

# Science plan for coastal hazard preparedness\*

K. S. Krishna

*The tsunami that hit the coast of India on 26 December 2004 reminded the country that our 7000 km long coastline is exposed to hazards and that we are not prepared to face all of them. Preparedness to guard against hazards requires that we examine scientifically all issues associated with them. Hence, a science plan, including its implementation to address these issues, was prepared at a national workshop held at the National Institute of Oceanography, Goa. The plan identifies the factors that determine vulnerability of a coastal area to hazards and the hazards that are experienced along the Indian coast. Preparedness is defined and the science issues that need to be addressed to enhance our preparedness are identified. The issues are categorized into seven areas. (i) Identification of past storm surges and tsunamis in tide-gauge data, and their simulation; (ii) reconstruction of time series of past storm surges and tsunamis from geological record; (iii) geomorphology, near-shore bathymetry, and coastal inundation; (iv) coastal pollution; (v) seismicity; (vi) engineering; and (vii) education. Plan for implementation is also presented.*

**Keywords:** Coastal hazard, implementation, preparedness, science plan, tsunami.

THE tsunami that hit the South Asian countries on 26 December 2004 served as a rude reminder that our coastal areas, so preferred for settlement that about 25% of India's population lives here, suffer from hazards for which we are unprepared. We need to take a holistic look at possible sources of coastal hazards and adopt a concerted approach towards our preparedness for these.

At the 'Brainstorming Session on the Great Tsunami of 26 December 2004' organized by the Department of Science and Technology (DST; This session was also supported by the Department of Ocean Development, Council of Scientific and Industrial Research, and Indian National Science Academy), it was decided that while we develop systems for warning of the probable occurrences of coastal hazards, we should also develop a plan that builds a better foundation for coastal hazard preparedness for the country.

This was followed by a 'National Workshop on Formulation of a Science Plan for Coastal Hazard Preparedness' at the National Institute of Oceanography (NIO), Goa, in which about 80 researchers from different R&D organizations, universities and government departments participated. The deliberations, which were based on a draft science plan circulated among the participants at the start of the workshop and on the proposals received from them, resulted in a science plan leading to preparedness to face coastal hazards. This article summarizes the different hazards that the coast of India is vulnerable to, discusses the science

issues to be addressed to quantify these hazards, and proposes an action plan to implement the science plan.

## Vulnerability of coastal areas

India has a long coastline (~ 7500 km) and a large exclusive economic zone (~ 2 million km<sup>2</sup>) that includes two major groups of islands, all of which are susceptible to different coastal hazards. Peninsular India comprises nine populous states, with a significant component of their economy related to the sea in some way. This includes fishing, shipping, ports and harbours, tourism and allied industries. The last few years have also seen new investment being made in our coastal waters (on the continental shelf and slope) for oil and gas exploration. The investment – over US \$ two billion per year by some estimates – involves construction of platforms, pipelines and other structures. These could eventually become a critical component of the national economy. With these new developments also come new threats: while these offshore structures are vulnerable to storm surges, tsunamis or submarine mudslides, they are also a potential source of oil spills, which too constitute a hazard affecting fisheries and coastal environment. The growing tourism industry is also a major stakeholder, because any coastal disaster has direct fallout and often paralyzes the economy in areas dependent on tourism. There are several factors that contribute towards the vulnerability of the coastal areas.

About 25% of India's population lives within 50 km of the coastline (Figure 1)<sup>1</sup>. An important component of the coastal population is the seafaring community, of which fishermen form a sizable part. Their vulnerability can be

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K. S. Krishna is in the National Institute of Oceanography, Dona Paula, Goa 403 004, India. e-mail: krishna@nio.org

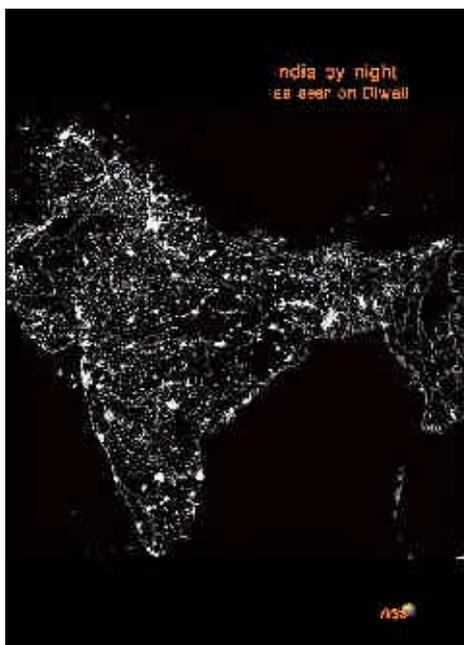
realized from Table 1, which shows that about 0.5 million fishermen are exposed to the vagaries of nature in the off-shore areas every day and that well over 3500 villages are exposed to hazards that coastal areas have to confront. Poorly constructed buildings in the coastal areas turn into killers in the face of these hazards like earthquakes, storm surges and tsunamis. Coastal topographic slope and absence of vegetation (and its type) are some of the factors that determine vulnerability to coastal hazards. Naturally occurring plants and trees in coastal areas act as 'bio-shields', shielding the regions from ferocity of storms and tsunamis.

