	Large and/or expensive plant required	Some construction plant required	No construction plant required	2	4	3	2	2	3	2	4	4	3	2	3	2	4	5	4	5	3	3	4	3	5	4	5
	Scalability	Highly site-specific	Site-specific modification required	Very generic	4	4	2	2	3	3	2	3	2	3	3	3	2	4	4	4	4	3	3	3	1	4	2	4
Social	**Use of local labor**	Local labour cannot be used	Some local labour	May be completed using local labour	2	3	3	2	2	4	2	3	3	3	2	2	3	4	4	4	5	3	3	4	2	5	3	5
	Beach access	Prohibits access	Access unchanged	Enhances access	3	4	4	2	4	4	2	2	1	2	1	4	3	2	3	2	2	1	1	1	5	2	4	2
	Aesthetic	Significantly differs from existing	Slightly differs from existing	In keeping with existing environment	3	3	3	2	3	3	2	1	1	3	1	3	3	2	3	3	3	1	1	1	5	2	5	2
	Cultural acceptability	Never used	Occasionally used	Widely used	4	3	3	2	3	3	3	2	2	2	1	3	3	3	3	3	4	1	1	1	5	4	5	4
Environmental	**Occupation of seabed**	Large occupation area (<3 x design wave height)	Moderate occupation area (1-2 x design wave height)	Small occupation area (less than 1 x design wave height)	1	2	1	1	2	2	1	4	4	5	5	3	1	3	3	4	4	4	4	4	1	4	1	1
	End effects	Enhances erosion of adjacent land	Neutral	Reduces erosion of adjacent land	3	3	3	3	3	3	3	1	1	2	1	3	4	2	2	2	3	2	2	2	5	3	3	4
	Effect on sediment budget	Depletes sediment budget	Neutral	Enhances sediment budget	2	2	2	3	3	3	3	2	2	2	2	4	4	2	2	2	2	3	2	2	4	5	5	4
	Effect on ecosystems	Significant adverse effect	Neutral	Significantly improves ecosystems	3	2	3	2	2	2	2	1	1	1	1	2	4	1	2	1	2	2	1	1	4	3	5	5
	Impact of construction activities	Significant and/or long-term adverse effects	Some and/or short-medium term effects	Negligible adverse impacts	4	3	4	4	4	4	4	4	4	3	2	4	4	2	2	2	2	2	3	2	4	4	4	5

Table 9: Summary of Technical Analysis Results

Engineering		
Best	**Worst**	
Rock revetment	Rubber tyres	Concrete pipes
Seabees	Filled drums	Biorock
Samoa Stone	Stacked coral	Grout-filled bags
Geotextile containers	Brush structures	Brush structures
Social		
Best	**Worst**	
Beach replenishment	Sheet pile walls	
Coastal planting	Rubber tyres	
Biorock coral augmentation	Filled drums	
Seabees	Concrete pipes	
Environmental		
Best	**Worst**	
Coastal planting	Mass concrete wall	
Biorock coral augmentation	Reinforced concrete	
Beach replenishment	Steel sheet pile	
Reef Balls	Filled drums/concrete pipes	

5 Cost analysis

5.1 Introduction

A range of technically viable options has been costed for comparative purposes. For this consideration, these options need to be immediately effective at protecting land; have design guidance available, sufficient for preliminary engineering design and costing purposes; and be moderately effective in protecting the backshore for the design life duration. Social and environmental considerations have been acknowledged in final recommendations, although these are not included in the cost analysis.

The methodology employed is to:

i. determine typical costs of materials used for the construction of coastal protection works;

ii. undertake generic designs and cost, assuming all materials are available locally;

iii. determine typical transport costs for a range of scenarios;

iv. determine costs of protection options, incorporating transport costs where necessary (some options include the use of local materials and, therefore, transport costs are not added in these cases);

v. convert to a cost/year based on typical—and well contracted—design life of the specific option;

vi. convert resultant costs/year to relative costs, compared to a locally produced rock revetment, so as to assess the most cost-efficient protection options for transport and wave-height scenarios.

5.2 Material costs

Typical materials required for the construction of these coastal protection works have been priced, assuming the project is of medium to large scale (>100 metres in length); most construction material is available locally and includes supply and placement on site; and includes all preliminary and general costs associated with site preparation (Table 10). Cost estimates are based on the following sources:

- Rawlinsons Construction Cost Handbook (2014)
- engineers' estimates and tendered prices for projects in Australia, Kiribati, New Zealand and Samoa.
- discussions with manufacturers, suppliers, contractors and estimators.

Table 10: Typical Costs of Local Materials Used for Coastal Protection Works

Material cost (supply and place)	Unit (cubic metres or number)	Local cost (A$)
Armour rock	m^3	150
Aggregate/underlayer	m^3	80
Sand	m^3	50
Mass concrete (standard 30 megapascals), including formwork	m^3	600
Reinforced concrete (marine grade, 50 megapascals), including reinforcing and formwork	m^3	1,000
Grout-filled sandbags	m^3	400
Concrete armour units—large units, random placement	m^3	1,000
Concrete armour units—small units, pattern placement	m^3	1,500
Geotextile—Bidim A64 or similar	m^3	12
2.5 m^3 GSC filled (beach sand) and placed	No.	1,000
0.75 m^3 GSC filled (beach sand) and placed	No.	400
Gabion basket (polyvinyl chloride (PVC) and zinc/aluminium-coated steel wire)	m^3	200

5.3 Coastal protection costs

Generic coastal protection options have been designed and costed for low (H_s=0.7 m), medium (H_s=1.5 m) and high (H_s=3 m) energy wave environments (Table 11). Wave period is assumed at 9 seconds, the seabed is assumed at 0 metre mean sea level, a toe depth is set at 1xHs below the sea bed and a crest elevation is set at the likely runup level, based on typical roughness factors (USACE, 2006). Options for value engineering exist in each case, including the use of wave return walls, backshore protection or accepting the risk of backshore damage and required repair. These have not been incorporated into the generic designs, as results are for comparative purposes only. Design life is based on a typical term of effectiveness (i.e. reported and observed) in the Pacific environment, with no or minimal maintenance.

Table 11: Indicative Cost for Coastal Protection Works, Assuming Local Materials[1] (AUD/linear metre)

Protection method	Details	Design life[2] (years)	A$/m for low wave energy ($H_s$ = 0.7 m)	Moderate wave energy (H_s = 1.5 m)	$/m for high wave energy (H_s = 3 m)
1. Rock revetment—high density	Assumes basalt or similar >2,600 kg/m^3	50	675	3,000	10,700
1b. Rock revetment—low density	Assumes limestone, coral or similar) ~ 2,200 kg/m^3	30	850	4,200	N/A[3]
2. Mass concrete	Assumes local aggregates are used	30	2,500	10,000	N/A
3. Reinforced concrete	High strength (50 MPa) marine-grade concrete	25	1,700	6,700	N/A
4. Grout-filled bag wall	Bags secured with a grout mix	5	950	N/A	N/A
5a. Geosynthetic container: 1 layer	Assumes 0.75 m^3 containers for low wave and 2.5 m^3 for moderate wave	10	1,900	3,900	N/A
5b. Geosynthetic container: 2 layer		20	3,350	7,100	N/A
6a. Seabees—Imported materials	Includes concrete cap and rock toe	25	1,200	3,300	12,500
7a. Tetrapods—Imported concrete	Includes rock toe	30	N/A	5,100	31,000
8. Grouted coral wall	Assumes 1:3 ratio concrete:coral block	10	900	N/A	N/A
9. Beach replenishment	Assumes 1:12 slope and 20% loss of material/year	5	1,000	4,200	17,500
10. Timber wall	Assumes piles driven and H6 marine grade timber	15	2,400	N/A	N/A
11. Gabion basket	Assumes local aggregates and PVC coated wire	7	650	N/A	N/A
12. Terrafix blocks	Assume T60 blocks	15	1,300	N/A	N/A
13. Small hand-placed bags	Assumes good quality polyester geotextile	2	350	N/A	N/A

[1] Costs are indicative for comparative purposes only and should not be used for project costing.
[2] Design life assumes typical term of effectiveness in a Pacific environment with no or minimal maintenance.
[3] N/A indicated method is not suitable for that wave climate.
Notes: m3 = cubic metre; kg = kilo; MPa = megapascal; PVC = polyvinyl chloride.

5.4 Transport costs

Transport is a major component of coastal protection costs at remote locations. Transport can occur by ***Road transport*** across land masses, although this is typically less than 50—100 kilometres (km) in Pacific island countries due to their small size. Road transport costs are typically in the order of A$0.50 to A$1.00/m^3/km; however, road conditions can be poor and travel times high. ***Scheduled container shipping*** runs between major ports. Shipping containers are typically capable of transporting 18-20 tonnes of material (i.e. up to 33 m^3 by volume). Shipping costs depend on the specific ports, although they generally range from A$3,000 to A$6,000 plus cartage to site.[9] Costs, such as taxes and duty, are additional. For transport to remote locations; locations without scheduled shipping; or transporting large shipments of bulk cargo, such as armour rock, ***chartered barges*** may be required or may be the most cost-effective option. Where no docking facilities are available at remote locations, barges with roll-on/roll-off capability are generally required, or cargo must be transferred to smaller local boats at significant time and high cost. For this report, it has been assumed that transport costs are up to A$0.30/m^3/km + A$100 per load/unload for a 1,000 tonne+ shipment.

The following transport scenarios have been considered:

Base: Material is produced locally and transported by road within 30 km. An example would be Suva, Fiji, where cement is produced locally and good quality volcanic aggregate is available.

Local transport: Local transport within 200 km is by road or barge, including one handling.
Assume a cost of A$150/m^3.

Primary port: Loaded at a primary port, the shipment is transported up to 3,000 km and then unloaded and transported locally to site. An example is South Tarawa, Kiribati. Based on typical freight costs, assume a cost of A$500/m^3, although this is likely to fluctuate, depending on location and local import taxes and duty.

Remote location: Shipment is loaded on to a barge at primary port, transported up to 2,000 km and then unloaded at wharf, jetty or directly onto land using a ramp. A mechanical plant is typically required to facilitate the offload. Assume a cost of A$1,000/m^3, based on typical barge hire rates.

Photo 21: Example of barge unloading gravel for replenishment at Tuvalu.
(Source: taiwanembassy.org)

5.5 Results

Results of the economic cost analysis are presented in Appendix B where the total cost/linear metre of coastal protection is presented for each protection option, transport scenario and wave condition. The annual cost of protection is also presented, factoring in a typical design life. Options not considered suitable for particular wave climates have been excluded from the analysis. Table 12, Table 13 and Table 14 present a summary of the relative annual cost proportional to a locally constructed rock revetment.

