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Climate resilient coastal protection: A case study of dune nourishment and vegetation at Bhatye, Ratnagiri, Maharashtra

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Beaches and dunes are some of the natural mechanisms provided by nature for the protection of the coasts. Re-nourishing the eroded beaches and dunes is widely accepted as a low-cost, nature-friendly coastal protection measure. Such projects are just being initiated for the Indian coastline. A pilot dune nourishment demonstration project, following Climate Change Adaptation Guidelines for India, was attempted at Bhatye in the Ratnagiri district of Maharashtra, India. The pilot project involved the nourishment of a 500 m long eroded dune designed following the Minimum Beach Level (MBL) concept, planting of the dune with native vegetation by involving the coastal community and fencing of the dune for its protection. The dune crest height was 5.5 m above Chart Datum (CD) with slopes of 1:5 on both sides. The sand required for the nourishment was borrowed from a shoal, which was a hindrance to safe navigation to the fishing harbour at the neighbouring river entrance. The restored dune has survived five monsoons and several cyclones since its completion in January 2019. The pilot project has successfully demonstrated that low-cost dune nourishment is a feasible option to prevent flooding of low-lying coastal areas and step up the post-storm dune recovery where aeolian sediment transport is slow.

[**Keywords**: Climate change, Dune nourishment, Nature-based coastal protection, Sand-based coastal solutions]

Introduction

Shoreline management strategies commonly followed belong to five generic options *viz*. do-nothing (no active intervention), managed realignment (retreat), limited intervention, hold the line, and advance to sea[1-2]. ‘Do nothing’ is a no-cost and expedient way to let the coast take care of itself, as there are no habitation or infrastructure requiring any protection, and thus is the most environment-friendly solution[1]. The policy of ‘managed realignment’, also called retreat, with the relocation of the settlements or infrastructure that are threatened by erosion, also allows the shoreline to adapt to the natural coastal processes[3]. The ‘limited intervention’ policy also works with nature but with limited interventions like sand-based solutions such as the beach or dune nourishment along with vegetative measures[4]. In ‘hold the line policy’, the sea cannot be allowed to encroach the settlements or infrastructure, which is achieved by constructing hard structures like embankments or seawalls[1]. Finally, the ‘advance to sea policy’, in which the offshore protection measures are adopted with major investments, is implemented to reduce the impact of waves on the coast, where the inhabited areas and assets are threatened by erosion[1,5].

While very few projects in India have adopted sand-based solutions[1,6-7], the overwhelming preference for coastal protection has been hard structures such as seawalls and groynes under the policy ‘hold the line’. International best practices have favoured a wider variety of solutions, including sand based such as 'dune care' for nurturing existing or artificial sand dunes; 'sand nourishment' for inducting new sand into the beach-dune system; and 'sand bypassing' to move past the blockage of sand trapped near a structure or river. Placing new sand on the beach–dune system is now widely favoured in many countries[8-13]. But they remain at the emergence stage in India. Nourishment of the Rama Krishna beach of Visakhapatnam and Puducherry beach with dredged sand from the harbour are perhaps the two major beach nourishment examples in India[14-15]. In combination with sand retention structures, Maharashtra has implemented three nourishment projects: 900 m and 400 m long beach nourishments along with mid-tide level sand-filled geotubes at INS Hamala, Mumbai and at Dahanu; and an 1100 m beach (with nourishment using 1,20,000 m^3 sand) at Mirya Bay, Ratnagiri along with submerged nearshore reef[1,16].

As regards artificial dune building, there is a case from Kalpakkam in Tamil Nadu where a combination of a few measures was adopted to protect an atomic power plant[17-18]. However, a portion of the dune (not covered by vegetation) lost its form due to wind[18]. 'Dune care' is practiced on a few coasts in India primarily under social forestry programmes where *Casuarina*, *Acacia* species or other deep-rooted and fast-growing trees are planted, which in many cases have finally resulted in the total disappearance of the dunes and massive erosion of the area, and finally uprooting of the trees[19-20]. Perhaps the first-ever successful experiment on 'dune care' in India was conducted at Miramar Beach, Goa[21-22]. Here, the dunes flattened by trampling were protected by fencing and facilitated to re-shape naturally by allowing the growth of native vegetation. It was noticed that the dunes started taking shape in three months of active monsoon. On several locations along the east coast of India (*e.g.*, southern Tamil Nadu, Andhra Pradesh, Odisha and West Bengal), earthen or rock embankments have been constructed to prevent coastal flooding from sea level rise due to local storms and cyclones, but without fully considering the dynamic nature and ecosystem services of coastal landforms. Nevertheless, some of the embankments have provided flood protection, although the ecological benefits are limited.

Scope of the work

The projections of the Intergovernmental Panel on Climate Change (IPCC)[23] indicate more frequent and sustained heat waves and rainfall events. As predicted, the ocean continues to warm and acidify, and the mean global sea level is on the rise[24]. The storm waves, coastal erosion, and storm surges are rising[1,25]. The impacts of climate change (over and above the natural wave, wind, and physical coastal dynamics) threaten the Indian coast further. Mitigation of global warming being a greater challenge, a feasible option is to adapt locally. Adaptation along the coast involves initiatives and measures that reduce the impact of climate change. Responses can include relocation of coastal infrastructure, enforcing coastal regulations, strengthening natural coastal systems, and protecting and artificially recreating the natural systems with technical interventions. The Global Environment Facility (GEF)/Asian Development Bank (ADB) funded Technical Assistance (TA): 'Climate Resilient Coastal Protection and Management Project (CRCPMP)' for the Indian coastline has generated Climate Change Adaptation Guidelines (CCAG) to achieve the above objectives[1,25].

The CCAG and the Environmental Softness Ladder (ESL) proposed therein recommended dunes as a first choice in low-cost and environment-friendly protection measure[1,25]. A dune is a hill, mound or ridge of sediment that has been deposited by wind landward of a beach on the coast[13,26-27]. Dunes provide a physical buffer between the beach and inland areas, which are dynamic and thus can naturally shift during storms. Inland areas become more vulnerable to storms when the beach and dune are weakened. Protecting these landforms helps prevent loss of life and property during high waves, storm surges and sea-level rise in the long run, preventing or delaying intrusion of waters into the inland areas[28-29]. In addition, because of their more natural appearance, dunes can be more aesthetically pleasing than hard structures[4]. Globally, coastal dunes are considered a cost-effective and nature-based method of protecting coastal infrastructure from storm damage[27, 29-32].

A pilot project on dune building and vegetation was implemented at Bhatye under the CRCPMP Project. This study documents the results of this pilot project which is of paramount importance for the country's coastal protection in a climate change scenario. The parameters used for testing the feasibility of such a scheme were to see whether the designed dune is suitable for the selected coast, whether the dune withstands the climatic variables such as cyclonic conditions, and how effective the vegetation was for its own survival and protection of the dune sand.

