Tuvalu Coastal Adaptation Project Feasibility Study

Introduction

1. The United Nations Development Programme (UNDP) is supporting the Government of Tuvalu (GoT) by submitting a proposal for funding to the Green Climate Fund (GCF) entitled the "Tuvalu Coastal Adaptation Project."

2. The proposed GCF project will enable the GoT to implement measures to reduce the impact of increasingly intensive wave action and associated impacts of sea level rise and the intensification of storm events on key infrastructure as a result of climate change induced sea-level rise and intensifying extreme events.

3. With GCF financing, it is expected that 35% of high-value vulnerable coasts (2,780m in length) will be made more resilient to withstand the effects of increased wave intensity, compared with the existing baseline of 7% (570m). The targeted GCF investments will occur at three locations that have a high concentration of residences and will bring direct benefits to 29% of the total population. The project will also strengthen institutional and community capacities for sustaining and replicating project results.

4. The interventions proposed by the GoT are predicated from previously successful interventions since the 1970s and are based on consultations at the island level on ways to manage climate induced damages to coastal infrastructure. The interventions are also based on the accessibility of sites to provide different types of coastal protection. The scope of the project, on coastal resilience, is a priority in all relevant government policies and strategies including the national development strategy (Te Kakeega II),[1] climate change policy (Te Kaniva), Climate Change Adaptation and Disaster Risk Management Action Plan and Tuvalu's National Adaptation Programme of Action.[2]

5. The project is led at the highest political level. The project has been designed in partnership with the Prime Minister and stakeholders in Tuvalu including a Technical Working Group comprising key Government departments, NGO associations and women's council representative. The key outcome of the exercise is to provide the necessary advice on sustainable coastal protection options for three target islands, along with supporting procurement support for all the recommended intervention measures proposed.

6. The **goal** of the project is to increase the resilience of coastal areas and community settlements to climate change throughout Tuvalu. The **objective** is to reduce the vulnerability of three islands of Tuvalu to coastal inundation and erosion.

7. This feasibility study provides the basis for the GCF proposed project, specifically, the coastal protection interventions. The feasibility study builds on key past experiences with climate information, previous coastal protection measures and designs for proposed interventions prepared by international engineering firms. These design are considered to provide approximately 90-95% of the information required in the overall design of the proposed interventions. This will be complemented by the island-level hydrodynamic modelling to complete the fine-scale verification of the alignment of the structure to avoid destabilization of the toe of the structure. This study examines the latest science on climate impacts in Tuvalu; reviews the current state of sea level rise and intensification of storm events; reviews existing projects that have been constructed and/or are under implementation; identifies gaps in current information where additional work is needed prior to construction; provides a strength, weakness, opportunities and threats (SWOT) analysis; and provides information on the significant benefits that will be achieved by the project that will increase the resilience of the most coastlines and communities of Tuvalu.

8. This study recommends two types of hard coastal protection infrastructure solutions on Funafuti as the location has good accessibility and the use of geo-textile containers on outer islands due to restricted accessibility. Both types of infrastructure will reduce vulnerability of Tuvalu.

[1] Government of Tuvalu, 2005. Te Kakeega II. National Strategies for Sustainable Development 2005- 2015. Economic Research and Policy Division, Ministry of Finance, Economic Planning and Industries. Funafuti. Sept.
[2] Tuvalu's National Adaptation Programme of Action Under the auspices of the United Nations Framework Convention on Climate Change (May 2007).

Profile of Tuvalu

9. Tuvalu is a Polynesian island nation located in the Pacific Ocean (Figure 1). The nation is made up of nine inhabited islands located between 5° to 10° South and longitude of 176° to 180° East.

10. Tuvalu has a population of 10,640 and a total land area of 26 km^2. The islets that form the atolls are all very low lying with topographic elevations generally less than 3 metres above mean sea level (MSL) (average elevation is 1.83m). Of the nine islands, three (Nanumanga, Niutao, Niulakita) are reef islands, while Funafuti, Nanumea, Nui, Nukufetau, Nukulaelae and Vaitupu are true atolls (Figure 2).

Figure 1 Location of Tuvalu in the Pacific

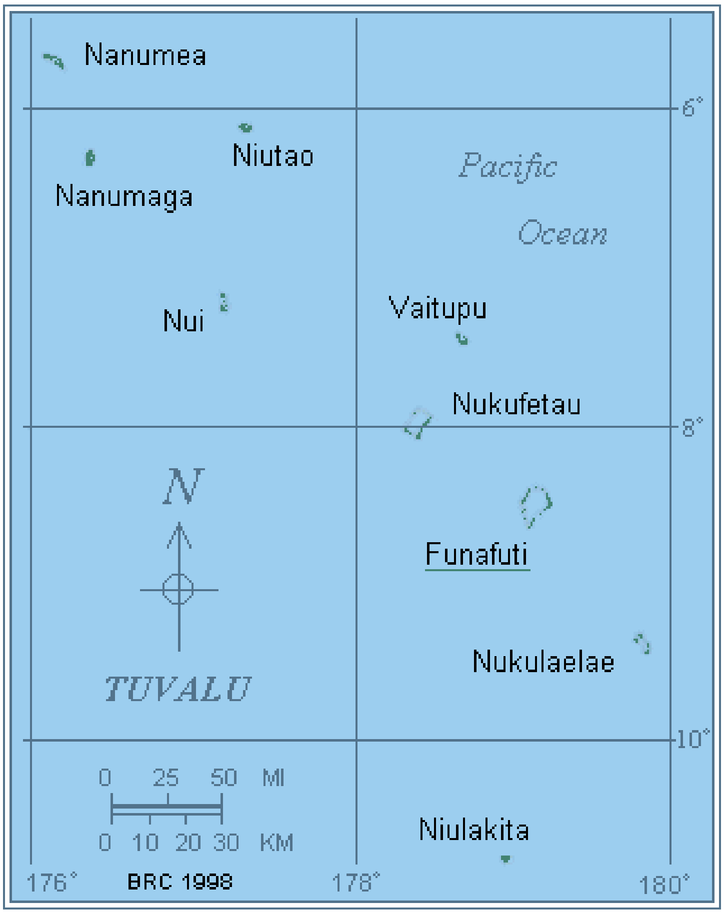

Figure 2 Map of Tuvalu

Baseline Conditions

Climate

11. The climate of Tuvalu is tropical and marine. Air temperatures in Tuvalu are relatively constant throughout the year and are closely related to sea-surface temperatures. The mean air temperature is 28ºC, with a mean maximum of 31ºC and a mean minimum of 25ºC.[3] In Funafuti, the capital of Tuvalu, there is little variation in temperature throughout the year. The maximum temperature is between 31–32°C and the minimum temperature between 25–26°C all year round. Air temperatures are strongly tied to the ocean temperatures surrounding the islands and atolls of Tuvalu.

12. Climate variability and extremes, in particular the El Niño-Southern Oscillation and tropical cyclones, are important features of the Tuvaluan climate. Tuvalu has two distinct seasons; a wet season from November to April and a dry season from May to October (Figure 3), however rainfall averages more than 200mm each month of the year in Funafuti and more than 160mm in Nanumea. This is due to the location of Tuvalu near the West Pacific Warm Pool, where thunderstorm activity occurs year round. The mean rainfall ranges from 2,300 mm to 3,700 mm annually.[4]

13. The strong seasonal cycle is driven by the strength of the South Pacific Convergence Zone, which is strongest during the wet season. The West Pacific Monsoon can also bring high rainfall to Tuvalu during the wet season.

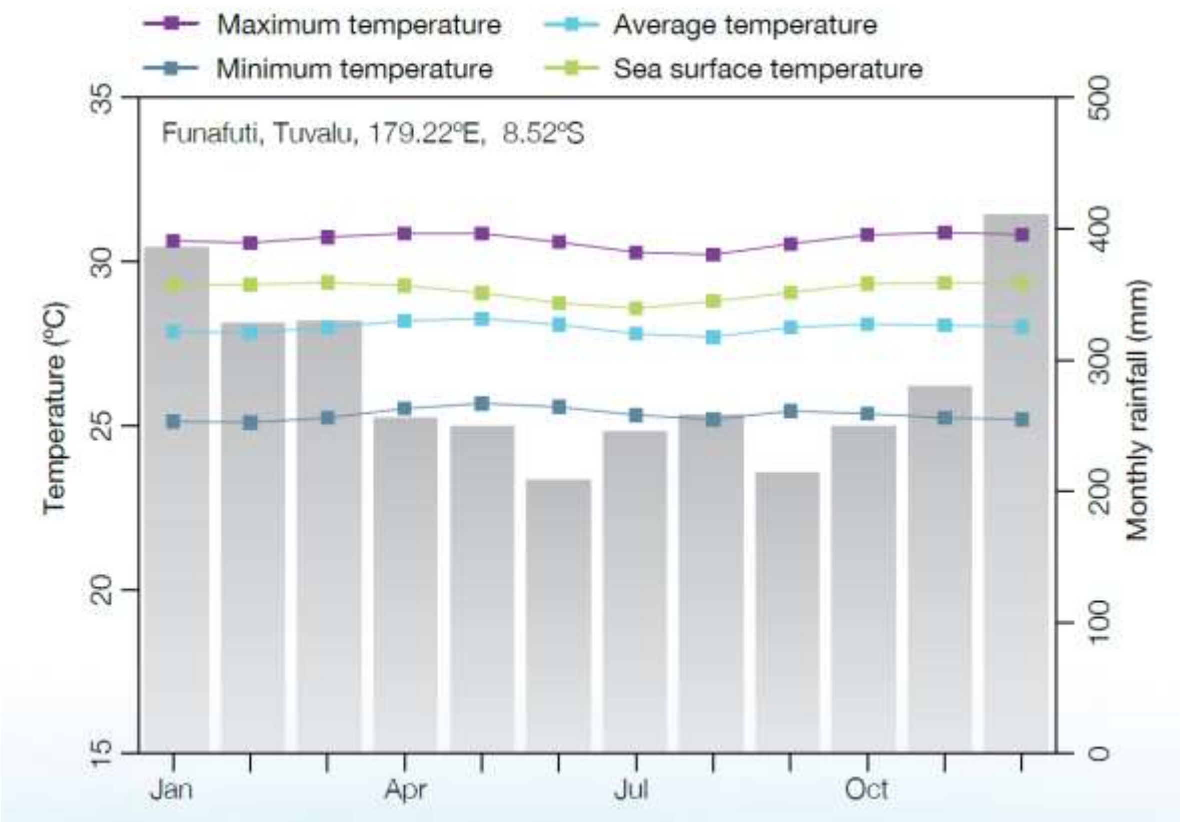

Figure 3 Seasonal rainfall and temperature at Funafuti[5]

[3] Tuvalu Meteorological Society
[4] ibid
[5] ibid

14. On average, Tuvalu experiences eight tropical cyclones per decade, with most occurring in the wet season. The high inter-annual variability in tropical cyclone numbers makes it difficult to identify any long-term trends in frequency; however Tuvalu has been impacted by a number of serious events including Category Five Tropical Cyclone Pam in 2015. In the 41-year period between 1969 and 2010, 33 tropical cyclones passed within 400km of Funafuti, an average of just under one cyclone per season. The number of cyclones varies widely from year to year, with none in some seasons but up to three in other seasons. Over this period, cyclones occurred more frequently in El Niño years.

