

Oceanographic validity of buffer zones for the east coast of India: A hydrometeorological perspective

Antonio Mascarenhas

Relentless hydrometeorological events are the major natural hazards that have afflicted the inhabitants of the east coast. Storm surges have attained a height of 12 m, and provoked sea water invasion 35 km inland. Loss of life (10,000 people in 1977) and destruction of property (12 lakh houses in 1999) are devastating. Monetary loss of a single event touched 2248 crore rupees. Flattening of sand dunes, removal of coastal forests, reclamation of wetlands, inappropriate layout of buildings and roads reduce the inherent functional potential of ecosystems and correspondingly enhance the degree of risk. Abandoning vulnerable coasts, managed retreat, or safer setback with intervening forested landforms are feasible long-term options. The Coastal Regulation Zone does not protect lowlands prone to inundations due to storm surges; hence adaptation rather than mitigation should be the key of hazard management. A public policy that identifies coastal geological processes, recognizes the protective value of coastal landforms, acknowledges mandatory buffer zones and considers options for adaptation, is the sustainable alternative to attenuate the ravages of hydrometeorological events.

THE most damaging oceanographic episode that coastal residents can face is a cyclone with a combination of wind, waves, surge and rain. Meteorological information shows that more than 1000 cyclonic disturbances occurred in the Bay of Bengal during the last century¹, among which over 500 were either depressions or deep depressions, and over 400 were either cyclonic storms or severe storms (Table 1). The east coast of India has been affected by a minimum of four high-intensity cyclones every year for the past 100 years². The accompanying surge of water is capable of massive damage when the cyclone hits the coast. The super cyclone that battered Orissa in November 1999 is a grim reminder of how the coastal population ultimately pays the price.

Research dealing with meteorological implications to society is replete with forecasts, predictions, wave, surge and inundation models, disaster zoning and mitigation measures³⁻¹⁰. The Tropmet 2001 seminar organized by India Meteorological Department (IMD) discussed similar topics under the theme 'meteorology for sustainable development'^{10,11}. More importantly, the Science and Technology Policy-2003 proposes technologies for the mitigation and management of natural hazards with special emphasis on forecasting, prevention and mitigation¹². However, no attempt is made to resolve whether or not coasts prone

to hydrometeorological hazards should be occupied, urbanized or regulated, or, whether adaptation or retreat rather than mitigation is the key.

An important prerequisite for sustainable development is resilience towards natural hazards and elimination of disasters. With this objective in view, this article attempts to draw attention on whether hazard-prone coasts are sustainable, whether coasts prone to natural hazards should be urbanized or regulated, whether greater setbacks or buffer zones need to be maintained, or whether lack of coastal hazard policies is the cause of recurring loss of life and property in the wake of recurring hydrometeorological events.

Damage potential of hydrometeorological events

Flooding of hinterland by storm surges

Historical records (Table 2) reveal how hydrometeorological events raised sea levels, leading to floods onshore. The super cyclone of October 1999 that generated a wind speed of 252 km/h with an ensuing surge of 7 to 9 m at Paradip, causing unprecedented inundations 35 km from the coast¹³, is another eye-opener. It is worth noting that, at times, persistent standing waters were identified in the satellite imagery even eleven days after the cyclone crossed the coast along the Krishna delta in May 1990 (ref. 4). Inundations lasted longer in Orissa in October 1999 (refs 13 and 14).

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

Threats to coastal population, buildings and dwellings

In October 1999, 12 coastal districts in Orissa suffered severe damage, 9885 persons died, 2142 people were injured and 12 lakh houses were damaged¹³. Similarly, more than 10,000 lives were lost around the Krishna delta in Andhra Pradesh in 1977 (ref. 15). Coastal hotels and resorts were inundated and habitations destroyed at Digha in August 1997 (ref. 16). The number of displaced people is increasing as more land is eroded following violent storms¹⁶. Most of the masses that occupy countless low-lying plains comprise farmers who live in mud houses; this section of society bears the recurring loss of humans, livestock and property (Table 3).

Damage to property, agriculture and livestock

Following every extreme event, private holdings, property and agricultural lands are invariably destroyed (Table 3).

After the super cyclone of October 1999, 12 lakh houses were damaged, over 2 lakh cattle perished, and crops over 13 lakh hectares were irreversibly affected¹⁵. Property damage is regional and increases with successive storms, as observed along the shorelines and channel banks of West Bengal¹⁶.

Threat to infrastructure (communications, roads, embankments)

Communication and transportation facilities are mostly paralysed. Roads are often submerged, communication towers crashed, even a railway train was swept away in 1964 in the Palk Strait². The damage potential seems to be increasing in various forms as defence structures such as embankments and seawalls are washed away, and hence unable to withstand the force of storms. The Digha seawall was damaged to a stretch of 1.5 km due to wave attack and overwash following successive cyclones¹⁶.

Table 1. Details of various types of wind systems that formed in the Bay of Bengal and affected the east coast of India during the period 1891–2000. (Compiled from refs 1, 5, 6, 9, 13, 16, 20 and 22.)

