



Coastal Zones: Ecology and Climate Change Need Concerted Attention for Sustained Productivity

H. S. SEN*

Former Director, ICAR-Central Research Institute for Jute & Allied Fibres (ICAR)
Barrackpore - 700 120, Kolkata, West Bengal

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Coastal ecosystem poses a delicate equilibrium between land and water masses amongst its different components but with high degree of vulnerability in spite of bountiful natural resources. The equilibrium is further under serious threat due to climate change and global warming, though on the other hand, it is significant that coastal marshes tend to sequester carbon continuously with increasing storage capacity and with time, and thus regarded as a valuable C sink per unit area, particularly in the tropics, to negate adverse impacts due to global warming. Planning for effective and sustainable development warrants specific attention to maintain the equilibrium. This will require adoption of integrated approach to soil and water management, in the first place, and through it or otherwise, necessary measures to conserve the ecology. Piecemeal approaches to reclaim location specific problems or interference with the hydrology of the rivers *per se* for short term gains for increase of productivity, disregarding completely the practices on integrated management of different intervention areas and thereby conserve the ecology in coastal plains, may offset the equilibrium, as experienced in different parts of the world, leading to such adverse impacts, such as seawater intrusion into inland areas, massive loss of mangroves, coral reefs, seagrasses and various other aquatic plant & animal species, sedimentation & erosion, tidal flooding, subsidence of land, etc. The influx of reckless application with fast increasing dose of nitrogen or other inputs resulting in nutrient imbalance through human activities in the adjoining inland and coastal areas are glaring examples leading to such phenomena as eutrophication and formation of dead end zones in the coastal water bodies. Policy approach for water budgeting of different water resources, preferably on watershed basis, with minimal or planned dependence on abstraction of the underground water should be an essential strategy to be drawn in order to ensure sustainable increase in crop water productivity as well as water productivity all along the coast.

(Key words: Coastal ecosystem, Sustained productivity, Ecology, Climate change, Integrated water management, Hydrology & E-flow in Ganga, Seawater intrusion, Sedimentation & erosion, C sequestration, Soil quality, Water budgeting, Nutrient imbalance, Population & climatic disaster, Future policy)

Coastal areas in India and elsewhere are by and large heavily populated. Nearly 40% of cities larger than 500,000 population in India are located in the coast. Overall about 50-70% of the global population live within 100 km of the coastline covering only about 4% of earth's land (Pooya and Balachandran, 2008), thereby drawing heavily on coastal and marine habitats for food, building sites, transportation, recreational areas, and waste disposal. According to another estimate (Wikipedia, 2009), coastal areas (within 200 km from the sea) share less than 15 % of the earth surface area, and this predicts that three-fourths of the world population are expected to reside in the coastal areas by 2025.

Coastal ecosystem poses a delicate equilibrium between land and water masses amongst its different components but with high degree of vulnerability in spite of bountiful natural resources. The equilibrium among

the different components in the ecosystem is further under serious threat due to climate change and global warming. While there are commendable progresses in the country affecting productivity of the ecosystem at a given time, significant changes in relevant parameters on spatial and temporal mode, are in sight drawing instances on the ecological damage from related areas within and outside the country, which suggests to concentrate our attention for effective and sustainable development in the long run by maintaining equilibrium amongst different components. The paper is a brief exposure to such direction of research in future.

Major coastal ecosystems of the world

The main ecosystems of the coastal ocean are: estuaries, macrophyte communities, mangroves, coral reefs, salt marshes and the remaining continental shelves (Table 1). These areas are only approximately known,

*Corresponding author : E-mail: hssen.india@gmail.com, hssen2000@hotmail.com

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and there is some double-counting among the ecosystem types. For example, coral reefs, estuaries and the “remaining shelf” all include macrophyte-dominated communities, totaling approximately 26 x106 km² area (Encyclopedia of Earth, 2007).

Mangrove swamps, as just an example, having significant role towards stability of the ecosystem, are found in tropical and sub-tropical tidal areas worldwide, like Africa, Americas (including Caribbean Islands), South America, Asia, Australasia, and Pacific Islands. A list of 15 countries having significant areas under mangrove swamps are given in Table 2. In the last 50 years, as much as 85 percent of the mangroves have been lost in Thailand, the Philippines, Pakistan, Panama and Mexico. Globally, about 50 percent of mangrove forests have been lost. An estimated 35% of mangroves have been removed due to shrimp and fish aquaculture, deforestation, and freshwater diversion.

