PACIFIC ISLANDS AT RISK: FORESHORE DEVELOPMENT AND THEIR VULNERABILITY AND IMPLICATIONS FOR ADAPTATION STRATEGIES TO CLIMATE CHANGE

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1. Introduction

The south and central Pacific Ocean is dotted with thousands of coral atoll islands, many of which are inhabited along narrow coastal strips and the foreshores are used for various socio-economic activities, ranging from port development to marine aggregate extraction. In this region which is serviced by the South Pacific Applied Geoscience Commission (SOPAC), there are sixteen (16) Small Island Developing States (SIDS), occupying a total land area of about 560,000 km^2, in an ocean space of about 26 Million km^2. These countries are the Cook Islands, the Federated States of Micronesia, Fiji Islands, French Polynesia, Guam, Kiribati, Marshall Islands, Nauru, New Caledonia, Niue, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu (Figure 1). Many of these SIDS consist of Pleistocene-Holocene coral atolls, which are geologically young, have low elevations above mean sea level, and are generally flat. Elevation generally ranges from 1-5m above mean sea level, and on many of these islands, it is possible to see from one side to the other. This makes these islands entirely coastal, in terms of systems interaction, their influence by the sea, their geographical disposition and their relative relief.

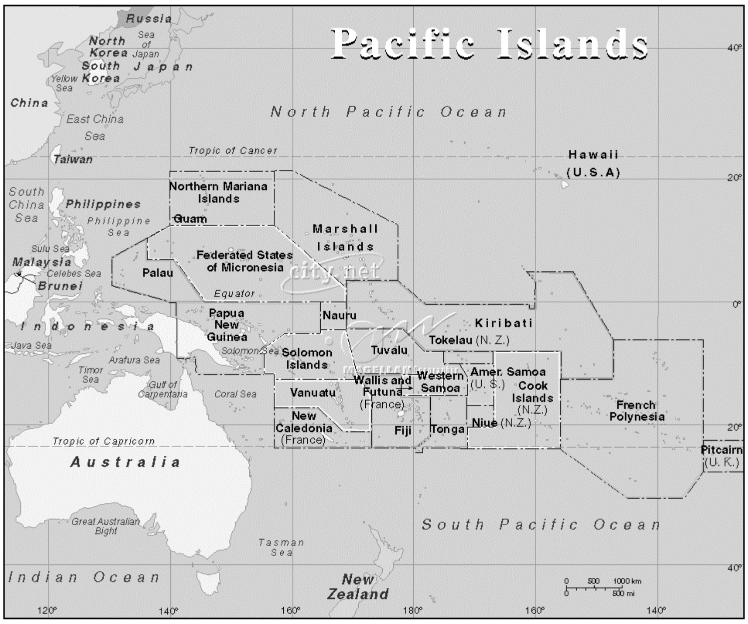

Figure 1. Location of south and central Pacific SOPAC countries (Magellan Maps, 2000)

As a result of their location and small land area, which varies between 0.0028 to 14.81% of their surrounding maritime area, many Pacific SIDS are exposed to large-scale regional oceanographic and weather phenomena. This includes annual cyclones and storms, which wreck havoc along these atoll island coasts, resulting in damage and destruction of property, agricultural land and constructed/infrastructure facilities. These also cause flooding, coastal erosion/land loss and in some cases, loss of life. The aerial coverage of many natural hazards, like cyclones, in Pacific Island Countries (PICs), are in many cases several orders of magnitude larger than the size of individual island systems, and consequently, are capable of engulfing entire island states. However, modification of coastlines for human habitation and extensive foreshore developments, like dredging, mining aggregate, port and harbour construction, airport construction, coastal protection works and reclamation and fill, make coastal communities more exposed to the sea and vulnerable to coastal erosion, increasing the risk to communities and infrastructure. These risks are compounded with the possible threat of global warming and associated sea-level rise, projected by IPCC to rise by 20-86 cm in 2100, and in these low SIDS, can exacerbate coastal erosion and property damage. Consequently, coastal communities are vulnerable and face the possible threat to their very existence. These natural events and human occupation of fragile coastal areas cause loss of scarce land, a culturally important and invaluable natural resource in many on these small and non-market oriented developing economies. With Pacific SIDS having an average poverty rate of 15%; GNP/capita between US $2,210 to ≤ $760; GNP from less than US $96 to $1,748 Million and external debt (as a % of GNP) as high as 56%, any loss of land and damage to infrastructure and facility can seriously impair national and regional economic development.

