CHAPTER I. GENERAL INTRODUCTION
Coastal ecosystems are known for biological productivity and high accessibility. They are found along the continental margins incorporating a broad range of habitats harboring rich bio-diversity. They are known to filter the pollutants from inland freshwater systems, store and cycle the nutrients and also help in protecting the shorelines from storms and erosion (Lauretta et al., 2000). For this purposes, the coastal zone is defined into (1) intertidal and (2) subtidal areas which are above the continental shelf and adjacent lands. Coastal zones also include the Exclusive Economic Zones (EEZ) within the National Jurisdiction (up to 200 nautical miles from the coastline) (Roonwal 1997; Kennedy et al., 2002 and Barbier et al., 2011).

On the basis of physical characteristics coastal regions are classified as 1) Near shore terrestrial – This includes Dunes, Rocky and Sandy shores etc. 2) Intertidal – Estuaries, Lagoons, Salt pans, Mangrove forests etc. 3) Benthic – Kelp forests, Seagrass beds, Coral reefs etc. 4) Pelagic – Open waters above Continental shelf, Free standing fish farms etc. (Lauretta et al., 2000). Diagrammatic representation of the zonations in the marine ecosystem is shown in Fig. 1.

Figure 1. Zonations in Marine ecosystem. (MHWS - Mean high water spring, MLWS - Mean Low water spring) (Source: http://www.dfo-mpo.gc.ca).
Amongst the intertidal region Estuaries are the most productive and highly diverse ecosystem on the earth. They are the potential source of food for human beings as well as used as shelters by many commercially viable fish and shellfish. In recent years these estuarine system is under immense stress due to rapid growth of population density and economic activities. Hence regular monitoring of the estuarine system has become necessary.

1.1. Estuaries

Estuaries with their associated river systems form an integral part of the inshore waters. They have a free connection with the open sea and within which freshwater derived from land drainage dilutes seawater measurably. Estuaries represent a stressful and harsh habitat defined by fluctuating salinities and temperature for the organisms since it is a mixing ground for freshwater and seawater. In spite of the extreme conditions, estuaries are fertile and excellent nursery grounds for variety of commercially important fishes and prawns (Malone and Chervin 1979; Elser et al., 1986; Kurupartkina 1991 and Piontkovski et al., 1995).

Different estuarine habitat and ecological processes within estuaries are affected by hydrological components which are associated with freshwater and marine inputs. Particulate material brought in by freshwater influx from the watershed sinks in the estuary due to decrease in flow. The inflow of seawater from the ocean moves interior along the estuary bottom, retaining these sinking particles and stratifying the water column thereby affecting the “health” of the estuary if the retained particles are contaminants or toxins (McCarthy et al., 1974; Durbin et al.,
Estuaries often harbor marshes or coastal wetlands that contain plants that are tolerant to varying salinity. Coastal marshes in the sub-tropical and temperate regions support grasses or similar plants which are supplemented by microscopic algae on their surfaces. Salt marshes are replaced by salt-tolerant shrubs i.e. mangroves in the intertidal zone. Growth of these plants depends on the sediment received from the land. The existence of extensive tracts of marshes or Mangroves vegetation is known to protect the adjoining land as well as human populations from stormy water produced during hurricanes and coastal storms. Marshes outreach the excess nutrients and contaminant in runoff thereby protecting the nitrogen-sensitive sea grass which play an important role in coastal food webs (McCarthy et al., 1974; Durbin et al., 1975; Walsh et al., 1978 and Lauretta et al., 2000).

Dobson and Frid 1998 classified estuaries based on water circulation the way that layers of water are formed within the estuary into four types are: a) Salt Wedge Estuary, b) Partially Mixed Estuary, c) Well mixed estuary and d) Fjord - type Estuary. He has also classified estuaries based on geological features as 1) Coastal Plain Estuary, 2) Tectonic Estuary, 3) Bar - Built Estuary and 4) Fjord.

1.2. Importance of estuaries to mankind

Estuaries are commercially important as they provide financial benefits for fisheries, tourism as well as related recreational activities as well as support public infrastructures such as ports and harbors required for transportation and shipping.
Estuaries represent a stressful and harsh habitat defined by fluctuating salinities and temperature for the organisms since it is a mixing ground for freshwater and seawater. In spite of the extreme conditions, estuaries are fertile and excellent nursery grounds for a variety of commercially important fishes and prawns. Tropical and temperate estuaries are known for their biological productive. Salt marshes and mangroves are important producers in the tropical estuaries. (http://www.biologyreference.com).