Table 1. Surface area of the main coastal ecosystems in the world

System	Surface area (10 ⁶ km ²)
Estuaries	1.4
Macrophyte-dominated	2.0
Coral reefs	0.6
Salt-marshes	0.4
Mangroves	0.2
Remaining shelf	~21
Total	26

Table 2. Estimated coverage with largest mangrove areas (Source: ITTO/ ISME, 1993)

Country	Mangroves ('000 ha)	Global % area
Indonesia	4250	30
Brazil	1376	10
Australia	1150	8
Nigeria	970	7
Malaysia	641	5
Bangladesh	611	4
Myanmar	570	4
Vietnam	540	4
Cuba	530	4
Mexico	525	4
Senegal	440	3
India	360	3
Colombia	358	3
Cameron	350	2
Madagascar	327	2

In Indonesia alone over 10,000 km² of mangrove forests have been converted into brackish water ponds (called *tambaks*) for the cultivation of prawns and fish. Valuation of intact tropical mangroves estimated at US\$ 1000 per ha drops to US\$ 200 per ha due to clearance by shrimp farming (Poyya and Balachandran, 2008).

Coastal plain: Major features and management issues

Coastal plain, within the ecosystem, is the landward extension of the continental shelf or the sea and used for agriculture and allied activities as well as for few other occupational purposes but is not always distinctly differentiated with sharp boundaries from the other ‘main’ components referred in Table 1.

Characteristics & distribution and factors affecting productivity in India

Coasts are dynamic systems, undergoing changes in form and processes in time and space in response to oceanographic conditions and geomorphic features. Indian coastline, stretching over 7,500 km along ten states and two archipelagos, is the sixth one in the world and has been subjected to many spells of sea level changes since the Last Glacial Maximum. The east and west coast are markedly different in topographic setup, tectonic features and geomorphic framework. The west coast is relatively narrow as compared to east coast and lacks any major delta formation. Of the two coastlines in India length of the East coast is higher than that of the West. The continental shelf is more stable than the coast. The continental shelf of 0-50 m depth spreads over 1,91,972 km² and between 0-200 depth over 4,52,060 km². The shelf is wide (50-340 m) along the East coast. The Exclusive Economic Zone is estimated at 2.02 million sq km.

Practically no systematic study was earlier made in India to demarcate the coastal soils based on well-defined scientific indices. Notable among the past works, however, was that of Yadav *et al.* (1983) who suggested 3.1 million ha area (including mangrove forests), while Szabolcs (1979) suggested 23.8 million ha under coastal salinity in India. The coastal saline soil has been referred by various workers almost synonymously with coastal soil which is not correct since all coastal soils are not saline in nature. None of the above estimates appears to have been made on sound scientific basis. However, the latest compilation made by Velayutham *et al.* (1998) on the soil resources and their potentials for different Agro-ecological Sub Regions (AESR) in coastal tracts of India show total 10.78 million ha area under this ecosystem (including the islands), which was the first scientific

approach for delineation of the coastal ecosystem. Different factors limiting agricultural productivity in the coastal plains are listed as (1) Excess accumulation of soluble salts and alkalinity in soil, (2) Pre-dominance of acid sulphate soils, (3) Toxicity and deficiency of nutrients in soils, (4) Intrusion of seawater into coastal aquifers, (5) Shallow depth to underground water table rich in salts, (6) Periodic inundation of soil surface by the tidal water vis-à-vis climatic disaster and their influence on soil properties, (7) Heavy soil texture and poor infiltrability of soil, (8) Eutrophication, hypoxia and nutrient imbalance, (9) Erosion and sedimentation of soil, and (10) High population density, etc.

Salinity build-up in soil and soil quality

Salinity build-up in soil due to ingress of saline ground water aquifers takes place through the following major processes: (1) excessive and heavy withdrawals of ground water from coastal plain aquifers, (2) seawater ingress, (3) tidal water ingress, (4) relatively less recharge, and (5) poor land and water management.

Seawater Intrusion : India's first Aquifer Atlas, released by the Central Ground Water Board (CGWB) recently, has further reiterated what other studies have shown about Chennai city. Over-exploitation of groundwater has rendered it vulnerable to sea intrusion in different pockets, putting to danger sensitive aquifers on which a major chunk of the population depends for water. According to the atlas, Chennai is one of the districts classified as Over-Exploited, with parts having salinity content higher than permissible limits. However, what striking is the fact that the Aquifer Vulnerable Map, which is part of the document, shows that the north of Chennai as one of only four pockets in entire Tamil Nadu, which has seen significant sea water intrusion, with the other two being pockets of Cuddalore, Ramanathapuram and Kanyakumari. Recent observations have shifted their focus to South of Chennai in areas such as Adyar and Besant Nagar, where officials pointed out that signs of intrusion are already showing (<http://www.ibnlive.com/news/india/sea-water-intrusion-a-big-challenge-for-city-aquifers-515082.html>).

