

Indian estuaries: Dynamics, ecosystems, and threats

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Abstract

Indian estuaries have special features that are derived from occurrence of the wet Indian Summer Monsoon (June-September) and hence have been called monsoonal estuaries. High runoff during the wet season and a 8-month long dry season with little runoff lead to striking temporal changes in salinity and velocity fields in these estuaries. A Number of habitats that have adapted to such changes are found in the estuaries. The Climate Change will have an adverse impact on the habitats. So will local anthropogenic impacts, which in some cases are severe, because many large cities have grown on banks of the estuaries. The country needs a major programme involving research, education, legislation, and public awareness to keep them healthy.

1. Introduction

An estuary is a channel or an embayment with a sea at one end and one or more rivers at the other. The freshwater brought by the rivers mixes with seawater in the estuary. Tides force the seawater in and out of the estuary and thus influence the mixing, as depicted in Fig. 1 (a). An estuary occurs over a coastal plain whose elevation does not exceed maximum tidal elevation which along the coast of India is a few metres at the most.

Channels of the estuaries found along the coast of India can be classified in three kinds of shapes. The most commonly observed estuaries have the simplest of the three shapes with a prominent long central channel to which a river joins at the upstream end, i.e. head of the estuary. A number of smaller rivers usually join the estuary along its length from its head to its downstream end or the mouth. A schematic of vertical section through main channel of such an estuary is shown in Fig. 1(a). A horizontal section through the main channel and its tributaries is

depicted in Fig. 1 (b). The Mandovi estuary in Goa, discussed later, is an estuary of this kind. The second kind of estuarine shape has a lake connected to a sea. The lake receives freshwater from rivers. Seawater enters the lake through one or more narrow inlets. The Vembenad lake in Kerala and the Chilka lake in Orissa are two examples of this kind of shape. The third kind has a complex network of channels that is fed by riverine runoff on one end of the channels, they join the sea through the other end. The Sundarbans consist of estuaries of this kind. They usually occur on a delta and hence are called delta-front estuaries. A horizontal section through an estuarine lake is shown in Fig. 1(c) and that through a delta-front estuary in Fig. 1(d).

A common feature of the estuaries belonging to all the three classes is seasonality in salinity of estuarine waters. It arises from seasonality in the quantity of freshwater brought by the rivers that join the estuaries. This seasonality is a consequence of India's monsoonal climate that has two prominent seasons, a wet and a dry season. The Indian Summer Monsoon (ISM), which normally occurs during June - September, is the wet season when India receives about 80% of its annual rains. Runoff in rivers is maximum during this season. The dry season lasts rest of the year. Runoff in the rivers decreases rapidly after the rains. There is usually hardly any or no runoff into the estuaries during the eight months of the dry season. Because of the seasonality, Indian estuaries are often called monsoonal (Vijith et al., 2009). The ecosystems and natural habitats that are associated with the estuaries must adjust to the seasonality.

This article provides a brief overview of the state of Indian estuaries. The next section describes

