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RESEARCH ARTICLE

Transitioning from "*Grey to Green*": Nature-Based Solution Seawall for Coastal Protection

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ABSTRACT

The Pacific Island countries are now facing a new threat to their survival due to Climate change. Small low-lying atoll countries, as well as the coastal populations of the small island countries, are constantly threatened by climate change. With the rise of the sea level, coastlines are eroding, and villages, houses, burial grounds, arable land, and other infrastructures are gradually being washed away. The only option for sites well below sea level is to relocate the entire population to higher ground. This option is very costly and not in the best interest of the communities, given that relocation not only means moving houses and people but also breaking away from the ancestral grounds and their heritage. Construction of brick and steel seawalls is a costly option, given the number and length of walls that need to be constructed. This paper provides an alternative model, a transition from these grey structures to green nature-based seawalls that are cheap, environmentally, ecologically sound, and culturally responsible. The seawall design, required materials, methodology of construction, and engineering aspects are presented in this paper. This is the first nature-based seawall in the world—an example of using nature to deal with a problem caused by nature itself.

Keywords: Climate change, Coastal erosion, Nature-Based solution, Seawall.

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1. Introduction

The Pacific Island region is seen as one of the world's most vulnerable regions concerning climate change. The region, home to approximately 10 million people, is subjected to numerous challenges arising from climate change. Sea-level rise, acute weather events, changing precipitation patterns, warmer temperatures, coastal erosion, and saltwater intrusion are some of the common problems climate change contributes, thus making the Pacific one of the worst-affected regions in the world. Noting the above, climate change also negatively affects the region's stock of natural capital, thus compromising intergeneration equity. Costanza and Daly [1] note that every country must have a minimum stock of natural capital for sustainable development, steady growth, and prosperity. Given the current reasonable state of welfare, the current stock can be taken as the minimum required for sustainable development and prosperity for the Pacific region. However, as argued by Costanza and Daly [1], using the "constancy of total natural capital" rule, external shocks such as Climate Change pose a severe threat to a country's minimum stock of natural capital. People in the Pacific experience extensive coastal erosion events, not just to their beaches but to their village/village lawns, burial grounds, and agricultural land. This has displaced some communities from the traditional living spaces (villages) they have occupied by their forefathers. Climate change and biodiversity loss are drastically pressuring populations into migration (dislocation) both transboundary and internally, putting pressure on urban spaces. These vulnerable coastal populations have lived around the coastal area for generations, some by choice, while others live in low-lying small atoll countries without any options. Any relocation will require adaptation to a new physical climate, access to new resources, change in life, and sourcing new livelihood opportunities. The World Bank [2] notes similar sentiments that climate change will push coastal households out of their ancestral places, thus resulting in the loss of their culture and family identity. The report notes that half the population in the Pacific live within 10 km of the coast, thus vulnerable to sea level rise, saltwater intrusion, and coastal erosion. If mitigation measures are not undertaken, many coastal households must leave their homes over the next three decades.

While the leaders of these vulnerable countries have been at the forefront of Climate Conferences arguing for increasing amounts of Climate Change mitigation funds, efforts should also be made to examine cheaper, resilient, and environment-friendly solutions to deal with problems arising from the changes to nature. In general, Nature-based solutions provide solutions to societal challenges that involve working with nature, and they can provide a holistic approach to not only mitigate against climate change damages but also deal with biodiversity losses, thus supporting sustainable development [3]–[5]. The country's long-term economic competitiveness and security depend on how natural resources are used sustainably [6]. While many reviews and technical reports have been prepared (see [7]), only a few actual on-the-ground NbS models have been implemented and shared. Thus, this paper will provide a detailed description of the Nature Based Solution (NBS) project implemented in Fiji to protect its coastal communities, save millions of dollars of government funding, resurrect the coastal environment, hence, food security for the coastal community and at the same time avoid mass relocation of the coastal community thus preserving the lifestyle, culture and geographical bonding.

The first section of the paper discusses the climate change challenges faced by Fiji. The second section provides an overview of Fiji's coastal erosion challenges. The third section details the NBS solution for coastal protection, provides examples of some of the implemented projects, and concludes with remarks. The fourth section provides details of the actual NbS Seawall, while the last section provides a summary and conclusion.

