Conceptual design and preliminary costing for coastal protection along the north coast of Tongatapu

Prepared for the GCCA+ SUPA Project

and the Kingdom of Tonga:

eCoast
eTakutai

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Disclaimer

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Abbreviations

JNAP	Joint National Adaptation Plan for Climate Change and Disaster Management
ICM	integrated coastal management
JICA	Japan International Cooperation Agency
MEIDECC	Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communications
MSL	mean sea level
NBS	nature based solutions
NBSAP	National Biodiversity Strategy and Action Plan
NEMO	National Emergency Management Office
SLR	sea-level rise
Tg	teregrams of CO_2 equivalent

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Acknowledgements

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Executive summary

The Global Climate Change Alliance Plus Scaling up Pacific Adaptation (GCCA+ SUPA) project is about scaling up climate change adaptation measures in specific sectors, supported by knowledge management and capacity building. The project (2019–2023) is funded with EUR 14.89 million from the European Union and implemented by the Pacific Community in partnership with the Secretariat of the Pacific Regional Environment Programme and the University of the South Pacific, in collaboration with the governments and peoples of Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Republic of the Marshall Islands, Nauru, Niue, Palau, Tonga and Tuvalu.

The overall objective is to enhance climate change adaptation and resilience in ten Pacific Island countries. The specific objective is to strengthen the implementation of sector-based, but integrated, climate change and disaster risk management strategies and plans.

The Government of Tonga selected coastal protection as the focus sector under Output 3: Scaling up resilient development measures in specific sectors.

In 2021, the GCCA+ SUPA project completed: (i) a detailed desktop coastal assessment with community input (Mead et al. 2020), and (ii) a conceptual design and feasibility study for coastal protection along the north coast of Tongatapu (Niutoua to Ha'atafu and including the Fanga'uta Lagoon) (Mead and Manuofetoa, 2021).

On 15 January 2022, the Hunga Tonga Hunga Ha'apai underwater volcano erupted. The eruption triggered a devastating tsunami that hit the Tongatapu, 'Eua and Ha'apai group of islands. The tsunami generated >15 m high waves in some parts of Tonga and caused four fatalities. Because the tsunami hit the Tongatapu coastline, there was a need to review and revise the options and costings for coastal protection along the northern coast of Tongatapu that were prepared in 2021 (Mead and Manuofetoa, 2021).

This report updates the 2021 report (Mead and Manuofetoa, 2021) and incorporates site visits undertaken in late October/early November 2022, interviews with members of the Joint National Adaptation Plan for Climate Change and Disaster Management (JNAP) Technical Committee, and the proposed revisions.

Tsunami events of the magnitude of the 2022 tsunami generated by the Hunga volcanic eruption are very rare, and the shallow ridge that the Tongan archipelago is located on restricts the maximum height of tsunamis on the northern coast of Tongatapu. However, the Kingdom of Tonga lies astride a large and tsunamigenic subduction zone to the east and an associated line of volcanic activity to the west running north-south.

The effects of the January 2022 tsunami along the northern Tongatapu coast have focused further attention on coastal protection, and the need to revise the 2021 report (Mead and Manuofetoa, 2021).

The proposed revisions include:

- further stating the benefits of mangrove re-establishment for tsunami protection, coastal protection and resilience to sea level rise;
- incorporation of the proposed Nuku'alofa foreshore works to the Unit 3 revisions;
- incorporation of the changes to the revised report to reflect the strategy for the Popua area based on the master plan.
- further recognition of the issues with flushing the lagoon, water quality and biodiversity as part of coastal resilience; and
- development of a monitoring and evaluation, and education section in the revised report.

This document presents the updated (i.e. post-tsunami) conceptual design and preliminary costing for measures to protect the communities living within two kilometres of the high water mark up to the 2030 and 2050 planning horizons (i.e. in 10 and 30 years' time). This includes specific conceptual design and costing for the use of donor funds under negotiation of T$ 6 million.

This updated report divides the area of interest into five sections of coastline (coastal units – Figure 1) on the northern side of Tongatapu, including the Fanga'uta Lagoon. These coastal units are: (i) Ha'atafu to Foui to the north-west (red); (ii) Foui to Sopu in the middle northern-west (yellow); (iii) Sopu to Nuku'alofa in the middle of the northern side and including the Fanga'uta Lagoon to the edge of Nuku'alofa city (blue); (iv) Nuku'alofa to Nukuleka (Lagoon main component) (pink); and (v) Nukuleka to Niutoua (green).

Figure 1. The five study sections along the northern coastline of Tongatapu, Kingdom of Tonga (Google Earth, 2020). Coastal unit 1 = red, coastal unit 2 = yellow, coastal unit 3 = blue, coastal unit 4 = magenta and coastal unit 5 = green.

The measures presented here have considered the 2030 and 2050 planning horizons (i.e. in 10 and 30 years' time), which represent 0.08 m and 0.3 m of sea-level rise (SLR) respectively when considering the Representative Concentration Pathway 8.5 climate change scenario (i.e. business as usual, which is still the current situation with carbon emissions worldwide). While the immediate 10 years with 8 cm of SLR may seem innocuous, this can affect the lowest-lying and flattest relief areas. In addition, the effects of climate change (CC) are also being reported to decrease the number of tropical cyclones (TCs) in the South Pacific, although their intensity is projected to increase (e.g. Walsh et al. 2012), as has been attributed to TC Winston and TC Harold. With respect to 30 cm of SLR, this represents a significant increase in inundation events and associated erosion, with events that are presently considered 1 in 200-year return periods likely to occur every 2.5 years on average. Therefore, planning and measures to reduce the effects of SLR are required now.

Some areas of the coast have significant coastal defences in place to prevent coastal erosion and inundation. This report includes hybrid solutions to create two lines of defence where possible. In addition, nature-based solutions through the combination of managed natural solutions and hybrid solutions have been considered.

Table 1 provides the preliminary cost estimates for conceptual designs of coastal protection measures for the entire northern Tongatapu coast, broken down into the five coastal units. Based on the perceived and known vulnerability of the various parts of the northern Nuku'alofa coast, the proposed priority list for the use of donor funds under negotiation is presented in Table 2.

Lessons learnt from the implementation of previous climate change resilience strategies include: (i) the need for supervision through to the end of the construction; (ii) regular maintenance for components of the strategies (e.g. the non-return valves and flood gates in Nuku'alofa, the Kanokupolu revetment and the Kovolai seawall); (iii) regular monitoring to determine the efficacy of the measures put in place and ways they can be improved; and (iv) adaptive management (e.g. the requirement for further groynes and sand renourishment to fill the gaps at Talafo'ou and Makaunga).

This project has highlighted the importance of developing a policy for integrated coastal management (ICM), which needs to consider responses to climate change and sea-level rise further into the future and whether to retreat from, accommodate or defend the low-lying northern coast and Fanga'uta Lagoon. Some of the challenges discussed by community members could be reduced by the development of an ICM policy through the Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communications (MEIDECC) to bring together the various components of coastal management (such as being developed through this current project) and clarify the over-arching aims for Tongatapu.

Table 1. Preliminary cost estimates for conceptual designs of coastal protection measures for the entire northern Tongatapu coast, broken down into the five coastal units. The highlighted items are those that are considered priorities for donor funding under negotiation which is broken down in Table 2.

Cost (T$)	Item	Location	Comment
		Coastal Unit 1	
$ 6,500.00	Remove access path to restore flow	'Ahau	Complete 2018 Plan
$ 196,840.00	380 m seawall with non-return valves	Ha'avakatolo	Based on aerial images and community consultation (requires survey)
$ 20,720.00	Complete seawall (40 m) as designed and repair/add non-return valves	Kovolai	Complete 2018 Plan
$ 40,500.00	0.9 ha mangrove	Kovolai	Seaward of seawalls to widen green belt
$ 85,000.00	Establish an additional mangrove nursery	Foui	widen green belt
$ 24,200.00	1.1 ha mangrove	Foui	widen green belt
$ 62,900.00	740 m brushwood fences	Foui	widen green belt
$ 35,000.00	Pig fencing/control	Foui	widen green belt — protect seedlings
$ 471,660.00	Estimated subtotal		
$ 70,749.00	15% contingency		
$ 542,409.00	Estimated total		
		Coastal Unit 2	
$ 3,420,000.00	76 ha mangrove planting	Masilamea to Matafonua	widen green belt
$ 425,000.00	5.0 km of brushwood fences	Masilamea to Matafonua	widen green belt
$ 255,000.00	Establishment of 3x mangrove nurseries	Masilamea to Matafonua	widen green belt
$ 2,610,000.00	58 ha mangrove replanting	Nukunuku to Sai'atoutai	mangrove gaps (cleared?)
$ 150,000.00	Pig fencing/control	Masilamea to Sai'atoutai	widen green belt — protect seedlings
$ 185,000.00	Ground surveys and modelling for flood control	Nukunuku, Matafonu, Fatai, Puke, Fotua Sopu and Isileli	Incorporates some 2.9—3.4 km of seawalls and non-return valves for v. low-lying and flood-prone areas
$ 621,600.00	900—1200 m of seawall with non-return valves	Nukunuku	Based on aerial images and community consultation (requires survey)
$ 518,000.00	700—1000 m of seawall with non-return valves	Matafonu and Fatai	Based on aerial images and community consultation (requires survey)
$ 362,600.00	600—700 m of seawall with non-return valves	Puke	Based on aerial images and community consultation (requires survey)
$ 300,440.00	580 m of seawall with non-return valves	Fotua	Based on aerial images and community consultation (requires survey)

$ 621,600.00	1.2 km of seawall with non-return valves	Sopu and Isileli	Based on aerial images and community consultation (requires survey)
$ 500,000.00	Estimated additional flood management	Sopu and Isileli	Unknown best solution (modelling and engineering investigations above)
$ 2,970,000.00	2.2 km of detached breakwaters	Sopu to Nuku'alofa	Extend foreshore protection
$ 25,000.00	Warning signage along the coast	Masilamea to Sopu	Estimated 10 signs
$ 12,964,240.00	Estimated subtotal		
$ 1,944,636.00	15% contingency		
$ 14,908,876.00	Estimated total		
Coastal Unit 3			
	Revetment repairs	Nuku'alofa	JICA
	Revetments/Detached breakwaters	Seisia	JICA — Erosion/inundation protection from extreme events
	Currently developing master plan	Pangatangata/Popua and Nukunkumotu Island (Seisai)	Creation of a cultural centre for tourism and more recreational space
$ -	Estimated subtotal		
$ -	15% contingency		
$ -	Estimated total		
Coastal Unit 4			
$ 569,800.00	1,100 m seawall with non-return valves	Pea to Veitongo	Based on aerial images and community consultation (requires survey)
$ 180,000.00	4 ha mangrove	Pea to Veitongo	widen green belt
$ 54,000.00	1.2 ha mangrove	Nukuhetulu	widen green belt
$ 170,000.00	Establish two mangrove nurseries	Pea to Veitongo	widen green belt
$ 75,000.00	Pig fencing/control	Pea to Nukuhetulu	widen green belt — protect seedlings
$ 240,000.00	12 km dykes/bunds	Nukuhetulu and Folaha	Based on daily earthworks costs
$ 140,000.00	Flood modelling and engineering	Nukuhetulu and Folaha	Modelling and flood controls for the dykes/bunds
$ 189,000.00	4.2 ha mangrove	Vaini to Longoteme 2.8 km long by 15 m wide	widen green belt
$ 165,760.00	320 seawall with non-return valves	Vaini	Based on aerial images and community consultation (requires survey)
$ 1,039,140.00	230 m seawall with non-return valves	Alaki	Based on aerial images and community consultation (requires survey)
$ 248,640.00	480 m seawall with non-return valves	Mua	Based on aerial images and community consultation (requires survey)
$ 225,000.00	5 ha mangrove	Mua and Alaki 3.3 km long by 15 m wide	widen green belt

$ 321,160.00	620 m seawall with non-return valves	Hoi	Based on aerial images and community consultation (requires survey)
$ 963,000.00	1.4 ha mangrove	Hoi	widen green belt
$ 85,000.00	Establish a mangrove nursery	Hoi	widen green belt
$ 75,000.00	Pig fencing/control	Mua to Hoi	widen green belt — protect seedlings
$ 4,740,500.00	Estimated subtotal		
$ 711,075.00	15% contingency		
$ 5,451,575.00	Estimated total		
Coastal Unit 5			
$ 466,200.00	900 m seawall with non-return valves	Nukuleka	Based on aerial images and community consultation (requires survey)
$ 85,000.00	Establish mangrove nursery	Nukuleka	widen green belt
$ 112,500.00	2.5 ha mangrove	Nukuleka 1.6 km long by 15 m wide	widen green belt
$ 136,000.00	1.6 km of brushwood fences	Nukuleka 1.6 km long by 15 m wide	widen green belt
$ 32,000.00	Pig fencing/control	Nukuleka	widen green belt — protect seedlings
$ 254,800.00	17 x groynes + 3,000 m3 sand	Talafo'ou and Makaunga	Fill gaps (Mead, 2019)
$ 115,200.00	3x dbw's	Manuka to Kolonga	Based on aerial images (requires further investigations)
$ 44,520.00	1 km of coastal planting	Manuka to Kolonga	Provide a wider buffer zone along the road
$ 1,246,220.00	Estimated subtotal		
$ 186,933.00	15% contingency		
$ 1,433,153.00	Estimated total		
$ 22,336,013.00	Grand total		
Long-term measures: reclamation estimates — require decision making			
$ 33,960,000	Reclamation	Sopu	1,900,000 m3 @ T$20/m3

Total excluding long-term reclamation measures: T$ 22,336,013.

Table 2. Updated priorities for the use of the donor funds under negotiation on parts of the Northern Tongatapu Coastal Protection project. Refer to Table 1 for the full breakdown of the 46 components of the project.

Coastal Unit	Cost (T$)	Item	Location	Comment
1	$ 70,400.00	Complete seawall and 0.9 ha add. Mangroves	Kovolai	40 m of seawall and mangroves seaward of those previously planted to widen the green-belt
1	$ 238,165.00	Mangrove reinstatement	Kolovai to Foui	Includes a nursery, brushwood fences and pig-control
1	$ 7,475.00	Remove access path to restore flow	'Ahau	Digger working on site for two days, including mob/demob
1	$ 226,366.00	380 m seawall with non-return valves	Ha'avakatolo	Extend from Kolovai seawall; includes five nonreturn valves
2	$ 25,000.00	Warning signage along the coast	Masilamea to Sopu	Six signs
2	$ 3,575,620.00	Flood control	Nukunuku to Sopu	Includes ground surveys and modelling/engineering advice
4	$ 437,000.00	12 km dykes/bunds	Nukuhetulu to Longoteme	To better protect low-lying crop land; includes ground surveys and modelling/engineering advice
5	$ 1,433,153.00	All recommendations	Nukuleka to Niutoua	Includes all items in Table 1 above
	$ 6,013,179.00	Total (includes 15% contingency)		

1 Overview

1.1 Project background

The Global Climate Change Alliance Plus Scaling up Pacific Adaptation (GCCA+ SUPA) project is about scaling up climate change adaptation measures in specific sectors, supported by knowledge management and capacity building. The 4.5-year project (2019–2023) is funded with EUR 14.89 million from the European Union and implemented by the Pacific Community in partnership with the Secretariat of the Pacific Regional Environment Programme and the University of the South Pacific, in collaboration with the governments and peoples of Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Republic of the Marshall Islands, Nauru, Niue, Palau, Tonga and Tuvalu.

The overall objective is to enhance climate change adaptation and resilience in ten Pacific Island countries. The specific objective is to strengthen the implementation of sector-based, but integrated, climate change and disaster risk management strategies and plans.

The Government of Tonga selected coastal protection as the focus sector under Output 3: Scaling up resilient development measures in specific sectors.

The Kingdom of Tonga is located in the central South Pacific Ocean between 15° and 23°S and 173° and 177°W (Figure 1-1). Tonga has a land area of 649 km^2 and is an archipelago of 172 coral and volcanic islands, of which 36 are inhabited. There are four main island groups: (i) Tongatapu (260 km^2) (Figure 1-1) and ‘Eua (87 km^2) in the south; (ii) Ha'apai (109 km^2) in the middle; (iii) Vava'u (121 km^2) in the north; and (iv) Niuafo'ou and Niua Toputapu (72 km^2) in the far north. The population of Tonga is 101,436 (2016 census).

Figure 1-1. Location of the Kingdom of Tonga and Tongatapu, home to the capital, Nuku’alofa.

Tongatapu has been experiencing beach erosion and inundation for many years and although little quantitative evidence is available, it is most likely due to human activities. For example, in many places, mangroves are cleared for fuel wood and the resulting space is used for land reclamation and other purposes (NBSAP 2010). Beach sand is mined and used as construction material and for the decoration of tombs. Accelerated SLR is contributing to beach erosion, which, in turn, is resulting in the wave overtopping and inundation being experienced on coastal roads in Tongatapu.

Over the last ten years, medium-scale coastal protection works – revetments, groynes and offshore breakwaters – have been constructed at a few sites along the north coast of Tongatapu, at Talafo'ou, Manuka and Kolonga on the north-east coast (Mead et al. 2013a,b; Mead 2014a,b; Mead 2015a,b,c; Mead 2019a), and at Kolovai and 'Ahau on the north-west coast, together with ecosystem-based measures involving coastal planting and mangroves (Mead and Atkin 2014a,b; Mead 2018a,b; Mead 2019b; Mead 2021). This is in addition to the older coastal protection measures protecting the capital, Nuku'alofa, which is a 1:4 (V:H) rock revetment and a number of port/wharf developments (Figure 1-2).

Figure 1-2. The Nuku'alofa coastline includes some 6.0 km of rock armour and port/wharf developments

Recognising the continuing and increasing challenges posed by climate change, the Government of Tonga wishes to adopt a holistic approach to coastal protection for the entire north coast of Tongatapu, from Niutoua in the east to Ha'atafu in the west and including the coastline of the Fanga'uta Lagoon.

In 2021 the GCCA+ SUPA Project completed: (i) a detailed desktop coastal assessment with community input (Mead et al. 2020) and (ii) a conceptual design and feasibility study for coastal protection along the north coast of Tongatapu (Niutoua to Ha'atafu and including the Fanga'uta Lagoon) (Mead and Manuofetoa 2021). This work divided the coast into five coastal units (Figure 1-) and recommended 52 coastal protection measures, with costings, for northern Tongatapu for the 2030 and 2050 planning horizons.

On 15 January 2022, the Hunga Tonga Hunga Ha'apai underwater volcano erupted (Figure 1-3). The eruption triggered a devastating tsunami that hit the Tongatapu, 'Eua and Ha'apai group of islands. The tsunami generated >15 m high waves in some parts of Tonga and led to four fatalities. The tsunami impacted the Tongatapu coastline and there is now a need to review and revise the options and costings for coastal protection along the northern coast of Tongatapu that were prepared in 2021.

Figure 1-3. The Hunga volcanic eruption rising to its climax at 5.24 pm (0424 UTC) on 15 January from ~10 km north of Tongatapu. (Photo: Branko Sugar); the upper plume is already >100 km wide (Borrero et al. 2022a).

This report updates the 2021 report on coastal protection along the northern coast of Tongatapu and incorporates site visits undertaken in late October/early November 2022, interviews with members of the JNAP Technical Committee, and the proposed revisions (Mead et al. 2023).

1.2 Project setting

The island of Tongatapu is flat and low-lying with the highest elevation being 70 metres above sea level. The island spans 35 km in an east-west direction and 15 km in a north-south direction. The north-west tilting of Tongatapu, coupled with the accelerated sea-level drop (some 20,000 years ago), caused land subsidence to most of the northern coastline, making all land and human development susceptible to inundation and flooding (). Furthermore,

tsunami modelling has demonstrated that, under a scenario of a magnitude 9.0 earthquake originating from the east (Tonga Trench), coastal communities and properties would be vulnerable to a rapid onset tsunami event (MLECCNR 2013; McCue 2014).

The south coast of Tongatapu borders the deep ocean. In contrast, the north coast faces a large lagoon (412 km^2) known as Tongatapu Lagoon (Figure 1-1), which has a mean depth of 13.0 m and a maximum depth of around 27.0 m depth. The lagoon is open from the north but mainly closed from the eastern and western sides by two barrier reefs. The eastern reef is open via a 500 m deep channel (Piha Passage) that is particularly wide.

The nearshore and intertidal areas of Tongatapu consist of a wide range of habitats, including mangroves, rock terraces, sand beaches, saline wetlands, estuary and mudflats, reef flats and coral reefs (barrier, fringing and submerged). The Fanga'uta Lagoon provides additional intertidal areas and is of ecological and cultural significance. The lagoon is characterised as a 36.6 km^2 semi-enclosed lagoon averaging 1.0 to 2.0 m depth and has a residency time of between 29 and 140 days, with tidal mixing at only 12% (very poor flushing). The nutrient-rich ground water essentially supplies the entire lagoon. (refer to Mead et al. 2020 for further details).

Following on from Mead et al. (2020a), this report divides the area of interest into five sections of coastline (coastal units) on the northern side of Tongatapu and includes the Fanga'uta Lagoon (Figure 1-4). These coastal units are: (i) Ha'atafu to Foui to the north-west (red); (ii) Foui to Sopu in the middle northern-west (yellow); (iii) Sopu to Nuku'alofa in the middle of the northern side, including the Fanga'uta Lagoon to the edge of Nuku'alofa city (blue); (iv) Nuku'alofa to Nukuleka (Lagoon main component) (pink); and (v) Nukuleka to Niutoua (green). Basic descriptions of these coastal units are presented below.

(1) Coastal Unit 1 – The north-western coastal unit faces north-east and comprises the villages Ha'atafu, Kanokupolu, Ha'akili, Kolovai and Foui. This coastal unit experiences easterly and north-easterly wind events. Waves that are generated by these wind directions break offshore on the large barrier reef and are also dissipated by the shallow western section of the Tongatapu Lagoon (Mead and Atkin 2014). The northern areas of this coastal unit (i.e. Ha'atafu) are topographically higher than the southern areas and are thus less vulnerable to flooding inundation hazards. Approximately 2,350 people reside in the villages in this area (McCue 2014).
(2) Coastal Unit 2 – This coastal unit comprises villages Foui, Masilamea, Nukunuku, Fatai, Sia'atoutai, Puke, and Sopu. The unit is considered low lying and vulnerable to flood inundation risks but is, however, somewhat protected by the adjacent Tongatapu

Lagoon, which prevents large waves from penetrating to the coastline. Approximately 2100 people reside in the villages tin this area (McCue 2014).

(3) Coastal Unit 3 – This middle coastal unit comprises the capital city (urban area) of Nuku'alofa, the area of which consists of the northern armoured and non-armoured beaches and part of the Fanga'uta Lagoon. Topographically, this area is only 1–2 metres above sea level and is subject to periodic flooding during heavy rain. The risk of coastal inundation and erosion is often intensified by development in the coastal area. Most coastal land has been significantly altered, either by conversion to agriculture/plantation use or by urban development of the villages that border the coastline. Some 30,000 people live in this area.

(4) Coastal Unit 4 – This coastal unit extends from the south-western to the north-eastern shores of the Fanga'uta Lagoon and includes the villages Pea, Ha'ateiho, Veitonga, Nukuhetula, Longoteme, Vaini, Holonga, Alkai, Mua and Hoi. The lagoon is shallow and almost closed off. It is an important breeding ground for birds and fish. The south-western shores are generally more low lying and are subject to greater inundation hazards.

(5) Coastal Unit 5 – This north-eastern coastal unit comprises the villages Nukuleka, Makaunga, Talafo'ou, Navutoka, Manuka, Kolonga, Afa and Niutoua. The unit is somewhat protected by a submerged fringing reef during high tide, with the reef edge being ~80 m from the beach at Niutou and increasing to >1,500 m further west at Navutoka. Topographically, the land from Kolonga towards Nukuleka (west to east) reduces in elevation. Most of the villages in this coastal unit are less than 2.0–3.0 m above sea level, which makes them vulnerable to the effects of climate change, disaster risk, sea-level rise, storm surges and coastal erosion issues (McCue 2014). The area has been subject to some 50–70 m of coastal erosion since the 1960s and has been subjected to various climate change resilience trials. These have seen the construction of sedi-tunnel groynes, detached breakwaters, and revetments. Approximately 2,200 people reside in the villages in this area.

When considering the interventions required to provide coastal erosion protection along the northern coast of Tongatapu, including the Fanga'uta Lagoon, it is important to recognise the large variation in biophysical environments of the coastline, which is due to variables such as wave and wind exposure, local water depth and geomorphology (of the foreshore and coastal landforms), as well as past human usage/impacts. An integrated design approach that considers the coast holistically is therefore required so that the various interventions (hard, soft and hybrid) are compatible with adjacent coastal areas/cells. This will ensure that the

strategy applied along one stretch of the coast does not negatively affect adjacent coastal areas and/or preclude the proposed intervention measures.

The project team's approach to developing the conceptual designs for coastal protection of the northern coastline of Tongatapu includes large- and small-scale measures due to the variety of biophysically different types of coastline and utilises a conceptual model of coastal processes. A conceptual model for this purpose has been developed by considering the information presented in Report 1 of this project, i.e. all the available metocean information. This includes, although is not limited to: (i) long-term wave and wind data; (ii) long-term tidal data; (iii) the 2011 LiDAR survey of Tongatapu (very useful to characterise geomorphology); (iv) existing charts; (v) existing modelling results (e.g. the SOPAC tsunami modelling; (vi) the modelling of the Fanga'uta Lagoon (Mead and McIntosh 2020); (vii) wind/wave modelling (used to develop the Manuka wave climate for engineering design, etc.); (viii) the historical aerial photographs, high resolution satellite images and Google Earth images; and (ix) climate change projections for Tonga to 2030 and 2050, etc. (see Mead et al. 2020a). The conceptual model of coastal processes for Tongatapu is presented in 5.

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Figure 1-4. The five study sections along the northern coastline of Tongatapu, Kingdom of Tonga. (Google Earth, 2020). Coastal Unit 1 = red, Coastal Unit 2 = yellow, Coastal Unit 3 = blue, Coastal Unit 4 = magenta and Coastal Unit 5 = green.

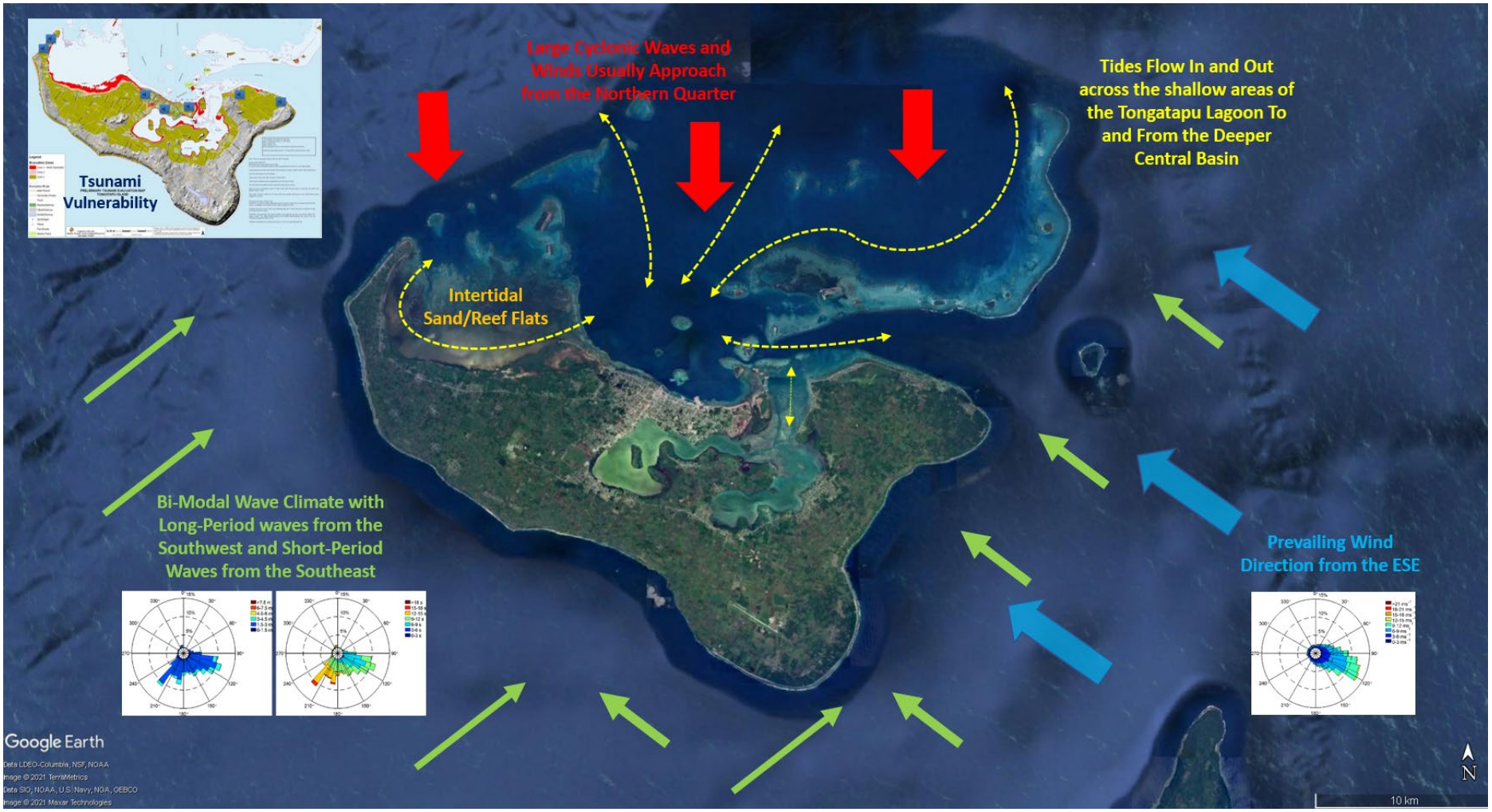

Figure 1-5. Conceptual model of Tongatapu coastal processes. The wave climate is bi-modal with long-periods swells arriving predominantly from the southwest and short-periods swells predominantly out of the southeast due to the dominant ESE wind climate. During the wet season (November to April), Tongatapu occasionally experiences cyclonic waves and winds out of the northern quarter. Tides flow in and out across the shallow areas of the Tongatapu Lagoon to and from the deeper central basin.

1.3 Mangroves

Mangroves are a significant component of the coastal protection measures proposed for implementation in this project. With respect to re-establishment of the mangrove 'green belt', replanting mangroves is a recommendation for areas within all five coastal units along the northern coast of Tongatapu, noting that not all areas within each coastal unit are conducive to mangrove planting (e.g. the northern Nuku'alofa foreshore and beaches). Mangroves are well-known to effectively protect coasts from wave action, wave-set-up, storm surge and tsunami (e.g. Figure 1-6), and have a range of additional environmental benefits, from high productivity and biodiversity through to carbon sequestration.

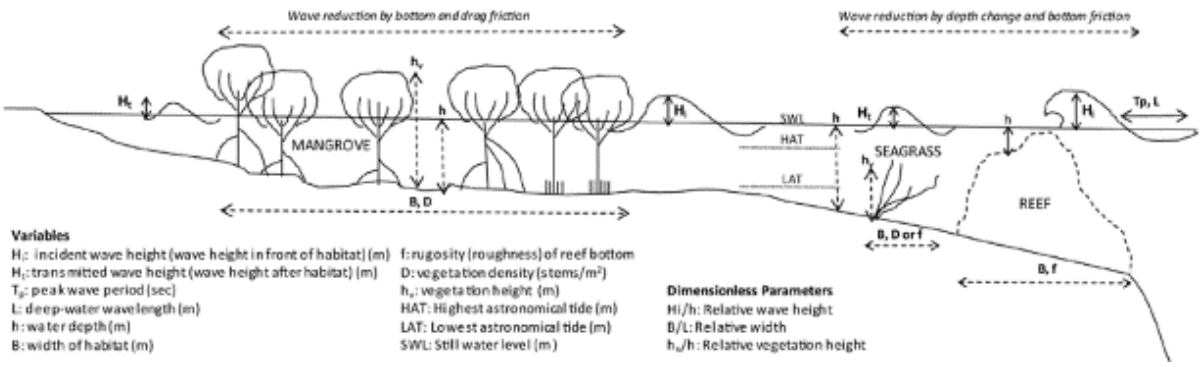

Figure 1-6. Schematic of wave height reduction across coastal habitats. Schematic shows general mechanics of wave height reduction through habitats using the examples of mangroves, seagrass, and coral reefs (Narayan et al. 2016)

Mangroves have been found to provide coastal resilience globally, through wave height attenuation and dampening, and have been shown to provide protection from erosion by tropical cyclones and tsunami where healthy stands exist. Mangroves are also important ecosystems with high biodiversity (partly driven by experiencing the two different states of high and low tides), and high productivity (which is important to nutrient inputs into tropic waters). They also provide valuable habitat, breeding and foraging areas for a wide range of marine species and avifauna (including many species associated with the outer coral reefs).

With respect to increasing climate change resilience of the northern Tongatapu coastline, replanting mangroves has an additional benefit associated with carbon storage, i.e. the main pollutant driving climate change and sea-level rise. Mangroves can reach maturity in ~20 years in favourable locations, which means that they have the potential to provide protection within the 10- and 30-year timeframes that this project is targeting. The first part of Appendix A provides more details on mangroves.

1.4 Nature-based solutions

The second part of Appendix A includes a review of nature-based solutions (NBS) for coastal protection. Many of the recommendations to increase climate change resilience for the northern coast of Tongatapu are in the category of 'hybrid' solutions that combine managed NBS (e.g. planting of mangroves and coastal plant species, sand renourishment) with structural engineering (detached breakwaters, brushwood groynes, bunds, dykes, etc.).

2 Review of the impacts of the Hunga eruption tsunami on the northern coast of Tongatapu and site visits

2.1 Environmental setting

The Kingdom of Tonga lies astride a large and tsunamigenic subduction zone to the east and an associated line of volcanic activity to the west running north-south (Figure 2-1), although it has relatively few records of significant tsunami. The northern coast of Tongatapu is where most of the Tongan population lives, with much of this area being very low and susceptible to inundation, over-topping and erosion during extreme metocean events. This is due to the northwest tilt of the Tongatapu landmass, with the southern parts of the island being >10 m elevation and large areas of the northern parts being only 1–5 m above mean sea level (MSL), which, together with the low-lying land surrounding Fanga'uta Lagoon, is home to most of Tongatapu's population (Figure 2-2).

There are two important aspects to consider with respect to the revision of the 2021 coastal protection report (Mead and Manuofetoa 2021). The first is that tsunami events of the magnitude of the 2022 tsunami generated by the Hunga volcanic eruption are very rare, which NIWA (2022) put into perspective in Figure 2-3. The second is the presence of the shallow ridge that the Tongan archipelago is located on, which restricts the maximum height of tsunamis on the northern coast of Tongatapu (Figure 2-1). Lavigne et al. (2021) demonstrated this with numerical modelling of a tsunami triggered by a voluminous debris avalanche entering the sea in the south flank of Tofua volcano (Figure 2-4).

Based on the work of Caulfield et al. (2011, cited in Lavigne et al. 2021), Lavigne et al. (2021) reconstructed the pre-caldera shape of the volcano with an elevation of 2000 m, with the Tofua caldera rim 500 m in elevation. They simulated an immediate collapse of 74 km^3, which is considered the worst case; the Hunga eruption was considerably smaller, with a collapse of ~10 km^3 by comparison. Close to Tofua, the main wave simulated was more than 200 m high, but the amplitude rapidly decreased, following the inverse of the distance law, because a volcano tsunami is generated very locally, as was the case with the Hunga tsunami. Due to the shallow water (<100 m) that the Tongan archipelago is located in (Figure 2-1), the tsunami wave is deflected and reduced in size on the northern coast; at Tongatapu, the amplitude simulated was lower than 15 m and only 5 m at the southeast sector (Figure 2-4).

A similar reduction of the Hunga volcano eruption tsunami was evident on the northern coast of Tongatapu, where tsunami wave heights of up to 18 m over-topped the western coast, especially the Ha'atafu to Kolovai area, where the bathymetry deepens significantly into very

deep water (Figure 2-1); by comparison, wave heights were mostly below 3 m on the northern coast (Borrero et al. 2022a,b).