Materials and Methods

Study area

Bhatye Beach in the Ratnagiri district of Maharashtra was selected as the pilot project site due to the continuous erosion of the existing low-level dunes and the potential for enhancing tourism and recreation. The Bhatye site, located on the Konkan coast of Maharashtra, lies at a distance of about 3 km south of Ratnagiri town (Fig. 1). The coastal sediment sub-cell of Bhatye has an overall length of 1.7 km bounded by two headlands with a gently sloping wide beach of more than 200 m width during low tide and a low elevation sand dune. The beach orientation is

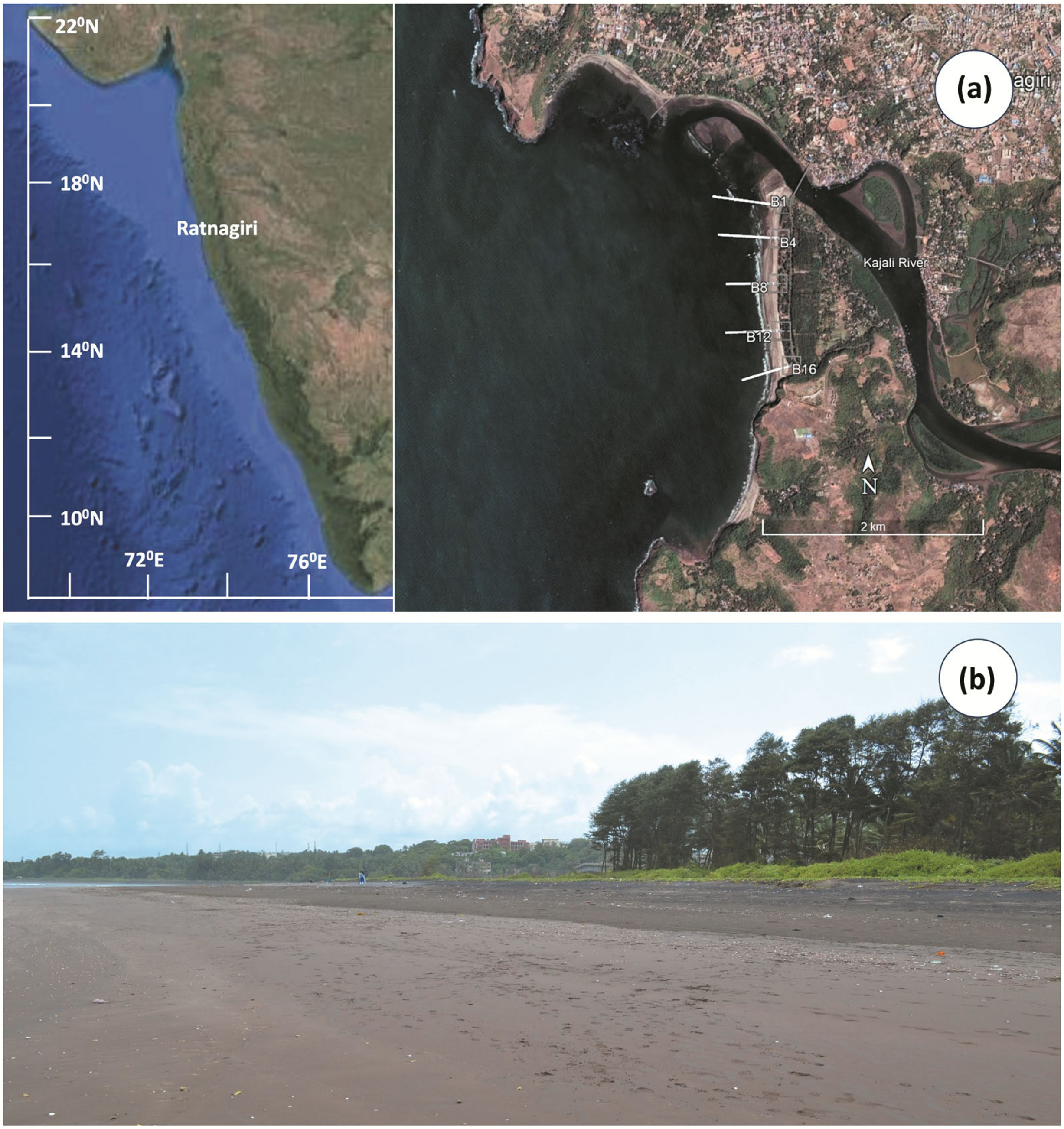

Fig. 1 — Dune nourishment project site at Bhatye, Ratnagiri, Maharashtra: (a) Close-up showing the beach profile measurement locations B1, B2, etc.; and (b) A view towards north of the wide Bhatye beach

almost north-south. The Kajali River in the north supports a fishing harbour, and the inlet is frequented by fishing boats.

The Bhatye Beach comprises primarily fine black sand with a veneer of white sand on the top during fair weather. The average mean and median sizes of sediments in the project site are 0.145 mm and 0.138 mm, respectively, which indicates that the sediments can be classified as fine sand as per the Wentworth Scale. Fair weather beach profiles at stations B1 to B16 (as shown in Fig. 1) covering the whole sediment sub-cell are presented in Figure 2. The beach face slope during fair weather is of the order of 1:60. The backshore has creeping vegetation throughout except for the central portion which is frequented by tourists. While the dune in the 200 m long northern part is

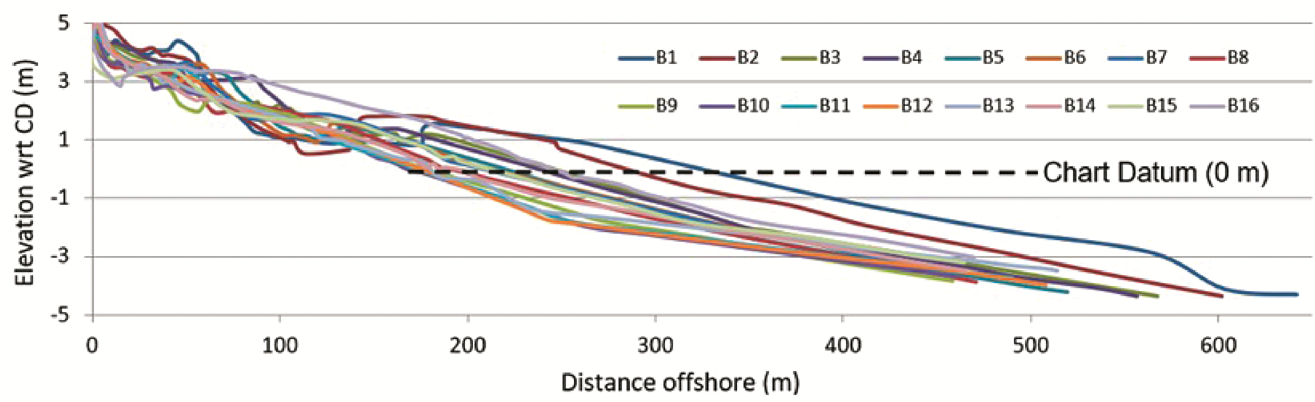

Fig. 2 — Typical profiles of the Bhatye beach (see Fig. 1 for the profile locations). B1, B2, B3, etc. are beach profile measurement transects covering the entire Bhatye beach starting from the north

intact, the dune in the central portion is flat due to human activities such as levelling for recreational activities, trampling and sand extraction. A degenerated dune is found in the central sector. The beach undergoes seasonal changes, with the dry beach width almost halved during the monsoon. However, there is not much elevation difference between the monsoon beach berm and the fair-weather berm.

The beach and the dune in the central and southern sectors are prone to erosion during episodic events. Figure 3 shows the extent of erosion and uprooting of trees that occurred in the southern sector due to the very severe cyclone 'Luban' that hit the Arabian Sea in October 2018. A 500 m stretch in the central part of the Bhatye Beach, which was severely eroded and frequented for rest and recreation, was chosen for the dune re-building and vegetation restoration project.