Modeling on ground water behaviour : Salt water intrusion takes several forms. Horizontal intrusion occurs as the saline water from the coast slowly pushes the fresh inland ground water landward and upward. Its cause can be both natural (due to rising sea levels) and man induced, (say, by pumping of fresh water from coastal wells) (Fig. 1a). Pumping from coastal wells can

also draw salt water downward from surface sources, such as tidal creeks, canals, embankment (Fig. 1b). This type of intrusion occurs within the zone of capture of pumping wells, which is local in nature, where significant drawdown of the water table causes induced surface infiltration. A third of intrusion is called 'upconing'. Upconing also occurs within the zone of capture of a pumping well, with salt water drawn upward toward the well from salt water existing in deeper aquifers (Fig. 1c) (Maimone, <http://cms.ce.gatech.edu/gwri/uploads/proceedings/1999/MaimoneM-99.pdf>).

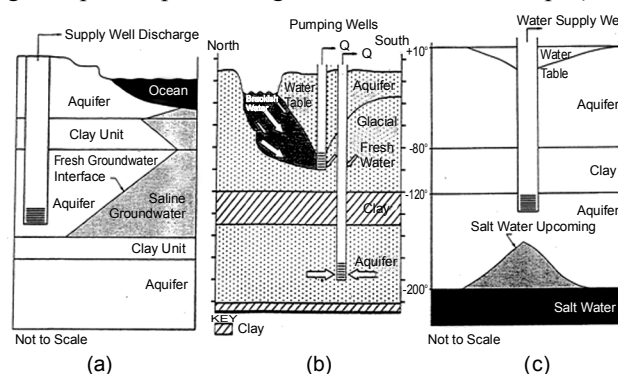


Fig. 1. Different forms of salt water intrusion (a) horizontal movement towards supply well (b) induced downward movement from surface sources such as creeks (c) upconing beneath a supply well

(Source: Maimone, <http://cms.ce.gatech.edu/gwri/uploads/proceedings/1999/MaimoneM-99.pdf>)

Management models and control of seawater intrusion: Indiscriminate use of water resources, particularly under ground, thus poses a major threat to destabilize the ecosystem. Different management models at varying degrees of success have been reported in the literature by various workers to find out developing withdrawal management methodologies for determining the number of viable locations for wells and the quantities of water which can be pumped from coastal aquifers while protecting the wells from seawater intrusion in order to satisfy the demand (social dimension), maximizing the economic benefits (economical aspects), and controlling the saltwater intrusion (environmental concern). One such optimisation model was developed for planning and managing saltwater intrusion (Da Silva *et al.*, <https://repositorium.sdum.uminho.pt/bitstream/1822/8682/1/Optimal%20Management%20of%20Grondwater%20Withdrawals%20in%20Coastal%20Aquifers.pdf>) into coastal aquifer systems using the simulation/optimisation approach for managing water resources in the areas, suggesting the best location of the wells with specific flow rate, and thereby, the best policies to

maximize the present value of economic results of meeting water demands, and to keep under control the saltwater intrusion.

Various engineering methods are in use worldwide for the control of coastal seawater intrusion. In India sporadic work has been done, as for example in Tamil Nadu (Chennai) and along Saurashtra Coast in Gujarat state (Mangrol-Chorwad-Veraval area). Methods that may be employed for control of seawater ingress into aquifers are listed and described as: (1) Modification of ground water pumping and extraction pattern, (2) Artificial recharge, (3) Injection barrier, (4) Extraction barrier, (5) Subsurface barrier, (6) Tidal regulators/ Check dam/ Reservoirs.

For an effective and long term solution to the problem of seawater intrusion into ground water aquifer in the coastal plain it is necessary to develop location-specific optimization model to decide on suitable locations of the pumping wells and rates of withdrawal of the ground water from these wells after due consideration of the relevant factors. Attempts for suitable constructions either by pushing saline water front further seaward through check dams or injection barriers, and/ or allowing more surface water infiltration to recharge the ground water through creation of reservoirs behind the dams, or through subsurface barriers, etc. are mostly in experimental stage though worth consideration, and its adoption is subject to economic viability.

Integrated water management : If the water table, rich in salts, is present at a very shallow depth (generally not exceeding a depth of 2 m below the soil surface), it contributes salts to the root zone during the dry season through upward capillary rise in response to evapotranspiration demand of soil moisture. The net salt loading in the root zone will be positive (salinity will build up) or negative (desalinization will take place) depending upon the relative rate of recharge of salts by upward rise to rate of downward flux of salts through leaching. The relative salt loading will thus be treated generally as positive during dry season, and negative (waterlogging on the soil surface) during wet season due to high rainfall, and the process will be repeated in the each year in a seasonally cyclic mode.

Sen and Oosterbaan (1992) presented a practical working method on integrated water management for Sundarbans (India) through surface gravity induced drainage during summer/ wet season (through land shaping)-cum-excess rainwater storage for irrigation during dry season. They computed for the same region

drainable surplus, which may be stored for irrigation during dry (deficit) period. Ambast and Sen (2006) developed a computer simulation model and a user-friendly software 'RAINSIM' for the same, developed primarily for Sundarbans region for small holdings, based on the hydrological processes (Fig. 2), and the same tested duly for different agro-climatic regions in India for (i) computation of soil water balance, (ii) optimal design of water storage in the 'On-farm reservoir (OFR)' by converting 20 % of the watershed, (iii) design of surface drainage in deep waterlogged areas to reduce water congestion in 75 % of the area, and (iv) design of a simple linear programme to propose optimal land allocation under various constraints of land, water or other critical inputs to arrive at a contingency plan for maximization of profit. They also reported use of remote sensing and GIS in mapping lowland lands, vegetation, crop yield estimation, along with performance assessment of irrigation/ drainage systems.