Type of disturbance	Cyclonic disturbance	Depression/deep depression	Cyclonic storm	Severe cyclonic storm
Number	1087	635	279	173
Maximum (1891–1991)	158 (Aug.)	131 (Aug.)	51 (Oct.)	38 (Nov.)
Minimum (1891–1991)	4 (Feb.)	1 (Mar.)	0 (Feb.)	1 (Jan.)
Yearly average	10	6	3	1.5
Per cent of total	–	58	26	16
Wind speed (km/h)	31–118	31–61	61–88	88–118

Table 2. Location, maximum wind speed, observed height of associated storm surges and actual inland penetration of sea water during some severe tropical cyclonic events that affected the east coast of India. (Source: Refs 1, 3, 6, 9, 13, 16 and 22.)

Period	Coast affected	Maximum wind speed (km/h)	Maximum surge height (m)	Hinterland inundation (km)
October 1737	Hoogly river, West Bengal	272	12.1	100
May 1823	Balasore, Orissa	–	–	10
November 1867	East of Calcutta, West Bengal	60	1.8	–
October 1942	Medinipur, West Bengal	–	5.0	40
October 1949	Masulipatnam–Kakinada, Andhra Pradesh	137	4.5	15
November 1952	Nagapatnam, Tamil Nadu	88	1.2	8
October 1955	Kalingapatnam, Andhra Pradesh	111	1.5	–
November 1955	Rajamadam, Tamil Nadu	193	4.5	16
December 1955	Tanjore, Tamil Nadu	200	5.0	3–8
October 1963	Cuddalore, Tamil Nadu	139	6.0	–
December 1964	Rameshwaram, Tamil Nadu	278	6.0	–
October 1971	Paradip, Orissa	170	6.0	10–25
November 1973	North of Paradip, Orissa	137	4.5	–
August 1974	Contai, West Bengal	139	3.0	–
September 1976	Contai, West Bengal	160	3.0	–
November 1977	Nizampatnam, Andhra Pradesh	193	5.0	8–15
November 1977	Divi–Machilipatnam, Andhra Pradesh	120	5.0	12
November 1978	Ramanathapuram, Andhra Pradesh	204	5.0	–
May 1979	South of Ongole, Andhra Pradesh	160	3.6	–
November 1989	Near Kavali, southern Andhra Pradesh	222	4.0	1–2
May 1990	Nellore, Andhra Pradesh	102	5.0	16
November 1991	Karaikal, Tamil Nadu	89	–	< 1
November 1992	Tuticorin, Tamil Nadu	113	1.0	–
December 1993	Karaikal, Tamil Nadu	133	4.0	2
October 1999	Paradip/Balasore, Orissa	252	9.0	35

Changes in land-use patterns

A drastic transformation in the patterns of coastal land use is the frequent result of a cyclone. Fertile areas have turned into saline wastelands due to marine incursions. Standing crops are destroyed; salt deposits from saline waters render farms barren and unproductive. An entire cropping season is completely offset. Areas struck by severe storm surges have often been the scene of famine a year or two later².

Modifications of coastal landforms

Severe cyclonic events are responsible for dramatic modifications of the landscape. The cyclone of October 1999 resulted in heavy sedimentation near the coast of Orissa¹⁴; the receding waters brought additional silt. Extreme events result in severe shoreline changes and hence affect coastline configuration: beach and dune erosion, modifications of dune complexes, dune breaching, overwash, inlet formation and, at places, complete elimination of sand-dune complexes is documented^{16,17}. In West Bengal, more and more land is being eroded following violent storms¹⁶.

Alterations of coastal vegetation

Casuarina plantations of 1954 and 1971 at Gahirmatha collapsed under the force of winds during the super cyclone of October 1999, as frontal trees did not withstand heavy winds¹⁸. Similarly, post-cyclone satellite images showed partial damage to coastal trees, including mangroves in Orissa¹⁴.

Effect on ports and fishing harbours

In November 1966, a tidal bore battered Madras port. Tuticorin harbour was directly hit in November 1992;

breakwater and pier heads were damaged¹⁹. Harbours were paralysed along Digha–Haldia sector in August 1997 (ref. 16). Minor ports of Machilipatnam and Krishna delta were affected in November 1977 (refs 1 and 20), and trawlers got drowned in Haldia in August 1997 (ref. 16). Should a seaport be shut down, as witnessed at Paradip in October 1999, the overall losses are beyond contemplation.

Vulnerability of the east coast of India

In terms of landfall, among the severe cyclones over a century (Table 1), 55 crossed the coast of Tamil Nadu, 69 hit Andhra Pradesh, 58 affected Orissa, 33 struck West Bengal¹. Available records reveal that the Andhra coast is the most vulnerable; about 32% of the cyclones that form in the Bay of Bengal makes landfall along this coastal state every year; followed by Orissa coast with 27%, Tamil Nadu with 26% and West Bengal with 15% (ref. 1). In the Bay of Bengal, cyclonic disturbances are the most frequent during September–November. The Andhra coast has been subjected to storms, with a highly significant increase in the mean frequency of severe storms incident on Andhra coast after 1965 as compared to earlier periods^{5,21}. Orissa is affected by the highest frequency of severe cyclones in October and November every year, with highest probability (56%) of at least one cyclone crossing the coast and 1% probability of four cyclones crossing Orissa every year⁹.