Fig. 3 — The eroded sand dune and uprooted trees in the southern sector of Bhatye beach in October 2018 due to the very severe cyclone Luban

Determination of Minimum Beach Level (MBL)

The most important task in the project was the design of the dune, for which the crest level had to be estimated first[33]. Black *et al.*[1] have proposed the concept of Minimum Beach Level (MBL), which is defined as the highest water level that may occur at a beach due to floods, waves, tides, storm surge and sea level rise for the climate change scenario. The crest level of the dune has to be built to the MBL to prevent flooding of the hinterland areas. A methodology for determining MBL incorporating climate change projections is provided in the guidelines[1]. To estimate the MBL[1], the following parameters are to be accounted for: tide, wave set-up, wave run-up, storm surge, sea level rise and seasonal sea level rise (Fig. 4). Minimum Beach Level which is normally estimated for a return period, say 25, 50 or 100 years depending on the life of the construction requires

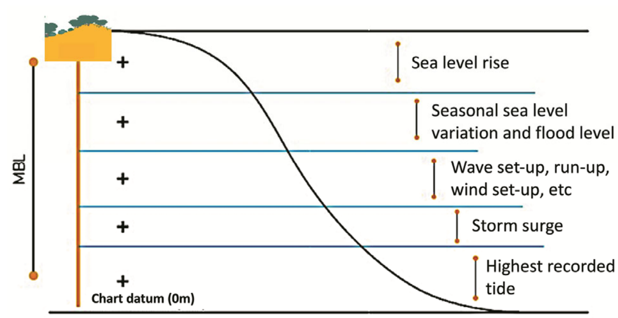

Fig. 4 — A schematic diagram showing the different components constituting the Minimum Beach Level (MBL) (source: Black *et al.*[1])

wave, storm surge and sea level rise projections for the relevant period[1]. For this pilot project, the MBL estimate provided in the reference manual[1] has been adopted for the dune crest level height. Thus, the dune crest elevation used a 50-year return wave period and projected sea level rise in 2050, and the MBL was

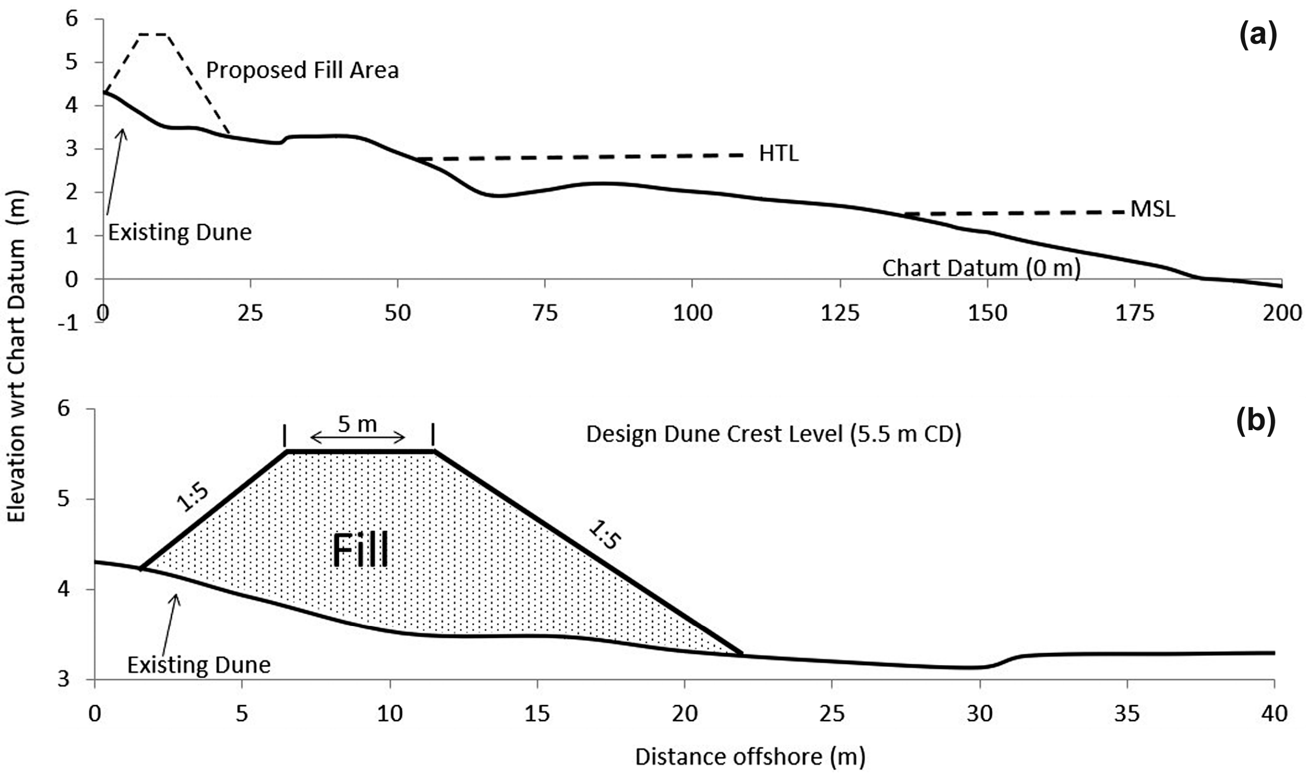

Fig. 5 — (a) A typical beach profile selected from the measured profiles with the designed dune between 0 and 20 m; and (b) A plan view of the designed dune

estimated to be 5.5 m with respect to Chart Datum (CD).

Dune design

Long-term hind cast wave and wind data sourced from the NOAA Wave watch III website and measured beach profiles were used for the dune design. Site visits were made during storm and fair-weather conditions to assess the extent of wave run-up during storm events. Further, stakeholder consultations were conducted to understand the site conditions. In addition to the hydrodynamics and ecological assessments, the design considered the wide intertidal zone, narrow dry beach during increased water level conditions, existing low elevation dune and sand availability. Social aspects such as the present beach use, the Gram Panchayat's beach development proposals, stakeholder support for the project and budget availability were also considered.

Since Bhatye is a dissipative beach with a wide and shallow intertidal zone, waves lose significant energy before they break, and hence, the wave run-up and set-up are much less than a reflective beach for the same wave conditions. A dune slope of 1:5 was taken for both the seaward and landward sides of the dune based on the existing dune slope, the dry beach width, and the sediment grain size[1]. To ensure some dry beach between the dune and the mean high tide line to prevent rapid erosion, the dune width considered was 20 m. A typical beach profile selected for the dune design and the designed dune plan view is presented in Figure 5.