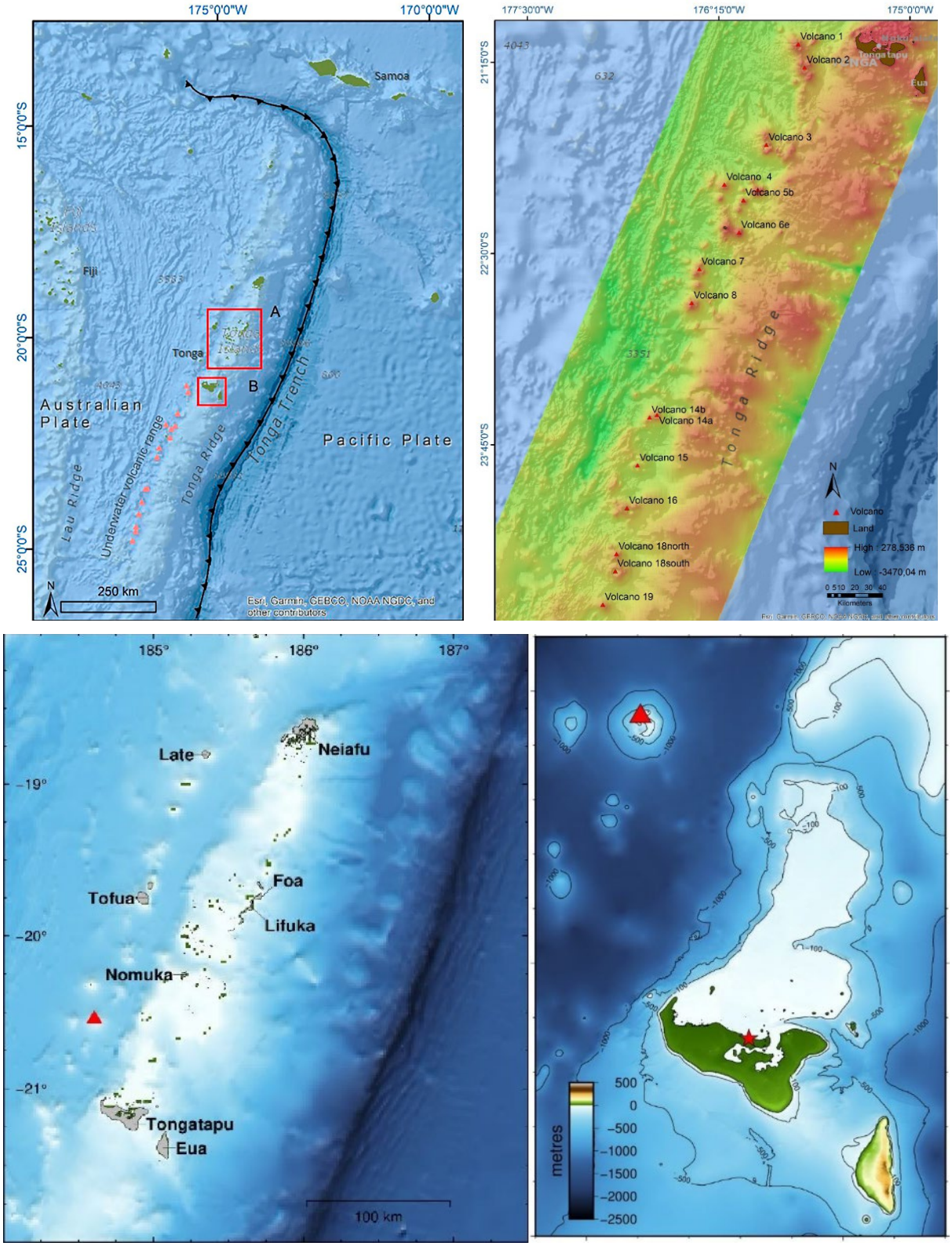

Figure 2-1. The tsunamigenic subduction zone. Top left: The large and tsunamigenic subduction zone, the Tonga Trench, lies to the east of the Tongan archipelago (Lavigne et al. 2021). Top right: The line of active volcanoes to the east of the islands, running north-south (Lavigne et al. 2021). Bottom: The location of the Hunga volcano (red triangle) (Borrero et al. 2022a).

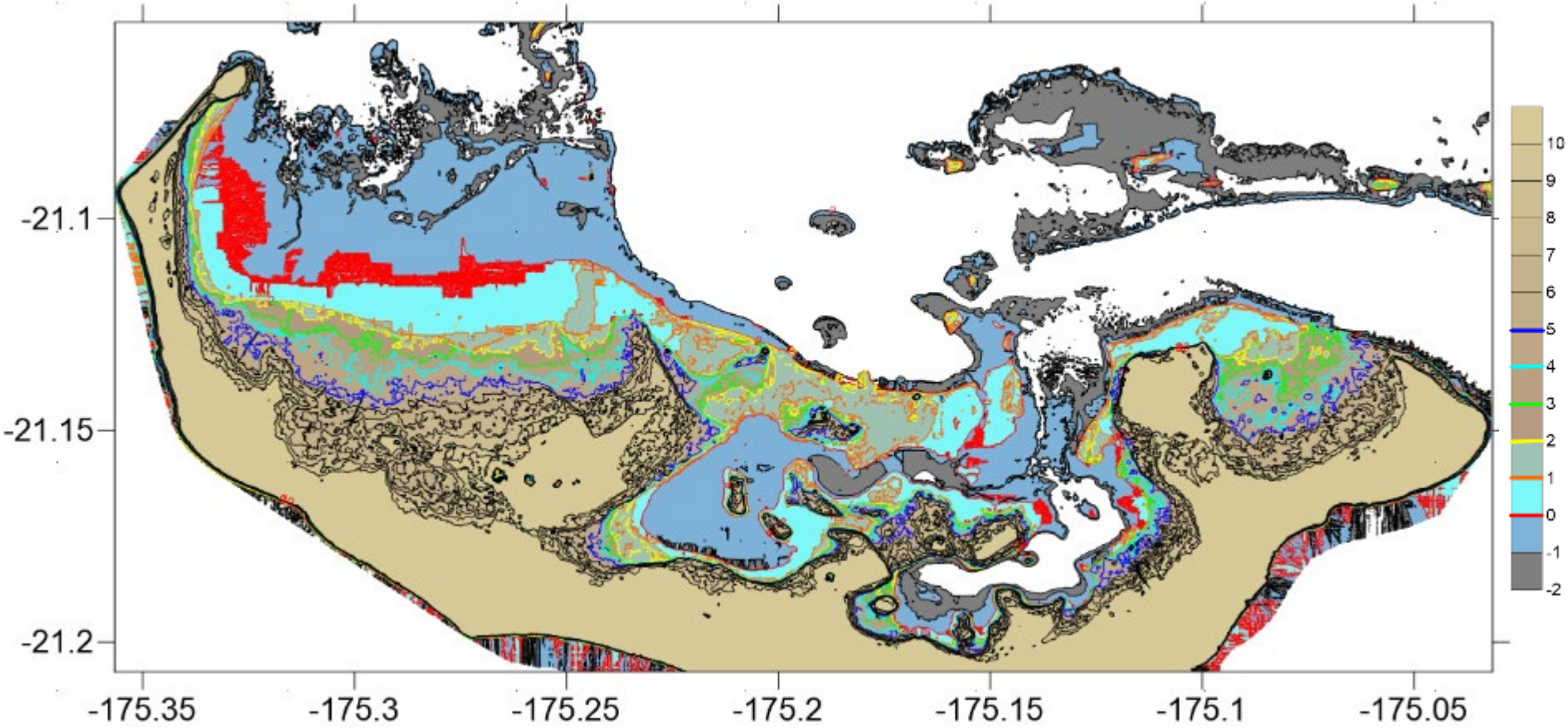

Figure 2-2. The 2012 LiDAR survey of Tongatapu. This clearly demonstrates the northwest tilt of the landmass, with the southern parts of the island being >10 m elevation and large areas of the northern parts of the island being only 1-5 m above mean sea level (MSL), which, together with the low-lying land surrounding Fanga'uta Lagoon, is home to most of Tongatapu's population.

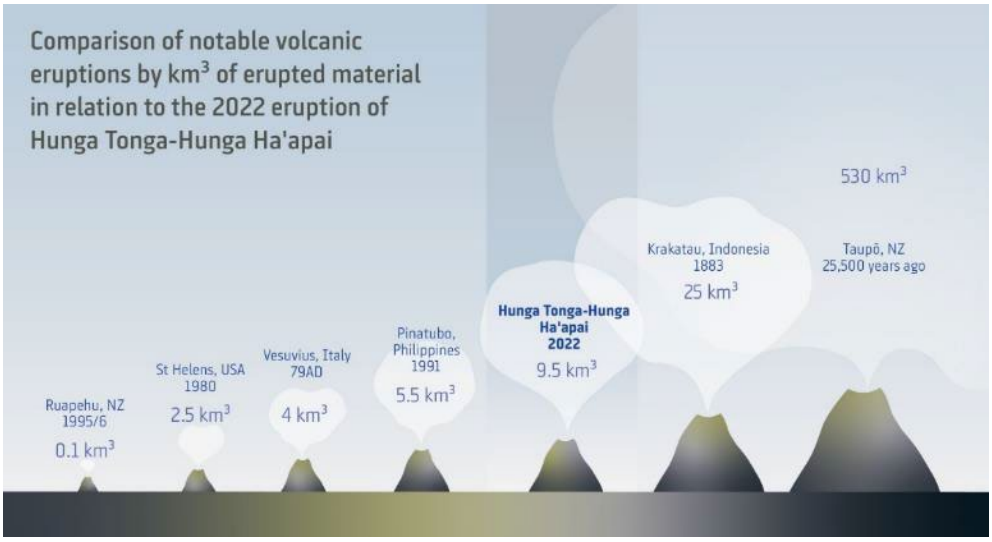

Figure 2-3. Hunga-Tonga Hunga-Ha'apai emitted the biggest atmospheric explosion recorded on Earth in more than 100 years. (NIWA, 2022).

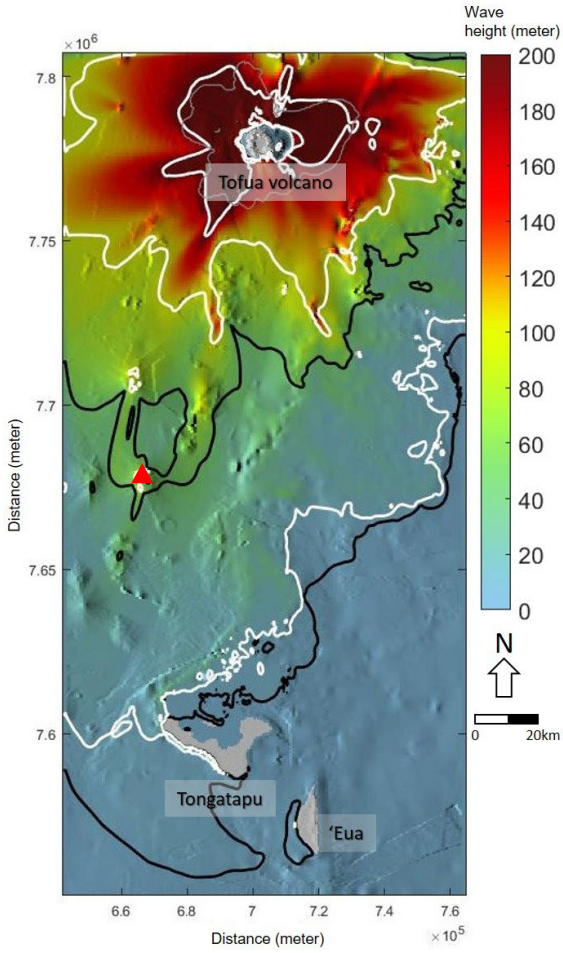

Figure 2-4. Modelling of a tsunami triggered by a voluminous debris avalanche entering the sea in the south flank of Tofua volcano. The shape of the Tofua caldera is a rim, 500 m in elevation.. Based on the work of Caulfield et al. (2011, cited in Lavigne et al. 2021), Lavigne et al. (2021) reconstructed the pre-caldera shape of the volcano with an elevation of 2000 m, and simulated an immediate collapse of 74 km^3, which is considered the worst case; the Hunga eruption was a collapse ~10 km^3 by comparison. Due to the shallow water that the Tongan archipelago is located in (Figure 2-1) the tsunami wave is deflected and reduced in size. At Tongatapu, the amplitude simulated is lower than 15 m and only 5 m at the SE sector. Hunga is the red triangle.

2.2 Tsunami impact review

Borrero et al. (2022a,b) undertook comprehensive field surveys of run-up and inundation throughout Tonga caused by the January 2022 eruption of the Hunga Volcano. Here, we focus on the northern coast of Tongatapu, and also present some of the findings of the run-up and inundation on the western coast. This shows the contrast in wave heights due to the shallow waters on the northern side of the island. Much of the following text has been transcribed from Borrero et al. (2022a,b).

On 15 January 2022, at approximately 4:47 pm local time (0347 UTC), several weeks of heightened activity at the Hunga volcano (Cronin et al. 2017) 65 km northwest of Tongatapu (Figure 1.1), culminated in an 11-hour long violent eruption. During the first 45 minutes of this eruption, a massive atmospheric pressure wave and a series of tsunamis were generated and observed around the world (Carvajal et al. 2022, Lynett et al. 2022). Inspection of the Nuku'alofa tide gauge data from the day before the tsunami indicated a period of sea-level agitation commencing at approximately 1800 hours on 13 January (UTC) and lasting for approximately 24 hours. The main tsunami event commenced at approximately 0425 hrs (UTC) on 15 January with the highest tsunami water level reaching just under 3.0 m relative to the tide gauge's datum in Nuku'alofa (Figure 2-5).

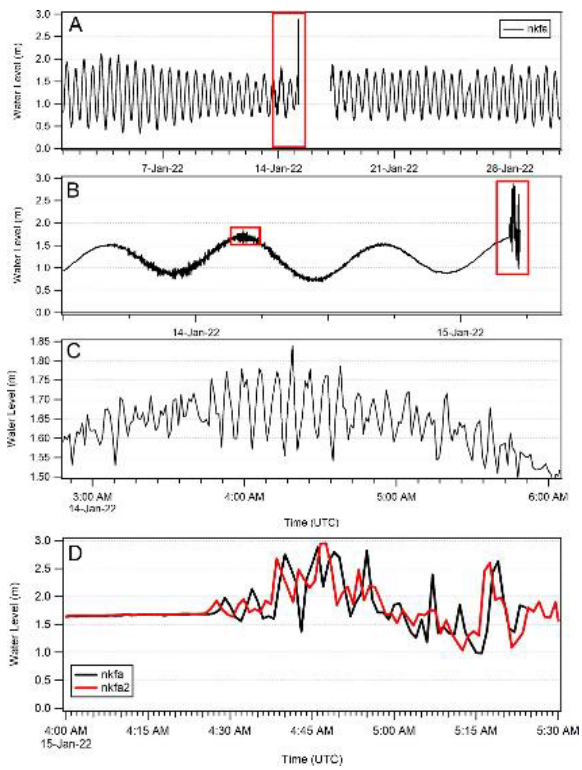

Figure 2-5. Tide gauge water level data from Nuku'alofa. Panel A shows data from January 2022 at Queen Salote. Note the gap in the record commencing shortly after the tsunami arrived. Panel B shows an enlargement of the time span indicated with the red box in A. Small tsunami activity can be seen commencing at ~1800 hrs on from 13 January 2022. Red boxes indicate areas enlarged in Panels C and D. Panel C shows a close-up of

this early tsunami activity with tsunami amplitudes of +/-15 cm. Panel D is a close-up of the main tsunami on 15 January with the data from Vuna Wharf (nkfa2) included. (Borrero et al. 2022a,b)

Over the next three months, the Tonga Geological Services (TGS) collected run-up and inundation data, with the remote assistance (due to COVID-19 restrictions) from a number of international government organisations, NGOs and independent experts. Figure 2-6 shows the locations where tsunami run-up data were collected around Tongatapu and Eua (Borrero et al. 2022).

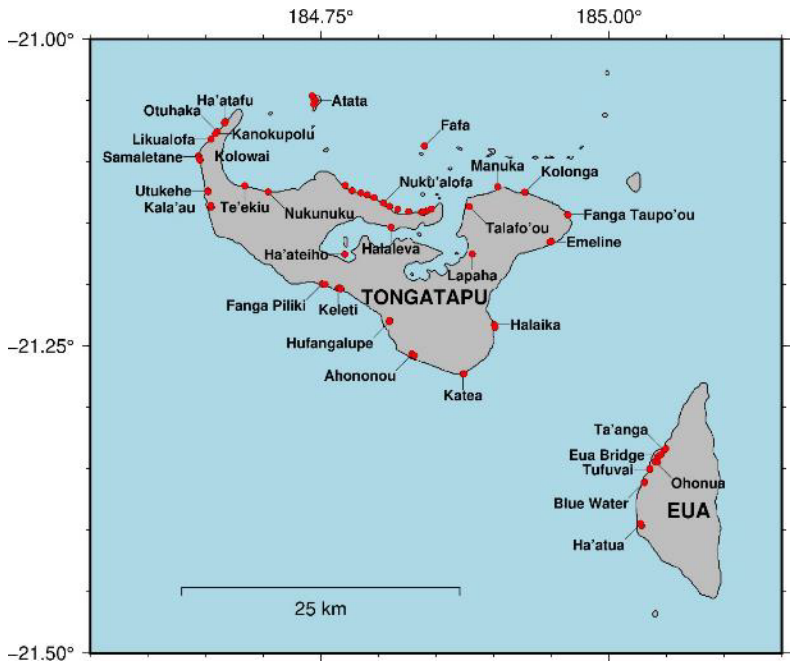

Figure 2-6. Locations where tsunami run-up data were collected around Tongatapu and Eua. (Borrero et al. 2022).

The overall maximum measured tsunami heights are plotted against location in Figure 2-7. On Tongatapu, tsunami waves caused catastrophic damage to the western part of the island with run-up heights greater than 15 m along the Hihifo Peninsula from Ha'atafu south to Utukehe. Maximum measured total tsunami heights of 18–19 m in the vicinity of Kanokupolu and Liku'alofa were recorded. Inundation distances varied greatly, ranging from less than 200 m on steeper coasts where there was no overtopping to more than 1000 m where the tsunami overtopped and inundated the entire peninsula at Kanokupolu (Figure 2-8).

In contrast, in the capital of Nuku'alofa, media reports showed videos of waves crashing over sea walls and flooding houses, suggesting tsunami run-up heights in the order of 3–5 m. These heights were confirmed during this survey (Figure 2-9). Note, no measurements of run-up and inundation were made along the eastern side of the Hififo Peninsula (Figure 2-7), although this area was visited in Oct/Nov 2022 (see the following section).

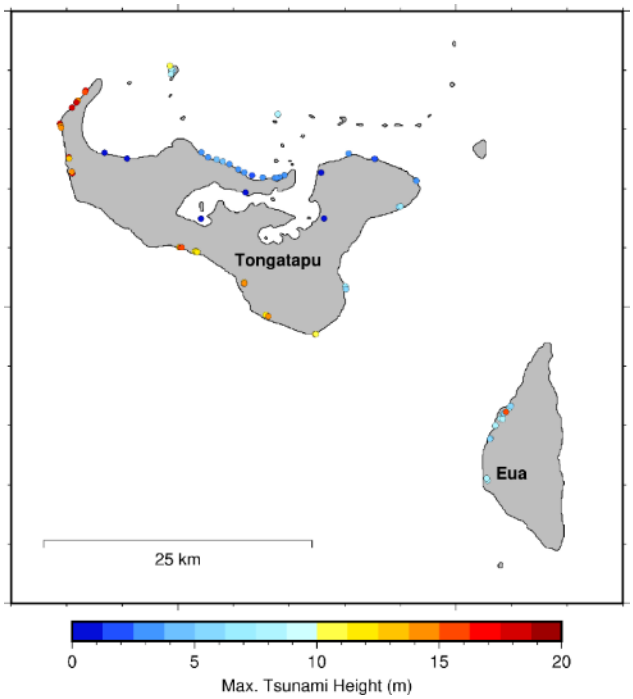

Figure 2-7. Overall maximum measured tsunami heights at Tongatapu and Eua. (Borrero et al. 2022a,b)

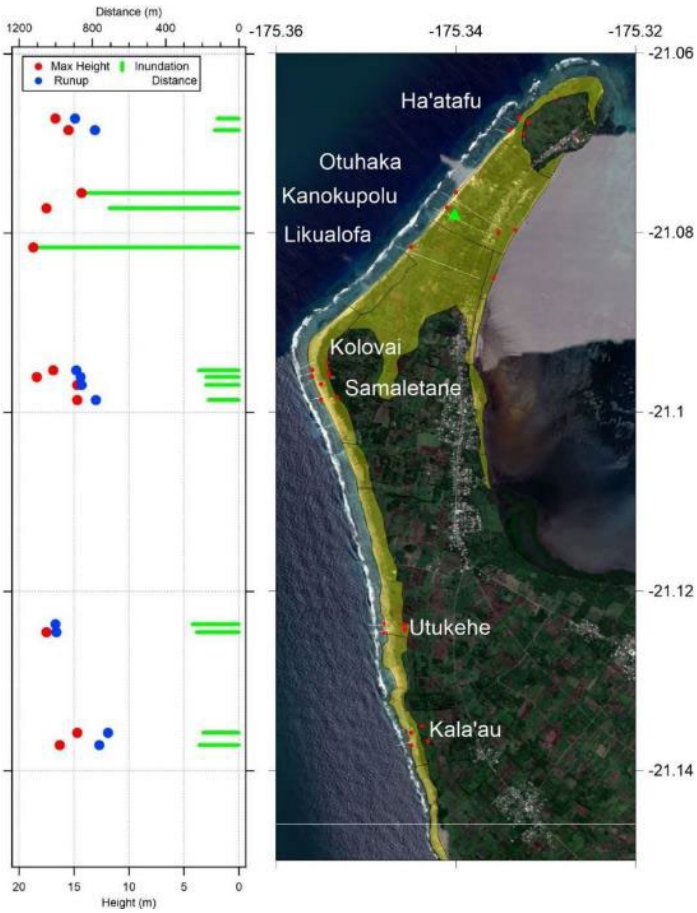

Figure 2-8. Locations surveyed along the western coast of Tongatapu. The start and endpoints of each transect are indicated by the red dot. The yellow shaded area indicates the extent of inundation. The left plot shows the maximum tsunami trace height and the maximum run-up height along each transect; the right plot shows the maximum inundation distance. (Borrero et al. 2022a,b).

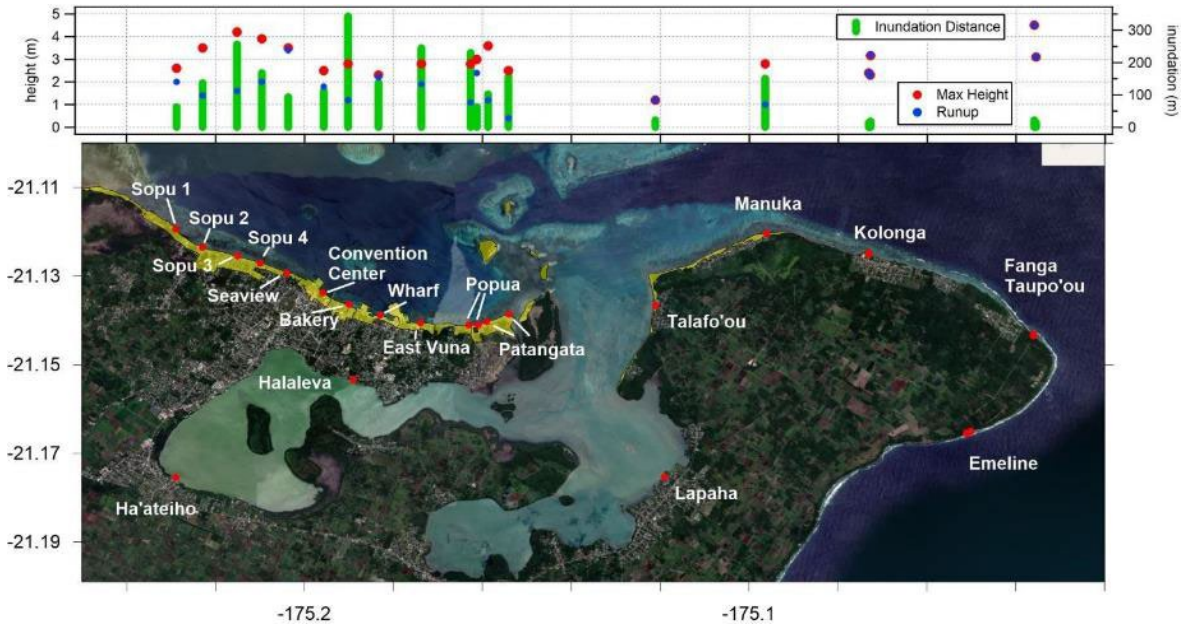

Figure 2-9. Maximum tsunami trace elevation (red) and run-up height (blue) along the north coast of Tongatapu. (Borrero et al. 2022a,b)

Borrero et al. (2022a,b) classified the damage from general observations, which indicate an overall correlation to flow-height/run-up between sites, as well as a clear gradient of destruction from the coast landward. The between site overall damage states were described in four categories as shown below, with the measurements and observations of north coast sites of Tongatapu being within categories 3 and 4 ('Flooding only/non-structural damage', and 'No damage or inundation', respectively).

1. **Near-total destruction** – run-ups >15–20 m, or local flow heights >8–11 m: soils and trees eroded from roots 100–500 m inland; all complex trees gone; many coconut trees destroyed; and all structures and low-vegetation removed up to 700 m from the coast (depending on local topography); very large debris piles (>6 m high). Concrete building foundations, ripped up, undermined and damaged. Examples: Kanokupolu-Liku'alofa, Tonumea and Nomuka-iki.
2. **Building-concentrated destruction** – run-up >8 m, or local flow heights >4–6 m: soils and trees eroded <50 m from beach edge; all houses stripped off foundations and either floating or totally destroyed up to 300 m from beach edge. Concrete foundations remain. Approximately 50% of complex trees toppled, large debris piles (>4 m high). Examples: Nomuka, Mango.
3. **Flooding only/non-structural damage** – Run-up of 1–3 m and low depths generally of 1 m. Structures were flooded, but there was no structural damage. Some fences or unreinforced block walls were toppled. Examples of this were along the Nuku'alofa waterfront.

4. **No damage or inundation** – Examples of this occurred at sites along the shore of the Fanga'uta Lagoon and along the north-facing, mangrove-dense, intertidal coastline of Tahi Toafa (Maria Bay) between Hihifo Peninsula and Nuku'alofa.

In summary, the tsunami along the northern coast of Tongatapu caused maximum run-up and inundation of mostly 1–3 m. There was no structural damage to buildings along the Nuku'alofa waterfront. Some fences and unreinforced walls were damaged, but there were areas where no damage or inundation occurred. This was mostly due to the shallow ridge (<100 m deep) that extends from the northern side of Tongatapu, rather than the source/direction of the tsunami; Hunga is located almost due north of Tongatapu and the shallow ridge and west-to-east reef/island system just off the northern shore of Tongatapu is clearly evident in Figure 2-10.

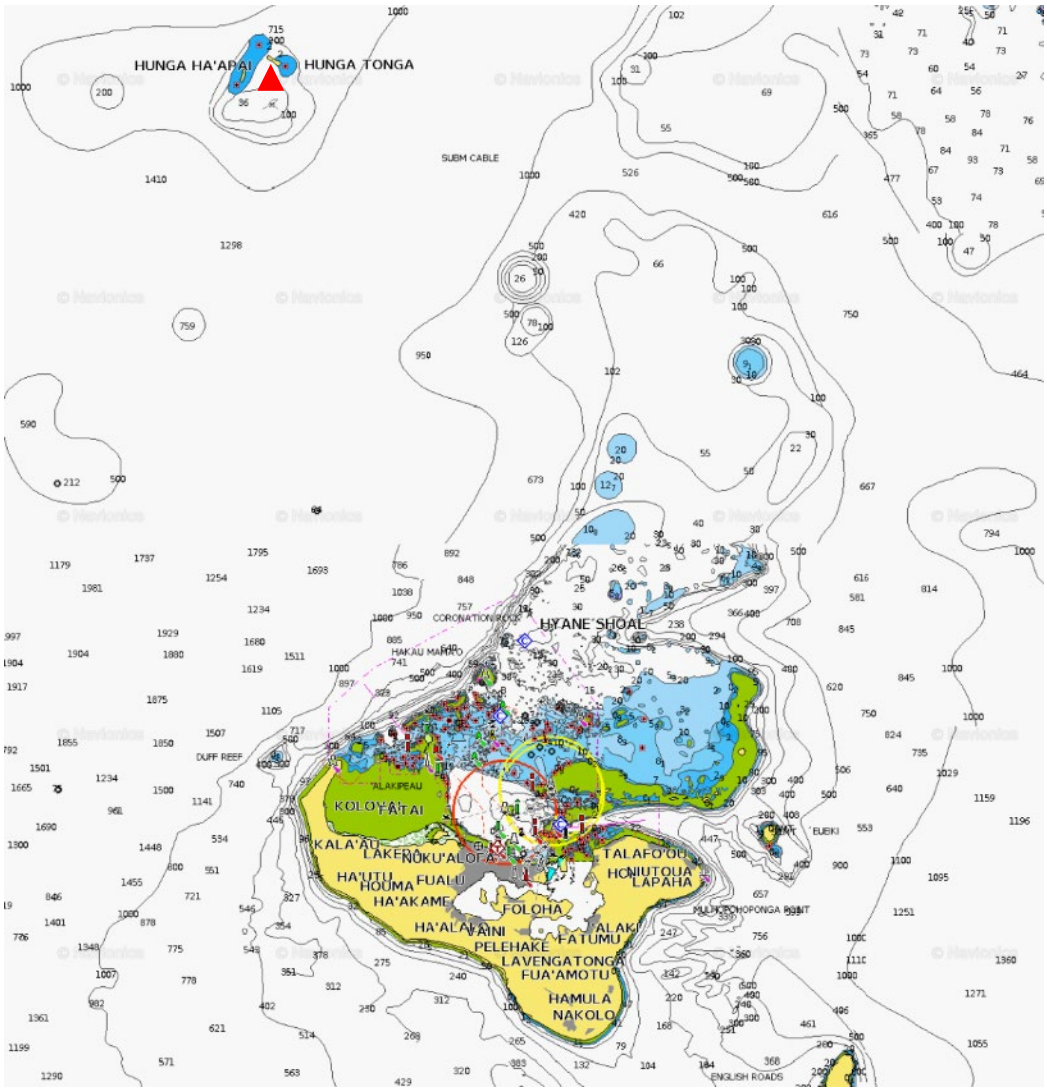

Figure 2-10. The shallow ridge upon which the Tonga archipelago lies. This extends to the north-north-east, with a large area of shallow reefs (<10 m) and islands extending west-to-east off the northern coast of Tongatapu.

2.3 Site visits

Site visits were conducted along the northern coast of Tongatapu in late October/early November 2022. Borrero et al. (2022a,b) found that there was no damage or inundation along three of the five study locations delineated for the coastal protection project (Mead et al. 2021; Mead and Manuofetoa 2021). They are Coastal Unit 1 (the eastern side of the Hihifo Peninsula), Coastal Unit 2 (Foui to Sopu) and Coastal Unit 4 (Fanga'uta Lagoon) (Figure 1-). No damage or inundation was reported along the Foui to Sopu coast, which is protected to the north by the width of the shallow lagoon and mangrove stands of over 1 km in some places (Figure 2-11). Nor was any damage reported around the shores of Fanga'uta Lagoon due to the shallow and constricted entrance (Figure 1- and Figure 2-2). The northern end of the revetment and road was, however, damaged on the eastern side of the Hihifo Peninsula between Ha'atafu to Kanukupolu (Figure 2-11).

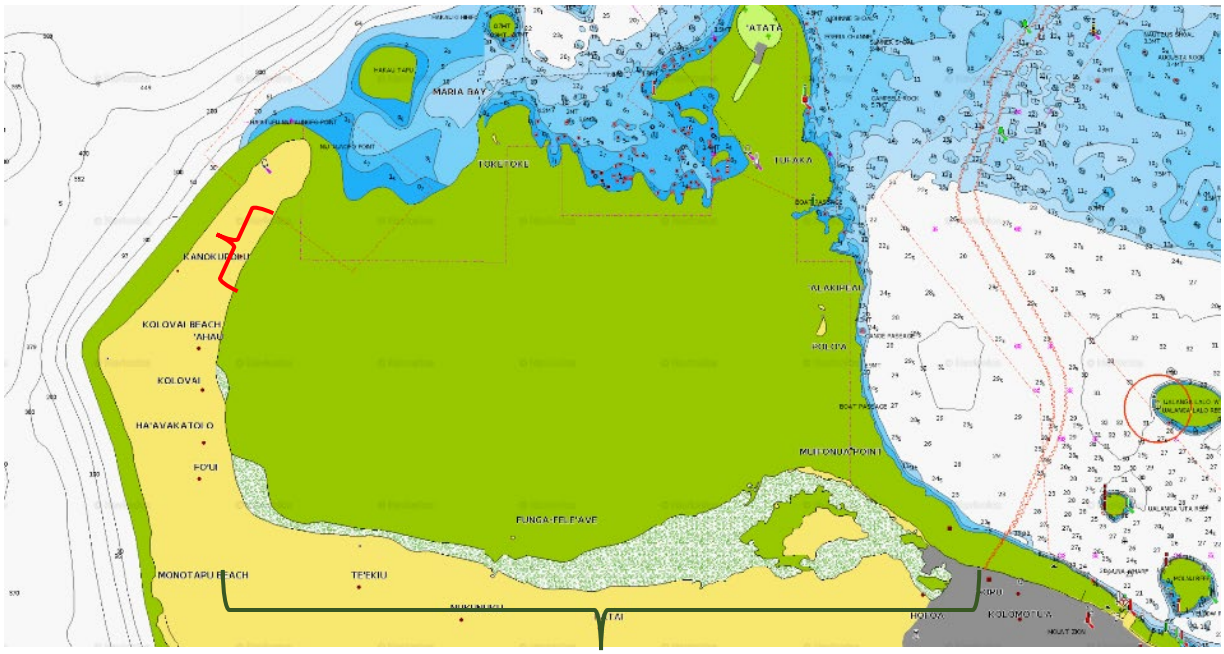

Figure 2-11. The northern coast in Coastal Unit 2 between Foui and Sopu. This (green bracket) is protected to the north by the width of the shallow lagoon and mangrove stands of over 1 km in some places. Eastern Ha'atafu to Kanokupolu (Coastal Unit 1), where the northern end of the revetment and road was damaged by the Hunga tsunami (red bracket).

The damage to the revetment and road between Ha'atafu to Kanokupolu is detailed in Mead and Manuofetoa (2022Work was scheduled to heighten the northern 600 m of the Kanokupolu, following the over-topping that occurred during TC Harold in April 2020. However, the scope of work was extended after the damage caused by the January 2022 tsunami, which hit the northern ~1,350 m of the structure. Revetment rock was removed offshore in many locations along this stretch of the revetment, and several areas were further damaged because of this

and the wash-out of the road behind the revetment, as documented in Appendix A. Construction and repair work began at Kanokupolu in early November 2022 (Figure 2-12).

Figure 2-12. The ‘breaking ground’ ceremony at Kanokupolu in early November 2022.

At Nuku’alofa, there was little remaining evidence of the January tsunami. As noted by Borrero et al. (2022a), the coastal revetment and walkway in Nuku’alofa survived largely intact (Figure 2-13), but some structures in the built-up areas of the Nukualofa waterfront suffered damage typical for a tsunami of this size, that is, toppled walls made of unreinforced masonry and the lower portions of walls being blown out. While there was no major damage, Borrero et al. (2022b) reported that several small boats floated out of the basin and were deposited on dry land, several shipping containers and boats washed back and forth within the port basin, the waterfront roadway in the port area was covered with debris, and the entire area was covered by a thick layer of volcanic ashFigure 2-14).

Figure 2-13. Impacts of the tsunami in Nuku'alofa. Top: An unreinforced masonry wall blown out by the tsunami. Bottom: The coastal revetment and walkway in Nuku'alofa survived largely intact. (Borrero et al. 2022a)

Figure 2-14. Scenes from Nuku'alofa. A) tsunami surge coming ashore on the grounds of the Royal Palace at 17:47 local time. B & C) smaller vessels floated onto the wharf or across the street. D) inundation at the Tanoa Hotel along the waterfront. (Borrero et al. 2022b).

At Coastal Unit 5 (the north-eastern coastal unit comprising the villages of Nukuleka, Makaunga, Talafo'ou, Navutoka, Manuka, Kolonga, Afa and Niutoua), four sites were surveyed, as reported by Borrero et al. (2022a,b), with a gradient of increasing tsunami wave height occurring from west to east. At Talafo'ou on the western side of the lagoon entrance, wave heights were ~1.0 m, increasing to heights of over 4.0 m at Fanga/Niutoua (Figure 2-9) due to the depth of the seabed offshore (i.e. deep water is closer and the coast is more exposed on the eastern end of this stretch of coast (Figure 2-10). However, inundation distances decreased, moving from west to east, because the coast becomes increasingly elevated, which also prevented any damage from eastern Manuka through to Niutoua (Figure 2-9).

At Talafo'ou, where sedi-tunnel groynes, renourishment and coastal planting had been established in 2014/15 as part the earlier phase of SPC's GCCA:PSIS project (Mead, 2014a,b; Mead 2015a,b,c) for coastal resilience, the sedi-tunnel groynes closer to the entrance (i.e. the northern end) were displaced by the January 2022 tsunami, and the low rock seawall was over-topped (Figure 2-15). The displaced sedi-tunnel groynes have since been reinstated (Figure 2-15).

Figure 2-15. Damage to sedi-tunnel groynes and low rock seawall. The sedi-tunnel groynes closest to the lagoon entrance (i.e. the northern end) were displaced by the January 2022 tsunami (top), and the low rock seawall was over-topped (middle). The displaced sedi-tunnel groynes have since been reinstated (bottom).

Along the northeastern coast from the western point to Manuka, inundation distances of over 150 m occurred in some places (Figure 2-9), and the low revetment along the stretch of coast to the west of Navutoka was over-topped and damaged at several points (Figure 2-16). Interestingly, no inundation was reported along the eastern Manuka detached breakwater trial site (Mead et al. 2013b)) (Figure 2-17). It is thought that the detached breakwaters helped dampen the height and prevented overtopping directly landward.

Figure 2-16. Over-topping and damage of the low revetment to the west of Navutoka

Figure 2-17. Overtopping at Manuka. Top: the locations of the over-topping and damage to the low revetment (left/west) and the eastern Manuka detached breakwater trial site (right/east). Bottom: One of the trial detailed breakwaters with the renourished beach and coastal planting in its lee.

3 Interviews and presentations with JNAP Technical Committee and staff of the Department of Climate Change

Interviews and email correspondence were undertaken with as many of the JNAP Technical Committee and staff of the Department of Climate Change/Environment as possible during the late October/early November visit to Tongatapu, as well as following up afterwards. In addition, the updates and proposed priorities were presented to the same group on 29 and 31 May 2023. Due to the government's preparations for COP27, not all members could be interviewed.

Two aspects of the Northern Tongatapu Coastal Protection revision were considered.

- Any insights with respect to particular parts of the coast following the Hunga tsunami, specifically: "From the impacts of the Tonga-Hunga tsunami, do you see any particular areas along the northern Tongatapu coastlines that should be prioritised for coastal resilience measures?"
- Comments on draft priorities for the use of the donor funds under negotiation (T$ 5.5–8.25 M) on parts of the project.