In terms of storm surges (Table 2), hydrometeorological phenomena cause extensive inundations of low-lying plains^{1,3,6,9,13,16,22}. The West Bengal coast is highly vulnerable to attack by storm surges with heights ranging from 2 to 12 m. The coast of Orissa has witnessed maximum storm surge heights of 7 m. The Andhra Pradesh and Tamil Nadu coasts are also in the list of vulnerable coasts, where observed surge heights are in the range of 1 to 6 m.

Table 3. Location and impact of some severe cyclones that affected Indian coasts during the last 25 years. (Source: Refs 1, 13, 15, 16 and 20.)

Period	Location	Impact/Damage
19 November 1977	Divi, Krishna River delta, Andhra Pradesh	At least 10,000 lives lost; standing crops washed away; persistent flooding even 11 days after the cyclone struck.
27–29 May 1989	24 Parganas/Medinipur, West Bengal	485 lives lost; 2,02,468 houses damaged; standing crops washed away; 239 km of protective works destroyed; dune barrier breached.
4–10 May 1990	Machilipatnam, mouth of River Krishna, Andhra Pradesh	967 deaths; 6,00,000 houses destroyed; 21,600 cattle, 35,00,000 poultry, 42,700 goats perished, damage to agriculture.
11–17 November 1992	Tuticorin, Tamil Nadu	170 killed; 160 missing; 1 to 2 m storm surge at Tuticorin.
1–4 December 1993	Near Karaikal, Tamil Nadu	111 killed; 1 to 1.5 m storm surge.
29–31 October 1994	Chennai and around, Tamil Nadu	304 killed; 1 to 2 m storm surge; 1,00,000 huts destroyed; 60,000 hectares of crops damaged.
7–10 November 1995	Gopalpur, Orissa	96 killed; 1.5 m surge; 2,84,253 hectares of crops damaged.
5–7 November 1996	Kakinada, Andhra Pradesh	978 killed; 2 to 3 m surge; 1375 missing; 6,47,554 houses damaged; 1,74,000 hectares of crops damaged.
22–24 August 1997	Digha–Haldia, West Bengal	400 fishermen missing; 1,60,400 people homeless; coastal hotels inundated; 40 trawlers drowned; 10,000 houses destroyed; over 600 m of seawalls and embankments devastated; prawn hatcheries swept away; harbours paralysed.
29–31 October 1999	Balasore/Paradip, Orissa	Super cyclone; 7–9 m surge; inundations up to 35 km from coast; 9885 persons died; 2142 people injured; 12 lakh houses damaged; over 2 lakh cattle killed; 13 lakh hectares of crops affected; port activity paralysed.

Andhra Pradesh and Orissa are the most vulnerable to coastal inundations⁹.

Lessons learnt

Impacts of tropical cyclones have been and continue to be the most disruptive recurring events for coastal inhabitants of eastern India. Nowhere are the losses more severe as in the coastal states surrounding the Bay of Bengal. About 60% of deaths due to surges has occurred along the flood prone coastal lowlands bordering the bay^{3,15}.

The coastal tract comprising Digha, Contai, Dariapur, Khajuri, Nandigram and Haldia is an example where all types of storm impacts have been documented¹⁶. Although inhabitants of coastal lowlands feel secure in the midst of surrounding embankments and seawalls, these structures neither survive nor can save themselves during a catastrophe, as evidenced by recurrent damage to 430 km of embankments at 24-Parganas, Medinipur and Digha by six cyclones between 1988 and 1997 (ref. 16).

In terms of monetary loss, records reveal that the damage due to storm surges during 1945–75 is estimated to be 7 billion USD³. Some independent estimates indicate the following^{1,16}: November 1969, Godavari, Rs 110 crores; November 1977, Nagapattinam, Rs 155 crores; November 1977, Nizampatnam, Rs 350 crores; October 1983, Bhemunipatnam, Rs 520 crores; May 1990, Machilipatnam, Rs 2248 crores; November 1991, Cuddalore, Rs 323 crores; May 1995, 24-Parganas, Rs 68 crores; August 1997, Hughli estuary, Rs 89 crores. These figures are by no means complete.

Every cyclone creates a considerable impact on the economy and slows down the economic activity of the region. We now know that the costs of impacts keep rising, probably due to the fact that coasts become more developed and diverse. Coastal planners should therefore realize that the monetary losses are recurring, prohibitive, ever-mounting, and hence unsustainable. Herein lies the need for an introspection.

Raison d'être for coastal buffer zones

Enhanced cyclogenesis: an issue of concern

In the Bay of Bengal, sea temperatures are increasing since 1951 (ref. 23). In the event of a warmer globe, it is likely that an increase in sea surface temperature will be accompanied by a corresponding increase in the intensity of wind speed. An eventual increase in the intensity, if not the frequency, of the Bay of Bengal cyclones is most probable²³. Higher sea temperatures can also result in an amplification of storm surge heights. Therefore, higher sea temperatures will invariably lead to higher storm surges, an enhanced risk of hazards along the east coast of India.

Existing data of 122 years already indicate an increasing trend and an enhanced cyclogenesis during November

and May. There has been a twofold increase in the cyclone frequency over the bay during November, and a 25% increase in the intensification rate of cyclonic disturbances to severe cyclone stage²⁴.

