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Coastal Protection Measures – Case of Small Island Developing States to Address Sea-level Rise

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

Small Island Developing States are considered as one of most severely affected by climate change and sea-level rise. Some atoll nations would virtually disappear with a sea-level rise of one metre. The objective is to derive a first-cut classification of coastal protection technology for the Small Island Developing States to address sea-level rise. First, an assessment is made of the existing and future adaptation measures to sea-level rise in the latest 35 English-language National Communications submitted by the Small Island Developing States to the UNFCCC. Next, a wide variety of adaptation measures is culled from key coastal engineering manuals and other sources with a focus on more innovative tools and ideas beyond the traditional hard and soft measures. This yielded several possible adaptation tools that could be used by the Small Island Developing States, and with further research, more tools could be applied. In conclusion, a first-cut classification of coastal protection technology is proposed for the Small Island Developing States to address sea-level rise. The resulting table shows eight categories graded from the usual hard and soft measures to new and innovative ideas.

Keywords: Small Island Developing States; coastal protection measures.

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1. INTRODUCTION

Small Island Developing States (SIDS) are considered as one of most severely affected by climate change and sea-level rise (SLR) [1,2,3]. The coral islands and atolls are some of the most threatened coastal systems (Maldives, Marshall Islands, Vanuatu). Guyana with its coastal area about 1.4 m below Mean High Tide (MHT) is extraordinarily vulnerable to SLR and storm surges.

Already the atolls are inundated by extreme spring tides and during storm events (Fiji, Kiribati, Marshall Islands, Palau). Extreme high tides as a preliminary indicator of SLR was first established in Singapore [4]. For the Maldives, the Indian Ocean tsunami of 2004 was a snap-shot of the slow onset of SLR.

In terms of its basics, SLR can be considered as a water level relative to the height of land (vertically, elevation and spatially, topography). What is critical is the height of the land relative to a water level, in which several incremental components that contribute to coastal flooding are spring high tide, storm surge allowance, relative (local) SLR allowance, wave run-up, and overtopping [5]. From the perspective of a barrier against a rising water level, it is the continued reduction of the freeboard that eventually leads to flooding.

Ideally, adaptation to SLR should be considered over time and space. SLR is obviously long term and best viewed as “grow with SLR” compared with other options in the short and medium terms [6]. Spatially, SLR should focus on a more “morphodynamic approach” [7] including island morphology and processes. SLR is not just about water level above elevation but should include morphology or spatial aspects that could be critical for small islands [7]. In particular, local place-based analysis of the coastal biophysical and social ecological systems is of critical importance [8]. Dunes, berms, and offshore bars [9] and natural shore protection structures and biotic protection [10] can be considered. Furthermore, numerous faros and large amount of available fill on islands, such as in the Maldives, are available for new island construction or island raising [11].

Adaptation to SLR encompasses a wide range of measures from assessment of vulnerability, monitoring, planning, policy, capacity building, land-use planning, building codes, communication and information, and actual coastal protection measures on the ground. The Intergovernmental Panel on Climate Change (IPCC) provides three strategies of adaptation - retreat, accommodation, and protection [12]. The three categories of adaptation are considered as planned adaptation to distinguish from autonomous adaptation where natural coastal ecosystems have a capacity to respond autonomously to climate change and can cope with SLR [13]. Ecosystem-based adaptation (EBA) is considered as no-regret or low-regret measures and promoted because of its cost-effectiveness [2].

This paper is concerned with coastal protection measures as defined in two groups of coastal protection technologies: (1) those incorporated within, or required to carry out, the implementation of three main coastal adaptation options – managed retreat, accommodation or protection; (2) technologies which are new, unproven, and which have not yet reach maturity [14]. Such measures have assessed more for the Caribbean and Pacific SIDS than the AIMS (Atlantic, Indian Ocean & South China Sea region) SIDS [15,16,17,18]. Assessment has been made on various options [19, 20] as well as hard and soft measures [21,22] and EBA [23, 24,25,26,27]. For the SIDS coastal protection measures also have implications for their sovereignty extending much further out to sea [28].

The Foresight exercise carried out by UNEP [2] to identify priority emerging environmental issues in the SIDS concluded that coastal protection measures should be based on the specific needs of the SIDS and developed using available resources, including local knowledge and traditional skills and technologies. It also concluded that coastal protection should be improved in the future.