The draft priorities for the use of the donor funds under negotiation included:

- mangrove reinstatement at Foui (Unit 1) – This item includes establishing an additional mangrove nursery and construction of 740 m brushwood fences;
- Kolovai Seawall Extension 356 m (Unit 1) as per the first detailed design report attached (Mead 2021b);
- flood control (Unit 2) – Incorporates some 2.9–3.4 km of seawall and non-return valves for the very low-lying and flood-prone (due to seawater) areas of Nukunuku, Matafonu, Fatai, Puke, Fotua Sopu and Isileli; requires ground surveys;
- revetment repairs and detached breakwaters, extension of bunds and drainage for Seisia and Popua (Unit 3);
- creation of approximately 12 km of dykes to better protect low-lying crop land (Fanga'uta Lagoon – Unit 4); and
- all recommendations for Unit 5; including 900 m of seawall and non-return valves, 2.5 ha of mangroves with 1.6 km of brushwood fences, pig control fencing, a mangrove nursery, 17 additional sedi-tunnel groynes, 3,000 m^3 of renourishment from the point, 3 detached breakwaters and 1 km of coastal planting.

In general, all the participants of the interviews agreed with the proposed use of the donor funds under negotiation and had little to add with respect to lessons learnt from the tsunami, although the buffering potential provided by wide mangrove stands (such as in Coastal Unit 2) was widely recognised, along with the additional benefits of carbon sequestration that mangroves provide. Another aspect that was repeated was the need for a whole-of-government approach in order to successfully implement recommendations in the Northern Tongatapu Coastal Protection strategy, with associated monitoring and evaluation, as well as educational outreach.

Several additional changes/modifications to the revision of the Northern Tongatapu Coastal Protection strategy were identified, some of which affect the draft priorities presented. These are presented in Section 9.

3.1 Nuku'alofa coastal protection

Discussion with representatives from the Ministry of infrastructure identified a project currently being undertaken by the Japan International Cooperation Agency (JICA), namely, repairs and extensions to the Nuku'alofa revetment that were recommended as part of the donor funds under negotiation As noted above, the recommendations in the Northern Tongatapu Coastal Protection strategy (Mead and Manuofetoa 2021) included revetment repairs and detached breakwaters, extension of bunds and drainage for Seisia and Popua, as well as coastal works on the western/Sopu end of the foreshore. Gaining an understanding of the extent and nature of JICA's proposed works on the foreshore will be important for finalising the revised Northern Tongatapu Coastal Protection strategy.

3.2 Future development of Pangatangata/Popua and Nukunkumotu Island (Seisai)

As described in the Northern Tongatapu Coastal Protection strategy, the eastern end of Nuku'alofa, from the northern seaward coast to the lagoon coast in the south, has been extensively modified in the past five years. This has seen breakwaters/seawalls and drainage channels constructed, both on the mainland (Pangatangata/Popua), as well as on Nukunkumotu Island (Seisai), for settlement. At the time of writing, there was some uncertainty with respect to plans for Siesia and Popua. If these new settlements are to be continued, which was an important question for the Government of Tonga, then several actions are required to improve climate change resilience in the 10 and 30 year planning horizons.

The recommendations were for planning and continuation of bunds/seawalls. Drainage around the settlements would provide some resilience in the next 10 years. However, due to the low-lying nature of the area, flood-gates requiring regular maintenance will be needed to prevent tidal inundation and allow for stormwater from heavy rainfall. Pump-stations will also likely be a necessary part of the drainage scheme. It was recognised that this would require planning extensive works – a lot of development has occurred in this area over the past 20 years (especially in recent years) and extensive flooding of properties is occurring throughout south-eastern Popua. Bunds created from material on site would likely be sufficient for Popua and the southern parts of Seisia to prevent inundation, although the northern coast of Seisia is vulnerable to erosion. Northern Popua is protected by the revetment at Pangatangata. It was recommended that detached breakwaters along the ~300 m of recent occupation would provide erosion protection and reduce inundation hazards for Seisia.

In addition, it was recommended that, over the longer term, a decision on whether to retreat from this area or further increase its resilience is required. In order to provide climate change resilience to these areas, large scale reclamation and filling is required (e.g. as is being considered in Kiribati, Tuvalu and the Marshall Islands).

Since finalising the Northern Tongatapu Coastal Protection strategy in February 2021, the Tongan government has been developing a master plan for this area which will be submitted to cabinet. The plan includes prioritising mangroves and reinstating the area that was flattened for a golf course, developing a culture centre for tourism, and creating more recreational space. There is currently a mangrove nursery for this area, although more Rhyzophera are needed, and some design/planning is required with respect to where to replant mangroves to develop a buffer to sea level rise and climate change impacts.

Planning and design for this area is linked to potential restoration of the lagoon, which is very poorly flushed due to the shallow entrance (which has gotten shallower due to sediment run-off in the past 40–50 years) (Mead et al. 2020 & 2022).

3.3 Fanga'uta Lagoon

Several respondents were concerned with the state of the Fanga'uta Lagoon, which has significantly degraded since it was given marine reserve status in 1974. Unfortunately, the marine reserve status was never enforced, and it was a similar case following the lagoon management plan in 2001; while the degradation since 1974 has continued (Mead and Loumoli 2020).

The Fanga'uta Lagoon catchment area is home to over 55% of Tongatapu's population (over 40,000 people in 8,000 households) (GoT 2011; cited in Talia'ul et al. 2016). The importance of this area and its value to people is not always considered on a day-to-day basis by national planners or residents. Many of the communities within the lagoon area are dependent on the ecosystem services the lagoon provides for their livelihoods and wellbeing (Talia'ul et al. 2016).

The lagoon is considered a life-support system for communities, providing a wide range of marine and intertidal values. It has provided goods such as mangrove wood (fuel), medicines, fish, seaweed and shellfish for generations (Morrison and Kaly 2010). In recent years, however, yields have dropped and some species are no longer sustainably exploited. For example, mangroves have been exploited and areas reclaimed (Pelesikoti et al. 2001a cited in Talia'ul et al. 2016). Simply put, the lagoon has been overfished and badly degraded, with degradation ongoing.

The main cause of the degradation is sediment run-off and stormwater and wastewater discharge into the lagoon. This is exacerbated by the very low flushing rate and shallowness of the water body. Recent numerical modelling indicates that complete flushing of the Pe'a sector and the Nuku'alofa branch of the lagoon could take roughly 140 days (Mead et al. 2020), which, due to the increasing population around the lagoon, has led to high rates of sedimentation, elevated nutrient levels and high levels of pollutants; consequently, a very degraded marine environment.

The 2015 baseline studies found that "pollution in the lagoon is severe, coming from sewage, illegal rubbish disposal, agriculture and chemical use". These land-based sources of pollution enter the lagoon through groundwater and surface run-off. The baseline studies describe a lagoon that has murky waters, with fish kills and green algae growing on the sea grasses and coral in a process known as eutrophication (Figure 3-1). Extremely high levels of arsenic, copper and chromium have been found on a Tonga Forest Products site at Tokomololo and in other areas.

Figure 3-1. The Pe'a sector of the Fanga'uta Lagoon at the end of the Nuku'alofa branch. This sector has the highest population density and lowest flushing times (~140 days), meaning that today it is eutrophic and polluted with low biodiversity and abundance of marine life (Mead and Loumoli 2020).

Part of the issue is due to an uplift event of 20–40 cm that occurred within the entrance area some 80–240+ years ago, which created a damning effect at the entrance. This uplift likely increased the rate of infill due to greater residency. In addition, sea-level rise rates in the Tongan region are presently estimated at ~10 mm/year (Church et al. 2006), further shallowing the lagoon system.

While the health of the Fanga'uta Lagoon may not be considered directly associated with coastal protection of the northern Tongatapu coastline (of which the lagoon is part), the physical changes that have led to the ecological degradation of the lagoon waters do affect flooding susceptibility around the coast of the lagoon. National Emergency Management Office (NEMO) has installed pump stations and outlets into the lagoon to reduce flooding during extreme events, although sea-level rise and continued sedimentation will continue to reduce the efficacy of this approach.

Dredging of the shallow entrance to the lagoon (Figure 3-2) was suggested by several respondents, to both assist with flushing and recovery of the biological status, and to reduce flooding due to heavy rainfall. A calibrated numerical has been established for the lagoon (Mead et al. 2020 & 2022), which could be applied to investigate the potential to dredge the

entrance to increase lagoon flushing. This is recommended before considering dredging, since it is a very complex water body, and there is the potential to exacerbate flooding during particular extreme events so various dredging and extreme event scenarios would require testing. In addition, the construction of dykes/bunds and mangrove replanting where the belt is narrow to reduce inundation of crops in the central area of the lagoon (Unit 4 in Section 7), would also reduce sediment and nutrients into the waterbody.

Figure 3-2. The entrance of the Fanga'uta Lagoon. This entrance (top right) is very shallow, with only one continuous narrow (~50 m in some parts) channel connecting it to the open sea. The colouration of the water indicates the eutrophic state of the western end of the Nuku'alofa branch (the Pe'a sector).

3.4 Revisions to the 2021 Report

As noted above, there are two important aspects to consider with respect to the revision of the 2021 coastal protection report (Mead and Manuofetoa 2021). The first is that tsunami events of the magnitude of the 2022 tsunami generated by the Hunga volcanic eruption are very rare, although Tonga lies astride a large, tsunamigenic subduction zone to the east and an associated line of volcanic activity to the west running north-south. The second aspect to consider is the presence of the shallow ridge that the Tongan archipelago is located on, which restricts the maximum height of tsunamis on the northern coast of Tongatapu (Figure 2-1).

This was demonstrated with numerical modelling of a tsunami triggered by a voluminous debris avalanche entering the sea due north of Tongatapu with an event ~7.5 times greater than the Hunga eruption (Lavigne et al. 2021).

Even so, the damage caused by the January 2022 tsunami along the northern Tongatapu coast have focused further attention on its coastal protection, with several aspects of the 2021 Northern Tongatapu Coastal Protection being proposed for revision.

The proposed revisions include:

- recognition of the benefits of mangrove re-establishment for tsunami protection, coastal protection and SLR/CC resilience;
- incorporation of JICA's proposed Nuku'alofa foreshore works to the Unit 3 revisions;
- incorporation of the changes to the revised report to reflect the strategy for the Popua area based on the master plan;
- further recognising of the issues with flushing of the lagoon, water quality and biodiversity as part of coastal resilience; and
- development of a monitoring and evaluation and education section in the revised report.

These revisions are incorporated into this updated report for Northern Tongatapu Coastal Protection.

4 Concept design – Coastal Unit 1: Ha'atafu to Foui

4.1 Biophysical setting

Village names are shown in Figure 4-1. As described in Mead et al. (2020a), this section of coastline is mostly less than 2.0 m above high tide and is vulnerable to inundation hazards from northerly storms and susceptible to storm surge. The coastline faces east towards the shallow western section of the Tongatapu Lagoon, which helps dissipate incoming wave energy. This shallow area/lagoon is about 10 km east-west and 5 km north-south (Figure 4-2 and Figure 4-3).

The nearshore environment largely consists of the rocky reef flats of the shallow western section of the Tongatapu Lagoon. These rocky reef and sand flats are largely exposed to the north and are overlain by sediment to the south. The south is a low-lying, low energy environment and is suitable mangrove habitat.

The bio-physical environment has been greatly influenced by humans. The northern section, Ha'atafu, has a relatively high elevation and rocky coast, and so is not vulnerable to inundation and erosion like the rest of this coastal unit. A mangrove belt once fringed the entire coastal unit. Mangroves near villages have been removed for various reasons and land has been reclaimed. The development of a wetland in the northern section occurred around ~1968 and a revetment/coastal road was constructed soon after (Howarth 1983). The wetland is currently disconnected from the open coast.

Various climate change resilience projects have been implemented in this coastal unit, which has seen revetments constructed from Kanukupolu in the north to A'hau in the south to prevent inundation and coastal erosion; wooden groynes and fences to protect mangrove seedlings and prevent damage by foraging pigs in Kolovai and A'hau; and a seawall along the Kolovai road with discharge outlets to prevent inundation and sustained flooding. Mangrove stands and wetlands are located in the south of the area.

LiDAR from 2012 confirms that the topography of the coastal unit is generally low lying, except for the northern area (Figure 4-3).

- At Kanokupolu the whole village is very low-lying (much <1 m above high tide).
- At Ahau most of the village is very low-lying (<1–2 m above high tide).
- At Kolovai the village area east of the main road is very low-lying (<1–2 m above high tide).
- The villages Ha'avakatolo and Fo'ui are mostly >2 m above high tide, except for a few properties that are on the most eastern edge of the mangrove fringe.

- Ha'atafu is located >4 m above high tide and is not considered vulnerable to coastal hazards.

A conceptual coastal processes model for Coastal Unit 1 is presented in Figure 4-4.

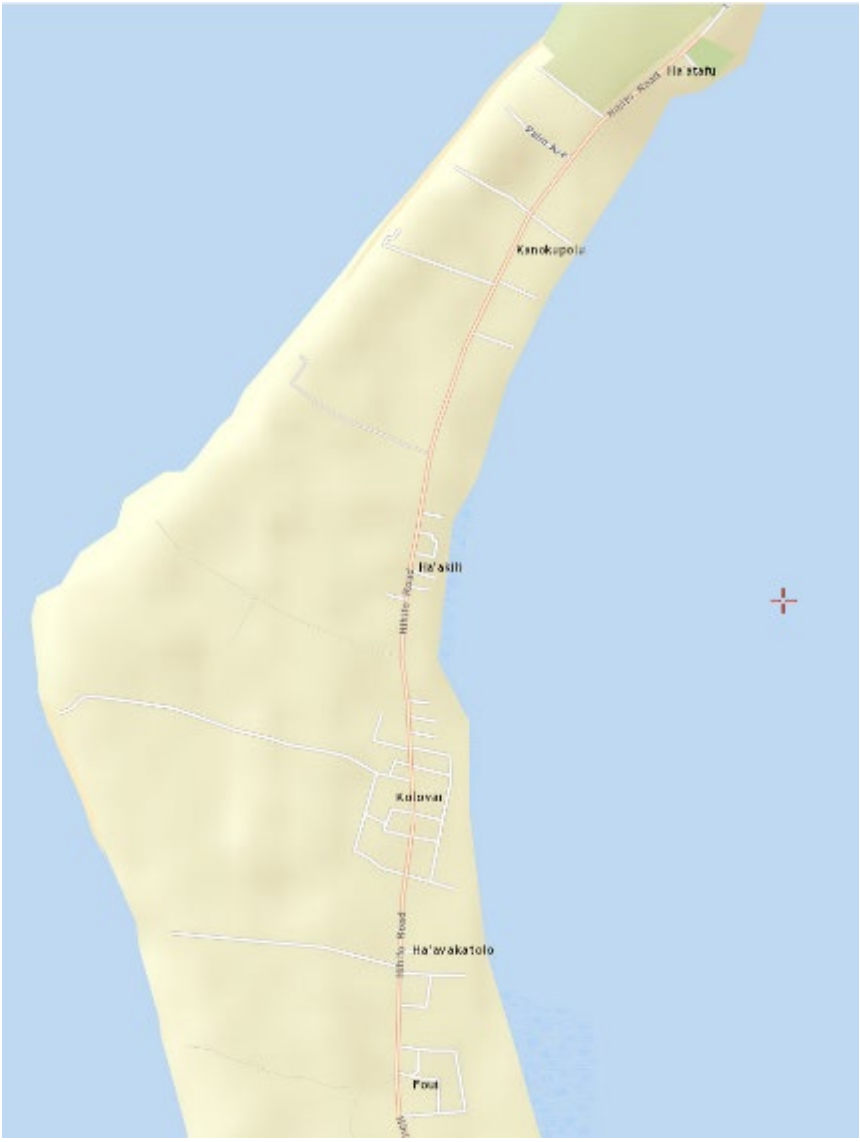

Figure 4-1. Street map of Coastal Unit 1. (https://satellites.pro/plan/Tonga_map#E-21.092008,-175.322850,15)

Figure 4-2. Location map of Coastal Unit 1. This unit (red line) is on the north-western coastline of Tongatapu between Ha'atafu and Foui (Google Earth 2020)

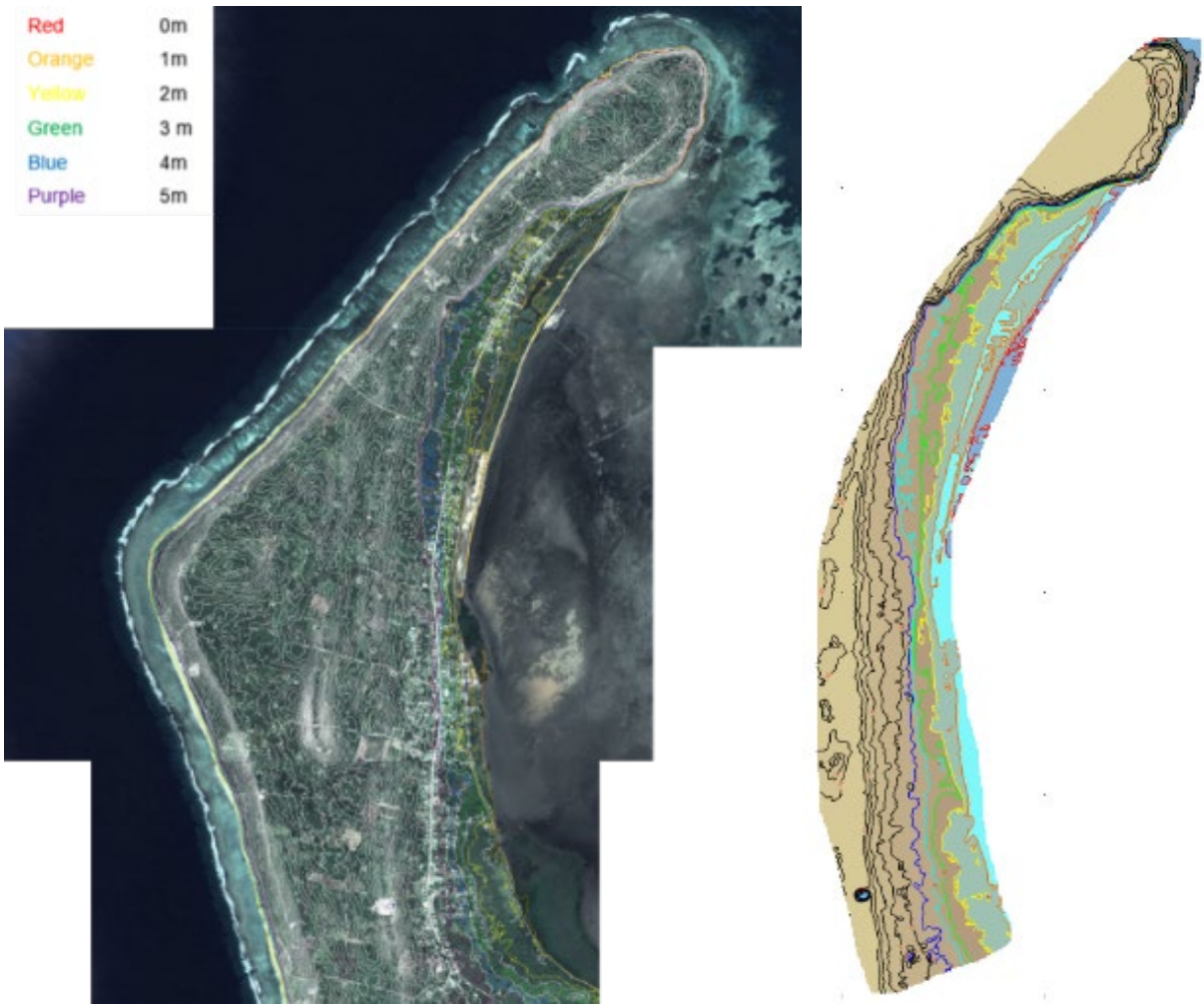

Figure 4-3. 2012 LiDAR of Coastal Unit 1. (Modified from Mead & Atkin, 2014)

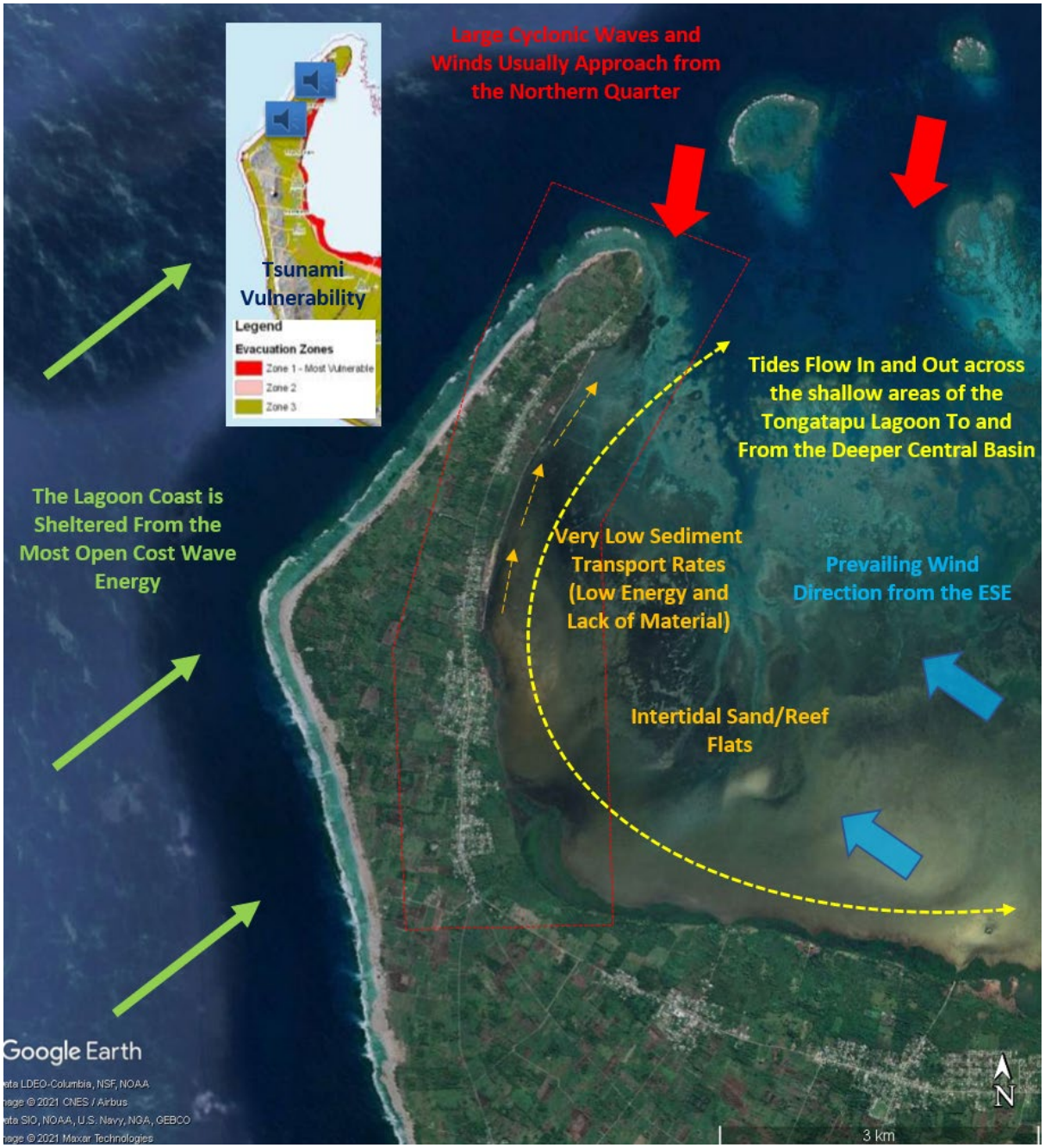

Figure 4-4. Conceptual coastal processes model for Coastal Unit 1

4.2 Existing coastal protection works and coastal hazards

The first coastal protection works were undertaken in this coastal unit in the late 1960s (Howarth 1983), and a series of recommendations – and implementation of some of the recommendations – has been ongoing since 2014. These are detailed in Mead et al. (2020a), and so are not repeated here. However, of note is the SSL's (2014a, b) recommended strategy for the Hihifo District, with many of these recommendations being modified/expanded on and

implemented until early 2020 (Mead and Atkin 2014; Mead 2018). SSL's (2014a) recommendations are summarised below.

a) Promote a district-wide green buffer coastal flood management intervention, involving a focused programme of mangrove planting.
b) Promote the improved establishment of mangroves in higher energy environment locations through the use of bamboo breakwaters or groynes to help reduce wave energy and to encourage fine material settlement along the Hihifo nearshore zone to enable mangrove propagules and juvenile trees to establish themselves.
c) Encourage the promotion of mangrove nurseries within the newly created wetland systems for each village (community ownership and responsibilities being established).
d) Construct secondary backing defences through the use of large sandbags (partly filled with cement) to improve resilience of the structure and for these structures to be placed in the quieter backwaters of the wetland lagoon areas of Kanukopolu and Ahau (cited in Mead *et* al. 2014).

These were expanded on in SSL (2014b), where rehabilitating mangroves for the whole area is recommended. Development of a green buffer along the coast involved the following sub-engineering components to ensure that the integrated concept of the green buffer would work:

a) improved community management of existing brackish wetlands at Kanukopolu and Ahau;
b) improved engineering management of the existing community coral block wall (from south of Ha'atafu southwards to Ahau village), creating "flushing gaps" in the defence to allow improved tidal circulation, which in turn will encourage improved water quality and hence create a more suitable environment for mangrove rehabilitation;
c) installation of bamboo groynes and breakwaters to act as "energy dampeners" along the coast to enable fine sediment accretion and thus help aid mangrove rehabilitation to occur in more higher energy tidal areas of the Hihifo coastline (namely the southern end of Ha'atafu, Kolovai and Ha'avakotolo, Fo'ui);
d) strategic placement of backing defences within the lagoonal areas (not high energy coastal areas) using large sandbag defences (or similar);
e) existing natural ecosystems to be preserved and, in other locations, the natural terrain and vegetation should be restored as far as possible, keeping visual effects also in mind;
f) The natural littoral woodland species will be the most used species because sandy shores border most of the peninsula.

g) wherever mangroves have been damaged or depleted, they should be rehabilitated and enhanced, and wherever they have been destroyed, they should be restored;
h) introduced/exotic species should be excluded;
i) footpaths through mangrove forests should preferably be raised board walks, to ensure minimum disturbance to the mangroves; and
j) at least a 15–20 m wide strip of natural littoral woodland and strand plants should be planted seaward of agricultural crops. Imitation of the typical plant species mix and distribution in the natural community would be the best, and natural vegetation should be integrated, not removed.

In late 2014, the first work, with a budget of USD 650 K, was undertaken in this coastal unit. These recommendations are detailed in Mead and Atkin (2014), with an important part of the overall strategy being the protection of existing parts of the mangrove green belt (e.g. the area to the north of Kolovai, and in front of Ha'avakatolo and Foui). However, most of the budget was used for remediation of the revetment, and only the works described below were undertaken.

1. At Kanokupolu – rehabilitation and maintenance of the existing revetment and incorporation of culverts with non-return systems to allow lagoon drainage.
2. At Ahau – opening the spit-lagoon to allow for more flushing in two locations, which was considered vital for the establishment of mangrove nurseries (two fenced areas within the lagoon) to supply the green belt development (these were not established). The low height of the existing revetment is to be built up to high tide with plantings behind (hibiscus/casuarina), and a single detached breakwater was also trialled to consider sand-trapping efficacy.
3. At Kolovai – none of the recommended works were undertaken (i.e. the beach was to be planted with hibiscus/casuarina trees, and four long groynes were proposed at this location, which is less exposed than locations to the north, with mangrove seedling trials from the Ahau nurseries in between the groynes.
4. At Ha'avakatolo – none of the recommended works were undertaken (i.e. two T-groynes for re-establishment of the mangrove green belt were to be trialled, the results of which would be compared to the adjacent Kolovai mangrove trials to determine the efficacy of T-groynes versus straight groynes).
5. At Foui – the village is mostly >3 m above high tide, and the area of proposed intervention is ~2 m above high tide, so planting of suitable coastal plants was recommended, although not implemented.

In late 2018, a further € 500 K was spent to carry out the coastal protection works in Coastal Unit 1 at A'hau and Kolovai through the EU-GIZ ACSE project (Mead 2018). These works included:

- reinforcing the existing A'hau barrier by the addition of armour rock;
- providing better flushing through the A'hau lagoon behind the barrier by opening a new entrance in the south, widening the existing entrance in the north, and removing the access road across the middle of the lagoon;
- building of a seawall at Kolovai to reduce inundation of properties during extreme metocean events;.
- ensuring that stormwater could be discharged to the sea (i.e. through the seawall) during extreme rain events to prevent flooding by strategic placement of non-return valves;
- building a wooden-stick groyne to provide a protected area for mangrove seedlings to be established; and
- using strategic fences to keep pigs out of the mangrove restoration areas.

Many of these initiatives were undertaken, and the stick groyne has proven successful at protecting mangrove seedlings so that they can grow along this coast that is regularly exposed to wind-generated waves at high tide.

GCCA+ (2021a) recently evaluated the performance of the climate change resilience works carried out along the Hihifo coast described above. The evaluation concluded that:

> The construction of the Kolovai Seawall and the Ahau Foreshore that were supported by the EU-GIZ ACSE project has restored some sense of security for these coastal communities. These adaptation measures have acted to safeguard the lives of nearly 800 people living in these areas.
>
> Despite the good news, there are compelling challenges reported by the community members and require urgent attention. The report on the water penetrating the seawall and entering nearby properties should be addressed urgently. The issue with the flip gate valves should also be addressed, otherwise, the community will continue to suffer.
>
> With regard to the 'Ahau foreshore, the concept appears to be working with few challenges, but this is to be expected as the impacts of climate change, particularly sea level rise, are known to be unpredictable.
>
> The biggest challenge with 'Ahau, however, is the fact that the community members are divided. This needs to be resolved first because, if these differences

continue, they will undermine the outcome of any project or activity in the 'Ahau community.

Through remote means (i.e. recent satellite imagery) and site investigations, it became clear that the challenges described in the evaluation are in part due to the fact that plans and recommendations for the EU-GIZ ACSE project (i.e. Mead 2018) were not all followed through to completion, while regular maintenance (i.e. of the non-return valves) has also been found to be an issue for the continued success of measures put in place. In the following section, these issues are addressed, along with further conceptual designs for Coastal Unit 1.

Some of the challenges associated with the division of the community members could be reduced by the development of an integrated coastal management policy by MEIDECC to bring together the various components of coastal management (such as those being developed through this current project) and clarify the over-arching aims for Tongatapu's climate change resilience (e.g. as recommended by McCue 2014).

As noted in Section 2.3 above, further funding for Coastal Unit 1 has been used to heighten and repair the Kanokupolu revetment. The damage to the revetment and road between Ha'atafu and Kanokupolu is detailed in Mead and Manuofetoa (2021/2022). Works were scheduled to heighten the northern 600 m of the Kanokupolu following the over-topping that occurred during TC Harold in April 2020. However, the scope of the work was extended after the northern ~1,350 m of the structure was damaged by the January 2022 tsunami. Revetment rock was removed offshore in many locations along this stretch of the revetment, with several areas being further damaged. with the loss of the revetment and the wash-out of the road behind the revetment, as documented in Appendix A. Construction and repair work began at Kanokupolu see Figure 2-12).

In addition, at Kolovai the recommendations from 2018 were undertaken to complete it to specifications (Mead, 2021; Mead and Manuofetoa, 2021/22). As shown in Figure 9-3, the design layout of the seawall was based on a ground survey to determine the inland extents to keep water out. However, the built layout did not follow the design path and does not extend far enough shoreward to prevent water coming around it (as reported during community consultation and the recent evaluation (GCCA+ 2021a)). Mead (2021) recommended building an additional 35–40 m of seawall In addition, there are several holes in the base of the seawall and two of the non-return valves require replacement.

The specific activities undertaken in 2022 for the repair of the Kolovai seawall included:

- repair of all holes along the base of the seawall and any gaps that are allowing water through;

- Replacement/maintenance of the existing two non-return valves to prevent inundation during extreme events; and
- Extension of the end of the seawall shoreward to prevent seawater coming around the end of the seawall and causing flooding (Figure 9-3).

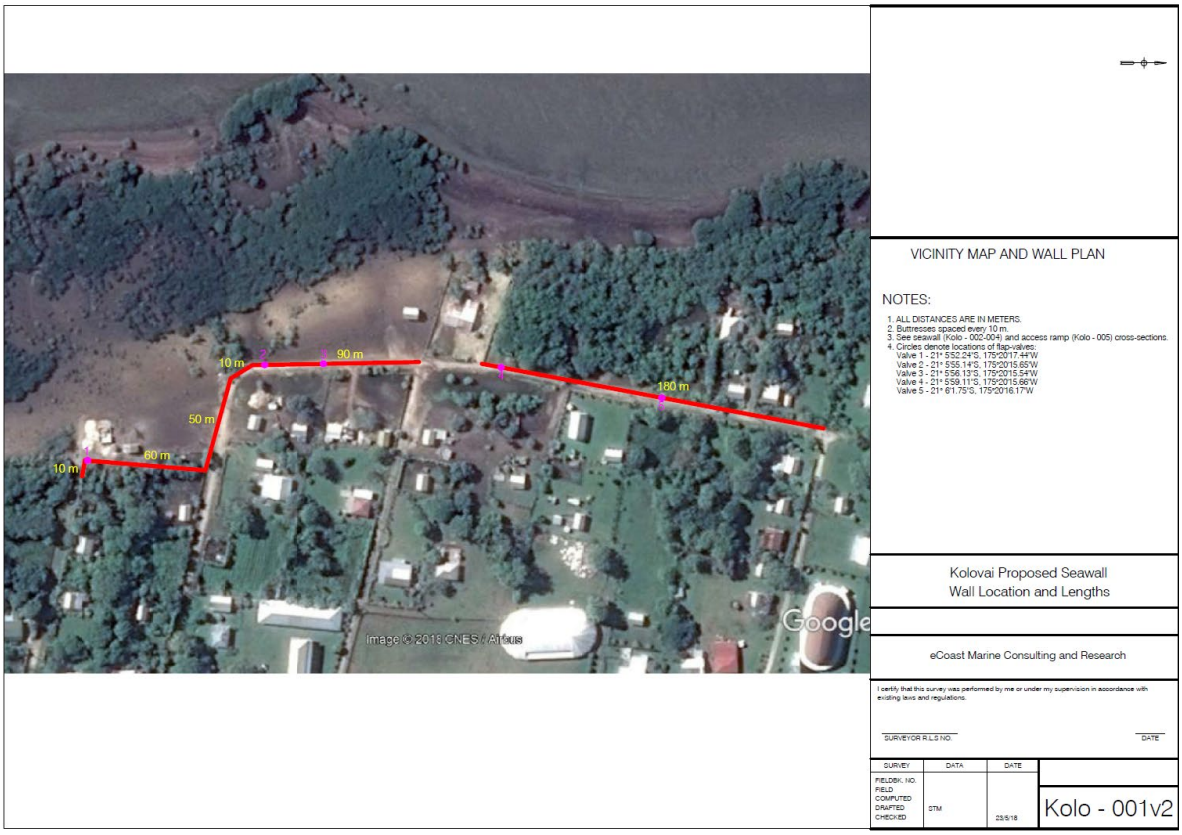

Figure 4-5. Top: The original design layout of the seawall. This was based on a total-station survey to determine the inland extents to keep water out. However, the built layout does not follow the design path and does not extend far enough shoreward to prevent water coming around it (as reported during community consultation and the recent evaluation). Bottom: An additional 35-40 m of seawall is required (red bracket).

4.3 Updated concept design for Coastal Unit 1

The concept design for Coastal Unit 1 builds on the recommendations of SSL (2014a, b), Mead and Atkin (2014), Mead (2018), Mead (2021), Mead and Manufetoa (2021) and Mead et al. (2023), with two distinct approaches:

- continued strengthening, maintenance and modification of the revetments that protect the wetlands and lagoons at Ha'atafu, Kanokupolu and A'hau; and
- continued re-establishment of the mangrove green belt from Kolovai to Foui and associated foreshore coastal defence measures.

Mangrove nurseries have been established in Tonga in recent years (Figure 4-6) and will require further development to support replanting of this important natural coastal hazard mitigator (see Sections 1.3 and 1.4, and Appendix A).

Figure 4-6. The mangrove nursery at Kolovai

For the revetment/road along the Ha'atafu and Kanokupolu coastline, the concept design includes:

- continued maintenance and repairs as required along the length of the revetment, noting significant works have recently been carried out – Section 2.3; and
- continued maintenance of two non-return valves on culverts to prevent flooding of low-lying properties on the western side of the wetland during heavy rainfall.

For the revetment and lagoon at A'hau, the concept design is a continuation of EU-GIZ ASCE works, and includes three works, described below.

1. Open up the southern end with a deeper channel to ensure flushing (as previously recommended (Mead, 2018)
2. Remove the central access way, which was planned as a temporary measure. As a result of leaving this in place, the southern entrance is not working/flushing (as reported during community consultation (Mead et al. 2020a) and the recent evaluation (GCCA+ 2021a). The northern part of the lagoon, which showed mangrove recovery, is also not flushing and this will lead to the loss of the mangrove buffer that requires re-establishment for climate change resilience. Mangroves in this area had been observed to be recovering and additional seedlings were established between 2014 and 2018.

3. Rather than a solid road-barrier, a stepping-stone path can be left in place to allow foot traffic access to the outer lagoon flats while flow through the lagoon is maintained. (Gaps in the accessway/stepping stones were in place prior to the works in 2018).

It is noted that the pathway across the A'hau lagoon was still present in August 2022, and is continuing to negatively affect lagoon circulation (Figure 4-7).

From Kolovai to Foui and along the coast of Ha'avakatolo, the conceptual design includes:

- a new seawall (~380 m) as designed for Kovolai with one-way valves to prevent inundation during extreme events, for seaward properties at Ha'avakatolo (Mead 2021);
- ceasing mangrove clearances from Kolovai to Foui and incorporating mangrove replanting programmes and stick groynes to re-establish the green belt where it was historically cleared along this part of the coast;
- continuation of the initial mangrove planting and protection with stick groynes southwards along the coast and further seaward to widen the buffer zone (Figure 4-8).
- planting of salt-tolerant shrubs above the highwater mark is also recommended to provide further protection from storm surge and wave action;
- establishing a second mangrove nursery (Figure 4-6); and
- continuing efforts to exclude pigs, by strategic fencing and penning of pigs that forage in these areas, causing a large amount of damage to the ecology and preventing mangrove seedlings from being established.

