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

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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 century, 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 years. 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 measures. The Tropmet 2001 seminar organized by India Meteorological Department (IMD) discussed similar topics under the theme "meteorology for sustainable development." 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 mitigation. 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 coast, 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).
GENERAL ARTICLES

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 damaged. 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 1999 (ref. 16). The number of displaced people is increasing as more land is eroded following violent storms. 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 affected. Property damage is regional and increases with successive storms, as observed along the shorelines and channel banks of West Bengal.

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 Strait. 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 cyclones.

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.)

<table>
<thead>
<tr>
<th>Type of disturbance</th>
<th>Cyclonic disturbance</th>
<th>Depression/deep depression</th>
<th>Cyclonic storm</th>
<th>Severe cyclonic storm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>1087</td>
<td>635</td>
<td>279</td>
<td>173</td>
</tr>
<tr>
<td>Minimum (1891–1991)</td>
<td>4 (Feb.)</td>
<td>1 (Mar.)</td>
<td>0 (Feb.)</td>
<td>1 (Jan.)</td>
</tr>
<tr>
<td>Yearly average</td>
<td>10</td>
<td>6</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>Per cent of total</td>
<td></td>
<td>58</td>
<td>26</td>
<td>16</td>
</tr>
<tr>
<td>Wind speed (km/h)</td>
<td>31–118</td>
<td>31–61</td>
<td>61–88</td>
<td>88–118</td>
</tr>
</tbody>
</table>

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.)

<table>
<thead>
<tr>
<th>Period</th>
<th>Coast affected</th>
<th>Maximum wind speed (km/h)</th>
<th>Maximum surge height (m)</th>
<th>Hinterland inundation (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 1737</td>
<td>Hoogly river, West Bengal</td>
<td>272</td>
<td>12.1</td>
<td>100</td>
</tr>
<tr>
<td>May 1823</td>
<td>Balasore, Orissa</td>
<td>–</td>
<td>–</td>
<td>10</td>
</tr>
<tr>
<td>November 1867</td>
<td>East of Calcutta, West Bengal</td>
<td>60</td>
<td>1.8</td>
<td>–</td>
</tr>
<tr>
<td>October 1942</td>
<td>Medinipur, West Bengal</td>
<td>–</td>
<td>5.0</td>
<td>40</td>
</tr>
<tr>
<td>October 1949</td>
<td>Masulpapuram–Kakinada, Andhra Pradesh</td>
<td>137</td>
<td>4.5</td>
<td>15</td>
</tr>
<tr>
<td>November 1952</td>
<td>Nagapatnam, Tamil Nadu</td>
<td>88</td>
<td>1.2</td>
<td>8</td>
</tr>
<tr>
<td>October 1955</td>
<td>Kalingapatnam, Andhra Pradesh</td>
<td>111</td>
<td>1.5</td>
<td>–</td>
</tr>
<tr>
<td>November 1955</td>
<td>Rajamadum, Tamil Nadu</td>
<td>193</td>
<td>4.5</td>
<td>16</td>
</tr>
<tr>
<td>December 1955</td>
<td>Tanjore, Tamil Nadu</td>
<td>200</td>
<td>5.0</td>
<td>3–8</td>
</tr>
<tr>
<td>October 1963</td>
<td>Cuddalore, Tamil Nadu</td>
<td>139</td>
<td>6.0</td>
<td>–</td>
</tr>
<tr>
<td>December 1964</td>
<td>Ramneshwaran, Tamil Nadu</td>
<td>278</td>
<td>6.0</td>
<td>–</td>
</tr>
<tr>
<td>October 1971</td>
<td>Paradip, Orissa</td>
<td>170</td>
<td>6.0</td>
<td>10–25</td>
</tr>
<tr>
<td>November 1973</td>
<td>North of Paradip, Orissa</td>
<td>137</td>
<td>4.5</td>
<td>–</td>
</tr>
<tr>
<td>August 1974</td>
<td>Contai, West Bengal</td>
<td>139</td>
<td>3.0</td>
<td>–</td>
</tr>
<tr>
<td>September 1976</td>
<td>Contai, West Bengal</td>
<td>160</td>
<td>3.0</td>
<td>–</td>
</tr>
<tr>
<td>November 1977</td>
<td>Nizampatnam, Andhra Pradesh</td>
<td>193</td>
<td>5.0</td>
<td>8–15</td>
</tr>
<tr>
<td>November 1977</td>
<td>Divi–Machilipatnam, Andhra Pradesh</td>
<td>120</td>
<td>5.0</td>
<td>12</td>
</tr>
<tr>
<td>November 1978</td>
<td>Ramanathpuram, Andhra Pradesh</td>
<td>204</td>
<td>5.0</td>
<td>–</td>
</tr>
<tr>
<td>May 1979</td>
<td>South of Ongole, Andhra Pradesh</td>
<td>160</td>
<td>3.6</td>
<td>–</td>
</tr>
<tr>
<td>November 1989</td>
<td>Near Kavali, southern Andhra Pradesh</td>
<td>222</td>
<td>4.0</td>
<td>1–2</td>
</tr>
<tr>
<td>May 1990</td>
<td>Nellore, Andhra Pradesh</td>
<td>102</td>
<td>5.0</td>
<td>16</td>
</tr>
<tr>
<td>November 1991</td>
<td>Karaikal, Tamil Nadu</td>
<td>89</td>
<td>–</td>
<td>&lt;1</td>
</tr>
<tr>
<td>November 1992</td>
<td>Tuticorin, Tamil Nadu</td>
<td>113</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>December 1993</td>
<td>Karaikal, Tamil Nadu</td>
<td>133</td>
<td>4.0</td>
<td>2</td>
</tr>
<tr>
<td>October 1999</td>
<td>Paradip/Balasore, Orissa</td>
<td>252</td>
<td>9.0</td>
<td>35</td>
</tr>
</tbody>
</table>
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 later[14].