In it’s 1997 flagship publication, A Future for Small States: Overcoming Vulnerability, the Commonwealth Secretariat, highlighted the fragility and susceptibility of many of these SIDS to natural disasters, including coastal hazards like sea-level rise and their associated effects, in particular, coastal erosion and coastal land loss. In turn, problems like coastal hazards affect economic and social development in developing SIDS economies and make them economic vulnerable. This point was also highlighted and discussed in an Interim Report of a Joint World Bank/Commonwealth Secretariat Task Force on Small States: Meeting the Challenge in the Gobal Economy, 1999 and at the Commonwealth Heads of Government Meeting (CHOGM) 1999, Durban, South Africa. To address current and future erosion problems and the possibly deleterious effects of sea-level rise in Pacific SIDS, requires assessment of site specific, local and regional environmental conditions. This also facilitates a rational approach to management of island resources. It is also necessary to understand the factors, which influence erosion susceptibility on these islands through time and space. This can be achieved only through a systematic and integrated approach, with sound data collection, analysis and management exercises. Only then, can optimum environmental and sustainable development strategies be formulated. This approach also facilitates the development of appropriate coastal adaptation technologies for anticipated sea-level rise. With country population (=coastal) growth as high as 4.2%, over the past decade, Pacific SIDS are therefore confronted with having to look towards development of appropriate coastal adaptation strategies for protecting their coastal communities and addressing these current and future development hurdles and the possible threat of sea level rise. For all south Pacific atoll communities, retreat (based on IPCC’s definition) is not possible, while accommodation is currently limited. Therefore, protection and sound planning (for accommodation) are essential, for successfully addressing the possible threats to sea level rise. To that end, development of ICZM or Island System Management plans and composite bio-engineering protection systems, are essential for Pacific atoll environments.

This paper examines various aspects of coastal/island systems in the south Pacific region, regional foreshore development activities, current, and future environmental problems, in relation to sea level rise. These are discussed in context of coastal vulnerability, and within the framework of development of coastal adaptation technologies to climate change and sea level rise in the region. Examples are presented from several Pacific SIDS, including Fiji Islands, Nauru, the Federated States of Micronesia, and Kiribati.

2. Methodology

Information was collected from a literature review and field surveys in several Pacific SIDS, including the Fiji Islands, Nauru, the Federated States of Micronesia (FSM), and Kiribati. Pacific SIDS was classified according to island types, while the socio-economic characteristics of the region were examined. Major coastal development activities sites were identified, with a detailed examination of some coastal development on Pohnpei Island, the Federated States of Micronesia and Nauru was done. Specific coastal development activities examined were coral reef mining, mangrove reclamation and fill, airport construction and port and harbour development. Finally, coastal foreshore developments were examined in relation to reef degradation; island elevation/mean sea level and chart datum and the possible impacts of sea level rise on coastal communities and infrastructure.