Results show that for small waves ($H_s < 0.7$ m), small hand-placed sandbags have the lowest initial capital cost (Appendix B), followed by rock—where available locally—and gabion baskets. Grout-filled bags and small hand-placed armour units, such as Seabees, are approximately 1.5 times the cost of rock. When transport costs rise, the overall cost of higher-volume approaches (e.g. rock revetments) will increase substantially. Rates of increase are less for lower-volume approaches (e.g. hand-placed armour units) or where only a compact, lightweight part of the structure requires transportation (e.g. geotextile containers, gabion baskets, grout-filled bags). Costs for replenishment do not increase if locally available materials are used, although some plant for transport and placement is required.

When design life is considered, the annual cost of protection can be assessed. This annualised value should be multiplied by the project length to give "whole of life" costs. Results show that relatively low-cost approaches (e.g. rock revetments where rock is available) with long design lives provide a low annual cost, while approaches with lower initial capital cost but shorter design life (e.g., sand-placed bags and grouted coral) are relatively expensive over a long time frame. This is because the same structure will require rebuilding multiple times or extensive maintenance. Given their long design life, rock revetments retain the lowest annual cost until transport costs become very high and other options (e.g. small concrete armour units, concrete walls with moderate design lives or gabion baskets with shorter lives) become more efficient, thus requiring ongoing maintenance and/or replacement.

Table 12: Relative Cost/Year for Low Wave Environment
(H_s = 0.7 metres)

Protection option	Design life (years)	Costs/year (proportion of local rock revetment)			
		Base	Local	Primary port	Remote location
1. Rock revetment: volcanic	50	1.0	2.1	4.6	8.2
1b. Rock revetment: limestone	30	2.1	2.8	4.3	6.6
2. Mass concrete: local concrete	30	6.1	6.5	7.4	8.7
3. Reinforced concrete	25	5.0	5.7	7.5	10.0
4. Grout-filled bag wall	5	13.9	15.3	18.4	22.8
5a. Geocontainer: single layer	10	13.9	14.5	15.9	17.9
5b. Geocontainer: double layer	20	12.4	13.0	14.1	15.8
6a. Seabees: imported materials	25	2.7	3.6	5.7	8.8
6b. Seabees: local materials	15	6.2	6.3	6.7	7.3
8. Grouted coral	10	6.6	6.9	7.7	8.7
9. Beach replenishment	5	14.8	14.8	14.8	14.8
10. Timber wall	15	11.9	13.6	17.8	23.7
11. Gabion basket	7	6.9	8.5	10.2	12.0
12. Terrafix blocks	15	6.5	7.3	9.1	11.8
13. Small hand-placed sandbags	2	12.7	13.7	16.0	19.4

For moderate wave conditions (H_s = 1.5 m), rock remains the lowest initial capital cost option, where available, with single layer Geosynthetics containers and single layer armour units also having a relatively low capital cost. In remote locations, Geosynthetics containers (geocontainers), single layer armour units using local materials and beach replenishments have significantly lower initial capital costs. Annualised costs show rock to be lowest, where locally available, although it is higher than concrete armour units when transport costs exceed from A\$300 m^3 to A\$500/m^3, and is higher than armour units and Geosynthetics containers in remote locations.

Table 13: Relative Cost/Year for Moderate Wave Environment

(H_s = 1.5m)

Protection option	Design life (years)	Costs/year (proportion of local rock revetment)			
		Base	Local	Primary Port	Remote location
1. Rock revetment: volcanic	50	1.0	2.1	4.7	8.4
1b. Rock revetment: limestone	15	2.3	3.0	4.6	6.9
2. Mass concrete: local concrete	20	5.9	6.3	7.1	8.4
3. Reinforced concrete	30	4.3	5.0	6.5	8.7
5a. Geocontainer: single layer	10	6.3	6.5	7.0	7.7
5b. Geocontainer: double layer	20	5.8	6.0	6.4	7.0
6a. Seabees: imported materials	30	2.2	2.9	4.4	6.6
6b. Seabees: local materials	15	5.1	5.2	5.5	5.9
7a. Tetrapods: imported materials	30	2.8	3.5	5.0	7.3
9. Beach replenishment	5	13.8	13.8	13.8	13.8

For larger wave heights, there are less viable coastal protection options—although a multitude of concrete armour units are feasible. However, the trends remain similar, with rock having the lowest initial capital and annual cost—where available—and single-layer armour units being more cost effective as transport costs increase.

Table 14: Relative Cost/Year for High Wave Environment

(H_s = 3m)

Protection option	Design life (years)	Costs/year (proportion of local rock revetment)			
		Base	Local	Primary port	Remote location
1. Rock revetment: volcanic	50	1.0	2.1	4.8	8.6
6a. Seabees: imported materials	30	2.3	2.9	4.3	6.3
7a. Tetrapods: mported materials	30	5.0	5.8	7.8	10.6
9. Beach replenishment	5	16.4	16.4	16.4	16.4

6 Conclusions and recommendations

6.1 Conclusions of technical analysis

Results of the technical analysis show that revetments constructed of conventional materials are the most effective at protecting land and have typically long design lives. They are moderately complex to design and construct with all materials, except Geosynthetics containers and Seabees, and depend on the construction methodology applied. They also require substantial construction plant. They are moderately resilient to climate change and can often be raised, although care needs to be taken that units are adequately designed for any increased wave climate and height. Social effects are typically average to poor without specific design consideration for access, although some methods (e.g. geotextile containers) do provide reasonable coastal access. Environmental impacts, likewise, are average to poor, as the natural system is interrupted by a fixed structure with a generally large occupation area.

Conventional vertical structures are also moderately effective at protecting land, although they dissipate less wave energy, are more vulnerable to toe scour and overtopping, and have limited resilience to climate change, as well as being difficult to raise or otherwise upgrade. They have poor social and environmental effects, restricting access to the shore, and may increase end-effect erosion through wave reflection. They do occupy a smaller area, however, than revetment structures.

Low cost solutions using local materials are typically simple and scalable, with good opportunities for local labour. However, they typically have short design lives and limited effectiveness at protecting land. They can have poor environmental effects and may release material (e.g. sandbags, rock, tyres) into the marine environment as they deteriorate and fail or if they are inadequately designed. Some potential opportunities were found to use commonly available materials, such as concrete Besser blocks in lower energy environments, and alternative placement configurations.

Ecosystem-based approaches, such as coastal planting and replenishment, tend to have the best environmental outcomes. However, beach replenishment is highly site-specific and dependent on an available supply of appropriate replenishment material. Furthermore, design life can be short if erosion is ongoing and replenishment material is rapidly lost. Protection of land is not guaranteed with high water levels often causing continuing erosion of the backshore, despite replenishment. Replenishment is often combined with harder "backstop" protection structures to improve effectiveness while maintaining environmental benefits. Coastal planting can be moderately beneficial in the long term as plants mature. This is especially so in its capacity to dissipate overtopping flows that occur on an infrequent basis, although it may be more limited in preventing erosion and ongoing loss of beach material that are subject to wave forces on a frequent basis. Furthermore, planting can restrict access and views of the coast for locals and tourists, thereby disconnecting people from the coast.

6.2 Conclusions of cost analysis

Results of the cost analysis are presented in Appendix B where total cost/linear metre of coastal protection is presented for each protection option, transport scenario and wave condition. The annual cost of protection is also presented by factoring in typical design lives. Options not considered suitable for particular wave climates have been excluded from the analysis. Table 12, Table 13 and Table 14 present a summary of the relative annual cost, proportional to a locally constructed rock revetment.

Conclusions are as follows:

- Hand-placed sandbags have the lowest initial capital cost, although they are limited in their design life and wave height. Alternative bag materials, however, may provide longer design lives and alternative placement configurations could improve stability under wave attack, making them more attractive options for temporary works and remote locations.

- Rock has the lowest annual cost where available, with higher density volcanic rock requiring smaller rock—and therefore lower seawall volumes at lower cost—than the lower-density limestone and coronus material.
- Where rock is unavailable and must be transported, the initial capital cost of rock revetments increases substantially, although the annual cost remains lower than many shorter design life "local" options.
- Low cost, "local" solutions often have low to moderate initial capital cost and do not increase substantially with remoteness, as most materials are available locally. However, short design lives (i.e. typically 2-10 years) substantially increase the annual cost and whole-of-life costs.
- Small hand-placed concrete armour units, such as Seabees, are typically two to three times more expensive than rock—where rock is available locally—although, being of lower volume, become more cost-efficient as transport costs increase. Furthermore, the larger the design wave height, the lower the transport cost where such units become cost effective.
- Large Geosynthetics containers are more expensive where rock is locally available; however, due to relatively low transport costs, they become less expensive in remote locations. This is comparable with single-layer armour units, although shorter design lives increase annual cost.
- Beach replenishment costs are highly dependent on material availability, which affects the capital cost, and ongoing material loss affects the design life. Where a low-cost supply of sand or gravel is available and ongoing, losses are not likely to be high. Control structures, however, may be used to extend the life. Such approaches may be cost effective compared to other methods, particularly in remote locations.

6.3 Regional analysis of material availability

Selection of the most appropriate coastal protection method is highly dependent on the local availability of material. The geology of Pacific islands comprises a mixture of dense volcanic rock and less dense coral and coronus (uplifted coral) rocks. Gray (2015) has reviewed aggregate availability in Pacific island countries (Table 2) and found that most countries include volcanic and coronus materials; Kiribati, the Republic of the Marshall Islands and Tuvalu, however, only have corals available. Where volcanic materials are present and available for use, rock revetments are likely to be the most technically robust and cost-efficient solution, whereas on islands without such rock —including some within countries with volcanic material—other protection materials are potentially more efficient.