Thus, several pertinent questions need to be asked. What are the existing and future coastal protection measures used by the SIDS? Have the SIDS considered morphology or local topography adequately? Are the SIDS fully aware of the latest measures to address SLR? Is there some framework to check various measures that can be used? This paper consolidates these aspects and help policymakers in considering measures to address SLR. It can be updated with new National Communications and new information on coastal protection measures.

2. METHODOLOGY

The methodology has several stepwise stages to provide answers to the questions raised. First, the National Communications (NCs) submitted by the SIDS to the UNFCCC were assessed for the existing and proposed protection measures addressing SLR. The NCs are prepared according to a common format and are not available for seven Caribbean SIDS (Anguilla, Aruba, British Virgin Islands, Montserrat, Netherlands Antilles, Puerto Rico, US Virgin Islands) and for five Pacific SIDS (American Samoa, French Polynesia, Guam, New Caledonia, Northern Mariana Islands). Excluding three NCs in French (Haiti, Comoros, São Tomé and Príncipe) and two in Spanish (Cuba, Dominican Republic) assessment was carried out on all remaining 35 English language NCs downloaded on 23 January 2017. The assessment was supplemented by other relevant sources on coastal protection measures in the SIDS.

Next, an assessment was carried out on major manuals on coastal protection and adaptation measures for various types and classifications of coastal protection measures. This was supplemented by the coastal technology databases of various agencies and a wide range of coastal protection measures available from various areas. Further inputs came from suitable coastal protection measures reported in the daily *Coastal News Today* [29] from January 2014 to July 2017.

Both assessments include the usual hard and soft measures [9] and the “attack” approach [30] that is similar to the “expand” option [31]. EBA as a nature or nature-based tool was also considered as were new and innovative measures addressing SLR.

The third stage was to establish a systematic first-cut classification of coastal protection technology to address SLR and coastal flooding in the SIDS. This serves as a reference for discussion and selection of strategies and measures and to consider relevant aspects that were previously left out.

Lastly, given the assessments made and the resulting first-cut classification, additional coastal protection measures could be proposed for addressing future SLR. This takes greater consideration of topographic aspects and coastal processes of the SIDS.

3. RESULTS FROM NATIONAL COMMUNICATIONS

Table 1 summarized the existing and future SLR adaptation measures and options of the SIDS. Local topography and coastal ecosystems are important and indicated in sequence: island, cay, atoll, coral reef, lagoon, beach, dune, aeolian ridge, beach ridge, seagrass, mangrove, and coastal vegetation. Coral reefs prevail in nearly all the SIDS and the term includes one or more of the following: barrier, fringing, reef flat, patch, and faros (small atolls inside atolls). Cays and atolls are singled as distinct island types. Cays are small sandy islands on coral reefs. Atolls are distinguished from raised atolls or makatea islands in the Cook Islands.

Three of four SIDS belonging to continents (Belize, Guyana, Suriname, Guinea-Bissau) have specific topographic features; the coastal plan is below MHT and edged by a parallel sand ridge in Guyana, extensive mud flats are in Suriname, and estuaries prevail in Guinea-Bissau. Other less common topographic features with potential to address SLR and coastal flooding include lithified dunes (Bahamas), beachrock (Marshall Islands), beach ridges (Bahamas), sand ridges (Guyana), debris ridges (Jamaica), mud banks (Suriname), and clay ridges (Suriname).

3.1 Adaptation Strategies

Retreat is not possible on many SIDS due to their small size, limited land, and low-lying nature. The removal of total population is a last resort (Papua New Guinea) and for the worst-case SLR scenario in the future (Marshall Islands). Managed retreat is a priority option in Guyana and gradual retreat is a longer-term option in Belize. Grenada opts for future abandonment and relocation where the cost of protection work is excessive.

Accommodation primarily in terms of elevated homes/buildings is traditionally practised in the Cook Islands, Belize, and Guyana. However, for Bahrain protection is the only adaptation option in the long term.