Figure 4-7. The solid road-barrier at the A'hau lagoon. This is reducing flushing of the northern part of the lagoon and adversely affecting mangrove health; a stepping-stone path can be left in place to allow foot traffic access to the outer lagoon flats while flow through the lagoon is maintained.

The locations of the proposed works for the conceptual design in Coastal Unit 1 are shown in Figure 4-9. These recommendations for the conceptual design are detailed further in Section 9, since this area of the northern coast includes specific conceptual design and costing for the use of Donor funds under negotiation.

Figure 4-8. The groyne constructed to protect mangrove seedlings at Kolovai

Figure 4-9. Location map showing the works for Coastal Unit 1. The required works are expanded on in Section 9, since this area of the northern coast includes specific conceptual design and costing for the use of donor funds under negotiation.

5 Conceptual design – Coastal Unit 2: Foui to Sopu

5.1 Biophysical setting

Village names are annotated in Figure 5-1. As described in Mead et al. (2020a), this section of coastline is very low lying and, like Coastal Unit 1, is vulnerable to inundation hazards from northerly storm surges. This coastline faces northwards towards the shallow western section of the Tongatapu Lagoon.

The nearshore environment largely consists of rocky reef and sand flats that are overlain by sediment to the west in the shallow western Tongatapu lagoonal area. To the east, there is a fringing coral reef, beyond which the water depth increases rapidly (Figure 5-2).

The bio-physical environment has been greatly influenced by humans. There is a mangrove belt along the entire coastal unit from Foui to Sopu. It is ~12 km long and ~1 km at its widest (eastern end) but it has been heavily modified for growing crops (Figure 5-2). It is evident that land reclamation has occurred, which has resulted in the removal of mangroves in some locations (Mead et al. 2020a). With the exception of Sopu, which is mostly <2 m below MSL, most of the dwellings and villages in this coastal unit are 3–4 m above MSL (Figure 5-3), making this coastal unit the least vulnerable area on the northern coast based on elevation.

Heavy rain and high tide issues cause flooding of properties between Foui and Sopu due to poor drainage, with low-lying and variable land heights, and land near the sea often being higher than more landward areas (Mead et al. 2020a). Mangrove removal has occurred historically, although mangrove senescence has also occurred in the past 20 years, which is likely due to impoundment caused by the separation of the mangrove area by bunds and roads around Sopu and Puke villages.

A conceptual coastal processes model for Coastal Unit 2 is presented in Figure 5-4.

Figure 5-1. Street map of Coastal Unit 2. (https://satellites.pro/plan/Tonga_map#E-21.123316,-175.274055,15)

Figure 5-2. Location map of Coastal Unit 2. This unit (yellow line) is on the north-western middle coastline of Tongatapu between Foui and Sopu (Google Earth 2020)

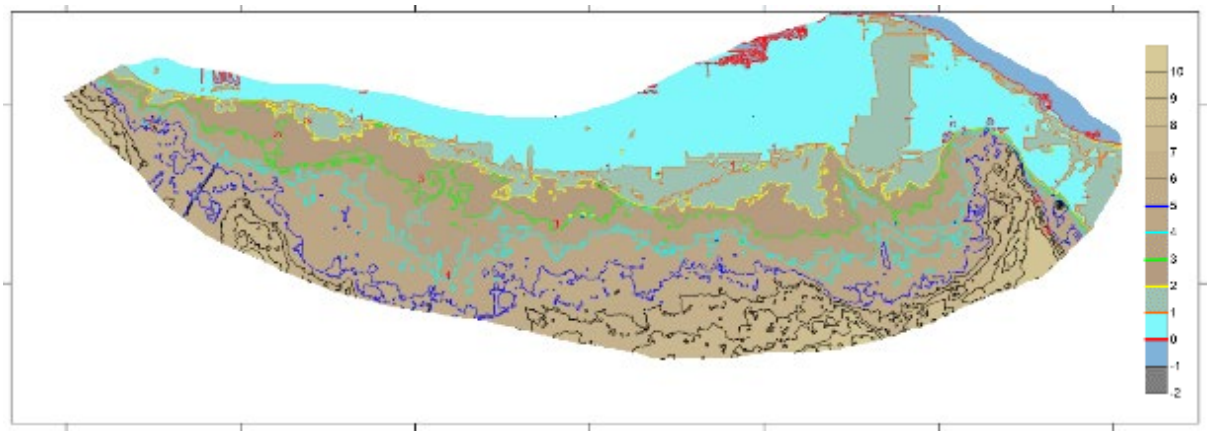

Figure 5-3. LiDAR contour plot of Coastal Unit 2. Note: Level refers to contours level (m) from MSL.

Figure 5-4. Conceptual coastal processes model for Coastal Unit 2

5.2 Existing coastal protection works and coastal hazards

This is the least modified coastal area in the study and has had little attention in terms of coastal protection and the fewest interventions. There is little in the way of engineering or coastal protection measures along this section of coastline, with the exception of the breakwaters/bunds that have been built around Sopu along the eastern-most section of this coastal unit.

During community consultation, the representatives of the villages between Foui and Sopu expressed a preference for more mangrove planting for climate change resilience (Mead et al. 2020a). This will require opening of some areas along the eastern side of this coastal unit to allow for better flushing.

Sopu/Isileli is the most vulnerable area in Coastal Unit 2 due to its low elevation and close proximity to open water. Sopu represents the westernmost part of Nuku'alofa, where the capital city has spread into the mangroves and lagoon flats (Figure 5-2). It is very vulnerable to over-topping and inundation, with saltwater coming around from the west and surrounding properties. Water gets trapped during king tides and heavy rainfall due to the roads and bunds being higher than the properties.

An additional coastal hazard reported by the villages of Coastal Unit 2 is the water-safety/drowning associated with foraging on the lagoon sand flats. The sand flats are open for fishing for all, and people walk out on the flats to forage at low tide. In 2021, six people across a range of age groups drowned during the sea cucumber harvesting season (Mead et al. 2020a). When the weather changes quickly (wind and waves) people are trapped on the sand flats and get swept out of channels on the edges of the lagoon by strong currents running off the flats and into deeper water.

5.3 Updated concept design for Coastal Unit 2

For Coastal Unit 2, the main recommendation is continuation of the green-belt of mangroves (Appendix A), to replace the landward mangroves historically cleared and widen the buffer zone out into the lagoon. The main coastal hazard here is inundation; wide mangrove stands will provide buffer zones to reduce the water level landward (Appendix A). This will require mass planting of mangroves and protection of the seedlings with brushwood breakwaters/groynes. At least three mangrove nurseries should be established (e.g. see nursery in Kolovai in Figure 4-6). Strategic fencing and penning will also be required to exclude pigs that forage in these areas. They can cause a large amount of damage to the ecology and prevent the establishment of mangrove seedlings.

Many of the villages experience inundation during heavy rainfall and spring tides, with onshore winds (which is often the situation with tropical cyclones and the less intense tropical depressions). Flooding also occurs on the landward side of the main road in some locations. Strategically placed culverts and drains to drain flood water from the low-lying areas on the southern side of the main road will help alleviate this coastal hazard. This will require more in-depth investigations in the detailed design phase to gather local knowledge on structures and culverts/one-way valves that can allow stormwater to run out towards the coast and keep the seawater out during low pressure and king tide situations.

In some locations, seawalls such as those at 'Ahau will provide a second line of defence from seawater inundation. It is noted that the LiDAR survey indicates that most habitable areas are 3.0 m or more above MSL,

Although many of the villages and dwellings in Coastal Unit 2 are 3.0 m or more above MSL, Sopu and Isileli at the eastern end of the unit are mostly only 1.0 m above MSL, face a deeper area of the lagoon (rather than intertidal flats), and are impounded by water from both sides; i.e. they are the most vulnerable areas in the unit. To provide this area with more resilience to coastal hazards in a 10- to 30-year planning horizon, a range of measures are required, although there is uncertainty about the approach. It is noted that, given the low-lying nature of this land, its future is limited due to SLR, and the villagers will require relocation. While discussions have been held in the Tongan Government concerning retreat/relocation, no plans have been formally developed. Another option is large-scale reclamation/infilling to raise the level of the land to 2.5–3.0 m above MSL. However, this area (and the whole of Nuku'alofa) is vulnerable to tsunami, which may preclude the option of creating more permanent habitable sites here in favour of relocation.

The revetment that runs along the northern coast of Nuku'alofa does not continue along the coast of Sopu and Isileli, although there is a small section at the western end from fisheries and across what may have historically been an entrance to the inner lagoon. Given the very low-lying nature of this area, in order to reduce overtopping and inundation from the coast, the most cost-effective option to 'buy-time' for the next 10 to 30 years is likely detached breakwaters. These structures can provide similar protection for a quarter of the cost of rock revetment, while still allowing access to the coast (Mead 2019). In addition, sandy beaches are present along this section of the coast, which negates the need to import sand to support the function of detached breakwaters.

Much of Sopu and Isileli is impounded and will require culverts and non-return valve systems to allow rainwater to drain away while preventing seawater from entering properties and compounding flooding. An additional issue leading to flooding of this area is the broken and

blocked flood gates and the roading inside the lagoon area which have blocked off natural flow paths and greatly reduced flushing. Repair of the floodgates and strategic placement of culverts to reconnect these waters to the wider lagoon will help reduce impounded water and improve mangrove health, which has suffered over the past 20 years or so. Successful completion of these works may also allow for replanting mangroves in areas where they have died.

Even so, there are many unknowns with respect to the best way to address this western end of Nuku'alofa. For example, establishing new and re-opening old entrances to the inner lagoon may reduce the need for seawalls and non-return valves to keep out seawater during extreme events. Like Popua and Seisia, the area is very low, and so decisions on relocation/retreat, reclamation/heightening and/or something in between to 'buy-time' over the coming short (10 years) to medium (30 years) time frames are required. These issues are discussed further in Section 9 below.

Although not a coastal hazard in terms of land and property protection, the loss of lives on the lagoon flats while foraging is an issue that can be reduced by providing signage, warning people of the risks, advising them to check the times of the tides, and the weather forecast, and to have a means of communication with them.

The locations of the proposed works for the conceptual design in Coastal Unit 2 are shown in Figure 5-5. These recommendations for the conceptual design are detailed further in Section 9, since this area of the northern coast includes specific conceptual design and costing for the use of donor funds under negotiation.

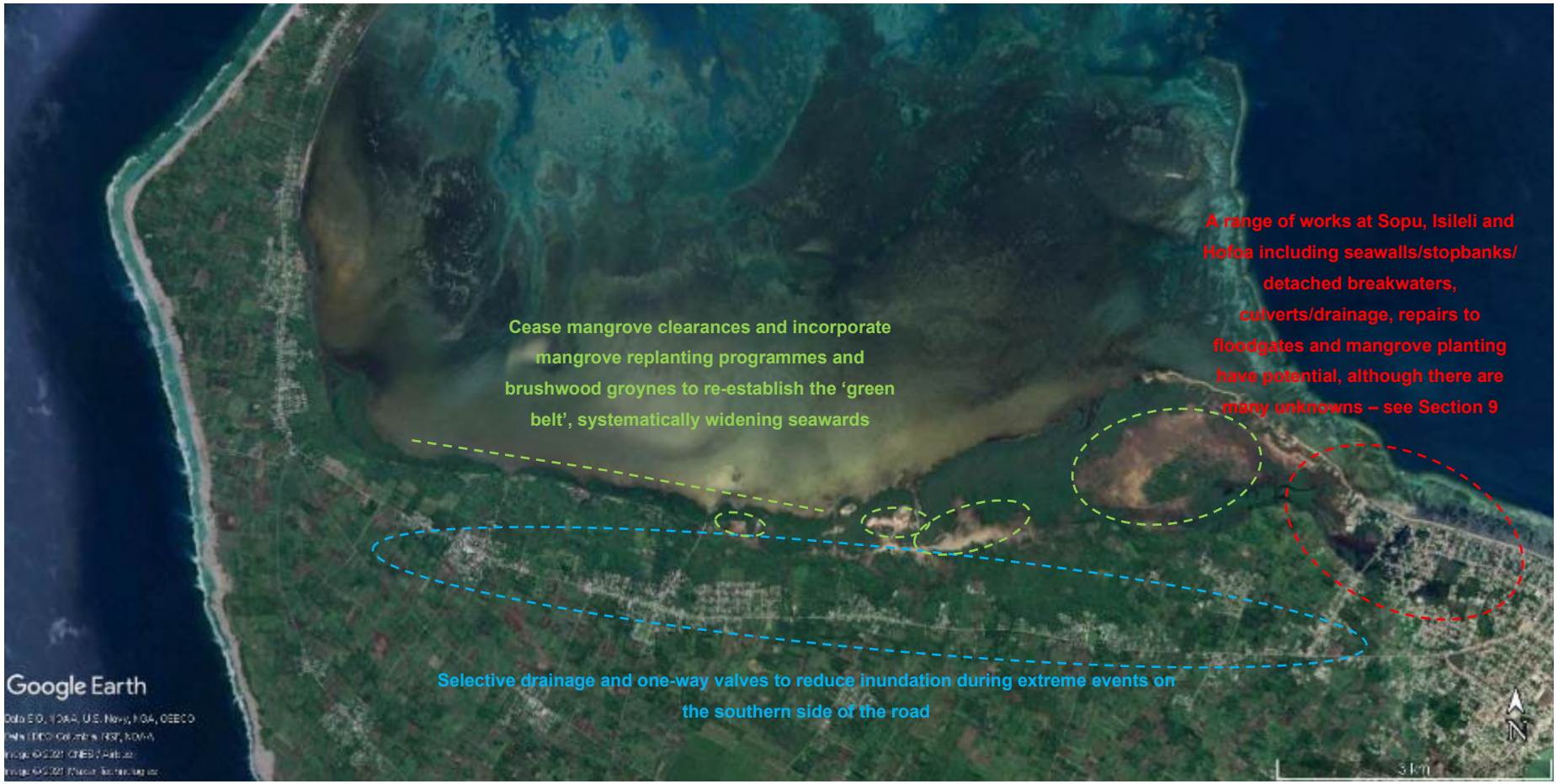

Figure 5-5. Location map showing the works for Coastal Unit 2. The required works are expanded on in Section 9, since this area of the northern coast includes specific conceptual design and costing for the use of donor funds under negotiation.

6 Conceptual design – Coastal Unit 3: Sopu to the Nuku'alofa shore of the lagoon

6.1 Biophysical setting

Village names are annotated on Figure 6-1. As described in Mead et al. (2020a), this coastal unit comprises a northern section (the north side of Nuku'alofa facing the Tongatapu Lagoon) and a southern section (the southern side of Nuku'alofa on the coast of the Fanga'uta Lagoon) (Figure 6-2). Nuku'alofa is the capital of Tonga and is densely populated (~30,000 people). The coastline is entirely urban and very low-lying with only three high ground areas >2 m above MSL (Figure 6-3). As such, this area is extremely vulnerable to inundation and coastal erosion hazards from storm events.

The northern section comprises a range of narrow beaches backed by breakwaters\seawalls; there is some 6.0 km of rock armour and port/wharf construction between Albert Street in the west and the end of the barrier spit adjacent to Nukunukumotu in the east (Figure 6-2). The middle northern area comprises the Vuna and Queen Salote Wharfs, which have seen various upgrades over time. The nearshore environment is comprised of rocky reef flats, which extend ~550 m in the west to ~300 m in the east. The fringing reef lies at the end of the rocky reef flats, beyond which the water depth significantly increases. Hence, the coastline along this area is highly exposed to northerly swells and storm surge.

The southern section of this coastal unit comprises the northern shores of the Fanga'uta Lagoon. The coastline along this area is largely urban with small pockets of fringing mangroves. It experiences very low wave action within the lagoon due to the limited fetches of this enclosed waterbody. These sectors of the lagoon are known as Pe'a (the western circular area with the central island) and Folaha (the narrower channel converging with the Mu'a sector and lagoon entrance). They are relatively shallow (maximum depth of ~6 m in the main channel) and eutrophic due to groundwater infiltration and the very low flushing rates (Mead et al. 2020b).

A conceptual coastal processes model for Coastal Unit 3 is presented in Figure 6-4.

Figure 6-1. Street map of Coastal Unit 3. (https://satellites.pro/plan/Tonga_map#E-21.146533,-175.190413,15)

Figure 6-2. Location map of Coastal Unit 3. This unit (blue line) is on the northernmost section of coastline of Tongatapu between Sopu and Nuku'alofa (Image sourced from Google Earth 2020)

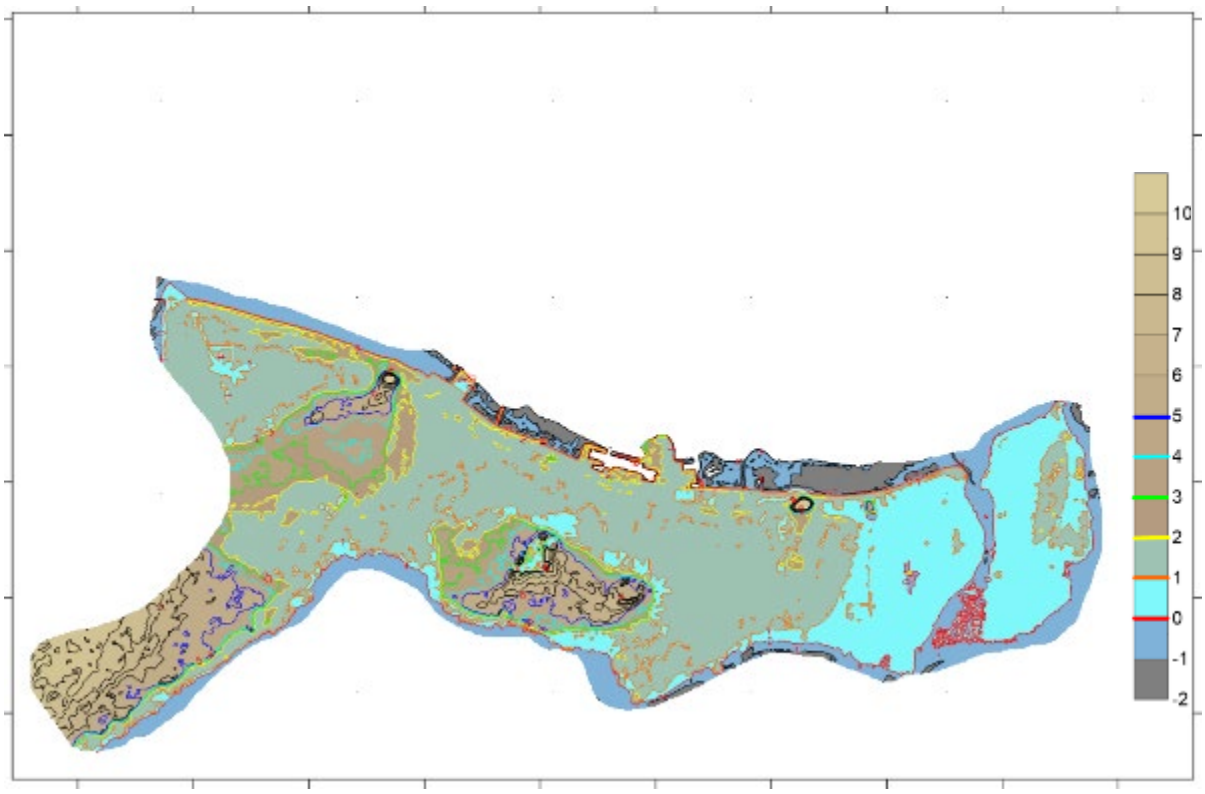

Figure 6-3. LiDAR contour plot of Coastal Unit 3. Note: Level refers to contours level (m). Three distinct pockets of high ground are evident.

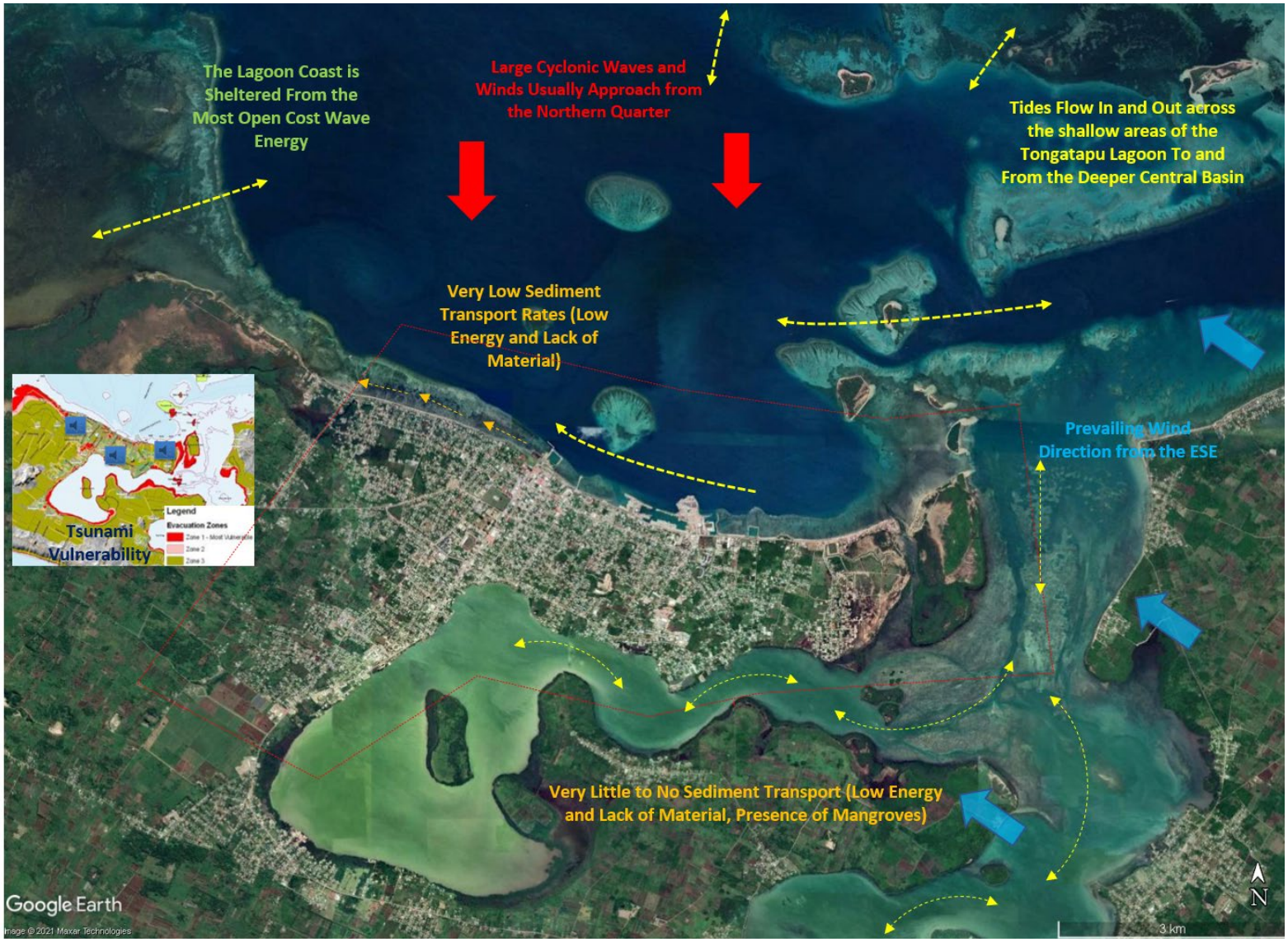

Figure 6-4. Conceptual coastal processes model for Coastal Unit 3

6.2 Existing coastal protection works and coastal hazards

As noted above, the northern section comprises a range of narrow beaches backed by breakwaters/seawalls; some 6.0 km of rock armour (Figure 1-2) and port/wharf construction between Albert Street in the west and the end of the barrier spit adjacent to Nukunukumotu in the east.

In the north-eastern corner of this coastal unit, near the entrance to the Fanga'uta Lagoon, significant works have been carried out; breakwaters/seawalls and drainage channels have been constructed, both on the mainland (Pangatangata/Popua), as well as on Nukunkumotu Island (Seisai), just east of Nuku'alofa. These areas have been developed in the past five years by refugees from the outer islands (Figure 6-5). They are very low-lying and much of them were previously intertidal areas. These developments have occurred without planning or support. Mangroves line the channel between the mainland and the island.

Figure 6-5. Sections of coastline at Pangatangata and Seisia. Top: Pangatangata and Seisia June 2016. Bottom: October 2020

The southern part of Coastal Unit 3, the northern shore of the Fanga'uta Lagoon, experiences mostly only very low wave action within the lagoon due to the limited fetches. Coastal protection structures are, therefore, largely non-existent, with only a few properties fronted by tipped rubble mound revetments.

6.3 Updated concept design for Coastal Unit 3

The recommendations to increase climate change resilience along the northern coast of Coastal Unit 3 are described below.

- Erosion along this coastal unit has been mitigated by the revetment repair work, but maintenance along the length of the revetment is required as some sections are failing and require attention. Small failures in revetments and other coastal structures can easily be compounded if left unattended and a stitch in time saves nine, i.e. one must be proactive As noted in Section 3.1 above, discussion with representatives from the Ministry of Infrastructure identified a current JICA project, which includes repairs and. extensions to the Nuku'alofa revetment that were recommended as part of the donor funds under negotiation spending (Mead and Manuofetoa 2023). Initial contacts have been made, but at the time of writing no details on the works proposed by JICA have been forthcoming.
- It was noted that Tropical Cyclone Harold caused over-topping and flooding along the road and some properties behind the Nuku'alofa revetment (Mead et al. 2020a) The cyclone struck during a high king tide with the associated storm surge and wind/wave set-up. This is very difficult to avoid and would likely require significant heightening of the revetment along its length. The combination of the arrival of the cyclone and a king tide (usually the highest tide of the year) is likely to be greater than a one-in-100-year event. However, given the projected increase in TC intensity and continued SLR, the initiation of formal monitoring and recording of over-topping is recommended, as some areas may require attention within the 10- and 30-year planning horizons.
- It is recommended that the 2.5 km gap in the revetment between Sopu and Nuku'alofa be extended and filled – much of this section is in Coastal Unit 2, where it is recommended that detached breakwaters be used rather than revetments, since this area is very low and retreat or other methods of climate change action will be required earlier there than in other parts of the northern Nuku'alofa coastline.
- As described in Section 3.2 above, in the 2021 version of this report, it was noted that there was some uncertainty with respect to the future plans for Siesia and Popua. If

the new settlements are to be continued, then a number of actions are required to improve climate change resilience in the 10- and 30-year planning horizons. The initial recommendations were for planning and continuation of bunds/seawalls and drainage around the settlements, which would provide some resilience in the next 10 years. However, due to the low-lying nature of the area, flood-gates to prevent tidal inundation and allow for stormwater from heavy rainfall will be needed and will require regular maintenance; pump-stations would also likely be a necessary part of the drainage scheme. It was recognised that this would require planning extensive works – a large amount of development has occurred in this area over past 20 years (especially in recent years) and extensive flooding of properties is occurring throughout south-eastern Popua.

- In addition, it was recommended that, over the longer term, a decision is required on whether to retreat from the Siesia and Popua area or further increase its resilience. In order to provide climate change resilience to these areas, large scale reclamation and filling is required (e.g. as is being considered in Kiribati, Tuvalu and the Marshall Islands).
- Since finalising the Northern Tongatapu Coastal Protection strategy in February 2021, the Tongan government has been developing a master plan for this area which will be submitted to cabinet. It includes prioritising mangroves and reinstating the area that was flattened for a golf course, developing a culture centre for tourism and creating more recreational space. There is currently a mangrove nursery established for this area, although more Rhyzophera are needed, and some design/planning is required with respect to where to replant mangroves to develop a buffer to sea-level rise and climate change events. Planning and design for this area is linked to potential restoration of the lagoon, which is very poorly flushed due to the shallow entrance (which has gotten shallower due to sediment run-off in the past 40–50 years) (Mead et al. 2020 & 2022) (Figure 6-7).

Along the northern side of the Fanga'uta Lagoon, the lowest areas are currently not inhabited, with the main issues being flooding of the urban areas such as Fanga and continued reclamation of the coast. In 2011, a law was passed making it illegal to undertake reclamation around the lagoon, but it has not been enforced and reclamation is still occurring. Flooding in this area occurs for a number of reasons, including the drains being blocked with sediment, broken non-return valves and a lack of pump stations, with some areas inland being lower than others around the edges of the lagoon, exacerbated by reclamation around the lagoon's edge. NEMO has developed a drainage plan with pump stations. Recommendations include:

- enforcing the law about reclamation around the edges of the lagoon since these works are exacerbating flooding impacts;
- undertaking regular maintenance of the existing drainage system; and
- Implementing the drainage plans and associated pump stations developed for the area by NEMO (much of these works are under way or completed).

The locations of the proposed works for the conceptual design in Coastal Unit 3 are shown in Figure 6-7. These recommendations for the conceptual design are detailed further in Section 9, since this area of the northern coast includes specific conceptual design and costing for the use of donor funds under negotiation.

Figure 6-6. Sections of coastline at Pangatangata, Seisia and Popua 2004. Top: Pangatangata, Seisia and Popua 2004. Bottom: 2020

Figure 6-7. Location map of the proposed works for the conceptual design in Coastal Unit 3

7 Conceptual design – Coastal Unit 4: Nuku'alofa to Nukuleka

7.1 Biophysical setting

Village names are annotated in Figure 7-1. This coastal unit comprises the southern coast of the Pe'a and Folaha sectors and the Mu'a and Vaini sectors of the Fanga'uta Lagoon (Figure 7-2). The Mu'a sector has depths of 3–6 m near the entrance, and the Vaini sector is relatively shallow (mostly 1–2 m deep). The southern shores of the lagoon are not typically subjected to large wave conditions due to the low energy nature of the lagoon, offshore wind conditions (predominantly south-easterly), and limited fetches (Mead et al. 2020a). Since 2011, the mangrove stands surrounding the lagoon have been protected by law. Despite this, mangrove removal has still occurred.

As noted in Section 4.1 above, the Fanga'uta lagoon is highly eutrophic due the low flushing rate (tidal residency of up to 140 days, depending on the sector of the complex lagoon system, with tidal mixing only 10–12% (Mead et al. 2020b)) and the significant amount of anthropogenic pollution and sediment that enters it. Despite this, the lagoon remains an important breeding and nursery habitat for fish and birds. Furthermore, the lagoon has been a life-support system for communities, providing a wide range of marine and intertidal resources, such as mangrove wood (fuel), medicines, fish, seaweed, and shellfish for generations. The nutrients that sustain lagoonal fauna and flora are largely derived from the groundwater, which seeps into the lagoon.

In contrast to the northern shores of the lagoon (Coastal Unit 3), the southern shores are significantly less developed and include considerable mangrove stands. The shorelines are a function of the environmental energy present in each area and range from dense aggregations of mangroves along sections that are shallow and sheltered, to thin stands along headlands and in deeper sections that are exposed to higher current velocities and longer fetches. Apart from Pe'a and Ha'ateiho on the western end of this coastal unit, most of the inhabited property is relatively high, at least 3–4 m above MSL (Figure 7-3). The mangrove belts are typically wider and continuous to the west of the coastal unit and broken to the east towards the more urbanised area of Alaki and Mu'a. A substantial number of mangroves have been removed between Veitongo and Nukuhetulu in the Mu'a sector in the recent past.

A conceptual coastal process model for Coastal Unit 4 is presented in Figure 7-4.

Figure 7-1. Street map of Coastal Unit 4. (https://satellites.pro/plan/Tonga_map#E-21.183812,-175.171251,15)

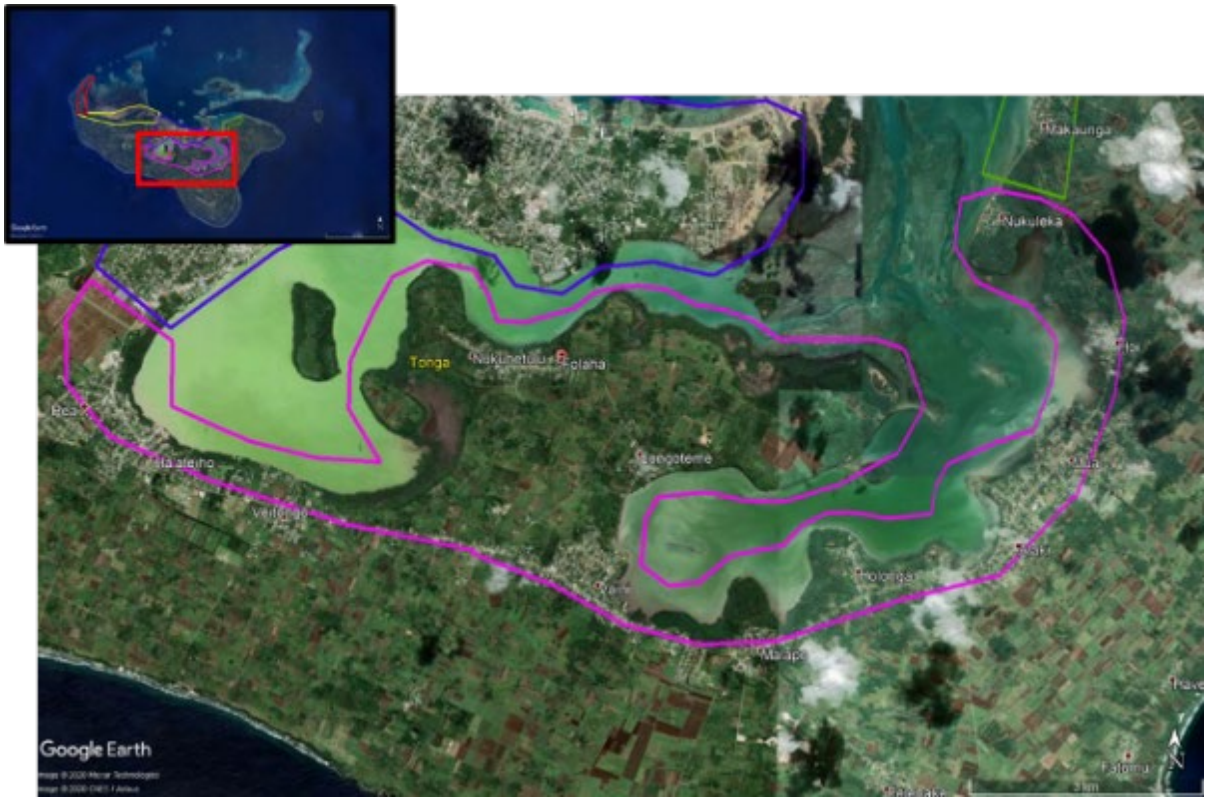

Figure 7-2. Location map of Coastal Unit 4. This unit (magenta line) lies along the southern shores of the Fanga'uta Lagoon, Tongatapu between Nuku'alofa and Nukuleka (Image sourced from Google Earth 2020).

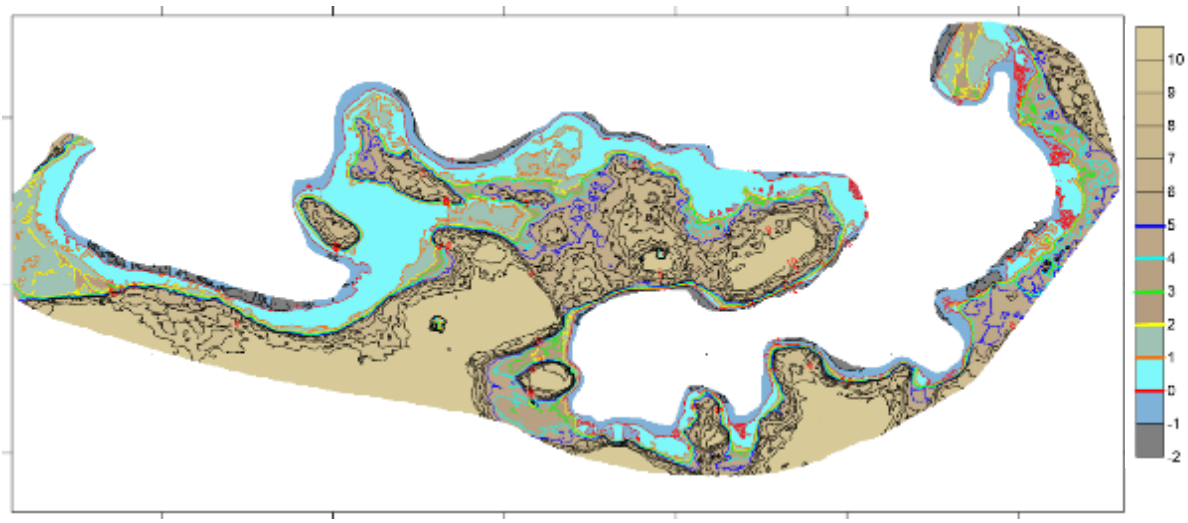

Figure 7-3. LiDAR contour plot of Coastal Unit 4. Note: Level refers to contours level (m) to MSL.