Inland gradients further indicate that most of the east coast north of Nagapatnam is a low-lying region. In the event of a sea level rise of 1 m, lower coastal slopes and higher cyclone frequency will lead to an increase in storm surge activity²⁵. Computed experimentation also indicates that maximum coastal inundations can be expected between Nagapatnam in the south and Gopalpur in the north. Inland penetration of storm surge waters are also expected to affect the same stretch up to 4 km on an average, the maximum penetration of 30 km being in the Ongole–Divi stretch²⁶.

Historical evidence reveals that Kakinada area, for example, was affected by several cyclones¹: December 1706, December 1878, November 1938, October 1949, May 1955, May 1969, November 1969, November 1996, October 1998. As a consequence, Kakinada has been attacked by storm surges of the order of 2.6 m in 1969 and 1.5 m in 1996 (ref. 5). The Krishna River delta area was swept by 16 severe cyclonic storms and about 60 cyclones in the past 100 years²⁷. Similarly, the West Bengal coast was relentlessly inflicted by storms, major ones occurring in 1943, 1950, 1970, 1983, 1988, and 1995; recurrence interval of cyclones with wind speed > 80 km/h is every 3.6 years, whereas storms with wind speeds > 150 km/h is every 5.5 years¹⁶.

The coastal lowlands of eastern India appear more and more prone to the recurring incidence of severe cyclones in future. This research confirms the kind of vulnerable situation that the inhabitants of the east coast are in.

Management of hazard-prone coastal lowlands

Behaviour of historical storm surges has led to the formulation of several models: areas prone to various degrees of flooding^{8,9}, high disaster risk zones^{4,7}, and flood hazard classes of vulnerable areas^{10,27}. Here, it is pertinent to note that most research concerns predictions and mitigation, and is only of academic interest. No attempt is made to tackle management and/or urbanization of coasts susceptible to hydrometeorological events¹¹.

The obvious natural hazards notwithstanding, intense coastal development and growth of settlements have proceeded at a rapid pace during the last two decades. In addition to coastal cities, the Nagore–Nagapattinam stretch where the poor have occupied sand dunes, Chennai–Mahabalipuram strip with high-value buildings along dune belts, and Uppada area north of Kakinada with an entire village along an eroding beach can be cited as some examples of crowded coastal strips. Modern development comprises resorts, dwellings and roads over sand-dune belts¹¹ and in wetlands, industries, mills, nuclear power stations and even spacecraft launch facilities, all located

in hazard-prone areas². Regrettably, perilous regions are being rebuilt as land reclamation projects encourage constructions in dangerously low-lying areas. Recent satellite images confirm these trends (Figure 1). Impacts are seen in the form of obstruction of natural drainage patterns, deterioration of channels, beach erosion, dune breaching and channel sedimentation as observed in Andhra^{4,27}, Orissa¹⁴ and West Bengal¹⁶. A multitude of people and structures in susceptible stretches only increases their vulnerability to hazards, as such settings are most severely inflicted. Apparently, the severity of damaging cyclones has not been a deterrent to coastal construction efforts.

Emplacement of embankments or seawalls along vulnerable stretches is believed to eliminate or reduce damage from sea water inundation. Reinforcing or raising the height of embankments has been adopted at places to protect high-value hinterland. West Bengal, with a coastal length of 350 km, has 4000 km of embankment within the low coasts¹⁶.

Although they guard against tides and reduce surge energy, storm surges have overrun and overtopped embankments in West Bengal¹⁶ and Bangladesh²⁸. Although susceptible regions have been engineered to secure shore-

lines, confirmed damage due to extreme events is often greater in stabilized areas^{17,29}. Hard protective structures provide a false sense of security often turning into hazards themselves, as they block or slow down return run-off of flood waters, as evidenced by persistent flooding^{16,17,28-30}, recurring loss of life and staggering economic loss following hydrometeorological events^{1,2,16}. The failure of artificial hard structures indicates the unsustainability of expensive coastal protection works.

Experiences from storms have set new directions for coastal management on a global scale^{30,31}. Knowledge of coastal geological processes is evolving into a modern endeavour of applied societal importance. In this, the interaction of forces of nature with human-built coastal environment is a fundamental process that has to be understood. Coasts offer natural buffer protection, a beneficial function that needs acknowledgement. But when human development gets in the way, coastal physical and storm processes turn into natural hazards that often culminate in disasters^{32,33}. Without the human-built environment to interact with, storms are a different matter^{17,31}. Impacts of hazards are thus consistently amplified by human alterations of the coastal environment. Therefore, when coastal