6.4 Recommendations

Based on the findings of this study, the following recommendations are made:

1. Avoid or retreat from hazardous coastline areas to ensure a more robust, long-term solution compared to shoreline armouring, although this may not be socially, economically or politically feasible.
2. Maintain and improve local sediment budgets to potentially reduce the impact of coastal erosion, thus reducing the need for and reliance on coastal protection structures.
3. Determine whether coastal planting of appropriate plant species can assist in reducing overtopping flows and wind-blown transport.
4. Consider conventional structures and lower-cost local approaches where coastal protection structures are required. Technical, environmental and social factors also should be taken into account. The financial assessment should include material availability and transport costs, which may vary substantially based on location.
5. Improve local approaches through the use of alternative materials, as well as design and construction methodologies in an effort to increase the design life and improve hydraulic performance. Examples include:
    a. higher quality ultraviolet, stabilised polyester geotextile bags rather than the low-cost woven polypropylene bags that are in use;
    b. alternative bag placement and bonding patterns to improve hydraulic performance, which would require additional hydraulic testing to extend guidelines;

   c. pre-cast blocks rather than bags in grouted seawalls to improve the unit material quality and the bond between units;

   d. more durable and robust gabion basket materials, subject to cost and affirmation of design life by manufacturers;

   e. extension of structure toe to a firm substrate or below expected scour depth to prevent undermining and toe failure;

   f. suitable geotextile behind structures to retain backshore soils, including in the event of the partial failure of a rigid structure; and

   g. extension of structures to sufficiently high levels to prevent frequent overtopping occurrences, or placement of stabilising materials, such as natural vegetation or armouring, within the overtopping zone.

6. Compare the manufacture of single-layer concrete armour units (e.g. Seabees) at a central location, as well as the transportation feasibility to the site, against local manufacture. The cost to produce, transport and place, as well as structure integrity and design life, should be compared for the two options, followed by a recommendation.

7. Undertake an assessment of commonly available materials for low-energy environments, such as concrete masonry (Besser) blocks, using alternative placement configurations..

8. Undertake hydraulic model testing of two coastal protection options to enable development of design guidance

   a. geosynthetic containers
      - Test alternative placement and bonding orientations of geosynthetic containers to extend current design guidance. Given the viable application of geosynthetic containers in remote locations where transport costs dominate, increasing the tolerable wave climate, particularly for smaller, hand-placed units (i.e. with good high-quality geotextile), would substantially improve their use. Current placement orientation is with the long bag axis along the coastline due to easier construction and precedent. Alternative bag orientations (e.g. long axis offshore and/or alternating courses) are likely to have increased stability, but this has not yet been quantified.

   b. concrete masonry block revetment
      - Testing of a revetment constructed using innovative placement of commonly available concrete masonry or Besser blocks. Testing should be undertaken to determine threshold wave conditions (i.e. height and period) for hand-placed concrete blocks, using a range of placement configurations and revetment slopes.

9. Produce a guidance document including:

   a. guidance on assessing design conditions;

   b. guidance on comparing options for shoreline protection, including non-structural options and selection of the most appropriate, to include:
      - design conditions
      - required design life
      - availability of materials, construction plant and local expertise
      - transport costs

   c. Concept-level designs and drawings of:
      - coastal planting
      - rock revetments
      - single layer, hand placed armour units, such as Seabees, or concrete blocks (i.e. depending on model testing results)
      - geotextile containers
      - beach replenishment
      - applicability for a range of wave height conditions.

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Endnotes

1 See Officine Maccaferri Group (www.maccaferri.com/officine-maccaferri-group-launches-pa6-new-environmentally-friendly-polymer-coating-wire-products), accessed 10 February 2016.

2 See Officine Maccaferri S.p.A. (www.maccaferri.com/products/gabion-welded), accessed 10 February 2016.

3 See Permathene Pty. Ltd. (Permethane Pty. Ltd. www.permathene.com.au/gabion-stainless.html), accessed 10 February 2016.

4 See Tensar (www.tensarcorp.com/Systems-and-Products/Triton-Systems/Triton-Gabions-and-Triton-Gabion-Mats#), accessed 10 February 2016.

5 See Geofabrics Australasia (www.geofabrics.com.au), accessed 10 February 2016.

6 See also Trellis Horticulture International (www.trellishorticulture.com/soil-conservation.php), accessed 10 February 2016.

7 See (i) Aussie Erosion (www.aussieerosion.com.au/product/products/erosion-control-blankets/coir-mesh-700gsm); (ii) Coirgreen (http://coirgreen.com); and (iii) GEI Works (http://www.erosionpollution.com/Coir.html), all accessed on 10 February 2016.

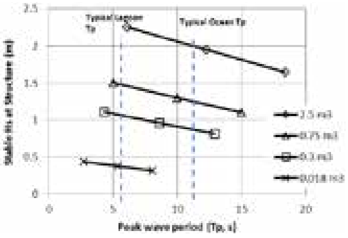
8 See also Aussie Erosion (https://aussieerosion.com.au/product/coir-mesh-700gsm).

9 From personal communications with Go Logistics NZ Ltd. in December 2015.

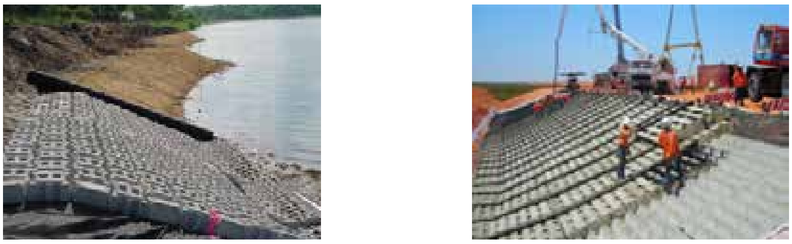
Appendix A Catalogue of Existing Approaches

Rock revetment	
Description	Rock revetments are conventional land protection structures that have been used extensively internationally. A rock revetment is formed using a geotextile filter fabric placed on a formed backshope slope, overlain by a cushioning layer of small rock and protected from wave energy by suitably large rock armour. The high porosity provided by the voids between the rock, together with the slope, provide a form of wave energy dissipation reducing both the reflected wave and wave overtopping. Rock armour slopes typically range from 1.5(H):1(V) to 4(H):1(V) with lower slopes requiring more construction material but enabling the use of smaller rock and resulting in less overtopping. The revetment should be extended sufficiently deep that the toe is not undermined by scour or erosion and sufficiently high to reduce overtopping to tolerable volumes. Rock density makes a large difference in required size with lighter rocks such as limestone (coral) requiring much larger sizes for similar wave height.  Rock revetment at Matatufu, Samoa  Rock revetment at South Tarawa, Kiribati
Materials required	▪ High quality, non-woven geotextile fabric. ▪ Rock of suitable density, quality and size (dependent on wave climate).
Locations used	Used widely internationally and throughout Pacific where suitable volcanic rock occurs (i.e. Samoa, Fiji, Cook Islands, etc) and in some locations where rock has been imported (i.e. South Tarawa, Kiribati)
Information sources	USP (2015), Tonkin & Taylor (2013), WRL (2012), CIRIA (2007), USACE (2006)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Suitable for Hs<1m to 4+ m where suitable rock size is available	5
	Design life	50+ years (Basalt or similar), 5-20 years (Coral/limestone or similar less durable materials)	5
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	High where suitably designed and constructed	5
	Effect on overtopping	Rocks dissipative with roughness 0.5-0.6. Typically reduces wave runup to <2.Hs	4
	Toe scour	Some but rock moderately effective in dissipating wave energy	3
	Design guidance available	Detailed guidance based on physical model testing and field examples available for design	5
	Resilience to climate change	Modification may be required where crest too low but relatively straightforward. Rock should be adequately sized to allow for larger waves otherwise modification is difficult.	3
	Construction complexity	Moderate level of expertise required for construction	3
	Construction plant required	Moderate to large plant required to obtain, transport and place rock (dependent on rock size)	2
	Scalability	Adjust rock size, toe depth and crest for specific site conditions	4
Social	**Use of local labour**	Minimal local labour used	2
	Beach access	Access over rock possible but difficult. Can install stairs or special rock placement. Access for boats via concrete ramp	3
	Aesthetic	Varies. Typically neutral on volcanic islands where rock available	3
	Cultural acceptability	Varies but widely used on volcanic islands	4
Environmental	**End effects**	Some but rock moderately effective in dissipating wave energy	3
	Effect on sediment budget	Reduces supply derived from land erosion (behind wall)	2
	Effect on ecosystems	Can restrict ecological connectivity between land and lagoon but can also provide additional habitat within rock voids	3
	Impact of construction activities	Generally short-term including sediment plumes during construction	4

Geotextile containers ("Geobags")	
Description	Geotextile containers are commonly referred to as "geobags". They comprise a geotextile pillow filled with sand. Their use in Australia has been documented in Coghlan et al (2009), Hornsey et al (2011) and Carley et al (2011). They have been widely used throughout the world. Commonly available sizes in Australia are 2.5 m^3, 0.75 m^3 and 0.3 m^3, although smaller 0.02 m^3 (30-40kg) bags are also available The only practical impediments to alternative sizes are efficient use of standard geotextile rolls, availability of filling frames and the fabric strength for larger sizes. Empty containers are light and can be transported readily, however, the cost of high quality geotextile makes the system comparable in cost to rock structures when suitable rock is available in close proximity to a site. Durability for high quality geotextiles exposed to the elements is typically 10 to 20 years, however, this can be reduced due to debris damage or vandalism. The modular nature of these structures is such that they will remain structurally coherent when up to 2% of individual containers are damaged or removed, especially if a double layer is used. For 10 second spectral peak wave periods, 2.5 m^3 containers can withstand significant waves of approximately 1.7 m, while 0.75 m^3 containers can withstand significant waves of approximately 1.3 m. Smaller 0.35m^3 bags are suitable for up to 1m waves and 0.02 m^3 for 0.5m waves. Geotextile tubes are prefabricated tubes constructed from geotextile and are colloquially referred to as "geotubes". They have been widely used throughout the world. They are filled hydraulically in situ with a slurry pump. There are similarities with geotextile containers, but they can substantially reduce the quantity of geotextile required.Their potential larger size can provide increased stability, but the low number of individual components means that damage can lead to catastrophic failure and is difficult to repair.  2.5m3 Elcorock® revetment (James Carley, WRL UNSW)  Rescaled model results for 2 layer geocontainer stability at 1(V):1.5(H) slope (source: T&T, 2014)
Materials required	Geotextile containers, Sand, Filling frame and slurry pump (for larger bags or tubes)
Locations used	Australia and widely throughout the world including recently at Funafuti, Tuvalu
Information sources	Coghlan et al (2009), Hornsey et al (2011) and Carley et al (2011).