Table 1. Some demographic and economic indicators for Pacific SIDS (Maharaj, 2000a)

SIDS	Land Area km″	EEZ, Million km″	Population, Thousands (1998-1999)	Population Growth, %/yr (1990-2000)	Population Density, Nos./km″	GNP, $ US Millions (1999)	GNP/Capita, $ US (1998-1999)	International Tourism, $ US Millions (1998)
Fiji Islands	18,333	1.29	790	1	43	1,748	2,210	266
New Caledonia	18,576	1.74	207	3	11	NA	High Income	110
Papua New Guinea	462,243	3.12	4,603	2.6	10	4,104	890	75
Solomon Islands	28,370	1.34	416	3.7	15	315	750	13
Vanuatu	12,190	0.68	183	3.1	15	231	1,170	45
FSM	701	2.978	113	2.4	161	204	1,810	NA
Guam	541	0.218	149	1.5	275	NA	High Income	1,378
Kiribati	811	3.55	86	2.5	106	101	910	NA
Marshall Islands	181	2.131	62	4.2	342	96	1,560	3
Nauru	21	0.32	9,919	1.8	472	NA	NA	NA
Cook Islands	237	1.83	19,103	-0.5	81	NA	NA	NA
French Polynesia	3,521	5.03	227	2	64	NA	High Income	354
Niue	259	0.39	2.088	-3.1	8	NA	NA	NA
Samoa	2,935	0.12	169	0.8	58	181	1,060	39
Tonga	649	0.7	99	0.4	153	173	1,720	12
Tuvalu	26	0.9	9,043	0.9	348	NA	NA	NA

Table 2. Pacific Island types and numbers (Maharaj, 2000a)

SIDS	Island Type/s	Number of Islands
Fiji Islands	High island with many atolls	320 islands, with less than 12 high islands
New Caledonia	Elevated coral with reefs	12 islands
Papua New Guinea	High island with few atolls	Over 600 islands
Solomon Islands	High island with few atolls	992, with 6 large islands and many small low-lying ones
Vanuatu	High islands	80 high islands
FSM	Atolls and few high islands	607 low-lying atoll islands, with four volcanic ones
Guam	Elevated coral, atolls with reefs	1 emergent island
Kiribati	Many atolls and elevated coral	33 low-lying atolls
Marshall Islands	Many atolls	34 low-lying atoll islands and 870 reefs
Nauru	Elevated coral and reefs	1 emergent coral island
Cook Islands	High island and many atolls	20 islands in 2 main groups, several are low-lying atolls
French Polynesia	High islands and reefs	118 islands in 5 main groups
Niue	Elevated coral and atolls	1 emergent island
Samoa	High islands and atolls	2 main islands and 6 smaller ones
Tonga	Many atolls	171, in 4 major island groups
Tuvalu	High islands and many atolls	9 low-lying atolls

Table 3. Some cyclones affecting the south Pacific(Maharaj, 2001a)

DECADE	**Oct/Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr-Jun**	**TOTAL**
1939-1979	15	42	77	86	67	36	285
1990-1999	7	7	13	10	20	5	62
TOTAL	22	49	90	96	87	41	347

3. Results

3.1 Pacific SIDS: environmental characteristics and development indicators

Table 1 and 2 present some island characteristics, demographic and socio-economic statistics for some Pacific SIDS. From this information, one can see that Pacific SIDS is characterised by high coastal population growth rates, high population densities and low economic returns. In addition, almost all countries have numerous coral atolls, with thousands of reefs and very small, low-lying islands (Table 2), with a high dependency on coastal resources for their sustenance, GDP and GNP. International tourism is one of the major regional coastal industries, the success of which is highly dependency on the availability of quality coastal resources, like beaches, reefs and cleans coastal water.

As an economic indicator and dollar value of beach and reef resources, Table 1 also presents some data on the financial returns of this key industry to national economies, which varies between US $12-254 Million, but can be a high as US $1,379 Million (Maharaj, 2000a). In the South Pacific, statistical data also show up to 17 major cyclones, with wind speeds > 120 kph, and up to 4 cyclones, with wind speeds > 185 kph, affected the region between 1958-1994. Data for 1990-present, show another 63 cyclones affected the region (Table 3), with 6,046 deaths, over 406,000 people affected, and with damage costs more than US $807 Million. In addition, 285 cyclones affected the region between 1939-1979 (Table 3; Maharaj, 2000a).