The ability of a community to respond to a natural hazard is dependent on the state of infrastructure, communication, roads and ability to mobilize resources such as medical facilities. For example, a warning system for tsunamis will have to work within a much shorter time frame than one for storm surges, because the latter develops gradually and cyclones or storms that give rise to such storm surges

can be tracked easily with available technology. This also implies that emergency procedures will have to be different for each hazard, and our ability to respond effectively is critically dependent on mass awareness.

The vulnerability also depends on location of the site and the type of hazard. For example, damage caused by a coastal event to a business centre such as Mumbai has a greater and more widespread impact on the economy and therefore affects a much larger population than merely that which is resident in the affected region. On the other hand, the impact on an offshore oil platform can affect the economy through a cascading effect, which makes it critical to develop a better preparedness.

The developed world prepares for hazards by estimating the expected losses from statistics on hazards and by providing insurance cover for the expected damage. Insurance cover does not reduce loss of life or property; it does, however, guarantee resources for recovery, and vulnerability increases in the absence of such guarantees.



**Figure 1.** National Remote Sensing Agency satellite picture<sup>1</sup> showing light from India as sensed by the OLS (Operational Linescan System) Sensor on-board the satellites of the Defence Meteorological Support Programme. Major urban concentrations are evident. Note, in particular, the continuous lighted coast north of Mumbai.

## Causes and effects of different coastal hazards

### Storm surges

Storms form over warm seas (sea surface temperature should exceed  $\sim 28^{\circ}\text{C}$  in the Indian Ocean<sup>2</sup>). The frequency of storms is highest in the Bay of Bengal (Figure 2). Though storms are tracked better now owing to satellite remote sensing, there is a need for improvement in modelling of storm track and intensity because this is one of the weakest links in storm-surge prediction. The impact of a storm as it crosses a coast is caused by the surge due to strong winds and low atmospheric pressure and the high waves riding over the surge.

### Tsunamis

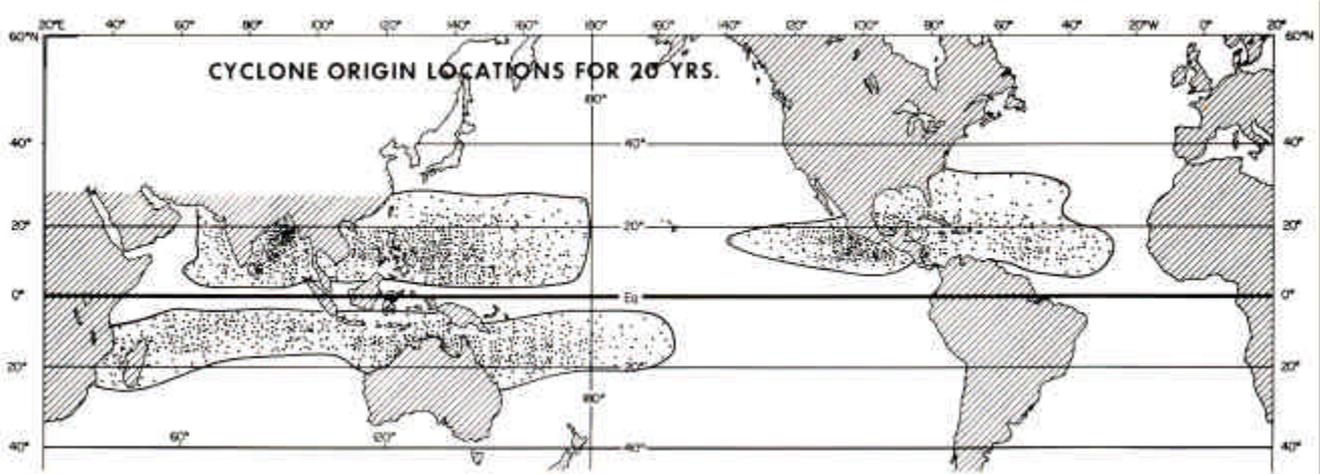
Tsunamis are caused by vertical displacement of a water column owing to earthquakes, volcanic eruptions or submarine mudslides. Though they are almost undetectable in the open sea owing to their low amplitude, tsunami waves can reach heights exceeding 10 m in the vicinity of a coast. The high impact they have on the coast is due to high water velocity and wave height. Tsunamis are not as frequent as storm surges along the Indian coast<sup>3</sup> (Table 2).