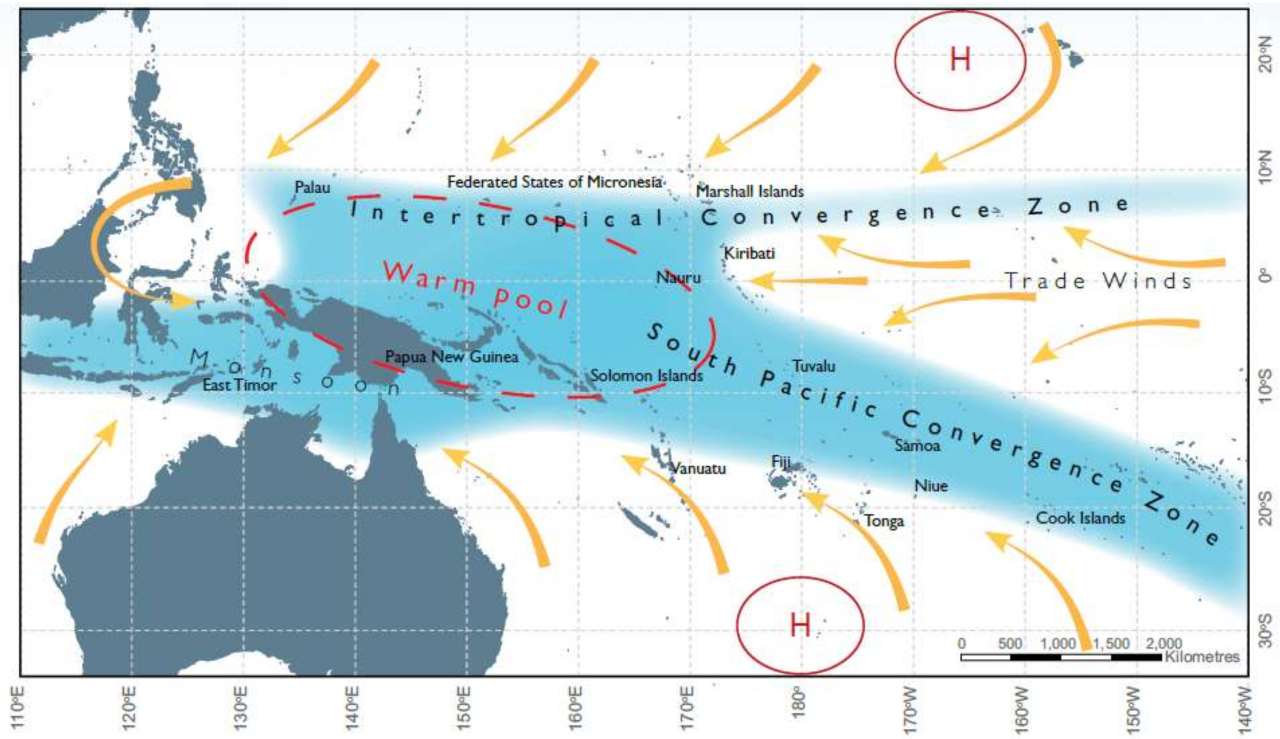

Figure 4 The average positions of the major climate features during the wet season. The arrows show near surface winds, the blue shading represents the bands of rainfall convergence zones, the dashed oval shows the West Pacific Warm Pool and H represents typical positions of moving high pressure systems[6]

Coastal Processes

15. The coastal processes of Tuvalu are governed by wave, tide and wind activity. The islands are dynamic features that respond to the forcing from each of these three components individually and cumulatively. The stability of the islands is a balance between the mobilisation of sediments due to wind and hydrodynamic forcing (waves and currents) that is counteracted by the protective action of coral reefs that dissipate wave energy and produce the sand that forms island's beaches.

16. Tuvalu lies within the trade wind zone but on the edge of the southwest Pacific equatorial where winds are often lighter. The dry season is dominated by winds mainly from the north east, which during the wet season, winds are predominantly from the west and northerly quadrants, and this period is when sixty percent of the rainfall is observed.[7]

17. Research suggests that left to entirely natural forcing, the atolls have shown resilience to gradual sea-level rise, with atolls and reef islands being able to grow under current climate conditions by generating sufficient sand and coral debris that accumulates and gets dumped on the islands during cyclones. However, if the increase in sea level occurs at a faster rate as compared to coral growth which would occur on a high level climate change scenario, or if the

[6] Tuvalu Meteorological Society
[7] ibid

reefs are damaged by ocean acidification or bleaching, then the resilience of the atolls and reef islands is less certain.[8]

Currents

18. Understanding the principle currents operating around oceanic islands, such as Tuvalu is vital as most are driven by the cyclone winds and therefore the potential impacts on the nation. The wind climate around most islands is dominated by two monsoons seasons, the south west and north east cyclones. Currents are also responsible for the spit formations on both ends of some islands. Broken sections can create barrier islands (offshore bank system) which are important natural features to provide a degree of coastal defence from larger storm waves though more importantly, act as a sediment source for island beaches. These areas are also subject to higher current speeds, particularly around the ends.

Waves

19. Waves tend to be either wind generated short waves during the westerly cyclone winds and long period swell during the north east trade winds which diffract around the islands. Some offshore waves energy propagates into the islands through the diffraction of waves from the north east to south east although the fetch is reduced when wave action hits the reed crests.

20. Persistent easterly trade winds blow throughout the year; however, they are generally stronger in the dry season. This contributes to a consistent wave climate along east-facing shores dominated by shorter period (7-9 sec) wind waves between one and two metres. During the dry season, long period (14-18 sec) swells from the southwest coming from intense storms in the southwest Pacific radiate through the island group. In the wet season, winds are more frequent from the west creating occasionally large, short period wave swells as tropical systems form in the waters to the west. If an intense cyclone forms near the equator and tracks towards the southeast, the swells from these systems can be quite large, affecting the western and southwestern facing shores. These waves can continue over the top of coral reefs and therefore, there is no reduction in fetch and the impacts on coasts can be far more significant.[9]

Tidal Action

21. Tuvalu has a diurnal tidal cycle consistent with other island nations in the Pacific. Of importance, King Tides (properly defined as Perigean spring tide) which is a term used in the Pacific for the highest spring tide can have a significant impact on the local infrastructure through overtopping and flooding. The height of a king tide is affected by the combined factors of spring tide, storm surge, climate variability, and, significantly, by the warm-water effect Tuvalu can be severely affected by king tides. The tides of February 2011 reached within about a metre of the level of the national government building, on the central lagoon. Recent surveys measured the lagoon ridge at about 4.12m above the lowest astronomical tide.[10]

22. Many areas of Tuvalu are impacted by king tides along with storm surges. Table 1 provides an overview of the number of houses in Tuvalu by island that are affected by either/both kind tides and storm surges.

[8] McCue, J (May 2014), Increasing Resilience of Coastal Areas and Community Settlements to Climate Change: Coastal Options and Feasibility Report – Nukufetau and Nanumea, report prepared for Sustainable Sea, Australian Aid, NAPA Tuvalu, United Nations Development Programme and the Government of Tuvalu

[9] Japan International Cooperation Agency, Kokusai Kogyo Co., Ltd and Fisheries Engineering Co., Ltd (Jan 2011), *The Study for Assessment of Ecosystem, Coastal Erosion and Protection/Rehabilitation of Damaged Area in Tuvalu*, report prepared for the Government of Tuvalu's Ministry of Foreign Affairs, Environment, Trade, Labour and Tourism

[10] Lin, C. C., Ho, R., and Cheng, Y, H (2014) "Interpreting and analysing King Tide in Tuvalu", *Natural Hazards Earth System Science*, 14, 209–217

Name of island	Affected by King Tides (3 yrs ago)			Affected by Storm Surges (5yrs ago)		
	Total	Yes	No	Total	Yes	No
Nanumea	115	10	105	115	14	101
Nanumaga	116	92	24	116	93	23
Niutao	123	88	35	123	37	86
Nui	138	43	95	138	14	124
Vaitupu	226	34	192	226	14	212
Nukufetau	124	1	123	124	3	121
Funafuti	845	445	400	845	285	560
Nukulaelae	67	6	61	67	6	61
Niulakita	7	2	5	7	1	6

Table 1 Number of households affected by king tides or storm surges by island

Coastal Erosion and Shoreline Change

23. Coastal erosion is evident on all the islands of Tuvalu. While natural processes cause coastal erosion, it has been exacerbated by human excavation of coastal aggregates for construction purposes. In addition, coastal development infrastructure can disturb natural current patterns and increase the speed of coastal erosion in certain areas. The predicted increase in the intensity of tropical cyclone under climate change is feared to accelerate the erosional force that is observed in Tuvalu as it was recently seen that a small islet in the Funafuti atoll disappeared after recent Cyclone Pam.

24. Xue (2005) presents an analysis of causes of erosion and shoreline change in five islands of Tuvalu (Funafuti, Nukufetau, Vaitupu, Nanumea and Nui)[11]. In the cases of both Funafuti and Nanumea, Xue confirmed that extensive excavation of sand for construction of runways and boat channels during the WWII had a significant impact in the alteration of the sediment movements.

25. **Figure 5** presents a diagram of the anthropogenic erosional forces in Funafuti and Nanumea. Climate change impacts, manifested in a rising sea level, warm ocean surface temperature and intensifying cyclone events, are likely to put additional risks. In 1997, two cyclones (Gavin and Hina) struck the country and approximately 6.7% of Tuvalu's total land mass is thought to have been washed away.[12]

[11] Xue, C. (2005). Causes of land loss in Tuvalu, a small island nation in the Pacific. Journal of Ocean University of China. Vol. 4, No.2, pp.115-123.
[12] New Zealand Ministry of Foreign Affairs and Trade (2015), Tuvalu, http://www.mfat.govt.nz/Countries/Pacific/Tuvalu.php