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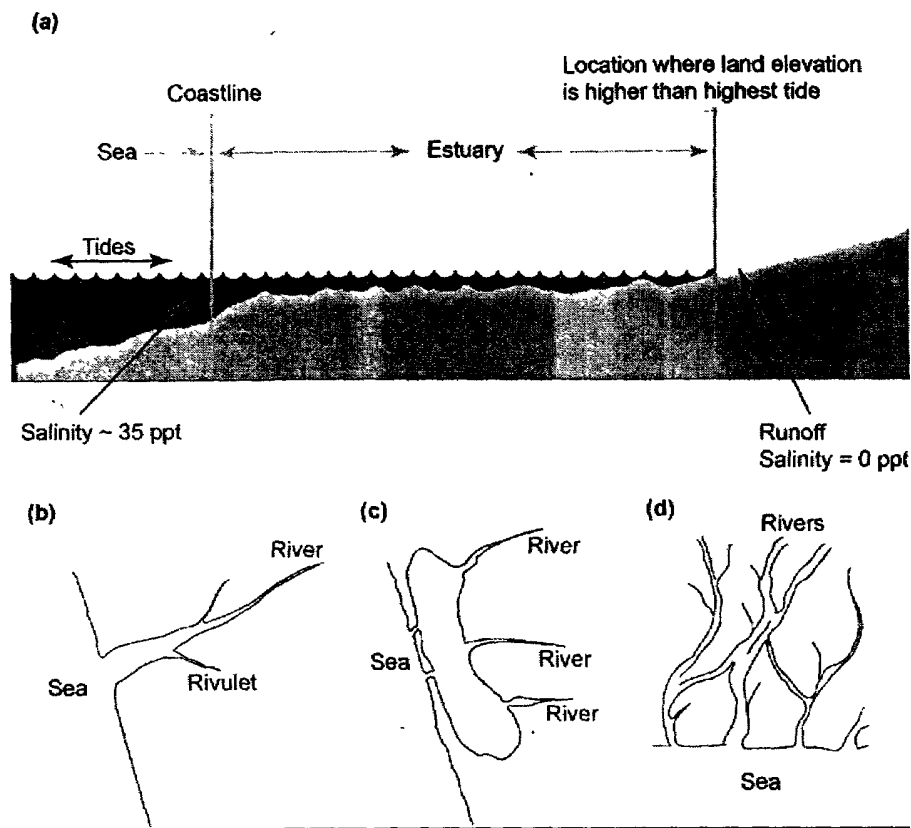


Fig. 1- (a) A schematic representation of vertical cross-section through the middle of the main channel of an estuary. Exchange of water between the channel and the sea at the sea-end is dominated by tide. Seawater enters the estuary as the tide rises during flood. Estuarine water enters the shelf sea during ebb as the tide falls at the mouth. The seawater, which has a salinity of about 35 ppt, and the freshwater (whose salinity equals 0 ppt) mix in the estuary. Horizontal sections in (b), (c), and (d) represent three classes of shapes of estuarine channels found along the coast of India.

The estuary in (b) has a dominant channel that receives freshwater from a river at its head and from rivulets that join the channel along its stretch from head to mouth. This class of estuarine channels shapes are common amongst Indian estuaries. The estuary in (c) has a large lake that joins the sea through one or more narrow inlets. The lake receives freshwater, from a number of rivers. The Kochi backwaters in Kerala have geometry of this kind, (d) A complex network of channels is a distinguishing feature of the estuaries in the Sundarbans, West Bengal. The upstream end of each of the channels has a river that brings freshwater. The downstream end is connected to the sea.

seasonality in salinity observed in the Mandovi estuary on the west coast of India in the state of Goa. It is one of the better studied estuaries of the country. Some of the ecosystem that have thrived in this estuary are described in Section 3. Some of the threats that the estuaries need to face due to the Climate Change and anthropogenic impacts are examined in Section 4. The article concludes with a

discussion on some of the steps that will need to be taken to maintain the country's estuaries in healthy state.

2. Salinity in the Mandovi estuary

Ocean sciences in India took a major step forward with the International Indian Ocean Expedition (IIOE) during 1961-65. The emphasis of