### Oil spills

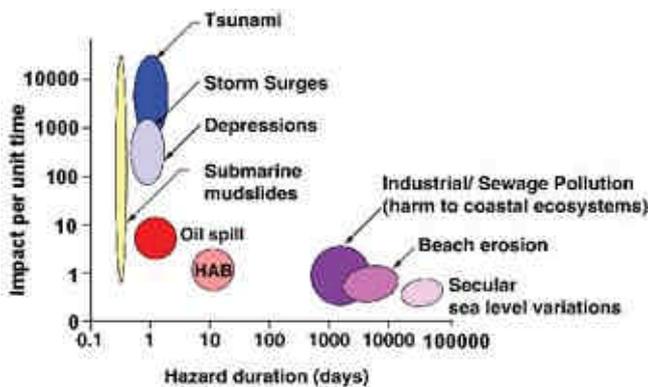
Oil spills are caused by accidents involving tankers, barges, pipelines, refineries or storage facilities while oil is being transported. Oil usually spreads out rapidly across the water surface to form a thin layer that we call 'oil spill'. Oil spills can harm marine life. The effect can cascade up the food chain to human beings.

**Table 1.** Statistics of India's fishing community

Marine fishermen population	3 million
Marine fishermen households	0.5 million
Number of active fishermen	1.03 million
Fraction of fishermen population that is active	0.33
Number of marine fishing villages	3638
Average number of sea-going fishermen per village	262
Average number of fishermen per village	825
Fish landing centres	2251



**Figure 2.** Points of initial detection of pre-cyclone disturbances over the world oceans<sup>5</sup> during 1955–75. Note the high frequency of occurrence in the Bay of Bengal.



**Figure 3.** Schematic of each hazard in terms of duration of an event (abscissa) and its impact on life and property per unit time (ordinate). HAB, Harmful algal blooms.

**Table 2.** Percentage of tsunamis worldwide (table 1.1 in ref. 3)

Location	Percentage
Atlantic east coast	1.6
Mediterranean	10.1
Bay of Bengal	0.8
East Indies	20.3
Pacific Ocean	25.4
Japan and Russia	18.6
Pacific east coast	8.9
Caribbean	13.8
Atlantic west coast	0.4

*Submarine mudslides*

As on land, mudslides can occur on the continental slopes. Apart from the obvious risk they pose to offshore platforms, they can also trigger a tsunami.

*Hazards related to global climate change*

Anthropogenic impact on climate is more certain now owing to increasing confidence in observations and models. There have been suggestions that the frequency of storms in the Bay of Bengal might increase<sup>4</sup>. Since surges due to storms already pose a considerable threat to the region<sup>5</sup> (Figure 3), any increase in intensity and frequency owing to global changes in climate will exacerbate the hazard.

*Long-time persistent hazards*

Industrial/sewage pollution, beach erosion and harmful algal blooms (HAB) constitute a long-term effect on human environment and population, and hence form a type of hazard.

*Magnitude of impact of different coastal hazards*

Each of the hazards mentioned above has its own unique features in terms of the duration of an event and its impact on life and property. Figure 3 is a schematic of each hazard in terms of these two variables. Some hazards like tsunami and storm surges are short-lived events having a high impact per unit time. Other hazards like coastal pollution occur over a long duration, i.e. they are not events but processes, and have a small impact per unit time. Any damage they cause occurs gradually and in an incremental fashion. These long-duration, low-impact hazards are less easily recognized and do not register as strongly in our minds as the short-duration, high-impact events. That they act more persistently, however, implies that the cumulative effect of these processes over some time usually will exceed that of the high-impact events.