3.2 Foreshore development: some examples

In PICs, building at the edge of the water or land is common and inevitable. Since historical times, the seas and oceans have been of considerable value, as a source of food and livelihood for Pacific islanders. However, with steady population increase over the years, and with the corresponding demand for housing and infrastructure, there is further development along shorelines. Much of this development is again, at the water's edge. With social and economic development, many industries have developed. Tourism is one of these and is quite a big industry in Pacific Island economies. With most of the land being owned by native island communities and the extended families, much private sector development is targeted at the shorefront, where reclamation, fill and development are feasible options to pursue for "land acquisition." While these developments brings economic boom and social amenity to island nations, there are many deleterious impacts of building along the shorefront in small island states. In addition, the potential threat of sea-level rise puts all shorefront development at high risk from wave attack and erosion, impacts by cyclones, storms and coastal inundation. These threaten the viability and performance of engineered facilities, and the economic growth and development of national economies.

Some of these activities and uses of the coastline and shorefront will now be discussed in further detail, especially as it relates to shoreline development and management for sea-level rise. Human modifications of the natural coastline will be highlighted, as issues related to optimum management of coastal system.

3.2.1 Mangrove distribution reclamation and fill in Fiji

Mangrove systems in Fiji are used as important fisheries, reclamation and construction sites, sources of firewood, housing material, timber, conversion to agricultural sites and as sites for urban development. In addition, they provide natural coastal protection against storms, and trap sediments from fluvial and littoral systems. Estimates of mangrove systems for Fiji based on 1:50,000 aerial surveys, by the Lands Department was 45,288 ha (Watling, 1985). The total mangrove area for Viti Levu was estimated at 23,463 ha, about 58% of the total area for the Fiji Islands. The larger systems are located in Ba, Rewa and Labasa Delta areas, with 3,714 ha, 5,130 ha and 1,473 ha respectively. These three systems represent about 40% of the mangrove area for Viti Levu. In addition, much mangrove have been reclaimed for sugar cultivation (1,292 ha in Labasa) and construction activities, e.g. 750 ha in western Viti Levu. Lands Department indicated that at September 1987, 2,457 ha were reclaimed or 6% of the original area and also indicated that at 1985, the remaining mangrove area for Fiji was approximately 38,543 ha. In terms of economic evaluation of mangal systems, mangrove associated fisheries provided subsistence in the order of 8.76 Million kg of fish. This was 60% of the total subsistence fisheries for Fiji, with a market price of FJ $17.52 Million in 1983. For 1983, the total mangrove fisheries in Fiji was estimated to have a total economic return of FJ $ 21.8 million, with mangrove contributing FJ $566/ha.

3.2.2 Coral reef dredging in Pacific atolls and in Micronesia

One of the main uses of coasts in PICs includes coral reef dredging and mining of marine aggregate. This includes a mixture of carbonate sand, gravel, cobbles and boulders, and include dead reef skeletal material and live coral heads or massive corals, e.g. Montstrea spp. Coral reef mining, has for many years, been the main source of construction aggregate for the building industry in Pacific Island Countries. Reef carbonates are used in four major activities. Marine carbonates are mined from reef crests, back-reefs and lagoons, in water usually less than 10 m deep. Common species of corals, which are mined, are *Montastrea spp.,* in addition to *Acropora spp.,* and *Porites spp*. Finely abraded gravel and sand are mined from shallow lagoons, contain branching corals, especially *Acropora spp.*, Mollusca, benthic foraminifera, *Halimeda spp., Rhodophyta spp*. and Echinoderm test fragments.

Most of the dredging and mining of aggregates for construction material take place in water depths of less than 50m, and in many cases between 10-25m. In some areas extraction proceeds from shore and progresses gradually into deeper lagoon areas, filling strips of the lagoon as dredging proceeds, by construction of access roads on fill sites. Most excavation takes place by using hydraulic back hoe excavators and drag-line excavators in all the Pacific Island countries, with some clam-shell and cutter suction dredging, e.g. in the Marshall Islands and Fiji respectively. All sites are backreef lagoon areas.