Criteria		Comment	Rating
Engineering	**Design wave conditions**	From 0.5 to 2m Hs	3
	Design life	15 to 20 years, likely shorter for single layer revetments	3
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Some failures observed requiring repair	4
	Effect on overtopping	Relatively little dissipation. High crest or Backshore protection required	2
	Toe scour	Relatively reflective exacerbating scour. Toe scour bag utilised	2
	Design guidance available	Yes	4
	Resilience to climate change	Bags should be oversized to accommodate	2
	Construction complexity	Relatively simple	3
	Construction plant required	None for smallest bags, small to medium earthmoving plant for 0.3 to 2.5m^3. Specialised filling frames and slurry pumps can be used as well as or instead of mechanical plant.	4
	Scalability	Adjust bag size, toe depth and crest for specific site conditions	4
Social	**Use of local labour**	Depends on size and filling technique	3
	Beach access	Yes, access over the top	4
	Aesthetic	Differs from natural environment but often accepted	3
	Cultural acceptability	Varies	3
Environmental	**End effects**	Some likely, bags relatively reflective	2
	Effect on sediment budget	Can deplete if beach sand is used to fill bags	2
	Effect on ecosystems	Can restrict ecological connectivity between land and sea	2
	Impact of construction activities	Generally short-term but bags can remain on beach when broken	3

Articulating concrete blocks/mats	
Description	Matrix of individual concrete blocks placed to form and erosion resistant overlay. Blocks may be restrained by interlocking of individual units, cables, ropes, geotextiles or geogrids. Smaller interlocking blocks may be hand placed and secured otherwise plant equipment is required. Many different systems are available, including: Flexmat– Precast on a permeable geotextile matting with a dense pattern of stiff synthetic loops. During casting and vibration the loops penetrate the fluidized base of the blocks. Armorflex – interlocking concrete blocks linked longitudinally by galvanised wire cables or polyester rope. Smaller blocks may be hand placed. Terrafix - interlocking concrete blocks that can be cabled together. Articulated Concrete Block Mattress (Maccaferri) – Rectangular unit of concrete blocks joined by polypropylene ropes.  Articulated concrete blocks (left – source: www.conteches.com, right - source www.flexmat.com.au)
Materials required	Precast concrete units, connections (cables or ropes) and geotextile or pre-assembled mats
Locations used	Typically US, Australia
Information sources	National Concrete Masonry Association (2014), MARECON (n.d.).

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Maximum wave height of 1-1.4m for Flexmat depending on slope and wave period (MARECON)	2
	Design life	Up to 20 years	3
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Effective at reducing erosion	4
	Effect on overtopping	Dissipates some wave energy	3
	Toe scour	Some	3
	Design guidance available	Limited	3
	Resilience to climate change	Low	2
	Construction complexity	Moderately complex	3
	Construction plant required	Some unless smaller, hand-assembled mats used	3
	Scalability	Some site specific modification	3
Social	**Use of local labour**	Some	3
	Beach access	Yes	4
	Aesthetic	Varies	3
	Cultural acceptability	Varies	3
Environmental	**End effects**	Neutral	3
	Effect on sediment budget	Reduces supply derived from land behind wall	2
	Effect on ecosystems	Partially blocks connectivity	3
	Impact of construction activities	Minimal	4

Tetrapod armour units

Description	Concrete armour units are cast in steel moulds and may be placed in a single layer where they are generally pattern placed to ensure interlocking, or in a double layer where they are placed randomly. Armour units overlie smaller underlayer rock and a geotextile similar to rock revetments. Units may be slender such as Dolos or Tribars, bulky such as Core-loc® and tetrapod or massive such as concrete cubes. While slender units often offer improved interlocking and energy dissipation, they can be vulnerable to breakage over time. Some units are also patented, requiring design and construction input from the patent-holder and payment of royalties. Overall, single-layer units generally require less total concrete volume but units need to be of high quality and accurately placed to ensure success as breakage or displacement of a single unit may result in complete failure of the structure. Double layer structures are generally more robust as they contain some redundancy in case of unit breakage or dislodgement but required more total material volume. Armour units require high strength concrete (generally >35 MPa at 28 days), although this is most critical for single layer and slender units. Tetrapods units have been used throughout the Pacific, although their use is generally restricted to protection of high value assets such as ports from large waves. Units typically only become economic for large (2m+) waves where rock is not available or undersized.  2T Tetrapod unit cast in Kiribati (source: I-Kiribati, 2013)  Tetrapods at Betio, Kiribati (BECA, 2010)
Materials required	Steel moulds, cement, aggregate, water, rock underlayer, geotextile
Locations used	Japan, Kiribati, Vanuatu
Information sources	USACE (2006)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Medium to large waves – inefficient for small waves	3
	Design life	20+ years with good quality concrete	4
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Highly effective	5
	Effect on overtopping	Highly dissipative (Runup < 1.5Hs)	5
	Toe scour	Some but moderately effective in dissipating wave energy	3
	Design guidance available	Some	4
	Resilience to climate change	Design to tolerate larger waves and sea levels	3
	Construction complexity	Complex formwork	2
	Construction plant required	Large plant typically required to place large units	2
	Scalability	Detailed design required for each project	2
Social	**Use of local labour**	No	2
	Beach access	Difficult	2
	Aesthetic	Significantly different from existing	2
	Cultural acceptability	Less acceptable than rock	2
Environmental	**End effects**	Some but rock moderately effective in dissipating wave energy	3
	Effect on sediment budget	Reduces supply derived from land erosion (behind wall)	3
	Effect on ecosystems	Can restrict ecological connectivity between land and lagoon but provides some habitat in voids	2
	Impact of construction activities	Generally short-term including sediment plumes during construction	4

Samoa Stone	
Description	Samoa Stone is a single layer, interlocking concrete armor unit developed in in Samoa in 2001 by the U.S. Army Corps of Engineers. The units are placed to interlock, forming a continuous but flexible single layer. The units were developed to minimise material by using a single layer, be flexible to allow movement without failure, to include voids for wave energy dissipation while maintaining relatively easy and safe public access over the units (this is often difficult with randomly placed similar units), to have structurally robust geometry of individual units to avoid structural failure and allow use of standard unreinforced concrete. No royalties are payable on Samoa Stone units outside of the US.  Example of Samoa stone revetment used in American Samoa (source: Melby, per comm 2013)
Materials required	Steel moulds, cement, aggregate, water, rock underlayer, geotextile
Locations used	American Samoa.
Information sources	Turk and Melby (2004), Melby and Turk (2001).

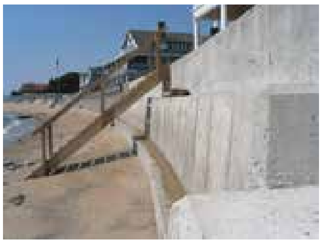
Criteria		Comment	Rating
Engineering	**Design wave conditions**	Hs = 1 to 5 m	4
	Design life	20+ years with good quality concrete	4
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	High effectiveness reported	5
	Effect on overtopping	Good dissipation characteristics (runup < 2Hs)	4
	Toe scour	Scour may occur and requires protection to prevent damage to structure	3
	Design guidance available	Yes	4
	Resilience to climate change		2
	Construction complexity	Casting of the units and placement relatively difficult	2
	Construction plant required	Moderate plant required to place units	2
	Scalability	Site-specific design required	2
Social	**Use of local labour**	No	2
	Beach access	Relatively easy	4
	Aesthetic	Differs from existing but relatively attractive	3
	Cultural acceptability	Varies	3
Environmental	**End effects**	Some but rock moderately effective in dissipating wave energy	3
	Effect on sediment budget	Reduces supply derived from land erosion (behind wall)	3
	Effect on ecosystems	Partially blocks connectivity	2
	Impact of construction activities	Generally short-term including sediment plumes during construction	4

Seabees	
Description	Seebees are pattern-placed hexagonal interlocking units. Once interlocked, the units act as a blanket with a high structural integrity to mass ratio compared to random placed concrete armour units. Layer thickness dictates stability and therefore the size (width) of units can vary dependent on specific site requirements (place by hand or machinery). While run up for this type of blanket structure is typically higher than for rock, run up can be reduced by using a 'paired upstand' design whereby every third unit is elevated increasing roughness characteristics. The toe and ends of such blanket walls also requires consideration as scour of the toe or outflanking of the ends may unravel the entire revetment. Seebees have been successfully used in high energy environments (Hs > 3m) in Australia, Argentina, Kuwait and the UK with units of over 4000 kg produced. The earliest walls were constructed in 1978 (initially ceramic units) with concrete units first used in 1982 at Abbot Point, Australia. These walls apparently remain in good repair. With units constructed of 35 MPa concrete, adequate toe and crest detailing and wall ends protected from outflanking, such revetments should have design lives of 30 years+. Bettington et al (2013) reports that advantages to Seabees in a Pacific context is that small units can be manufactured to be hand placed and that they are seen as visually pleasing by communities and allow foreshore access.  Seabee seawall Boigu, Torres Strait (Source: Bettington et al. (2013))  Seabee Structure, Cronulla
Materials required	Cement, supply of aggregates, moulds and, depending on the size of the seabees, plant equiment for placing (if too large to be hand placed).
Locations used	Australia, Torres Strait Islands
Information sources	Bettington et al. (2013), WRL (1997), Chris Brown pers comm 2013-2015

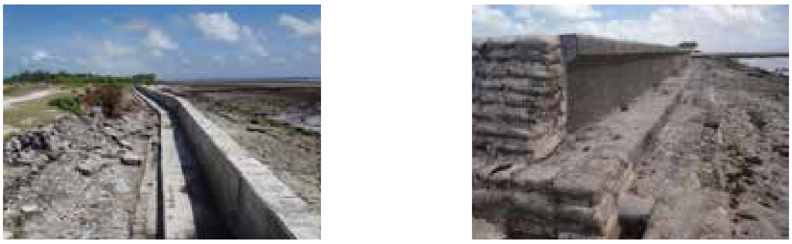
Criteria		Comment	Rating
Engineering	**Design wave conditions**	<1m to 4m Hs (WRL, 1997)	5
	Design life	20+ years with good quality concrete	4
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Very effective	5
	Effect on overtopping	Moderate, can be improved with upstand unit	3
	Toe scour	Scour may occur and requires protection to prevent damage to structure	3
	Design guidance available	Yes (WRL, 1997)	5
	Resilience to climate change	Not directly but size units to withstand larger waves and can add additional units at crest	3
	Construction complexity	Moulds are relatively simple but some dewatering may be required at toe dependent on depth	3
	Construction plant required	Required for concrete batching and placement if units are too large to be hand placed and for dewatering dependent on toe depth.	3
	Scalability	Site-specific design required	3
Social	**Use of local labour**	Yes if hand-placed units	4
	Beach access	Relatively easy	4
	Aesthetic	Differs from existing but reportedly seen as relatively attractive	4
	Cultural acceptability	Varies	3
Environmental	**End effects**	Some and vulnerable to outflanking without rock to dissipate wave energy	3
	Effect on sediment budget	Reduces supply derived from land erosion (behind wall)	3
	Effect on ecosystems	Partially blocks connectivity	2
	Impact of construction activities	Generally short-term including sediment plumes during construction	4