Addressing SLR within a coastal zone management (CZM) framework can be useful. Barbados has a CZMU (CZM Unit) that includes hard and soft engineering measures for beach protection, stability, and enhancement. CZM in Vanuatu is a “ridge to reef” approach to build resilience of coral reefs, mangroves, and

Table 1. Topographic features and existing and proposed adaptation measures of 35 SIDS

SIDS (latest NC)	Significant topographic features (pages)	Existing adaptation measures (pages)	Proposed adaptation measures and options (pages)	Comments on EBA and other aspects
Caribbean (13 SIDS)				
Antigua and Barbuda (2015, 3rd)	Mixed lithology islands, coral reefs, beaches, dunes, seagrasses, mangroves (12, 15, 16)	Coastal defences (18); Reef and mangrove conservation (111)	Flood defences; Raising dike level (97); Projects addressing coastal ecosystems (107)	Existing measures poorly designed; Scope for EBA (coral reefs, mangroves)
Bahamas (2015. 2nd)	Low islands, cays, coral reefs, beaches, lithified aeolian ridges, beach ridges, mangroves, coastal coppice (45, 47, 63, 69)	Mainly seawalls (140)	Seawalls (109); Raised dock height; Beach nourishment (152); Restore sand dunes, beach ridges, mangroves and coral reefs (144, 148)	Scope for EBA (beach ridges)
Barbados (2001, 1st)	Non-volcanic island, coral reefs, beaches, dunes, seagrasses, mangroves (4, 20, 86)	Various engineering and non-engineering measures for beach protection, stabilization and enhancement (91)	Revetments, groins, breakwaters; Beach nourishment (43); Beach improvement, dune restoration (95)	Scope for EBA (dunes); Coastal Zone Management Unit
Belize (2016, 3rd)	Mainland, islands, cays, coral reefs, beaches, seagrasses, mangroves, littoral forests (15, 18, 77)	Hard structures and beach nourishment (79, 80, 118)	Sea and river defence structures; Mangrove restoration (153); Gradual retreat option (79)	Scope for EBA (mangroves)
Dominica (2012, 2nd)	Mountainous and volcanic island, coral reefs, beaches, seagrasses, mangroves (3, 113, 114)	Sea defences, gabion baskets, revetments, boulders (117); Traditional methods (coconut-leaf walls, coconut-fibre stone units) (122)	Wide range of hard and soft structures; Retreat, accommodation or protection options (122-124)	Scope for EBA (traditional methods)
Grenada (2000, 1st)	Mountainous volcanic islands, cays, coral reefs, beaches, seagrasses, mangroves (1-4)	Seawalls (63)	Seawalls; Mangrove replanting (63, 64); No-regret measures (58); Abandonment and relocation options where protection cost is high (63)	Scope for EBA (no-regret measures)
Guyana (2012, 2nd)	Mainland, coastal plain below MHT, parallel sand ridges, beaches, mangroves (47)	Network of concrete coastal structures, earth embankments, canals and sluices (48, 285); Riprap structures and gabion baskets (285)	Dikes, levees, floodwalls (207); Mangrove restoration (286); Raising homes (284); Retreat as option (299)	Scope for EBA (sand ridges)
Jamaica (2011, 2nd)	Mountainous island, limestone cliffs, debris ridge, coral reefs, beaches, mangroves (42, 347-351, 360)	Groins (354); Debris ridge (371)	Revetments, groins (392); Beach nourishment and offshore sand supply (372); Mangrove regeneration (392); Relocation, elevation and protection as options (370)	Scope for EBA (mangroves)