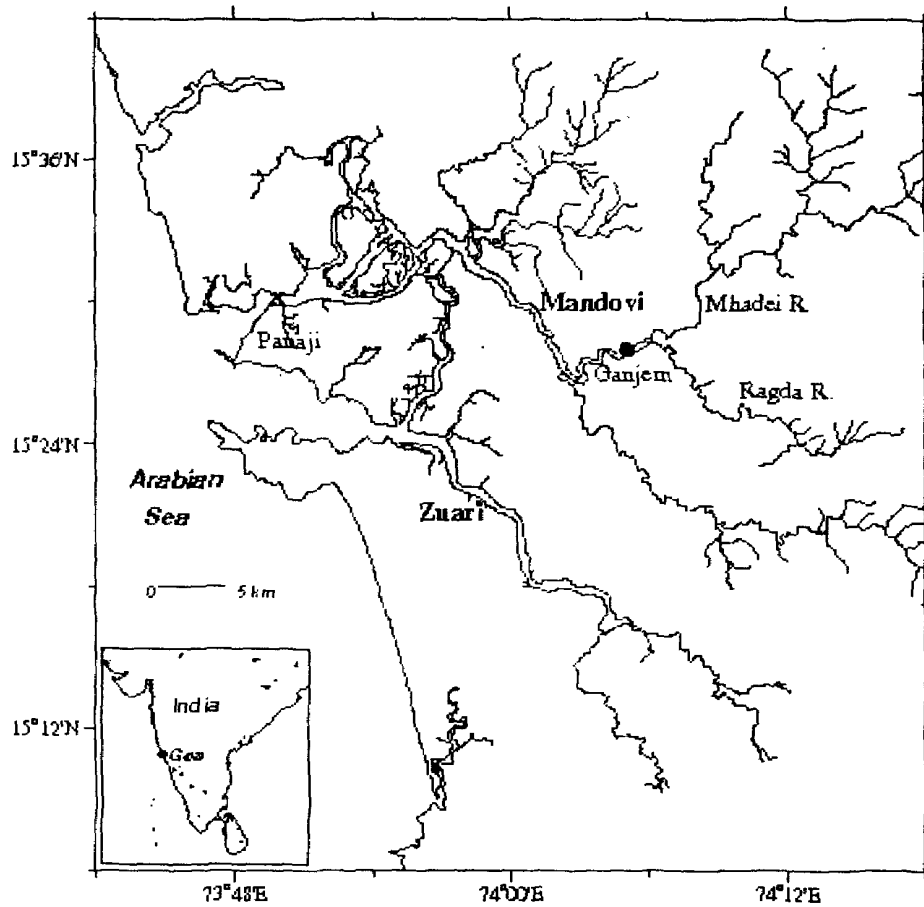


Fig. 2-The Mandovi estuary located in the state of Goa, west coast of India (inset). Rivers Mhadei and Ragda join the estuary at its upstream end. Other rivers join at other points along the length of the main channel of the Mandovi estuary. Location of Ganjem is shown with a 'filled circle'. Runoff measured at Ganjem is shown in Fig. 4. (Taken from Vijith *et al.*, 2009)

the expedition was large-scale oceanography of the North Indian Ocean. The same emphasis continued when the nation initiated oceanographic research in India. Small scale systems, estuaries and coasts for example, did not receive as much attention. A notable exception is the Mandovi estuary in Goa. Fig. 2 shows a map of the estuary. Oceanographers from the National Institute of Oceanography (CSIR), Goa, which is located close to the mouth of the estuary, have been studying this estuary. Shetye *et al.*, 2007, provide a summary of the present knowledge of the estuary. Sufficient data have now accumulated to describe the annual cycle of events that determine salinity variation in the estuary.

2.1 Channel geometry and tide

Elevation of the land along the west coast of India has two prominent features. The first is a belt of coastal plain that borders the Arabian Sea. The second is a rise in elevation that occurs farther inland due to the Sahyadri mountain range, also known as the Western Ghats. The Mandovi, like other estuaries along the coast, meanders on the coastal plain. Up to about 50 km upstream from its mouth elevation of the Mandovi channel is small enough for tidal influence to be felt. Farther upstream, as the elevation rises, tidal influence decreases and importance of runoff to flow of water increases. At