Irrigation water resources: In spite of the coastal ecosystem presenting a delicate equilibrium among the different components there is however no firm strategy, as of now, for exploitation of water resources for irrigation and other purposes for long term solution in any sector. The European Commission (2007) observed, based on a study by Spanish researchers, how an inappropriately planned coastal development could lead to increasing water consumption to unsustainable levels,

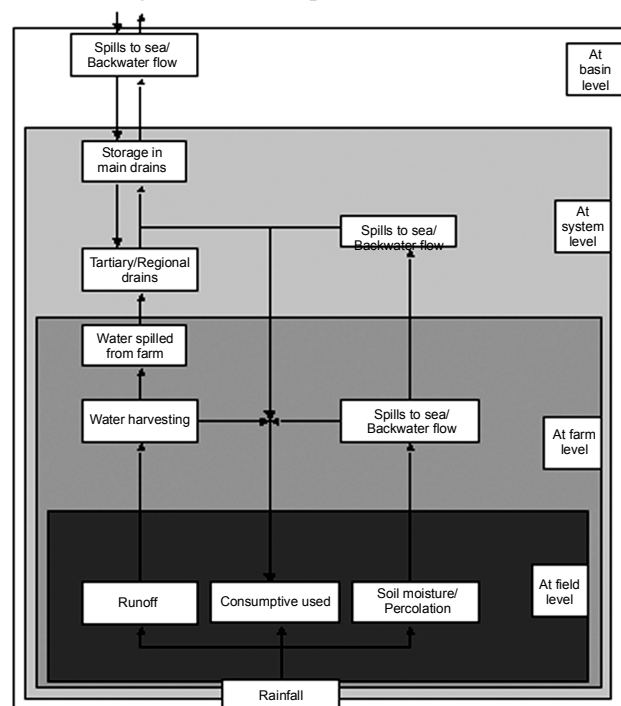


Fig. 2. Comprehensive framework of hydrological processes at different scales (Source: Ambast and Sen, 2006)

for which future planning for sustainable development, based particularly on water resources, should be such as not to disturb the ecosystem in the long run. The technological developments in this region should focus on the areas, viz. artificial recharge of the aquifer, recycling of water, desalinization of seawater, weather modification, improved irrigation management practices, and use of marginally poor quality water.

It is suggested that location-specific programme on water allocation under different sources should be drawn up for each region, based on soil, climate, water, and crop parameters, with minimal dependence on abstraction of water from the underground aquifer, but with increasing dependence on other means, like use of surface water sources by recycling of rainwater stored and fresh water available using innovative seawater desalination technology, and conjunctive use of marginally saline water available, with overall target to increase water productivity and cropping intensity phasewise, and conserve the ecosystem at the same time.

With a vision on source-wise water allocation for irrigation for higher productivity and stability of the coastal irrigated plains in India, an analysis shows need for stepwise increase in water use under different modes along with suggested increase in cropping intensity from 150 % to 225 % during 2020 to 2050. A Field Water Balance model has been utilized to estimate surface water storage opportunities, which should gradually dominate over under ground water use for stability of the coastal plain (Fig. 3). It is suggested to introduce coastal watersheds having multiple components for computation of overall water balance of the ecosystem through integrated approach (Sen *et al.*, 2012).

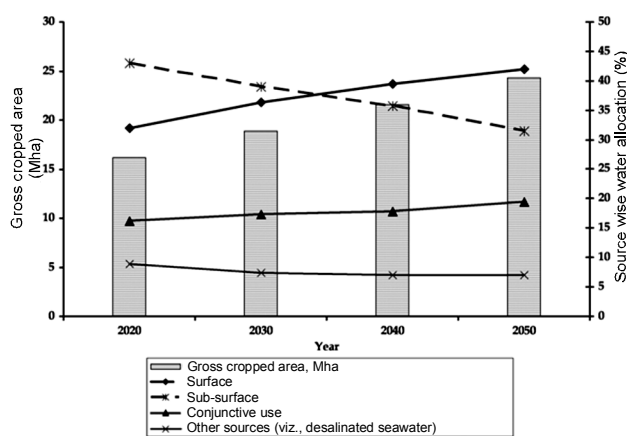


Fig. 3. Percent water allocation source-wise with respect to total amount of irrigation water of the cropping system and gross cropped area per year during coming four decades in the coastal areas of India (Source: Sen *et al.*, 2012)