SIDS (latest NC)	Significant topographic features (pages)	Existing adaptation measures (pages)	Proposed adaptation measures and options (pages)	Comments on EBA and other aspects
St Kitts & Nevis (2015, 2nd)	Volcanic islands, cliffs, coral reefs, beaches, salt ponds, freshwater lagoons, seagrasses, mangroves (1, 2, 4)	Seawalls, revetments, groins, breakwaters (58)	Coastal protection structures (58); Elevated buildings (66); Habitat restoration (62); No-regret measures (57)	Scope for EBA (no-regret measures); Elevated homes
St Lucia (2011, 2nd)	Volcanic island, coral reefs, seagrasses, mangroves, freshwater swamps (29, 45, 46)	Beach replenishment (137)	Sea defences; Natural defences (mangroves, corals); Abandon and retreat options (149)	Scope for EBA (mangroves, coral reefs)
St Vincent & Grenadines (2015, 2nd)	Volcanic islands, cays, coral reefs, beaches, dunes, mangroves (36, 37, 175, 176)	Seawalls (190)	Seawalls (190); Natural defences (175, 176)	Scope for EBA (dunes)
Suriname (2016, 2nd)	Mainland, mud flats, sandy shell beaches, salt to brackish lagoons, mangroves, low swamp forests (26, 27, 36)	Polders: dikes, canals, ditches, sluices and pumps (116); clay dams (119)	Dikes and dams; Engineering measures to increase sedimentation and support mangrove growth (148); Mangrove restoration; Mud bank nourishment (149, 159)	Scope for EBA (mud banks or ridges)
Trinidad & Tobago (2013, 2nd)	Mountainous islands, coral reefs, beaches, mangroves (6, 80, 89)	Seawalls, breakwaters (84)	Protection of coastal ecosystems (89)	Scope for EBA (coral reefs, mangroves)
Pacific (15 SIDS)				
Cook Is (2011, 2nd)	High volcanic islands, atolls, raised atolls, cays, coral reefs, beach forests (21, 25)	Seawalls; Coastal Protection Energy Dissipater (COPED) (45); Raised houses (84)	Coastal protection measures; Coral replanting (46); No-regret resilience (89)	Scope for EBA (coral reefs, no-regret measures); COPED
Fiji (2014, 2nd)	Volcanic islands, atolls, coral reefs, beaches, seagrasses, mangroves (2, 67)	Coastal structures (59)	Seawalls; Beach nourishment (92); Replanting/ restoration of coastal vegetation (68)	Scope for EBA (coastal vegetation)
Kiribati (2013, 2nd)	Limestone island, atolls, coral reefs, seagrasses, mangroves (30, 36)	Mangrove rehabilitation (87)	Seawalls; Mangrove replanting (171, 172)	Scope for EBA (mangroves)
Marshall Is (2015, 2nd)	Atolls, raised coral islands, coral reefs, beaches, beachrock, mangroves (25, 35, 82, 83)	Protective structures (77); Beachrock (temporary) (82)	Shoreline defences; Elevating structures (121); Retreat option for worst case scenario (77)	Elevated homes
Micronesia (2015, 2nd)	Volcanic high islands, atolls, coral reefs, mangroves, strand forests (5, 6)	Seawalls (79); Coral rubble banks (78)	Seawalls, groins (70); Re-vegetate strand forests, mangroves (63); Raised buildings (76)	Scope for EBA (rubble banks); Elevated homes

SIDS (latest NC)	Significant topographic features (pages)	Existing adaptation measures (pages)	Proposed adaptation measures and options (pages)	Comments on EBA and other aspects
Nauru (2014, 2nd)	Raised coral island, coral reefs, mangroves (27, 32)	Protection structures (102)	Hard structures; Replanting coastal vegetation (103)	Scope for EBA (coastal vegetation)
Niue (2014, 2nd)	Raised atoll, cliffs, coral reefs, littoral forests (12, 20, 29)	Wharf (56)	Strengthen structures; Protected reefs and nearshore areas; ICZM (78)	Scope for EBA (coral reefs)
Palau (2002, 1st)	Volcanic and limestone islands, atolls, coral reefs, beaches, seagrasses, mangroves (2, 7, 45)	Seawalls; Revegetation (67)	Seawalls; Restoration of coastal ecosystems (67); No -regret measures (65)	Scope for EBA (no-regret measures)
Papua New Guinea (2014, 2nd)	Part of volcanic large island and small islands, atolls, coral reefs, lagoons, mangroves, swamp forests (2, 13, 14)	Seawalls; Planting mangroves (69)	Wide range of structural measures and non-structural (beach nourishment, planting mangroves, reef rehabilitation) measures; Elevated buildings (67- 69)	Scope for EBA (mangroves, coral reefs); Elevated homes
Samoa (2010, 2nd)	Volcanic high islands, coral reefs, mangroves (17,21, 53)	Cement and rock walls (47); Mangrove rehabilitation (60)	Hard and soft measures including mangroves (61)	Scope for EBA (mangroves)
Solomon Is (2004, 2nd)	Volcanic islands, atolls, corals reefs, mangroves (2, 27)	Seawalls; Re-vegetation (30)	Seawalls; Re-vegetation (30); No-regret measures (29)	Scope for EBA (no-regret measures)
Timor-Leste (2014, 1st)	Mountainous islands, cliffs, coral reefs, lagoons, beaches, seagrasses, mangroves (5)	NA	Mangrove protection and rehabilitation (91); CZM (129)	Scope for EBA (mangroves)
Tonga (2012, 2nd)	Volcanic and coral islands, coral reefs, beaches, mangroves (6, 17, 115)	Seawalls, revetments (113, 115)	Coastal reforestation and afforestation (120)	Scope for EBA (mangroves)
Tuvalu (1999, 1st)	Raised limestone islands, atolls, coral reefs (2, 17)	NA	Restoration of coastal ecosystems (23-24)	Shift to EBA (coastal ecosystems) rather than hard structures
Vanuatu (2014, 2nd)	Volcanic islands, cays coral reefs, seagrasses, mangroves (22, 26, 66)	NA	Coastal defences (125); Mangrove rehabilitation (77); EBA (79, 132)	Scope for EBA (mangroves)
AIMS (Atlantic, Indian Ocean & South China Sea region) (7 SIDS)				
Bahrain (2012, 2nd)	Islands, coral reefs, seagrasses, mangroves (2, 9)	Hard structures, land reclamation (27)	Hard structures (28); Rehabilitate mangroves (29); Artificial reefs (46); Protection as only option over retreat and accommodation (27)	Scope for EBA (mangroves, artificial reefs)
Cape Verde (2010, 2nd)	Volcanic islands, coral reefs, beaches (2, 11, 12)	Coastal structures (28)	Hard and soft measures; Artificial reefs (137)	Scope for EBA (artificial reefs)