Table 4 shows the location of some major coral reef and nearshore dredging activities in Fiji Islands, Kiribati, Marshall Islands, Tonga, Tuvalu and Samoa. All dredging sites are also in backreef areas. In some cases, it was possible to estimate the quantities of material dredged. In many cases, this information remained confidential and was not accessible. While some of the quantities appear to be small, when one compares similar operations in larger countries, for islands and countries with small areas such as those in the Pacific, these are large quantities and represent a considerable volume of available aggregate. Field investigations in Pohnpei, FSM, have revealed fifty-one (51) reef mining sites, of which forty-seven (47) are dredge sites, with fourteen (14) recently active areas (Table 5). These sites represent dredging and mining activities over the past two decades. From the list, many of these sites have had a history of dredging activities, with up to eleven (11) license renewals for extraction.

3.2.3 Port/Harbour and airport development in Nauru

Nauru recently completed a new harbour at Anibare Bay, on the east coat of the island. The facility involved dredging 29,579m^3, building 434.8m^3 of boat ramp, 1667.1m^3 of steel-reinforced concrete breakwater, 2085.2m^3 of wharf and apron, 1139m^3 of sand barriers, 70.2m^3 of road access, 1 mooring basin and steering area, 2 navigational aids and lighting fixtures and 650m^2 of boat parking facilities. This facility was constructed in the backreef environment, in a maximum water depth of 3.0m below chart datum (1.57m below mean sea level). The maximum elevation on any part of the facility is the concrete breakwaters, at 4.80m above chart datum. On an EHWST, the breakwaters are only 2.16m above water level. Pre- to post- construction evaluation show that the adjacent beaches were completely eroded and all sediments (clean, medium carbonate sands, 1.75m thick) from the site were eroded, which has caused the land areas to be affected by severe erosion. Erosion scarps are common on both flanks of the facility and the coastal roadway is threatened of being eroded as well (Maharaj, 2000b). A similar facility is being planned for the southwest of Nauru, in the short-term. If we assume a worse cause scenario of sea-level rise of 50-100cm, by 2100, this harbour facility will be only 1.66-1.26m above EHWST. This can affect the serviceability of the harbour, and cause damage to the facility. Numerical analysis of wave overtopping and run-up has shown this to be the case.

Table 4. Some dredging areas in Pacific Island Countries (Maharaj, 2001b)

COUNTRIES	SOME MAJOR MINING SITES
FSM	See Figure 3, Pohnpei Island. Lagoons around atolls in Kosrae, Pohnpei, Chuuk, Yap States. More than 500,000m^3 dredged around Pohnpei Island alone. The current extraction rate in Pohnpei is about 15,000-20,000m^3.
FIJI ISLANDS	Lagoons in Laucala Bay, since 1962. Averaging 60,000-75,000 tons/year, but can be up to 600 tons/day or up to 120,000 tons/year.
KIRIBATI	Coastal lagoons in South Tarawa, including the islands of Betio, Bairiki, Bikemaan, Bikenibeu, and Buota. Between 1992-1993, 40,000-50,000m^3 of sand/year was extracted from back-reef areas.
MARSHALL ISLANDS	At least three main sites in Majuro Lagoon.
TONGA	Vava'u, Koloa, and Fafa Islands. Intertidal fringing reef area to the east of Nuku'alofa, as well as, Sopu and the Kolovai peninsula area.
TUVALU	Funafuti Lagoon, from Muliteafala in the northeast, to Funamanu inlet in the Southeast.
SAMOA	Offshore coastal lagoon in Vaiusu Bay (8,000 m^3/year), Aleipata lagoon of eastern Upolu and Salelologa to Pu'apu'a lagoons of eastern Savai'I (about 500,000 m^3 extracted over the past 15 years).