Fertility management and soil quality

With regard to soil fertility, the coastal soils are usually rich in available K and micro-nutrients (except Zn), low to medium in available N and are having variable available P status (Bandyopadhyay *et al.*, 1985; Bandyopadhyay, 1990; Maji and Bandyopadhyay, 1991). Major portion of the applied N fertilizer is lost through volatilization (Sen and Bandyopadhyay, 1987). Effect of salinity on the microbial and biochemical parameters of the salt affected soils in Sundarbans (India) was studied at nine different sites showing that the average microbial biomass C (MBC), average basal soil respiration (BSR), and average fluorescein diacetate hydrolyzing activity (FDHA) were lowest during the summer season, indicating adverse effect of soil salinity. About 59%, 50%, and 20% variation in MBC/OC, FDHA/OC, and BSR/MBC (metabolic quotient, qCO_2), respectively, which are indicators of environmental stress, could be explained by the variation in ECe. The decrease in MBC and microbial activities with a rise in salinity was ascribed as probably one of the reasons for the poor crop growth in salt affected coastal soils (Tripathi *et al.*, 2006). It was suggested that integrated nutrient management should be very effective for increasing its use efficiency for higher and sustainable yield of crops (Bandyopadhyay *et al.*, 2006; Tripathi *et al.*, 2007).

Bandyopadhyay and Rao (2001) were of the opinion to introduce systems approach involving organic, inorganic and biofertilizers compatible with the farmers' practice. According to them, it is imperative to view the nutrient elements and their interactions with the salt components together instead of considering each of them in isolation.

The importance of improved soil quality in the coastal plains through higher SOC level of the soils was highlighted by Mandal *et al.* (2008). IRRI characterized lowland rice soils (excluding deepwater rice) in Asia in respect of soil quality (Haefele and Hijmans, 2009), which includes large areas under coastal plains (Fig. 4). They grouped soil qualities into four categories. These were: Good, Poor, Very Poor and Problem soils. 'Good' and 'Poor soils' represent those with different degrees of weathering but without major constraints; 'Very Poor' represents soils with multiple chemical constraints (acidity, deficiency of phosphorous, or toxicities of iron and aluminum); while 'Problem soils' represent those with the most frequently cited soil problems, including acid sulphate, peat, saline, and alkaline soils, which partly cause low fertility, and partly soil chemical toxicity.

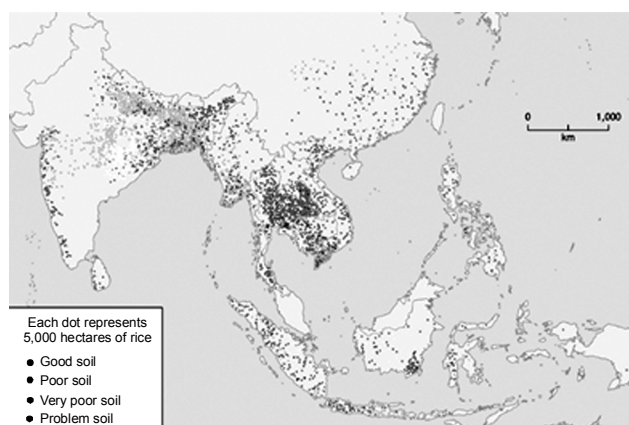


Fig. 4. Distribution of rainfed lowland rice soil quality area in Asia. Each dot is coloured to represent the assumed dominant soil class (Source: Haefele and Hijmans, 2009)

Major ecological factors

Carbon sequestration : Modeling C sequestration so far indicated that coastal marsh ecosystems tend to sequester C continuously with increasing storage capacity as marsh age progresses and its area increases. Thus, C sequestration in coastal marsh ecosystems under positive accretionary balance acts as a negative feedback mechanism to global warming. Choi and Wang (2004) were of the opinion that dynamics of carbon cycling in coastal wetlands and its response to sea level change associated with global warming is still poorly understood. However, they also observed during their study at Florida that salt marshes in this area have been and continue to be a sink for atmospheric carbon dioxide. Because of higher rates of C sequestration and lower CH_4 emissions, coastal wetlands could be more valuable C sinks per unit area than other ecosystems in a warmer world. Brigham *et al.* (2006) stated that the estuarine wetlands sequester carbon at a rate about 10-fold higher on an area basis than any other wetland ecosystem due to high sedimentation rates, high soil carbon content, and constant burial due to sea level rise.

In India, possibly, the first ever study made by Bhattacharyya *et al.* (2000), about a decade back showed SOC pool in two soil strata under different physiographic regions including coastal areas. The data based on soil analyses covering 43 soil series showed the SOC data varied from 2.4 Pg to 10.9 Pg from 30 cm to 150 cm soil depth. It will be prudent to concentrate on elaborate studies in future on monitoring SOC pool in different soil strata in coastal areas over a long period of time, and relate them with sea level rise, extent and nature of land submergence with water, seawater quality, extent and nature of vegetative cover, relevant soil and climatic

parameters, nature and amount of agricultural, industrial and city effluents discharged into the sea, and any other anthropogenic factors of the locality likely to influence SOC, etc. It should also be possible to create databank on SOC and related factors of the past using radiocarbon dating.