SIDS (latest NC)	Significant topographic features (pages)	Existing adaptation measures (pages)	Proposed adaptation measures and options (pages)	Comments on EBA and other aspects
Guinea-Bissau (2011, 2nd)	Mainland, islands, estuaries, mangroves (14, 17)	Dikes (bunds) (50)	Mangrove protection (72)	Scope for EBA (mangroves)
Maldives (2016, 2nd)	Atolls, coral reefs, beaches, seagrasses mangroves (14, 19)	Seawalls, groins breakwaters; Land reclamation; Beach nourishment; Coastal vegetation; Raised ridges (93-94); Artificial reefs (97)	Hard structures; Soft structures; Options identified in 2015 coastal protection guideline: hold the line, move seaward, manage realignment, limited intervention, do nothing (91-94)	Scope for EBA (raised ridges, artificial reefs); Land elevation
Mauritius (2016, 3rd)	Islands, atolls, coral reefs, beaches, dunes, seagrasses, mangroves (1, 42, 51, 60)	Groins, breakwaters, armouring (43-44); Beach nourishment; Dune replenishment; Artificial reefs (45)	Beach nourishment; Dune replenishment (183); Mangrove planting; Artificial reefs (68); Elevated road (57); EBA (103)	Scope for EBA (artificial reefs)
Seychelles (2011, 2nd)	Granite and coral islands, atolls, coral reefs, beaches, dunes, mangroves, coastal vegetation (69, 199, 207, 209, 288)	Seawalls, breakwaters, groins; Dune and/or berm restoration; Planting (209-211)	Hard and soft measures; Raised buildings (212, 215)	Scope for EBA (hybrid); Elevated homes
Singapore (2014, 3rd)	Islands, coral reefs, mangroves (12, 32)	Raised reclaimed land level (30)	Long-term protection strategies (under study) (30)	Scope for EBA (mangroves)

Source: compiled from 35 NCs downloaded on 23 January 2017 from http://unfccc.int/national_reports/non-annex_i_natcom/submitted_natcom/items/653.php),
NA = not available

seagrasses to climate change. Adaptation is addressed through CZM in Timor-Leste. Ecosystem protection/restoration at the local level is addressed through a similar framework in Trinidad and Tobago. Coastal management is in a number of agencies in Antigua and Barbuda.

3.2 Hard and Soft Measures

Hard measures are most evident in the polders of Guyana and Suriname. With the constraints of high costs, seawalls are thus limited to protection of key locations (Belize, Micronesia, Solomon Islands), impractical on a large scale (Palau, Solomon Islands), and used only in critical situations (Grenada). Guyana planned to use HESCO barriers (commercially produced earth-filled barriers for erosion and flood control) to replace traditional gabion baskets but costs are high. Better-designed coastal protection units – Coastal Protection Energy Dissipator (COPED) – are deployed at the airport at Rarotonga, Cook Islands.

