Extreme events, intrinsic landforms and humankind: post-tsunami scenario along Nagore–Velankanni coast, Tamil Nadu, India

Antonio Mascarenhas

Extreme oceanographic episodes have regularly afflicted the east coast of India. Storm surges strike annually, devastating for a period of 24–36 h, and inducing a run-up of 9 m and inundations reaching 35 km. Comparatively, the December 2004 tsunami appeared after 63 years, lasted for 1 h and caused a run-up of 6.5 m, with flooding up to 0.8 km inland. Whereas storm surges devastate vast areas, the tsunami destroyed areas within 80 m from the dune. Major impacts are: erosion and breaching of dunes, destruction of shorefront dwellings, formation of inlets and new water bodies. Extreme events confirmed that sand dunes and dense forests possess an innate capacity of attenuating wave up-rush, evidenced respectively by negligible overwash, and by modest damage only to a narrow frontal casuarina strip of 10 m average width. Recurring storm surges are of greater societal concern than an occasional tsunami.

Keywords: Coastal hazards, humankind, Nagore–Velankanni coast, storm surge, tsunami.

DESPITE frequent hydrometeorological events along the Indian east coast[1–6], the occurrence of a tsunami that devastated the Indian seafront[7–11] is yet another cruel reminder of the acute vulnerability of the coastal residents. More particularly, human loss along the Nagore–Velankanni sector (Figure 1) has sent distress signals about the viability of coastal management in India.

In view of the above, several critical issues have to be debated and resolved: sustainability of hazard-prone coasts, urbanization of vulnerable seafronts, rebuilding of devastated shores, relocation of infrastructure, need for larger buffer zones and role of ecosystems during extreme events. This article elucidates a model depicting coastal scenarios before and after the tsunami and the significance of functional coasts in the wake of natural hazards, by taking the Nagore–Velankanni coast as a case.

Bitter lessons of the past

During 1891–2000, about 26% of cyclones that formed in the Bay of Bengal hit the coast of Tamil Nadu; around 55 severe cyclones crossed this region[1]. Tamil Nadu is a vulnerable coast, as observed surge heights ranged from 1 to 6 m (refs 1 and 5), and inundations were recorded up to 16 km in the hinterland[5], compared to 35 km from the coast of Orissa[2] in October 1999. The tsunami of December 2004 was equally destructive (Table 1). Run-up levels ranged from 0.7 to 6.5 m asl, and flooding varied from 31 to 862 m from the swash zone[7,9,10]. The average inundation was around 247 m.

Around 60% of deaths due to surges has occurred along the flood-prone lowlands of eastern India[1,3]. The kind of human suffering witnessed every year following severe cyclones (Table 1), and in the aftermath of the tsunami that eliminated villages such as Keechankuppam and Akaripettai (Figure 1), is another warning that all is not well with the way our coasts are developed and colonized.

The monetary loss incurred due to extreme events over the last 50 years is staggering (Table 1). Economic damage by the super cyclone of October 1999 in Orissa crossed 2750 crore rupees[12], whereas the tsunami of December 2004 witnessed a financial loss of 512 and 2730 crore rupees in Pondicherry and Tamil Nadu respectively[13]. The figures in Table 1 are by no means complete, as the overall losses are beyond contemplation.

Coastal use, tsunami and humankind: a true copy

The brunt of natural hazards on the coasts and their people can be explained in the form of a model (Figure 2) that depicts an inhabited coast, impacts of extreme events on coastal landforms and infrastructure, and the need for a functional coastal zone for the well-being of its people. This reproduction can be based on, applied to and validated by the recurring impacts of storm surges and more particularly, the tsunami that demolished Indian coastal

Antonio Mascarenhas is in the National Institute of Oceanography, Dona Paula, Goa 403 004, India. e-mail: antmas@nio.org

strips in general, and the Nagore–Velankanni sector in particular.

Scenario 1 – A peopled coast with usurped landforms

The inhabited stretch between Nagore and Velankanni is described based on the state of landforms in November 1998. A human-altered coast is represented in Figure 2 *a*.