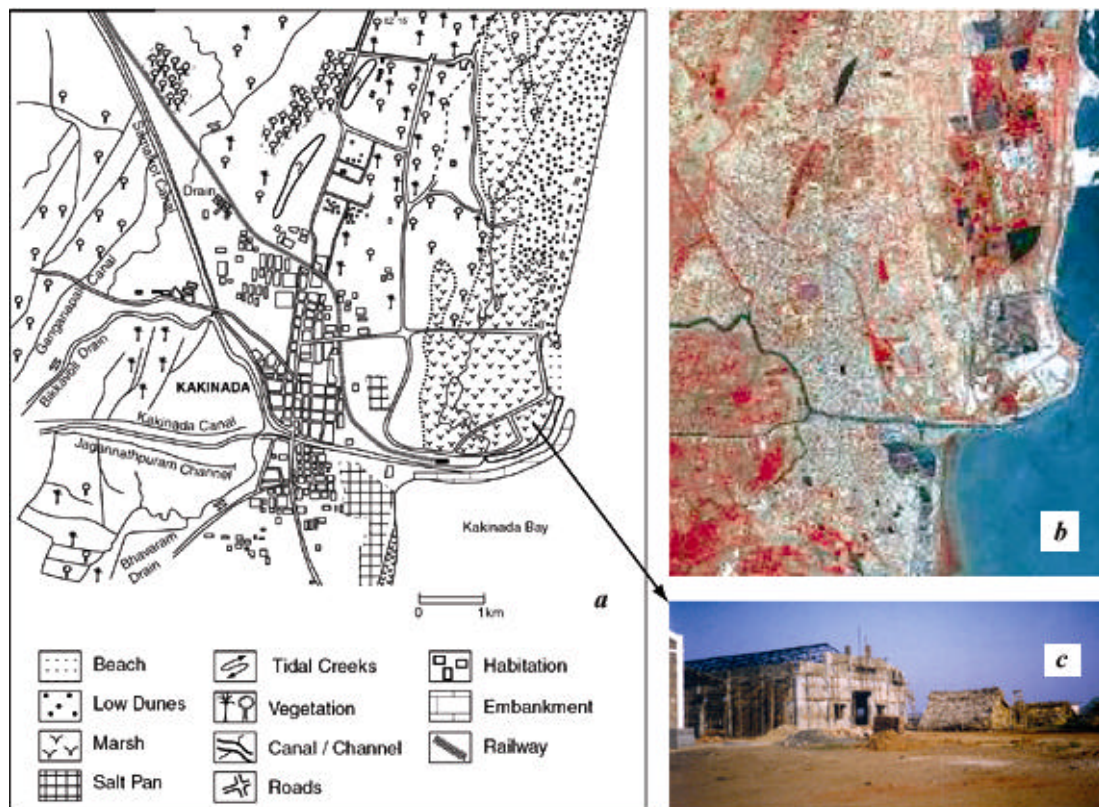


Figure 1. Map showing the geomorphology around Kakinada. *a*, The network of canals, channels and drains amidst cultivated fields acted as pathways that facilitated the quick release of storm surge water back into the sea after the cyclone of 1996. The coastal strip, 2.5 km in width, consisted of tidally influenced marshy wetlands adjoining a sandy beach-dune system in 1975. *b*, A recent IRS LISS II satellite image shows that these coastal lowlands are now being reclaimed. *c*, Several godowns (?) under construction (in November 2000) without an appropriate setback now occupy this open sea coast. (Map is based on Survey of India Toposheet No. 65 L/I of 1975; Photo: Antonio Mascarenhas.)

processes are ignored and natural protection removed, the vulnerability to hazards is increased as there is no way to defend an onshore structure against direct surge attack. Historical events have continually proved this fact.

The benefits of a sustainable coast that offers natural functional refuge compared to artificial hard structures that render false protection, are management options that have to be considered, as each destructive event often leads to a new suite of coastal structures. The new seaward-most construction line often remains the same, or gets even closer to the shore than it was prior to the storm^{31,33}. Therefore, retreating further inland by adopting safe setbacks is the only feasible long-term management option for vulnerable coasts.

Rationale for coastal setback lines and buffer zones

The shore front is a site of extraordinary release of natural energy. As such, risks afflict those structures that come directly in the path of the storm-driven, physically powerful oceanic forces. Cost-effective approach to coastal development is the one that respects the strength of natural energy operating at the shore. Coasts need to be functional, for which coastal systems need space to evolve.

A close look at the dynamics of coastal spaces reveals that anthropogenic modifications of natural landforms affect coastal storm response. Hard structures along coastal strips alter coastal geological processes and enhance their impacts^{16,22,29-31}; roads and beach access become over-wash passes for flood and ebb currents; seawalls obstruct lateral sediment movement; jetties block sand transport; removal of vegetation results in erosion by wind and water. The ocean front is the most hazardous to build, a place where mistakes can be costly³¹, provided the functions of coastal systems are accounted for.

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

The protective role of dune fields in the wake of extreme events is well documented globally^{30,31,33,34} and can also be demonstrated for the Digha coast of West Bengal¹⁶. Urbanization of sandy coasts demands levelling and hence large-scale removal of sand dunes. Razing of dunes and a consequent sediment deficit over time resulted in man-induced erosion, shoreline recession, submergence of beaches and loss of wave-absorption capacity of dune coast. Human interference on dunes leads to inundations and destruction of habitations, dwellings and resorts during extreme events in West Bengal¹⁶.

Building and nourishing sand dunes eliminate the need for hard structures. Dunes should be allowed and be able to migrate, develop and evolve freely and naturally in form and space. However, coastal dunes are under serious threat due to indiscriminate anthropogenic activities (see Figure 1) and hence these features are unable to act as protective landforms against wave attacks. As such, an adequate cushion between water and artificial structures is crucial for the functioning of coastal dune systems. Sand dunes are of immense value to society.