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 Orissa[15]; 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 storms[16].

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 winds[18]. Similarly, post-cyclone satellite images showed partial damage to coastal trees, including mangroves in Orissa[19].

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 damaged[19]. Harbours were paralysed along Digha-Haldia sector in August 1997 (ref. 16). Minor ports of Machlipatnam 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 Bengal[1]. 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[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 year[9].

In terms of storm surges (Table 2), hydrometeorological phenomena cause extensive inundations of low-lying plains[21,22]. 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.)

<table>
<thead>
<tr>
<th>Period</th>
<th>Location</th>
<th>Impact/Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 November 1977</td>
<td>Drivi, Krishna River delta, Andhra Pradesh</td>
<td>At least 10,000 lives lost; standing crops washed away; persistent flooding even 11 days after the cyclone struck.</td>
</tr>
<tr>
<td>27–29 May 1989</td>
<td>24 Parganas/Medinipur, West Bengal</td>
<td>485 lives lost; 2,024,688 houses damaged; standing crops washed away; 239 km of protective works destroyed; dune barrier breached.</td>
</tr>
<tr>
<td>4–10 May 1990</td>
<td>Machilipatnam, mouth of River Krishna, Andhra Pradesh</td>
<td>967 deaths; 60,000 houses destroyed; 21,600 cattle, 35,000,000 poultry, 42,700 goats perished; damage to agriculture.</td>
</tr>
<tr>
<td>11–17 November 1992</td>
<td>Tuticorin, Tamil Nadu</td>
<td>170 killed; 160 missing; 1 to 2 m storm surge at Tuticorin.</td>
</tr>
<tr>
<td>1–4 December 1993</td>
<td>Near Karaikal, Tamil Nadu</td>
<td>111 killed; 1 to 1.5 m storm surge.</td>
</tr>
<tr>
<td>29–31 October 1994</td>
<td>Chennai and around, Tamil Nadu</td>
<td>304 killed; 1 to 2 m storm surge; 100,000 huts destroyed; 60,000 hectares of crops damaged.</td>
</tr>
<tr>
<td>7–10 November 1995</td>
<td>Gopalpur, Orissa</td>
<td>96 killed; 1.5 m surge; 2,84,253 hectares of crops damaged.</td>
</tr>
<tr>
<td>5–7 November 1996</td>
<td>Kakinada, Andhra Pradesh</td>
<td>978 killed; 2 to 3 m surge; 1,375 missing; 6,47,544 houses damaged; 1,74,000 hectares of crops damaged.</td>
</tr>
<tr>
<td>22–24 August 1997</td>
<td>Digha-Haldia, West Bengal</td>
<td>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.</td>
</tr>
<tr>
<td>29–31 October 1999</td>
<td>Balasore/Paradip, Orissa</td>
<td>9885 persons died; 2,142 people injured; 12 lakhs houses damaged; over 2 lakhs cattle killed; 13 lakhs hectares of crops affected; port activity paralysed.</td>
</tr>
</tbody>
</table>
Andhra Pradesh and Orissa are the most vulnerable to coastal inundations. 