COPED (Coastal Protection and Environmental Development) units	
Description	COPED units are coreless precast concrete units invented and developed in the Cook Islands by Mr Don Dorrell. They can be used in a number of configurations to form offshore breakwaters, and sloping and vertical seawalls. The Rarotonga COPED breakwater has survived numerous tropical cyclones since construction. Physical modelling showed a 60-90% reduction in wave heights in the vicinity of beachfront buildings.  COPED offshore breakwater, Rarotonga, Cook Islands (Source: Left - WRL, 2006, right - Carley , Mariani and Dorrell, 2007).
Materials required	Precast concrete units. Plant and equipment for construction.
Locations used	Rarotonga, Cook Islands.
Information sources	Walker, Dorrell, and Cox (2001), SOPAC (1999), Carley , Mariani and Dorrell (2007)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Moderate, upper limit of components not yet known	3
	Design life	30+ years with good quality concrete	4
	Time period to become effective	Immediate protection. Sand build up and marine growth take time	5
	Effectiveness at protecting land	Porous nature means additional land protection may be required	3
	Effect on overtopping	Dissipation through structure reduces waves at shore	3
	Toe scour	Generally placed on reef or bedrock	3
	Design guidance available	Some, including physical modelling. Capacity of components not known	2
	Resilience to climate change	Adjustments can be made to crest height	3
	Construction complexity	Casting and placement are complex	2
	Construction plant required	Yes, for batching and casting and for placement. May also be require for excavation or reef or bedrock	2
	Scalability	Scalable but upper limits not yet known. Also requires hard substrate	2
Social	**Use of local labour**	Some	2
	Beach access	Minimal change when located offshore	2
	Aesthetic	Variable	2
	Cultural acceptability	Variable	3
Environmental	**End effects**	Neutral except for salient formation	3
	Effect on sediment budget	A salient may form in the lee	3
	Effect on ecosystems	Provides habitat	2
	Impact of construction activities	May need to be cut into reef platform	4

Mass concrete wall	
Description	Retaining wall reliant on the mass of concrete to provide stability against sliding or overturning. Concrete is either poured in-situ or mass concrete blocks are placed. Walls may be vertical, sloped or stepped with typically large concrete volumes required. Concrete walls tend to have poor dissipative characteristics with toe scour and high overtopping often. Walls must be founded on a stable base to ensure they do not fail by toe scour and are better suited to environments with hard, stable substrate.  Example of vertical seawall at Lake Erie (ohiodnr.gov)  Example stepped seawall (Coastline consulting LLC)
Materials required	Formwork, cement, aggregate, water
Locations used	Worldwide and throughout the Pacific, particularly during WWII
Information sources	USACE (2006)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Up to 3m+ but crest height becomes very high and structure very large	4
	Design life	20-30 years with good quality concrete, reduced for poor concrete	4
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Effective unless failure occurs due to undermining or end effects where failure will be rapid	4
	Effect on overtopping	Poor particularly vertical structures	1
	Toe scour	Increases scour and vulnerable to undermining	1
	Design guidance available	Guidance available for retaining wall structures	4
	Resilience to climate change	Low	1
	Construction complexity	Relatively simple but formwork and care with concrete mix required	3
	Construction plant required	Some plant required for concrete batching	4
	Scalability	Hard substrate generally required	2
Social	**Use of local labour**	Some	3
	Beach access	Difficult for vertical wall but stairs can be installed or stepped structure used	2
	Aesthetic	Poor aesthetic qualities	1
	Cultural acceptability	Not generally acceptable	2
Environmental	**End effects**	Increases reflection	1
	Effect on sediment budget	Reduces supply derived from land behind wall	2
	Effect on ecosystems	Adverse, blocks ecological connectivity	1
	Impact of construction activities	Some plumes during construction unless silt fencing used	4

Reinforced concrete wall	
Description	Vertical reinforced concrete seawalls are often used to provide backshore protection in areas where rock is not available, horizontal space is limited or a clean coastal edge is required. They do not include any wave dissipation characteristics resulting in significant wave reflection and run-up. This may negatively affect the adjacent coastline as reflected wave energy is transmitted alongshore or they may cause high wave overtopping rates as waves are deflected upward. The use of a wave return walls as shown below in Kiribati helps to reduce overtopping by deflecting the wave offshore. This type of wall is more suited to hard rock coastline or large, deep foundation must be used. The structure crest level needs to be sufficiently high to minimise overtopping flows during design conditions to levels not likely to cause damage to backshore land or protection should be used. Care must be taken that the concrete aggregates and water do not contain salt. Any salts present in in unwashed coral aggregates destroy the passivity of embedded steel and lead to corrosion. Higher strength concrete (50Mpa) is generally used for marine grade reinforced concrete structures, although increased cover can provide improved protection.  Reinforced concrete seawall at Temaiku, Kiribati
Materials required	Formwork, reinforcing material (steel, fibres), cement, aggregate, water
Locations used	Worldwide, Fiji, Kiribati, RMI,
Information sources	USACE (2006), BECA (2010)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	0 to 2m but crest height becomes high	3
	Design life	20+ years with good quality concrete	4
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Effective unless failure occurs due to undermining	4
	Effect on overtopping	Poor unless return wall used. High crest generally required	1
	Toe scour	Increases and vulnerable to undermining. Better on hard substrate	1
	Design guidance available	Yes	4
	Resilience to climate change	Low, difficult to raise to accommodate greater overtopping	2
	Construction complexity	Complex	2
	Construction plant required	Required for concrete batching	4
	Scalability	Hard substrate generally required	2
Social	**Use of local labour**	Some	3
	Beach access	Difficult unless stairs case	1
	Aesthetic	Poor	1
	Cultural acceptability	Not generally acceptable	2
Environmental	**End effects**	Increased and vulnerable to outflanking	1
	Effect on sediment budget	Reduces supply derived from land behind wall	2
	Effect on ecosystems	Adverse	1
	Impact of construction activities	No unless the structure fails	4

Timber pile retaining wall

Description	Timber retaining walls are comparised of planks or logs attached to driven timber piles. Sizing is dependent on the retained height with piles generally embedded twice the retained height. This should be backed by geotextile filter cloth or a stone filter to prevent loss of fines from within the sturcutre. Vertical timber structures are highly reflective and prone to toe scour so riprap toe protection should be provided or cross planks extend sufficiently deep.. Timber should be specially treated for marine construction (H6 or equivalent) to protect against biological attack.  Timber pile retaining wall in New Zealand being undermined and outflanked (source: Shand, 2014)
Materials required	Timber piles, timber walers, geotextile or rock filter, bolts, toe armour if required
Locations used	Worldwide
Information sources	USACE (1981)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	2
	Design life	Depends on treatment. Should be 20+ years when high standard	3
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Generally good when adequately designed	3
	Effect on overtopping	Poor	1
	Toe scour	Increased	1
	Design guidance available	Yes	4
	Resilience to climate change	Low	1
	Construction complexity	Local contractor generally capable	3
	Construction plant required	Pile driving equipment for the timber piles	3
	Scalability	Some site specific modification	3
Social	**Use of local labour**	Some	3
	Beach access	Difficult unless stairs constructed	2
	Aesthetic	Varies	3
	Cultural acceptability	Varies	3
Environmental	**End effects**	Yes as structure is reflective	2
	Effect on sediment budget	Reduces supply derived from land behind wall	2
	Effect on ecosystems	Adverse as ecological connectivity blocked	1
	Impact of construction activities	Nosie and vibration from pile driving	3

Sheetpiles	
Description	Sheet piles are either driven to a suitable depth to act as a cantilever or anchoring is required. Sheetpiles may be steel, aluminium, wood or plastic. Steel can be driven into hard dense soil or soft rock whereas aluminium and high density plastic can be used in softer soils. Car must be taken when driving the the piles interlock to prevent loss of fine materials. Extremely reflective and exhibit similar high overtopping and toe scour as vertical concrete and timber walls. Typically used in low wave environments and toe protection may be required.  Aluminium sheet pile wall (USACE 1981)  Vinyl sheet pile wall with toe protection (everlastseawalls)
Materials required	Sheet piles (Steel, aluminium, plastic), rock toe armour
Locations used	Worldwide
Information sources	USACE (1981), Everlastseawalls.com

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	2
	Design life	Depends on treatment. Should be 20+ years when high standard	3
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Generally good when adequately designed and constructed	3
	Effect on overtopping	Poor	1
	Toe scour	Increased	1
	Design guidance available	Some	3
	Resilience to climate change	Low	1
	Construction complexity	Moderate	3
	Construction plant required	Pile driving equiptment	2
	Scalability	Some site specific modification	3
Social	**Use of local labour**	No	2
	Beach access	Difficult	1
	Aesthetic	Significant difference	1
	Cultural acceptability	Not usually accepted	1
Environmental	**End effects**	Increased	1
	Effect on sediment budget	Reduces supply derived from land behind wall	2
	Effect on ecosystems	Adverse	1
	Impact of construction activities	Noise and vibration from pile driving	2

Sandsaver

Description	Polyeythylene module with tapered holes, allowing the wave carrying sand to pass through then trapping the sand behind the module. Units weigh 5000 pounds each per the manufactures website (unclear on whether or not these are filled with concrete). Evolution of the Sandgrabber, a system of light weight cinder blocks in the 1970s and what appear to be larger precast concrete blocks in the 1990s. (1) Installed in Hawaii in 1977. Showed noticeable build up of sand when the wave attack was perpendicular to the structure, otherwise some erosion occurred. (2) Installed in 1994 for 11 months in Grand Isle, Louisiana, USA. Accretion of sand behind the structure was occurred within 1-2 months, along with significant settlement and displacement of the units at both ends. Removed 2 months after a severe storm due to damage. Sand was noticed to still be accreting behind and in front of the structure.(3) Sandgrabber installed at Lake Michigan for 2 years, from April 2011 to April 2013. Accretion was observed along the beach, however was higher where the sandgrabber modules were located (4). Note: All literature and reports are all from the manufacturers website.  *Source: http://www.grangerplastics.com/*
Materials required	Pre-cast modules and plant equipment for placing.
Locations used	Hawaii, USA 1997. Grand Isle, Louisiana, USA 1994.
Information sources	Schultz Land and Water Consulting Inc. (2013), Underwood, S. and Long, A. (1995), Wilson, Okamoto and Associates. (1978).