Table 5. Dredging site around Pohnpei Island, Federated States of Micronesia (Maharaj, 2001b)

PROJECT	MUNICIPAL	RENEWALS	ABANDON	ACTIVE	INACTIVE
DREDGING	NINLEU, MADOLENIM	3		ACTIVE	
DREDGING	TEMWEN, MADOLENIM	2		NOT STARTED	
DREDGING	MESENPAL, MADOL	6	5 - 30 - 91		INACTIVE
DREDGING	METIPW, MADOL	6		ACTIVE	
DREDGING	AREU, MADOL	2		ACTIVE	
DREDGING	POHNAULENG, MADOL	4	6 - 20 - 88		INACTIVE
DREDGING	LEHNDIADI, MADOL	1	10 - 30 - 90		INACTIVE
DREDGING	ROHI, KITTI	2		ACTIVE	
DREDGING	NANKELEU, KITTI	4	2 - 09 - 84		INACTIVE
DREDGING	SEKERENLI, SOKEHS	2		NOT STARTED	
DREDGING	DANPEI, SOKEHS	3		ACTIVE	
FILL/DREDGE	SAPWOHN, SOKEHS	3		ACTIVE	
DREDGING	SAPWOHN, SOKEHS	3	6 - 06 - 96		INACTIVE
DREDGING	IOHL, SOKEHS	2		NOT STARTED	
DREDGING	DEH, SOKEHS	1	6 - 30 - 94		INACTIVE
DREDGING	IPWAL, SOKEHS	4	5 - 01 - 89		INACTIVE
DREDGING	DEH, SOKEHS	2	9 - 30 - 84		INACTIVE
DREDGING	DEKETIK, KOLONIA	1	3 - 26 - 86		INACTIVE
DREDGING	AIRPORT, DEKETIK	3	10 - 19 - 87		INACTIVE
DREDGING	DEKETIK, KOLONIA	1	12 - 19 - 79		INACTIVE
DREDGING	LIDAKIKA, KOLONIA	1	12 - 19 - 79		INACTIVE
DREDGING	DEKETIK, KOLONIA	1	4 - 28 - 82		INACTIVE
DREDGING	DEKETIK, KOLONIA	3		ACTIVE	
DREDGING	DEKETIK, KOLONIA	2		ACTIVE	
DREDGING	DEKETIK, KOLONIA	2	12 - 31 - 88		INACTIVE
DREDGING	TIMWENPWEL, NETT	5		ACTIVE	
DREDGE/FILL	IPAT, NETT	2	11 - 30 - 91		INACTIVE
DREDGING	DEKETIK, NETT	1	3 - 30 - 95		INACTIVE
DREDGING	NAN UH, UH	1	5 - 30 - 95		INACTIVE
DREDGING	AWAK PAH, UH	1		ACTIVE	
DREDGING	SOUNA, UH	4	10 - 30 - 90		INACTIVE
DREDGING	AWAK, UH	1	2 - 28 - 95		INACTIVE
DREDGE\FILL	KEPINLE, KOLONIA	2		ACTIVE	
DREDGING	KEPINLE, KOLONIA	1	2 - 28 - 93		INACTIVE
DREDGING	KOMWON, KOLONIA	1	2 - 28 - 93		INACTIVE
DREDGING	KOMWON, KOLONIA	1	5 - 30 - 95		INACTIVE
DREDGING	NANSOU, UH	9		ACTIVE	
DREDGING	OHWA, MADOLENIM	7	12/31/91	RE-ACTIVATE	
DREDGING	NIHKEWE, SOKEHS				INACTIVE
DREDGING	NIHKEWE, SOKEHS	11 renewals			INACTIVE
DREDGING	NIHKEWE, SOKEHS		9 – 30 - 96		INACTIVE
DREDGING	NIHKEWE, SOKEHS				INACTIVE
DREDGING	NIHKEWE, AUMOR, SOK	4 renewals	6 – 30 - 94		INACTIVE
DREDGING	NIHKEWE, AUMOR, SOK				INACTIVE
DREDGING	SEINWAR, KITTI	8		ACTIVE	
DREDGING	SEINWAR, KITTI	2		ACTIVE	
DREDGING	KEPIROSHI, MAD	6	12/31/88	RE-ACTIVATE	
DREDGING	DEKETIK	3	8/18/88		INACTIVE
DREDGING	MEILAP, KITTI				INACTIVE
DREDGING	DENPEI SOKEHS				INACTIVE
DREDGING	AWAK (METIPW) U				INACTIVE