2. Climate Change: the Case of Fiji

Fiji, with a population of 870,000, is considered one of the most developed countries in the Pacific region; however, Climate Change is threatening to increase the vulnerability of both human and ecological systems in Fiji and could ultimately make Fiji an example of climate disaster in the region if mitigation projects are not implemented urgently. As an island nation with a limited landmass, consisting of 332 islands, about one-third of which are inhabited, comprising a total land area of 18,333 km^2, surrounded by a vast area of ocean, marine Exclusive Economic Zone (EEZ) of 1.6 M km^2, that ultimately defines her right to survive, is now fast becoming its most significant threat.

With reasonable arable land settlements, villages, cities, towns, critical infrastructure, and the tourism sector alongside the coastline, climate change is the most critical threat to the Fijian economy. The tourism sector, the largest foreign income earner, is highly vulnerable and dependent on the sea, coral ecosystems, and marine biodiversity. Climate change is also affecting inland resources, in particular, the waterways. Fiji has abundant freshwater resources, rivers, creeks, lakes, and other water bodies, thus contributing to a unique inland bio-diversity. The country's entire agriculture sector depends on these waterways and water bodies for its water needs. In interior communities, water consumption requirements depend on these water bodies.

Water from these waterways is also captured in dams and pumped to reservoirs, which are then distributed to settlements, peri-urban and urban dwellers, and the commercial and industrial sectors for their use.

However, due to climate change, these waterways are now affected in numerous ways. Flooding, siltation, washing in of debris, and logging by-products are ways the overall capacity is gradually reduced. Further, with reduced capacity and high intensity and frequency of rainfall, flooding has now become a regular feature of contemporary Fiji, occurring throughout various parts of the country, where some larger towns and economically and strategically essential towns (Nadi, Ba, Nausori, and Labasa) have now been classified as a highly flood-prone area. These floods contribute to property loss and damage to public infrastructure such as roads, jetties, and buildings, thus significantly disrupting economic activity and absorber of government resources.

The advent of climate change is also not sparing the biodiversity. Fiji and the Pacific Island countries are known for their flora and fauna, which are their unique and strategic natural environment features. In response to this, Fiji has several strategic documents and policy papers to guide its climate mitigation works, which include (i) The Strategic Action Programme for the Pacific International Waters, (ii) The Regional Action Plan on Sustainable Water Resource Management, (iii) Convention on Biological Diversity; (iv) The Ramsar Convention on Wetlands; (v) The Cartagena Convention and Protocols; (vi) The United Nations Convention to Combat Desertification (UNCCD); (vii) Fiji's 5-Year and 20-Year National Development Plan; (viii) National Green Growth Framework for Fiji; (ix) Fiji's National Adaptation Plan Framework; and, (x) Fiji's National Climate Change Policy (2012). However, the actual implementation of these plans and frameworks has been slowed due to external shocks such as the COVID-19 pandemic and lack of financial resources.

3. Coastal Erosion: the Billion Dollar Challenge

For several reasons, Fiji and other Pacific Island countries have a large proportion of their population living along the coastline and are highly susceptible to climate change. Firstly, some countries, known as atoll countries, are very low. Waves from king tide can pass across the island from one end to the other. Secondly, the coast population tends to live right on the edge of the waterways primarily for sustenance. The sea is the prime source of food, and the sea is also used as a means of transportation to travel from one village to another or from one part of the island to another. Their dwellings, burial grounds, and arable land are alongside the coastline. So, sea level rise and tidal waves will wash off the villages and burial grounds, thus pushing the community out of their ancestral homes for good. Thirdly, saltwater intrusion will render the coastal agricultural land unsuitable for crop agriculture, thus further exacerbating the food security of these coastal populations.

The Australian Bureau of Meteorology and CSIRO [8] notes that the sea level around Fiji has risen by a record 6 mm since 1993, which is higher than the global average.

Given the discourse at the global level, controlling the factors contributing to global warming and, thus, sea level rise will take a long time; thus, further sea level rise is inevitable.

Despite this concrete scientific evidence of rising sea levels, coastal communities are reluctant to move out of these vulnerable areas. They argue that their ancestors constructed their houses alongside the coast and sourced their livelihood from the sea and coastal environment. Their tradition, culture, and lifestyle were intertwined with the seaside and ocean resources. The very source of their existence is now threatening their survival. There are villages whose burial grounds have been washed away, lawns have been washed away, and arable land and dwellings have been washed away. The government started constructing concrete seawalls, and each 100 m would cost around US$250,000. The capacity to finance these Seawall constructions falls far less than the demand. As of 2022, there have been requests to construct 108 seawalls that would protect 142 villages with a total length of 38.2 km.