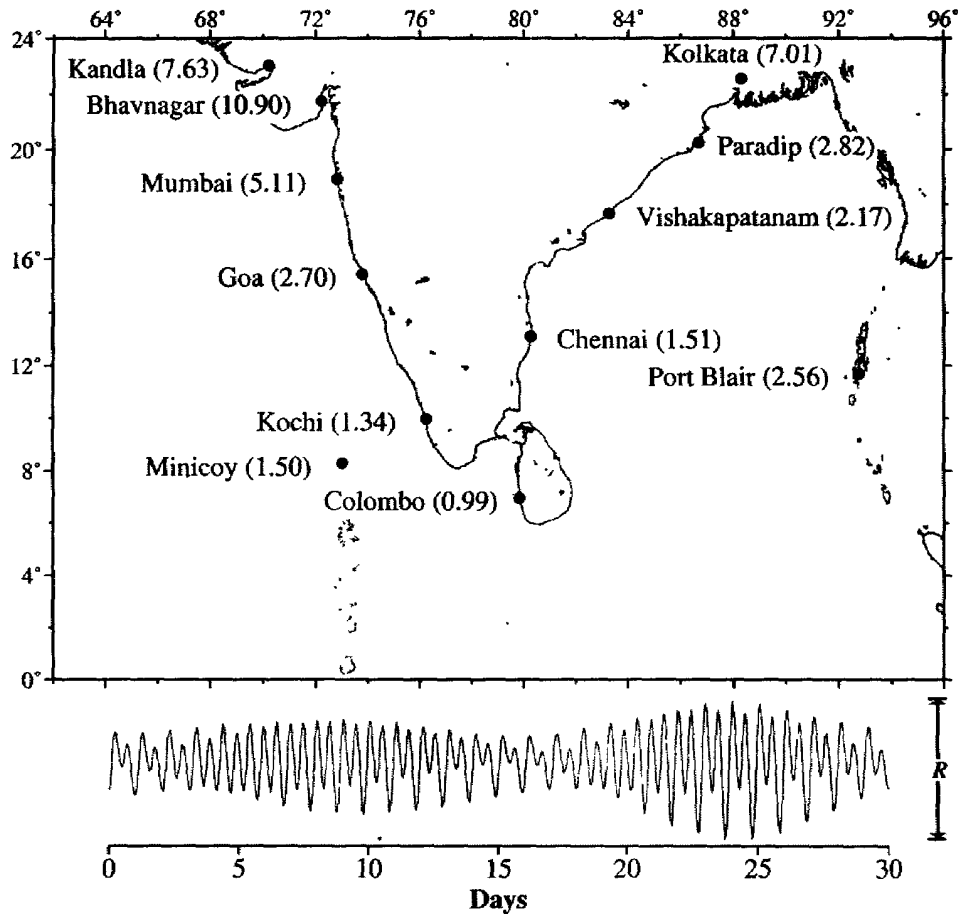


Fig. 3- The astronomical tide along the coast of India consists of a mixture of semi diurnal (period ~ 12.5 hours) and diurnal (period ~ 24 hours) oscillations of sea level. The record of variation of sea level during a month often looks like the one shown at the bottom of the figure. Tidal range (difference in water level between maximum and minimum water level) differs from place to place and is shown in m in brackets after the name of a location. Range is high at locations near upstream end of channels and gulfs along the coast.

the head contribution of the tide to the flow is negligible.

The main channel of the Mandovi narrows from a width of about 4 km at the mouth to 1 km four kilometers upstream. Farther upstream the channel continues to get narrower almost linearly with distance along the channel. The channel is about 50 km long from the mouth to the head. At the head the channel is about 100 m wide. Depth of the channel with respect to mean water level is usually maximum in the middle of a cross-section. This depth fluctuates with distance from the mouth. This depth varies from a couple of metres to about ten metres. There is also a

trend, the channel shallows from a depth of a over 5 m at the mouth to about two metres at the head.