**Table 3.** Coastal hazards and our current knowledge of these hazards with respect to India

Hazard	Region most affected	Frequency of occurrence	Magnitude of impact	Remarks
Storm surge	Bay of Bengal	See Figure 3	Biggest killer in this part of the world	Impact event by event is not easily available, but it should be possible to assemble for the last century at least based on instrumental records. Research is needed to extend the record back in time
Tsunami	Needs further study	Sporadic, not known	Highly damaging	Need to document occurrence in the past and evaluate the impact (if possible)
Submarine mudslide	Not predictable as it depends on soil/sediment structure and texture	Not known	Can have serious impact on offshore structures, and results in huge loss for the oil sector	Need for a detailed study of past events using palaeontological methods, and sediment stratification classification
Oil spill	Usually along shipping routes and around harbours, but in the event of an accident, almost anywhere	Variable	Harmful effect on the coastal or marine ecosystem	Need to understand how a potential spill will spread, and for studies related to new methodology to reduce the effect of harmful toxins
Coastal pollution	All major coastal industrial areas, ports, major cities and towns on the coastline	Persistent, but sporadic bursts of heavy pollution may occur	Affects biodiversity and tourism industry, and human health through the marine food chain	Impact needs to be monitored on continuous basis. Need to generate database of major pollution constituents and their effects on ecology. Not well documented or quantified in spite of several EIA studies. Need to integrate the results of disparate EIA studies to form a coherent picture
Coastal erosion	Not fully known	Persistent hazard, but exacerbated by other hazards like cyclones, storms, floods, tsunamis, etc. and by anthropogenic activities	Variable, but can be disruptive	As with pollution, there is a need to integrate the results of several small-scale disparate studies
Harmful algal blooms (HABs)	Mostly off the southwest coast of India, but also occur at other places	Annual event (may be more), but of short duration	Variable; affect seafood chain, tourism; human health hazard	Need to understand causative effects and spatio-temporal spread; satellite remote sensing is a promising tool
Impact of global change	Global, but projections suggest an increase in the already high frequency of storms in the Bay of Bengal	Projected increase in the frequency of storms in the Bay of Bengal	Not known, subject to uncertainty inherent in global climate models	Needs to be taken seriously because an already stressed and fragile coastal zone may be subject to more intense and frequent hazards

Some hazards like HABs may not cause loss of life, but can lead to outbreak of diseases, thereby affecting normal life and economy, if they find their way up the food chain to human beings. Some hazards like secular sea-level rise may not cause fatalities, but have the potential for disrupting life if it becomes necessary to abandon flourishing coastal towns and cities. Likewise, coastal erosion has a serious impact on coastal settlements and infrastructure along the coastline. Submarine mudslides too, though not affecting life directly, have the potential to disrupt economy on a large scale because they directly affect the basis for modern industrial civilization, namely fossil fuels.

It is necessary to quantify these hazards to determine our vulnerability to each of them. Information is needed on the frequency of their occurrence, on their spatial distribution and on the magnitudes of the extremes associated with them. This is essential if their economic impact is to be assessed; insurance premium calculations, for example,

require an estimate of the potential risk. Since these hazards do not affect all coastal regions uniformly, it is essential to map them quantitatively. Table 3 provides a summary of our knowledge about different coastal hazards.

### *Coastal hazard preparedness*

Having examined the vulnerability to coastal hazards along the Indian coast, the following elements need to be considered for our preparedness for such hazards:

- (i) Awareness about (a) evolution of a hazard based on past experience and its frequency of occurrence, and (b) distribution of the magnitude of past hazardous events.
- (ii) Appreciation (quantitative as far as possible) of vulnerability to a hazard.

- (iii) Ability to predict either deterministically or stochastically.
- (iv) Response readiness before and after the hazard(ous) event.
- (v) Education at all levels.

### Science issues

The scientific issues that need to be addressed to improve our coastal hazard preparedness are the following.

#### *Identification of past storm surges and tsunamis in tide-gauge data and their simulation*

Tide-gauge data are available for several Indian coastal stations for over half a century. Some of these go back over a century, making them the most reliable records of past tsunami and storm-surge events. The past tsunami events may have escaped us either because of their infrequent occurrence, implying a long gap between two events, or because of their impact having been low or because the usual practice of digitizing these data at 1 h interval is not enough for capturing a tsunami, which has a smaller period.