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	1
	Design life	5-15+ years with good construction	3
	Time period to become effective	Weeks to months	3
	Effectiveness at protecting land	Minimally effective under storm conditions	2
	Effect on overtopping	Doesn't prevent overtopping	1
	Toe scour	Partially reflective	4
	Design guidance available	Some guidance from manufacturer	3
	Resilience to climate change	Low	2
	Construction complexity	Relatively simple	4
	Construction plant required	Required for placement	3
	Scalability	Design fairly generic	2
Social	**Use of local labour**	No	2
	Beach access	Access possible across structures but reduces boat access	4
	Aesthetic	Neutral	3
	Cultural acceptability	Varies	3
Environmental	**End effects**	Neutral	3
	Effect on sediment budget	Reported to trap sand improving locally	4
	Effect on ecosystems	Reduces ecological connectivity	2
	Impact of construction activities	Minimal	4

Reef Ball (Artificial reef)	
Description	Artificial reef modules constructed from concrete mixed with microsilica to match the pH of seawater. Effective in water < 2m deep. Have been implemented as submerged breakwaters in some projects, however, the primary purpose it to provide habitat. Was observed to reduce wave heights in normal conditions when in ~2m or less water depth. Beaches in lee were observed to accrete. Dominican Replublic structure remained stable through 1998 hurricanes, however, storm surge and wave heights were greater than could be attenuated by the breakwater.  ReefBall Breakwater, Antigua (Source: http://www.reefballaustralia.com.au)  Texas, USA (Source: http://reefinnovations.com)
Materials required	Precast units. Smaller reef balls weigh 120-150kg, however the larger reef balls weigh from 0.75-40+ tonnes and would require machinery to move and place
Locations used	Various (as breakwaters) including the Dominican Republic and Grand Cayman
Information sources	Fabian, Beck & Potts (n.d.), ReefBall Australia (2011)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Moderate waves. More wave transmission at high water levels	3
	Design life	Medium to long term (concrete)	3
	Time period to become effective	Likely to be years for sand accretion and marine growth	2
	Effectiveness at protecting land	Fully or partially submerged primarily for habitat	2
	Effect on overtopping	Fully or partially submerged offshore, so may reduce wave height at shore	3
	Toe scour	Dissipative structure	5
	Design guidance available	Some, though less protection offered with higher water levels	2
	Resilience to climate change	Less effective with increased sea level	2
	Construction complexity	Complex to manufacture	2
	Construction plant required	Yes. Reef balls are deployed using floating plant (boats, barges, cranes)	2
	Scalability	Can add additional units and alter size, but limit is wave transmission	2
Social	**Use of local labour**	Some	3
	Beach access	Unchanged	3
	Aesthetic	Varies	3
	Cultural acceptability	Varies	3
Environmental	**End effects**	Minimal impact except for salient formation	4
	Effect on sediment budget	A salient may form in lee	4
	Effect on ecosystems	Provides habitat	4
	Impact of construction activities	Minimal	4

Grouted-filled sand bag wall

Description	Low strength woven plastic or hessian bags filled with sand and cement mortar (mixed on beach) and stacked with mortar mix between bags. Some walls included double bag layer, deeper toe, geotextile behind and higher upstand wall at crest. Bags are stacked with their long axis parallel to the shore and joint offsets like brick work and may be stabilised by steel rods driven through the bags. Advantages are the ease of construction and moderate cost. Disadvantages are that they are only suitable for low energy environments and have a relatively short life compared to over revetments. Toe protection should be provided or the toe should be buried. Performance varies depending on design and construction technique. Early walls prone to bags slumping and bursting during construction, rapid deterioration of low strength polypropylene woven bags (weeks to months), cracking along bag planes and subsequent loss of internal material and collapsing failure, undermining of toe and damage by overtopping. Often fail within 1-2 years. Some walls (i.e. construct in Kiribati under KAPII in 2010) have deeper toe excavation, are higher and double layer and include a geotextile. Walls remain in reasonable condition 5 years after construction but outflanking is often evident. Improvement could be attained by using a higher quality polyester geotextile (Restall pers. comm. 2016)  KAPII wall 2010 Nanikai South Tarawa  Loss of cohesive strength between bags
Materials required	Sandbags, cement, sand, water ,geotextile
Locations used	Multiple locations in South Tarawa Kiribati. Notably at Nanikai and Ambo Causeways during Kiribati Adaptation Project II (KAPII) and at Betio Landfill
Information sources	BECA (2010), T&T (2014), USACE (1981)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	1
	Design life	2-5 years if well constructed, 1-2 years if not	2
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Moderate, often overtopped or fails structurally	2
	Effect on overtopping	Poor, no dissipation	1
	Toe scour	Yes as structure is reflective	1
	Design guidance available	Some (BECA 2010)	2
	Resilience to climate change	Low	1
	Construction complexity	Simple	4
	Construction plant required	Not required but helpful for toe excavation	4
	Scalability	Adjust height, slope and bag size for different conditions	4
Social	**Use of local labour**	Yes, with oversight	4
	Beach access	No but ramps can be included	2
	Aesthetic	Significantly different from existing	2
	Cultural acceptability	Varies	3
Environmental	**End effects**	Yes as structure is reflective	2
	Effect on sediment budget	Reduces supply derived from land behind wall	2
	Effect on ecosystems	Blocks connectivity and no additional habitat is provided.	1
	Impact of construction activities	Generally short term but bags may break down and enter the marine environment	2

Gabion baskets and mattresses	
Description	Gabion baskets are wire baskets filled with small stones, used in conjection with a filter material such as gravel or geotextile. Gabions baskets are best for mild wave climates and, if exposed, have a relatively short life span. A longer life span can be expected when constructed as a last line of defence at the back of the beach and buried. Foundations need to be secure and rock needs to be tightly packed otherwise the rock abrades the wire/plastic/pvc coatings and the baskets deteriorate. The advantages of gabion baskets is that they are low cost, easy to install, and easy to maintain. They can be built without heavy equipment, are flexible enough to allow for settlement and can be repaired by opening the baskets, refilling them and wiring shut again. Disadvantages are that baskets may be opened by wave action and damage to the pvc wire coating can lead to rapid corrosion of the wire and failure of the baskets. Though typically pvc coated wire mesh gabions may also be constrcuted from stainless steel mesh or geogrids. Marine mattresses are rock-filled containers constructed of high-strength geogrid. Geogrid panels are laced together to form mattress-shaped baskets that are filled with small stones similar to construction of gabions. Applications include shoreline revetments and dune stabilisation and foundations for breakwaters, jetties, groins and dikes. Costs for installed marine mattresses depend on such factors as application, proximity and cost of rock-fill material, site accessibility, placement method (land-based or from barge), availability of equipment, and project size.  Gabion Revetment (Source: http://www.gabions.net)  Cape May State Park geogrid mattress revetment (Source: Hughes 2006)
Materials required	- Suitable filter material, such as geotextile fabric. - Wire gabion baskets or geogrid mattresses - Supply of rock to fill the baskets.
Locations used	Gabion baskets have been used in shore protection structures in multiple locations, internationally and throughout the pacific. Locations include Vanuatu, Solomon Islands, Fiji and Republic of Marshall Islands. Marine mattresses have been used in various locations as revetments, breakwater and groin bedding mats and toe scour protection.
Information sources	Motyka and Welsby (1987), Paeniu et al. (2015), SOPAC (1994), USACE (1981), USACE (1986), Hughes (2006), Tensar International Corporation (2011).

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	1
	Design life	5-10 years depending on gabion material	2
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Generally good until damage of wire	3
	Effect on overtopping	Limited energy dissipation	2
	Toe scour	Moderate but some dissipation of wave energy	2
	Design guidance available	Some manufacturer guidance but limited on wave conditions	4
	Resilience to climate change	Low	1
	Construction complexity	Simple but care is required	4
	Construction plant required	Gabions can be filled in situ but plant required to bring rock.	4
	Scalability	Design can be adjusted for site specific conditions	4
Social	**Use of local labour**	Yes, with oversight	4
	Beach access	Possible but may result in injury if baskets are damaged	3
	Aesthetic	Varies	3
	Cultural acceptability	Varies	3
Environmental	**End effects**	Yes as structure is mostly reflective	2
	Effect on sediment budget	Reduces supply derived from land behind wall	2
	Effect on ecosystems	Can restrict ecological connectivity	2
	Impact of construction activities	Rock may be lost onto the beach once wire fails.	2

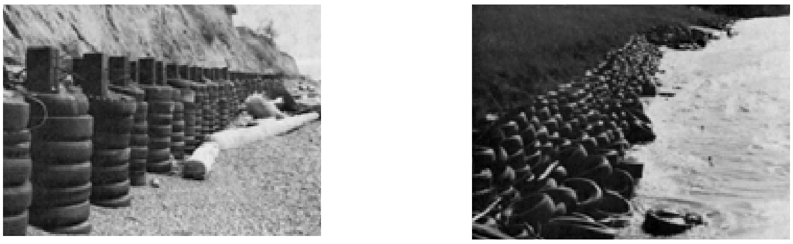
Grouted Rock

Description	Vertical or sloped seawall constructed from rock cemented together using grout mix. Christmas Island, Australia has a ertical seawall constrcuted at the rear of the beach from 5-20kg locally quarried limestone and cemented together. The total length of the wall is approximately 660m. Overtopping has been observed in extreme storm conditions. A 21m section was repaired in 2008 after collapsing in a significant storm event. Evidence of scour at the base of parts of the wall. Sinkhole appeard behind the wall in 2010. Soil is believed to have been lost underneath the wall, rather then through it.  Sloped grouted rock wall in Bali, Indonesia (Shand)  Undermining of the sea wall at Christmas Island Torres Strait (source: Government of Western Australia (2009))
Materials required	Supply of suitable stone or coral . Cement, aggregate and water.
Locations used	Christmas Island Saibai, Torres Strait
Information sources	Government of Western Australia Department of Transport (2009), Bettington et al. (2013)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Commonly low using coral and low strength concrete	2
	Design life	Low	2
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Moderate, often overtopped or fails structurally	2
	Effect on overtopping	Poor, no dissipation	2
	Toe scour	Yes as structure is reflective	1
	Design guidance available	No	2
	Resilience to climate change	Low	1
	Construction complexity	Simple	4
	Construction plant required	Required for concrete batching	4
	Scalability	Can be designed for site specific conditions	4
Social	**Use of local labour**	Yes	4
	Beach access	Impeded	2
	Aesthetic	Varies	3
	Cultural acceptability	Varies	3
Environmental	**End effects**	Yes as structure is mostly reflective	2
	Effect on sediment budget	Reduces supply derived from land behind wall	2
	Effect on ecosystems	Blocks connectivity and no additional habitat is provided.	1
	Impact of construction activities	Rock may be lost onto the beach as concrete breaks down	2