Land reclamation is generally practised as means to increase land area (Maldives). In Bahrain government policy has encouraged land reclamation. However, there is also the danger of being locked into an unhealthy "adaptation path" in hard measures, for example, in the Maldives, where the high cost of hard measures has led to greater interest towards a ''soft path", especially EBA [11].

Of the soft measures, beach nourishment is the most common, followed by dune and berm restoration. It has grown in popularity as a solution for alleviating coastal erosion and helping beach stabilization in Barbados [32]. Beach nourishment dominates St Lucia but its costs can be high in Belize. Palmetto trunks are used on beaches to dissipate wave energy and retain sand in Belize. Walls of low sunken logs protect the beach at Praslin, Seychelles. Jamaica has proposed to identify offshore sand deposits for beach nourishment.

Coastal dunes are a natural coastal defence in St Vincent and Grenadines. In St Kitts dunes function as reservoirs of sand, available for supply to the beach during storms [33]. Dune and berm restoration is carried out at a number of beaches in Seychelles.

3.3 Ecosystem-based Adaptation

More than 30 SIDS cite EBA measures for future use. The most common EBA is mangrove and coral reef restoration with artificial reefs in the Maldives and Mauritius.

Mangroves are natural defences against the sea (Guyana) and from storms (Antigua and Barbuda), and act as buffer zones, sediment traps (Antigua and Barbuda), and as a filter (Palau). They also keep up with SLR [34].

On-going projects on protecting, rehabilitating, and planting mangroves have been reported by a number of SIDS: protecting mangroves in Suriname, mangrove rehabilitation in Guyana, mangrove planting on Moch Island, Micronesia, and on islands and in northeast of Papua New Guinea, and mangrove replanting in Kiribati. The mud banks in Suriname have a significant protection role in relation to the mangroves. They provide primary protection on which mangroves take over [35].

Coral farming and transplantation is encouraged in Mauritius. Coral nurseries have been implemented in Belize. Other proposed measures included restoring beach vegetation [36].

Besides mangroves, coral reefs and dunes, EBA also includes other specific ecosystem and topographic features. EBA is part of autonomous adaptation or no-regret measures considered as most beneficial (Solomon Islands, Cook Islands, Grenada, Palau). No-regret resilience is advocated for the Cook Islands and it can be effective within a CZM framework (St Kitts and Nevis).

3.4 Traditional and Other Technologies

Traditional construction methods have been in use across the Pacific as a means of reducing vulnerability to tropical cyclones and floods in rural areas. In the Solomon Islands traditional practices include elevating concrete floors on Ontong Java and building low, aerodynamic houses with sago palm leaves as roofing material on Tikopia [1]. Traditional technologies such as coconut-leaf walls and coconut-fibre stone units are used in Dominica.

Traditional raised buildings exist in Belize and Guyana and the Cook Islands. Buildings are built at least 2.6 m above MSL in Fiji to prevent damage from storm surge and some resorts are already built on the reefs (over-water bungalows) in the Maldives and Fiji [37]. The floor level of houses has been proposed for raising in Micronesia, St Kitts and Nevis, and Seychelles.

4. RESULTS FROM GENERAL ASSESSMENT OF COASTAL PROTECTION MEASURES

In general many of the recent developments in coastal management and engineering have originated in the United Kingdom and other European coastal states and in North America [32]. Examples of common hard and soft measures are listed in boxes of a guide issued by the European Commission [38]. In the USA the measures are classified as coastal armouring structures, beach stabilization structures, non-structural alternatives, and combinations and new technologies [39]. Thirteen adaptation technologies for responding to coastal erosion and flooding are grouped under protect, accommodate, and retreat approaches [5]. In general, trends in coastal protection have increasing incorporated nature and shifting toward soft but novel, eco-friendly methods [40]. A guidance on EBA measures is provided by Travers et al. [41].