Identifying past tsunami events in tide-gauge records and developing the ability to simulate them will allow us to generate reliable statistics on this hazard. In the case of a tsunami, confidence in a model is critical because it will allow us to prepare a scenario database that can be used for ascertaining which areas are vulnerable, once a tsunami is triggered in some part of the Indian Ocean. Given that not many tsunamis have occurred in the Indian Ocean during the last century, model-based scenarios constitute a viable risk-assessment tool. Such scenarios are critical for the Indian Ocean because the travel time is too small (less than 3 h on 26 December 2004) to permit a model to be run after the cause is detected. Tsunami models have to be developed specifically for the Indian Ocean because tsunami patterns here may be different from those in the Pacific. The smaller basin size restricts dissipation and dispersion of the waves, making wave reflection important. Interaction with currents, tides and winds also needs to be considered. A good high-resolution map of near-shore bathymetry and near-coastal topography is essential for mapping the tsunami run-up. The primary use of these models will be to identify vulnerable areas. For a warning system, however, a more promising approach is to compute the Green's function for shallow-water equations for bathymetry of the Indian Ocean. With present-day computers, it may be possible to use this approach in conjunction with bottom-pressure gauges to discern the source of the tsunami and to make a quick assessment of the risk.

Tide-gauge data also record storm surges. Identifying past surges and simulating them accurately (with validation based on tide-gauge data rather than on eyewitness accounts) will lead to better, more reliable models and

statistics. Since the damage is caused not just by the surge but also by the high waves due to the storm, it is necessary to identify high-wave concentration zones. In storm-surge modelling, the major bottleneck today is the prediction of cyclone tracks. Improving predictions using super-ensembles of different models is promising. Climate change scenarios have often suggested an increase in the frequency and intensity of storms in the Bay of Bengal, with a corresponding increase in the extent of the threat posed by storm surges. Ascertaining the risk due to this hazard therefore makes it necessary to simulate surges forced by wind 'data' from climate models.

The complexity of the coastal topography can perhaps be tackled using hybrid methods involving finite elements and fractals. Soft computing and artificial intelligence tools like neural networks (ANN) or fuzzy logic can be used to complement results of the differential equation-based numerical models.

#### *Reconstruction of time series of past storm surges and tsunamis from geological records*

Instrumental data records do not go back more than a century. Hence, as with climate studies, it is necessary to use proxies to construct a longer time series for generating better statistics, especially for extreme events. Unlike instrumental data, which allow detection of events of a wide range of intensities, it is likely that the geological proxies obtained from core samples will yield information only on the bigger events. It is, however, necessary to assemble the information into a quantitative framework that coastal engineers can use.

Such records of storm surges, tsunamis, submarine mudslides and volcanic eruptions need to be created to estimate the likelihood of mega extreme events along the Indian coast. Studies elsewhere, not much more complete than those along the Indian coast, suggest that catastrophic mega events (especially due to tsunamis) are not as rare as thought at present<sup>3</sup>. Extreme events tend to disrupt normal sedimentary deposition and leave an imprint in the sediment strata. By a careful study of sedimentary sequences through time and space, it is possible to unravel the occurrence of past events and determine their frequency and periodicity. It is therefore necessary to reconstruct records of storm surges, tsunamis, submarine slope failures and volcanism from the sediment strata along the coast and offshore regions of India. Information on submarine mudslides is particularly critical in view of the growth in offshore exploration for oil and natural gas.

#### *Geomorphology, near-shore bathymetry, and coastal inundation*

Both storm surges and tsunamis cause devastation in the vicinity of the coast. The damage in a region is critically

influenced by the near-shore bathymetry and geomorphology of the region. Surges and tsunami waves tend to concentrate in certain locations because of wave refraction due to local bathymetry; the run-up and extent of inundation is similarly a function of land topography and near-coastal geomorphology. Hence, information on geomorphology and near-shore bathymetry (say water depth less than 20 m), is a crucial input to models for coastal inundation.

The coastal areas are also vulnerable to oil spills. Mapping vulnerable areas is essential for formulating emergency evacuation plans. Though mapping the geomorphology is a major task by itself, what is more critical is making the exercise quantitative. Vegetation such as mangroves is known to help mitigate the effects of storm surges and tsunamis. It is, however, necessary to quantify the protection such bio-shields provide to coastal habitation. For example, it is necessary to determine the threshold beyond which they cease to be effective and the extent of protection they provide.

The 26 December 2004 tsunami, like the storm surges in recent times, has left its imprint on coastal geomorphology. The tsunami caused severe erosion in places and deposited heavy minerals in several locations. Such morphological changes must have also occurred in the past, with the bigger events leaving major marks. This is therefore another tool for identifying past events. A more pervasive coastal hazard is erosion. Identifying areas vulnerable to erosion and quantifying its extent is essential for mitigation and formulating area-specific regulations and building codes.