Stacked coral	
Description	Walls made from stacked coral blocks/rocks. Blocks are typically small and light reducing stability under wave attack but careful placement can result in relatively good interlocking. Typically constructed at near vertical slope resulting in catastrophic failure when units displaced or toe undermined. Relatively cheap and easy to construct and widely used through the Pacific. Retains some ability to protect shoreline post-failure as the rubble forms a dynamic revetment with protection afforded dependent on volume.  A stacked coral block walls in Kiribati (Beca, 2010)  Collapsed wall following spring high tides (Shand, 2013)
Materials required	Coral blocks or rock
Locations used	Throughout Pacific
Information sources	N/A

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	1
	Design life	Very short	1
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Not very effective	1
	Effect on overtopping	Moderate, some dissipation while structure is intact	3
	Toe scour	Somewhat dissipative	3
	Design guidance available	None	1
	Resilience to climate change	None	1
	Construction complexity	Simple	5
	Construction plant required	Plant required to bring rock if not available on site.	4
	Scalability	Used in most low energy environments	4
Social	**Use of local labour**	Yes	5
	Beach access	Not provided	2
	Aesthetic	Similar to existing	3
	Cultural acceptability	Quite well accepted	4
Environmental	**End effects**	Moderately dissipative	3
	Effect on sediment budget	Reduces supply derived from land behind wall and uses local aggregates	2
	Effect on ecosystems	Obtaining coral blocks can be damaging to reef ecosystems	2
	Impact of construction activities	Coral blocks end up scattered over the foreshore when damaged	2

Rubber Tyres	
Description	Rubber tyres are used mostly in floating breakwaters and to protect harbour moorings, as well as other configurations, such as stacked to form walls or partially buried. Used tyres may be strung over posts and filled with gravel to form a vertical wall. This method requires the posts to be set close together so may not result in any cost savings. Stacked tyres filled with gravel have also been used but are not recommended as the connections between tyres failed and the gravel washed out allowing them to be lifted by waves. Rubber tyre revetments tested in the USA in low energy environments (USACE 1981) were found to fail within 2 years in most cases.  Used rubber tyre and post wall (left) and stacked used tyre revetment (right) (Source: USACE 1981).
Materials required	Scrap yyres Variable depending on design. Posts and gravel if used to form a wall, or a suitable connection system if being used as a floating structure.
Locations used	USA, Fiji and the Republic of Marshal Islands
Information sources	Motyka and Welsby (1987), USACE (1981), Paeniu et al. (2015), Ford and Coastal Consultants (2013), Mimura and Nunn (1998), USACE (1981).

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	1
	Design life	Less than 2 years	1
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Generally fail	1
	Effect on overtopping	Limited energy dissipation	2
	Toe scour	Yes	2
	Design guidance available	No	1
	Resilience to climate change	No	1
	Construction complexity	Simple	4
	Construction plant required	Required if driven posts are used	3
	Scalability	Design can be site specific	3
Social	**Use of local labour**	Some	3
	Beach access	Difficult	1
	Aesthetic	Significantly different	1
	Cultural acceptability	Generally not acceptable	1
Environmental	**End effects**	Yes	2
	Effect on sediment budget	Neutral	3
	Effect on ecosystems	Restricts ecological connectivity	2
	Impact of construction activities	Tyres lost into marine environment when damaged	2

Concrete pipes	
Description	Economical and practical only if there is an available supply of pipes. Wall should not be more than 2 pipe diameters high without anchoring or toppling failure likely. Loss of fines from behind structure likely unless geotextile used. May have a short life span due to possible deterioration of the concrete pipes.  Used concrete pipe wall (USACE 1981))  Filled concrete pipes Bali
Materials required	Used concrete pipes, ties or anchors
Locations used	Kiribati, Bali
Information sources	USACE (1981)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	2
	Design life	Relatively short	2
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Prone to sediment loss	1
	Effect on overtopping	Poor	1
	Toe scour	Yes	1
	Design guidance available	No	1
	Resilience to climate change	Low	2
	Construction complexity	Simple but must be adequately tied or anchored	3
	Construction plant required	May be required for placement depending on the pipe size	3
	Scalability	Design can be site specific	3
Social	**Use of local labour**	Some	3
	Beach access	Difficult	1
	Aesthetic	Significantly different	1
	Cultural acceptability	Generally not acceptable	1
Environmental	**End effects**	Yes	2
	Effect on sediment budget	Neutral	2
	Effect on ecosystems	Restricts ecological connectivity and Concrete can enter the marine environment as the pipes degrade	1
	Impact of construction activities	Short term	3

Filled drums	
Description	Concrete filled fuel drums can be used as vertical seawalls. No information could be found on on construction dates or performance. Per USACE (1981) the system is only reliable in artic regions sue to rapid corrosion of the barrels in warm water.  Tuvalu (Source: ABC News)  Concrete filled drums in Kiribati (source: Beca, 2010)
Materials required	Supply of cement, aggregate, water and fuel drums
Locations used	Worldwide and in the Pacific. Examples found on Tuvala and Fiji
Information sources	ABC News 8 Dec 2011. USACE (1981).

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	1
	Design life	Short	1
	Time period to become effective	Immediate	5
	Effectiveness at protecting land	Mostly ineffective	1
	Effect on overtopping	Poor	1
	Toe scour	Yes	1
	Design guidance available	No	1
	Resilience to climate change	Low	2
	Construction complexity	Simple	4
	Construction plant required	May be required for cement batching	4
	Scalability	Design can be site specific	3
Social	**Use of local labour**	Yes	4
	Beach access	Difficult	1
	Aesthetic	Significantly different	1
	Cultural acceptability	Generally not acceptable	1
Environmental	**End effects**	Yes	2
	Effect on sediment budget	Can lead to loss of sediment	2
	Effect on ecosystems	Restricts ecological connectivity	1
	Impact of construction activities	Adverse	2

Beach replenishment	
Description	Beach replenishment also known as beach nourishment, is the artificial addition of sand or gravel to the coast to improve the capacity of a beach to act as a buffer against storm erosion, coastal recession or tidal inundation to protect the land behind. The volume of sand required is dependent on the volume likely to be lost during storms and on local sediment transport regimes. Beach replenishment can be used to provide both coast protection and amenity, particularly in situations where the recreational amenity of the coast is important, such as developed urban foreshores or tourist areas. Replenishment may also be used in conjunction with these other measures such as groynes and offshore structures with the aim of limiting project capital cost, minimising environmental impacts and extending the time before further replenishment is necessary. To be financially feasible over other coastal protection methods, a relatively inexpensive and readily accessible sediment source must be available and benefits such as recreational amenity generally need to be taken into account.  Gravel replenishment in Tuvalu (Source: Taiwanembassy.org)  Beach nourishment at Torpedo Bay, NZ held by control structures (source: Tonkin & Taylor Ltd.)
Materials required	Sand
Locations used	Worldwide and in the Pacific including Fiji and Samoa, generally for tourist amenity.
Information sources	Beach management manual (CIRIA, 2010)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Can be designed for most wave conditions	4
	Design life	Typically short without ongoing nourishment or control structures	2
	Time period to become effective	Near immediate	4
	Effectiveness at protecting land	Moderate while sand lasts	3
	Effect on overtopping	Reduces overtopping	5
	Toe scour	No	5
	Design guidance available	Yes, i.e. CIRIA (2010)	4
	Resilience to climate change	Moderate	4
	Construction complexity	Moderate	3
	Construction plant required	Yes, to place and spread sand	3
	Scalability	Highly site specific.	1
Social	**Use of local labour**	No	2
	Beach access	Improves	5
	Aesthetic	Improves	5
	Cultural acceptability	Generally yes	5
Environmental	**End effects**	No	5
	Effect on sediment budget	Improves locally	4
	Effect on ecosystems	Can smother ecosystems but maintains connectivity	4
	Impact of construction activities	Short-term sediment plumes	4

Brush structures	
Description	Brush structures constructed of branches, palm fronds, coconut fibre string are intended to catch sediment and allow dunes and beaches to rebuild. Used in conjection with vegetation replanting and controlling beach access. Sites established in Kiribati in 2013 are reported to be showing improvement. Brush could be used as a temporary breakwater to shelter young vegetation but is not suitable as a permanent structure.  Kiribati (Source: https://www.sprep.org)  End effect protection, Australia (James Carley, WRL UNSW)
Materials required	Branches, palm fronds, coconut fibre string
Locations used	Kiribati
Information sources	SPREP (2015), USACE (1981)

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	1
	Design life	<2 years	1
	Time period to become effective	1-2 years	2
	Effectiveness at protecting land	Low, does not halt erosion and most sediment deposited by wave overtopping rather than wind-blown sand	1
	Effect on overtopping	May slightly reduce	4
	Toe scour	Not applicable	3
	Design guidance available	No	1
	Resilience to climate change	Partially	3
	Construction complexity	Simple	5
	Construction plant required	No	5
	Scalability	Yes	4
Social	**Use of local labour**	Yes	5
	Beach access	Paths required to allow beach access	2
	Aesthetic	May block views	2
	Cultural acceptability	Likely ok	4
Environmental	**End effects**	N/A	3
	Effect on sediment budget	Unchanged	3
	Effect on ecosystems	May partially block connectivity	3
	Impact of construction activities	Not significant, though branches must be gathered locally	4

Biorock (Artificial reef)	
Description	Biorock passes a low voltage current through a sumberged conductive structure. Corals attached to the structure reportedly grow significantly faster (4-6 times) than normal. Coral grown on biorock structures has been reported to be more resiliant and to suffer minimal damage in hurricane conditions. Improvement of coral reefs is likely to provide additional sediment to the coastal system and, if substantually large, provide some wave dissipation although at storm tide levels this is likely to be minimal.  Biorock frame being submerged and corals attached (Source: Global Coral Reef Alliance, 2009))
Materials required	Frame - usually made from welded steel reinforcement. Requires a stable power source.
Locations used	Maldives, Indonesia, Caribbean.
Information sources	Global Coral Reef Alliance (2009), Wells et al. (2010), Goreau et al. (2012).