With the shift from hard structures and towards soft and natural structures, there is a change in terminology and classification. The most evident is in the USA where the terms *natural, nature-based, nonstructural*, and *structural* describe the full array of coastal protection measures employed by the US Army Corps of Engineers (USACE) [42, 43]. The latest is the recognition by the USACE and National Oceanographic and Atmospheric Administration (NOAA) of the value of the hybrid engineering approach that integrates soft or "green" natural and nature-based measures, with hard or "grey" structural ones giving rise to SAGE, or a Systems Approach to Geomorphic Engineering ranging from green to grey techniques [44]. This is currently in practice or considered for climate change adaptation in the coastal areas of the USA [45].

The adaptation technology database of the Asia Pacific Adaptation Network [46] provides a wide range of hard, soft, and hybrid measures under various categories. Soft and natural and nature-based measures transcend the classification used in Australia [47] that has a separate category on emerging technology and novel approaches. Coastal EBA has become increasingly important and of ten coastal EBA options identified by UNEP, nine can address SLR [23].

With increasing use of natural defences, the coastal protection measures are categorized as built, natural, and hybrid (combination of built and natural) [48]. The importance of mangroves, coral reefs, and other coastal ecosystems has led to the use of two other terms: "green infrastructure" [49] and "coastal green infrastructure" [50] referring to such ecosystems. In particular, hybrid approaches are of increasing attention, e.g. living shorelines. The protection of estuaries, which include mud flats and mangroves and low-energy coasts comes under further attention by Restore America's Estuaries [51]. A handbook by the Construction Industry Research and Information Association covers the protection of levees [52]. A much wider term "nature-based solutions" (NbS) is now in use for natural and hybrid measures [53].

In the USA the continuum of options from grey to green became more popular after Hurricane Sandy in 2012 [45]. The "Rebuild by design" produces six innovative coastal infrastructure projects each with a significant hybrid infrastructure component [50]. Elsewhere, the "Building with nature" focuses on an innovative approach using very large nourishment – the "Delfland sand engine" at South Holland, Netherlands [54, 55]. Other ideas include "Living with water" [56], "Give back land to the sea", and "Floating or sea-encircled artificial dwelling mounds" [57].

There are three or four approaches towards SLR – avoid, retreat, accommodate, and protect – depending on whether the first two are considered under the heading "retreat". Structures are implemented under the "protect" and "accommodate" approaches [58]. A spectrum of possible categories for coastal protection is suggested by Tam [59]. Excluding managed retreat, at least six strategies can be identified for the hard, soft, and hybrid measures for managing SLR: barriers, coastal armouring, elevated development, floating development, floodable development, and living shorelines.

5. FIRST-CUT CLASSIFICATION OF COASTAL PROTECTION TECHNOLOGY

The assessments on the present and future adaptation tools used by the SIDS and other sources including databases and manuals on coastal engineering/adaptation measures give rise to several basic and sequential points. These are essential in developing a first-cut classification of adaptation technology to SLR for the SIDS.

First, consider the situation before SLR in which a variety of hard and soft measures has been in use for coastal protection and flooding. Second, with SLR it is more than just coastal protection as there is a need or ability to keep up with a rising sea level and its consequences. This point has somewhat been overlooked in discussion of many coastal measures addressing SLR; hard and soft structures can protect the coast from coastal erosion and coastal flooding but may not address SLR.

Third, there is an increasing trend of hybrid measures in which nature integrates with hard and soft structures for coastal protection. It is fine to develop, encourage or improve the biodiversity at the toes or slopes of the hard structures but this does not keep up with a rising sea level. Hybrid measures need to increase their general elevation and to offer coastal protection. The level of the habitat must keep up with SLR besides providing protection to the coast. For example, sedimentation in mangroves and upward growth of corals must be sufficient. Regardless of which coastal ecosystem is used in EBA the basic considerations addressing SLR are a general rise in elevation and a luxuriant growth to lessen the impact of wave energy.

Fourth, several separate measures have been designed to imitate nature or natural processes in order to protect the coasts and to address SLR. The best examples are from the Netherlands – the “Sand engine”, “Building with water”, and “Living with water” [54].

Fifth, since time immemorial, floating is one way to survive on water. Traditional settlements on stilts or floating settlements have been in use before SLR, e.g. along the coasts in Southeast Asia or in the seasonal Tonle Sap, Cambodia. Floating and amphibious structures are in use in developed countries, e.g. Maasbommel, Netherlands.