Identification of the source of sand for nourishment

There were wide-ranging discussions with the stakeholders on the sand source for the project. It was noted that the Kajali River entrance has many shoals (Fig. 6), which contain a sufficient quantity of sand that could be used for nourishment. The size characteristics of the shoal sediments with average mean and median size values of 0.205 mm and 0.198 mm, respectively, were found to be quite suitable for the dune in the location. It has been reported that sediments coarser than the beach material will be better for the dune for the latter's stability[26,28]. The fishermen welfare associations of four villages, including Bhatye, have been requesting the Ratnagiri Port department to remove the sand shoals to ensure

Fig. 6 — Sand shoal dredged for dune nourishment at Kajali river inlet adjoining Bhatye beach

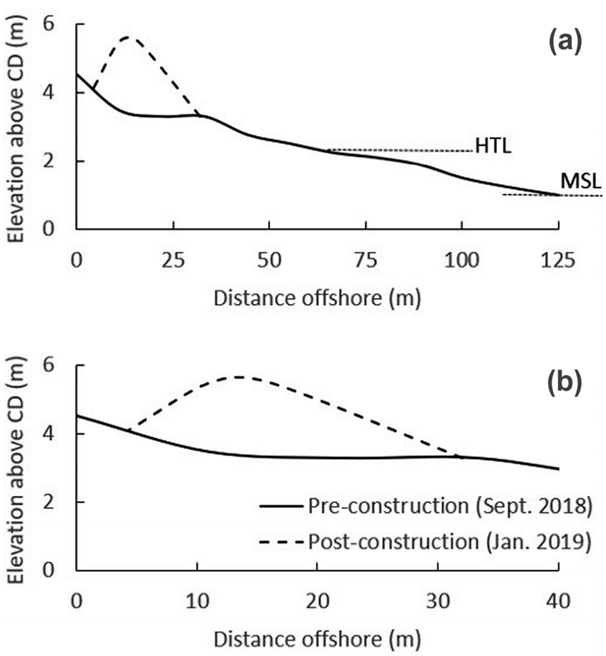

Fig. 7 — Typical pre- and post- construction beach profiles: (a) Total profile showing the MSL, HTL and dune; and (b) A magnified view of the dune part of the profiles

safe navigation. A proposal was made to utilize the dredging sand from the shoals for the project, which received enthusiastic support from all stakeholders. Accordingly, it was decided to utilize the sand shoals of the Kajali River as the sand source for nourishment. This ensured community support for the dune nourishment initiative. Bhatye, being a domestic tourism location, has a lot of beach tourism activity in the central and southern parts of the site. The Bhatye Gram Panchayat (GP) was interested in promoting tourism further, for which they had a master plan, and hence, they were supportive of the project as divulged during the stakeholder meetings.

Dune building

The sand volume required for the dune nourishment was estimated to be 14,000 cu m. It was confirmed that the required quantity of sand was available in the shoals of the Kajali River mouth. The dune building commenced in October 2018, immediately after the monsoon and was completed by January 2019 (Fig. 7). The nourished dune sand volume was about 16,500 cu m as against the design estimate of 14,000 cu m. A comparison of the pre-construction beach profiles with the design study survey of December 2015 shows significant erosion of the upper beach and the dune base. Three cyclones, including a severe cyclonic storm, Cyclone Ockhi (28 November – 03 December 2017), occurred between the survey periods. Though no regular beach profile measurements are available from Bhatye, the occurrence of the successive cyclones is likely to have caused the erosion of the upper beach and the frontal dune before dune construction (Fig. 3).

Dune vegetation

The last part of the project implementation was dune vegetation using native plants, fencing to avoid pedestrian or vehicle traffic damage and providing a beach access path for the public[34]. A nursery for the dune vegetation was established and a three-tier planting scheme (Fig. 8) was planned for the dune. The native dune-forming species initially chosen were *Ipomoea pes-caprae* (Rail plant) in the 1st tier on the seaward side, *Vinca rosea* in the middle, and *Chrysopogon zizanioides* (Grass vetiver) on the landward side. Due to the unavailability of the Grass vetiver, it was decided to plant the native *Clerodendrum inerme* (Wild Jasmine, Seaside *Clerodendrum*; chhoti-ari), *Terminalia catappa* (Sea almond), and *Lawsonia inermis* (Henna) on the landward side of the dune (Fig. 8).

A dune care group was formed to ensure community participation in the project. The dune care

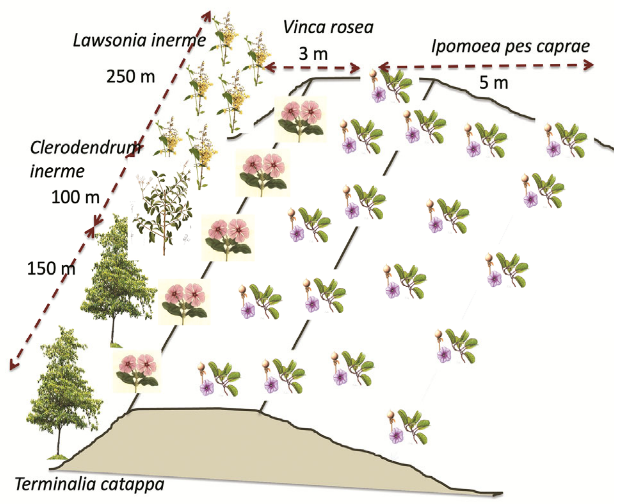

Fig. 8 — Dune vegetation scheme adopted at the Bhatye dune

group members and other local women involved in the project were trained to develop a nursery (Fig. 9a), transplant on the dune (Fig. 9b) and also make seed balls. Around 30,000 plants of *Ipomoea pescaprae* were planted on the foreshore with a plant distance of 1 × 1 m and row spacing of 1 m. Seedlings were developed through stem cuttings in the project nursery. About 4 kg of *Vinca rosea* seeds were used to make seed balls that were directly sown on the dune. As the small seeds of *Vinca rosea* could be blown out before germination, seed balls were planted, which supported higher germination and establishment on the dune. Behind the *Ipomoea* planting zone, the seed balls were placed at a ball space of about 30 cm each and a row spacing of 1 m. In the third zone, thirty plants of *Terminalia catappa* were planted at a grid spacing of 5 × 5 m for a distance of 150 m length and 300 *Lawsonia inermis* plants were planted at a spacing of 0.5 × 0.5 m for 250 m till the end which formed a natural fence and also held the sand from being blown out. Around 200 *Clerodendrum inerme* plants were planted along the rest of the 100 m length zone of the landward side at a spacing of 0.5 × 0.5 m. *Clerodendrum inerme* also naturally existed on the existing dune in some pockets. All four sides of the vegetated dune were provided with fencing to protect the dune from trampling by pedestrian or vehicle passage. A view of the completed dune immediately after the vegetation is given in Figure 9(c).

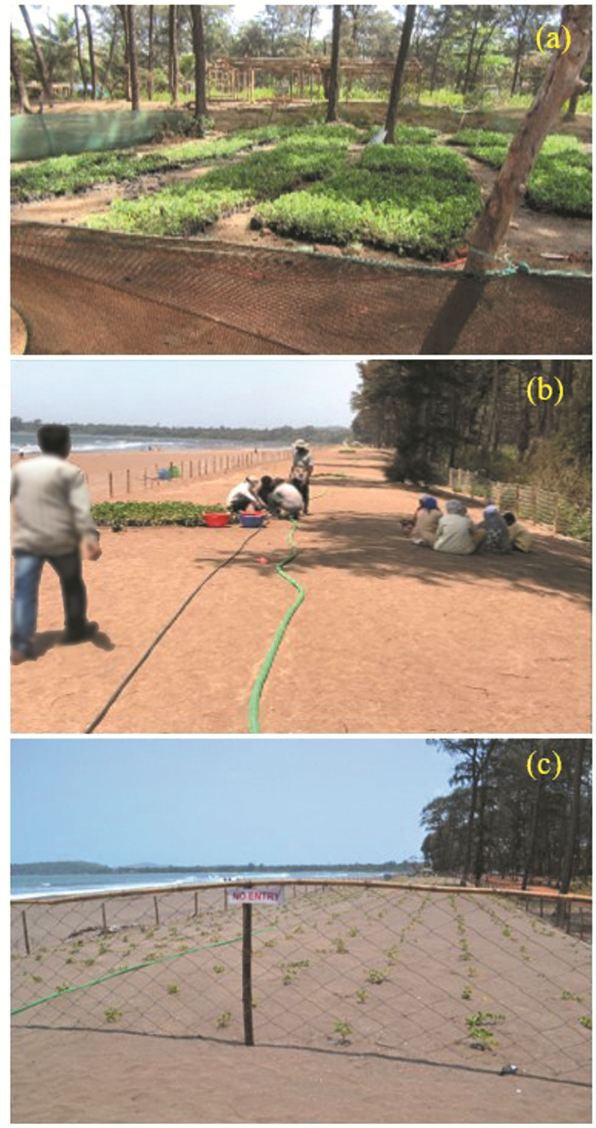

Fig. 9 — (a) A view of the nursery developed behind the nourishment site; (b) Initiation of planting of vegetation; and (c) A view of the dune immediately after planting the vegetation. The fencing to stop pedestrian or vehicle passage through the dune can be seen