Occupied sand dunes: The beach front from Nagore to Nagapattinam (lighthouse) largely comprises a linear sandy beach backed by low, medium or markedly high (6 m) sand dunes. Dunes can be thickly or sparsely vegetated or bare. Luxuriant casuarina plantations are seen back shore at several places, particularly at Silladi. However, sand dunes are occupied by countless huts as observed at Nagore, Samanthanapettai and Nagapattinam coasts (Figure 3 *a*). Paths leading to the beach terminate on sand dunes. Active traditional fishing activity with boats occupying large spaces is noted all along, specially at Samanthanapettai.

High-value assets, unplanned harbour: The long beach is interrupted by a narrow inlet opposite the Nagapattinam lighthouse. Fronted by a sea wall, the creek packed with fishing craft, is used as a minor harbour. In addition, several high value, huge, oil storage tanks are located on the sea front, and along the creek. Backed by a road bridge, the port and oil tanks do not have any natural protection.

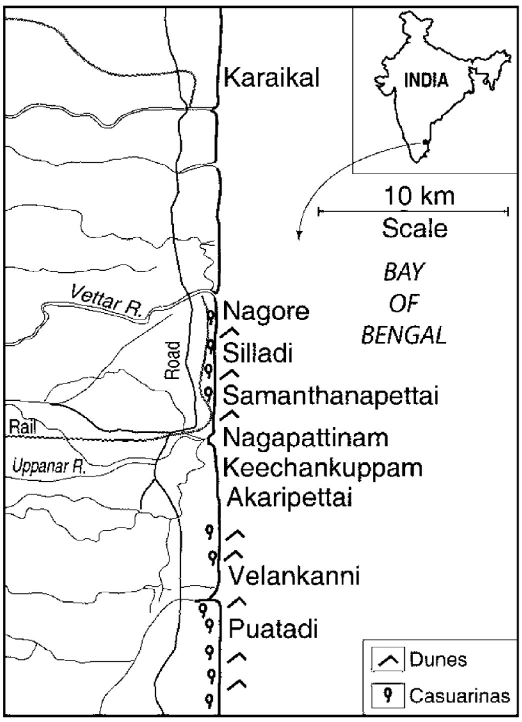

Figure 1. Location map of Nagore–Velankanni coast, Tamil Nadu (based on Survey of India toposheet no. 58 N).

Razed sand dunes: The 2 km long Keechankuppam–Akaripettai shore front was densely populated, with innumerable, small residential houses. Sand dunes have been razed and levelled to accommodate dwellings. Roads built over dunes end on the beach. More importantly, there was no adequate setback along the open sea front as houses are often built on the beach, close to the water line. Fur-