Nauru also completed an extension of their airport runway in the early 1990's that involved fill and reclamation of about 90,000m^3 of coral and limestone to a height of maximum 6m above mean sea level. The airport was extended by about 100m into the surf zone, and is now about 100m from the reef crest and open ocean. The present structure is not overtopped by EHWST, but under storms and rough seas is affected by significant salt spray and can be affected by overtopping. Further any extreme change in sea level can increase the probability of overtopping under extreme events, including 1 in 25-50 year, 5-5.34m high waves. The adjacent beaches and land areas are now being continually affected by eroding by waves diffracting around the extension site (Maharaj, 2000c). This has threatened adjacent residential property infrastructure and facilities. Many coastal trees have been eroded away, while residential buildings are at risk of collapsing into the surf zone. For a small island like Nauru (Table 1), any loss of land and infrastructure is significant.

4. Discussions

4.1 Reef and coastal system degradation

Coastal construction is responsible for degradation of reefs and erosion of coastal areas in all Pacific SIDS, including those examples presented. The Pacific, with about 40% and the largest cluster of the worlds' reefs, 41% of these reefs are under medium-high pressure from human developments, especially those of Fiji, Marshall Islands, French Polynesia, Solomon Islands, Vanuatu and Papua New Guinea (World Resource Institute, 2000). About half of the Solomon Island reefs are potentially threatened and two-thirds of the reefs off Fiji are at risk. The reefs of Christmas Island, Kiribati, are under medium-high threat, while those of Majuro and Kwajalein in the Marshall Islands are under medium threat from coastal development. Those of Chuuk Lagoon, FSM, are also under high threat. Coastal/foreshore development, in particular dredging and fill are two of the greatest threats to these ecosystems.

Coral reefs protect much of the land areas and shorefront development from extreme wave attack and open ocean conditions, acting as ideal natural submerged breakwaters and wave dissipaters. Construction and development activities like dredging, port, harbour and airport construction alters nearshore bathymetry and increases effective water depth, causing larger waves to be propagated into the surf zone and on beaches. These result in significant erosion of natural beaches and shorelines, and threaten coastal communities and infrastructure. With nearly all development in Pacific SIDS restricted to the foreshore, the risk to coastal communities is high. In addition, the worse case scenario of sea-level projection by the next century will cause effective submergence of all foreshore facilities by between 20-100cm. This reduces the effective heights of all residential and critical facilities, above mean sea level, and increases their vulnerability to overtopping, erosion and engineering failure under normal and storm/cyclone wave attack. Any associated rise in sea-surface temperatures will also add to the damage to reefs, and increase storm and cyclone frequency and magnitude, as has already been noted in the south Pacific from El Niño events over the past decade. The damage to reefs will reduce the effective protection of coastal, beach areas from severe/open ocean wave attack, and exacerbate current coastal erosion, increasing the risk to communities and infrastructure. Coastal communities will therefore become more vulnerable and are predisposed to, much higher risks to adverse sea-state conditions.

4.2 Land elevations and tidal datum-examples from Nauru, Fiji and Kiribati

In the Pacific SIDS considered here, land elevations, with respect to mean sea level (MSL), are relatively low. In Nauru, coastal areas have average elevations between 3-7m, but elevations between 3-5m are typical. Shorefront slopes are typically vertical and rocky. However, extreme high water spring tides (EHWST) for Nauru is an additional 1.03m above MSL, while wave set-up associated with predominantly easterly gusts and rough seas can cause water levels to rise additional 2.3m. In Tarawa, elevations are between 3-7m, but typically 2-3m, especially in the south and west of the atoll.