Post-implementation monitoring

Wave, wind and pressure data from the NOAA Wavewatch III website for the post-implementation period till 2021 have been studied (Figs. 10 – 12) to identify cyclones and other episodic events. The initial survival rate and health of seedlings was assessed physically for six months after implementation. Thereafter, the assessment of the health, survival and vegetation cover was done remotely using photographs acquired with the support of the local office of the Maharashtra Maritime Board (MMB) and by examining satellite images. Based on the photographs and satellite images, an assessment of the vegetation health and spread and dune stability was carried out periodically. Figure 13 presents a

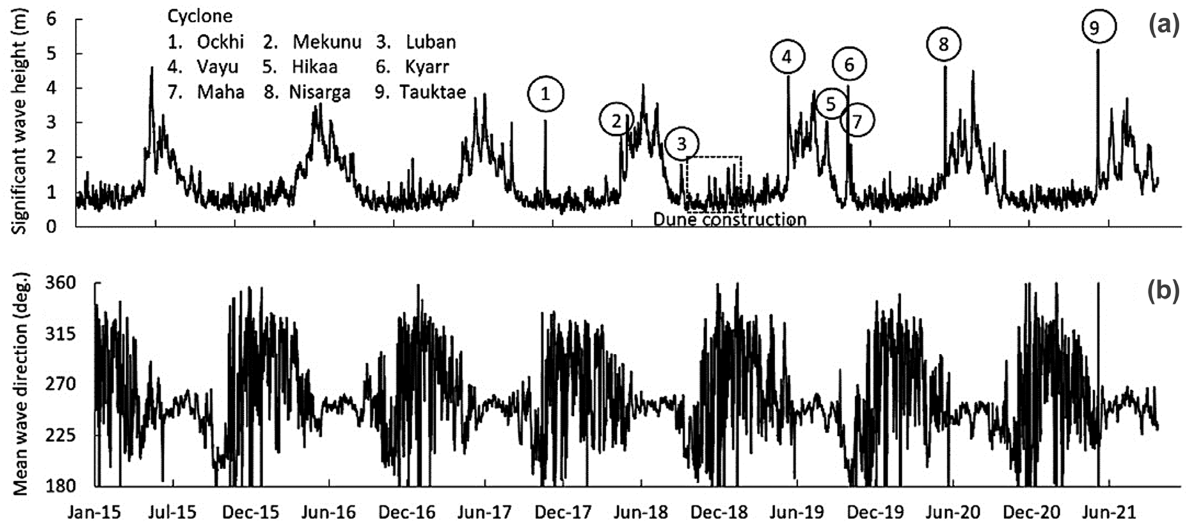

Fig. 10 — Time series: (a) Hindcast significant wave height; and (b) Mean wave direction off Ratnagiri during 2015-2021. The cyclones that traversed the Arabian Sea during the period are also numbered and shown (Source: NOAA Wavewatch III website)

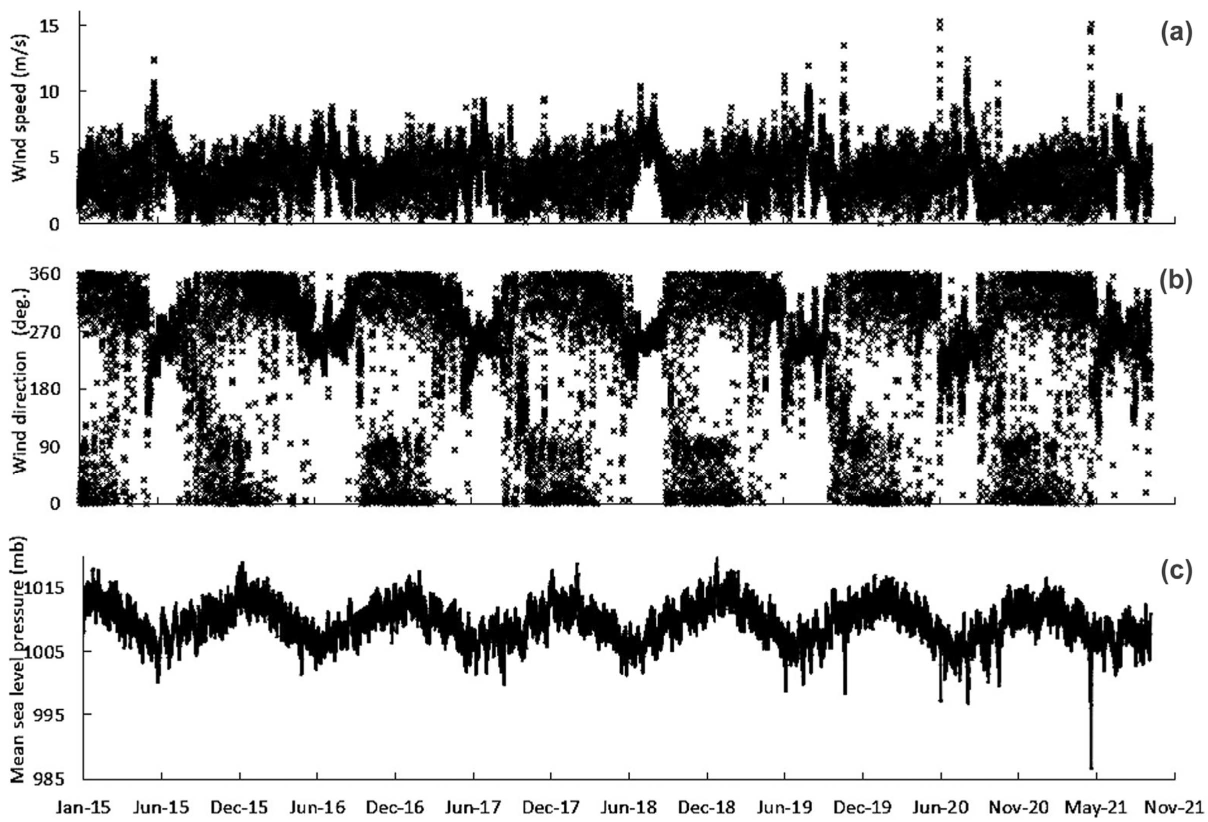

Fig. 11 — Time series: (a) Surface wind speed, (b) Wind direction; and (c) MSL atmospheric pressure off Ratnagiri during 2015-2021. (Source: NOAA Wavewatch III website)

chronological view of the vegetated dune for the period till November 2023. The above data were integrated to arrive at conclusions on the performance of the dune and vegetation.