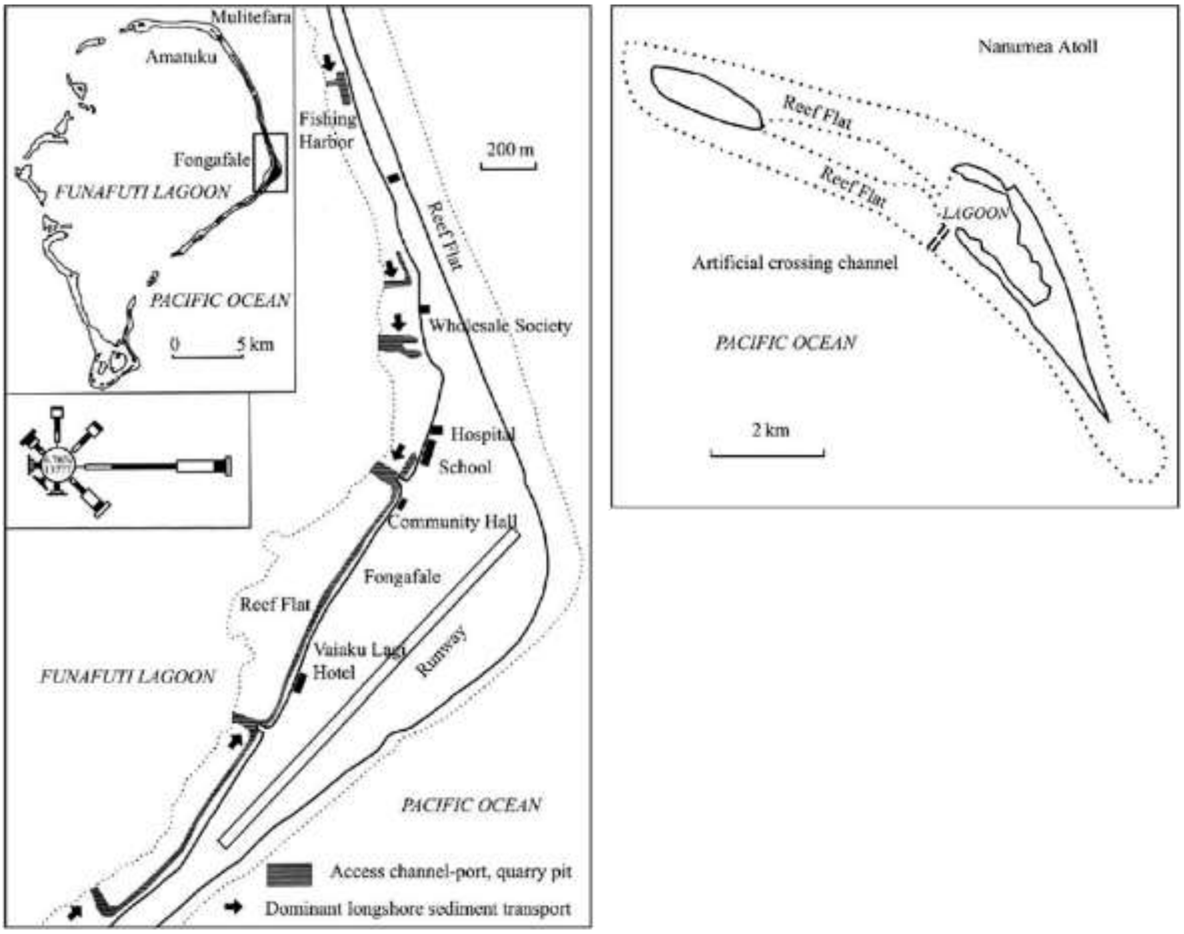

Figure 5 Anthropogenic coastal erosional forces in Funafuti and Nanumea (Xue, 2005)

Socio-Economic Conditions

26. Economic development in Tuvalu is extremely challenging for a number of reasons. These include the small size of the country and its economy, its remoteness and distance from international markets, making it extremely vulnerable to external shocks, as well as its limited natural resource base. The economy of Tuvalu and the government revenues rely significantly on foreign aid, license fees from foreign fishing vessels, remittances from seafaring (thought to provide employment to 15% of the adult male population), and income from the Tuvalu Trust Fund. The Fund was established in 1987 by the UK, Australia and New Zealand to contribute to the long-term financial viability of Tuvalu by providing an additional source of revenue for recurrent expenses of the Government of Tuvalu. Per capita income is relatively high, but the economy is fragile as these sources of income are highly volatile, and the high income is considered "barely sufficient to cover the high economic cost for the government and households alike"[13].

27. Since Tuvalu is comprised of small coral reef islands and atolls, land resources are scarce with low productivity in terms of agriculture and domestic fisheries. Due to the scarcity of domestic resources, particularly on the main island, the population relies heavily on imports in terms of foodstuffs and other daily necessities, resulting in large trade deficits. On the outer atolls, inhabitants rely primarily on a subsistence economy. It is this sector of the economy that is most vulnerable to the effects of climate change. Changing patterns of rainfall and increased

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[13] UNCTAD (2012) "Vulnerability Profile of Tuvalu"

occurrence of flooding during high sea levels have started to impact on freshwater supplies, particularly groundwater.

Current Trends of Climate Change

28. **Tuvalu is extremely vulnerable to climate change, sea level rise and the increase in tropical storm events.** Warming trends have been evident since the 1950 in both annual and seasonal mean air temperatures at Funafuti. Projected increases in rainfall are consistent with the expected intensification of the South Pacific Convergence Zone, Intertropical Convergence Zone and the West Pacific Monsoon. In Funafuti maximum temperatures have increased at a rate of 0.21°C per decade. These temperature increases are consistent with the global pattern of warming.

29. Not all meteorological modelling outputs show consistent results giving rise to some uncertainly in rainfall projections; however it is anticipated that there will be less frequent droughts.

30. Sea-level rise near Tuvalu has been measured by satellite altimeters since 1993 at about 5mm per year. This is larger than the global average of 2.8–3.6mm per year. This higher rate of rise may be partly related to natural fluctuations that take place year to year or decade to decade caused by phenomena such as the El Niño- Southern Oscillation. The rate of sea level rise is expected to be higher than the rate of coral growth. Coral reefs are also highly sensitive to increases in sea-surface temperature and atmospheric carbon dioxide concentrations, both global effects associated with climate change. Destruction of the coral reefs, expected from rising sea surface temperatures, will be significant as it reduces the fetch of waves and thus reduces the potential impacts on the islands themselves and the communities which live on the islands.

31. Impacts of climate change though increasing intensity storms is also apparent, including, Tropical Cyclone Pam in March 2015 which caused widespread damage by large waves and storm surges. Cyclone Pam affected 467 households or nearly 30% of the total households in the country. It is estimated that 45% of the total population was internally displaced and the total economic loss and damages were Aus$13.95 million (US$10.34 million).[14] Bringing lives and livelihoods back on track will take years and the recovery efforts will put further strain on the Government that is already suffering from limited human capacity and financial resources.

32. King tides are another type of extreme events affecting the country. A study analysed 28 king tide events that have caused flooding between 1994 and 2012, five of which have occurred since 2010. All of these events are thought to have flooded half of the island of Tuvalu based on the average elevation of the islands of Tuvalu.[15] The study estimates that warm water contributed to the king tide phenomenon by an average of 5.1% and a maximum of 7.8%. This indicates that the effect of king tides will be greater under a warming climate where warm water will compound with a rising sea level. Damage included seawater flooding and destruction of agriculture and infrastructure, contamination of water supplies, coastal erosion and scouring.

Expected Trends due to Climate Change

33. The Pacific Climate Change Science Program (PCCSP) has created a rigorously researched, peer-reviewed scientific assessment of the climate of the western Pacific region. Building on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, the PCCSP has created a two volume publication, *Climate Change in the Pacific: Scientific Assessment and New Research*, which represents a comprehensive resource on the climate of the Pacific.

34. The first volume of Climate Change in the Pacific: Scientific Assessment and New Research provides a regional overview of climate change across the PCCSP region, and includes annual and seasonal climatology, variability and long-term trends, methodology, climate model evaluation, and projected changes in atmospheric and oceanic variables from global and

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[14] Government of Tuvalu. (2015) Tuvalu Tropical Cyclone Pam Report: Recovery and Vulnerability Reduction Plan indicates damages and losses from TC Pam to be AU$ 13,954,076. Using the UN Operational Exchange Rate of 1.349 (as of 15 Jul 2015), the loss and damage from TC Pam is estimated at US$ 10,344,014.
[15] Lin, C. C., Ho, R., and Cheng, Y, H (2014) "Interpreting and analysing King Tide in Tuvalu", *Natural Hazards Earth System Science*, 14, 209–217

downscaled climate models. Volume 2 presents individual country reports which provide country-specific projections and relevant climate information.

35. Projections for all emissions scenarios indicate that the annual average air temperature and sea surface temperature will increase in the future in Tuvalu. By 2030, under a high emissions scenario, this increase in temperature is projected to be in the range of 0.4 –1.0°C.

36. Almost all of the global climate models project an increase in average annual and seasonal rainfall over the course of the 21st century. Wet season and dry season increases are expected mainly due to the projected intensification of the South Pacific Convergence Zone. However, there is some uncertainty in the rainfall projections and not all models show consistent results. Drought projections are inconsistent across Tuvalu.

37. On a global scale, the projections indicate there is likely to be a decrease in the number of tropical cyclones by the end of the 21st century. But there is also likely to be an increase in the average maximum wind speed of cyclones by between 2% and 11% and an increase in rainfall intensity of about 20% within 100km of the cyclone centre. In the Tuvalu region, projections tend to show a decrease in the frequency of tropical cyclones by the late 21st century and an increase in the proportion of the more intense storms.

38. Projections of sea-level rise under the high emissions scenario (A2) indicate that by 2030, Tuvalu will experience sea-level rise in the range of 7 cm to 27 cm. The sea-level rise combined with natural year-to-year changes will increase the impact of storm surges and coastal flooding. As there is still much to learn, particularly how large ice sheets such as Antarctica and Greenland contribute to sea-level rise, scientists warn larger rises than currently predicted could be possible. This will also result in increased coastal inundation and erosion by climate change induced sea-level rise and intensifying extreme events.

39. Wave overtopping events during king tides and cyclones will also cause damage to natural assets such as Tuvalu's fragile groundwater lens and many other economic/social/cultural assets. As such, immediate action as proposed by this project is necessary to reduce the impacts of climate change on Tuvalu.

Policy Frameworks for Climate Change Adaptation

40. Tuvalu's NAPA (2007) identified a range of priority adaptation measures to enhance community livelihoods and promote sustainable development by reducing adverse effects of climate change, variability and extreme events. Seven priority projects were identified, in the following areas: coastal; agricultural; water; health; fisheries (two projects); and disasters. In terms of local plans, climate change is integrated in the Island Strategic Plan for Funafuti, whilst the Island Strategic Plans for Niutao/Niulakita and Nanumea refer to the environment, but not directly to climate change. The Island Strategic Plans for Funafuti refer directly to the NAPA project. All Island Strategic Plans were supposed to be reviewed and updated in 2013, however it is understood this has not yet occurred.

41. A number of adaptation actions are underway in Tuvalu, predominately through its involvement in a number of regional climate change projects. Most of the programs are focused on coastal zone management, agriculture and water, consistent with Tuvalu's top three priority areas for adaptation. Tuvalu has also received funding from the Least Developed Countries Fund to support implementation of the projects "*Increasing Resilience of Coastal Areas and Community Settlement to Climate Change*" and "Effective and responsive island-level governance to secure and diversify climate resilient marine-based coastal livelihoods and enhance climate hazard response capacity" both of which address urgent and immediate adaptation actions identified in its NAPA.

42. Tuvalu's public service delivery to outer islands was in the past, primarily driven by the central government, whose development finance in turn was largely dependent on foreign aid. The *Falekaupule Act of 1997* brought in a two-tiered governance system that comprises the national government and island-level administrations and provided the legal basis for the current decentralisation process.

43. This Act devolved the local governance authority to the island council (kaupule), which is the executive arm of island assembly (falekaupule), to implement national and community-level

development priorities. In principle, this puts local communities, led by respective *Kaupules*, at the Center of Local Development Process. The Act also gave rise to the Island Strategic Plans and to financial allocation systems to support the implementation of the development priorities identified in Island Strategic Plans. Falekaupule Trust Fund was established with donors' financial assistance (New Zealand, Australia, Japan, and the Republic of Korea) along with the enactment of the *Falekaupule Act 1997* to supplement the financial needs of outer island development. Falekaupule Trust Fund distributions to outer islands are on average $64,000 per year for fulfilling their development needs.