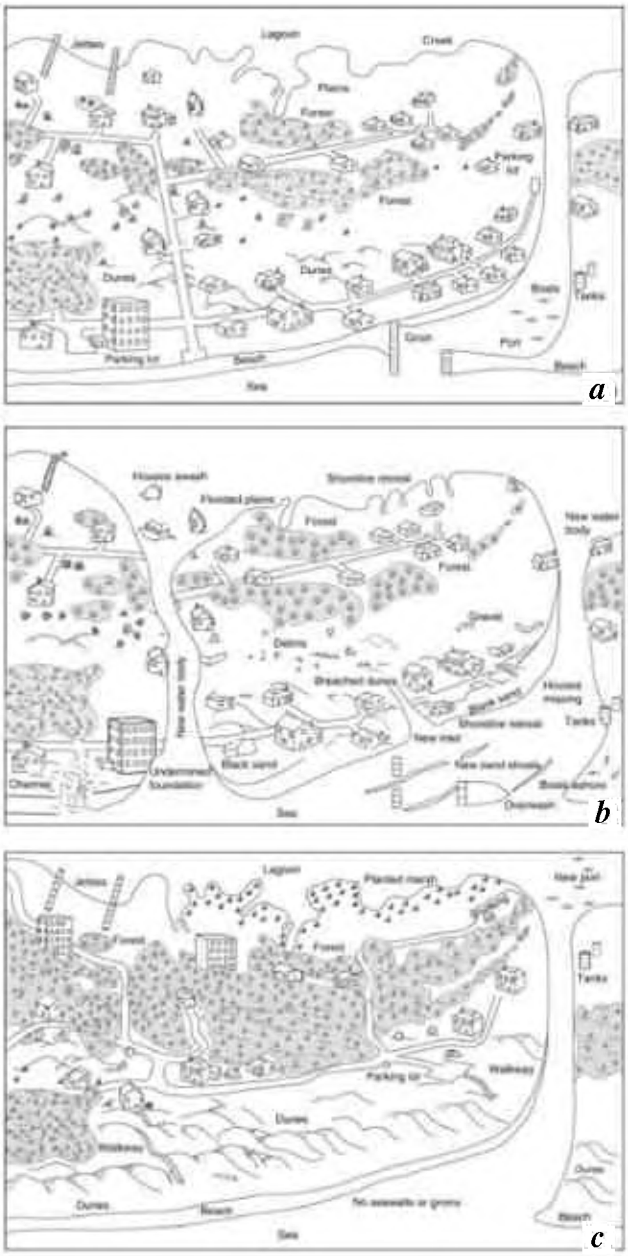

Figure 2. A model coast before and after a powerful oceanographic episode. ***a***, A human-altered coast: sand dunes are levelled, forests are cleared, roads, dwellings and infrastructure are located close to water line, setbacks are lacking. ***b***, Drastic landform changes after extreme events: sand dunes are breached, new inlets and water bodies are formed, sea walls are overtopped and uprooted, sea front dwellings are demolished. ***c***, Prudent restoration of a damaged coast: sand dunes are recreated, forests are extended, roads are redesigned, buildings are relocated inland, port is shifted upstream, sea walls are avoided, adequate buffer zones are designated.

Table 1. Human and monetary loss (crops, property, infrastructure), wave heights and actual inland penetration of sea water as a consequence of extreme events along the Indian east coast during the last 53 years (source: refs 1–7, 9, 10, 12, 13, 22)

Year of event	Place	Surge/run-up height (m)	Inland inundation (km)	Damage to embankments (km)	Overall monetary loss (crores)	Human lives lost
November 1952	Nagapattinam	1.2	8	–	6.00	400
October 1955	Kalingapatnam	1.5	–	–	1.00	–
November 1955	Rajamadam	4.5	16	–	–	500
December 1964	Rameshwaram	6.0	–	(Train, bridge swept off)	8.00	900
October 1967	Puri	–	25	–	> 1.00	~ 1000
November 1969	Kakinada	3.0	9	–	110.00	~ 900
October 1971	Paradip	6.0	10–25	–	> 1.00	~ 10,000
December 1972	Cuddalore	–	–	–	> 40.00	80
November 1976	Madras	–	–	–	7.00	95
November 1977	Nagapattinam	–	–	(Rail tracks breached)	155.00	560
November 1977	Nizampatnam	5.0	8–15	–	350.00	10,000
November 1978	Kilakkarai	5.0	–	(Road bridge dislocated)	5.00	915
October 1983	Bheemunipatnam	–	–	–	520.00	120
October 1987	Ongole	–	–	–	34.00	48
November 1988	24-Parganas	7.0	–	2	02.79	–
	Medinipur	7.0	–	20	06.36	–
May 1989	24-Parganas	6.0	–	182	56.69	485
	Medinipur	6.0	–	59	02.37	–
November 1989	Kavali	4.0	1–2	–	–	69
May 1990	Nellore	5.0	16	–	~2248.00	967
November 1991	Cuddalore	–	<1	–	323.00	201
November 1992	Tuticorin	2.0	–	–	–	~335
December 1993	Karaikal	4.0	2	–	–	111
October 1994	Around Chennai	–	2	–	–	304
May 1995	24-Parganas	7.0	–	155	44.17	–
	Medinipur	7.0	–	12	23.86	–
November 1996	Kakinada	4.0	–	–	~150.00	2000
August 1997	Digha–Haldia	2.5	–	<1	89.17	400
October 1999	Balasore–Paradip	9.0	35	–	>2750.00	9885
August 2000	Kakinada	–	–	–	~776.75	131
December 2004	Pondicherry	6.5	0.24	–	512.00	107
(tsunami)	Karaikal	2.6	0.20	(Sea wall uprooted; bridge column broken)		484
	Cuddalore	3.9	0.37	–	2730.00	606
	Nagore	3.1	0.86	–		6629
	Samanthanapettai	3.3	0.15	(Rail tracks breached)		
	Nagapattinam	3.9/5.2	0.75/0.80			
	Velankanni	3.9	0.32	–		~900

ther south, a low, flood-prone 300 m-long sandy area occurs at Kallar.