Role of coastal vegetation: Coastal vegetation plays a significant role in shore-front dynamics. Beach and dune grasses baffle winds thus causing sand deposition and creating higher, wider and laterally continuous dunes. Similarly, marsh grass traps sediments, allowing the marsh to build upwards. Coastal forests, particularly mangroves, substantially reduce wind speed of cyclones, and also reduce the height of associated surges. Lack of vegetation along coasts implies unstable sedimentary landforms³⁰.

Imageries of Orissa coast show healthy vegetation, whereas post-cyclone images show that damaged mangroves regained their original status within two months¹⁴. It is found that the Sunderban mangrove areas of Bengal suffer less from wind and surges than those areas with less or no mangroves²⁸. Similarly, casuarina trees can survive wind speeds of 100 km/h¹⁸. This evidence confirms the utility and role of coastal forests as shelter belts along coasts.

Green shelter belts can be created by strip planting of shorelines. Such buffer zones serve several purposes: (a) shrubs control erosion and stabilize the shore; (b) green belts significantly alleviate wind energy thus protecting the hinterland from oceanic forces; (c) a green belt of trees effectively reduces the force of devastating storm surges and waves; (d) trees are beneficial for biodiversity and can induce habitats for wildlife³⁰; (e) people inhabiting hazard-prone coasts would benefit from green belts in terms of security, access to food, materials, shelter and income^{30,35}; (f) strips behind the green belts serve as areas of peace and tranquillity.

For functional green belts, a gradation of species from the edge of open-sea coastline towards the hinterland is needed: a pioneer zone of shallow-rooted herbs, a mid-shore zone of medium-rooted shrubs, a backshore zone of deep-rooted hydric species of taller trees as casuarinas, coconut, and eventually fruit-bearing trees on higher land. This gradation forms a natural slope that forces winds to deflect upwards and onrushing waters to attenuate energy.

In this respect, Bangladesh has already planted fringing coastal mangroves and is now planning a green belt to infill the entire occupied coastline^{28,30}. Casuarina plantations that we see along Nagore–Nagapatnam stretch, Vailankani coast, the strip adjacent to the east coast highway in Tamil Nadu, Kakinada–Uppada sector, Gahirmatha zone in Orissa¹⁸ are some examples of protective coastal forests along the Indian east coast.

Role of wetlands: Coastal lowlands are nature's flood reservoirs as channels, lakes, ponds and marshes distribute flood waters, whereas natural topographic depressions can hold large amounts of surge water. However, such settings are fast diminishing as structures are being located in reclaimed low-lying vulnerable areas, as observed close to the shoreline of Kakinada (Figure 1). In West Bengal, reclaimed coastal lowlands are presently inhabited by seven million people¹⁶. Similarly, anthropogenic pressures and inappropriate land-use patterns on wetlands of Krishna delta region^{4,27} have led to obstruction of natural drainage channels thus reducing tidal spill areas, deteriorated channels due to erosion, increased channel sedimentation and hence decreased channel depth. Wetlands are thus unable to function, resulting in persistent standing waters and increased flooding and damage following extreme events. For this reason, floodlands need to be designated so that excess water from marine incursions may be accommodated³⁰.

The significance of a network of canals and drains, in addition to tidal creeks, within the lowlands of East Godavari district need to be noted. Such interlinked drainage systems have alleviated the impacts of storms by receiving, accommodating and returning surge waters back into the sea (Figure 1). Desilting of reservoirs and drainage improvements are essential. The role of wetlands in dispersing storm energy has rarely been documented.

In brief, natural coastal landforms take the brunt of storms and thus protect lives and property. Bitter lessons of the past emphasize the need to utilize the natural buffer capacity of coastal ecosystems such as sand dunes, coastal forests and wetlands. That is why protection against natural hazards begins with preservation of natural coastal landforms that have natural resistance against wave attack, flooding or erosion. Vegetated landforms have an inherent hazard-prevention value and hence reinforce the need to classify them as critical areas to be preserved. Therefore, setback lines should be delineated at a safe point inland and all development kept beyond it.

Policies for natural coastal hazards

The Coastal Regulation Zone (CRZ) Notification³⁶ has placed India amongst the select countries in the world to frame laws to legally protect sensitive coastal ecosystems, to formulate guidelines for coastal activities, and to demarcate areas for conservation³⁴. CRZ I protects ecologically fragile systems, and also includes areas likely to be inundated due to rise in sea levels due to global warming. However, there is no provision whatsoever to mitigate, control or adapt to the rise in water levels due to hydrometeorological phenomena, which frequently flood our eastern coastal lowlands. The CRZ should, as well, have protected lowlands susceptible to inundations due to storm surges.

Coastal bodies rarely address natural hazards. Protection strategies do not consider coastal processes, and vul-

nerability is seldom included in management decisions³⁷. In the United States, research has helped refine public understanding of physical coastal processes; reliance on engineered shoreline has been replaced by beach nourishment and land-use regulations³⁸.