Previous Coastal Protection and Adaptation Responses

44. Among the eight outer islands of Tuvalu, coastal erosion and shoreline change processes, and community-level responses, have been relatively well-documented on the island of Nukufetau. From this, work, it can be deduced that the other islands are similar in nature. During 1960s, the removal of sand, rubble and coral stones for construction purposes accelerated erosion processes. As a result, the reef ridge has become much smaller (verified in the comparison of aerial photographs from 1943 and 1984) and wave actions on the reef flat and erosion of the ocean coast became stronger.

45. An artificial channel (passage) was dredged in 1981 for small fishing boat access. The channel is 550m long, 7m wide and over 2m deep, extending from the lagoon reef flat edge across the reef flat to a position within 36m of the 1981 shoreline. After the artificial channel was built in 1981, the erosion along the southeast section of the lagoon coast became severe.

46. Erosion has also occurred on some sections of the south and west coast of Savave. This might have been caused by beach mining although this is anecdotal. Since the reef flat between Savave and Fale is higher than the adjacent lagoon and ocean reef flats, the beach sediment thickness is less than 1m. Therefore a little sediment removal can result in shoreline retreat; for example, the coastline has retreated 6m on the coast southwest of the school.[16] The artificial channel on the north east of the island as well as eroded shorelines are shown in Figure 6.[17]

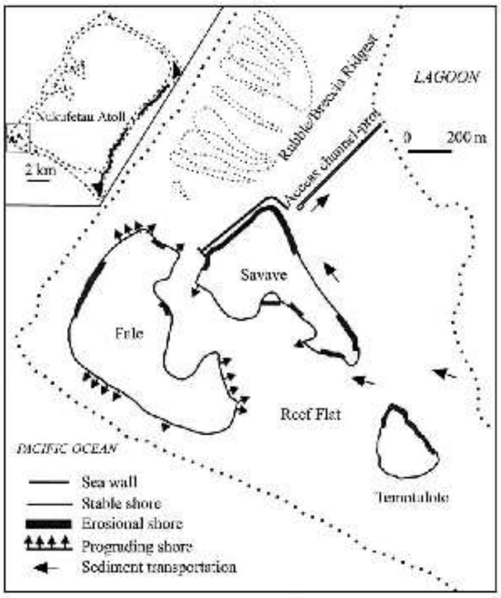

Figure 6 Coastal erosion and sediment movements in Nukufetau (Xue, 2005)

47. In response to these changes in the shorelines on the island, several coastal protection measures were put in place. In 1978, a gabion basket seawall was built with financial assistance from a regional development agency, and this has been subsequently replaced by

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[16] Xue, C. (1996) "*Coastal Erosion and Management of Amatuku Island, Funafuti Atoll, Tuvalu*" SOPAC Secretariat August 1996 SOPAC Technical Report 234.
[17] Xue, C. (2005). "*Causes of Land Loss in Tuvalu, a Small Island Nation in the Pacific*." Journal of Ocean University in China. Vol. 4, 2, pp.115-123.

the present block seawall.[18] When the seawall was constructed, a large area of land was also reclaimed and the natural beach alignment was modified. Since there was an opening at the southeast between the seawall and the old shoreline, sand was transported in and deposited. Bushes and a few very young coconut trees have grown there, even though this area is lower than the surrounding areas.

48. In Funafuti, coastal protection measures are concentrated on the lagoon side of Fongafale Island. The Japan International Cooperation Agency (2011) (JICA) undertook a site survey of the Island and observed two sections of coastline (about 70m in length), which have a vertical concrete seawall. One was in front of Vaiaku Hotel (about 50m in length) constructed with support from a bilateral donor and the other is structurally part of a wharf (about 20m).[19]

49. Engineering studies suggest the Vaiaku Hotel seawall is reaching its structural life and it is unlikely to withstand strong wave or wind energies. The level of structural durability of the wharf seawall against future impact of climate change requires a more detailed analysis. The remaining coastal protection in Fongafale were observed to be ad-hoc and poorly designed with the result being a severely degraded shoreline in terms of both the physical and ecological characteristics and functions.

50. These assessments reveal one of the key underlying barriers that explains suboptimal coastal protection responses in Tuvalu. Due to the combined factors of the lack of financial resources to conduct a proper site assessments for the design of the coastal defence and lack of technical capacity to design and construct coastal protection measures that are informed by such assessments, previous responses that can be observed both in Funafuti and outer islands are largely ad hoc, structurally inadequate response that do not withstand the constant wave actions. Figure 7 and Figure 8 show existing coastal protection measures in Nukufetau and Funafuti, respectively. The former shows the concrete block seawall built in 1989, which were destroyed in Cyclone Pam in 2015. All photographs in Figure 8 are from JICA's assessment report. The two pictures on the top panel show the seawall in front of the Vaiaku Hotel during the low-tide (left) and wave run-ups (right). The remaining four pictures show past failed efforts to armour the foreshore. These pictures include both privately-financed work and public works led by the Government.

Figure 7 Block seawall in Nukufetau before (left) and after (right) Cyclone Pam

[18] Xue, C. (1996). "*Coastal sedimentation, erosion and management of southwest Nukufetau atoll, Tuvalu*" SOPAC Technical Report, 238

[19] Japan International Cooperation Agency, Kokusai Kogyo Co., Ltd and Fisheries Engineering Co., Ltd (Jan 2011), *The Study for Assessment of Ecosystem, Coastal Erosion and Protection/Rehabilitation of Damaged Area in Tuvalu*, report prepared for the Government of Tuvalu's Ministry of Foreign Affairs, Environment, Trade, Labour and Tourism

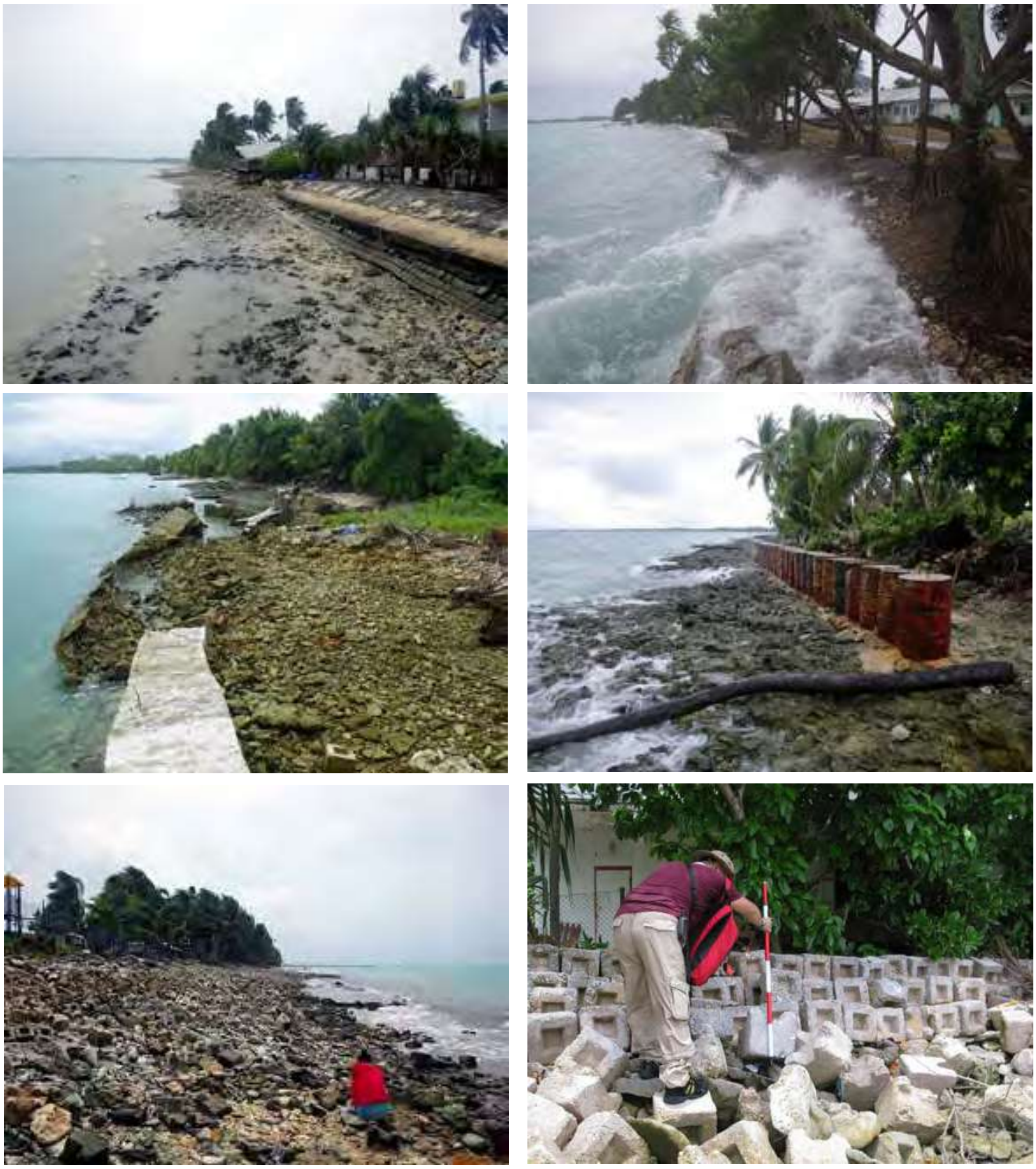

Figure 8 Previous coastal protection measures in Funafuti (JICA 2011)

51. Donor assistance for engineered coastal protection infrastructure is emerging only in the last five years. JICA is establishing artificial gravel beach along a 180m stretch of coastline on the lagoon side of Fongafale Island. The work is expected to complete in 2017. The Government of Tuvalu is financing the construction of geo-textile container revetment structures in the island of Nukufetau, building on initial work (design and the EIA) financed by the Least Developed Countries Fund. This work has been used as a basis for this proposal as it provides the design prepared by an international engineering firm for geo-textile container revetments (See Annex C).

Needs Assessment

52. According to the assessment carried out during the preparation of this proposal related to this feasibility study, the total length of coast in the nine inhabited islands is 81,900m.[20] Of this, according to the World Bank's preliminary coastal assessment, 21,300m is considered vulnerable coastlines that require foreshore protection.[21] Of this length of vulnerable coastlines, 7,930m is considered "high-value" coastlines based on the concentration of houses and other social and economic assets (through secondary observations for outer islands and primary observations for Funafuti).

53. In Tuvalu, in many locations, retreat of the coast line is impossible due to the limited land area available. Funafuti, with a population density of 2,600/km^2, has a range of critical environmental and social issues associated with overpopulation such as over extraction and groundwater pollution, solid waste management and general over-crowding. In outer islands, even in areas where physical space is available, retreat could impose a significant alteration in the way people's subsistence livelihoods are practiced as residential areas have been established to ensure close proximity to ocean. At the same time, the country's ability to 'accommodate' climate change threats is also considerably limited due to the lack of space in conjunction with limited resources. Options that developed countries employ, such as land use modification, ecosystem protection, change of building practice and regulation, are often infeasible or impractical in Tuvalu.