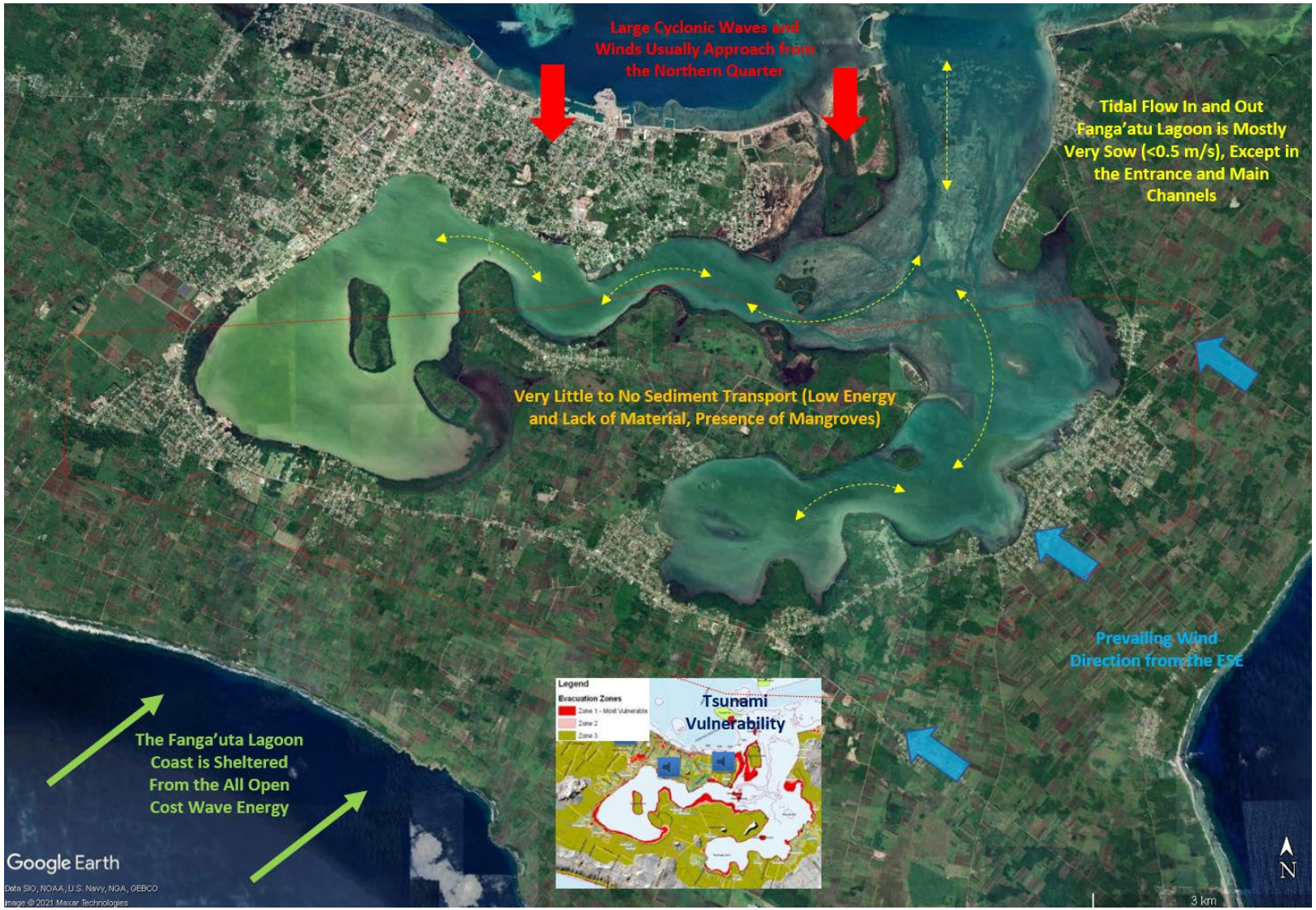

Figure 7-4. Conceptual coastal processes model for Coastal Unit 4

7.2 Existing coastal protection works and coastal hazards

As noted above, the southern coastline of the lagoon is not typically subjected to large wave conditions due to the low energy nature of the lagoon, offshore wind conditions (predominantly south-easterly), and limited fetch (Mead et al. 2020a). Therefore, coastal protection structures are few.

The villages of Alaki and Mua are exposed to higher wave energy than other areas, so there are rocky reef flats with little overlying sediment. There is, however, a small breakwater between Alaki and Mu'a, which has provided shelter for sediment accumulation and mangrove development.

Pe'a, Ha'ateiho and western Veitongo villages are the most susceptible areas to inundation due to their low-lying nature. Village representatives of this area are concerned that reclamation in the northern lagoon is leading to additional flooding, but this is not so, due to the opening/entrance to the lagoon. The flooding is more likely associated with historical mangrove clearance (reducing the dampening effect mangrove has on coastal inundation and SLR). These days, the high tide comes in and floods across the road, especially during northerly winds. Similar flooding occurs to the east, although this land is not as low-lying.

Nukuhetulu and Folaha, located on the northern side of the isthmus between the Pe'a and Vaini Sectors (Figure 7-2), are losing farmland due to inundation, which is likely being compounded by SLR.

At Vaini, which is located at the western end of the southern arm of the lagoon on the coast of the Vaini Sector, the road north to Longoteme was 20 m inland a few decades ago but has been lost to the sea due to removal of mangroves. During community consultation, the village representatives indicated that they would like to replant with mangroves. At high tide and with onshore winds, seawater floods and crosses the road into these areas, the village representatives indicated that seawalls might be a better option..

Between Vaini and Hoi at the north-eastern boundary of Coastal Unit 4, the land is relatively high, with only a few vulnerable properties in low-lying coastal sites.

7.3 Updated concept design for Coastal Unit 4

The recommendations for climate change resilience for Coastal Unit 4 are discussed below.

- As noted in Section 3.3, a number of contributing factors have led to the degradation of the Fanga'uta Lagoon. While the health of the Fanga'uta Lagoon may not be considered to be directly associated with coastal protection of the northern Tongatapu coastline (of which the lagoon is part), the physical changes that have led to the

ecological degradation of the lagoon waters affects flooding susceptibility around the coast of the lagoon. NEMO has installed pump stations and outlets into the lagoon to reduce flooding during extreme events, but sea-level rise and continued sedimentation will continue to reduce the efficacy of this approach.

- Dredging of the shallow entrance to the lagoon (Figure 7-6) was suggested by several respondents, to both assist with flushing and recovery of the biological status, and to reduce flooding due to heavy rainfall. A calibrated numerical has been established for the lagoon (Mead et al. 2020b & 2022). This could be applied to investigate the potential to dredge the entrance to increase lagoon flushing. It is recommended before considering dredging, since it is a very complex water body, and there is the potential to exacerbate flooding during particular extreme events. Various dredging and extreme event scenarios would, therefore, require testing. In addition, the construction of dykes/bunds and mangrove replanting where the belt is narrow to reduce inundation of crops in the central area of the lagoon would also reduce sediment and nutrients into the waterbody.
- To provide increased resilience at present, seawalls are recommended to protect properties in Pe'a (Figure 7-5) and Ha'ateiho, similar to those in Kolovai. This requires topographic surveys, and strategic placement of non-return valves. Replanting mangroves in the pockets/areas where they have been removed from behind the seaward mangroves would likely also require strategic fencing and penning of pigs that forage in these areas, causing a lot of damage to the ecology and preventing the establishment of mangrove seedlings. Veitonga is mostly located in an area that is above 5 m high, with the exception of a small number of properties on the lagoon edge, where mangroves have been removed and land reclaimed.
- Establish two mangrove nurseries for the area.
- At Nukuhetulu and Folaha, most dwellings are on high ground (only a small number adjacent to mangroves), and it is the farmland that is currently affected. Food security is also an important aspect of climate change resilience, with protection of these low-lying productive areas in the next 10 to 30 years likely best achieved with the creation of dykes and flood gates (similar to those being constructed in eastern Nuku'alofa – Figure 6-6). Due to the protected nature of these areas behind a relatively extensive ribbon of mangroves, simple soil dykes similar to those developed in the past decade at Popua, are a relatively cost-efficient method of protection. This would likely require flood/inundation modelling for design purposes.
- Planting of mangroves between Longoteme and Vaini to reduce inundation of the road may require heightening the road and incorporating culverts along this very low corridor

for the 30-year timeframe. It will likely also require strategic fencing and penning of pigs that forage in these areas. Only a small number of properties are vulnerable to inundation at Vaini, and seawalls/culverts similar to Kolovai could address these issues.

- At Malapo, water comes in on both sides of the village and causes flooding of some properties, especially during high tide and northerly winds. However, most of the village is over 5 m high, and inundation of the properties on the eastern and western sides of the village could be addressed with seawalls/culverts similar to those in Kolovai.
- From Alaki to Hoi, most of the land is above 5 m high. However, inundation occurs along some of the coastal properties on low-lying sites. Replanting of mangroves, which have been removed from much of this coast, and selective seawalls could be applied to these sites to increase resilience over the next 10 to 30 years.

The locations of the proposed works for the conceptual design in Coastal Unit 4 are shown in Figure 7-6. These recommendations for the conceptual design are detailed further in Section 9, since this area of the northern coast includes specific conceptual design and costing for the use of donor funds under negotiation.

Figure 7-5. Low-lying properties in Pe'a

Figure 7-6. Location map of the proposed works for the conceptual design in Coastal Unit 4

8 Conceptual design – Coastal Unit 5: Nukuleka to Niutoua

8.1 Biophysical setting

The village names are annotated on Figure 8-1. As detailed in Mead et al. (2020a), the coastline of Coastal Unit 5 (Figure 8-2) is very low-lying, like the Nuku'alofa area, with much of the western part of this coastal unit less than 2 m above MSL. The inhabited areas of the eastern coastline are, however, mostly >4 m above MSL (Figure 8-3).

This coastal unit can be described as having a west-facing Fanga'uta Lagoonal entrance component (Nukuleka, Makaunga and Talafo'ou), a northern component facing the open Tongatapu Lagoon (Navutoka and Manuka), and a north-eastern component bordering the open ocean (Kolonga, Afa and Niutoua) (Figure 8-2). The western nearshore component is characterised by intertidal sandy reef flats within the entrance of the Fanga'uta Lagoon. The northern nearshore environment is characterised by an intertidal rocky reef and sand flats with a fringing barrier reef in the Tongatapu Lagoon, beyond which the water depth drops away rapidly into the deep Piha Channel (Figure 8-2). The fringing reef along the eastern section of coastline reduces from ~500 m wide to ~100 m from Manuka to Niutoua and becomes increasingly exposed as the Piha Channel widens and the coast begins to face open ocean.

There is a trend of increasing exposure to the prevailing south-east wind and associated wave conditions from the west to the east, with the western coastline being adjacent to the entrance to the Fanga'uta Lagoon and being the most protected. There is also increasing exposure to

the east from Navutoka through to Niutoua in the east. However, all of the coast is exposed to the northerly storms and tropical cyclones, and as such is susceptible to storm surge, inundation and coastal erosion hazards.

The western and northern shorelines are comprised of thin sandy beaches, backed by a coastal road along much of the length. From Kolonga village, which is located in the central part of this coastal unit (Figure 8-2), the elevation increases and the shoreline becomes a mix of limestone and volcanic rock along the coasts of Kolonga, Afa and Niutoua villages.

A conceptual coastal processes model for Coastal Unit 4 is presented in Figure 8-4.

Figure 8-1. Street map of Coastal Unit 5. (https://satellites.pro/plan/Tonga_map#E-21.139989,-175.086880,15)

Figure 8-2. Location map of Coastal Unit 5. This unit (green line) lies along the eastern side of the Fanga'uta Lagoon entrance and the north-eastern coast of Tongatapu between Nukuleka to Niutoua (Image sourced from Google Earth 2020)

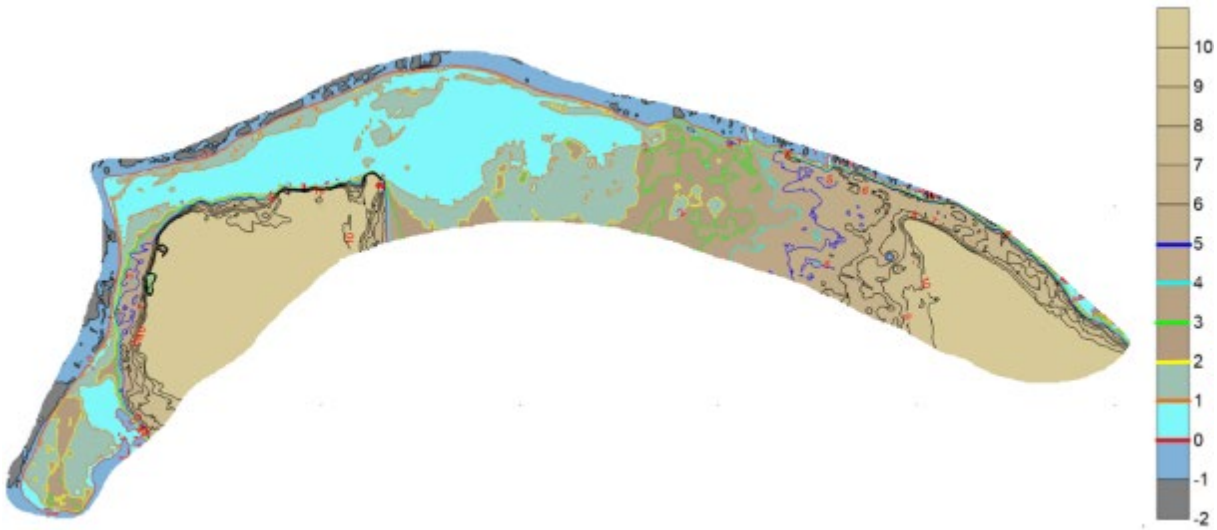

Figure 8-3. LiDAR contour plot of Coastal Unit 5. Note: Level refers to contours level (m) to MSL.

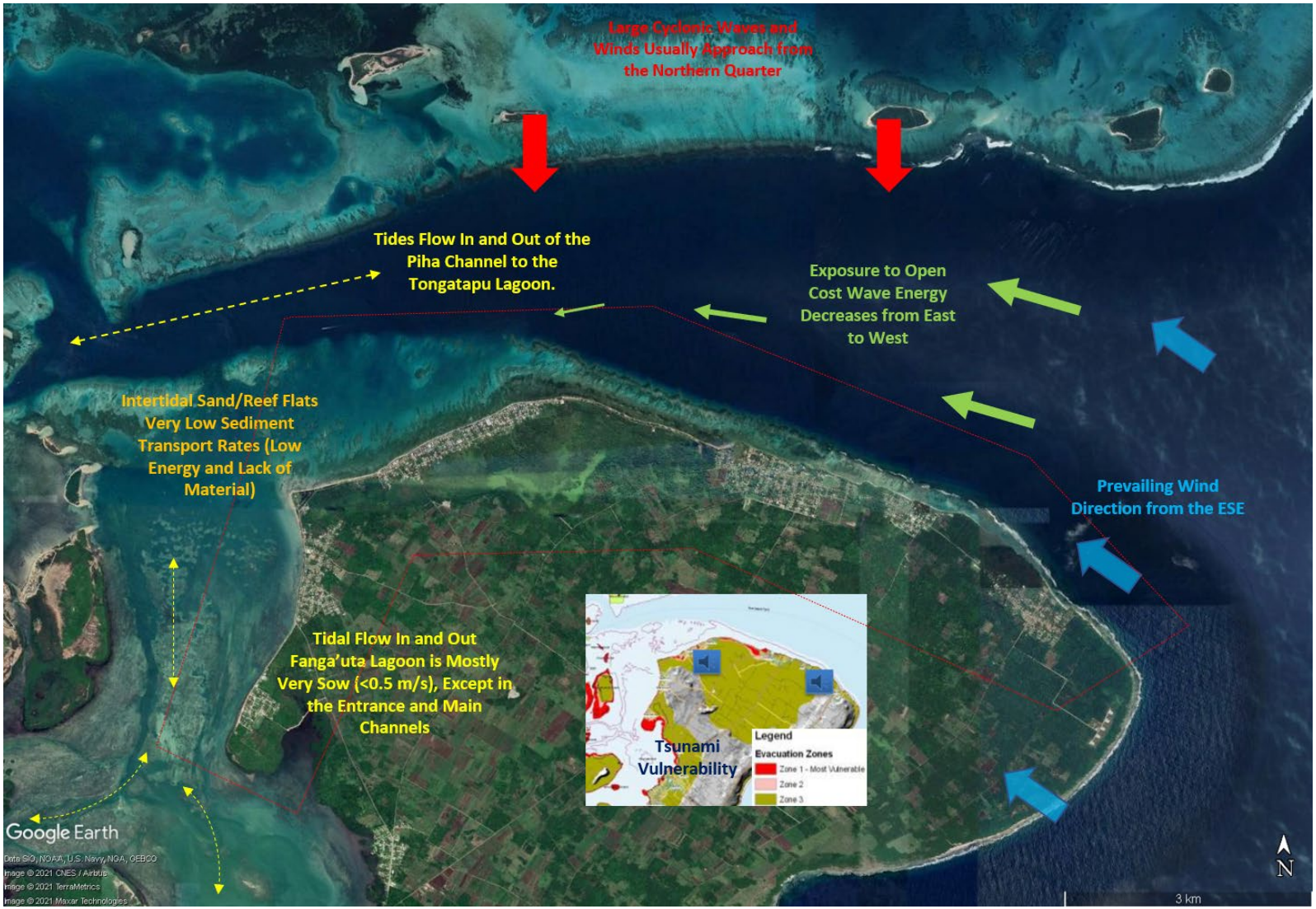

Figure 8-4. Conceptual coastal processes model for Coastal Unit 5

8.2 Existing coastal protection works and coastal hazards

As noted above, the eastern and northern shorelines are comprised of thin sandy beaches, backed by a low-lying coastal road along much of the length. This road has historically been susceptible to over-topping during extreme events but as the elevation increases from Kolonga village in the east and the shoreline becomes a mix of limestone and volcanic rock, vulnerability to inundation and erosion decreases. This means that Kolonga, Afa and Niutoua villages are somewhat protected by the composition and elevation of the shoreline.

Like Sopu, water comes around both sides of the village at Nukuleka. It has become worse in recent years and is coming up on both sides of the road at the top of the channel through the mangroves.

Several climate change resilience projects have been constructed to prevent inundation and coastal erosion hazards at Nukuleka and Manuka. Between Makaunga and Talafo'ou, a groyne field has been constructed and beaches have shown signs of growth and stability during a recent evaluation. On the northern side, a combination of revetments and detached breakwaters have been constructed from west to east, respectively. Along the northern coastline, historical shoreline analysis has revealed that between 10 and 25 m of retreat/erosion has occurred since 1968, with most of it occurring after 1981.

GCCA+ (2021b) recently evaluated the performance of the climate change resilience works carried out along the Hihifo coast described above. The evaluation concluded that:

> Both the GCCA: PSIS project and the CRSP project have helped the people of Makaunga, Talafo'ou, Navutoka and Manuka cope with the negative impacts of climate change – notably the problem of sea level-rise, inundation, coastal erosion and flooding. The installation of 20 sets of sedi-tunnel groynes in Makaunga and Talafo'ou has widened the coastline and the height of the coast has been lifted. The construction of 10 detached breakwaters at Manuka has allowed deposit of sediments between each breakwater. These sediments accumulated and have gradually built the land inward by 15–20m. The intervention helped restore security for the people along the area. The Manuka and Navutoka community resilience level has been boosted by the CRSP project through the construction of the 2 km long rock revetment along the coasts.
>
> Although both projects were successful in fulfilling their prime objective of enhancing the resilience of the selected communities, there are issues that need to be considered, particularly when attempting to scale up coastal protection measures. The issues are:

1. the lack of a monitoring mechanism to ensure that the success of the measures is properly managed;
2. overtopping, coastal erosion and inundation are still occurring in Makaunga, Talafo'ou and north eastern Manuka;
3. the two access-ways at the rock revetment were not sufficient, considering that there are about 2,500 people that need access to the sea; and
4. the elderly in Navutoka and Manuka find it difficult to get to the beach as the revetment is very high.

It is noted that, while there is potential for overtopping to occur at Makaunga and Talafo'ou due to some of the larger spaces in the trial groyne field, this is unlikely the case at Manuka, unless it is with reference to the coastal road northeast of Manuka beyond the detached breakwaters. As noted in the evaluation, claims of recent over-topping at Makaunga and Talafo'ou could not be verified, and claims that the borrow pits for sand remained open were also found to be baseless (the historical satellite images on Google Earth indicate that the borrow pits filled within a month (Mead 2019)). As with the development of the GCF coastal adaptation proposal, there is a local preference for quarried limestone revetments along the coast, the same as the revetment in Nuku'alofa. The two-kilometre revetment along Navutoka is the same design as the Nuku'alofa revetment (in terms of rock gradient) and was built because it was the local people's preferred option. However, it provides a false sense of security against SLR; has limited access (two points in two kilometres); has resulted in the loss of amenity, aesthetics, and tourism opportunities for this part of Tongatapu (a goal of the original GCCA works); and cost four times the price of detached breakwaters (i.e. far more coast could have been protected).

As noted in Section 2.3 above, at Talafo'ou, where sedi-tunnel groynes, renourishment and coastal planting were established in 2014/15 as part the earlier phase of SPC's GCCA:PSIS project (Mead 2014a,b; Mead 2015a,b,c) for coastal resilience, the sedi-tunnel groynes closer to the entrance (i.e. the northern end) were displaced by the January 2022 tsunami and the low rock seawall was over-topped. The displaced sedi-tunnel groynes have since been reinstated. In addition, along the north-eastern coast from the western point to Manuka, tsunami inundation distances of over 150 m occurred in some places, and the low revetment along the stretch of coast to the west of Navutoka was over-topped and damaged at several points). Interestingly, no inundation was reported along the eastern Manuka detached breakwater trial site (Mead et al. 2013b). It is thought that the detached breakwaters helped dampen the height and prevented overtopping directly landward.

Figure 8-5. Breakwaters at Manuka and revetment at Navutoka. Top and middle: The detached breakwaters at Manuka. Bottom: The revetment at Navutoka

8.3 Updated concept design for Coastal Unit 5

The recommendations for climate change resilience along Coastal Unit 5 are dicussed below.

- At Nukuleka, the western properties are sometimes inundated as the road is higher than the land. Drainage and non-return valves, mangroves along the coast to reduce the inundation, and seawalls around the north-eastern side of the town similar to Kolovai should be constructed. In addition, the mangrove belt that used to exist along the coast of the Fanga'uta Lagoon entrance (which is still present on the western side of the entrance at Nukunukumotu) should be replanted to provide further protection from north-westerly wind events. A mangrove nursery should be established for this area (Figure 4-6). Efforts will also be required to exclude pigs such as strategic fencing and penning of pigs,
- At Talafo'ou and Makaunga, there are reports that over-topping is still occurring in some areas at high tide when the wind is from the northwest. As noted from the site inspection in 2019 (Mead 2019), the 30 m groyne spacing is performing very well, and more groynes to fill in the 120 m and 60 m spaces and more sand from the borrow area will result in this stretch of the coast being >10 m wider. The recommendations of Mead (2019) are:
    a) fill the gaps of 60 and 120 m spacing to have groynes at 30 m intervals along the beach;
    b) use the half open configuration for all additional groynes;
    c) rotate the half open units at the six southern groynes to be fully closed; and
    d) bring in an additional 3,000 m^3 of sand from the sand collection area to distribute in the areas of the additional groynes, and the southern areas of the site where none has yet been placed.

  Continued management of pigs that forage in these areas, causing a large amount of damage to the ecology, is also required to help restore the sand flats and sand-production.

- The low road between the detached breakwaters at Manuka and Kolonga regularly experiences over-topping and inundation, which was severe during TC Harold. Given the area with its scarcity of people, villages and other familiar assets, as well as the elevation of <1.0 m above high spring tides (i.e. very vulnerable to inundation, with SLR compounding this in the next 30–50 years and beyond), it is a challenging area with respect to the best approach to mitigate CC vulnerability. In line with the GCF proposal for coastal adaptation, climate change resilience for 10- and 30-year planning horizons for this stretch of coast should incorporate soft engineering options, such as

planting salt-tolerant plants to create a buffer to reduce over-topping, with strategic detached breakwaters where the coast in front of the road is narrowest and overtopping frequently occurs. Sediment is moving from the east to the west along this stretch of coast and, as has been observed at the Manuka detached breakwaters, the volume of sediment transport has significantly increased in this area in addition to the material placed there.

The locations of the proposed works for the conceptual design in Coastal Unit 5 are shown in Figure 8-6

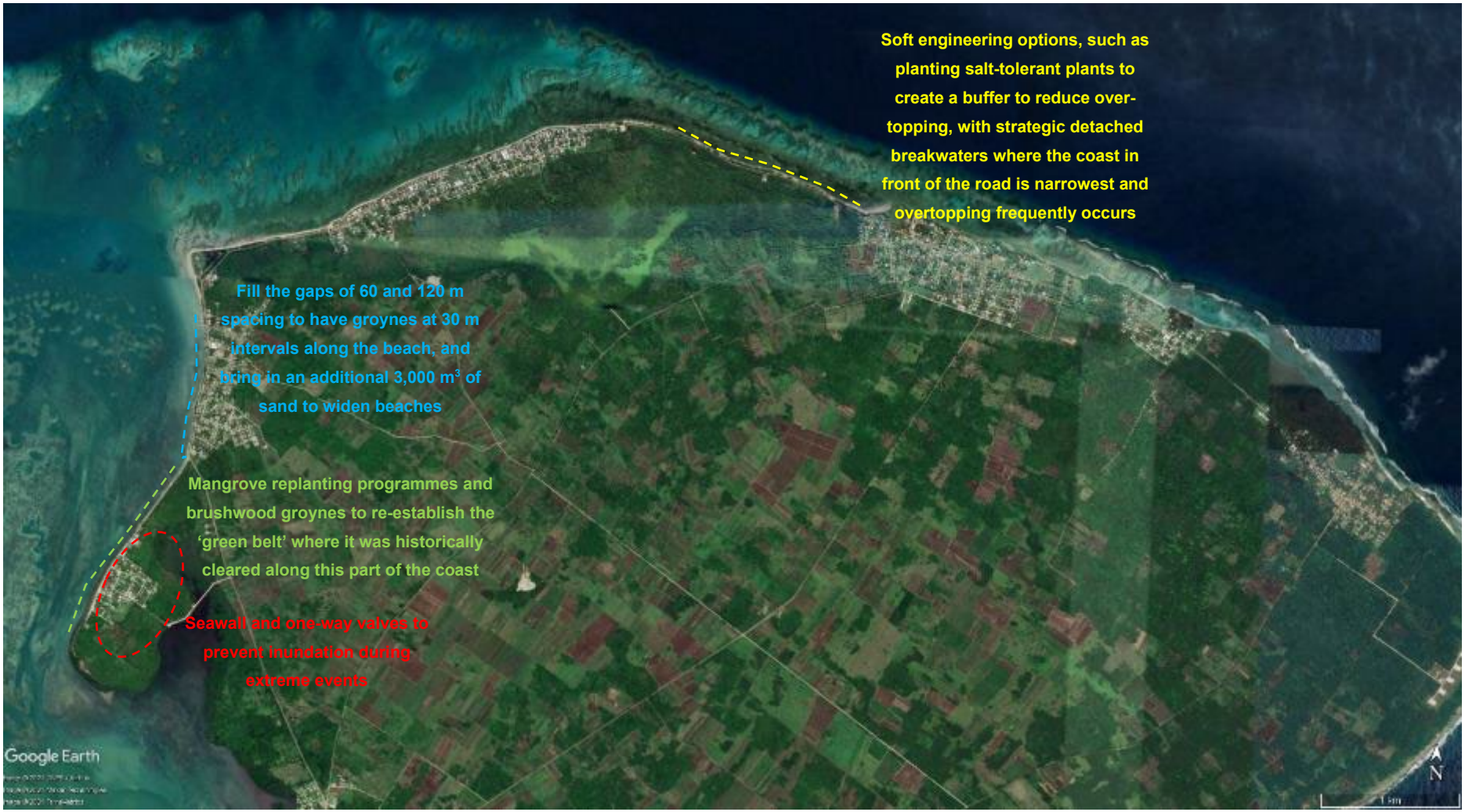

Figure 8-6. Location map of the proposed works for the conceptual design in Coastal Unit 5. These recommendations for the conceptual design are detailed further in Section 9, since this area of the northern coast includes specific conceptual design and costing for the use of donor funds under negotiation.

8.4 Development of monitoring, evaluation, and educational measures associated with the coastal protection of the northern Tongatapu coast.

Lessons learnt from the implementation of previous climate change resilience strategies include the need for supervision through to the end of the construction, regular maintenance for components of the strategies (e.g. the non-return valves and flood gates in Nuku'alofa, the Kanokupolu revetment and the Kovolai seawall), regular monitoring to determine the efficacy of the measures put in place and ways that they can be improved, and adaptive management (e.g. the requirement for further groynes and sand renourishment to fill the gaps at Talafo'ou and Makaunga). Monitoring and evaluation (M&E) strategies should be developed for each of the proposed works set out in this report, which should include and incorporate the local community. M&E strategies should also support education about the various coastal protection measures and how they operate, and the important aspects of local buy-in/ownership.

This project has highlighted the importance of developing a policy for integrated coastal management (ICM), which needs to consider responses to climate change and sea-level rise further into the future and whether to retreat, accommodate or defend the low-lying northern coast and Fanga'uta Lagoon. Some of the challenges associated with the division of the community members could be reduced by the development of an ICM policy through MIEDECC to bring together the various components of coastal management (such as are being developed through this current project) and clarify the over-arching aims for Tongatapu climate change resilience (e.g. as recommended by McCue, 2014).

9 Priorities for the use of donor funds under negotiation for parts of the Northern Tongatapu Coastal Protection project

In the 2021 report, this section considered specific conceptual design and costing for a minimum of 10 small-scale (to the value of up to €10,000 each, or approximately T$ 28,000) hard and soft engineering measures for the northwest coastal stretch from Sofu to Ha'atafu to be considered for implementation during the period mid-2021 to end 2022.

As with many of the coastal protection measures recommended for the northern coast, two lines of defence are often applied, mostly hybrid nature-based solutions with soft and hard engineering components working together (Appendix A).

Several of the small-scale projects have been delivered with the prior funding. This section has been updated to consider the priorities for the use of the donor funds under negotiation (T$ 5.5–8.25 M) on parts of the Northern Tongatapu Coastal Protection project.

9.1 A'hau lagoon flushing and Kolovai seawall

The 'Ahau Lagoon was also subject to further climate change resilience measures in 2014 and 2018 (Mead 2018) but the recommendations from 2018 were not completed. These included removal of the temporary access path to the foreshore 'living wall' to allow flushing, but this pathway has not been removed. As a result, the southern entrance is not working/flushing (as was reported during community consultations and in the recent evaluation GCCA+ 2021a). The northern part of the lagoon, which showed mangrove recovery, is also not flushing and this will lead to the loss of the mangrove buffer that requires re-establishing for climate change resilience (Figure 9-1 and Figure 9-2).

The deepening of the southern channel and removal of the accessway (or at least incorporating cuts to allow water to flow through) are considered to take no more than a day each with a digger and driver, plus mobilisation and demobilisation. The estimated cost is T$ 7,475.

Figure 9-1. Recommendations for A'hau Lagoon (1). Top: The recommendations in 2018 included removal of the temporary access path to the foreshore 'living wall' to allow flushing (notation circled in red). Bottom: This pathway has not been removed and as a result the southern entrance is not working/flushing and the northern part of the lagoon, which showed mangrove recovery, is also not flushing. This will lead to the loss of the mangrove buffer that requires re-establishing for climate change resilience.

Figure 9-2. Recommendations for A'hau Lagoon (2). Left: June 2018 prior to the EU-GIZ ASCE works (Mead 2018), the southern causeway entrance was on the eastern side and did not flush the southern part of the lagoon well. The access track to the central part of the 'living-wall' was partially open. Mead (2018) recommended moving the entrance to the south and widening and removing the central access path. Right: May 2020. The southern entrance has been moved and widened as recommended, and the 'living-wall has been made more robust by adding more rock on the seaward side. The central access path has been made higher and more permanent, all but closing off the northern half of the lagoon. As a result, the southern entrance is not flushing and the northern part of the lagoon, which showed mangrove recovery, is also not flushing. This will lead to the loss of the mangrove buffer that requires re-establishing.

At Kolovai, a similar situation has occurred, with the recommendations from 2018 not being undertaken to specifications. As shown in Figure 9-3, the design layout of the seawall was based on a total-station survey to determine the inland extents to keep water out. However, the built layout does not follow the design path and does not extend far enough shoreward to prevent water coming around it, as was reported during community consultation and the recent

evaluation (GCCA+ 2021a). An additional 35–40 m of seawall is required and replacement/maintenance of non-return valves. Based on the linear metre cost, it is estimated that T$ 20,720 is required at Kolovai.

Figure 9-3. Recommendations for Kolovai. (Top) The design layout of the seawall was based on a total-station survey to determine the inland extents to keep water out. However, the built layout does not follow the design path and does not extend far enough shoreward to prevent water coming around it. Bottom: An additional 35–40 m of seawall is required (red bracket).

Mangrove planting should also include the approximately 0.9 ha between the new seawalls and existing mangroves to replace the mangroves cleared in the past and provide additional

buffer/protection during extreme events, as was previously recommended (Mead 2018), The estimated cost is T$ 40,500. A total of T$ 70,400 (including 15% contingency) for extending the wall and planting an additional 0.9 ha of mangroves.

9.2 Kolovai to Foui

The Kolovai brushwood fence has proven effective at protecting mangrove seedlings (M. Manuofetoa, pers. obs.). Additional mangrove and brush breakwater/groyne protection is recommended for the Kolovai to Foui coast, where mangroves were historically removed (Figure 9-4). This approximately 740 m stretch of coast has properties/dwellings that are mostly above 3.0 m MSL, with Kolovai being the lowest (hence the section of seawalls) and the land raising toward Foui. The brushwood fencing is estimated to cost T$ 62,900, and 1.1 ha of mangrove planting, with mangrove seedlings estimated at T$ 20 each, a total of T$ 20,400. There is also the establishment of another nursery with an estimated cost of T$ 85,000, and additional pig fencing (T$ 35,000). The grand total of all this is T$ 238,165 (including 15% contingency).

Figure 9-4. Recommendations for Kolovai to Foui. Recommended mangrove and brush breakwater/groyne protection (approximately 740 m by 15 m wide)

9.3 Signage for Unit 2

As mentioned above, although not a coastal hazard in terms of land and property protection, the loss of lives on the lagoon flats while foraging off this coastal area is an issue that can be reduced by providing signage, warning people of the risks, advising them to check the times of tides and the weather forecast, and to carry a means of communication. The estimated cost to design, manufacture and erect six signs at access points along this coast as a small-scale measure is T$ 25,000.

9.4 Flood control for Nukunuku, Matafonu, Fatai, Puke, Fotua, Sopu and Isileli

Properties as far as the main road between Masilamea to Matafonua are affected by inundation – often a combination of spring tides, northerly wind events and heavy rain (Mead et al. 2020). Measures to address this issue (which would be reduced with the planting of mangroves; see Appendix A and Section 5.3), are physical measures to keep out the water in terms of robust seawalls. To be successful, these measures require topographic survey to determine the layout of the seawalls and to strategically place non-return valves of the appropriate diameter. The estimated cost to build seawalls in locations identified by aerial imagery between Nukunuku and Puke is T$ 1,502,200, with an additional T$ 922,040 estimated to build seawalls adjacent to the low-lying waters at Fotua and Sopu/Isileli (Figure 9-5).

The most vulnerable and currently affected area of Coastal Unit 2 is Sopu, Isileli and Fotua (Figure 9-5). As noted in Section 3.3 above, Sopu and Isileli at the eastern end of the unit is mostly only 1.0 m above MSL, faces a deeper area of the lagoon (rather than intertidal flats), and is impounded by water from both sides. This makes it the most vulnerable area in the unit. To provide this area with more resilience to coastal hazards in a 10-to-30-year planning horizon, a range of measures is required, although there is uncertainty as to the approach.

It is noted that, given the low-lying nature of this land, its future is limited due to SLR, and the people will require relocation. There have been discussions in the Tongan Government concerning retreat/relocation, but no plans have been formally developed. Another option is large scale reclamation/infilling to raise the level of the land to 2.5–3.0 m above MSL. However, it is noted that this area (and the whole of Nuku'alofa) is vulnerable to tsunami, which may preclude the option of creating more permanent habitable sites here in favour of relocation.

The revetment that runs along the northern coast of Nuku'alofa does not continue along the coast of Sopu and Isileli, although there is a small section at the western end from Fisheries and across what may have historically been an entrance to the inner lagoon. Given the very low-lying nature of this area, in order to reduce overtopping and inundation from the coast, the most cost-effective option to 'buy-time' for the next 10 to 30 years is likely detached breakwaters (Figure 9-5). These structures can provide similar protection for a quarter of the cost of rock revetment, while still allowing access to the coast (Mead 2019). In addition, sandy beaches are present along this section of the coast, which negates the need to import sand to support the function of detached breakwaters. Note the natural response to a small offshore

height spot on the reef flats, which supports the efficacy of this approach with detached breakwaters (inset Figure 9-5).

Much of Sopu and Isileli is impounded and will require culverts and non-return valve systems/flood gates to allow rainwater to drain away while preventing seawater from entering properties and compounding flooding. Also leading to flooding of this area are the broken and blocked flood gates and the roading inside the lagoon area. These have blocked off natural flow paths and greatly reduced flushing. Repair of the floodgates and strategic placement of openings/culverts to reconnect these waters to the wider lagoon will help reduce impounded water and also increase mangrove health, which has suffered over the past 20 years or so (Figure 9-5). Successful completion of these works may also allow for replanting mangroves in areas where they have died off.

In addition, seawalls and strategically placed non-return valves could also be applied to reduce inundation (Figure 9-5). There are, however, many unknowns with respect to the best way to address this western end of Nuku'alofa. For example, establishing new and re-opening old entrances to the inner lagoon may reduce the need for seawalls and non-return valves to keep out seawater during extreme events. Like Popua and Seisia, the area is very low, and so decisions on relocation/retreat, reclamation/heightening and/or something in between to 'buy-time' over the coming short (10 years) to medium (30 years) time frames are required.

The cost estimates for the measures are:

- T$ 1,502,200 for 2.9 km of seawalls with non-return valves for Nukunuku and Puke;
- T$ 922,040 for 1.68 km of seawalls with non-return valves for the Sopu/Isileli area (Figure 9-5);
- T$ 185,000 for ground surveys, modelling studies and design;
- T$ 500,000 (a ballpark figure) for additional flood management in the Sopu/Isileli area; and
- T$ 34,000,000 for reclamation (long-term measure).

It is noted that the 2.2 km of detached breakwaters extending from the Nuku'alofa revetment as an erosion control measure is presently being investigated by JICA.