Results and Discussion

Since the construction of the dune in 2018 – 19, five monsoons (2019 – 2023), six cyclones and several depressions have occurred over the Arabian

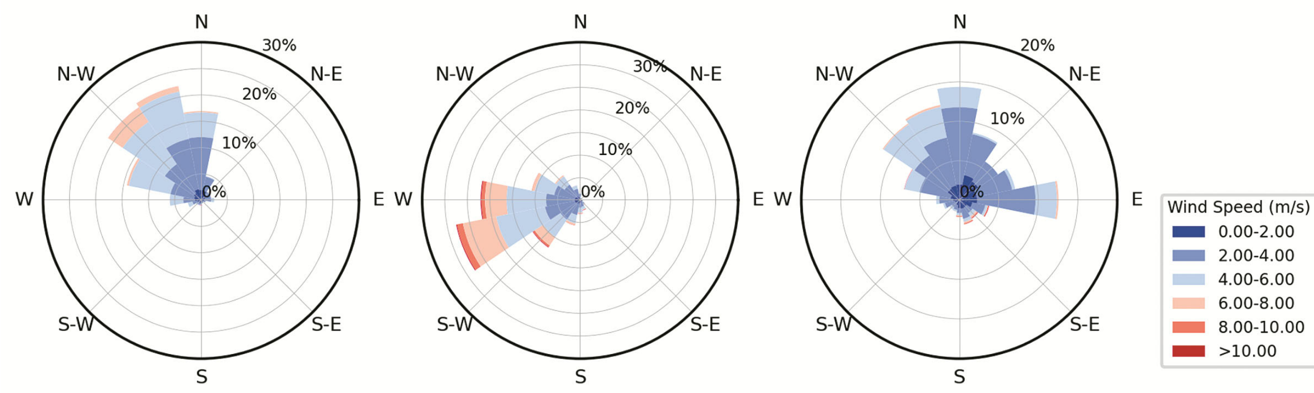

Fig. 12 — Rose diagram of wind for the 7 years period 2015-2021: (a) Pre-monsoon (January-May); (b) Monsoon (June-September); and (c) Post-monsoon (October-December)

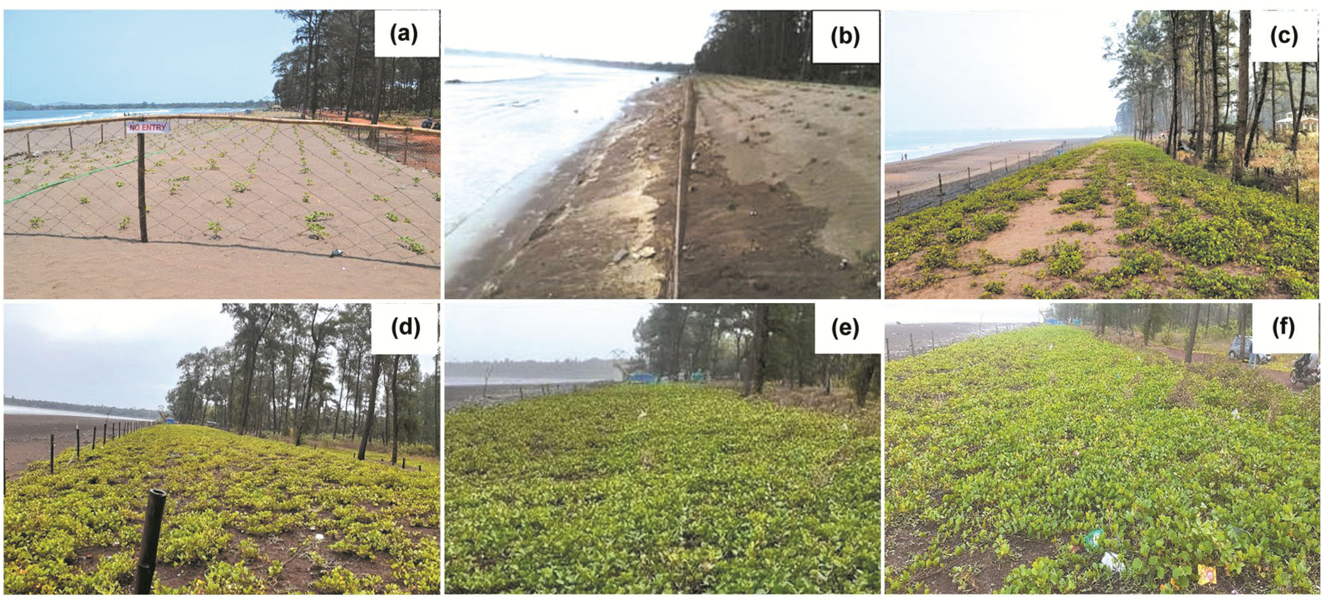

Fig. 13 — A chronological view of the growth of plants at different timelines: a) Immediately after planting, January 03, 2019; (b) 6 months after planting, June 30, 2019, the impact of the washout of the seaward face by Vayu cyclone in June 2019 is seen; (c) 17 months after planting, May 15, 2020; (d) 30 months after planting, June 18, 2021; (e) 43 months after planting, July 15, 2022; and (f) 59 months after planting, November 27, 2023

Sea till 2021 (Fig. 10). Offshore significant wave height exceeded 4 m during the cyclones, while it is less than 4 m during a typical monsoon. Likewise, the wind speed also exceeded 10 m/s during the cyclones (Fig. 11). Atmospheric pressure was up to 986 mb on 16th May 2021 during cyclone Tauktae (Fig. 11). These suggest that the water levels during the cyclones due to low atmospheric pressure, storm surge and wave set-up were much higher than the normal monsoon conditions. Although there weren't any direct water level measurements during the cyclones, it was noted from the predictions in the CRCPMP Reference Manual[1] that an additional rise in water level of a minimum of 1.0 m due to wave set-up and storm surge over and above tide was very likely during cyclones.

For the Maharashtra coast, there are three main wave sources (Fig. 10). In the monsoon, the waves come from the Horn of Africa and Yemen and arrive at an angle around 260° N. Many of the Maharashtra beaches, including Bhatye, are close to perpendicular to the monsoon wave direction, suggesting that large waves have acted to align the open beaches onto an orientation that is close to shore-normal in the monsoon. In the post-monsoon, long-period (12 – 20 s) swells come from the large storms in the Southern

Ocean. They arrive offshore of Maharashtra from 225° N. The third group of waves is the "Shamal" coming from the Oman region[1]; strong desert winds generate waves that arrive with an angle of around 315° N.

It can be seen from the wind data (Fig. 12) that the monsoonal winds (June – September) are strong and onshore, while winds are predominantly shore parallel during the non-monsoon periods (October – May). The southwest monsoon season features winds from the west and south of the west, while the post-monsoon (October – December) and Shamal seasons December – May) feature winds from the northwest and west of the north. Although aeolian processes (sand transport by wind over the sub-aerial beach) is a major process for dune building (and rebuilding after a storm), sediment mobility is affected by several factors, including wind speed and direction, sand delivery to the beach, moisture content of the beach sediment, sediment grain size and density[26]. Although Bhatye beach is wide, gently sloping and dissipative, during the monsoon, when the winds are stronger and onshore, sediment transfer between the beach and the dune by aeolian sand transport is limited due to wet conditions and high moisture content of the sand. On the other hand, during non-monsoon dry conditions, when sand is delivered to the beach by waves, the wind is mostly shore parallel, limiting the sand transport by the wind in the landward direction. So, dune rebuilding after a storm is a prolonged process. The presence of high-density black sand, which is dominant for the Bhatye beach, is another reason for slow dune growth. However, the slow dune growth process helps maintain the beach sediment budget rather than cause a loss to the dune.