The astronomical tide at the mouth determines the nature of flow in an estuary near its mouth. The tide along the coast of India is mixed, i.e. it consists of a mixture of oscillations with a period of about 12.5 hours (semi-diurnal oscillation) and with a period of about a day (diurnal oscillation). Tidal range along the coast increases from south to north, as seen in Fig. 3. The range is particularly high in gulfs such as the Gulf of Kutch or the Gulf of Khambhat or a channel like the Hooghly river, all of which get narrower away from their sea end.

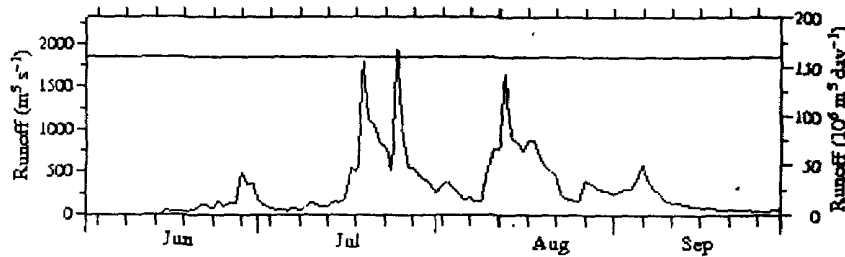


Fig. 4- Runoff ($\text{m}^3 \text{s}^{-1}$) in the Mandovi estuary, measured at the head, Ganjetn (see Figure 2) during the Indian Summer Monsoon of 1992. The horizontal line represents a runoff of $1852 \text{ m}^3 \text{s}^{-1}$ i.e. $160 \times 10^6 \text{ m}^3 \text{ day}^{-1}$. Volume of the Mandovi below mean sea level is $160 \times 10^6 \text{ m}^3$. It is expected that when volume of runoff in a day exceeds the volume of the estuary, such as what happened on 26 July 1992 when the runoff at the head was $168 \times 10^6 \text{ m}^3 \text{ day}^{-1}$ the estuary turns into a freshwater system like a river. The figure is reproduced from Vijith *et al.*, 2009.

Narrowing and shallowing of the Mandovi channel from mouth to head leads to decrease in cross-sectional area with distance from the mouth. This in turn leads to a small increase in tidal range from mouth to head Sundar and Shetye, 2005 until the elevation of the channel rises sufficiently to prevent the tide from propagating further.

2.2 Runoff

The Mandovi receives its runoff at its head from the river Mhadei and other tributaries of different sizes that join the Mandovi along its length. The tributaries carry freshwater runoff during the wet ISM, June-September, and for some time, often couple of months, after its withdrawal. Rainfall during the ISM has active and break periods. So does the runoff which derives its freshwater from the rain. Typical variation of runoff in the Mhadei is shown in Fig. 4. The times of high runoff coincide with active rainfall spells. Such spells sometimes can be heavy enough that runoff during a day from Mhadei alone equals volume of the estuary. On such a day the estuary turns into a freshwater river. It has been estimated by Suprit and Shankar (2008) that the tributaries other than the Mhadei that join the Mandovi bring runoff of the same order as that contributed by the Mhadei. It is further estimated that the normal runoff entering the Mandovi during the wet season is of the order of 40 times the volume of

the estuary, and hence can flush the estuary that many times.

After withdrawal of the wet season runoff in the estuary decreases rapidly. By early January it reaches negligible levels. With decrease in runoff seawater migrates into the estuary. The rate of migration increases as runoff decreases.

2.3 Salinity

The unit of measurement of the salt in seawater is salinity, which is the ratio of the weight of dissolved salt to the weight of seawater, and is normally given as parts per thousand (ppt). Average salinity of seawater is about 35 ppt. The salinity in an estuary is influenced by two boundary conditions. The first is amount of runoff that brings freshwater (salinity ~ 0) to the estuary. The second is the tide which during flood pushes seawater (salinity ~ 35 ppt) into the estuary. The seawater and the freshwater mix in the estuary. During ebb the tide pulls the mixed water out of the estuary through its mouth. Different processes within an estuary contribute to mixing of the two waters, the important among these in the Mandovi estuary are: influence of the tide on the advective field within the estuary; circulation, often called gravitational circulation, arising from density variation due to salinity variation; circulation set up by entry of freshwater into the estuary; and, horizontal and vertical mixing