Given the present vulnerability of this area, it is recommended that a financial allocation of T$ 3,575,620 (which includes 15% contingency) is utilised to implement flood controls for the very low-lying and flood-prone (due to seawater) areas of Nukunuku, Matafonu, Fatai, Puke, Fotua Sopu and Isileli. This includes undertaking a scoping and feasibility study to consider: a) the short-, medium- and long-term plans for the western end of Nuku'alofa; and b) refine the costs to develop a functional flood management plan.

Figure 9-5. Potential measures to increase climate change resilience for Sopu, Isileli and Fotua. While the recommended detached breakwaters will provide additional inundation protection, it is currently unknown what the most effective components for flood management of the inner lagoon will be. This is compounded by decisions on the longer-term future use of this area – retreat/relocate reclaim.

9.5 Dykes for food security

At Nukuhetulu and Folaha, most dwellings are on high ground (only a small number adjacent to mangroves), and it is the farmland that needs protection. Food security is also an important aspect of climate change resilience, with protection of these low-lying productive areas in the next 10 to 30 years likely best achieved by the creation of dykes and flood gates (similar to those that were constructed in eastern Nuku'alofa – Figure 6-6). Due to the protected nature of these areas behind a fairly extensive ribbon of mangroves, simple soil dykes are a relatively cost-efficient method of protection. This would likely require flood/inundation modelling for design purposes. The modelling and design is estimated at T$ 140,000, with the earthworks estimated to be $T 242,000; that is a total of T$ 347,000 (which includes 15% contingency).

9.6 All of Unit 5 recommendations

All the recommendations for Coastal Unit 5 are recommended as priorities for the use of donor funds under negotiation. This includes 900 m of seawall and non-return valves, 2.5 ha of mangroves with 1.6 km of brushwood fences, pig control fencing, mangrove nursery, 17 additional sedi-tunnel groynes, 3,000 m^3 of renourishment from the point, 3 detached breakwaters and 1 km of coastal planting. The cost is T$ 1,433,150 (which includes 15% contingency).

There are also options of small strategic fencing/planting from Masilamea to Sai'atoutai. They require further community consultation to properly identify the most critical sites, although these areas are not presently considered as vulnerable as the low-lying Sopu and Isileli sites.

10 Preliminary cost estimates

Table 10-1 presents the preliminary cost estimates for conceptual designs of coastal protection measures for the entire northern Tongatapu coast, broken down into the five coastal units; 46 items are listed, reduced from 52 items in the 2021 report. The measures presented have considered the 2030 and 2050 planning horizons (i.e. in 10 and 30 years' time), which, when considering the Representative Concentration Pathway 8.5 climate change scenario (i.e. business as usual, which is still the current situation with carbon emissions worldwide), represents 0.08 m and 0.3 m of sea level rise (SLR), respectively. While the immediate 10 years with 8 cm of SLR may seem innocuous, this can/will affect the lowest-lying and flattest relief areas. In addition, the effects of climate change (CC) are also being reported to decrease the number of tropical cyclones in the South Pacific, although their intensity is predicted to increase (e.g. Walsh et al. 2012). With respect to 30 cm of SLR, this represents a significant increase in inundation events and associated erosion, with events that are presently considered 1 in 200-year return periods likely to occur every 2.5 years on average. Therefore, planning and measures to reduce the effects of SLR are required now.

In many areas, re-establishing a buffer of mangroves is recommended as a first line of defence – in favourable conditions, mangroves will reach maturity in approximately 20 years. An additional cost per seedling of T$ 20 has been used in cost estimates to include transport and initial start-up costs, although seedlings can presently be purchased for T$ 12 and up (depending on the age/size) from the existing nurseries. More mangrove nurseries will also be required to cater to the mass plantings planned, and so it is expected that seedling costs will come down. Initially, the first plantings consist of a first row of 15 m thick mangrove belt. These should be expanded over the next 10 years to create 30–40+ m buffer zones in order to increase the buffering capacity (see Appendix A) as sea levels continue to rise.

As noted above, there is uncertainty with respect to the western end of Nuku'alofa (i.e. Sopu/Isileli), due to its very low-lying nature in a very vulnerable location, which requires governmental decisions for the longer-term (i.e. >30 years' time; SLR will not stop for centuries to come, although the pace of it and the ultimate maximum height may be slowed and reduced by changes to human carbon use). At Popua and Seisia (also low-lying and vulnerable at the eastern end of Nuku'alofa), a master plan is being developed that will re-establish the mangroves and wetlands, while the complexities of the impounded waters at Sopu and Isileli require further investigation. Estimations of large-scale reclamation have also been made for Sopu/Isileli.

The total cost estimate for coastal protection measures for 10-to-30-year planning horizons for the northern coast of Tongatapu is T$ 22,336,013, noting that there is some uncertainty for

the western end of Nuku'alofa, which may reduce costs (e.g. flood management in Sopu and Isileli could potentially reduce the requirements for seawalls). Even though several conceptual designs have now been removed from the northern coast strategy (e.g. Nuku'alofa foreshore and Popua/Seisia), this total cost is some T$ 1.5 M greater than the 2021 cost estimates, which indicates the increased costs in the past two years or so.

Table 10-2 presens a summary of the updated priorities for the use of the donor funds under negotiation on parts of the Northern Tongatapu Coastal Protection project which have an estimated total cost of T$ 6,013,179.

Table 10-1. Preliminary cost estimates for conceptual designs of coastal protection measures for the entire northern Tongatapu coast. These costs are broken down into the five coastal units. The highlighted items are those that are considered priorities for the donor funds under negotiation , which is broken down in Table 10-2.

Cost (T$)	Item	Location	Comment
		Coastal Unit 1	
$ 6,500.00	Remove access path to restore flow	'Ahau	Complete 2018 Plan
$ 196,840.00	380 m seawall with non-return valves	Ha'avakatolo	Based on aerial images and community consultation (requires survey)
$ 20,720.00	Complete seawall (40 m) as designed and repair/add non-return valves	Kovolai	Complete 2018 plan
$ 40,500.00	0.9 ha mangrove	Kovolai	Seaward of seawalls to widen green belt
$ 85,000.00	Establish an additional mangrove nursery	Foui	widen green belt
$ 24,200.00	1.1 ha mangrove	Foui	widen green belt
$ 62,900.00	740 m brushwood fences	Foui	widen green belt
$ 35,000.00	Pig fencing/control	Foui	widen green belt — protect seedlings
$ 471,660.00	Estimated subtotal		
$ 70,749.00	15% contingency		
$ 542,409.00	Estimated total		
		Coastal Unit 2	
$ 3,420,000.00	76 ha mangrove planting	Masilamea to Matafonua	widen green belt
$ 425,000.00	5.0 km of brushwood fences	Masilamea to Matafonua	widen green belt
$ 255,000.00	Establishment of 3 mangrove nurseries	Masilamea to Matafonua	widen green belt
$ 2,610,000.00	58 ha mangrove replanting	Nukunuku to Sai'atoutai	mangrove gaps (cleared?)
$ 150,000.00	Pig fencing/control	Masilamea to Sai'atoutai	widen green belt - protect seedlings
$ 185,000.00	Ground surveys and modelling for flood control	Nukunuku, Matafonu, Fatai, Puke, Fotua Sopu and Isileli	Incorporates some 2.9-3.4 km of seawalls and non-return valves for v. low-lying and flood-prone areas
$ 621,600.00	900—1200 m of seawall with non-return valves	Nukunuku	Based on aerial images and community consultation (requires survey)
$ 518,000.00	700—1000 m of seawall with non-retun valves	Matafonu and Fatai	Based on aerial images and community consultation (requires survey)
$ 362,600.00	600—700 m of seawall with non-return valves	Puke	Based on aerial images and community consultation (requires survey)
$ 300,440.00	580 m of seawall with non-return valves	Fotua	Based on aerial images and community consultation (requires survey)

$ 621,600.00	1.2 km of seawall with non-return valves	Sopu and Isileli	Based on aerial images and community consultation (requires survey)
$ 500,000.00	Estimated additional flood management	Sopu and Isileli	Unknown best solution (modelling and engineering investigations above)
$ 2,970,000.00	2.2 km of detached breakwaters	Sopu to Nuku'alofa	Extend foreshore protection
$ 25,000.00	Warning signage along the coast	Masilamea to Sopu	Estimated 10 signs
$ 12,964,240.00	Estimated sub-total		
$ 1,944,636.00	15% contingency		
$ 14,908,876.00	Estimated total		
Coastal Unit 3			
	Revetment repairs	Nuku'alofa	JICA
	Revetments/Detached breakwaters	Seisia	JICA — Erosion/inundation protection from extreme events
	Currently developing master plan	Pangatangata/Popua and Nukunkumotu Island (Seisai)	Creation of a culture centre for tourism and more recreational space
$ -	Estimated subtotal		
$ -	15% contingency		
$ -	Estimated total		
Coastal Unit 4			
$ 569,800.00	1,100 m seawall with non-return valves	Pea to Veitongo	Based on aerial images and community consultation (requires survey)
$ 180,000.00	4 ha mangrove	Pea to Veitongo	widen green belt
$ 54,000.00	1.2 ha mangrove	Nukuhetulu	widen green belt
$ 170,000.00	Establish two mangrove nurseries	Pea to Veitongo	widen green belt
$ 75,000.00	Pig fencing/control	Pea to Nukuhetulu	widen green belt — protect seedlings
$ 240,000.00	12 km dykes/bunds	Nukuhetulu and Folaha	Based on daily earthworks costs
$ 140,000.00	Flood modelling and engineering	Nukuhetulu and Folaha	Modelling and flood controls for the dykes/bunds
$ 189,000.00	4.2 ha mangrove	Vaini to Longoteme 2.8 km long by 15 m wide	widen green belt
$ 165,760.00	320 m seawall with non-return valves	Vaini	Based on aerial images and community consultation (requires survey)
$ 1,039,140.00	230 m seawall with non-return valves	Alaki	Based on aerial images and community consultation (requires survey)
$ 248,640.00	480 m seawall with non-return valves	Mua	Based on aerial images and community consultation (requires survey)
$ 225,000.00	5 ha mangrove	Mua and Alaki 3.3 km long by 15 m wide	widen green belt

$ 321,160.00	620 m seawall with non-return valves	Hoi	Based on aerial images and community consultation (requires survey)
$ 963,000.00	1.4 ha mangrove	Hoi	widen green belt
$ 85,000.00	Establish a mangrove nursery	Hoi	widen green belt
$ 75,000.00	Pig fencing/control	Mua to Hoi	widen green belt — protect seedlings
$ 4,740,500.00	Estimated subtotal		
$ 711,075.00	15% contingency		
$ 5,451,575.00	Estimated total		
Coastal Unit 5			
$ 466,200.00	900 m seawall with non-return valves	Nukuleka	Based on aerial images and community consultation (requires survey)
$ 85,000.00	Establish mangrove nursery	Nukuleka	widen green belt
$ 112,500.00	2.5 ha mangrove	Nukuleka 1.6 km long by 15 m wide	widen green belt
$ 136,000.00	1.6 km of brushwood fences	Nukuleka 1.6 km long by 15 m wide	widen green belt
$ 32,000.00	Pig fencing/control	Nukuleka	widen green belt — protect seedlings
$ 254,800.00	17 x groynes + 3,000 m^3 sand	Talafo'ou and Makaunga	Fill gaps (Mead 2019)
$ 115,200.00	3x detached breakwaters	Manuka to Kolonga	Based on aerial images (requires further investigations)
$ 44,520.00	1 km of coastal planting	Manuka to Kolonga	Provide a wider buffer zone along the road
$ 1,246,220.00	Estimated subtotal		
$ 186,933.00	15% contingency		
$ 1,433,153.00	Estimated total		
$ 22,336,013.00	Grand total		
Long-term measures: reclamation estimates — require decision making			
$ 33,960,000	Reclamation	Sopu	1,900,000 m3 @ T$20/m3

Total excluding long-term reclamation measures: T$ 22,336,013.

Table 10-2. Updated priorities for the use of the donor funds under negotiation on parts of the Northern Tongatapu Coastal Protection project. Refer to Table 10-1 for the full breakdown of the 46 components of the project.

Coastal Unit	Cost (T$)	Item	Location	Comment
1	$ 70,400.00	Complete seawall and 0.9 ha add. Mangroves	Kovolai	40 m of seawall and mangroves seaward of those previously planted to widen green-belt
1	$ 238,165.00	Mangrove reinstatement	Kolovai to Foui	Includes a nursery, brushwood fences and pig-control
1	$ 7,475.00	Remove access path to restore flow	'Ahau	Digger working on site for two days including mob/demob
1	$ 226,366.00	380 m seawall with non-return valves	Ha'avakatolo	Extend from Kolovai seawall; includes five nonreturn valves
2	$ 25,000.00	Warning signage along the coast	Masilamea to Sopu	Six signs
2	$ 3,575,620.00	Flood control	Nukunuku to Sopu	Includes ground surveys and modelling/engineering advice
4	$ 437,000.00	12 km dykes/bunds	Nukuhetulu to Longoteme	To better protect low-lying crop land; includes ground surveys and modelling/engineering advice
5	$ 1,433,153.00	All recommendations	Nukuleka to Niutoua	Includes all items in Table 10-2
	$ 6,013,179.00	Total (includes 15% contingency)		

Appendix A. Mangroves and nature-based solutions

11. Mangroves

11.1 Introduction

A useful summary of mangroves is provided in the *World atlas of mangroves* (Spalding et al. 2010). In 2010, mangrove forests occupied roughly 15 million hectares of tropical and subtropical coastline worldwide (Spalding et al. 2010), with this number likely significantly less now. Mangroves are found in 123 countries and territories globally (Spalding et al. 2010). Despite only amounting to 1% of tropical forests, mangroves are highly productive ecosystems, rich in biodiversity. They consist of a wide variety of plant species that provide important habitats for a wealth of fauna, including mammals, birds, reptiles, fish, and molluscs (Spalding et al. 2010). Mangroves also contribute to livelihoods, both locally and globally, by providing forest resources, such as medicine, timber, thatching materials and dye.

Mangroves are largely restricted to the tropics and a few warm temperate regions, with the greatest abundance and diversity located along wetter coastlines, as well as in deltaic and estuarine areas (Spalding et al. 2010). The Sundarbans, Niger Delta, and the complex deltaic coastlines of northern Brazil and southern Papua comprise the largest expanses, accounting for some 16.5% of mangroves globally.

The work carried out by Spalding et al. (2010) considered 73 species and recognised hybrids of mangroves. These species are almost exclusively divided between the Indo-West Pacific realm (62 species) and the Atlantic Eastern Pacific Realm (12 species, with one being common to both groups).

Global research has shown that mangroves have higher levels of primary activity than most other tropical or temperate forests (Spalding et al. 2010). Even in low stature forests, their standing biomass can be very high, due to the high biomass below ground. Their biomass and considerable ability to store organic carbon means that, despite their small global extent, mangroves have an important role to play in global carbon budgets and in mitigating the effects of climate change. Spalding et al. (2010) report that preliminary estimates indicate that the total above ground biomass may be over 3,700 teregrams of CO_2 equivalent (Tg) with about 14–17 Tg of carbon sequestrated into the sediments per year.

Recent studies have demonstrated that mangrove stands (also known as mangals) have the ability to keep pace with the rising sea level, and so maintain coastal protection as time progresses. In addition, mangroves are known to have higher levels of primary activity than most other tropical or temperate forests, which translates to the marine food-web, as well as a large capacity for the sequestration and storage of carbon (i.e. mitigation of CC and associated SLR). A recent study to consider mangrove carbon sequestration in Fiji found that

mangrove areas sequester 10 times the amount of carbon than does terrestrial rainforest, with much of this captured within the below-surface biomass (Cameron et al. 2021). This means that, along with providing coastal resilience and important ecosystem services, planting mangroves also offsets CO_2 emissions that are resulting in increased effects on coastal areas. Appendix A provides a review of mangroves and nature-based solutions, some of which have been incorporated into the concept designs for coastal protection of the northern coastline of Tongatapu.

There is increasing awareness of the indirect benefits of mangroves in protecting coastlines from erosion, storm surge and even tsunami. There is evidence that suggests that mangroves reduced the impact of the 2004 Indian Ocean tsunami at many locations. Since then, more and more restoration and planting projects of mangrove stands have been undertaken to protect coastlines and coastal communities.

Spalding et al. (2010) reports that, according to the work carried out by the Food and Agriculture Organization (FAO), some 35,600 km^2 were lost (human removal) between 1980 and 2005 with total estimates of more than 50,000 km^2, of the estimated 200,000 km^2 original cover, lost. Between 2000 and 2005 ~0.66% of mangroves were removed, which equates to 3-5 times the global forest loss rate. Spalding *et al.* (2010) argue that the greatest drivers of mangrove forest loss are direct conversion to aquaculture, agriculture, and urban land uses because coastal areas are often dense and competition for land is intense. Even where mangroves exist, they are often over-harvested and degraded by polluted waters and other impacts (Spalding *et al.,* 2010).

In recent times, climate change concerns have raised new threats to mangroves through rising sea levels. As noted above, Spalding *et al.* (2010) argue that, to a limited degree, mangroves may be able to keep up with slight rises in sea level through the accumulation of sediment and organic matter in their soils. Recent work in New Zealand supports this argument (Swales et al. 2018). There is, however, some evidence which suggests that this will be insufficient in many areas due to restricted space; as mangroves migrate inland, as sea levels rise, this migration will likely be impeded by adjacent human land uses and coastal engineering projects.

There is, however, some good news, with over one quarter of the remaining mangrove stands incorporated into protected areas that have been established for the purpose of conservation (Spalding *et al.,* 2010). Interestingly, the economic value of mangroves ranges between $2,000 and $9,000 USD per hectare, which, in the long term, is far high than the value of almost every other use (aquaculture, agriculture and even urban spaces) (Spalding *et al.,* 2010), although they have historically been cleared for these other uses.

11.2 Mangrove morphological and eco-physical adaptations

The term mangroves collectively refers to woody *Halophyitic angiospermic* trees inhabiting the intertidal zone of coastal estuarine regions. They display a number of morphological and eco-physiological adaptations, including viviparous germination, aerial roots (pneumatophores) and physiological mechanisms to cope with salinity, inundation and exposure pressure to maintain water and carbon balance (Chakraborty 2013). The following are direct excerpts from Chakraborty (2013), which describe mangrove eco-physical and morphological adaptations.

11.2.1 Adaptations to low oxygen

Red mangroves, especially *Rhizophora spp*. inhabiting inundated areas, prop themselves up above the water level with stilt roots and can then take in air through pores in their bark (lenticels). Black mangroves, like *Avicennia spp*. living on higher tidal levels, develop many pneumatophores, having a height of a few metres and are covered in lenticels. The roots also contain wide aerenchyma to facilitate oxygen transport within the plant. Common examples of this type of root are visible in several species of mangroves, like *Avicennia spp., Sonneratia spp., Heritiera sp. and Lumnitzera sp.* It is to be noted that *Heritiera fomes (Sundari*) shows numerous woody peg like pneumatophores or blind root suckers.

11.2.2 Adaptations for support

Certain mangrove shrubs, like *Acanthus sp* and climbers like *Derris spp*. And *Ipomea sp*., grow on the edges of rivers, saline waterbodies, dunes and marshes where the anchorage is not very strong. In these cases, short roots grow obliquely downwards from near the base of the stem and act like stilts, providing additional support, as well as anchorage to the stem.

11.2.3 Adaptations to high salinity

Mangrove species have a wide range of salinity tolerance; as such, mangroves survive and grow in the frequently tidal inundated saline coastal zones and estuarine mouths. The soil and water in these coastal and estuarine zones may interact with mangrove species by three different ways, by osmotic inhibition of saltwater absorption, by specification effects on nutrition or by causing toxicity.

All mangroves exclude most of the salts in seawater. Thus, mangroves are endowed with a unique system of ion influx-efflux regulation by virtue of which they regulate their cellular ionic

contents and have classified mangroves into three categories (Walter 1961): salt excluding, salt excreting and salt accumulating types. In salt excluding species like *Rhizophora mucronata, Bruguiera gymnorhiz*a and *Ceriops decandra,* the root systems possess an ultra-filtration mechanism, which is just like an insurance of this particular group to dominate in the mangrove community.

The salt excreting species of mangrove community, like *Avicennia alba, Avicennia marina, Avicennia officinalis, Aegiceros corniculatum,* and *Acanthus ilicifolius,*. regulate their internal salt levels through foliar glands. However, salt accumulating species, like *Sonneratia apetala, Lumnitzera racemosa, Exoecaria agallocha, Sesuvium portulacastrum* and *Sueda maritima,* have the ability to accumulate high concentrations of salts in their cells and tissues, which impart succulence. *Avicennia spp*. can grow better in higher saline soils and regular tidal inundated areas than in less saline zones. These species can accumulate sodium ion in its leaf-tissue 10 times higher than potassium ion. *Heritiera fomes* can also grow best in less saline soils and are found to accumulate more potassium ion than sodium ion (Karmarkar 1985; Naskar et al., 2004). Red mangroves exclude salt by having significantly impermeable roots which are highly suberised, acting as an ultra-filtration mechanism to exclude sodium salts from the rest of the plant. Analysis of water inside mangrove plants has shown that anywhere from 90% to 97% of salt has been excluded at the roots. Any salt that does accumulate in the shoot is concentrated in old leaves which are then shed, as well as stored away safely in cell vacuoles. White (or grey) mangroves can secrete salts directly; they have two salt glands at each leaf base (hence their name – they are covered in white salt crystals). The most distinctive trichome (appendages which are epidermal in origin) that develops in certain mangrove leaves is the structure for secreting certain ions like Na+ and Cl-. These form a general class of secretory structures referred to as ‘salt glands’ by Fahn (1979).

11.2.4 Adaptation for limiting water loss

Because of the limited availability of freshwater in the salty soils of the intertidal zone, mangrove plants have developed ways of limiting the loss of water, either through transpiration or evaporation that they lose through their leaves. The orientation of their leaves vary to avoid the harsh midday sun and so reduce evaporation from the leaves, and their stomatal openings lie below the surface of the leaves (shrunken stomata). Mangrove leaves are almost leathery, coriaceous, thick, fleshy and more or less translucent with obscure leaf veins, which mean that there are no vein sheaths surrounding the veins. Sometimes, the cuticle is thick and smooth with small hairs, giving the plant a glossy appearance (Mitra et al. 2004).

11.2.5 Adaptation for nutrient uptake

The mangroves face the biggest problem in nutrient uptake; thriving in perpetually waterlogged soil, having little free oxygen. The osmotic potential of the leaf cells of mangroves is high, which is essential to absorb saline water having higher density with its high negative water potential. Thus, anaerobic bacteria liberate nitrogen gas, soluble iron, inorganic phosphates, sulfides, and methane, which make the soil much less nutritious and contribute to a mangrove's pungent odour. Prop root systems allow mangroves to take up gases directly from the atmosphere, and various other nutrients, like iron, from the inhospitable soil.

11.2.6 Adaptations for increasing survival of offspring

In this harsh environment, mangroves have evolved a special mechanism to help their offspring survive. Mangrove seeds are buoyant and therefore suited to water dispersal. Alternately, a viviparous mode of germination has been developed to ensure the settling of saplings in the soft soil of a mangrove forest floor and thereby avoid the shifting of the propagules by tidal water.

11.3 Mangrove zonation

Mangrove species have distinct niche preferences, often showing strong spatial patterns of zonation associated with salinity, elevation (inundation), and sediment properties (Spalding et al. 2010) (Figure 11-1). Vertical zonation patterns are most common with dominant species on seaward shores (e.g. *Rhizophora stylosa*, *R. samoensis* and *R.* x *selala*) changing to species such as *Brugiera gymnorhiza*, *Heritiera littoralis* and *Xylocarpus* sp. on the landward side (Ramsey & Lundquist 2011). Canopies can often reach 30 m, typically inland (Ramsey & Lundquist 2011). For example, canopies in Kosrae and Pohnpei in the Federated States of Micronesia are typically high because disturbances to canopies are rare (Spalding et al. 2010, cited in Ramsey & Lundquist 2011). Temporal patterns of zonation representing successional dynamics are also observed (Spalding et al. 2010, cited in Ramsey & Lundquist 2011).

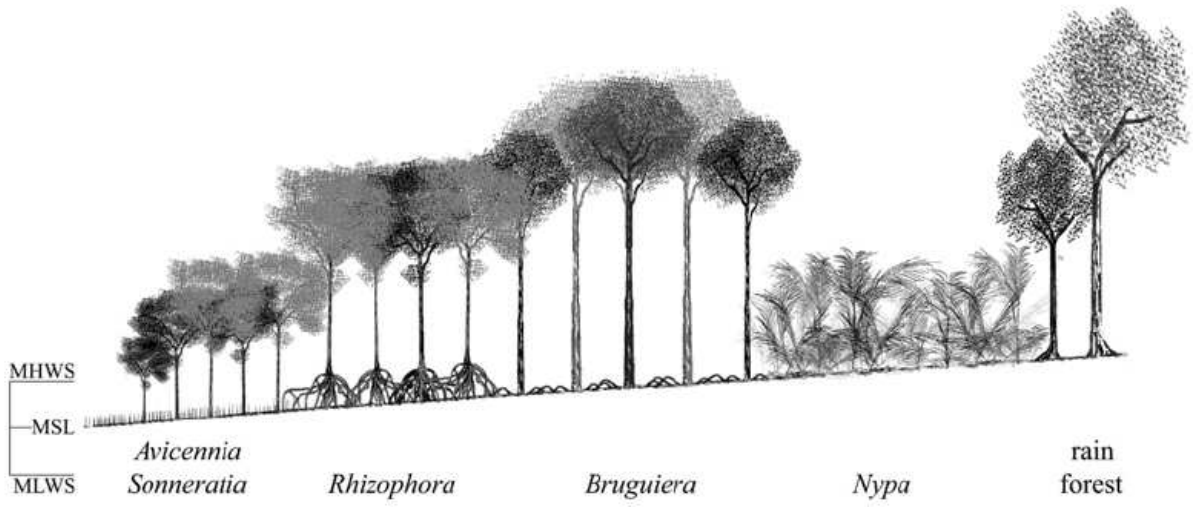

Figure 11-1 Mangrove zonation from mean tide to high tide typical of Papua New Guinea and Solomon Islands. (Modified from Ellison 1997, cited in Ramsey & Lundquist 2011).

Mangroves occur in a variety of tropical coastal settings (Figure 11-2), e.g. Kjerfve (1990), some of which are described below.

- In deltaic mangrove forests occurring at the mouths of large river systems, found on larger volcanic islands such as Fiji, (e.g. at the mouths of the Nadi and Rewa rivers) and Papua New Guinea. In Papua New Guinea, deltaic floodplains account for more than 50% of the southern coastline on the mainland and about 10% of the northern coastline (Sullivan 1991). These typically have the most developed patterns of mangrove species zonation (Figure 11-1).
- In estuary and estuary lagoon systems occurring on high islands, for example Kosrae in Federated States of Micronesia, where species zonation includes *Rhizophora mucronata* found close to river mouths, *R. apiculata, Bruguiera gymnorhiza and Sonneratia Alba* in the interior of the mangrove and patches of *Nypa fruticans* and *Xylocarpus granatum* towards the interior (*Whitesell* et al. 1986).
- In lagoon systems on low islands with no river inputs, for example Fanga'uta Lagoon on Tongatapu, Tonga.
- In fringing mangrove systems along atoll lagoon margins and tidal passages (e.g. Tarawa Lagoon), sheltered areas on fringing reef systems (e.g. Kosrae, Federated States of Micronesia) and back reefs behind barrier reef systems (e.g. Pohnpei, Federated States of Micronesia) (Ramsey & Lundquist 2011).

Figure 11-2. Examples of mangrove environments in the tropical Pacific. A: Extensive mangrove strand on the north-west coast of Viti Levu, Fiji. B: Lagoon mangroves behind the fringing coastal berm on the south coast of Kosrae, FSM. C: Fangakakau Lagoon on Tongatapu, Tonga. Fringing mangroves stands in lagoon tidal passage in Tarawa (D), on a sheltered open coast fringing reef on Kosrae (E) and on back reefs behind the barrier reef system on Pohnpei (F) (Ramsey & Lundquist 2011).

In the tropical Pacific, rainfall in the highlands has a major influence on mangrove characteristics, with climatic variation across some of the larger islands influencing mangrove distribution and ecology (Watling 1985, cited in Ramsey & Lundquist 2011). For example, across Vitu Levu in Fiji, strand widths tend to be narrower and have less species diversity. There is stunted mangrove growth, larger strand gaps and areas of salt flat in the drier leeward north-west shoreline, where rainfall amounts are lower and seasonal relative to the windward south-east shoreline, where mangrove growth is more productive and diverse due to the

higher and near-continuous year-round rainfall (Ellison 2009, cited in Ramsey & Lundquist 2011).

In the tropical Pacific, diversity of species is highest in Papua New Guinea, closest to the global peak of mangrove biodiversity in the Indo-West Pacific (Spalding et al. 2010). The region is dominated by tropical mangrove taxa, but also includes species with broad distributions, such as *Avicennia marina* (Spalding et al. 2010). Over 40 co-occurring species have been recorded here, with a rapid decrease in the number going in an easterly direction across the Pacific Islands (Ramsey & Lundquist 2011) (Figure 11-3).

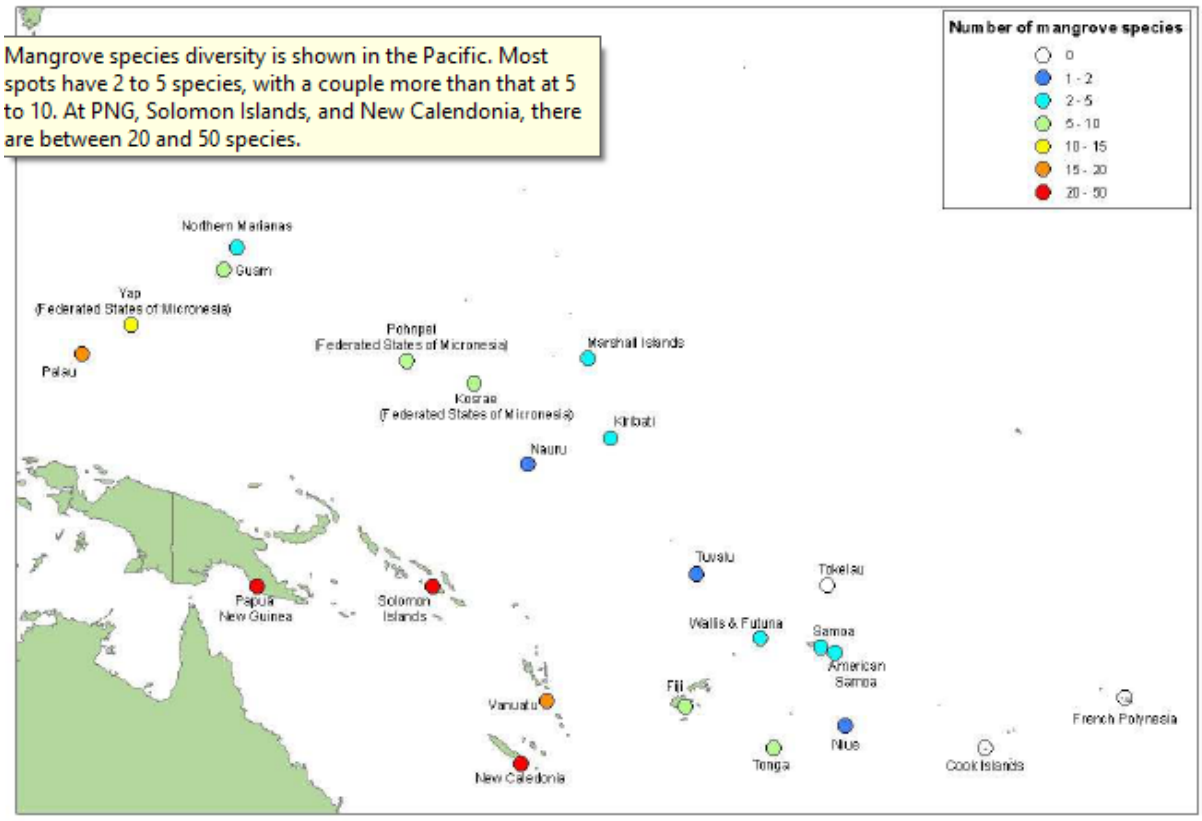

Figure 11-3 Mangrove species diversity in the tropical Pacific region. (Spalding et al. 2010)

11.4 Mangrove productivity

Mangrove ecosystems enjoy two high and two low tides a day, which offers a unique environment for biodiversity development (Chakraborty 1995). During high tides, a major portion of mangrove ecosystems is inundated and receives inputs from estuarine water in the form of moisture recharging components of the bottom soil deposition of sediments and nutrients (macro, micro and trace elements) (Chakraborty 2013). In contrast, during low tides,

receding waters remove large amounts of mangrove detritus to adjoining systems. Phytoplankton utilise the nutrients released from the detritus.

Being perennial evergreen plants, mangroves produce huge amounts of leaf litter throughout the year. These often fall on the moisture-rich surface of silt-clay loaded bottom soils and are broken down by a galaxy of benthic fauna (crabs, gastropods, microarthropods, etc.) into smaller pieces, providing more scope for microbial communities (bacteria, fungi, protozoa) to act upon them for detritus production through litter decomposition (Chakraborty 2013). Deposit feeders such as crabs, molluscs, polychaetes, and nematodes, through their feeding activities, turn over the surface sediment layer, which exposes new litter surfaces to microbial actions (Chakraborty 2011). By some estimates, this detritus-based coastal ecosystem is highly productive, about 20 times higher than the average ocean production (Goudha & Panigraphy 1996).

Schelake and Odum (1962) report that productivity in mangrove environments is attributed to four reasons: (i) three types of primary production units (marsh, vegetation, benthic algae, and phytoplankton); (ii) ebb and flow of water movements, resulting from tidal action; (iii) abundant supplies of nutrients; and (iv) rapid regeneration and conservation of nutrients due to the activity of microorganisms and filter feeders (Figure 11-4 and Figure 11-5) (cited in Chakraborty 2013).

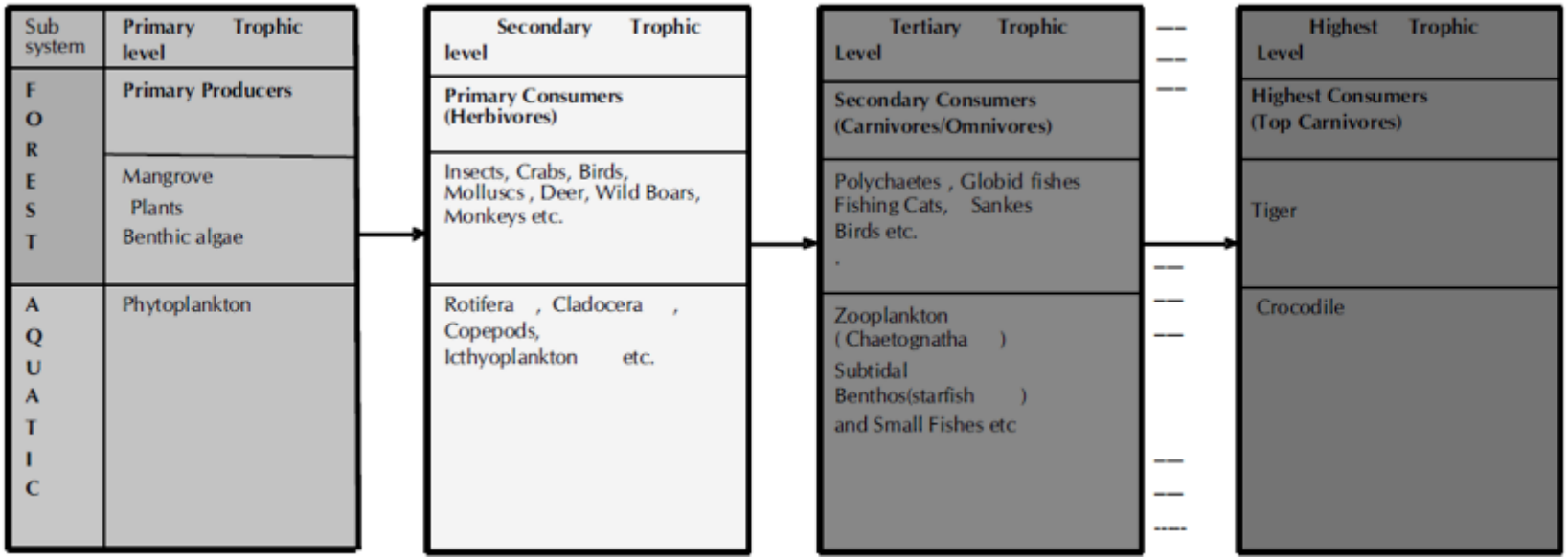

Figure 11-4 Trophic relationships in mangrove ecosystems. (Chakraborty 2013)

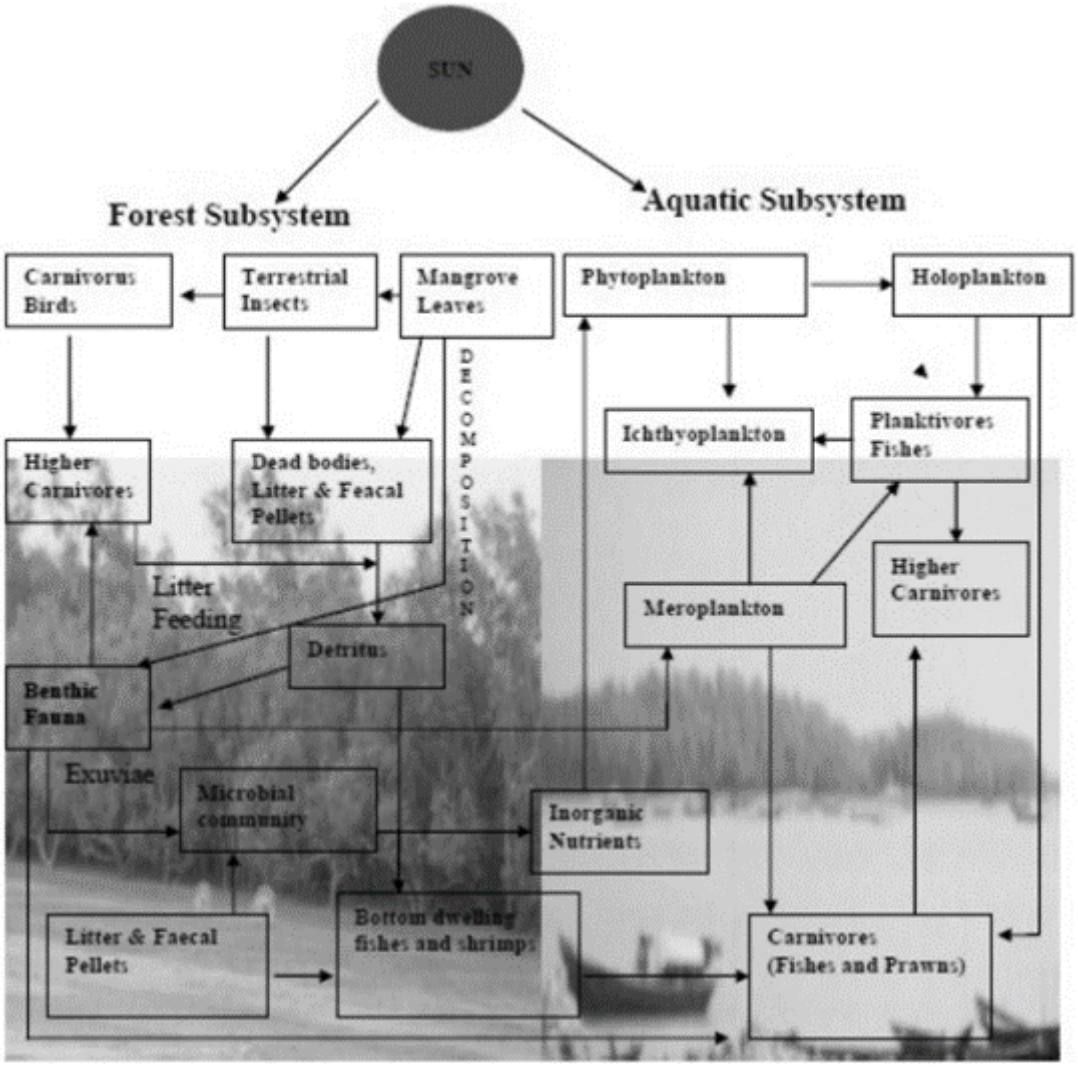

Figure 11-5 Diagrammatic representation of food-web in typical mangrove ecosystems. (Chakraborty 2013)

11.5 Projected vulnerability of mangroves to tropical Pacific climate change

The following are direct excerpts from Waycott et al. (2011) and describe the projected vulnerability of mangroves to climate change within the tropical Pacific.