A pristine coast, an overused beach: From Velankanni to Puatadi in the south, the strip forms a fairly pristine coast with well-developed, high, vegetated, prominent sand dunes and thriving casuarina forests. A notable exception however is the kilometre-long stretch off the Velankanni shrine, a tourist coast that consisted of a wide, flat beach occupied by thatched, make-shift restaurants, shops and shacks up to the water line (Figure 3 *c*), making this sector a degraded one.

Scenario 2 – Impacts of extreme events on coastal morphology, development and society

The tsunami drastically transformed the landscape from Nagore to Velankanni as observed in April 2005. Impacts of an extreme event are illustrated in Figure 2 *b*.

Obliteration of sand dunes: Frontal sand dunes were flattened (Nagore), some were breached (Silladi), and others were eroded (near the lighthouse; Figure 3 *b*). A 30 m long damaged dune at Samanthanapettai stands testimony to the ravages of extreme events. Overtopping and overwash was noticed at places, as evidenced by gaps along the dune line, and by plant remains and dead wood debris flung on hind dunes. Dune plants were uprooted, often without a trace.

At Cuddalore, dune heights were lowered by 2 m and a 6 m high dune was razed; at Poompuhar, 1 m sand was removed, dunes were breached and levelled; barrier islands were dissected (G. V. Rajamanickam, pers. commun.). Erosional escarpments up to 2 m high were recorded on beaches of Java after the 1994 tsunami[14]. In comparison, storm surge-related beach/dune erosion was recorded at Digha, West Bengal[6] following six successive storms. Surge-induced elimination of coastal dunes is reported in the US[15,16].

Figure 3. Scenes before (November 1998) and after (April 2005) the tsunami. ***a***, Human occupation of dunes near lighthouse at Nagapattinam (11/1998). ***b***, All huts/shacks flattened by the tsunami (04/2005). ***c***, Crowded improvized structures on the beach opposite the shrine at Velankanni (11/1998). ***d***, Make-shift structures washed-off in totality by violent waves (04/2005). ***e***, Casuarina plantations survive tsunami onslaught at Silladi (04/2005) and ***f***, Trees planted by villagers by levelling a dune at Keechankuppam due to fear of another tsunami attack (04/2005) (Photos: A. Mascarenhas and S. Jayakumar).

Exposure of black sands: A distinctive black sand seam was exposed on the beach at Nagore, Silladi and opposite the lighthouse at Nagapattinam. Our surveys also revealed surficial black sand at Karaikal and Poompuhar.

At Nagore, fine-grained, heavy-mineral sands changed to medium grain size; its origin is not known. At Poompuhar, 100% black sand deposits were identified, and at Karaikal, enrichment of black sands from 13 to 75% was observed (G. V. Rajamanickam, pers. commun.). Exposure of black sands is a unique phenomenon, hitherto neither reported after storm surge events nor after tsunami attacks worldwide.

New water bodies: A characteristic permanent saline water body now occupies a former flood-prone low beach at Kallar. A narrow inlet, also a new feature, connects the lagoon to the sea. The lagoon has linked itself with the existing river inland. A similar phenomenon, on a lower scale, was identified at Silladi resulting in the road to the beach being cut-off by the new lagoon. Invasion of saline water on antecedent lowlands was frequently reported following storm surges in India[4–6,17], and after major storms in the US[16].

Roads, creeks, dune breaches as tsunami pathways: Roads leading to the beach served as conduits for the tsunami to travel inland, as in Nagore, Silladi, Nagapattinam lighthouse and opposite the shrine at Velankanni. Near Mahabalipuram and Chidambaram, roads perpendicular to the coast aided in the passage of the tsunami. Similarly, coastal roads facilitated flow of storm-surge waters in Orissa, after the 1999 supercyclone[2]; incidents are also reported along the US coast[16].

The inlet opposite Nagapattinam lighthouse promoted tsunami movement into the hinterland; boats were tossed ashore. The foundations of two large oil storage tanks suffered severe erosion on the creek side due to undermining by waves. At Karaikal, the tsunami travelled about a kilometre inside the river and smashed an arched column of a heritage bridge. At Vedaranyam, the sea water crossed more than 2 km inland[9]. Likewise, gaps on dunes and inter dune valleys also contributed to overtopping, overwash and tsunami advance as in Nanjalingampettai near Cuddalore, where sea water reached 372 m inland[10]. Similar episodes were reported at many places along the Indian coast[7,9,10].