The ballpark estimate for constructing concrete seawalls would be around US$95.5 M. Given competing demands from other sectors, allocating this financial resource would weaken the government. The Ministry of Waterways 2019 designed and constructed a Nature-Based Solution seawall, transitioning from "*grey to green*"–from traditional concrete masonry to nature-based, boulder-type seawalls for coastal protection. Not only does this Nature-Based Solution seawall reduce the financial burden on the government, but it is eco-friendly and also contributes to the restoration and expansion of natural biodiversity stock. Furthermore, it protects the community, their property, and their social and cultural heritage by avoiding mass relocation. The Ministry noted that the sustainable solution to a problem caused by nature lies in nature itself. If implemented appropriately, such solutions will save millions of dollars of government finances, rehabilitate the coastal environment, establish an ecosystem, and bring new hope to the communities for their continued living. So, while the Ministry will solve a problem arising out of nature by using nature, they will also enhance, build resilience, and expand the stock of natural resources.

4. Nature-Based Seawall: Description, Design, and Process

An integrated approach has been implemented in Fiji to combat the impacts of Climate Change. As a small island nation, Fiji has faced challenges over the years to keep its coastal communities safe from the drastic effects of Climate Change. One such approach is the "Nature-Based Solution-NbS" seawall for coastal protection works in vulnerable areas. The NbS seawall consists of four lines of defense, the first being rows of mangroves, the second being boulder protection, the third being a wall constructed of clay or rotten rocks, and the fourth being rows of vetiver grass.

4.1. Mangrove: First Line of Defense

The first line of defense is the tidal forest known as the mangrove forest (*Rhizophora mangle*). *Mangroves* are naturally occurring plants that serve as protectors of offshore regions. It provides much balance in the ecosystem in the coastal region. It acts as the wave breaker that directly protects the coastline, a natural habitat for marine organisms, and a source of livelihood for communities. Depending on the wave actions, it is planted at different distances and angles from site to site. Mangroves also have robust root systems that allow them to remain standing and absorb some energy and power in storm surges and floods. Their roots also provide habitats for mud crabs, fish, and other marine animals, supporting livelihoods and food security in nearby communities. The trees also sequester carbon.

Mangroves provide a friendly ecosystem for marine organisms and human beings. It becomes the natural habitat and source of food for aquatic organisms. Over the years, humans have utilized mangroves for medicines, fuel, food, and many other benefits. While planting mangroves, the potting holes should be at least 10 cm to 15 cm deep, spacing between the slips should be approximately 2 m, and rows are also 2 m apart. Each row starts in the middle of columns 1 and 2 of the previous row (see Fig. 1). However, planting distance and angle differ from site to site based on the wave action.

4.2. Stone Boulders: Second Line of Defense

Between the mangrove and soil wall, rock/stone boulders are placed. The rocks and stones act as a barrier, helping prevent erosion from water. The anchor boulder and the wave breaker strengthen the seawall and reduce the impact of wave actions. The material for boulder fill shall be rugged, durable, angular quarried stones of 800 mm to 1200 mm diameter in sizes for toe protection and revetment and 500 mm to 750 mm diameter in size for stone masonry and placed by the methods described in the specifications and drawings for the seawall. The most commonly used rocks are igneous and coral polyps. Igneous rocks are readily available at most of the places in Fiji. However, coral rocks are only available in some regions. Different stones have different binding properties, and as for coral rocks, they stick to each other and form a solid, sticky bond on each other over the period. Boulder protection creates a natural ecosystem that shelters marine organisms and provides a breeding place. The specific weight for 500 mm to 750 mm is an average of 550 kg, while 800 mm to 1200 mm is 900 kg.

The advantage of using boulder protection seawalls is that they do not require mesh to keep rocks in place. This gives them a more natural and appealing look that blends much better into the environment, unlike the gabion and lacing wire boxes. They are a cheaper solution to deflecting wave energy. Before the boulders are placed, a spread of geotextile fabric cloth is placed between the boulder and the soil wall to hold them in place so a storm surge or flood cannot break them apart.