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.

The coastal tract comprising Digha, Contai, Dariapur, Khajuri, Nandigram and Haldia is an example where all types of storm impacts have been documented. 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 USD. Some independent estimates indicate the following: November 1969, Godavari, Rs 110 crores; November 1977, Nagapattinam, Rs 155 crores; November 1977, Nizampattinam, Rs 350 crores; October 1983, Bheemunipatnam, Rs 520 crores; May 1990, Mahilipatnam, Rs 2248 crores; November 1991, Cuddalore, Rs 323 crores; May 1995, 24-Parganas, Rs 68 crores; August 1997, Highli 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 development 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 probable. 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 stage.

Inland gradients further indicate that most of the east coast north of Nagapattinam 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 activity. Computed experimentation also indicates that maximum coastal inundations can be expected between Nagapattinam in the south and Gopalpur in the north. Inland penetration of storm surge waters are also be expected to affect the same stretch up to 4 km on an average, the maximum penetration of 30 km being in the Ongole–Divi stretch.

Historical evidence reveals that Kakinada area, for example, was affected by several cyclones: 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 years. Similarly, the West Bengal coast was relentlessly inflicted by storms, major ones occurring in 1943, 1950, 1970, 1983, and 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 years.

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, high disaster risk zones, and flood hazard classes of vulnerable areas. 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 events.

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 belts and in wetlands, industries, mills, nuclear power stations and even spacecraft launch facilities, all located
in hazard-prone areas. 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, Orissa and West Bengal. 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 coasts.

Although they guard against tides and reduce surge energy, storm surges have overrun and overtopped embankments in West Bengal and Bangladesh. Although susceptible regions have been engineered to secure shorelines, confirmed damage due to extreme events is often greater in stabilized areas. 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, recurring loss of life and staggering economic loss following hydrometeorological events. 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. 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. Without the human-built environment to interact with, storms are a different matter. 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\textsuperscript{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\textsuperscript{16,22,29–31}: roads and beach access become overwash 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 costly\textsuperscript{31}, 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\textsuperscript{30,31,33,34} and can also be demonstrated for the Digha coast of West Bengal\textsuperscript{16}. 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-erosion capacity of dune coast. Human interference on dunes leads to inundations and destruction of habitations, dwellings and resorts during extreme events in West Bengal\textsuperscript{16}.

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 landforms\textsuperscript{35}.

Imageries of Orissa coast show healthy vegetation, whereas post-cyclone images show that damaged mangroves regained their original status within two months\textsuperscript{14}. It is found that the Sunderbans mangrove areas of Bengal suffer less from wind and surges than those areas with less or no mangroves\textsuperscript{36}. Similarly, casuarina trees can survive wind speeds of 100 km/h\textsuperscript{19}. 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 wildlife\textsuperscript{37}; (e) people inhabiting hazard-prone coasts would benefit from green belts in terms of security, access to food, materials, shelter and income\textsuperscript{35,38}; (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\textsuperscript{28,30}. Casuarina plantations that we see along Nagore–Nagapattinam stretch, Vairunthi coast, the strip adjacent to the east coast highway in Tamil Nadu, Kakinada–Uppada sector, Gahirmatha zone in Orissa\textsuperscript{18} 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 people\textsuperscript{36}. Similarly, anthropogenic pressures and inappropriate land-use patterns on wetlands of Krishna delta region\textsuperscript{37,38} 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, floodplains need to be designated so that excess water from marine incursions may be accommodated\textsuperscript{39}.

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) Notification\textsuperscript{37,38} 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 conservation\textsuperscript{39}, 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 vulnerability is seldom included in management decisions\textsuperscript{37}. 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 regulations\textsuperscript{39}.

Globally, the major thrust has always been on mitigation rather than adaptation. Coastal adaptation against hazards comprises several options: protect, managed retreat, accommodate\textsuperscript{40}. 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 countries\textsuperscript{40}. 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 following\textsuperscript{41}. 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, Valdiya\textsuperscript{35} 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. Valdiya\textsuperscript{35} 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 CRZ\textsuperscript{37}, 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\textsuperscript{4,10,30,31}. Placing development in hazardous zones needs mitigation in the form of structural modifications, a process that ends up being unsustainable\textsuperscript{16,17,28,31}. Natural processes active in the coastal zone need recognition, as the best actions are those that mimic nature\textsuperscript{31}.
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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.


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