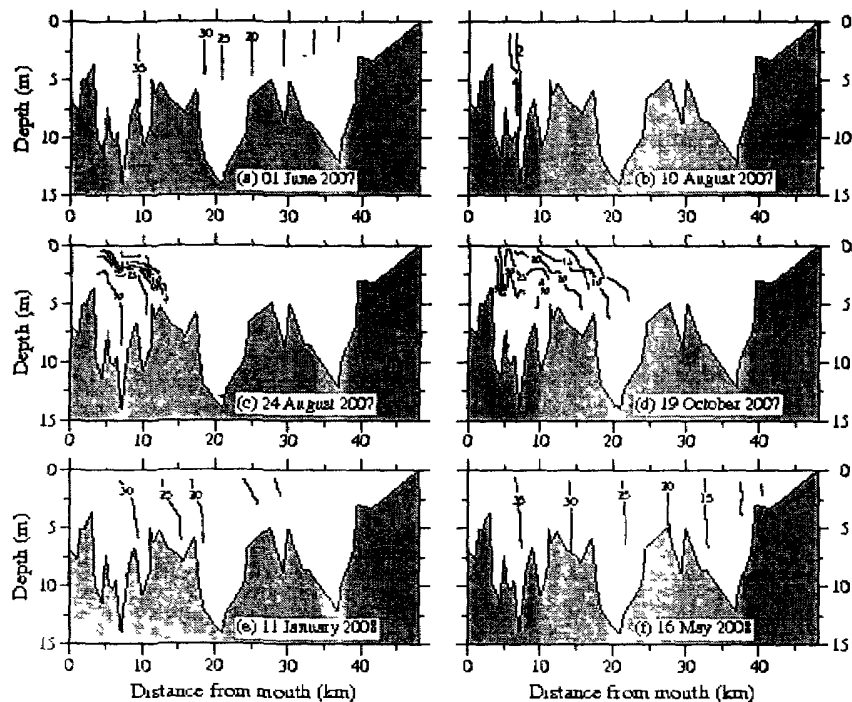


Fig 5 (a-f) Along channel salinity sections made during a year starting 1 June 2007. The date on which a section was made is shown at the bottom of each figure. The figure is reproduced from Vijith *et al.* 2009.

due to turbulence. As a result of advective and mixing processes, salinity in an estuary has a range of ~ 0 -35 ppt. Salinity is the most important factor that determines density of water in an estuary.

The impact of boundary conditions and internal processes in the Mandovi on its salinity field can be seen in the annual cycle of salinity variation shown in Fig. 5 which is based on data recorded during a year, June 2007 - May 2008. On 1st June 2007, before onset of the ISM that year, salinity within the estuary was close to the largest values that are observed in the estuary at a location during a year. Two months later, on 10 August 2007, by which time significant amount of rainfall had occurred over the catchment area of the Mandovi, the estuary had its other extreme in salinity, now lowest at a location, with freshwater in most of the channel. Following a lull in precipitation, and hence in runoff, during the next two weeks seawater migrated into the channel as seen in the salinity field on 24 August 2007. Vertical stratification near the mouth was high at this time. As rainfall and runoff decreased salinity

migrated upstream (see salinity field on 19 October 2007). Following withdrawal of the ISM that year, migration of salinity into the channel continued (see the figure for 11 January 2008). By 16 May 2008, the salinity field was similar to that observed a year earlier thus marking completion of an annual cycle.