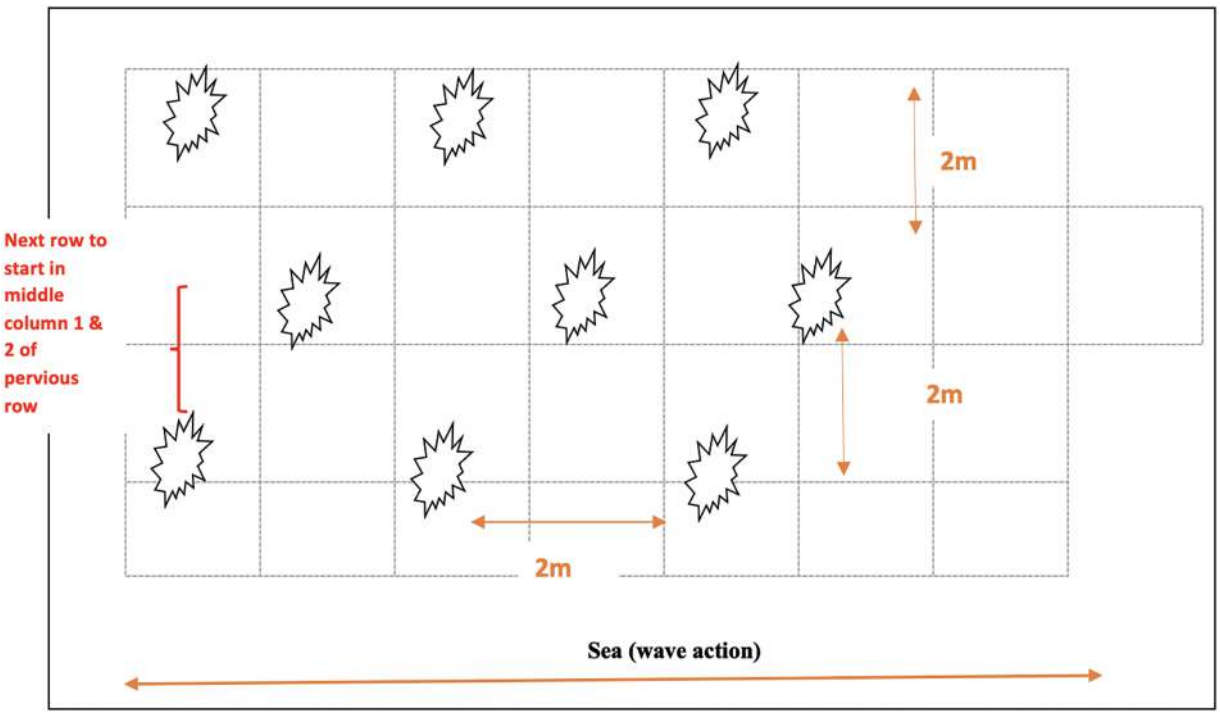

Fig. 1. Mangrove planting guidelines.