The design of a dune with appropriate size and shape and nourishment with compatible sediment characteristics ensured its stability, and planting appropriate native vegetation with robust root systems helped trap and anchor the sand and enhanced its resilience. The dune stands firm with fully covered sand-binding vegetation. The nourished dune successfully demonstrated that it is an effective flood protection method in low-lying coastal areas with a low gradient dissipative beach and sufficient dry beach between the dune and the high tide line. Since the nourishment of the dune, there have been six cyclonic storms till 2001 (Fig. 10) accompanied by strong wind, high waves and flooding of the low-lying west coast of India. Many coastal areas around Bhatye were also affected. However, the dune at Bhatye survived the impacts and maintained its constructed shape. The dune supported enhancement of the ecological and economic status of the coastal area.

Figure 13 presents a picture of the growth of the dune plants in chronological order since the planting. As can be seen, the vegetation which was in a healthy condition after 3 months, was partially washed out in June 2019 due to high waves during the passage of cyclone Vayu. But that was made up subsequently, and the dune vegetation was quite healthy in August 2021. As expected, the performance of the sand binder species (*Ipomoea*) was excellent, with 95 per cent survival. The dune coverage of the creeper was considerably faster and denser within 2 – 3 months as the plants reached maturity. In addition to that, the same species from outside the dune fence crept onto the dune, which made a good vegetation cover, protecting the sand from blowing off. The growth of the plants was satisfactory, and the plants survived even without watering as the sand-binding vegetation system was stabilised and matured.

The present effort to restore and nourish a dune enabled to note the following aspects. Knowledge of the local hydrodynamic conditions, beach morphology, sediment properties, ecology and the beach behaviour under storm events and fair weather are essential for a successful dune design[35]. The dune's high crest can prevent or reduce overtopping by big waves in storms[33]. The dune provides a sediment reservoir that may be redistributed in large storms, thus reducing the impacts of the wave forces on the coast and returning the sand to the dune in calm weather[26]. Therefore the natural cycles of beach and dune erosion and recovery are[26]: (i) erosion of the beach with the onset of monsoon: at this stage, the dune need not necessarily be affected; during major storms, waves erode the beach and the frontal dune; (ii) the eroded sediments get deposited as offshore bar systems; (iii) the bars help to protect the beach by breaking waves offshore and thereby dissipating excess wave energy; and (iv) during fair weather the swells bring back the sand from the bar to beach and then the wind takes it from the beach to the dune. However, there needs to be enough sediment available in the beach environment and favourable wind conditions to facilitate this. The dynamic nature of the sand dunes results in adjusting to wave and wind conditions and sediment supply[36].

Dunes naturally migrate landwards under sea level rise[25,29]. However, the increasing human encroachment in the coastal zone has led to a shortage of coastal sediments and space[1]. The encroachments have resulted in coastal squeezing, whereby less and less space is available for natural coastal processes to accommodate eroding forces or adjust to changes such as increased water levels[32]. Significant reductions in coastal sand availability and space have made many Indian beaches more vulnerable to erosion. In addition to this, the urbanization of the coast has exacerbated natural erosion phenomena into problems of growing intensity[1]. Thus, natural dune development is either very slow or not possible due to unfavourable meteorological conditions and/or anthropogenic activities. However, landward migration may be halted if enough sand is added to the beach to allow the dunes to grow upwards with sea level rise[29]. In low-lying coastal areas, where sand dune development is very slow, or the existing dune's height is inadequate, artificial dune nourishment is a feasible option against flooding[1-2]. Compatible sediments are essential for a dune project[26]. Also, the location of the source and the method of delivery to the beach are equally important[1]. In addition to the coastal protection benefits, the dune also has significant ecological and tourism benefits.

Vegetation is vital for the survival of dunes, both for the binding of sediment by root systems and facilitating the build-up of dunes by sediment trapping[27]. Dune project sites must be vegetated with native plants to maintain stability and achieve dune restoration and nourishment[34]. The plants, at the same time, must be able to survive burial by blowing sand, sandblasting, salt spray and saltwater flooding[34].

Community participation in coastal protection is indeed a welcome initiative and must be encouraged[31]. There are several community-based organizations, such as women self-help groups, youth associations, and fishermen associations in the coastal areas. Their participation is expected to bring a sense of ownership to the community, which will go a long way in the upkeep and maintenance of the structure too. Consultations with the Gram Panchayat and the tourism departments enable the development of tourism plans that accommodate dune care and other sand-based shore protection solutions, thereby contributing to the economic upliftment of the local community.

Conclusions

The Climate Change Adaptation Guidelines for Coastal Protection and Management and the Environmental Softness Ladder provided therein help decide the appropriate schemes for a given coastal location. The 'dune restoration' suggested is one of the soft options for coastal protection. Degraded or low-lying dunes can be strengthened and made climate change resilient by increasing their height and stability through nourishment coupled with vegetation. Bhatye dune project demonstrated how this could be achieved. Dune projects, once established, can be easily managed by the local community with some amount of technical guidance. The success of the Bhatye dune restoration project underlines the fact that coastal protection and management measures shall try to emulate natural systems wherever possible while designing measures for coastal protection, particularly in the context of climate change.

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Conflict of Interest

This is to certify that the reported work in the paper entitled "Climate resilient coastal protection: A case study of dune rebuilding at Bhatye, Ratnagiri, Maharashtra" involves no competing or conflict of interest.

Ethical Statement

This is to certify that the reported work in the paper entitled "Climate resilient coastal protection: A case study of dune rebuilding at Bhatye, Ratnagiri, Maharashtra" submitted for publication is an original one and has not been submitted for publication elsewhere. I/we further certify that proper citations to the previously reported work have been given and no data/table/figure has been quoted verbatim from other publications without giving due acknowledgement and without the permission of the author(s). The consent of all the authors of this paper has been obtained for submitting the paper to the "Indian Journal of Geo-Marine Sciences".

Author Contributions

MB: Conceptualization, supervision of field investigation and dune construction, original draft, finalisation of the manuscript; NPK: Field investigation, data processing, contributions to the original draft, review and editing; and SDO: All work relating to the planting of vegetation starting with plant nursery, contribution to the section on dune vegetation and results.

References

1 Black K P, Baba M, Mathew J, Chandra S, Singh S S, *et al.*, *Reference Manual on Climate Change Adaptation guidelines for Coastal Protection and Management in India*, Vol 1 & 2, edited by K P Black, M Baba & J Mathew, prepared by FCG ANZDEC (New Zealand) with the support of the Global Environment Facility (GEF) and Asian Development Bank (ADB) for CWC/MoWR, RD & GR, 2019, pp. 72 (Vol 1) & 335 (Vol 2).

2 Kurian N P, Black K, Kulkarni K B, Naik B G & Mathew J, *Karnataka Shoreline Management Plan*, Report prepared for the Department of Public Works, Ports and Inland Water Transport, Government of Karnataka (FCG ANZDEC, New Zealand), 2020, pp. 524.