### *Coastal pollution*

With a boom in the economy of the coastal states, there is an increase in the industrial activity in the coastal zone along with an increase in the population resident there; with modern industrial activity being heavily dependent on fossil fuels, the risk of pollution owing to an oil spill is greater today. Any industry that is set up in the coastal zone needs to go through an environmental impact assessment (EIA). Hence, many EIA studies have been conducted in the coastal waters of India. There is a need to integrate the results of the EIA studies to generate a national database, and to determine the 'carrying capacity' of the coastal waters of India. A beginning towards determining the carrying capacity of Indian coastal waters has been made with the ICMAM (Integrated Coastal and Marine Area Management) and COMAPS (Coastal Ocean Monitoring And Prediction System) programmes, but there is clearly much that still needs to be done.

In addition to pollution due to industrial and domestic effluents, there are natural pollution hazards due to HABs on marine ecosystem and they could be enhanced by anthropogenic pollution. Though such blooms have been observed along the Indian coast, particularly off the west coast, there is no systematic study that documents these blooms, their causes, and their potential impact on environ-

ment and also on commercial activities such as fishing, aquaculture, tourism, etc.

### *Seismicity*

Submarine earthquakes, which can generate tsunamis, could not only be a threat to offshore platforms, but also to coastal infrastructure and habitat. It is therefore necessary to monitor and evaluate the return periods of strong earthquakes. Since much of the tsunami threat to India comes from the seismically active regions of the Indian Ocean – the Andaman–Java–Sumatra and Makran subduction zones – it is necessary to map the stress field of active regions to determine the potential for future strong earthquakes and to measure periodically co-seismic deformations and identify such deformational features in the island-arc and trench region. There is also a need for comprehensive delineation and characterization of seismo-tectonic units, lineaments, and major and minor fault systems in order to assess seismicity and possible sites of future tsunamigenic earthquakes in the Indian Ocean.

### *Engineering*

Quantitative risk assessment, leading to better preparedness, is contingent upon good instrumentation and easy availability of data. Long-term monitoring using automatic instrumentation is essential for identifying a hazard before or as soon as it occurs. These data are also crucial for validating models (tsunamis or storm surges). Engineering solutions for control and remediation are important where and when cheaper and less intrusive natural methods are ineffective. With exploration for oil gaining momentum, offshore structural engineering is gaining importance. The potential threat to such structures from submarine mudslides necessitates engineering design solutions to mitigate the impact of such mudslides. Since poor quality of construction has been identified as one of the causes of higher fatalities due to natural hazards in India, quantification of these hazards must also lead to better regulations and viable building codes.

### *Education*

Different sections of the society need to be educated about the possible causes, effects and means of preparedness for different types of coastal hazards. For better preparedness, open access to information is needed to build greater public awareness. It is not only necessary that good, quantitative research be done on coastal hazards, but also that the results of such research reach those who need them: planners, developers, insurers, the public and also the academia who generate such information. Information must therefore be available in an easily accessible, publicly documented format to enable wide and open access. Experi-

ence with disaster management programmes throughout the world shows that they have to be inclusive in order to succeed. It is critical that all sections of the society, including women, need to be involved. Apart from education, this aspect of preparedness calls for an interaction among scientists who study the physical aspects, and social scientists who study the way society deals with them.

### Plan for implementation

The plan proposed below takes into account the science issues discussed above and research programmes proposed by the participants in the workshop.

#### *Identification of past storm surges and tsunamis in tide-gauge data and their simulation*

The action plan for this category is presented under five heads. The first of these (creation of a digital database) is a pre-requisite for implementation of the second and third (modelling).

##### *Tide-gauge data:*

- To digitize the tide-gauge charts available with Survey of India (SOI) (for the past 120 years or so) at a finer interval (say 5 min), so that the signals due to tsunamis will not be missed. This should be taken up in collaboration with SOI.
- To collect information on past events of weather disturbances (cyclones, storm surges, etc.) and earthquakes from all available sources and corroborate them with the extreme sea-level signals (storm surges or tsunami) identified in the tide-gauge records.
- To analyse the events identified in the tide-gauge records to determine their statistics (return periods, frequency of occurrence, etc.).

##### *Tsunami modelling:*

- To develop numerical models for tsunamis in the Indian Ocean.
- To simulate past tsunami events identified in the tide-gauge records.
- When required, to use inverse methodology to reconcile source parameters with arrival times.
- To construct Green's function for the Indian Ocean bathymetry. Use the output of numerical models to test the Green's function approach. This is a fast, computationally efficient method for predicting tsunami propagation in the Indian Ocean.
- To develop finite element and fractal models for tsunami run-up simulations, and soft computing tools (ANN, fuzzy systems and hybrid approaches) to evaluate water levels due to tsunamis.