Sedimentary deposits and other debris: A red, clayey deposit was noted about 100 m inland at Perikalapet (Pondicherry). Gravel was flung 60 m inland at Tarangambadi, whereas sand was transported 430 m from the swash zone of Nagapattinam[7]. Interestingly, beach profiles at Nagore showed 50 m^3 of sand in January 2005, which changed to 24 m^3 in February 2005, indicating that tsunami had induced accretion (G. V. Rajamanickam, pers. commun.). Also, displaced roof tiles, broken masonry, wooden pieces, tree branches and dead wood were common backshore occurrences during surveys.

Run-up associated with global ocean extreme events revealed that a 2002 storm deposit extends 40 m inland compared to 200 m for a 15th century tsunami of North Island, New Zealand[18]. Granule to cobble-size clasts, extending 200 m landward, form a distinctive tsunami deposit on sand dunes of Great Barrier Island, New Zealand[19].

Beach front structures washed out: All houses and particularly huts situated on frontal dunes over a long beach tract at Nagore, Samanthanapettai and Nambiar Nagar were demolished in totality. The worst affected was the Keechankuppam–Akaripettai village strip that is now abandoned. Improvised shops and temporary structures at Velankanni were washed off (Figure 3 *d*). Such a ghastly scenario of water-front houses in ruins was observed at more than 25 sites wherever the tsunami made its presence felt.

Shattered dwellings were also reported from other coasts of the mainland[7–9] and the Andamans[8,9]. Storm surges created similar disasters[1–3,6]. Elsewhere, extensive damage was observed in Sicily and Calabria, Italy[20] in 1908 and in coastal Java[14] in 1994, where dwellings were levelled by violent tsunami waves.

Casuarina trees intact, an exception: Casuarina plantations survived the onslaught; only frontal trees within a narrow strip of 10 m average width were affected (Figure 3 *d*).

Scenario 3 – A natural, functional and sustainable coast

Lessons learnt from extreme events have set a new paradigm for coastal management worldwide[15,16,21]. Knowledge of coastal ecosystems and geological processes is gaining importance. Sand dunes, coastal forests and wetlands have an explicit role to play and valuable functions to perform[16,22]. Coastal inhabitants thus stand to benefit. To substantiate our concept, Figure 2 *c* attempts to: (i) restore a damaged coast by accounting for natural systems, and for which spaces have to be designated, and (ii) simultaneously grant adequate place for human needs.

Functions of sand dunes: As geomorphic features, sand dune complexes act as physical barriers and protect the hinterland from the forces of the ocean, including wave run-up due to extreme events. Wide beaches and high dunes act as efficient dissipators of wave energy. Sand dunes serve as a store that waves draw on and, as such, act as natural shields between the ocean and inland property.

The high dunes at Samanthanapettai and Nambiar Nagar (Figure 1) stopped the tsunami from advancing further as the run-up was 1.9 to 3.2 m (ref. 10), and lower than the dune; the overwash was minimal (Table 1). Also, the dune coast of Silladi and Puatadi withstood the test. Sand dunes efficiently blocked the advance of the tsunami at other sites as well[7,9,10]. In comparison, Nagore witnessed sea levels of 3.1 m followed by water intrusion 862 m inland[10]; a road from the razed dune provoked the advance of the tsunami. Similarly, the lighthouse point experienced wave heights of 3.9 (ref. 9) and 5.2 m (ref. 7), and sea water intrusion of 750 (ref. 9) and 800 m (ref. 7), specifically because sand dunes were levelled and occupied. The Nagapattinam lighthouse wall collapsed, and foundations of oil-storage tanks were eroded. These high-value structures lacked natural buffers.

That sand dunes stand guard in the wake of extreme events is well documented[3,6,15,16,21,22]. Human interference on dunes in West Bengal[6] led to sediment-deficit over time, resulting in man-induced erosion, shoreline recession, submergence of beaches evidenced by inundations, destruction of habitations and resorts during successive storms. Sand dunes should therefore be allowed and be able to develop, migrate and evolve freely and naturally in form and space.