11.5.1 Solar radiation

Exposure and sensitivity

Mangrove habitats in much of the tropical Pacific are expected to be exposed to reductions in light as a result of the increase in the percentage of cloudy days due to intensification of the hydrological cycle (Chapter 2). Conversely, in New Caledonia, projected decreases in rainfall of 5–10% by 2035 and 5–20% by 2100, and in cloudy days, are expected to increase solar radiation. Because the requirements of mangroves for light are lower than the average levels of solar radiation in the region, mangroves are not expected to be sensitive to the projected changes in levels of solar radiation caused by a more intense hydrological cycle. During periods of high solar radiation, however, the absorption of light translates into heat energy, which can be expected to exacerbate the effects of higher temperature on water loss.

Potential impact and adaptive capacity

The potential impact of altered solar radiation on mangroves is expected to be low, except where mangroves have high exposure to solar radiation combined with limited freshwater supply. These conditions occur, for example, on the leeward side of high islands such as Viti Levu and Vanua Levu in Fiji, and on the west coast of New Caledonia where total rainfall is projected to decline (Chapter 2). If slow rates of sea-level rise were to occur they may enhance the adaptive capacity of mangroves to increased exposure to light by increasing tidal flushing and freshwater supply. However, such slow rates are not expected and thus limited adaptive capacity is expected for mangroves which are exposed to high levels of solar radiation.

Vulnerability

Relative to other factors, the vulnerability of mangroves to projected changes in solar radiation is low, except in areas of combined high radiation and restricted runoff and tidal inundation, where vulnerability is expected to be moderate.

11.5.2 Temperature

Exposure and sensitivity

Mangroves in the tropical Pacific will be exposed to projected increases in air temperature and sea surface temperature (SST) of 0.5–1.0°C in 2035 for the B1 and A2 emissions scenarios, 1.0–1.5°C for B1 in 2100 and 2.5–3.0°C for A2 in 2100. The sensitivity of mangroves to increased surface air temperature and SST is not well known (Saenger, 1983) but is likely to be moderate. For example*, Rhizophora mangle* develops more silt roots per unit area when subjected to a 5°C increase in water temperature and produces more but significantly smaller leaves (Canoy, 1975). Also, young seedlings of a species of *Avicennia* are killed by water temperatures between 39°C and 40°C, although established seedlings and trees are not affected (Gilman et al., 2006; Alongi, 2008). On the other hand, mangroves growing near coastal power stations show little or no visible effects from warmer effluent water (Thorhaug et al., 1979).

Potential impact and adaptive capacity

Mangroves have a high degree of tolerance to heat stress compared with other plants (Smillie, 1984). Thus, even for the A2 scenario in 2100, the projected increases in air temperature are not expected to have substantial effects on the growth and survival of mangroves because the projected increases are below those known to cause detrimental effects. Respiration (CO2 efflux) from plants and microbial communities in sediments approximately doubles with every 10°C increase in temperature, so that on hot days there would be reduced net carbon gain, increased methane emissions and decreases in soil carbon storage (Lovelock & Ellison, 2007). In addition, mangroves have a range of adaptations, such as reducing the apertures of their stomata, to cope with water loss induced by increased evaporation under heat stress (Farnsworth & Ellison, 1996; Gilman et al., 2006).

Vulnerability

Mangroves are expected to have very low vulnerability to the projected increases in air temperature and SST. However, an indirect vulnerability to increases in SST may result from the projected decreases in coral cover due to thermal bleaching, which are expected to reduce sediment supply to mangroves on low islands, and increase exposure to wave action.

11.5.3 Rainfall

Exposure and sensitivity

In equatorial areas of the Pacific, rainfall is expected to increase by 5–15% for the B1 emissions scenario and 5–20% for the A2 scenario in 2035, and by 10–20% in 2100 for both emissions scenarios. In the subtropics, rainfall is projected to decrease by 5–10% for B1 in 2035, and by 10–20% for A2 in 2035 and for both scenarios in 2100. Extremes in wet and dry periods are likely to become more extreme, and droughts associated with the projected changes in rainfall are expected to be more intense due to the increase in temperature.

Mangroves are expected to be moderately sensitive to these changes because soil salinity along the intertidal gradient is affected by the interaction of tidal inundation and rainfall. At locations with low rainfall and high evaporation, soil salinity in the upper intertidal gradient may be high, even though inundation is infrequent. On the other hand, where rainfall greatly exceeds evaporation, for example, in Kosrae, FSM (Ewel et al., 1997), salinity levels do not build up in the soil, and soil salinity is negatively correlated with distance from the seaward edge of the mangrove habitat.

Potential impact and adaptive capacity

The effects of lowered salinity associated with increases in rainfall are likely to benefit mangrove ecosystems in equatorial areas but are expected to be negative in the subtropics where decreases in rainfall (increases in salinity) are projected. Reduced runoff from catchments in New Caledonia may decrease the delivery of sediment to mangrove habitats near estuaries, making it more difficult for the trees at the seaward margins to accumulate sediment and adapt to rising sea levels (Ellison, 2009). Increased drought conditions may also reduce the flowering and fruiting of mangroves (Tyagi & Pillai, 1996; Tyagi, 2001), and perhaps increase the areas of upper intertidal salt flats currently found in the drier areas of the region, such as the leeward side of Viti Levu in Fiji. Depending on environmental conditions, mangroves can minimise water loss and maximise growth by using water more efficiently and reducing transpiration rates. Such physiological plasticity is one reason why mangroves are so successful across the intertidal seascape and these attributes may assist them to adapt to drier conditions. Too much fresh water also poses problems for mangroves. In stagnant flooded soils, roots of many mangroves develop a very thin, slightly oxidised zone that can effectively isolate the actively growing root area (Youssef & Saenger, 1998). Seedlings without well-developed aerial roots would suffer more in this situation than mature trees.

Vulnerability

Mangroves are expected to have low to moderate vulnerability to the projected changes in rainfall, and subsequently salinity, under both scenarios in 2035, with some benefits to plant growth possible from increasing rainfall in equatorial areas. However, as rainfall changes are magnified over time, the vulnerability of mangroves will increase to moderate in 2100 under both scenarios, particularly in areas of the Pacific that experience declining rainfall.

11.5.4 Nutrients

Exposure and sensitivity

The projected changes in rainfall outlined above are expected to alter runoff patterns and the delivery of nutrients to mangrove habitats. Future changes in nutrient supply are hard to quantify because they will be related to the intensity of rainfall. However, increases in nutrients derived from runoff are expected in equatorial areas of the Pacific, and decreases in New Caledonia. Nutrient enrichment enhances vertical accretion and surface elevation of mangrove forests through increased deposition of roots (McKee et al., 2007). Where nutrients are limited, the responses of mangroves are complex; they differ across different types of mangrove forests or locations, depending on the availability of the various nutrients required (Lovelock, 1993; Feller et al., 2003). For example, *Rhizophora mangle* in Belize is limited to different degrees by nitrogen and phosphorus, depending on the zone in which it occurs (Feller, 1995; Lovelock et al, 2004). Belowground decomposition is generally enhanced by additional phosphorus but not additional nitrogen (Lovelock et al, 2004). In contrast, both nitrogen and phosphorus are limiting for mangroves in Florida, USA (Lovelock, 1993).

Potential impact and adaptive capacity

In equatorial areas, the addition of nitrogen and phosphorus is likely to increase plant productivity by altering both tree growth and nutrient dynamics, with the magnitude and pattern of response differing for different nutrients (Feller et al, 2003; Lovelock et al., 2004). In general, increased nutrients may benefit mangroves, or assist them to adapt to rising sea levels (Morris et al., 2002; McKee et al., 2007). But changes in nutrient delivery, when coupled with low rainfall, have the potential to affect mangroves negatively. For example, projected decreases in rainfall (e.g. New Caledonia) may be expected to increase mangrove mortality where nitrogen concentrations increase (Lovelock & Ball, 2009). Ultimately, community composition could be affected, with

different mangrove species surviving at different rates, depending on their requirements for nitrogen and phosphorous (Lovelock, 1993, Lovelock et al., 2004). Because mangroves have large nutrient and carbon stores in soils and plant biomass (Robertson et al, 1992; Chmura at al., 2003), small changes in nutrients alone are not likely to have significant effects. However, when a decrease in nutrients is coupled with increases in temperature and atmospheric CO2 (and associated increases in respiration), negative effects on plant tissue balance may occur (Lovelock et al., 2007). The adaptive capacity of mangroves to changes in nutrient delivery will mostly be at the community level, with different species dominating under different nutrient conditions, and community composition shifting accordingly. This will have implications for the diversity and structure of mangrove habitats (Lovelock et al., 2007), and the services they provide to fish and invertebrate species harvested by coastal fisheries.

Vulnerability

The effects of the projected increases in nutrient delivery on mangroves around high islands in the equatorial Pacific are likely to be positive. In contrast, mangroves in New Caledonia are expected to be negatively affected by the projected decreases in availability of nutrients. The vulnerability of mangroves in New Caledonia is assessed as low, however, due to their inherent adaptive capacity.

11.5.5 Cyclones and storms

Exposure and sensitivity

Although global climate models do not project an increase in the frequency of cyclones in the tropical Pacific, there is the possibility that cyclones and storms will become more intense within the cyclone belt over the remainder of this century. In particular, wind speeds associated with cyclones may increase by 1–8% for every 1°C rise in SST. Mangroves are sensitive to strong winds associated with cyclones and storms, which damage foliage, desiccate plant tissues, and increase evaporation rates and salinity stress (Ellison, 2009). The landward margin of mangroves is particularly prone to high evaporative loses and drying-out of the substrate. Increased wave surge during cyclones erodes sediments in the seaward mangrove zone and reduces the stability of plants normally provided by their root systems (Wolanski et al., 1992; Kathiresan & Bingham, 2005). On the positive side, stronger winds may facilitate pollination of species such as *Rhizophora* and *Excocaria,* and the dispersal of seeds.

Potential impact and adaptive capacity

Under prolonged and severe wind conditions, evaporative losses may result in die-back of mangroves. Stronger wave surges are also likely to remove mangroves from the seaward edge of mangrove habitats. While the logs from fallen trees may provide some shelter for juvenile fish if washed into subtidal areas, losses in primary productivity can be expected to exceed such benefits in many places. The movement of large, woody debris in mangrove areas during high tide can also disturb establishment of seedlings.

After a cyclone, there is usually a narrow zone of damage to mangroves along the coast due to storm surge, and complete defoliation in the path of the storm. Mangrove species have different tolerances to cyclone damage (Baldwin et al., 2001). *Rhizophoraceae* have low tolerance and cannot resprout from dormant buds, whereas species of *Avicennia* can resprout. Mortality of mangroves as a result of storms has led to collapse of peat soils and changed hydrological conditions (Cahoon, 2003). In general, mangroves grow new leaves after cyclones and storms unless there is structural damage to the trees or burial of the roots by sediments. Over time, recruitment of seedlings occurs from adjacent undamaged areas, and the mangrove habitat is re-established. This natural adaptive capacity can be enhanced and accelerated by replanting programmes.

Vulnerability

Mangrove habitats in the tropical Pacific are considered to have moderate vulnerability to the effects of more intense cyclones. Damage is expected to occur during these high-energy events, but the trees should eventually recover from the effects of wind and waves, prolonged inundation and sediment deposition, where the physical conditions required for growth and survival are restored.

11.5.6 Carbon dioxide

Exposure and sensitivity

For the B1 and A2 emissions scenarios, atmospheric concentrations of CO2 are projected to be ~ 400 ppm in 2035. By 2100, CO2 levels are expected to be 450–500 ppm for B1, and 750–800 ppm for A2207. The projected levels of CO2 are also expected to increase the acidity of the ocean and reduce the availability of carbonate ions. The few studies on the impacts of elevated CO2 on mangroves suggest that primary production of mangroves is likely to be enhanced under future climate change

scenarios. In situations of increased moisture stress, enhanced CO2 may also partially reduce the negative effects of reduced humidity and rainfall (Ball et al., 1997). Increased levels of CO2 may also change the patterns of species dominance and accelerate mangrove encroachment into adjacent inland brackish and freshwater environments. However, when increases in CO2 are combined with higher temperature and nutrient levels, there may be negative effects on plant tissue balance.

Potential impact and adaptive capacity

The projected increases in atmospheric CO2 are expected to increase productivity of mangroves, provided that salinity and humidity are also conducive to tree growth. The increased acidification of the ocean is not likely to affect mangrove habitats greatly, although the process by which dissolved calcium from dead shells makes some brackish waters alkaline may be weakened as acidification increases. Even if, soil acidity increases, however, mangroves are not expected to be affected adversely, because many mangrove soils are neutral to slightly acidic due to sulphur-reducing bacteria and the presence of acidic clays (Waycott et al., 2007). In Malaysia, mangroves occur in very acidic brackish waters, probably due to the aeration of soil sulphates, forming sulphuric acid.

A common plant adaptation to elevated CO2 concentrations is decreased nitrogen investment in leaves and a concomitant increase in the carbon:nitrogen ratio of plant tissues (Twilley et al., 1992). If mangroves respond in this way, the changes in plant tissue balance will have knock on effects for food webs (Stilling et al., 1999), and on nutrient cycling (Bosire et al., 2011).

An indirect impact of increased ocean acidity on mangrove systems could be reduction in the supply of carbonate sediment, expected to result from reduced rates of calcification by corals. This may reduce the ability of mangroves on low islands to adapt to sea-level rise.

Vulnerability

Mangroves are unlikely to suffer negative effects as a result of increased atmospheric CO2 alone. Rather, they are expected to grow faster and become carbon sinks in some places. There may also be increased allocation to below-ground biomass with elevated CO2, resulting in greater gains in soil surface elevation and stability under sea-level rise (Langley et al., 2009). In some locations, synergies with increased temperature and altered nutrient delivery may result in negative effects on plant tissue balance. In such places, mangroves are likely to have a very low to low vulnerability to elevated CO2.

11.5.7 Sea-level rise

Exposure and sensitivity

The conservative projections for sea-level rise made in the IPCC Fourth Assessment Report (IPCC-AR4) of ~ 10 cm for the B1 and A2 emissions scenarios in 2035, ~ 20–40 cm for B1 and ~ 20–50 cm for A2 in 2100, have now been increased substantially. More recent estimates are 20–30 cm for the B1 and A2 scenarios in 2035, 70–110 cm for B1 and 90–140 cm for A2 in 2100. Mangroves grow between mean sea level and mean high water, and the zonation of mangrove species (Figure 11-6) is determined by inundation frequency controlled by the tides. If the tidal conditions under which mangroves grow are altered, the growth and survival of the trees are affected. In experiments to simulate the effects of inundation due to sea-level rise on the growth *of Rhizophora mangle,* for example, seedlings maintained under conditions where an increase of 16 cm was imposed on normal tidal water levels were 10–20% smaller than control plants after 2.5 years (Ellison & Farnsworth, 1997).

Potential impact and adaptive capacity

The projected rise in sea level could potentially have a powerful effect on mangroves. However, where mangroves can continue to accumulate sediments at appropriate rates, the effects are likely to be less severe. The capacity of mangrove forests to resist sea-level rise is likely to depend on the source of sediment, and the rate of sedimentation, which in turn is influenced by rainfall, tidal amplitude, coastal currents and wave energy (Gilman & Ellison, 2008). Biogenic processes, particularly root growth rates, will also be important in the response of mangroves to sea-level rise (McKee et al., 2007).

Sedimentation is expected to be slower in areas of natural subsidence, such as southern PNG, American Samoa and western Viti Levu in Fiji (Ellison, 2005; Gilman et al., 2007; Ellison & Fiu, 2010). Mangroves on low islands may be able to compensate for low rates of sea-level rise through accumulation of peat (Ellison, 1993; McKee et al., 2007). Most continental and high island mangroves are expected to adapt if the rate of sediment deposition exceeds the rate of sea-level rise. However, various surface and subsurface processes, such as sediment accretion and erosion, biotic contributions, below-ground primary production, sediment compaction, fluctuations in water-table levels and pore water storage, make sedimentation rates alone a poor indicator of mangrove responses to rising sea level (Cahoon et al., 2006; Soares, 2009). The potential impact of sea-level rise on mangroves will be greatly reduced in those locations where they can migrate landward (Soares, 2009). The

scope for migration will depend on the rates of sea-level rise and accumulation of sediments, and changes in elevation. Historical records show mangrove die-back under accelerated rates of sea-level rise, followed by re-establishment as sea level falls (Figure 11-6). Landward migration will, however, be constrained in many locations by barriers such as coastal roads and settlements, and where steep terrain occurs behind mangroves. In addition, the projected acceleration in the rate of sea-level rise after 2050 (Soloman et al., 2007) is expected to make it difficult for mangroves to re-establish and reach reproductive maturity before their, intertidal elevation envelope is reduced again. PNG, Solomon Islands and FSM have freshwater swamp forest or marsh on the landward margin of mangroves that could become mangrove habitat with rising sea level. Thus, establishment of mangroves in new landward areas is only likely where (1) the topography is suitable for colonisation, (2) the rate of sea-level rise is compatible with the life cycles of mangrove species, (3) the hydrology and sediment composition is suitable, and (4) there is limited competition with non-mangrove species (Gilman et al., 2008; Soares, 2009).

Vulnerability

The vulnerability of mangroves to projected sea-level rise is high for both scenarios in 2035, particularly in locations where the coastline is subsiding and sedimentation rates are low. Vulnerability is expected to be very high for both B1 and A2 scenarios in 2100 where landward migration is blocked by infrastructure, where there is intensive land use and steep gradients, and as the magnitude of sea-level rise increases later in the century.

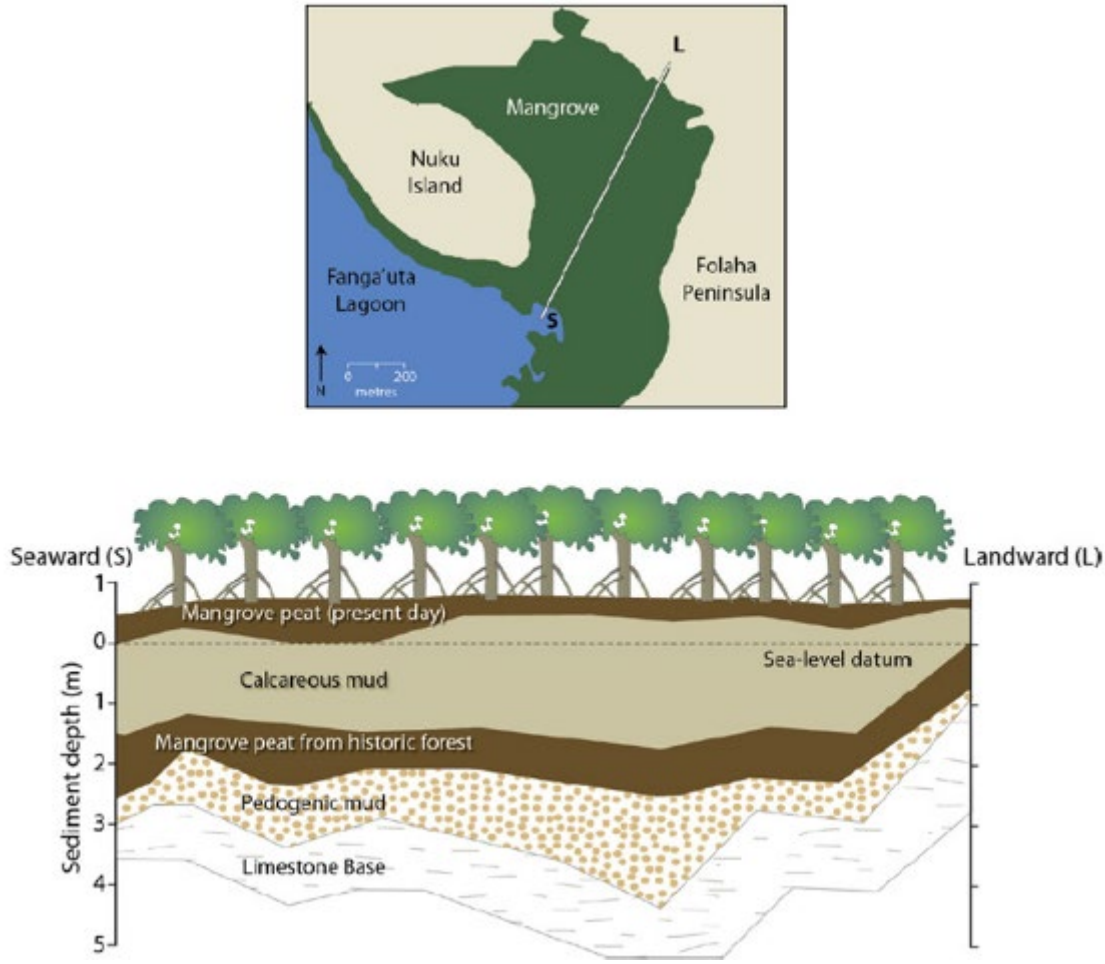

Figure 11-6 Sedimentary evidence of the extent of mangroves at Folaha, Tongatapu, Tonga. 7000–5500 years ago when forests growing 1.5–2.5 m below the present sea level were exposed to accelerated sea-level rise (1.2 mm per year). The mangroves died back to create a lagoon, ultimately re-establishing after a fall in sea level (Ellison 2008).

12 Nature-based solutions

The term nature-based solutions (NBS) is used to describe solutions for wave attenuation and erosion reduction on coastlines. In recent decades, coastal protection work has seen a shift from traditional hard or grey engineering that exclusively involves structural features like seawalls and breakwaters to softer, more eco-friendly solutions. The term soft engineering appeared in the 1980s and describes solutions that attempt to have beneficial influence on coastal processes. In more recent times, terms such as building with nature, living shorelines, engineering with nature, ecological engineering and green infrastructure have begun to appear. In general, NBS describes all these terms (Pontee et al. 2016).

Pontee et al. (2016) argue that NBS is defined and consists either wholly or partially of natural features that are designed to offer or improve coastal protection. They include:

- fully natural solutions (e.g. naturally occurring coral reefs, marshes and mangroves);
- managed natural solutions (e.g. artificial coral/oyster reefs, renourished beaches and dunes, planted saltmarshes and mangroves);
- hybrid solutions that combine structural engineering with natural features (e.g. marsh–levee systems or dune–dyke systems); and
- environment-friendly structural engineering (e.g. vegetated engineering or bamboo sediment fences).

For fully natural solutions, the natural coastal habitat provides the coastal protection service (i.e. erosion control, wave reduction, or flood storage) and is not specifically managed. In contrast, managed NBS is where a coastal habitat is created and/or managed for the purpose of coastal protection (Pontee et al. 2016). Examples of managed NBS include coastal dune management in the UK (Pye et al. 2007) and Netherlands as well as oyster reefs in Louisiana and Florida (Kirkpatrick 2013). Hybrid solutions provide coastal protection through a combination of natural solutions and hard engineering defences that are either located landward (dykes) or seaward (sills) of the natural habitat. Another example of a hybrid solution is vegetated engineering or greenwashing, which is the practice of modifying or retrofitting coastal protection structures to create or enhance ecological value (e.g. establishing ecological niches on breakwaters (Chapman and Underwood 2011)). Environmentally friendly engineering could be the use of bamboo to create wooden fences or groynes to trap sediment or block wave action and foraging animals (e.g. bamboo fences protecting mangrove seedlings Kolovai, Tongatapu, Tonga (Mead 2019)).

Pontee et al. (2016) discuss the fact that guidelines and manuals for NBS are less well established than for conventional engineering approaches. There are, however, an increasing

number of studies that can and are contributing to the development of NBS guidelines and manuals. For example, a couple of guidelines, such as the "building with nature" and "managed realignment" guidelines from the Netherlands and UK respectively, have been developed from various NBS projects and lessons learnt from those projects (Leggett et al. 2004). Recently, the US Army Corps of Engineers provided a framework and metrics for assessing and ranking NBS alternatives with other coastal protection designs for the Atlantic coast of USA (Bridges et al. 2015; cited in Pontee et al. 2016). Examples of large-scale NBS implementation include the living shoreline projects on the east coast of USA and the green belt mangrove and saltmarsh restoration projects in China (Chung 2006, cited in Pontee et al. 2016) and the mangrove belts in front of dykes in Vietnam (IFRC 2011).

Pontee et al. (2016) argue that several factors will determine the effectiveness of coastal protection NBS:

- *type of habitat* – this is controlled by the environmental conditions, such as wave energy, tidal range, sediment and nutrient supply;
- *water depths* – wave dissipation over/through habitats is governed by the depth of water relative to the habitats; and
- *habitat characteristics* – for example, high reef crests or high and/or dense mangrove stands tend to be effective at dissipating wave energy.

Pontee et al. (2016) point out that it is often perceived that NBS provide a lower standard of coastal protection than does hard engineering. Some NBS, however, provide protection levels as high as traditional hard engineering structures, such as the managed coastal dunes in the Netherlands, which achieve a 1:10,000-year protection standard in some places (Most & Wehrung 2005). Coral reefs are often referred to as being highly effective natural offshore breakwaters (Ferrario et al. 2014) and oyster reefs can offer suitable alternatives to traditional breakwaters where some form of seaward protection is required for an intertidal or coastal habitat (Kirkpatrick 2013, cited in Pontee et al. 2016).

In general, the cost of NBS can vary significantly, depending on the habitat and site characteristics. For example, while marshes provide an inexpensive option under naturally favourable conditions, restoration after storm damage or in unsuitable areas can be expensive (Barbier 2013, cited in Pontee et al. 2016). Despite this, NBS are often seen as low-cost 'no regret' solutions, which are easier and cheaper to maintain than hard engineering structures. Furthermore, hybrid NBS in front of hard structures such as dykes have been shown to greatly reduce the cost of maintenance and, in certain instances, have allowed a reduction in dyke crest height by complementing the protective function of the hard structure (Anthony & Gratio 2012, cited in Pontee et al. 2016).

12.1 Fully natural and managed-natural solutions

12.1.1 Wave height attenuation mechanisms

Two mechanisms control wave reduction in habitats:

a) wave-breaking due to changes in water depth (i.e. in reefs); and
b) damping of wave energy and wave height through friction (i.e. in wetland habitats like mangroves, marshes or seagrass beds).

In general, the wave height depends on habitat and site-specific ecological and geophysical parameters that influence the dynamics of incoming waves (Figure 12-1). Wave reduction in coral reefs is mainly influenced by: (i) the relative wave height, i.e. the ratio H/h where h is the depth of the reef and H the wave height; and (ii) the relative width, i.e. the ratio B/L, where B is the width of the reef and L the length of the incoming wave (Mendez & Losada 2004; Duarte et al. 2013).

In vegetated habitats, the height, geometry and shoot/stem density of the habitat have all been shown to affect wave reduction in flume studies and models (Borsje et al. 2011; Suzuki et al. 2012; Guannel et al. 2015). A key parameter in intertidal vegetated habitats, such as mangroves and marshes, is the relative height of the vegetation, i.e. the ratio hv/h, where hv is the height of the vegetation canopy and h the water depth. In addition, these habitats are known to trap sediments (Borenstein et al. 2005; McIvor et al. 2013), raising the near-shore bathymetry and thereby increasing their capacity to reduce waves. Wave heights within deeper vegetated habitats, such as seagrass beds, are also affected by changes in bathymetry (Duarte et al. 2013). For further details on the calculations, refer to Narayan et al. (2016).

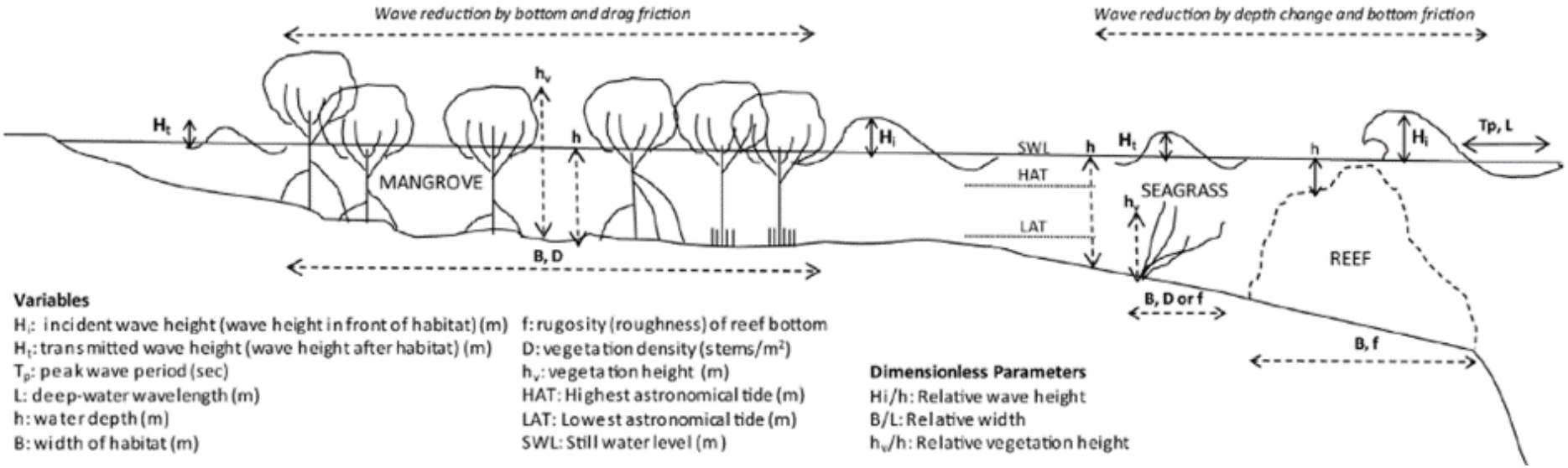

Figure 12-1 Schematic of wave height reduction across coastal habitats. Showing the general mechanics of wave height reduction through habitats using the examples of mangroves, seagrass and coral reefs (Narayan et al. 2016).

Some coastal wetland plants are above ground and in direct contact with sea water and waterborne sediment. Plant features, such as the stems and leaves, slow water velocity, reduce turbulence, and increase deposition (Redfield 1972; Christiansen et al. 2000; Gedan et al. 2011). This works because, as water flows through a vegetated canopy, the vegetation exerts a drag force counter to the direction of motion. Increased shear stress and potential scouring of the bed can, however, occur when stem densities are low, which results in the drag locally enhancing turbulence (Nepf 1999; Bouma *et al.,* 2009; Gedan *et al.,* 2011). Under stem densities characteristic of a typical marsh canopy, however, vegetation reduces turbulence, slows water velocity, and diminishes shear stress near the bed (Leonard & Luther, 1995; Nepf, 1999; Gedan et al. 2011). Neumeier & Ciavola (2004) report that comparisons between paired vegetated and unvegetated sites indicate that marsh vegetation reduces near-bed water velocity. Moreover, Gedan et al. (2011) state that basal shear stresses are rarely high enough for sediment entrainment in a vegetated canopy inundated by tidal flow (Christiansen et al. 2000) or wind waves (Carniello et al. 2005). This effect appears to be true whether wetland vegetation is partially submerged or deeply submerged. Gedan et al. (2011) report that hydrodynamic implications of reduced sediment erosion (i.e. Hir et al. 2007) and promotion sediment settling (Leonard & Luther 1995; Furukawa et al. 1997; Mudd et al. 2010) occur when deeply submerged water velocities and shear stress, near the bed (those relevant for sediment erosion), remain strongly dampened and become decoupled from velocities near the water surface (Neumeier & Ciavola 2004).

Plant roots below ground directly slow rates of erosion by stabilising the soil substrate (Gedan et al. 2011). Below ground vegetation biomass increases the shear strength of wetland soils since plant roots tend to enhance the cohesion and tensile strength of their substrate (Micheli & Kirchner 2002). Tidal creeks can become stabilised as roots can provide a physical barrier between open water and soil (Mazda et al. 2007; Wolanski et al. 2008). Physical protection against erosion is limited to the depth of the roots, typically one metre. This results in greater protection in micro- and meso-tidal estuaries than in macro-tidal estuaries, where erosion occurs and bank slumping results below the root level (Figure 12-2).

Figure 12-2 Mangrove roots cover the upper banks of the Daly Estuary, Australia. Providing a protective barrier against erosion of the upper banks, although not protecting against undercutting in the lower banks (Wolanski et al. 2008, cited in Gedan et al. 2011).

12.1.2 Coral reefs, mangroves, salt marshes and seagrass

Narayan et al. (2016) carried out a meta-analysis of 69 studies worldwide and: (i) examined measures of effectiveness of coral reefs, mangroves, salt-marshes, and seagrass/kelp beds for wave height reduction; (ii) synthesised the cost and coastal protection benefits of 52 nature-based defence projects; and (iii) estimated the benefits of each restoration project by combining the information on restoration costs with data from nearby field measurements. The analysis revealed that coastal habitats have significant potential for reducing wave heights, which varies by habitat and site.

In general, coral reefs and salt marshes have the highest overall potential. Narayan et al. (2016) concluded that habitat effectiveness is influenced by two components: (i) the ratios of wave height-to-water depth and habitat width-to-wavelength in coral reefs; and (ii) the ratio of vegetation height-to-water-depth in salt marshes.

On average Narayan et al. (2016) observed coastal habitats reduced wave heights between 35% and 71%. Coral reefs reduced wave heights by 70% (95% CI: 54–81%), salt-marshes by 72% (95%CI: 62–79%), mangroves by 31% (95% CI: 25–37%) and seagrass/kelp beds by 36% (95% CI: 25– 45%).

With respect to coral reefs, the most effective reefs are at least twice as wide as the wavelength and located at depths that are, at most, half the incoming wave height. With respect to salt marshes, wave reduction in saltmarshes was highest when the canopy was close to the water surface. This suggests that height designs of green belts for coastal protection, rather than width-based criteria, are more important for salt marsh nature-based solutions.

Gedan et al. (2011) carried out a meta-analysis of wave attenuation by vegetated and unvegetated wetland sites to highlight the critical role vegetation plays in attenuating waves. The authors noted that, although coastal wetland vegetation can be an effective shoreline buffer, wetlands cannot protect shorelines in all locations or scenarios. The authors state that large-scale regional erosion, river meandering, large tsunami waves, and storm surges can overwhelm the attenuation effect of vegetation. Despite this, however, the authors state that, due to a nonlinear relationship between wave attenuation and wetland size, even small wetlands afford substantial protection from waves.

Furthermore, Gedan et al. (2011) report that combining man-made structures with wetlands in ways that mimic nature is likely to increase coastal protection. For example, oyster domes can be used in combination with natural wetlands to protect shorelines and restore critical fishery habitat (Figure 12-3) (Gedan et al. 2011). The authors conclude that coastal wetland vegetation modifies shorelines in ways (e.g. peat accretion) that increase shoreline integrity

over long timescales, providing a lasting coastal adaptation measure that can protect shorelines against accelerated sea-level rise and more frequent storm inundation.

Figure 12-3 New restorations pairing salt marshes and oyster domes. This increases the effectiveness of shoreline protection services (B. Silliman) (cited in Gedan et al. 2011).

Table 12-1 summarises the costs, coastal protection benefits, objectives and exposure of 52 nature-based solutions (NBS) defence projects in coral reef, oyster reef, mangrove and salt-marsh habitats presented by Narayan et al. (2016). The authors found that salt marshes and mangroves can be two to five times cheaper than submerged breakwaters for wave heights up to half a metre and, within their limits, become more cost-effective at greater depths. This cost, however, varies with geographical location. For example, in Vietnam (water-depth dependent), mangrove NBS can be three to five times cheaper, while salt marsh NBS in Europe and USA can be just as expensive as breakwaters or three times cheaper. Further, NBS also reported benefits ranging from reduction in storm surge damage to reduction in coastal structure maintenance and rebuild costs.