54. Previous studies[22] identified several options suitable to alleviate some of the erosion and inundation problems currently facing Tuvalu. Each of the options described in these studies has undergone preliminary design studies; however, none of the strategies themselves have been fully implemented.

55. The JICA (2011) report is a comprehensive and detailed feasibility and final design study, including public consultation and cost estimation that focuses on the proposed intervention of a large-scale gravel beach renourishment and reclamation project for 2.6 km of the lagoon side coastline along the Vaiaku waterfront on Funafuti. The study covers all of the necessary components for a feasibility study including detailed data collection of the physical and biological environment, an extensive site survey and historical review, social and community engagement, numerical modelling, engineering design and costing. Overall the study presents a very strong case explaining how its proposed intervention scheme would be effective in reducing overtopping and flooding along some of Tuvalu's most vulnerable and economically valuable coastline.

56. The UNDP (2014) assessment provides adaptation options for sites in Nukufetau and Nanumea. The study also provides a good synopsis and overview of adaptation options in general. For the Nukufetau site, located inside the lagoon facing a wide reef flat, the recommendation is to replace a failing seawall with a revetment made form sand-filled geo-textile containers. This recommendation is based on the lack of accessibility of larger vessels carrying rock armour. Additionally, the report suggests that the material from the removed seawall could be repurposed to form a set of low cost wave break structures to be positioned on the reef flat fronting the new revetment. The study also calls for the planting of salt tolerant plant species on the more protected side of the island to help retain sediment and minimize erosion there. The second study site discussed in the UNDP report is located in Nanuamea lagoon. For this site the recommendation is a soft intervention approach that uses native trees to construct small-scale breakwaters on the eastern shore of the lagoon. The purposes of these

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[20] In the Funafuti atoll, there is a small community living in an island north of the main island of Fogafale. However, to avoid confusions and follow the local convention, Funafuti is considered one island throughout this proposal, but the length of coastline for Funafuti includes these two islands. Assessment was carried out by Alan Resture in 2013 (unpublished data).

[21] AECOM (June 2015), *Tuvalu Coastal Protection Scope Definition*; report prepared for the World Bank

[22] Japan International Cooperation Agency, Kokusai Kogyo Co., Ltd and Fisheries Engineering Co., Ltd (Jan 2011), *The Study for Assessment of Ecosystem, Coastal Erosion and Protection/Rehabilitation of Damaged Area in Tuvalu*, report prepared for the Government of Tuvalu's Ministry of Foreign Affairs, Environment, Trade, Labour and Tourism; McCue, J (May 2014), Increasing Resilience of Coastal Areas and Community Settlements to Climate Change: Coastal Options and Feasibility Report – Nukufetau and Nanumea, report prepared for Sustainable Sea, Australian Aid, NAPA Tuvalu, United Nations Development Programme and the Government of Tuvalu; AECOM (June 2015), *Tuvalu Coastal Protection Scope Definition*; report prepared for the World Bank

structures is to provide areas of calm water to foster the growth of juvenile mangrove trees which will in turn serve to protect the adjacent shoreline.

57. The World Bank (2015) study investigated the extent of the coastal protection needs and categorized the foreshores into three priorities of 1) vulnerable, higher value zones; 2) vulnerable, lesser value zones; and 3) less vulnerable zones. The study looked at all of the islands in the Tuvalu archipelago and compiles information from each on the effects of Tropical Cyclone Pam. The study found that damage from Tropical Cyclone Pam was worst in communities exposed to the west with short distances from the foreshore to the reef edge. The islands of Nui, Nanumanga, Nanumea and Niutao were the worst affected suffering severe damage. High sea levels caused saline contamination of agricultural land and damage to built infrastructure due to high velocity of flooding seawater. Damage was assessed on Vaitupu, Nukulealea, Nukufetau, Funafuti and Niulakita as being significant but less severe than that on the previously mentioned islands. The communities on these islands were relatively less exposed to the west so escaped severe damage this time.

58. The report also provides a high-level assessment, designs and costing of construction options for engineered coastal protection structures including revetments made from rock, precast concrete units and geo-textile sand filled containers. The study concluded that 4.7 and 3.6km of 'higher value' coastline were in need of protection in the outer island and Funafuti respectively. Cost assumptions provided by this study suggested US$5.25 million/km for geo-textile container revetment, US$7.14 million/km to construct rock armour revetment, and US$10.05 million for pre-cast concrete revetment (or US$11.53 million if auxiliary wave return wall is included).

Gaps, Barriers and Needs for Scaling-up Coastal Adaptation

59. There is a considerable gap between the need to manage Tuvalu's vulnerable coastal zone from encroaching impact of climate change and what has been done to date. National and international assistance in this area has been limited to date although the GoT has been vocal in the last several years in its need for rapid assistance.

60. As highlighted above, the few coastal protection measures that do exist in Tuvalu have been completed in a largely ad-hoc manner or in response to specific events. The current national approach to coastal zone protection lacks a comprehensive and integrated framework for the implementation of coastal protection strategies on a nationwide or even island-wide basis.

61. There is a pressing need for detailed studies and assessment of the alternatives for coastal protection in all the islands of Tuvalu, particularly true in the outer islands. The lack of resources and the high cost of travel and transport along with the limited opportunity for economic return has stalled any efforts to properly address the effects of climate change related sea level rise in these areas. Despite Tuvalu's aspiration to reduce its vulnerability to climate change and on-going international support that contributes to fulfilling this aspiration, there are several barriers that need to be removed in order to bring about transformational impact that is both effective and sustainable.

62. Barriers include limited national financial resources and dependency on fragmented external funding. Tuvalu's narrow economic base makes it extremely difficult for national budgets to be invested for effective coastal protection infrastructures. Additional barriers include constraints of accessing outer islands with larger vessels due to shallow waters and lack of maneurverability. As a result, past coastal protection investments have been financed through the small discretionary budgets available for outer island administration, private financing, or donor funding. All of these sources are often too small and fragmented to provide a comprehensive, lasting solution. The lack of financing can also lead to a design that is not based on a feasibility assessment without proper consideration of climate change impacts.

63. A further impediment to the success of many of the projects and the ongoing maintenance in particular is the high staff turnover and limited number of qualified professionals is another barrier to the successful implementation of coastal protection and climate change adaptation strategies. Although the majority of the workforce in Tuvalu works for the public or semi-public sectors, the small total population size limits the core group of professional staff available to work on climate change to a handful of individuals. For example, the Department of

Environment, consisting of a Director and one other staff (as of January 2016) covers all issues related to the environment, including climate change, biodiversity, pollution control, hazardous substance, etc. Although climate change initiatives are increasingly coordinated across various sector Ministries and Agencies, technical skillsets needed for effective coastal protection and operation and maintenance, such as data collection and monitoring of coastal dynamics, need to be developed within relevant Ministries and Departments. There is a significant need for this to change.

64. This project proposal has been formulated to overcome these gaps. The three interventions and their designs are built on experience from the region and assessments already undertaken in Tuvalu earlier. The designs have been prepared in earlier feasibility assessments (See footnote 24) and this will be complemented by site-specific hydrodynamic modelling that will help make fine-scale adjustment in the alignment and protection design of the toe to increase the longevity of the structure, a common feature that was often absent in earlier unsuccessful attempts to protect the foreshores of Tuvalu. Institutional and individual capacities will be built in a manner that complements the investments towards building physical protective infrastructure.

Proposed Project Sites

65. The main island of Funafuti, Nanumea and Nanumaga have been selected as target islands for the proposed GCF project. Selection of target islands was carried out during a GCF Technical Working Group meeting in which a number of Government agencies, an NGO association and Women's Council representative participated. The selection of Funafuti was on the basis of several factors – the concentration of economic, social, political and institutional assets are likely to generate the largest impact from the GCF investment. Moreover, the JICA initiative has produced a feasibility study for the gravel beach nourishment work, which includes the detailed hydrodynamic and coastal processes, an ESIA, and financial and economic analysis. Nanumea and Nanumaga were among the four islands that have been severely damaged by recent Cyclone Pam.

66. At Funafuti, the project aims to rehabilitate 1,000m of the eroded and degraded foreshore on the lagoon-side of Vaiaku waterfront of Fongafale Island. The selection of the site was made on the basis of an analysis of multiple criteria that included but were not limited to the concentration of economic, social, political and institutional assets that are likely to generate the largest impact from the GCF investment. Moreover, JICA (2011) provided a detailed feasibility study for the gravel beach nourishment work, which includes the detailed hydrodynamic and coastal processes conditions, an environmental and social impact assessment, and financial and economic analysis. Figure 9 shows the proposed locations on Funafuti and the proposed GCF interventions are along the sections L-C and L-D, the most vulnerable shoreline according to the JICA assessment. Designs for the proposed interventions in Funafuti have been prepared by international engineering firms. The only requirement before the commencement of construction is to undertake small scale hydrodynamic modelling and geomorphological assessments to ensure the structures are perfectly aligned with coastal processes and also ensure the structures are designed and constructed to reduce potential damage from for example, structural destabilisation of the toe of the structure from coastal processes.

67. Investigation and selection of technical solutions and their feasibility in outer islands have relied on the UNDP (2014) and World Bank (2015) studies as they are among the most recent studies currently available with design by international engineering firms that would be undertaken once this project was funded. Nanumea and Nanumaga sites were chosen due to their highly vulnerable population centres and the fact that both sites were severely affected by overtopping waves and currents generated by Tropical Cyclone Pam in March 2015. About 760m and 450m will be rehabilitated for Nanumea and Nanumaga, respectively. See

68. Figure **10** for the maps of selected sites for these islands (See also Annex IX for larger maps).

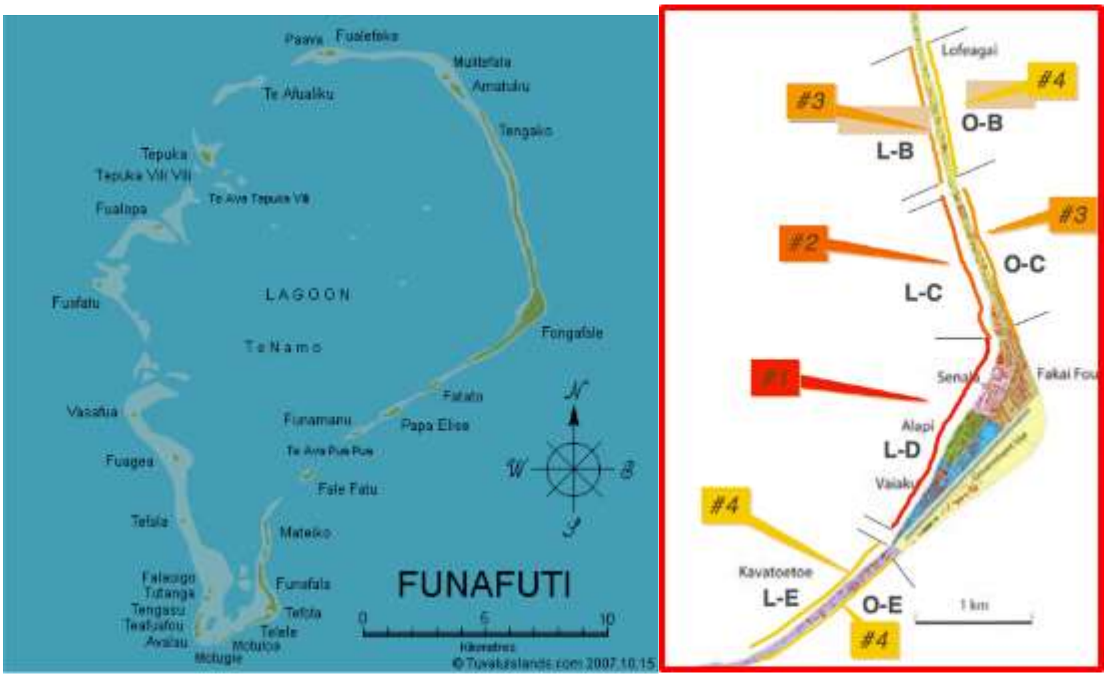


Figure 9 Overview of Tuvalu and selected sites on Funafuti

Figure 10 Proposed coastal protection (red line) on Nanumaga (left) and Nanumea (right)