Globally, the major thrust has always been on mitigation rather than adaptation. Coastal adaptation against hazards comprises several options: protect, managed retreat, accommodate³⁹. Managed retreat, the strategy proposed in this article, has to consider increasing setback zones, shifting of buildings, no development in susceptible areas, relocation, realignment, creating upland buffers, hazard insurance, appropriate land use, regulation of hazard zones and improved drainage.

It is pertinent to note that the concept of managed retreat as a form of adaptation is mandatory in several countries⁴⁰. Designed to attenuate impacts due to hazards, relocation inland prevents natural systems from being overrun by development or by an advancing sea. Global examples of managed retreat include the following⁴⁰: In Canada, setback for development is fixed from the landward limit of coastal features. Sri Lanka has identified setback strips and no-development zones in coastal management plans. In 1998, the House of Commons in the UK endorsed the concept of managed realignment as a long-term strategy for coastal defence. The US implements rolling easement policies to ensure that wetlands and beaches can migrate inland as sea level rises. More importantly, Australia insists on coastal setback and minimum elevation policies to accommodate potential sea-level rise as well as storm surges.

In India, Valdiya³⁵ strongly advocates restrictions in the form of a public policy for the management of vulnerable coasts. Policy plans include enforcing laws and regulations for preventing and restricting development in lands prone to natural hazards. Since restrictive measures do not work, another effective way to abandon hazardous tracts would be to impose a series of disincentives: denial of assistance for development, loans, essential supplies, and insurance. Valdiya³⁵ also suggests that alternatively, governments can acquire these areas for recreation parks, wildlife sanctuaries, afforestation and agriculture by forbidding constructions. Therefore, productive use of hazardous coastal land can be made while simultaneously lowering the levels of vulnerability.

The key issue in modern management programmes is sustainability. Since coastal hazard requirements have not appeared in acts such as CRZ¹¹, we need a policy that reviews the scenarios starting from their natural state to the development of a coast. Risk zones can be identified using geological, ecological and meteorological factors^{3-10,30,31}. Placing development in hazardous zones needs mitigation in the form of structural modifications, a process that ends up being unsustainable^{16,17,28-31}. Natural processes active in the coastal zone need recognition, as the best actions are those that mimic nature³¹.

Therefore, the most ideal low-risk development is the one that recognizes coastal geological processes, preserves natural coastal landforms, and promotes coastal afforestation. A public policy for coastal hazard management, by considering suitable options for adaptation, together with appropriate setbacks in the form of forested natural landforms, may well be the last chance to save coastal lowlands and its inhabitants from the ravages of recurring hydrometeorological events.