Shorefront slopes are typically concave and eroded sandy slopes. EHWST is an additional 1.211m above MSL. In Suva peninsula, Fiji, elevations can be between 1.2-3.5m above MSL, with typical vertical seawall slopes and concave natural, eroded soil slopes. High water spring tide (HWST) is an additional 0.64m above MSL. In all of these three areas, coastal land elevations are relatively low with respect to monthly and seasonal EHWST or HWST. In addition, these coastal areas are the sites of concentration of commerce, population and major infrastructure. Under normal EHWST, all these coastal areas are frequently overtopped by waves. Further, under storms, cyclones and other low-pressure systems, overtopping is significant, with considerable overwash. An example is presented below for Nauru, based on numerical analysis.

Calculations of wave run-up on coastal areas, for 10sec, 3.9 m high (1-year return interval) waves, with average easterly wind of 4.34m/sec, during EHWST, can exceed the average elevations (4m) of coastal areas and overwash shorefront facilities, with overtopping greater than 60 litres/sec. Under 10sec, 4.48m (5-year return interval) waves, with easterly winds of 13.37m/sec (maximum wind speeds), overtopping increases to 127 litres/sec; and to 225 litres/sec, under a 5m (25-year return interval) and to over 300 litres/sec, under a 5.34m (50-year return interval) wave. Typical storms affecting Nauru generate 16-20sec, 3.9-5.2m high waves, and are associated with winds of 8-27m/sec. These cause overtopping in excess of 200 litres/sec. If we add the projected Intergovernmental Panel on Climate Change (IPCC) sea-level rise maximum prediction of about 1m (by the year 2100), to the above scenarios, and therefore, submerge Nauru by 1m, then coastal overtopping and inundation, for the four wave regimes above will be 176, 333, 530, 680 litres/sec respectively, an increase by more than 300 % in some cases.

For many Pacific SIDS, typically low-elevation coral atolls like Tarawa, this can mean almost total submergence of land areas and coastal communities. However, we do not know how reef and beach systems will respond to sea-level rise, and if these systems may be able to cope with such changes in water level, and counteract some of the deleterious effects of climate change. To that end numerical analysis and prediction is difficult, and more efforts has to be dedicated to real-time instrumentation and monitoring of beaches and reef systems. In addition, we also need to examine the behaviour of the landmass with respect to tidal levels; especially those affected by tectonic submergence. Kirbati is one of these, that is affected by tilting to the Southwest, measured over the past 18 years and showing a 72mm rise in sea level (Schofield, 1977).

5. Conclusions

Based on the foregoing analysis and discussions, coastal developments have already created many deleterious impacts on nearshore systems, including reefs, lagoons and beach environments. Coastal construction have also exposed island environments to open ocean wave climates and have increased their vulnerability to, and risk from, natural hazards, especially storms and cyclones. At the same time, foreshore developments continue, even within the surf zone, with very little or no consideration for these risks, and the additional component of risk, due to climate change and sea-level rise. This predisposes almost all coastal communities in Pacific Island environments to the deleterious impacts of sea-level rise. Pacific SIDS therefore face very high risk of coastal inundation, waves erosion and damage to communities and infrastructure by normal and storm/cyclone wave climate, if the IPCCC estimates of sea-level rise is realised by 2100. For almost all of these islands, retreat is almost impossible, as land area is small and land is not available. It may be possible to accommodate sea-level rise, if appropriate technology exists for the local environments, and an understanding of the natural systems (reef-lagoon-beach system) is achieved. In addition, any option for protection also requires an understanding of natural systems, via the system or holistic approach to environmental management. To this end, there is an urgent need to study natural systems, and examine the response of nearshore systems to any sea-level changes. This include reef response, beach response and sediment pathways. These would also be beneficial in the development of appropriate coastal protection systems, and in the formulation of policies, for pursuing accommodation options, to reduce any deleterious impacts of sea level rise on coastal communities and development. Adaptation strategies should also focus one those, which include transferable technologies and which are practical (technically and economically) and realistic for Pacific island and atoll/reef communities.

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