Sedimentation and erosion : The dynamics of alluvial landscapes and natural sedimentation patterns that determine the nutrient and energy flows in coastal areas are increasingly being modified by human activities, in particular those that affect water flows (dams, increased water extraction, deviation of rivers) and erosion, especially due to deforestation. This prevents or slows down vertical accretion, thus aggravating salt water intrusion and impairing drainage conditions in riverine, delta or estuarine areas. It reduces or blocks sediment supply to the coast itself, which may give rise to the retreat of the coastline through wave erosion. Beach erosion is a growing problem and affects tourism revenue, especially in island nations. In the Caribbean, as much as 70 percent of beaches studied over a ten-year period were eroded (<http://www.cep.unep.org/publications-and-resources/marine-and-coastal-issues-links/sedimentation-and-erosion>).

Eutrophication, hypoxia, dead zones and nutrient cycle:

The urban developments are taking up fertile agricultural land and leading to pollution of rivers, estuaries and seas by sewage as well as industrial and agricultural effluents. In turn, this is posing a threat to coastal ecosystems, their biological diversity, environmental regulatory functions and role in generating employment and food. Overuse of fertilizer can result in eutrophication, and in extreme cases, the creation of 'dead zones'. Dead zones occur when excess nutrients—usually nitrogen and phosphorus—from agriculture or the burning of fossil fuels seep into the water system and fertilize blooms of algae along the coast. As the microscopic plants die and sink to the ocean floor, they feed on bacteria, which consume dissolved oxygen from surrounding waters. This limits oxygen availability for bottom-dwelling organisms and the fish that eat them. In dead zones, huge growths of algae reduce oxygen in the water to levels so low that nothing can live. There are now more than 400 known dead zones in coastal waters worldwide, compared to 305 in the 1990s, according to a study undertaken by the Virginia Institute of Marine Science. Those numbers were up from 162 in the 1980s, 87 in the

1970s, and 49 in the 1960s. In the 1910s, only four dead zones were identified (Minard, 2008). Hypoxia in the Northern Gulf of Mexico, commonly named as the 'Gulf Dead Zone', has doubled in size since researchers first mapped it in 1985, leading to very large depletions of marine life in the affected regions (Portier, 2003). He studied changes in microbial communities as a result of oxygen depletion, the potential contribution of increasing hypoxia to marine production and emission of N_2O and CH_4 , and the effect of hypoxic development on methyl mercury formation in bottom sediments.

The World Resources Institute reported that driven by a massive increase in the use of fertilizer, the burning of fossil fuels, and a surge in land clearing and deforestation, the amount of nitrogen available for uptake at any given time has more than doubled since the 1940s. In other words, human activities now contribute more to the global supply of fixed nitrogen each year than natural processes do, with human-generated nitrogen totaling about 210 million metric tons per year, while natural processes contribute about 140 million metric tons (Table 3). This influx of extra nitrogen has caused serious distortions of the natural nutrient cycle. In some parts of northern Europe, for example, forests are receiving 10 times the natural levels of nitrogen from airborne deposition, while coastal rivers in the Northeastern United States and Northern Europe are receiving as much as 20 times the natural amount from both agricultural and airborne sources (Coastal Wiki, 2008).

Table 3. Global sources of biologically available (fixed) nitrogen

Anthropogenic sources	Annual release of fixed nitrogen (teragram)
Fertilizer	80
Legumes and other plants	40
Fossil fuels	20
Biomass burning	40
Wetland draining	10
Land clearing	20
Total from human sources	210
Natural sources, viz. soil bacteria, algae, lightning, etc.	
Total from natural sources	140

Source: World Resources Institute (2006)

Climate Change

Climate change has a phenomenal influence through all the components on E-flows on temporal scale. It is now well established that glaciers around the world – and especially in the Hindu Kush Himalayas – are retreating due to global warming, as a result the predicted water flow, based on Kathmandu-based study of the International Centre for Integrated Mountain Development (ICIMOD), from the glaciers to the basins would reduce by 25-50% by the end of this century (the thirdparty.net).