1. Shrestha, M. L. (ed.), *The Impact of Tropical Cyclones on the Coastal Regions of SAARC Countries and their Influence in the Region*. SAARC Meteorological Research Centre, Agargaon, Bangladesh, 1998, pp. 329.
2. Raghavan, S. and Sen Sarma, A. K., Tropical cyclone impacts in India and neighbourhood. In *Storms* (eds Pielke, R. and Pielke, R.), Routledge Hazards and Disaster Series, New York, 2000, vol. I, pp. 339–356.
3. Murty, T. S., Flather, R. A. and Henry, R. F., The storm surge problem in the Bay of Bengal. *Prog. Oceanogr.*, 1986, **16**, 195–233.
4. Rao, R. S., Role of remote sensing in flood management – the May 1990 cyclone. *Int. J. Remote Sensing*, 1994, **15**, 1557–1558.
5. Rao, Y. R., Chittibabu, P., Dube, S. K., Rao, A. D. and Sinha, P. C., Storm surge prediction and frequency analyses for Andhra coast of India. *Mausam*, 1997, **48**, 555–566.
6. Dube, S. K., Rao, A. D., Sinha, P. C., Murty, T. S. and Bahulayan, N., Storm surge in the Bay of Bengal and Arabian Sea: The problem and its prediction. *Mausam*, 1997, **48**, 283–304.
7. Kumar, K. V., Bhattacharya, A. and Subramanyam, C., Coastal morphological influence for tropical cyclone track deviation along Andhra coast. GIS and remote sensing-based approach. *Curr. Sci.*, 1998, **75**, 955–958.
8. Jayanti, N., Cyclone hazard, coastal vulnerability and disaster risk assessment along the Indian coasts. In *Tropmet 1999 – Meteorology beyond 2000*, India Meteorological Society, 1999, pp. 291–296.
9. Dube, S. K., Chittibabu, P., Rao, A. D., Sinha, P. C. and Murty, T. S., Extreme sea levels associated with severe tropical cyclones hitting Orissa coast of India. *Mar. Geod.*, 2000, **23**, 75–90.
10. Marchand, M. and Valk, B., Integrated coastal zone management in Andhra Pradesh. In *Tropmet 2001 – Meteorology for Sustainable Development*, India Meteorological Society, Mumbai, 2002, pp. 545–551.
11. Mascarenhas, A., Need for setback lines in coastal zone management: a meteorological point of view. In ref. 10, 2002, pp. 564–568.
12. Sen, N., Science and technology policy – 2003. *Curr. Sci.*, 2003, **84**, 13.
13. Thapliyal, V., Desai, D. S. and Krishnan, V., Cyclones and depressions over north Indian ocean during 1999. *Mausam*, 2000, **51**, 215–224.
14. Nayak, S. R., Sarangi, R. K. and Rajawat, A. S., Application of IRS-P4 OCM data to study the impact of cyclone on coastal environment of Orissa. *Curr. Sci.*, 2001, **80**, 1208–1213.
15. Anon., International tsunami warning system. IOC Annual Report Series, 1998, No. 5, pp. 46–50.
16. Paul, A. K., Cyclonic storms and their impacts on West Bengal coast. Proceedings of the International Seminar on Quaternary Sea Level Variation, Shoreline Displacement and Coastal Environment (eds Rajamanickam, G. V. and Tooley, M. J.), New Academic Publishers, Delhi, 2001, pp. 8–31.
17. Dolan, R. and Davies, R. E., An intensity scale for Atlantic coast northeast storms. *J. Coast. Res.*, 1992, **8**, 840–853.
18. Dash, J., Exotic tree species backfiring for Orissa beaches: greens. Indo-Asian News Service, 21 April 2002.
19. Thomas, T. J. and Mani, P. R., Damages caused by cyclonic storm and remedial measures at Tuticorin Port. Proceedings of the Second Indian National Conference on Harbour and Ocean Engineering, Inchoe 97, Thiruvananthapuram, 1997, pp. 436–446.
20. Dikshit, S. K., Desai, D. S. and Bhandari, S. C., Cyclones and depressions over north Indian ocean during 1996. *Mausam*, 1997, **48**, 343–350.
21. Mooley, D. A. and Mohile, E. M., A study of the cyclonic storms incident on the different sections of the coast around the Bay of Bengal. *Mausam*, 1983, **34**, 139–152.
22. Mani, J. S., Coastal processes in Tamil Nadu and Kerala: environmental and socio-economic aspects. In *Environmental Problems of Coastal Areas in India* (ed. Sharma, V. K.), Bookwell Press, New Delhi, 2000, pp. 201–216.
23. Lal, M., Tropical cyclones in a warmer world. *Curr. Sci.*, 2001, **80**, 1103–1104.
24. Singh, O. P., Khan, T. A. M. and Rahman, M. S., Has the frequency of intense tropical cyclones increased in the north Indian Ocean? *Curr. Sci.*, 2001, **80**, 575–580.
25. Shetye, S. R., Gouveia, A. D. and Pathak, M. C., Vulnerability of the Indian coastal region to damage from sea level rise. *Curr. Sci.*, 1990, **59**, 152–156.
26. Dube, S. K. and Rao, A. D., Sea level rise and coastal flooding by storm surges in the Bay of Bengal. *Proc. Indian Natl. Sci. Acad. USA*, 1991, **57**, 565–572.
27. Murty, M. V. R., Rao, R. S. and Bhagavan, S. V. B. K., Geomorphological studies for disaster mitigation – a case study of the Krishna Delta, Andhra Pradesh, India. *Int. J. Remote Sensing*, 1993, **14**, 3269–3274.
28. Ali, A. and Chowdhury, J. U., Tropical cyclone risk assessment with special reference to Bangladesh. *Mausam*, 1997, **48**, 305–322.
29. Dolan, R. and Davis, R. E., Coastal storm hazards. *J. Coast. Res.*, 1994, **12**, 103–114.
30. Clark, J. R., *Coastal Zone Management Handbook*. Lewis Publication, USA, 1996, p. 694.
31. Pilkey, O. H., Bush, D. M. and Neal, W. J., Storms and the coast. In ref. 2, pp. 427–448.
32. Stenchion, P., Cyclones and disaster management. *Mausam*, 1997, **48**, 609–620.
33. Nordstrom, K. F., *Beaches and Dunes of Developed Coasts*, Cambridge University Press, 2000, pp. 338.
34. Mascarenhas, A., The Coastal Regulation Zone of Goa: oceanographic, environmental and societal perspectives. *Curr. Sci.*, 1999, **77**, 1598–1605.
35. Valdiya, K. S., Public policy for natural hazard management. *Curr. Sci.*, 2001, **80**, 486–487.
36. Ministry of Environment and Forests, The Gazette of India, Notification, S.O. No. 114(E), 20 February 1991.
37. Fischer, D. W. and Arredondo, M. C., Municipal coastal hazard planning: Los Angeles and Orange County city responses, California. *J. Coast. Res.*, 1999, **15**, 974–984.
38. Platt, R. H., Evolution of coastal hazards policies in the United States. *Coast. Manage.*, 1994, **22**, 265–282.
39. Klein, R. J. T., Nicholls, R. J., Ragoonaden, S., Capobianco, M., Aston, J. and Buckley, E. N., Technological options for adaptation to climate change in coastal zones. *J. Coast. Res.*, 2001, **17**, 531–543.
40. McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. and White, K. S., Climate Change 2001: Impacts, Adaptation and Vulnerability, Third Assessment Report, Intergovernmental Panel on Climate Change, UNEP (on CD-ROM), 2002.

ACKNOWLEDGEMENTS. I am grateful to the Director, NIO, Goa for permission to publish this paper. Dr G. Raj, ISRO, Bangalore, provided the imagery. Mr A. Mahale and Mr P. Pawaskar, NIO, Goa prepared the figure. This is NIO contribution No. 3868.

Received 29 August 2003; revised accepted 5 January 2004