3 Esteves L S, Is managed realignment a sustainable long-term coastal management approach? *J Coast Res*, Special Issue No. 65 (2013) 933–938. https://doi.org/10.2112/SI65-158.1

4 Nassauer J I, The aesthetics of landscape, *Landsc J*, 19 (2) (2000) 163-179.

5 Lokesh A, Sundar V & Sannasiraj S A, Artificial Reefs: A Review, *Int J Ocean Clim Syst*, 4 (2) (2013) 117-124. https://doi.org/10.1260/1759-3131.4.2.117

6 Kudale M D, Mahalingaiah A V & Tayade B R, Use of sand-filled geotextile tubes for sustainable coastal protection – case studies in Indian scenario, *Indian J Geo-Mar Sci*, 43 (7) (2014) 1241-1246.

7 Ramana Murthy M V, Mani J S & Subramaniam B R, Evolution and performance of beach fill at Ennore Seaport, southeast coast of India, *J Coast Res*, 24 (1) (2008) 232–243. https://doi.org/10.2112/05-0537.1

8 Bakker M A J, Vanheteren S, Vonho Gen L M, Van der Spek A J F & Van der Valk L, Recent coastal dune development: effects of sand nourishments, *J Coast Res*, 28 (3) (2012) 587–601.

9 Dean R G, *Beach Nourishment*: *Theory and Practice*, *Advanced Series on Ocean Engineering*, Vol 18, (World Scientific, Singapore), 2002, pp. 420. https://doi.org/10.1142/2160

10 Jenks G K, Disaster to Restoration: The power of People, paper presented at the *New Zealand Association of Resource Managers, 50th Annual Conference*, (New Zealand), 2003, pp. 25.

11 Miller D L, Thetford M & Yager L, Evaluating sand fence and vegetation for dune building following overwash by Hurricane Opal on Santa Rosa Island, Florida, *J Coast Res*, 17 (4) (2001) 936-948.

12 Nordstrom K F, Lampe R & Vandemark L M, Re-establishing naturally functioning dunes on developed coasts, *Environ Manag*, 25 (1) (1998) 37-51.

13 USACE, *Coastal Engineering Manual*, Part V, Chapter 4, (United States Army Corps of Engineers, Washington, DC), 2003, pp. 109.

14 Black K & Mathew J, *Puducherry Beach Restoration Study: Feasibility Studies for Design Alternatives*, Report submitted to National Institute of Ocean Technology (NIOT), (Ministry of Earth Sciences, Government of India), 2015, pp. 270.

15 Kathula Supriya & Sooraj Ganga, The coastal protection measures and techniques for shoreline of Visakhapatnam, *Int J Multidiscip Res*, 5 (2) (2023) 1-32.

16 ADB, *India: Sustainable Coastal Protection and Management Investment Program - Tranche 1*, ADB Completion Report, Project Number 40156-023, (Asian Development Bank), 2021, pp. 72.

17 Mani J S, Tsunami mitigation measures along the coast of Kalpakkam, *Proc. Indo-Japan Workshop on Coastal Problems and Mitigation Measures - Including the Effects of Tsunami*, (Indian Institute of Technology, Madras), 2007, pp. 38-46.

18 Mani J S & Ramana Murthy M V, Design of coastal protective structure for waves and tsunami affected sea front, *Proc. Eighth International Conference on the Mediterranean Coastal Environment*, *MEDCOAST*, (Alexandria, Egypt), 2007, pp. 1105-1112.

19 Chakraborty T, Mondal A K & Mondal S P, Studies on the prospects and some problems of sand dune vegetation at the fragile coastal zones of West Bengal and Orissa, in Eastern India, *Afr J Plant Sci*, 6 (2) (2012) 48-56. https://doi.org/10.5897/AJPS11.208

20 Das N, Dune changes and its impact at Digha coast of West Bengal, *Int J Soc Sci Interdiscipl Res*, 4 (4) (2015) 37-43.

21 Mascarenhas A, Sand fences: An environment- friendly technique to restore degraded coastal dunes, *J Geol Soc India*, 71 (2008) 868–870.

22 Mascarenhas A & Murali M, Restoration of degraded sand dunes on flattened beaches of Goa: implications for coastal management, *Proc National Conference on Coastal Processes*, *Resources and Management*, (Centre for Earth Science Studies, Thiruvananthapuram), 2010, pp. 254-258.

23 Masson-Delmotte V P, Zhai A, Pirani S L, Connors C, Péan S, *et al.*, Summary for Policymakers, In: *Climate Change 2021: The Physical Science Basis*, Contribution of Working Group I to the Sixth Assessment Report of the Inter-governmental Panel on Climate Change, (IPCC, US), 2021, pp. 1-40.

24 Church J A, Clark P U, Cazenave A, Gregory J M, Jevrejeva S, *et al*., Sea Level Change, In: *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker T F, Qin D, Plattner G K, Tignor M, Allen S K, *et al*., (Cambridge University Press, Cambridge, United Kingdom and New York, USA), 2013, pp. 123.

25 Black K P, Baba M, Mathew J, Kurian N P & Ilic A, Guidelines to prepare India's coast for climate change, *J Coast Res*, 37 (6) (2021) 1117–1129. https://doi.org/10.2112/JCOASTRES-D-21-00065.1

26 Komar P D, *Beach Processes and Sedimentation*, 2nd edn, (Prentice-Hall, Inc, New Jersey), 1998, pp. 544.

27 Martinez M L, Hesp P A & Gallego-Fernandez J B, Coastal Dunes: Human impact and need for restoration, Chapter 1, In: *Restoration of Coastal Dunes*, Springer Series on Environmental Management, edited by Martinez M L, (Springer-Verlag, Berlin, Heidelber), 2013, pp. 1-14. https://doi.org/10.1007/978-3-642-33445-0_7

28 Martinez M L & Psuty N P, *Coastal dunes: formation, evolution management*, (John Wiley & Sons), 2004, pp. 390.

29 Psuty N P & Silveira T M, Global climate change: An opportunity for coastal dunes? *J Coast Conserv*, 14 (2010) 153–160.

30 NSW Department of Land and Water Conservation, *Coastal Dune Management: A Manual of Coastal Dune Management and Rehabilitation Techniques*, (Coastal Unit, DLWC, Newcastle), 2001, pp. 96.

31 Jackson D W T, Costas S, González-Villanueva R & Cooper A, A global 'greening' of coastal dunes: An integrated consequence of climate change? *Glob Planet Change*, 182 (2019) p. 103026. https://doi.org/10.1016/j.gloplacha.2019.103026

32 Johnston K K, Dugan J E, Hubbard D M, Emery K A & Grubbs M W, Using dune restoration on an urban beach as a coastal resilience approach, *Front Mar Sci*, 10 (2023) p. 1187488. https://doi.org/10.3389/fmars.2023.1187488

33 Davidson-Arnott R, Hesp P, Ollerhead J, Walker I, Bauer B, *et al*., Sediment budget controls on foredune height: Comparing simulation model results with field data, *Earth Surf Proc Land*, 43 (9) (2018) 1798–1810. https://doi.org/10.1002/esp.4354

34 Avis A M, An evaluation of the vegetation developed after artificially stabilizing South African coastal dunes with indigenous species, *J Coast Conserv*, 1 (1995) 41–50.

35 Gadgil R L & Ede F J, Application of scientific principles to sand dune stabilization in New Zealand: Past progress and future needs, *Land Degrad Dev*, 9 (1998) 131–142.

36 Farrell E J, Fernandez I D, Smyth T, Li B & Swann C, Contemporary research in coastal dunes and aeolian processes, *Earth Surf Proc Land*, 49 (1) (2024) 108-116. https://doi.org/10.1002/esp.5597