Besides, destruction of habitats in coastal ecosystem is caused by natural disasters, such as cyclones, hurricanes, typhoons, volcanism, earthquakes and tsunamis causing colossal losses worldwide. Each year an estimated 46 million people risk flooding from storm surges. Ironically, the frequency of natural disasters is increasing with time, almost exponentially, due to climate change, as sea level rise also follows almost the similar trend (Sen, 2009). Coasts in many countries, therefore, increasingly face severe problems on account of sea level rise as a consequence of climate change (Fig. 5), leading to potential impacts on ecosystems including damage to reefs or move large amounts of bottom material, thus altering habitat, biological diversity, and ecosystem function. The worst scenario projects sea level rise of 95 cm by the year 2100. It is projected, as extreme cases, the majority of the people who would be affected in different countries are China (72 million), Bangladesh (13 million people and loss of 16 percent of national rice production), and Egypt (6 million people and 12 to 15 percent loss of agricultural

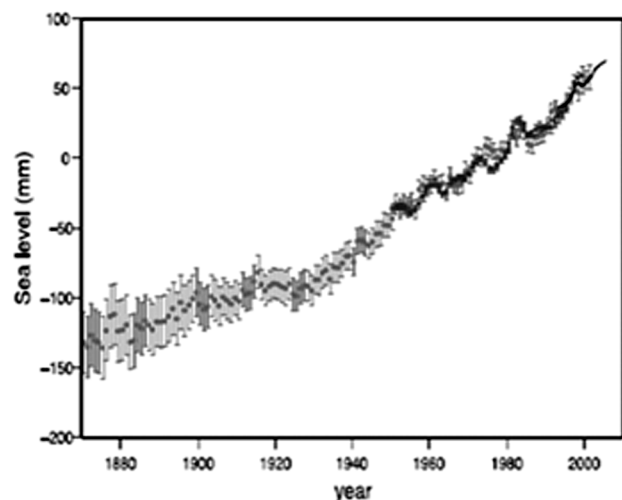


Fig. 5. Global average sea level rise since 1961 at an average rate of 1.8 mm per year and since 1993 at 3.1 mm per year (Source: Pachauri, 2008b)

land), while between 0.3 percent (Venezuela) and 100 percent (Kiribati and the Marshall Islands) of the population are likely to be affected (Pachauri, 2008a,b). In India, potential impacts on 1 m sea level rise might lead to inundation of 5,763 km² of land including *Ganges-Brahmaputra delta* facing flood risks from both large rivers and ocean storms.

Population growth as the driver

Apart from climate change population growth is possibly the single most factor, other than those directly or indirectly related to crop production, impacting livelihood in the coastal ecosystem. Around the world maximum people die of drowning by storm surge. It is just astonishing to note that in the cyclone of 1970 that struck Bangladesh more than 300000 people met a watery grave. Similar things happen in Australia too, but casualties were less because of lesser density of population on the vulnerable areas (Joshi, 2007). A list of 5 deadliest natural disasters on the coast is shown in Table 4. It has been projected that number of people living within 100 km of coastlines will increase by about 35 percent in 2050 as compared to that in 1995. This type of migration will expose 2.75 billion people to coastal threats from global warming such as sea level rise and stronger hurricanes in addition to other natural disasters like tsunamis (Goudarzi, 2006). In another estimate (Schwartz, 2005), the expected change of the population (or population density) from 2000 to 2025 regionwise shows increase in almost each coastal area. The estimates (population within 100 km of the coastline) show increase by 25% in Asia (except Middle East), 52% in Middle East and North Africa, 81% in Sub-Saharan Africa, 20% in North America, 31% in Central America and Caribbeans, and 32% in each South America and Oceania, while there may be decrease by 2.5% in Europe. In India, according to the Department of Ocean Development, there are 40 heavily polluted areas along the Indian coast (Dubey, 1993).

Ecological impact: Deteriorating E-flow in Ganga on South Bengal

The Hooghly's flow is oscillating; the water level fluctuates twice a day, owing to the tides, and changes its hydro-morphology. Its estuary below Diamond Harbour being funnel-shaped, it restricts the optimum tidal influx which primarily governs the channel regime and its navigability. The sediment movement in tidal estuary of the Hooghly is the function of a complex fluvial system that can hardly be governed by inducing 40000 cusec (1132 cumec) of flow. The available flow even dwindled

to 454 cusec in the first week of April causing declining in the navigability for the Kolkata Port. The adverse effect in the Indian part could be verified from the fact that the annual quantum of dredging increased from 6.40 MCM during pre-Farakka days to 13.24 MCM during post-Farakka days quoted up to 1995, and then to 21.18 MCM quoted for 1999-2003 (Rudra, 2006). Besides, sediments are trapped in the barrage-pond raising the level significantly and also encouraging the river course to change its direction both upstream and downstream.

It is true that there are interferences of the Ganga's regime due to construction of Farraka Barrage giving rise to problems and disadvantages – changes with water level, discharge, sediment movement, bed slope, etc. caused by aggradations and degradation of the bed and the entire reach from Rajmahal to Farakka in the upstream and from Farakka to quite a distance downstream. Alluvial fans formed on the right side and the deep channel shifted to the left above the Barrage. Bank erosion got worse and was usually highest during August and September. There were direct and indirect effects of sedimentation pattern of the Ganga-Padma in Bangladesh as well, which would eventually increase siltation and erosion of the river beds and banks, ultimately affect the channel and cause other morphological changes.