Functions of coastal forests: Coastal vegetation plays a protective role as energy dissipators during powerful oceanographic events[15,17,22,23]. Our post-tsunami surveys confirmed that casuarina plantations and coconut groves are intact and healthy after the tsunami onslaught. Only frontal casuarina strips of less than 10 m average width were attacked, bent and their leaves stripped-off by wave up-rush. This phenomenon was verified in Puatadi, Samanthanapettai, Silladi, Karaikal, Nanjaligampettai and Maha-

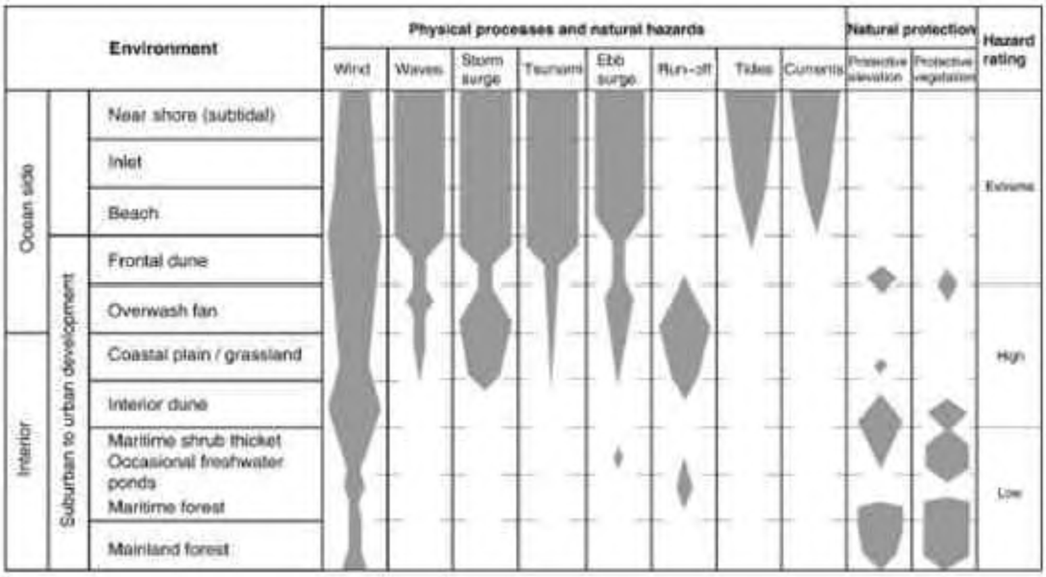

Figure 4. Intensity of natural hazards and corresponding risks in a natural coastal environment; thickness of hatched portions indicates intensity of or protection from hazards (adapted and modified from Pilkey *et al.*[16]).

balipuram along Tamil Nadu coast, and Karaikal and Perikalapet in Pondicherry. Sea-water intrusion was negligible in areas covered with thick vegetation, and damage to assets was less on shorelines lined by mangroves[7,11] compared to bare lands of the Andamans[8,11].

Interestingly, at Mahabalipuram, casuarinas were unharmed, whereas acacias in the same row were totally bent and their leaves stripped-off, and some were dead. The selection of species for coastal afforestation needs prudent planning. All the same, due to fear about future tsunamis, or for want of authoritative guidance, or due to lack of awareness, villagers at Keechankuppam planted trees on the beach, by levelling existing dunes, and by creating a sand barrier along the water line (Figure 3*f*). Such 'afforestation' efforts are inappropriate.

Functional bio-shields involve a progression of species landward from the dune line[15]. Herbs–shrubs–bushes–trees form a gradation and a natural slope wherein winds get deflected upwards and on-rushing waves decay quickly. In this respect, Bangladesh has planted fringing mangroves to infill the occupied coastline[15,23]. Casuarina plantations along Nagore–Nagapattinam–Velankanni[22], Karaikal and Cuddalore coasts are some examples of dense, natural bio-shields that need protection.

Coastal environments and associated processes as natural hazards are depicted in Figure 4. Physical forces and geological processes in natural environments are more intense on the ocean side. Strips closer to the coast are therefore vulnerable to oceanic power, and hence hazardous to build. Man-made modifications of the coast experience extreme processes owing to lack of natural protection. Such sites become vulnerable to natural hazards[16]. In comparison, the forested highlands are sufficiently protected. This function is demonstrated by casuarina forests (and coconut groves) that acted as efficient soft barriers to tsunami advance. Therefore, protective vegetation (and elevation) is the only coastal environment where risks of impacts due to extreme events are modest.

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