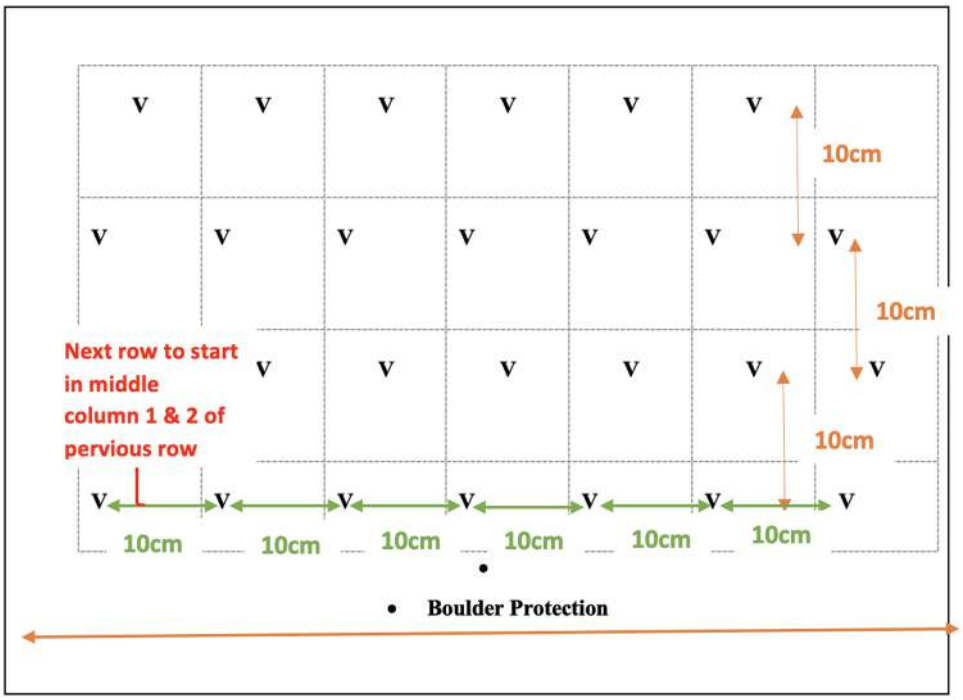

Fig. 2. Vetiver grass planting guidelines.

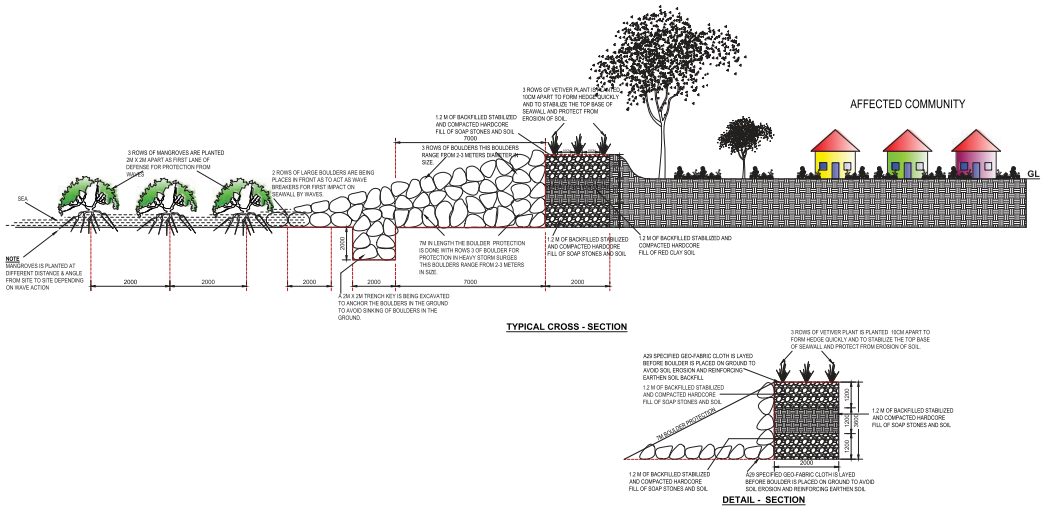

Fig. 3. NBS seawall structural design.

Fig. 4. Nabubu village NbS seawall.

Fig. 5. Vaidogo village NbS seawall.

Fig. 6. Nabukadra village NbS seawall.

4.3. Soil Wall: Third Line of Defense

The soil wall is established using either clay soil or rotten rocks. The wall is at least 2 m high above the king tide level and sourced from near the targeted community. As the soil is dumped, a truck is continuously driven on it to make it compact, and more soil is poured and compacted, continuing until the required height is reached. The imported backfill material used should be classified for different layers. The base of the backfill should be molten rock (rotten rocks), which needs to be compacted; the mid layer should be soapstone, and the top layer for easy binding should be clay soil. The mentioned backfill materials have different physical and chemical properties, making them ideal for seawall backfilling. One of the good adoptive properties of soapstone, which makes it suitable for usage as a backfilling material, is that it is soft and easy to carve, nonporous, nonabsorbent, has low electrical conductivity, is heat resistant, and has high specific heat capacity. The clay soil has some distinct properties, making it appropriate for seawall backfilling. Firstly, clay soil has high density, allowing it to retain moisture well. Furthermore, because the particles that make clay soil are negatively charged, they have a higher probability of attracting and holding positively charged particles such as magnesium, calcium, and potassium and, thus, are richer in terms of nutrients. This property of the backfill material is critical as vetiver grass will be planted on the seawall to bind it; thus, its germination probability is enhanced with clay soil.