Owing to temporal shift of the river course at a number of points along the river course between Farakka and Rajmahal (53 km upstream in Jharkhand) and the consequent changes in morphometric parameters, a detailed study leading to river bank erosion and flooding was conducted spanning over the period 1955 to 2005 from LANDSAT and Indian Remote Sensing Satellite (IRS) images along the stretch (Thakur, 2014). It was reported that the bank failure was mainly due to soil stratification of the river bank, presence of hard rocky area (Rajmahal), high load of sediment and difficulty of dredging and construction of Farakka Barrage itself as an obstruction to the natural river flow. The victims are mostly Manikchak and Kaliachak-II, Kaliachak-III and Ratua-I blocks of Malda district, with a loss of around 1,670 ha agricultural land since 1977 in these blocks alone (Thakur, 2014) as well as in several other areas in Murshidabad district resulting in high and frequent incidence of bank erosion, flooding of land, and consequently population migration from the villages (Banerjee, 1999; Rudra, 2004) leading to colossal losses of wealth in the Indian part as a ritual annually. Series of study by the Department of Forest and Environmental

Sciences (Government of West Bengal) showed that owing to deteriorating E-flow or lack of fresh water flow in Ganga-Bhagirathi river system there is rise of soil salinity along with subsidence of land, destruction of mangroves, sediment deposition in the Indian Sundarbans (Raha *et al.*, 2014) affecting the dynamics of the estuary.

The complacency of the administration, on the other hand, looking the other way concentrated on construction of roadways and bridges through silted up river beds in the Indian Sundarbans in the name of development at the expense of drying up of the rivers which is an antithesis to development blunderingly ignoring the ecology in the area.

Table 4. List of 5 deadliest natural disasters on the coast (Source: Wikipedia, 2009)

Rank	Event	Location	Death toll
1	1931 China floods	China	2,000,000-4,000,000
2	1887 Yellow River Flood	China	900,000-2,000,000
3	1970 Bhola cyclone	Bangladesh	500,000
4	1839 India cyclone	India	≥ 300,000
5	2004 Indian Ocean tsunami	Indian Ocean	229,866

Way forward

The lower Ganga delta face threats due to dwindling water diversion via Farakka Barrage and deteriorating water quality of the river in the upstream at different places in India. There is need for a holistic and focused attention for which the following suggestions are made to seek for a lasting solution (Sen and Ghorai, 2014).

- There appears to be a need for revisiting the design of the Farakka Barrage, as well as the discharge and distribution norms of water in the interest of the two countries, keeping in view of the predicted flow of upstream Ganga water in long term perspectives, and if necessary, fresh norms to be decided.
- Predicted flow of water through Ganga-Brahmaputra, both originating in Tibet, river system on account of retreat of glaciers and other parametric uncertainties due to climate change needs to be studied and refined with appropriate climate models in deciding the future norms for distribution of water via Farakka Barrage with as much precision as possible in different time scales.

- Need for fresh installation of hydro-electric power and irrigation projects in India must be given extremely careful consideration with stringent norms for discharge of river water into the upstream so that ecology of the area is not disturbed.
- Past hydro-electric power and irrigation projects in the upstream already in commission need also to be reviewed in terms of the norms for discharge of water decided, and if necessary, to be revised, scientifically so that ecology of the area is not disturbed.
- Provisions should be mandatory to make impact analysis of the discharge of water from different projects, be it hydro-electric power and irrigation projects or any others, on the ecology of the area for all past and future installations in India.
- Strict administrative vigilance to be maintained to stop acts on unscrupulous diversion of water forthwith by private agencies in India.
- Location specific integrated water development and management schemes at strategic points over the entire flow length in different time scales to be prepared and their methods of implementation be worked out, with adequate participation and vigilance from the local inhabitants, to ensure maintaining prescribed water quality throughout the year.
- Impacts of the water flow at different strategic points into lower delta in respect of salinity in soil & water, flow rate, tidal amplitude and fluctuations, sedimentation/ hydrological parameters, navigation through rivers, ground water table depths and qualities, all important components of biodiversity, and any other related parameters should be taken up and monitored with a holistic plan, over minimum five year phases, through a central task force comprising of scientists, NGOs, government officials, local inhabitants, and the same placed in public domain.

It is believed, in conclusion, that there may be no short-cuts to improve the ecology for sustained livelihood of the inhabitants in this area other than ensuring E-flows via Farakka Barrage, for which careful considerations may be given to the suggestions made above.

CONCLUSION

Although management of soils due to salinity or other stress factors catches immediate attention of all concerned for augmenting productivity in the coastal ecosystem, the various ecological factors discussed

above, to speak the least, besides a few others, like under-sea tectonic movement along with off-shore and on-shore protection measures required to be undertaken, demand that it should be mandatory to give a holistic look to their interaction matrix, and not the management of the stressed soils alone, to ensure lasting stability of the ecosystem.

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TRIBUTE

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