##### *Storm surge modelling:*

- To simulate past storm surge events identified in the tide-gauge records.
- To run storm surge simulations using HadRM3 winds for future surge scenarios.
- To develop finite element and fractal models for surge run-up simulations, and soft computing tools (ANN, fuzzy systems, hybrid approaches) to evaluate water levels due to surges.

##### *Waves:*

- To model wave climate along the coast of India for different cyclones and identify high wave concentration zones.

##### *Prediction of cyclone tracks:*

- To improve model initial conditions using 3D/4D variable data assimilation.
- To generate ensemble members based on WRF model platform with different dynamical and physical frameworks.
- To improve model parameterizations.

#### *Reconstruction of time series of past storm surges and tsunamis from geological records*

Evaluation of available data and identification of reliable proxies (sedimentological, palaeontological, geochemical, isotopic, geomorphological and structural) is the first action required under this category. The rest of the action plan is divided on the basis of the hazard.

##### *Storm surges and tsunamis:*

- To acquire sediment cores from selected geologically important locations near the coast (lagoons, dunes, deltas, coastal lakes, peat beds, low-lying coastal plains and high sedimentation regions of continental shelf).
- To look for variations in grain size and faunal composition and geo-chemical proxies at close intervals in the cores. Presence of coarser material (sands, shells) within fine-grained strata indicates deposition resulting from a storm surge or tsunami. These events have to be confirmed with other palaeontological and geo-chemical proxies and the sediments have to be dated with isotopic methods to assign ages.
- If possible, to distinguish between deposits due to storm surges and tsunamis on the basis of number of layers present, aerial extent and grain-size characteristics.

##### *Submarine mudslides:*

- To collate available sub-bottom profiler data from the continental shelf and slope regions and analyse these records for slope failures.

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- To acquire high-resolution bathymetry, shallow seismic and side-scan sonar data for delineating their aerial extent.
- To acquire sediment cores where mass flows are shallow and ascertain age of the deposit through  $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$  or  $^{14}\text{C}$  dating techniques.
- To tie some of the shallow seismic profiles with drill sites and assign ages for older events.
- To build a record of slope failures and mass flows through time and space and determine the frequency of occurrence.

### *Volcanism:*

- To acquire sediment cores in the regions of volcanic activity, especially in the Andaman Sea.
- To perform sedimentological and geochemical analyses at close intervals based on grain size, grain morphology, and major, trace and rare-earth element geochemistry and identify volcanic deposition.
- To date horizons of volcanic material to determine age and periodicity of these events.

### *Geomorphology, near-shore bathymetry, coastal inundation*

#### *Geological:*

- Detailed mapping of coastal topography, near-shore and shelf bathymetry (including inlet configuration) is needed for providing input for predictive models for inundation vulnerability.
- Large-scale mapping of coastal landforms (particularly the wave protective beach ridges, berms, etc.) is needed.
- To map near-shore bathymetry (water depth less than 20 m). Work has already begun on mapping the bathymetry beyond the 10 m isobath under the EEZ programme of the Department of Ocean Development, but this needs to be extended up to the coast because much of the amplification of tsunami and storm-surge waves occurs in this regime.
- To understand sediment dynamics, coastal processes and shoreline changes.
- To quantify extent of erosion along the coast (using a combination of remote sensing and field surveys) and determine the cause (natural or anthropogenic). This is essential for the success of any scheme for mitigating the effects of erosion.

#### *Modelling studies and experiments:*

- To use high-resolution models with high-resolution bathymetry and near-shore topography and geomorphology as inputs to determine regions at risk from inundation.
- To design suitable experiments to test the viability of natural ecosystems like mangroves and sand dunes as buffer zones. One has to quantify the extent of protec-

tion provided by these bio-shields, identify areas where adequate protection exists and those where it is possible to generate or regenerate such natural protection and validate the effectiveness of these bio-shields.

#### *Output:*

- To compile relevant data in digital and open-access GIS-compatible format.
- To prepare theme-based coastal atlas (including features like coastal landform, artificial construction, cultivation, extended aquaculture, etc.).

### *Coastal pollution*

The action plan for this category is presented under two heads: industrial and domestic effluents and HABs. This distinction is necessary because the latter, though affected by anthropogenic pollution, also have natural causes.