Sixth, although an obvious factor in relation to water or flood level, topography is not given sufficient weightage for adaptation to SLR compared to hard and soft measures and EBA. Elevated points or local features along the coasts can be used effectively. Reclaimed land is probably the most common measure to elevate above the water level and a measure to adapt to SLR, but it is expensive.

The above comments will be considered in constructing the first-cut classification of coastal protection technology for the SIDS (Table 2). The table is not meant to be comprehensive but to provide an improved perspective for measures addressing SLR and coastal flooding by further considering local conditions of elevation and configuration. It is meant to provide a basis and additional information on available and new methods, materials, technologies, and innovative ideas. It has eight categories graded from the usual hard and soft measures to new and innovative ideas.

Several available technologies for the SIDS can be identified and examples are given for each category. For Guyana and Suriname there is scope for “Dutch-type” measures (“Living with water”) as the coastal plain in Guyana is 1.4 m below MSL and both countries have polders. A recommendation has been made to develop a pilot “Living with water” in Guyana [35]. The COPED units have been used in the Cook Islands and it would not be difficult to add a biodiversity component to become a “Living shoreline” that could be applied to other SIDS. Guinea-Bissau has suitable low-energy estuaries for “Living shorelines”. Jamaica could explore its offshore sand supply to consider a smaller version of the Dutch-type “Sand engine”. More practical options exist for elevated homes in the SIDS considering the overwater resort in the Maldives and residences on the Cook Islands, Belize and Guyana. More recently the Maldivian environmentalist group Bluepeace has suggested constructing three metre-high islands throughout the atolls [11].

Floating and amphibious infrastructures offer a promising solution to address SLR. Amphibious infrastructures stay dry under normal times and float when necessary as distinguished from floating infrastructures. Floating infrastructures in existence include floating houses and apartments (mainly in the Netherlands) and a floating solar power plant (Japan); others to be implemented include a floating school (Nigeria), floating wind mills (Japan), and floating low-income housing (Bangladesh) [60]. Floating, or sea-encircled artificial dwelling-mounds are suggested as a long-term strategy for safe buildings in the lowest parts of the Netherlands and Flanders [57]. The French government and

Table 2. First-cut classification of coastal protection technology for the SIDS

Protection technology	Assessment for SIDS
A. Hard structures Seawalls & revetments Dikes Breakwaters & groins	Costly; deployed for critical structures; for 'no retreat' options; affordable by richer SIDS
B. Soft structures Beach nourishment Sand bags	Short-term; for selective deployment, e.g. tourist coasts
C. Hybrid structures Living shorelines	Scope for SIDS but generally restricted to lower-energy coasts; research required for deployment to higher-energy coasts
D. EBA Mangroves Coral reefs Dunes	Currently best and wide scope for SIDS; can be combined with hybrid structures; further research required
E. Topography/elevation Reclamation Save some islands	Costly; but can be more permanent than "A" category technology
F. Float Stilt/elevated homes Floating/amphibious homes Floating islands	Should be considered more seriously given new materials and technologies
G. Imitate nature Building with nature Living with water	Research required for deployment in SIDS
H. New and innovative ideas	To be updated regularly given new materials and technology in future

the Seasteading Institute have agreed on a pilot floating city project in French Polynesia [61].

6. CONCLUSION

Based on an analysis of their latest NCs to the UNFCCC the SIDS use three major categories of conventional coastal measures to address coastal flooding and SLR – hard measures, soft measures and EBA. An analysis of manuals and databases of coastal protection measures provides further insights to measures beyond hard and soft measures and EBA. The combination of both assessments resulted in a first-cut classification of coastal protection measures in eight categories with an assessment given for each category for the SIDS.

This first-cut classification provides an improved perspective of measures addressing SLR and coastal flooding by further considering local conditions of elevation and configuration in the SIDS. It provides a more balanced dimension to low-lying areas or areas liable to flooding by considering new measures and the wide scope for floating and amphibious structures. It can be further modified to accommodate future innovative measures, materials, technology and ideas. The classification also has implications for applications in other coastal zones facing SLR and coastal flooding. In the face of climate change and SLR the table can be modified and incorporated into Integrated Coastal Management, Climate Change Adaptation and Disaster Risk Reduction programmes at various scales.

COMPETING INTERESTS

The author has declared that no competing interests exist.

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