Potential Coastal Protection Solutions

69. The decision to build coastal protection infrastructure to defend the coast is usually taken when the existing assets are considered sufficiently valuable to protected from recession and erosion. Commonly by establishing engineered (hard-permanent or quasi-permanent) structures the community has a sense of security behind the seawall. A number of options are possible to accomplish this goal. These include gravel nourishment and reclamation, rock armour revetments, revetments made from precast concrete or revetments made from sand-filled geo-textile containers. In the review and selection of engineered solutions, the option of "seawall", defined as a vertically erected, self-standing structure; was ruled out in favour of "revetment" options, which are similar to seawalls but inclined at a more horizontal slope. This is due to multiple reasons including the cost, maintenance requirements, potential loss of access of Tuvaluans to the ocean, and potential environmental and social impacts of alternative interventions.

70. Soft measures were initially considered as part of the coastal protection solutions. Numerous climate change reports have discussed the growing of mangroves on Tuvalu including an FAO report that indicated that Funafuti has got a small mangrove swamp inside the main islet; some other inland mangroves also occur on Niutao and Nanumanga. Mangroves in Vaitupu which are cut off from the sea reach six metres in height. The total area of mangroves is estimated at 40 hectares. The main true mangrove species found in this archipelago are *Lumnitzera littorea* and *Rhizophora stylosa*. However, as no mangroves have been previously observed at the sites identified by the Government which are to be addressed with GCF financing, and the conditions for mangroves as a solution is unviable given soil characteristics, mangrove plantation as an option was not further considered as part of this feasibility study. However, there are other soft measures such as planting of coastal vegetation, such as fetau tree (*Calophyllum inophyllum*) and dune restoration, which are considered in conjunction with the engineering solutions proposed in this document.

SWOT Analysis

71. To assess the positive and negative impacts of each type of hard structure, a strength, weakness, opportunities and threats (SWOT) analysis of the key options proposed for consideration based on the three feasibility assessments[23] was undertaken to provide valuable input into the decision making process. These are described in the table below.

[23] Three assessments are: 1) AECOM (June 2015), Tuvalu Coastal Protection Scope Definition; report prepared for the World Bank; 2) Japan International Cooperation Agency, Kokusai Kogyo Co., Ltd and Fisheries Engineering Co., Ltd (Jan 2011), The Study for Assessment of Ecosystem, Coastal Erosion and Protection/Rehabilitation of Damaged Area in Tuvalu, report prepared for the Government of Tuvalu's Ministry of Foreign Affairs, Environment, Trade, Labour and Tourism; and 3) McCue, J (May 2014), Increasing Resilience of Coastal Areas and Community Settlements to Climate Change: Coastal Options and Feasibility Report – Nukufetau and Nanumea, report prepared for Sustainable Sea, Australian Aid, NAPA Tuvalu, United Nations Development Programme and the Government of Tuvalu

Geo-textile Container Revetments

Strengths	Weaknesses
- Provide some flexibility when there is a high degree of uncertainty about the level of threat in Tuvalu - Allow for easy extension should the structure result in erosion and/or deposition - Their construction and design is less complex than permanent seawalls and can be constructed by local labor using aggregates extracted directly on-site - Can be suitable for most shoreline erosion situations where a rock revetment would normally be used - Provide a softer finish and will often become covered in sand in sandy environments - Such structures have been shown to be highly durable and long lasting and able to withstand the impact of large cyclone driven waves and tides - Visually less objectionable than rock armour - An attractive and viable alternative given the lack of space available to the community for relocation and the fact that only a very narrow beach presently exists between the village and the reef flat - Have been proposed for the country because they offer a sufficient level of protection and at the same time they are quasi-permanent structures - This intervention has an advantage for very remote islands where transportation costs and logistical challenges could limit the construction of more complex interventions	- Limited lifetime in contrast to hard infrastructure – approximately a 25 year design life – some manufacturer's warranty is only 10 years; however is double lined when filling, this can double the life of the containers - Damage issues include abrasion, UV resistance and destruction during very large storm events - Source of sand potentially difficult to obtain – will require off shore dredging of sand which could increase erosion in other areas and affect the ecosystem - May be necessary to undertake ongoing beach profiling to ensure geo-textile structure remains stable - Need ongoing maintenance to repair/replace damaged containers - Need significant slope to build a long term geo-textile structure above 1.5 metres that will be structurally sound - Need to ensure that the foundations of the revetment are sufficiently deep for stability to cater for the loss of the beach – typically requiring deeper foundations the more seaward the revetment is located - Require a similar degree of back preparation to rock revetments and the large footprint means they should not be used in sensitive coastal environments
Opportunities	**Threats**
- Easily extended as required - Easily repaired with local workforce creating longer term employment after construction	- Potential public perception that they are not the best option as visually, they do not convey the same type of barrier a vertically erect sea-wall tends to project - Identification and access to sources of suitable nourishment sand is a key issue, as is the cost (dependent on the applied volume, the sand source etc) - If revetment is not adequately designed or constructed, complete reconstruction may be needed - Coastal protection structures can provide

	long lasting protection to the community, but in case they are not properly maintained their lifetime will be reduced substantially and might result in maladaptation - During large storm events, the structure, if not properly designed may result in additional damage - Geo-textile containers can be subject to vandalism - Ongoing inspections are necessary to ensure the structure is not posing a hazard to the public which may be a threat given limited local capacity - Construction and excavation of toe of wall can be difficult and dangerous, often filling with water and collapsing during a limited working window

Pre-cast Concrete (Seabee) Revetment and Wave Deflection

Strengths	**Weaknesses**
- Resilient to significant events and reduces flooding - Experience indicates that careful design in full cognisance of the prevailing coastal and ocean processes can result in excellent outcomes - Suitably founded for stability against scour at the toe of the structure, particularly on a receding shoreline - Combined with wave return wall, are an effective solution to protect from flooding in high value asset areas - When combined with rock armour, maintain access to ocean environments above that of rock armour while ensuring protection from erosion and undercutting with an overlap of rock armour - Involve local labour and need to be well designed and carefully constructed to persist overtime	- More expensive than rock armoured revetments and gravel nourishment($10,045 / metre) - Less visual amenity of concrete units - Potential to change hydrodynamics if not designed and constructed correctly - Removes potential for beach renourishment - Accumulation of sediment on their updrift side and initial erosion on down drift side can result in impacts to the community and marine environment - Need to ensure that the foundations of the revetment are sufficiently deep for stability to cater for the loss of the beach, typically requiring deeper foundations the more seaward the revetment is located - Part of the materials will need to be imported - Likely to need repair more regularly than rock armour (but less so than geo-textile containers) - Deflected waves can 'scour' sea bed and undermine the sea wall foundations if not designed and constructed correctly
Opportunities	**Threats**
- Reduces wave action although can be overtopped - Allows for continued access to ocean environments - Allows local employment during	- Effectively isolates the sand located behind the wall from the active beach system and may lead to other adverse consequences - Can rust overtime if not properly made thereby creating additional hazards (this is

construction	less so with advances in technology and moulding methodologies

Rock Armour Revetment

Strengths	Weaknesses
- Revetments are robust structures constructed along the shoreline which provide a physical barrier separating the erodible material immediately behind the structure from wave and current forces acting on the beach itself - Protect the coastal line, land and buildings against erosion - Will significantly reduce coastal flooding in some areas - Provides the best option for asset protection - Allow the sediment build-up of a beach within the wall - Provide excellent defence where wave energy is high, reassures the public and has a long life span - At least a 50 year design life although rock armour, when designed and engineered correctly, will last > 100 years - Provide three dimensional habitat for sessile and motile invertebrates and small fishes - Designs that are built using local corals provide less protection, but are significantly less expensive and they can be built using local labour - Limited maintenance or repair of the structures - Least cost option ($8,036 / metre)	- Structural options typically may have adverse side effects on the beach system - potential to significantly change hydrodynamics - On smaller islands, requires land access that may not be available due to draft of vessels and a lack of offloading facilities - Rock armour units would need to be imported - Design built with igneous rock provides higher protection, but needs to be build using heavy machinery and imported materials - Can affect beach access - Curved sea walls can increase the erosion of beach material through the reflection of wave energy back to the sea. This means that the waves remain powerful. - Over time the wall may begin to erode if proper armour rock is not used - May not keep pace with rising sea levels - Recurved sea walls cause greater erosion at the base of the wall
Opportunities	**Threats**
- Rock structures by their nature are subject to movement and settlement over time. They are also subject to damage during storm events although they are designed to withstand major wave attack. As such, limited ongoing maintenance will be required to ensure the structural stability - Ongoing maintenance cost of 1% per year is typically adopted for rock structures subject to storm wave attack - Provide excellent defence where wave energy is high - Rock structures reassure the public as the	- If damaged, difficult to quickly repair as will require a full shipment of new material, therefore being costly - There could be a delay in shipping due to severe weather - Can affect beach access, recurved sea walls can increase the erosion of beach material - Necessitate maintaining access to the top of any revetment to allow 'top up' works to be carried out

most stable option	

Gravel nourishment and soft structures

Strengths	Weaknesses
- Maintaining natural shoreline dynamics and healthy sand movement across a coastal cell - Trapping sand to rebuild eroded shorelines or maintain current shoreline form - Providing or enhancing important shoreline habitat - Reducing wave energy impacts at or seaward of the shoreline - Absorbing storm surge and flood waters - Filtering nutrients and other pollutants from the water - Maintaining beach and intertidal areas that offer public access opportunities for wading, fishing and walking - Reducing the costs of stabilisation of hard structural approaches - Creating a carbon sink and thereby helping mitigate climate change - Cheap, retains the natural appearance of the beach and preserves the natural appearance of the beach.	- Not an independent intervention and will not reduce flooding - Does not in itself provide protection to communities from wave induced impacts - Highly site specific - Not appropriate for high energy environments - Not effective where much of the shoreline is already hardened - More difficult to design and install than more traditional hard structural approaches - Limited information available on the effectiveness of living shorelines for different types of shorelines, energy regimes, and storm conditions - Need regular maintenances - Less likely to be effective against extreme storm events - Off-shore dredging of sand and shingle could increase erosion in other areas and affects the ecosystem. Large storms will require beach replenishment, increasing costs. - Large storms will require beach replenishment, increasing costs
Opportunities	**Threats**
- Existing project in Tuvalu allows for increased and continued employment maintaining sites - A very strong case explaining how their proposed intervention scheme would be effective in reducing overtopping and flooding along some of Tuvalu's most vulnerable and economically valuable coastline - Still allow access to the coast	- Depending of coastal processes, may be quickly removed if local conditions are altered from the time of the design - Managed retreat is a cheap option, but people will need to be compensated for loss of buildings - Significant ongoing costs for maintenance which may not be available post the project

Site Specific Proposals

72. Based on the SWOT and a multi-criteria analysis of the coastal protection options considering their advantages and disadvantages, it was concluded that, for Funafuti, pre-cast concrete (Seabee) revetment (400m in the middle of the rock armour) and rock armour 300m either side of the pre-cast concrete revetment is the most effective least cost option to achieve the level of protection needed from the projected impact of climate change such as storm surge from both king tides and storm events and cyclone-induced coastal erosion. The designs of these options also permit access to the sea for local people. When undertaking the initial design which was a full rock armour revetment, a number of drawbacks were recognized. Most importantly, the initial proposed rock armour structure would adversely affect access to the lagoon which local communities use for multiple purposes. Conversely, the final proposed structure of pre-cast concrete revetment in the 400m will allow beach access and opportunities for local employment and rock armour which resulted in an increase in the increment of capital investment of 25-30%. As such, the most preferred option for Funafuti is rock armour either side of pre-cast concrete revetment.