Once the required height is reached, a geotextile cloth is spread before the boulders are stacked. Bidim nonwoven geotextiles provide an effective, economical solution to various engineering problems, including weak soil, rutted and cracked roads, and liquid and gas leaks from landfill sites [9]. Bidim nonwoven geotextiles have a three-dimensional structure designed to improve drainage performance. Its versatility means it is used in various applications, from reinforcing earth to erosion control against tidal action and construction of seawalls. High-quality fill material can become contaminated when placed directly in contact with soft or poor-quality ground, resulting in a loss of performance of the fill material. Geotextiles separate the two distinct materials to limit the contamination and subsequent strength loss.

In NbS application, the geo fabric is a binding and separation material between the building works and the backfilling material. This successfully avoids the erosion of backfill material during wave actions. The ideal grade of geo fabric for coastal protection works is A29 type and above. The A29 geo fabric has the "ISO 9001:2008 certification N. QEC1773". A29 is generally available in most developing countries with industrial suppliers with class C strength, with a dimension of 150 m long and 6 m wide.

4.4. Vetiver Grass: Fourth Line of Defense

The vetiver grass (*Chrysopogon zizanioides*) is planted at the top of the wall, creating a natural, solid barrier between the wall and the land. Vetiver grass is remarkably effective at mitigating floods and storm surges. Its roots grow between 2 m and 4 m into the ground and thus anchor soil, riverbanks, and coasts and shield them from the force of storm surges and floods. Vetiver grass only grows where planted, so it does not threaten local crops or other ecosystems with time. Vetiver System (VS) is a simple, practical, inexpensive, low maintenance, and effective means of soil and water conservation, sediment control, land stabilizations, and rehabilitation. VS major

applications require a large number of plants, and the quality of the planting material is essential for the successful application of the VS.

While planting the Vetiver grass, the tillers should be split from a mother clump, so each slip includes at least three tillers (shoots) and a part of the crown (see Fig. 2). After separation, the slips should be cut back to 20 cm length. These tillers should be planted in furrows at least 15 cm deep, with spacing between the slips approximately 10 cm and rows 10 cm apart.

The above four components, when implemented on the coast, will lead to the establishment of an NbS Seawall with its engineering strength. Fig. 3 provides an engineering design of the NbS Seawall.

5. Nature-Based Solution Seawalls in Fiji

In 2022, 108 sites required the construction of NbS seawall for 38.18 km to protect households living in villages along the coastline. By 2022, 12 sites were completed, protecting thousands of families and their properties (see Figs. 4–6 for photo of three completed NbS Seawalls). NbS solution seawall costs US$20,000 per 100 m compared to standard brick and steal walls, costing US$250,000 for the same length, thus contributing to substantial savings. Constructing a seawall for the entire 38.2 km will cost US$95.5 M instead of US$7.6 m using the NbS model, a fraction of the conventional model cost.

6. Concluding Remarks

The Pacific communities will continue to be affected by climate-related factors as causal factors are beyond their control. However, what needs to be done is to develop cost-effective, eco-friendly mitigation strategies to protect their communities and their assets. With sea level rise, coastlines are eroding, and villages, houses, burial grounds, arable land, and other infrastructures are gradually being washed away.

The only option for sites well below sea level is to relocate the entire population to higher ground. However, relocation should be avoided for other sites that can be protected via seawall construction, given the various challenges and associated problems. This option is very costly and not in the communities' best interest, given that relocation not only means moving houses and people but also breaking away from the ancestral grounds and their heritage. Instead, nature-based solution seawalls should be constructed, given their positive effect on environmental rehabilitation and the low financial costs of their construction. This paper has provided a model nature-based solution seawall that governments can construct where their coastal population is being threatened by rising sea levels. It is an environmentally, ecologically sound, and culturally responsible option to construct a nature-based solution seawall at the same site and not dislocate the community. In this process, we will use nature to deal with a problem caused by nature itself.

Conflict of Interest

The authors declare that they do not have any conflict of interest. Dr. Reddy was the Minister for Agriculture, Waterways and Environment from 2018 to 2022 when he gave the idea and conceptual framework for NbS Seawall, Mr. Singh was the Senior Technical Officer who did the teachnical drawing of the NbS Seawall and Mr. Reddy was the Director Waterways who implemented the projects in the various communities.

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