Based on the data in Fig. 5 and other similar data we find that the following are the important features associated with the annual cycle of salinity field in the Mandovi. Variation in salinity is rapid during the ISM and is dominated by runoff. Salinity increases when runoff drops and vice versa. There are occasions when the entire estuary turns into a freshwater river when runoff is high enough. After withdrawal of the ISM salinity keeps increasing continuously till onset of the next monsoon. Behaviour similar to that seen in the Mandovi is common in Indian estuaries. The large seasonal variation in salinity seen in these estuaries due to occurrence of the ISM has prompted naming of these estuaries as "monsoonal estuaries".

3. Estuarine habitats

Marine life in monsoonal estuaries has adjusted to the variation in salinity in the estuaries. The Mandovi, for example, has a variety of clams living on inter-tidal mudflats. Located on banks of the estuary, the mudflats are covered by water when the tide is high and are exposed at low tide. The clam fishery has been a traditional means of livelihood in Goa.

Mangroves form another habitat observed in the Mandovi and many other monsoonal estuaries. Mangroves are trees and shrubs that grow in marine sediment and can survive on water with a wide range of salinity. Mangrove forests on the banks of estuaries provide a quiet and well protected environment for marine organisms to survive and thrive. These include algae, barnacles, oysters, and sponges. Shrimps and crabs make their home in muddy bottoms of mangrove forests.

There are marine organisms that spend a part of their lifecycle in estuaries. For example, penaeid prawns lay eggs in the open sea. They migrate to an estuary during the larval stage and spend post-larval stage in an estuary. Juveniles then migrate offshore.

These are but a few of the habitats found in estuarine environment of India. It is expected that not all have been identified yet. Very few have been studied.

4. Threats

Throughout history estuaries have been favoured locations for human settlement for whom a major attraction has been easy access to sea routes for trade. Ports have been located on estuaries because they provide sheltered anchorage. Shipyards too are located there for the same reason. Nowadays estuarine and coastal areas are favoured locations for power plants and petrochemical complexes because they use seawater as coolant. Chemicals and fertilizer industry have used estuaries and coastal areas for discharging effluents. Hence estuaries in India have come under severe anthropogenic impact. In addition, the Climate Change threats loom on the horizon.

4.1 The Climate Change impacts

Three Climate Change related impacts have been discussed widely: sea level rise, ocean acidification, and Harmful Algal Blooms (HAB). The first and the second would bring present habitats under pressure because the environment they have survived on so far would change. HABs often result when a changing environment favours a newly introduced organism, leading to its excessive growth in population (a bloom). The new organism can be toxic thus hurting other organisms that feed on it.

While such impacts have been discussed, two others, also related to Climate Change, have not received sufficient attention. Predicted Climate Change scenarios shows an increase in frequency of extreme events. Two are particularly relevant in the Indian context: extreme rain events; and, cyclones and associated storm surges.

Extreme rainfall events pose a special threat on the west coast of India which is a region of high precipitation, the annual precipitation being over 250 cm. The most discussed event of this kind in recent years occurred in Mumbai on 26 July 2005. In about 24 hours beginning 8:30 a.m. on that day Mumbai received 94.4 cm of rainfall, the highest ever in the history of the city. Of this, 88.5 cm, i.e. about 94%, was received in 12 hours from 11:30 a.m. Precipitation of this magnitude is bound to lead to flooding. The best that can be done is to be aware of the possibility and have a disaster management plan. Locations in a region where such disasters could occur can be identified in advance by analyzing topography of the region. Such analyses invariably highlight the importance of keeping river and estuarine channels clear of undesirable debris by desilting of their beds. This alone, however, may not be enough if the flooding is intense. There needs to be a disaster management plan prepared in advance for an estuary, and the people living on its banks need to be made aware of the plan.

The east coast of India is known to be susceptible to storm surges produced by cyclones that form in the Bay of Bengal and then cross the coastline to move inland. When a surge propagates in an estuary, it can cause severe damage not only to the habitats in the estuary, but also to the life and property on the banks of the estuary. Due to **frequent**

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Table 1- Estuaries on whose banks some of the major cities of the country exist. Listed are the estuary, the major city, its population and waste water discharge (wherever known).