73. In the two outer islands of Nanumea and Nanumaga, a limiting factor restricting the viability of many engineered coastal protection options is the lack of a landing facility on the islands, which precludes the rock armour and pre-cast concrete revetment that are considered in Funafuti. As a result, geo-textile container revetments were considered a viable option. This measure can potentially be complimented with soft measures including beach nourishment and dune restoration. Design of geo-textile container revetments have been prepared by international engineering firms.

Funafuti Option – Rock Armour Revetment and Pre-cast Concrete (Seabee) Revetment

74. A conventional double layer rock armour revetment is the most economical and robust solution and thus is usually preferred for coastal protection where suitable sized rock is available. However, the rock armour does restrict access to the ocean due to its structure. As such, the mix as highlighted above with pre-cast concrete revetment will provide similar protection to that of a rock armour revetment. The drawback of a concrete block wall is a small increase in cost; however the benefits of continual access to the coastal environment outweigh the cost implications.

75. For Tuvalu, no substantial rock is available so the rock and concrete blocks will need to be imported. For a project/programme such as this, rock would need to be sourced from an established large rock quarry, preferably with experience supplying armour rock grade material. Quarries will exist in Australia, New Zealand and Fiji where rock armour can be produced on demand. Concrete block will be in both Australia and New Zealand. An economically attractive alternative to sourcing rock off the island is the mining of the reef material such as the armour used around the boat ramp and jetty. However, this option has been discarded for this study on the grounds of environmental and community concern, and that the size of material is likely to be far too small.

76. Rock armour and pre-cast concrete revetment are extremely durable when designed and constructed correctly to consider hydrodynamic processes[24]. Large scale revetments built of large rock are robust, which means that even if conditions exceed the design, the revetment, while it may sustain some damage, it will remain functional in some form. This is an important feature in a location with little metocean data and considering possible impacts of climate change into the more distant future. In combination with the pre-cast concrete revetment, there will be an overlap of the rock armour to ensure the protection of the extremities of the concrete revetment to reduce erosion through longshore process. The fine-scale verification of the final design will incorporate the island-level hydrodynamic modelling outputs to ensure the structure is built for the long term.

[24] The design life of 50 years is assumed following the standards for normal maritime structure. But as experience has demonstrated in the region, rock armour, in particular, can be extremely durable lasting up to 100 years or longer when designed and constructed correctly.

77. Rock armour units are sized using Hudson Formula and checked using the Van der Meers Formulae and a revetment slope of 1:1.5.[25] In terms of rock armour density, the design for this proposal uses a density of approximately 2.6t/m^3 following good practices from the Pacific. This would result in median primary armour of 300kg, resulting in a double layer armour thickness of approximately at least 1m although full detailed assessments would be needed to confirm that calculation. Figure 11 shows an example rock armour coastal protection wall and Figure 12 shows an example of a pre-cast concrete revetment that was constructed in Australia in the 1984 (photo taken in 2015). An engineering design of a rock armour wall is included in Appendix A while an engineering design for a pre-cast concrete revetment is included in Appendix B.

Figure 11 Rock Armour Revetment

[25] CIRIA, CUR Centre for Civil Engineering and CETMEF, (2012) "*The Rock Manual: The use of rock in hydraulic engineering* (2nd edition)" *Report C683*, CIRIA, London

Figure 12 Pre-cast Concrete Revetment

Outer Island Option – Sand Filled Geo-textile Container Revetment

78. A semi-permanent coastal protection unit is the sand filled geo-textile container. Unlike the sand containers used to protect locations in the past, sand filled geo-textile container are relatively large and the constructed of long lasting vandal resistant geotextile. Sand filled geotextile containers are similar to rock armour in that the mass of the individual elements is the primary source of strength for the revetment and as such the structure is considered robust.

79. A significant advantage of using sand filled geotextile container, particularly given appropriate port facilities do not exist on the outer islands, is that large quantities of heavy material does not need to be imported, can be brought in on pallets and the fill is taken from the local beach, or as is proposed, from dredge material (see below). It should be noted that because the containers are buried back in the beach, there is no net loss of volume by using in-situ sand if sand is taken from the beach. By contract, when sand from dredge material is used, which is likely the case for the targeted islands for the GCF project, it will significantly increase the height of the coastal protection thus increasing protection.

80. Another known advantage is that geo-textile containers are considered to have lesser environmental impact compared with rock or concrete structures.[26] This is largely because the wave absorption structure, rather than fighting against the wave force, prevents scouring of the beach, if appropriately designed and placed. Also the three-dimensional structure provides marine life habitats.

81. A disadvantage of sand filled geo-textile container in contrast to rock armour or pre-cast concrete revetment is the limited life of the geotextile container. The container breaks down over time when exposed to UV radiation. The majority of the literature and manufacturers' statements suggest sand filled geo-textile container will last for at least 25 years fully exposed, though anticipate longer life as the existing installations in the region are holding together well. It is anticipated that the lower areas of the revetment will be buried for much of the design life

[26] Hornsey, W. P., Carley, J. T., Coghlan, I. R., and Cox, R. J., (2011) "Geotextile sand container shoreline protection systems: Design and application" *Geotextile and Geomembranes* Vol 29, 4, pp.425-439

and those containers that are exposed will have regular maintenance to ensure they last. Where a container is ripped, it will be repaired or replaced.

82. To improve performance of sand filled geo-textile container revetments and its life, the feasibility study recommends that they be double lined (e.g. one geo-textile container inside another). This can result in doubling the life of the wall and plus reduced potential damage as a result of vandalism. Figure 13 shows the filling of geotextile containers. An engineering design of a sand filled geotextile container revetment is included in Appendix C.

83. Previously, geo-textile containers have been considered more suitable for mild or limited wave climates[27] due to their durability concerns in high wave energy environments. However, continuous development of specialized materials in recent years has shown that the materials are able to withstand harsher conditions in exposed environment.[28] As a result, geo-textile containers have proven their effectiveness in the various forms of coastal protection such as groynes, revetments, breakwaters and seawall structures.[29] Figure 13 shows two examples of geo-textile container revetments in wave impacted environments.

Figure 13 Filling geo-textile containers

[27] Cummings, P., Gordon, A., Lord, D., Mariani, A., Nielsen, L., Panayotou, K., Rogers, M., and Tomlinson, R., (2012) "Climate change adaptation guidelines in coastal management and planning" in Cox, R., Lord, D., Miller, B., Nielsen, P., Townsend, M., and Webb, T., (Eds) *The National Committee on Coastal and Ocean Engineering*, Engineers Media, Australia
[28] Hornsey, W. P., Carley, J. T., Coghlan, I. R., and Cox, R. J., (2011) "Geotextile sand container shoreline protection systems: Design and application" *Geotextile and Geomembranes* Vol 29, 4, pp.425-439
[29] Paeniu, L., Iese, V., Jacot Des Combes, H., De Ramon N'Yeurt, A., Korovulavula, I., Koroi, A., Sharma, P., Hobgood, N., Chung, K., and Devi, A., (2015) *Coastal Protection: Best Practices from the Pacific,* Pacific Center for Environment and Sustainable Development, USP, Suva

Figure 14 Use of geo-textile containers in high wave energy environments

Design Principles

84. Design considerations for each site are important and will need careful consideration. Designs of the proposed interventions have been prepared by international engineering firms and are presented in Annexes.

85. When considering the design, there is a need for not only a coastal protection option that will reduce the vulnerability of coastal communities from intensifying wave actions due to climate change, but it also needs to allow them to continue to interact with the coast, ocean and lagoon. All option must ensure that it reduces climate risks, but it also does not impact on Tuvaluans and their livelihoods, food acquisition and leisure. This study has presented the feasibility of the proposed coastal protection options from a technical viewpoint based on international experiences, known local conditions and the design consistent with international good practice and design criteria. The proposed design and preferred options presented in this study require fine scale verification with additional information that will be collected during the implementation, including site-specific hydrodynamic and geomorphological conditions as well as the information about how different groups of community (women, youth, elderly and children) interact with the sea on a daily basis, therefore allowing fine adjustments in the design of the intervention. With this information, the proposed coastal protection infrastructure will be designed and constructed in such a way that it is accepted, owned and sustained by the community in the long-run rather than the previous ad hoc design which has resulted in the failure of a number of coastal protection options.

86. It is also important to emphasize that no coastal protection options will eliminate the future damages from flooding and wave overtopping. To minimize design event overtopping/flooding, a high wall would be required behind the crest of the seawall/revetment. Such a structure would be expensive and detrimental to community amenity. This study uses the assumption that a lower structure that improves the resilience of the community to overtopping events is considered more desirable in the circumstances.

87. When undertaking the design of the infrastructure, it will be important to adopt well-accepted design criteria such as AS 4997 – 2005 "*Guidelines for the design of maritime structures*" and "*The Rock Manual: The use of rock in hydraulic engineering* (2nd edition) (2012). By using guides such as this, the detailed design will be able to consider design life and the hazard to people in the assessment of design criteria. The design prepared by the international engineering firms have used this Guideline along with other international good practice design criteria.

Wave Climate

88. Studies of wave climates over flat reef tops revealed that the maximum sustainable wave height is usually 0.55 times the depth of water. Additional calculations will be sourced from the hydrodynamic modelling and will be incorporated into the design drawings before the commencement of construction

Beach Levels

89. It is anticipated that the revetment will be a last line of defence. To construct the revetment beach material will need to excavate down to solid foundations on either substantial beach rock or the reef platform (estimated to be 2.0m LAT under the beach). This is particularly important for sand filled geo-textile container and concrete revetments as without a proper footing, the toe of the wall can erode over time. Once the revetment is built the beach should be re-instated to its original level and profile behind the wall. This information will be collected before the construction begins.

Design Logistics

90. The machinery and equipment to unload rock from barges onto islands is often not available in Tuvalu and more often than not, needs to be imported or "loaned" from overseas. Therefore the construction phase of developments is costly and often takes time as machinery needs to be hired purposely for the job. Purchasing this machinery is not often undertaken as there can be many months "window" between projects that need this equipment (e.g.: "caterpillar excavator machinery is not used every week").