Table 12-1 Costs and coastal protection benefits of NBS restoration projects. (Narayan et al. 2016). Note: Tables referred are presented in Narayan et al. (2016).

Habitat	Reported Restoration Project Costs^ as US $ Per m^2: Median (Range)	Estimated Replacement Cost Ratios*: Average (*95% CI*)	% of Projects implemented for coastal protection	% of Projects in High Exposure Regions #	% of Projects reporting coastal protection benefits♀
Coral Reefs (*n = 19*)	115.62 (2–7490)	NA	5	80	ER– 5; FL– 5
Oyster Reefs (*n = 4*)	135.63 (107–316)	NA	75	50	NA
Salt-Marshes (*n = 17*)	1.11 (0.01–33)	2 (0.95–3.01)	69	77	ER– 6; FL– 41; ST– 18; BC– 6
Mangroves (*n = 12*)	0.1 (0.05–6.43)	5 (3.1–6.9)	76	35	FL– 50; ST– 34; BC– 41

n = total no. of projects for each habitat type. CI = confidence interval.

^: Project costs not scaled; areas for which costs are reported vary across studies (see S3 Table).

*: Replacement cost ratio = submerged breakwater cost / nature-based defence cost (see Methods).

#: High exposure regions defined as regions with > 10 J/m^2 average annual wave energy based on global deep-water wave climate dataset in [44].

♀: Coastal protection benefit types = ER–savings in erosion damage costs; FL–savings in damages costs from storms; ST–savings in costs of adjacent coastal structures; BC–project benefit / cost ratio > 1.

Note: some projects report multiple benefits (see S3 Table).

Figure 12-4 compares the total restoration costs of mangroves (Vietnam) and salt marsh (Europe and USA) NBS projects with submerged breakwater construction costs for a range of depth and wave height reduction values (see Narayan et al. (2016) for methods). The habitat and degree of wave height reduction is also indicated. It was found that water depth is crucial, with both habitats showing an increase in cost-effectiveness at greater depths, due to the relatively steep increase in construction cost of submerged breakwaters.

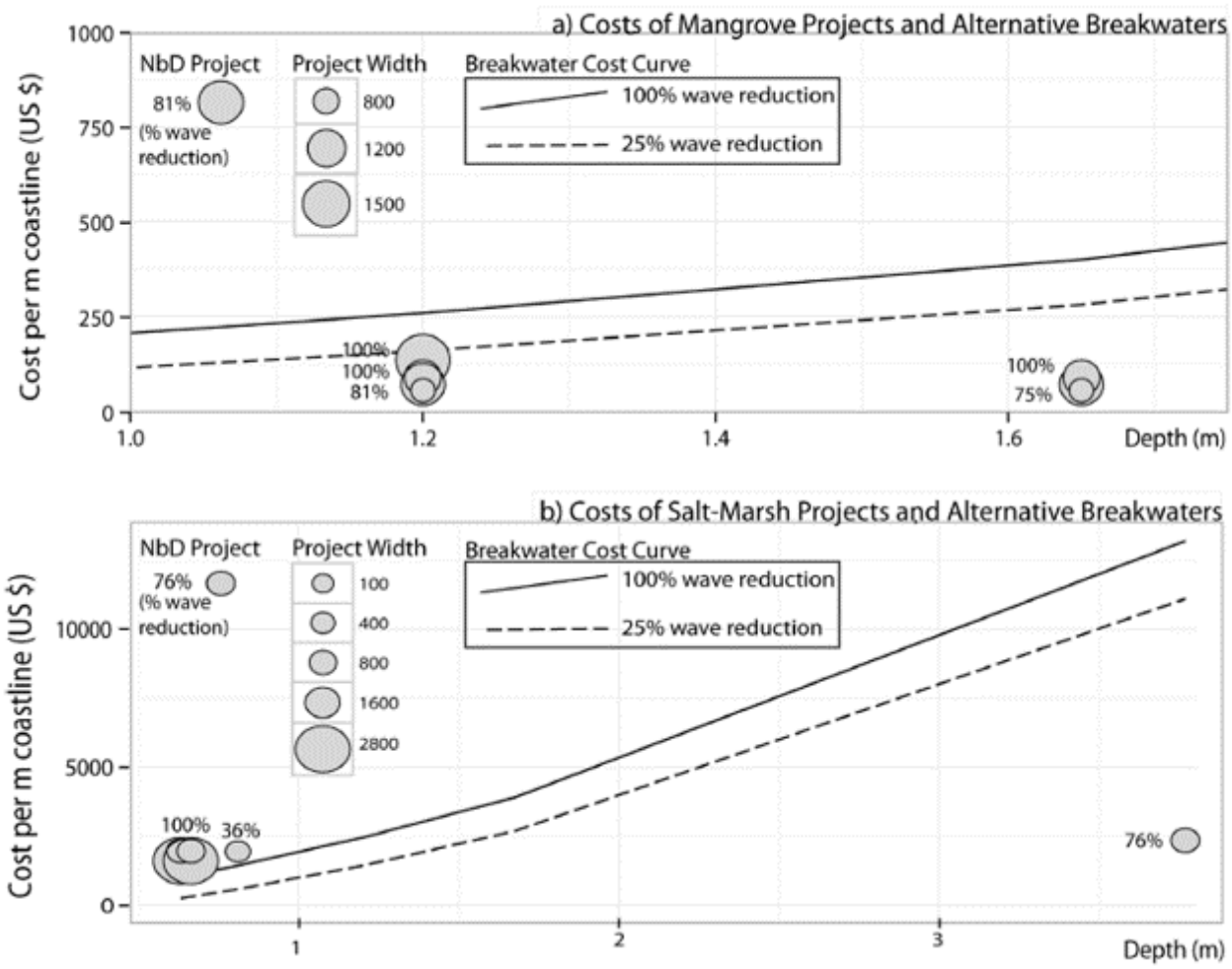

Figure 12-4 Costs versus water depth and wave height reduction extents of NBS projects and alternative submerged breakwaters. Costs of NBS and cost curves of alternative breakwater structures plotted versus water depth are plotted for a) mangroves (n = 7) and breakwaters in Vietnam and; b) salt-marshes (n = 6) and breakwaters in Europe/USA. Circles represent NBS and lines represent submerged breakwaters cost-curves in both panels. NBS that fall below breakwater cost curves are cost-effective in comparison. Breakwater cost curves are for an incident wave height Hs of 0.2 m. All costs are represented on a per-metre coastline length basis. The figure shows only mangroves and marshes, as these were the only habitat types and locations for which project information was found in close proximity to field measurements (Narayan et al. 2016).

It should be noted that the construction cost was assumed to be uniform across Europe and USA and ten times lower in Vietnam. Such geographical differences were also reflected in the reported NBS costs in these countries (Narayan et al. 2016). The authors state that, while accurate estimates of construction costs require detailed information on structure profile, material and labour, etc., water depth is often the critical driver of construction cost and is therefore the main influence on cost-effectiveness.

12.1.3 Oyster reef breakwaters

In recent decades, there has been a conscious effort to reverse the global decline of oysters (~85% functionally extinct (Beck et al. 2011)) via oyster reef restorations (Gillies et al. 2017), with initial focus on recovering oyster harvests and associated fisheries. The focus, up until recently, however, has been towards maximising other benefits, such as water quality and shoreline protection (Grabowski et al. 2012). Morris et al. (2019) state that, in addition to erosion control, oyster reefs (and other living shorelines) are environmentally adaptive (Taylor & Bushek 2008), as they are able to recover quickly from major storm events (Livingston et al. 1999) and accrete at rates equal to or greater than sea-level rise or local subsidence (Rodriquez et al. 2014). In contrast, traditional breakwaters or artificial reefs require maintenance, rebuilding, and upgrading in response to changing climates and at significant expense (Hinkel et al. 2014) (Figure 12-5).

In respect to NBS, the primary expectation of an oyster reef is to create a structure that will remain intact and provide coastal defence through wave attenuation and shoreline stabilisation. To establish an oyster reef, juveniles require a hard substratum to settle on and many artificial types of substrate have been developed for this purpose. They vary in material, unit shape, size (height, length and width), and placement relative to the shoreline (at depth, intertidal, shoreline) (Table 12-2) (Morris et al. 2018). Creating oyster reefs from recycled oyster shells, either loose, in netted bags or attached to mats, is common practice (Bersoza-Hernandez et al. 2018). Oyster mats purposely have low profiles and can be placed on dead natural reefs, while bags can be used to build reefs on soft sediments (Morris et al. 2018).

Most oyster reefs are developed by considering the engineering principles associated with empirical equations characterising hydrodynamics and wave attenuation for breakwaters (Chasten et al. 1993; Allen & Webb 2011). The key design parameters include structure porosity, reef crest height and width, water depth and freeboard (difference between structure height and still water depth) (USACE 2002). In general, wave attenuation is greatest when the crest of the structure is at or above the still water level, with little wave attenuation during

submergence for breakwaters (Allan & Webb 2011). These trends should also apply to oyster reef breakwaters (Servold et al. 2015; Chauvin et al. 2018; Morris et al. 2018).

Oyster reef NBS not only need to incorporate empirical approaches but also an understanding of the coupled bio-hydrodynamic interactions within newly deployed reef structures and throughout stages of recruitment and development. Morris et al. (2018) state that this would result in the combined ecological-engineering approach that acknowledges the heterogeneity of shorelines and the dynamic nature of living organisms. Ideally, oyster reefs will be designed to optimise abiotic and biotic conditions, using just enough substrate to allow the colonisation and development of the population. Therefore, as the population increases, the shoreline protection measure increases (Figure 12-5, Figure 12-6, and Table 12-3) (Morris et al. 2018).

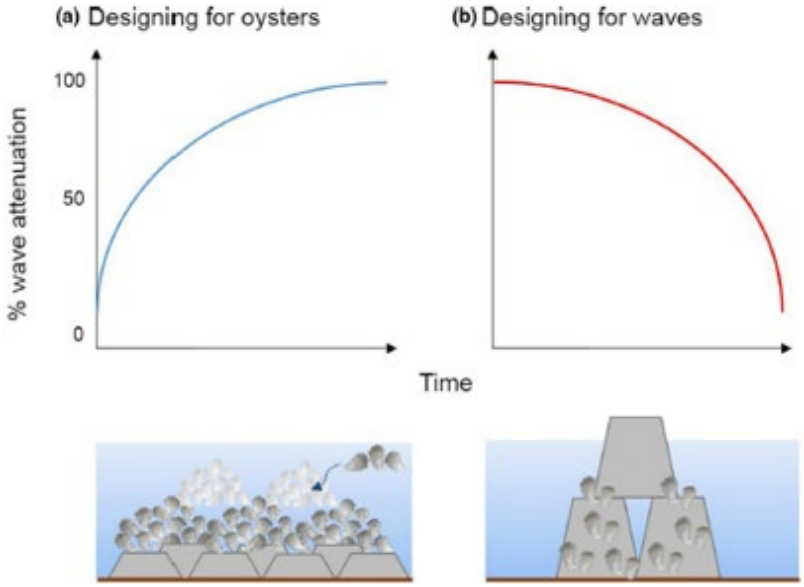

Figure 12-5 Hypothesised effect on wave attenuation for oyster reef living shorelines. These are designed for (a) oysters or (b) waves. It is expected that wave attenuation will improve over time with the accretion of oysters under appropriate environmental conditions. In contrast, reefs that are not designed to maximise oyster colonisation will have a design life akin to traditional breakwaters. Symbols are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/) (Morris et al. 2018).

Morris et al. (2018) report that in a controlled hydrodynamic study of a newly deployed oyster reef living shoreline carried out by Spiering et al. (2018), wave attenuation was maximised (83± 5%) when water levels were one centimetre below the crest of the reef structure. When the mean water level was 5 centimetres above the reef structure, wave heights were reduced by 42± 3%. Morris et al. (2018) state that this wave attenuation is similar to that observed in mature mangroves (36± 6%) and exceeds that of bare shorelines (11± 7%). Crest height, however, may be compensated with crest width, with higher, narrower crests attenuating the same amount of energy as low, wider crests, with the latter akin to how naturally occurring oysters reefs attenuate wave energy (Allen & Webb 2011; Morris et al. 2018).

Table 12-2 Examples of oyster reef living shorelines used throughout the United States of America. Values for reef size are presented as an estimated range of length (L) width (W) and height (H) from smallest to largest projects. WAD/WAU = Wave Attenuating Device/Unit. All examples are from microtidal locations (defined as a tidal range of 0–2 m as per Davies, 1964) (Morris *et al.,* 2018).

State	Structures used	Size (m)	Tidal height	Example
New Jersey	Bagged shell Oyster castles®	L: 1.8-9.1 W: 1.0-5.8 H: 0.5-1.0	Intertidal	
Virginia	Bagged shell Oyster castles® Ready Reef Reefball™	L: 1.2-278.9 W: 0.6-3.1 H: 0.3-1.0	Intertidal Subtidal	
Florida	Bagged shell Oyster mats	L: 6-83 W: 3-10 H: 0.05-0.13	Intertidal	
Alabama	Loose shell Bagged shell Reefball™ ReefBLK℠ WAU®	L: 17.0-250.0 W: 2.3-6.0 H: 0.5-2.0	Intertidal Subtidal	
Louisiana	ShoreJAX™ Oysterbreak™ Reefball™ ReefBLK℠ WAD®	L: 25.0-9656.0 W: 1.0-6.5 H: 0.75-1.4	Subtidal	

Table 12-3 Examples of design criteria for oyster reef living shorelines. (a) important design criteria to be addressed from an ecological, engineering or interactive perspective for oyster reef living shorelines where the ecological goal is a self-sustaining oyster reef and the engineering goal is to provide coastal defence; and (b) key research questions that arise from the integration of ecology and engineering to inform when and where oyster reef living shorelines are a viable alternative to traditional structures (Morris et al. 2018).

(a) Effect of:	Ecology	Engineering	Interaction
Restored reef presence	Larval supply—availability and timing Habitat suitability (e.g. salinity, hydrology) Trajectory of colonization	Decrease in cross-shore sediment transport Wave attenuation	Influence of oyster metrics (e.g. density, size) on waves and sediment transport Influence of wave energy on oyster persistence (e.g. recruitment, survival, mortality) Sediment accretion and oyster settlement, survival
Reef material	Spat settlement Refuge from predation	Structural integrity	Wave-induced turbulence on spat settlement and how this changes with different reef complexity or rugosity
Reef length (parallel to shore) Reef width (perpendicular to shore)	Patch size and shape—impacts on reef recruitment (e.g. edge effects) Spatial configuration of patches—impacts on reef recruitment and survival (e.g. edge effects on settlement, food)	Enhancement of shore-parallel currents Relationship between width of the reef and incident wavelength for wave attenuation	Influence of oyster metrics (e.g. density, size) on currents Reef edge effects (e.g. velocity magnitude) on oyster metrics and persistence (e.g. recruitment, survival, mortality)
Reef height/depth	Optimum tidal range and depth for oyster settlement, growth and survival	Wave breaking Wave set-up	Change in wave breaking and set-up with oyster colonization over time
(b) Key research questions			
What is the optimum environment and reef material required for settlement of oysters?			
What is the effect of oyster colonization and growth on reef hydrodynamics?			
What is the timeline for oyster reef living shorelines to provide coastal defence?			
What is the scale of oyster reef needed for coastal defence?			
What factors affect the resilience of oyster populations and is there any risk associated with this?			

12.1.4 Tsunami and cyclones mitigation

Ingram and Khazai (2012) explored how species and ecosystems can contribute to risk reduction from disasters, such as the Indian Ocean tsunami in 2004 and Hurricane Katrina in 2005. The authors reviewed a variety of experimental studies looking at wave buffering. The results of the review suggest ecosystems could play an important role in reducing the effects of coastal hazards by littoral vegetation, namely mangroves, reducing wave action.

Mangroves

At an open tidal flat, at the beginning of mangrove vegetation and inside a mangrove stand, Quartel et al. (2007) used field instrumentation to test current velocity and water level. The results showed that mangroves reduced wave heights between 5 and 7.5 times more effectively than non-vegetated beach plains, which clearly indicates the effectiveness of mangrove forests for buffering wave action. The dense network of trunks, branches and above ground roots of the mangrove vegetation creates a high drag force. The degree of this force depends on mangrove species composition and the density of the stems (Ingram & Khazai 2012). Furthermore, Massel (1999) used numerical modelling and field observations in Australia and Japan to show that the rate of wave energy attenuation by mangroves was a function of the density of stems in the stand, the diameter of mangrove roots and trunks, and the spectral characteristics of the incident waves (cited in Ingram & Khazai 2012).

Harada et al. (2002) carried out a hydraulic experiment to study the tsunami reduction effect of coastal permeable structures using model coastal forests, mangroves, a wave dissipating block and a rock breakwater, as well as houses. The results indicated that mangroves can be as effective as concrete seawall structures for reduction of tsunami effects on house damage (cited in Ingram & Khazai 2012).

One of the first studies on these issues after the 2004 Indian Ocean tsunami was conducted by Dahdouh-Guebas et al. (2005). The authors used a semi-quantitative assessment technique to assess the protective capacity of mangroves in relation to the tsunami. In January 2005, 24 mangrove lagoons and estuaries were surveyed along the south-west, south and south-east coasts of Sri Lanka. Protection in sites occurred where mangroves were found, but the degree of ecological degradation of the mangroves was a critical factor influencing a mangrove stand's ability to protect communities from the tsunami waves. Thus, mangrove species associated with degraded stands were found to offer less protective capacity than species found in more ecologically intact stands (cited in Ingram & Khazai, 2012). Ingram & Khazai (2012) suggest that this indicates that conservation of mangrove composition, as well as extent, is critical for retaining their protective capacity.

Furthermore, in coastal south-eastern India, observational evidence by Danielsen et al. (2005), Kathiresan and Rajendran (2005), Vermaat and Thampanya (2006), and Olwig et al. (2007) have shown that villages located behind mangrove buffers were spared the tsunami damage experienced by nearby exposed villages.

Sand dunes

Sand dunes were also thought to have played a major role in buffering against the 2004 Indian Ocean tsunami, especially in places where sand dunes were tall and densely vegetated. Fernando et al. (2006) reported that in Yala National Park, Sri Lanka, sea incursion by the tsunami occurred where dunes were deficient, as in lagoons or river outlets or in places where dunes had been removed. Ingram and Khazai (2012) observed that in Yala National Park one hotel that had removed sand dunes for an unobstructed beach view was destroyed by the tsunami with an almost complete loss of life (at high occupancy). Another lodge, only a few hundred metres away, was virtually undamaged due to the protective barrier of sand dunes that had been conserved (Figure 12-6). Dunes, however, were also observed to be inefficient at reducing the tsunami's force when located at the centre point of an arc-shaped bay (Ingram and Khazai 2012).

Figure 12-6 Tsunami protection provided by sand dunes. The importance of landscape context in determining their functional performance: (a) large, vegetated sand dunes surrounding a hotel, which was almost unaffected by the tsunami due to the protective dune system; (b) the site of a hotel located a few hundred meters from the hotel pictured in a, where the dunes had been removed to create an unobstructed view of the ocean. Occupancy in the hotel was high and there was an almost complete loss of life. (c) Large, vegetated dunes that were breached and located at the centre point of a bay ringed by sand dunes (Ingram and Khazai 2012).

12.2 Hybrid solutions

12.2.1 Mangroves in front of dykes

In Vietnam, 9,426 ha of mangrove forest costing USD 8.88 million were planted in 166 communities stretching 100 km in front of a dyke line. These mangroves were planted between 1994 and 2010 to provide a buffer to the dykes against typhoons, thereby adding protection (IFRC 2011). The International Federation of Red Cross and Red Crescent Societies (IFRC) (2011) found that, when comparing damage caused by typhoons before and after the afforesting of mangroves, reports indicated that damage to dykes had been reduced by USD 80,000 to USD 295,000 in studied communities. The savings were less than the expense of the mangrove planting. For communities, substantial savings due to avoided risk were found, with savings exceeding USD 15 million.

There were also added ecological benefits reported. Mangroves led to an increased yield from wild aquaculture collection (e.g. oysters) by 209 to 789% providing more income for coastal communities (particularly the poorest members). The direct economic benefits were found to be between USD 344,000 and USD 6.7 million to local communities.

One of the most important benefits associated with the mangrove afforestation was the carbon value. IFRC (2011) extrapolated local research on accumulated carbon and CO_2 absorption capacity to show that the mangroves planted will have absorbed at least 16.3 m t of CO_2 emissions by 2025. Assuming the price of CO_2 emission is USD 20 per tonne and applying the discount rate of 7.23%, this represents a value of USD 218.81 million.

12.2.2 Flood storage and wetland restoration scheme – managed realignment

The Alkborough Scheme UK is a fundamental factor in the delivery of the environment agency's Humber Estuary Flood Risk Management Strategy, providing both flood storage to reduce extreme water levels in the estuary and creating a new intertidal habitat to contribute to the future integrity of the estuary's environmental status (Wheeler et al. 2017) (Figure 12-7). The project converted some 450 ha of arable farmland into a new intertidal habitat and incorporated new flood defences. The area acts as a flood storage reservoir during extreme events, helping to lower water levels in the inner and middle parts of the Humber Estuary. This reduces the amount of work needed to improve the existing hard defences around the estuary, thus reducing future maintenance cost.

Implementation of the scheme cost GBP 11.14 million (Wheeler et al. 2017). Based on the reduction in peak tide levels identified by the hydrodynamic modelling, the deferment of flood defence expenditure at various locations in the estuary resulting from the development of

Alkborough Flats was estimated. Assessments were made of the required future flood defence expenditure in the estuary without the development of Alkborough Flats (the baseline case) and with the implementation of flood storage facilities on the site.

The value cost of the works in the baseline expenditure plan was GBP 238.8 million (Wheeler et al. 2017). With deferment of expenditure on defences throughout the estuary, the value cost of the works was reduced to GBP 226.5 million. The flood defence benefit of the Alkborough Flats development was therefore calculated to be GBP 12.3 million. The value of the environmental benefits was estimated to be (370 ha x GBP 944/ha x 29.8 discount GBP factor x 1.089 inflation allowance) = GBP 11.3 million.

The overall present value of the benefits of developing Alkborough Flats, accounting for both flood defence and environmental benefits, was assessed to be GBP 23.6 million (Wheeler et al. 2017). The present value of the cost of developing Alkborough Flats was GBP 8.7 million. The present value cost of the benefits arising was GBP 23.6 million, which gave the scheme an average benefit to cost ratio of 1:2.7.

Figure 12-7 Aerial view of the Alkborough flood management area inundated. (Wheeler et al. 2017).

12.2.3 Retrofitting armoured shorelines

Hybrid NBS can also include retrofitting existing armoured shorelines to create ecological habitats. Chapman and Underwood (2011) present a number of examples where armoured walls have been retrofitted to provide ecological habitats (Figure 12-8). In Sydney (Australia),

a seawall of sandstone blocks was partitioned into two sections, with saltmarsh planted in a horizontal “garden” in the middle of the wall (Figure 12-8a). The authors state that many species of saltmarsh plants continue to grow and the aesthetic value to area, that was previously dominated by a steep concrete and blocked wall, has significantly increased.

In some areas, it is not possible to build a revetment of unconsolidated boulders, rather than a solid wall because of regulations or a lack of space or for perceived public safety. Therefore, it might be appropriate to build a wall of small blocks stepped up a slope, as was done in White Bay, Sydney Harbour (Figure 12-8b). The replacement of vertical concrete walls with sloping walls of unconsolidated boulders can also increase intertidal habitat diversity, such as those constructed at Quakers Hat Bay, Sydney Harbour. At two sites, the slope was continuous; at another two sites, a horizontal shelf of boulders was built at the intertidal level. This was immersed during low tide and submersed during high tide (Figure 12-8c).

Chapman and Underwood (2011) state that there are many limitations on what can be done to alter the major structure of a seawall, pier or offshore defensive structure. Many structures are already in place and cannot or will not be altered in any major way. There has, however, been some research on how to increase the complexity of existing structures to provide additional habitats. The simplest method is to add small cavities (pits or crevices) into an existing wall (Figure 12-8d).

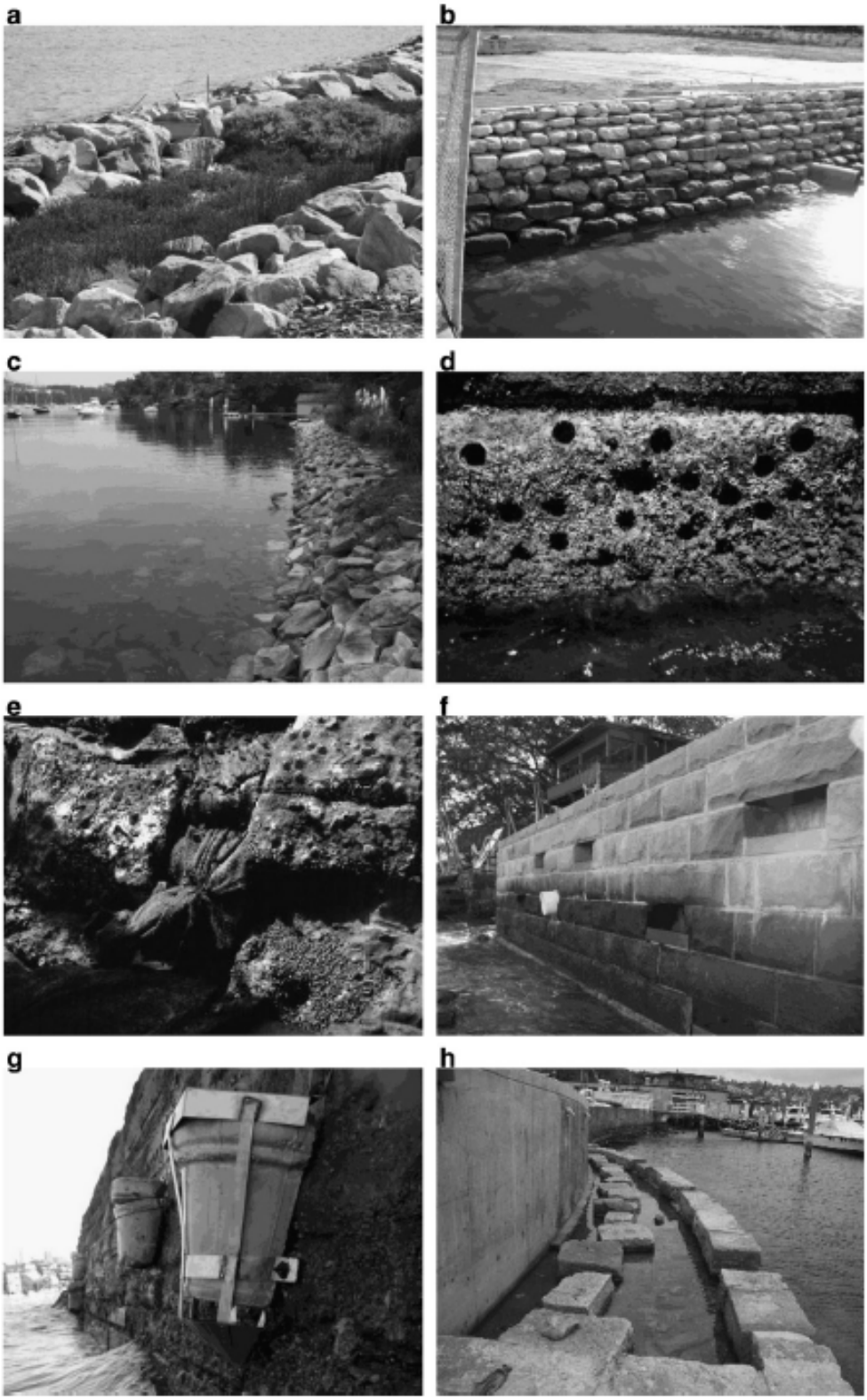

Figure 12-8. Various forms of "ecological engineering" on seawalls in Sydney Harbour. (a) saltmarsh planted in a "garden" created in a new sloping wall composed of boulders at Kogarah Bay; (b) a stepped stone wall built at White Bay to replace a sheet metal wall; (c) a wall composed a loose boulders with an extended intertidal platform built to replace a concrete wall at Quakers Hat Bay; (d) holes drilled into sandstone blocks on the wall at Farm Cove, designed to provide habitat for small gastropods; (e) sandbags used to create cavities designed to mimic rock-pools in a wall at Rose Bay; (f) custom-designed experimental cavities designed to mimic rock-pools in a wall at McMahon's Point; (g) "flower pots", designed to mimic rock-pools, attached to a seawall in North Sydney; and (h) an intertidal pool created in the top of a new seawall at The Spit.

Chapmam and Underwood (2011) state that for many larger species of animals that tend not to live on seawalls, attempts have been made to add to vertical wall habitats that may mimic rock-pools to entice occupation. The first attempt used sandbags in place of blocks of a sandstone wall that was being repaired at Rose Bay (Sydney Harbour; Figure 12-8e). After the repairs were complete, the sandbags were removed leaving small holes in the wall. The next attempt was custom-built cavities into a new sandstone seawall that was being used as a façade on a concrete wall, created in replicate sites at three intertidal heights (Chapman & Blockley 2009; Chapman & Underwood 2011). These were built by omitting blocks and using a shallow lip across the entrance to the cavity, which retained water during low tide (Figure 12-8f), creating a rock pool. These cavities were colonised by numerous taxa and supported increased diversity of algae, sessile and mobile animals compared to the number of species that lived on the seawall itself.

To increase sunlight hours and potentially taxa, flowerpots or designs similar (Figure 12-8g) could be installed onto walls. Research shows that many species colonise these habitats (Chapman & Underwood 2011). In future wall designs, these pools should not only be included into the walls but also along the tops of walls, or splits in walls (akin to the saltmarsh between the revetment) (Figure 12-8h).

12.3 Environment-friendly structural engineering solutions

12.3.1 Wooden groynes and fences

On the Island of Tongatapu, Tonga, temporary groynes were constructed out of bamboo and brushwood to protect mangrove seedlings from the sea. Fences were also constructed landward, built with the same materials, to protect seedlings from predators (mainly pigs) (Mead 2019).

Mead (2014) designed each groyne to be 70 m long (either a 40 m length and 30 m T-section, or a straight 70 m groyne), ~1.0 m high and 0.5 m wide (Figure 12-9 and Figure 12-10). The groyne design comprised 50–75 mm diameter poles sunk into the intertidal zone (each pole is ~2 m long to allow ~1 m driven into the soil), at 400 mm spaces, two rows wide, with a low and high rail (near the ground and 0.5 m high) on both rows (Figure 12-9). These were then filled with dried brush to create wave dampeners (Figure 12-10). The design required a total of:

- 11,860 m of 50–75 mm diameter sticks, and;
- 490 m^3 of brush wood.

Figure 12-9 An example of a bamboo/brushwood groyne and sedimentation field. (SSL, 2014b)

Figure 12-10 An example of a bamboo/brushwood groyne. (SSL, 2014b)

An evaluation of the wooden groynes (Mead 2019) confirmed that, although they were not to specifications, they served the purpose well, with mangrove seedlings protected both from the sea and from land predators.

Appendix B. Performance evaluation of eastern Tongatapu climate change resilience trials

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Climate Change and Communication (MEIDECC)

Dear Manu

Re: Performance evaluation of eastern Tongatapu climate change resilience trials

It was great to get a chance to visit Talafo'ou to Makaunga and Manuka trial sites on my recent visit to Tonga. While we are both disappointed that formal monitoring hasn't been done, walking along both sites provided some good insight into how they are performing. I am particularly satisfied that the different options chosen were the most appropriate for both sites, including the detached breakwaters in preference to the recently constructed ~2 km tipped rock revetment along the northern coastline.

Talafo'ou to Makaunga groyne field

The results of the sand retention for the groynes at Talafo'ou to Makaunga indicate that:

- the all open and half-open groynes are working well in the northern part of the site;
- the fully closed groynes result in the usual groyne effect with more sand on one side than the other;
- 3x the length of the groyne for the gap between each one is the best spacing (similar to temperate groyne field design);
- the southern groynes where there is less wave energy are probably more suited to fully closed groynes, noting that sand transfer did not occur for these groynes;
- the groynes and associated beaches are being utilized by the local people, especially since there is now no scarp and rocks in these areas (they have been covered by the accumulated sand; and
- some of the end units have been dislodged, which is believed to be due to boats being moored to them (even though the units weigh 700 kg each).

See Figures 1 to 4.

The recommendations from here, should funds become available, are:

- to fill the gaps of 60 and 120 m spacing to have groynes at 30 m intervals along the beach;
- to use the half-open configuration for all additional groynes;
- to rotate the half-open units at the six southern groynes to be fully closed; and

- to bring in an additional 3,000 m^3 of sand from the sand collection area to distribute in the areas of the additional groynes and the southern areas of the site where none has yet been placed.

With respect to the last dot point above, although no formal monitoring was undertaken at this location, the borrow pits were filled and indistinguishable within a month of removing the sand, indicating that this area was indeed a deposition zone where the northern and eastern coastline converge. Therefore, removal of sand from here is considered sustainable, especially since this area is uninhabited.

Figure 1. The beach width increased by some 10 m behind the fully open sedi-tunnel groyne has greatly reduced the beach scarp height

Figure 2. The half-open groynes seem to be the most effective without causing a 'groyne-effect'

Figure 3. The fully closed structures create 'groyne-effect' (i.e. less sand/erosion on the down-coast side of the groyne); these configurations can be applied at the southern end of the groyne field, but not in the areas further north.

Figure 4. The groynes and associated beaches are being utilised for recreation by the local people all along this stretch of the coast.

Detached breakwaters at Manuka

The detached breakwaters at Manuka have been extremely effective at widening the beach to provide a buffer zone and stop over-topping onto the road. Prior to their construction, the water

came to the edge of the road and over-topping threw debris onto the road two or three times a year during storm events (Figures 5 and 6). Now there is 10–30 m of buffer zone and a series of crescent shaped beaches (Figures 7 & 8). The coastal response is very obvious in Figure 9, and this trial proved that detached breakwaters with sand transfer are an effective solution to this part of the northeastern coast; interestingly, SOPAC were promoting this type of intervention some 25 years ago (Figure 10).

It was disappointing to see the 2 km long revetment built on this coast adjacent to the detached breakwater trial site. While this large, armoured structure will protect the land from erosion and reduce inundation, it does so at a large cost: loss of amenity in terms of connection to the sea/beach (there are only two access points along the 2 km length); does not address erosion (it will continue in front of this long seawall); and greatly detracts from amenities and aesthetics (Figures 11 to 13). When the trials at Talafo'ou to Makaunga and Manuka were planned, part of the drive was to look at tourism opportunities for this part of Tongatapu – the construction of this seawall has negated this possibility.

Detached breakwaters such as at Manuka provide a similar level of protection, although they enhance amenity, aesthetics and beach access that are not only a benefit to the local people, but could also promote tourism, while being only a quarter the cost of the revetment seawall. That is the detached breakwaters and sand transfer at Manuka cost USD $ 300,000 to enhance and protect 400 m of this coast, while the 2 km long revetment cost USD $6,000,000 – 8 km of coast using better and more appropriate measures (i.e. detached breakwaters) could have been protected and enhanced with the ADB funds, or the majority of funds could have been directed to other projects to increase Tonga's climate change resilience.

In my opinion, this 2 km revetment is a narrow-minded response that has wasted valuable funding and resulted in the loss of amenity, aesthetics, access and tourism opportunities for this part of Tongatapu.

Figure 5. Over-topping threw debris onto the road two or three times a year prior to the construction of the trial detached breakwaters.

Figure 6. The tide came into the rocks at the base of the road prior to the construction of the trial detached breakwaters.

Figure 7. There is now a 10–20 m buffer of land and beach in front of the road and over-topping no longer occurs.

Figure 8. The series of crescent-shaped beaches now form a buffer along the Manuka coast.

Figure 9. Top: Before July 2014. Bottom: After May 2016 construction – 30 m buffer zone where the road previously regularly over-topped.

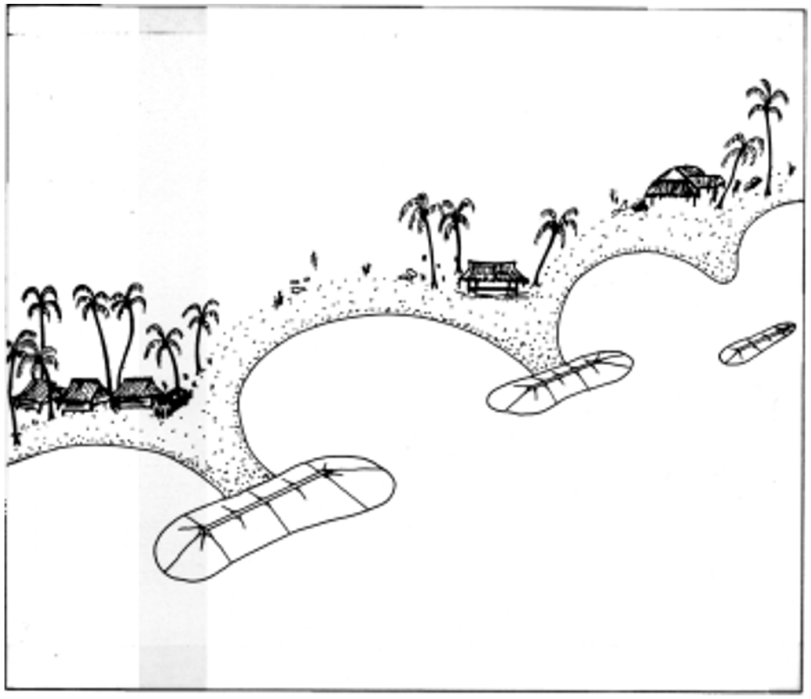

Figure 10. Stylised detached breakwaters leading to managed advance (SOPAC 1994)

Figure 11. The 2 km long revetment along the northeastern coast of Tongatapu

Figure 12. There are only two accessways along this 2 km stretch of revetment.

Figure 13. The necessity of this large obtrusive structure is questionable in this location, especially when there already exists a significant land buffer in many areas.

Please don't hesitate to contact me if you have any further questions or need clarification on anything above.

Yours sincerely

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