Estuary/River	Major city	Population (10 ⁶)	Waste water discharge (10 ⁶ m ³ /day)
Sabarmati	Ahmedabad, Gandhinagar	4.7	14
Narmada	Jabalpur, Bharuch	13	N.A.
Tapi	Sural	2.8	N.A.
Mahim, Ulhas, Thane	Mumbai	16.5	2.8
Cochin Backwaters	Kochi	14	0.1
Cauvery	Thiruchirapalli, Erode	13	~0.1
Ennore, Adyar	Chennai	6.7	0.01
Krishna	Hyderabad, Vijaywada.	6.7	N.A.
Hooghli	Kolkata	13.2	15.3

occurrence of cyclones on the east coast of India, disaster management plans here are well developed. However, more needs to be done to make a cross-section of population aware of the plans.

4.2 Anthropogenic impacts

While the Climate Change impacts are worrisome, greater concern today is from anthropogenic impacts on the estuaries arising from discharge of civil and industrial effluents. Table 1 lists a few of the estuaries of India that have a major city on its banks. Three of India's largest cities, Mumbai, Chennai, and Kolkata, are each located on the banks of an estuary. Discharge into these estuaries has led to problems that need immediate attention.

One such problem arises from discharge of raw sewage. Goa's Mandovi estuary is taken to be a clean estuary based on data on biochemical variables (Biological Oxygen Demand, BOD; nitrates; phosphates; etc.). However, total coliform counts

near Panaji, a city located on the Mandovi, is always greater than 10 per ml, and often exceeds 100 per ml (Ramaiah *et al.*, 2007). According to the European Standard "European Blue Flag Beach Criteria" conform count in excess of 5 per ml makes a water body unsafe for bathing, but "5-100 per ml are allowed a few times during the season". In the USA count greater than 10 is considered unsafe.

Civil and industrial discharge leads to another problem, this one arising from excessive nitrates. Large areas of Vembenad lake, around which the Kochi city has grown, are now covered by water hyacinth, a free-floating perennial aquatic plant native to South-America. If not controlled, it could cover the backwaters entirely. Based on experience elsewhere, growth of this plant has been found to impact water flow, block sunlight from reaching native aquatic plants, and starve the water of oxygen, often killing fish (or turtles). The plants also creates a prime habitat for mosquitoes (en.wikipedia.org/wiki/water-hyacinth).

5. The way ahead

Though historical developments favoured growth of large-scale oceanography in the country, social imperatives now demand attention on water bodies distributed along the coast of India. At least a hundred estuaries situated on the coast are used extensively by people and industries located on the banks of these systems. Each estuary is expected to have a situation peculiar to it. Each needs to be studied so that a plan can be drawn to manage it.

Gathering data on the large number of estuaries poses a challenge. It also offers an opportunity. Educational institutions, colleges, and university departments could be encouraged to take up study of estuaries located in their proximity. This would introduce opportunity to faculty of the educational institutions to participate in real world environmental data gathering and research. It would also offer students first hand experience in environmental studies and enlarge their awareness of current environmental issues.

Involvement of educational institutions as envisioned above in gathering data alone will not be sufficient. Such data will need to be analysed by experts in estuarine oceanography. The country needs to enhance significantly the number of multidisciplinary oceanographers in the field of estuarine studies. With well over 100 estuaries spread over 7,000 km long coastline the task of creating such manpower may well have to be achieved by establishing one or more institutions

dedicated for this purpose. Such an institution will need to develop expertise in management of India's estuaries through policy formulation and application of suitable technologies. Cleaning up of the badly affected Indian estuaries and bringing them back to health will also need a legal framework to ensure that management plans are implemented to produce desired results. Hence it will require suitable legislation which in turn will need public awareness of the problems that our estuaries are experiencing today.

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