91. As highlighted above, rock armour and concrete revetments will need to be imported from Australia, Fiji and/or New Zealand. All construction should be undertaken during the dry season to reduce the need to demobilise during a storm event. Further, by undertaking activities during the dry season, rainfall is less and therefore the loss of sediment from the beach will be reduced through the movement of equipment.

Dredging

92. Dredging will be required to fill the geo-textile containers on the outer islands. As highlighted in the proposal, it is anticipated that approximately 30,000m^3 will be required. The use of a backhoe dredge will have significantly less impact on the marine environment as there is no overflow that can impact water quality. Importantly, it allows additional advantages in that the geo-textile containers can be filled with the same equipment as highlight in Figure 13 thus reducing the need for additional machinery. It is anticipated that a dredge of this nature will be procured from Australia, Fiji or New Zealand.

93. As above, dredging should be undertaken during the dry season to reduce the need to demobilise during a storm event.

Costs

94. The cost of each of the options considered in this feasibility study is listed in Table 2.

Island	Length	Protection option	Cost per meter
Funafuti	1000m	Rock armour	$8,036
		Pre-cast Concrete (Seabee) Revetment + wave deflection wall	$10,045 + $1,488
Nanumea	760m	Geo-textile sand retainer revetment	$8,370
Nanumaga	450m	Geo-textile sand retainer revetment	$8,370

Table 2 Costs of Different Coastal Protection Options

Summary and conclusions

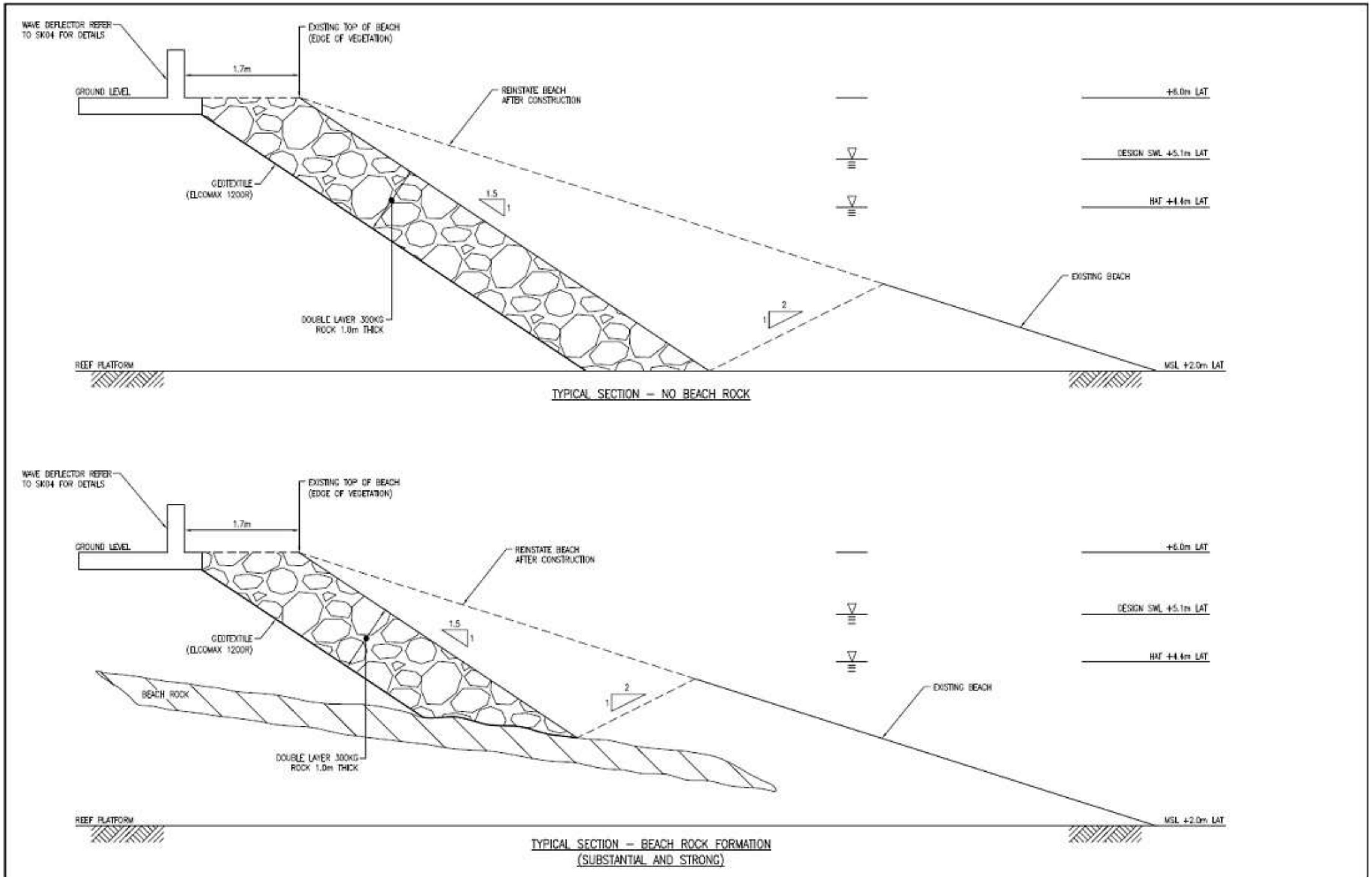
95. Tuvalu is located in the equatorial south Pacific and is highly vulnerable to climate change impacts, particularly those related to sea level rise and more intense tropical cyclones. The nation is comprised of nine islands and atolls that are very low lying with topographic relieve generally less than 3 m above mean sea level. At present, high tides in conjunction with storm events resulting in increased wave height caused flooding and coastal erosion. This fact was easily observable in 2015 when Tuvalu were inundated and suffered severe damage as a result of the high waves and storm surges generated by Tropical Cyclone Pam, one of the strongest tropical cyclones ever recorded.

96. Sea levels in the vicinity of Tuvalu have been rising steadily in recent years and scientific predictions indicate that this trend will continue and possibly accelerate in the coming decades. As such, Tuvalu faces an existential crisis in that continued erosion and flooding will eventually make the islands uninhabitable. This funding proposal focuses on alleviating the vulnerability and increasing the adaptive capacity and resilience of three sites in Tuvalu; namely the Vaiaku waterfront on Fongafale Island in Funafuti Atoll as well as the outer islands of Nanumea and Nanumaga which both suffered considerably during Cyclone Pam.

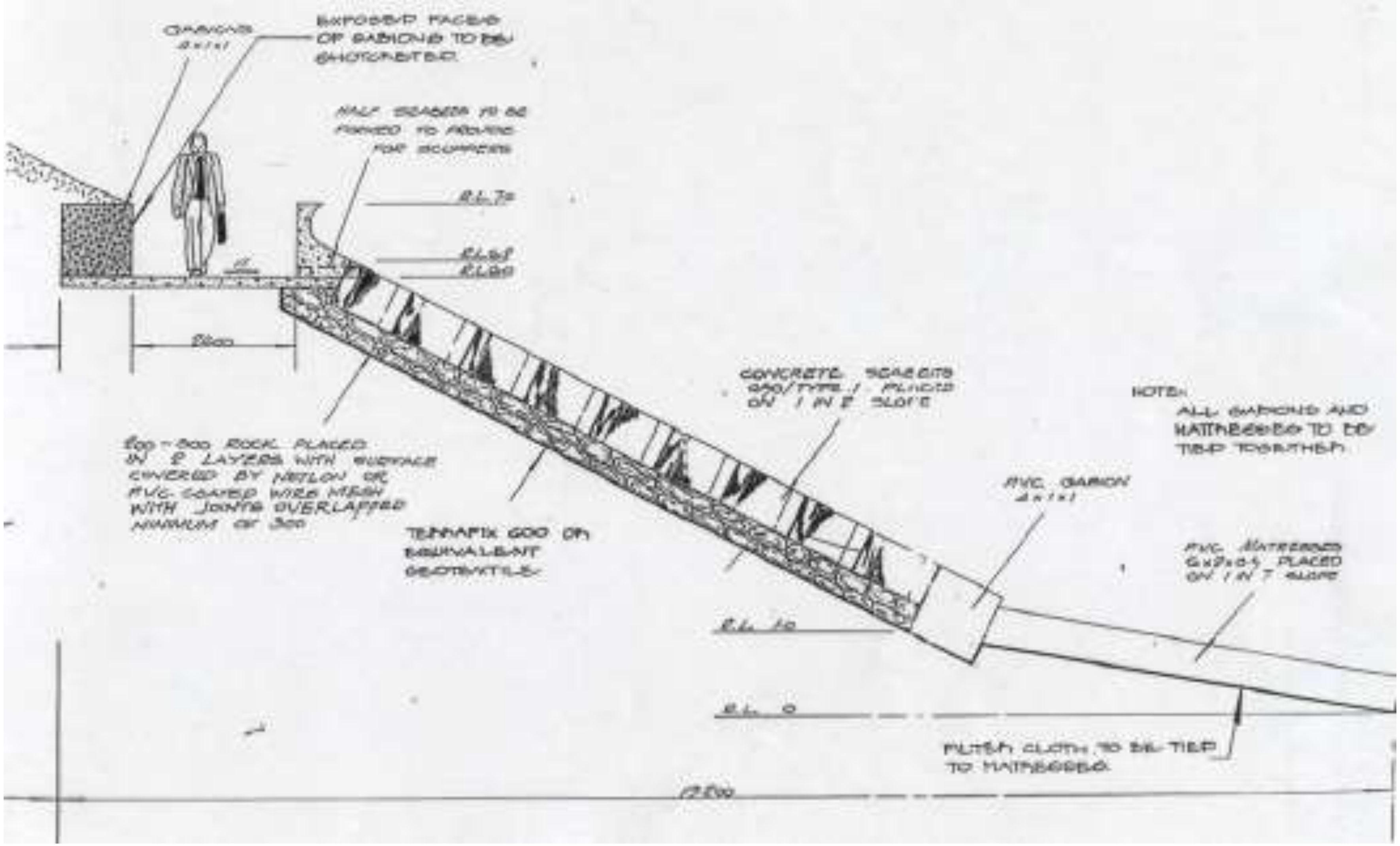
97. Measures considered for the different sites resulted in a preference for hard engineering solutions. For Funafuti, the option was for a combination of rock armour revetment in the locations needing rehabilitation and pre-cast concrete (Seabee) revetment in areas that local peoples still require access to the coastal zone. For the outer island sites, sand filled geo-textile containers are recommended based on their long life span as well as ease of construction where no port infrastructure is available. This can also be supplemented by other softer approaches such as coastal vegetation and dune rehabilitation.

98. The project interventions are sustainable in that they take into consideration “cross sectional variation” across the reef lagoon to outer reef. In addition, the techniques also demonstrate a range of highly effective engineering solutions that have been observed to be effective measures for coastal protection internationally. By adopting this approach, it is anticipated that the solutions will have significant benefit to the people of Tuvalu.

Appendix A Rock Armour Revetment Design



Appendix B Pre-cast Concrete (Seebee) Revetment Design



Appendix C Geo-textile Container Revetment Design