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low to medium	3
	Design life	Medium-long term (while power maintained)	3
	Time period to become effective	Long as coral becomes established and adds to sediment budget	1
	Effectiveness at protecting land	Low in the immediate-term	1
	Effect on overtopping	Not applicable	3
	Toe scour	Not applicable	3
	Design guidance available	Some	3
	Resilience to climate change	Yes	5
	Construction complexity	Complex. May require divers to place frame and connect power source	2
	Construction plant required	In most cases no but welding equiptment required	4
	Scalability	Moderate, although site-specific design likely for power	2
Social	**Use of local labour**	Some	3
	Beach access	Unaffected. May create a tourist amenity	4
	Aesthetic	May create a tourist amenity	5
	Cultural acceptability	Usually acceptable	5
Environmental	**End effects**	Neutral	3
	Effect on sediment budget	May contribute to sediment budget	5
	Effect on ecosystems	Positive	5
	Impact of construction activities	Negligible although surrounding reef may be temporarily damaged to site structure and obtain coral for use	4

Planting mangroves and vegetation

Description	Vegetation is used to stabilise shorelines as a substitute for, or supplement to, a structure. It does not always prevent erosion and the types and effectiveness of vegetation are limited by site characteristics (USACE 1981). Marois & Mitsch (2015) undertook a review of coastal protection provided by mangrove wetlands. They found that the effectiveness of mangroves in providing coastal protection during cyclones has been difficult to separate from elevation changes and the tendency of mangroves to be located in sheltered areas. They concluded that comprehensive coastal protection programs should not rely solely on mangroves for protection. In a study of the Tong King delta, Vietnam (Mazda et. al 1997) wave reduction (5 to 8 s period waves) was up to 20% per 100 m when the mangrove trees were sufficiently tall, but was negligible on another site with young (low) trees. Paeniu et. al (2015) noted that mangroves can reduce the impact or erosion by trapping sand. They observed that replanting of mangroves in Fiji and Kiribati has been less successful in areas without soft sedimentary mud, and that juvenile mangroves should be planted in low wave energy zones. It is often advocated to grow and re-plant coastal littoral vegetation such as shrubs, grasses, plants and trees for stabilising the coast. Coastal wetlands are effective at reducing erosion in low energy environment, but less so in high energy environments (Gedan et al 2011).Vetiver grass can be used as bank protection on shorelines exposed to wind waves, though care needs to be taken during the planting process (Verhagen et al. 2008). Feagin et al. (2010) recommended not relying on vegetation for storm protection. They noted that, while vegetation may be effective in attenuating short period waves, for extreme events such as cyclones and tsunamis a long duration of water level elevation occurs, and this is not attenuated by vegetation. Bettington et al (2013) stated that "Vegetation management cannot reverse past changes within suitable time frames" and vegetation management (and prevention of future removal) is described as a largely educational process, involving increasing awareness of the role of vegetation on coastal processes.  Mangrove Planting, Tuvalu (Source: Paeniu et. al (2015)
Materials required	Seedlings, fertilizer, stakes
Locations used	Vietnam, Fiji, Kiribati and other locations.
Information sources	Bettington et al (2013), Feagin et al. (2010), Gedan et al (2011), Marois & Mitsch (2015) Mazda et. al (1997), Paeniu et. al (2015), USACE (1981), Verhagen et al. (2008).

Criteria		Comment	Rating
Engineering	**Design wave conditions**	Low	1
	Design life	Long term	4
	Time period to become effective	Years for mangrove to establish and grow	1
	Effectiveness at protecting land	Low unless width is substantial (>50m)	2
	Effect on overtopping	Reduces by reducing wave height	4
	Toe scour	Reduces by reducing wave height	3
	Design guidance available	Some	2
	Resilience to climate change	Mostly resilient if land is available for mangroves to retreat with sea level rise	4
	Construction complexity	Simple	5
	Construction plant required	No	5
	Scalability	Yes	4
Social	**Use of local labour**	Yes	5
	Beach access	May inhibit	2
	Aesthetic	Can block views	2
	Cultural acceptability	Generally acceptable	4
Environmental	**End effects**	Minimal	4
	Effect on sediment budget	Can trap sand	4
	Effect on ecosystems	Can provide habitat	5
	Impact of construction activities	Minimal	5

Appendix B Cost Analysis: Results

Low Wave Environment (H_s = 0.7 m)

Protection option	Design life (years)	Assessed costs (A$/linear metre)			
		Base	Local	Primary port	Remote location
1. Rock revetment: volcanic	50	675	1,403	3,100	5,525
2. Mass concrete: local concrete	30	2,460	2,618	2,985	3,510
3. Reinforced concrete	25	1686	1,938	2,526	3,366
4. Grout-filled bag wall	5	940	1,030	1,240	1,540
5a. Geocontainer: single layer	10	1,880	1,961	2,150	2,420
5b. Geocontainer: double layer	20	3,360	3,497	3,815	4,270
6a. Seabees: imported materials	25	910	1,218	1,935	2,960
6b. Seabees: local materials	15	1,248	1,284	1,367	1,486
8. Grouted coral	10	888	932	1,033	1,178
9. Beach replenishment	5	1,000	1,000	1,000	1,000
10. Timber wall	15	2,400	2,760	3,600	4,800
11. Gabion basket	7	648	804	968	1,138
12. Terrafix blocks	15	1,322	1,481	1,852	2,382
13. Small hand-placed sandbags	2	343	370	433	523

Protection option	Design life (years)	Assessed costs (A$li metre/year)			
		Base	Local	Primary port	Remote location
1. Rock revetment: volcanic	50	14	28	62	111
2. Mass concrete: local concrete	30	82	87	100	117
3. Reinforced concrete	25	67	78	101	135
4. Grout-filled bag wall	5	188	206	248	308
5a. Geocontainer: single layer	10	188	196	215	242
5b. Geocontainer: double layer	20	168	175	191	214
6a. Seabees: imported materials	25	36	49	77	118
6b. Seabees: local materials	15	83	86	91	99
8. Grouted coral	10	89	93	103	118
9. Beach replenishment	5	200	200	200	200
10. Timber wall	15	160	184	240	320
11. Gabion basket	7	93	115	138	163
12. Terrafix nlocks	15	88	99	123	159
13. Small hand-placed sandbags	2	171	185	216	261

Medium Wave Environment (H_s = 1.5 m)

Protection option	Design life (years)	Assessed costs (A$/linear metre)			
		Base	Local	Primary port	Remote location
1. Rock revetment: volcanic	50	3,084	6,494	14,449	25,814
2. Mass concrete: local concrete	20	10,896	11,583	13,186	15,476
3. Reinforced concrete	30	6,684	7,685	10,019	13,354
4. Grout-filled bag wall	5	N/A	N/A	N/A	N/A
5a. Geo-container: single layer	10	3,870	3,998	4,295	4,720
5b. Geo-container: double layer	20	7,120	7,345	7,870	8,620
6a. Seabees: imported materials	30	3,422	4,427	6,772	10,122
6b. Seabees: local materials	15	4,690	4,808	5,084	5,478
7a. Tetrapods: imported materials	30	5,152	6,394	9,292	13,432
8. Grouted coral	10	N/A	N/A	N/A	N/A
9. Beach replenishment	5	4,250	4,250	4,250	4,250
10. Timber wall	15	N/A	N/A	N/A	N/A
11. Gabion basket	5	N/A	N/A	N/A	N/A
12. Terrafix blocks	20	N/A	N/A	N/A	N/A

Protection option	Design life (years)	Assessed costs (A$/linear metre/year)			
		Base	Local	Primary port	Remote location
1. Rock revetment: volcanic	50	62	130	289	516
2. Mass concrete: local concrete	20	363	386	440	516
3. Reinforced concrete	30	267	307	401	534
4. Grout-filled bag wall	5	N/A	N/A	N/A	N/A
5a. Geo-container: single layer	10	387	400	430	472
5b. Geo-container: double layer	20	356	367	394	431
6a. Seabees: imported materials	30	137	177	271	405
6b. Seabees: local materials	15	313	321	339	365
7a. Tetrapods: imported materials	30	172	213	310	448
8. Grouted coral	10	N/A	N/A	N/A	N/A
9. Beach replenishment	5	850	850	850	850
10. Timber wall	15	N/A	N/A	N/A	N/A
11. Gabion basket	5	N/A	N/A	N/A	N/A
12. Terrafix blocks	20	N/A	N/A	N/A	N/A

High Wave Environment (H_s = 3 m)

Protection option	Design life (years)	Assessed costs (A$/linear metre)			
		Base	Local	Primary port	Remote location
1. Rock revetment: volcanic	50	10,668	22,838	51,233	91,798
2. Mass concrete: local concrete	20	N/A	N/A	N/A	N/A
3. Reinforced concrete	30	N/A	N/A	N/A	N/A
4. Grout-filled bag wall	5	N/A	N/A	N/A	N/A
5a. Geo-container: single layer	10	N/A	N/A	N/A	N/A
5b. Geo-container: double layer	20	N/A	N/A	N/A	N/A
6a. Seabees: imported materials	30	12,462	15,627	23,012	33,562
6b. Seabees: local materials	15	N/A	N/A	N/A	N/A
7a. Tetrapods: imported materials	30	31,740	37,163	49,815	67,890
8. Grouted coral	10	N/A	N/A	N/A	N/A
9. Beach replenishment	5	17,500	17,500	17,500	17,500
10. Timber wall	15	N/A	N/A	N/A	N/A
11. Gabion basket	5	N/A	N/A	N/A	N/A
12. Terrafix blocks	20	N/A	N/A	N/A	N/A

Protection option	Design life (years)	Assessed costs (A$/linear metre/year)			
		Base	Local	Primary Port	Remote Location
1. Rock revetment: volcanic	50	213	457	1025	1,836
2. Mass concrete: local concrete	20	N/A	N/A	N/A	N/A
3. Reinforced concrete	30	N/A	N/A	N/A	N/A
4. Grout-filled bag wall	5	N/A	N/A	N/A	N/A
5a. Geo-container: single layer	10	N/A	N/A	N/A	N/A
5b. Geo-container: double layer	20	N/A	N/A	N/A	N/A
6a. Seabees: imported materials	30	498	625	920	1,342
6b. Seabees: local materials	15	N/A	N/A	N/A	N/A
7a. Tetrapods: imported materials	30	1,058	1,239	1,661	2,263
8. Grouted coral	10	N/A	N/A	N/A	N/A
9. Beach replenishment	5	3,500	3,500	3,500	3,500
10. Timber wall	15	N/A	N/A	N/A	N/A
11. Gabion basket	5	N/A	N/A	N/A	N/A
12. Terrafix blocks	20	N/A	N/A	N/A	N/A

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