#### *Industrial and domestic effluents:*

- To create a comprehensive database on industrial and domestic effluents released into the Indian coastal waters and use remote sensing and GIS to generate easily usable digital data.
- To use isotopes to study the pollutant pathways in the control environment and use numerical models of coastal circulation and biogeochemistry to quantify the fate of effluents, and to determine the carrying capacity of the coastal waters.
- To map ecologically sensitive areas using remote sensing and GIS.

#### *HABs*

- To use remote sensing as a tool to detect algal blooms and provide inputs for generating advisories based on ground-truth validation in such situations using taxonomy, and toxin characterization and toxicity evaluation.
- To initiate process studies at potential sites (identified from remote sensing data to be more prone to such blooms) for developing empirical and predictive numerical models.
- To install suitable organisms-based watch programme for quantifying toxic or threat constituents and their longevity in the environment, for providing necessary advisories through implementing agencies in the respective region.

The above plan delineates what can and should be done in the short term. In the long term, however, the objectives are more holistic and include the following.

- Capacity building in taxonomy and culture
- Population ecology (including cyst/resting cells)
- Prediction models
- Identification of toxins

- Bio-magnification and eco-toxicology
- Toxicity evaluation
- Decision support systems

#### Seismicity:

- To monitor and evaluate source parameters of earthquakes occurring along tectonic plate boundaries in the Indian Ocean and continental margins, including evaluation of return periods of strong earthquakes.
- To determine crustal (including sedimentary) and upper mantle structure of earthquake prone regions in oceanic and continental margins. Techniques used could be multi-channel seismic, ocean bottom seismometry, dynamic inversion of waveforms, tomographic analysis and surface wave dispersion.
- To simulate expected ground motion from an oceanic earthquake (particularly with regard to a tsunamigenic earthquake) of presumed magnitude and focal mechanism (including attenuation modelling using broad band seismic networks).
- To conduct GPS-based geodetic investigations, including detailed mapping of stress field of active regions.
- To conduct earthquake precursory studies using seismological, geo-electric, geomagnetic, magnetotelluric, geochemical, electromagnetic and other geophysical and geological methods. Generation of remotely sensed data on thermal status of earthquake-prone regions, periodic measurements of coseismic deformations and identifying such deformational features in the island arc and trench region are required. Archival of large historic earthquakes, tsunamis and their effects in the form of structured and programmable database would be useful.
- To disseminate information in the form of geophysical products from the investigating institutions through a scientific interface to the concerned authorities.

#### Engineering

- To expand existing tide-gauge network and modernize it to enable on-line data transmission to the concerned monitoring agency (SOI).
- To expand the network of met-ocean data buoys and make data available to the concerned monitoring agency (IMD) and for research. Meteorological and wave data are critical for validating wave models and enabling identification of high wave concentration zones.
- To identify failure mechanisms in coastal and offshore structures and devise solutions.
- To evolve better regulations for coastal structures and viable building codes.

#### Education

- To prepare material in the form of print (stories, comics and cartoons, particularly for school children, bro-

chures, manuals, charts, etc.), audio-visual, and electronic media for distribution/dissemination especially in local languages to explain the causes and effects of coastal hazards, means to mitigate the effects, and measures for preparedness.

- To include topics on coastal hazard preparedness in academic curricula: in schools, undergraduate and post-graduate curricula, backed by teachers' training programmes and web-based lectures.
- To use mass communication channels for capacity-building among the 'local population' – involving them in data collection and building awareness through lectures, story-telling, plays, theatre, etc. in local languages.

To harness the power of the internet by developing a web portal, and making available data and information on coastal hazards at a single source of reference that is open to all. Funding agencies should make it mandatory for project leaders to place the information/data collected through the project on websites within a stipulated period. Open access to data in a publicly documented, easily accessible format is critical for the viability of any programme aiming at improving our preparedness.

#### Epilogue

The science plan presented here is based on more than 75 one-page research proposals that were discussed during the workshop. The key to formulating the plan was the idea of preparedness: all proposals were required to lead to enhanced preparedness. A tentative estimate for implementing the science plan as suggested above, is approximately rupees 15 crores. The science plan has been submitted to three funding agencies, DST, DOD and CSIR, which came together under the auspices of INSA to organize the brainstorming session in New Delhi in January 2005. The agencies are expected to finalize the science plan, work out the funding mechanism and call formally for proposals, which will then undergo the normal process of review. A tentative target date for funding of projects is January 2006.

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