The animal productivity is supported by primary production which is increased due to nutrients received through runoff. Kennedy et al., 2002 have reported considerable increase in the commercial harvesting shellfish as well as fish due to their dependence on estuaries for spawning as well as feeding. Estuaries are also recognized as recreational centers (Environmental Health Center, 1998). Halpern et al., 2008 have reported Estuaries and coastal most globally threatened ecosystem. Estuaries are vulnerable to human activities such as shore land reconstruction for housing, recreational, agricultural and transportation. Growing population is also exerting more pressure on the resources derived from these ecosystems.

1.3. Factors affecting functioning of estuaries

The abundance and distribution of population within estuaries are influenced by the physico-chemical and biological factors. Which are as follows:

**Tides:** Gravitational forces by the Moon and Sun together with the rotation of the earth cause rise and fall in the sea level which promotes flushing of estuary 12.42 hours. In and out movement of salt water and fresh water results in to cleansing
effect. Erosion, deposition and sediment transport are also caused by the movement of tidal water (www.soest.soton.ac.uk).

**Light:** Light is the major factor having direct correlation with photosynthesis. Entire food web is directly governed by this process.

**Temperature:** Abundance and distribution of organism is governed by this abiotic factor. Metabolism, vegetative and reproductive growth of plants is affected by temperature. Migratory behavior of phytoplankton is the response to the temperature in many species (www.userpages.umbc.edu).

**Oxygen:** Due to mixing of both fresh and saline water and constant inflow oxygen levels in the estuary are high. The primary production increases when sediment is enriched with nutrients. This can result into hypoxic or anoxic zone formation which controls the distribution of organisms (Kaiser *et al.*, 2005).

**Nutrients:** Major nutrients like Nitrogen, Phosphorus and Silicate are essential for the growth. Trace nutrients include Iron, Magnesium, Copper, Nickel etc are required for the metabolic activities. Increase in the nutrients level by means of land run-off may lead to eutrophication (www.soest.soton.ac.uk).

**Salinity:** Estuarine area is known for continuous fluctuations in the salinity which are due to the tidal cycles. Evaporation and precipitation also play important role in determining salinity. The community structure varies from head (Fresh water) to mouth (Saline). (www.userpages.umbc.edu).

**Turbidity:** Turbidity is the optical characteristics of water which describes the clarity of water column. Turbidity results from influence of dissolved organic matter from
sewage treatment plants and washes out from construction sites, shoreline erosion which includes suspended particulate matter in the water column. Turbidity is usually high in tidal driven areas specially estuaries. It limits light penetration in to the water column there by hampering process of photosynthesis. Benthic algae dominated intertidal part of the estuary while uppermost section of the water column is dominated by phytoplankton (Cloern 1997). According to Wilson and Parkes 1998 estuarine species are detritivorous and obtain their energy from organic matter present in the sediment or from suspension. So deposit feeders and filter feeders play major role in transferring energy.

Biotic factors include living organisms like phytoplankton, zooplankton, other organisms includes bivalves, crabs, fishes etc. Out of this phytoplankton plays a very important role in the food chain of the estuary.

1.4. Role of Phytoplankton

Life in the estuarine system can be divided into three different categories: the benthos, the nekton and the plankton. The benthos group consists of bottom dwelling organisms which are either sedentary or can cover a distance with the help of appendages (eg. crustaceans, gastropods). The nekton consists of those organisms that can maintain their position and move against the local currents (eg. fish, squids). On the other hand, the planktonic group consists of those organisms that drift according to the wind and currents. Though some of them are motile, the motility is weak in comparison to the prevailing movement of the water. Plankton consists of phytoplankton, which includes the plant life and zooplankton, which includes the animal life (Hunchinson 1967 and Valiela 1984).
Phytoplankton is the autotrophic, microscopic, free floating plant community and are the primary producers of the aquatic ecosystem forming the base of marine food web which sustains zooplankton, fish and ultimately human beings. Phytoplankton are found mostly in the euphotic zone (i.e. the upper 100 m) of the water column of ocean so as to absorb solar energy required for the process of photosynthesis (Mann 1982).

Depending on the size Malone, 1980 and Kawaguchi et al., 2001 classified phytoplankton as picophytoplankton (<5 µm), nanophytoplankton (>5 µm to <10 µm), microphytoplankton (>10 µm to <20 µm) and macrophytoplankton (>20 µm). Phytoplankton belongs to the following taxonomic groups. Taxonomic features of these groups are given below.

- **Bacillariophyta:** They are known as Diatoms unique feature of cells is that they are enclosed within a cell wall made of silica called a frustule. Diatoms are unicellular, colonial. The major pigments present are carotenoids and fucoxanthin. Diatoms are broadly divided into Centrales or Centricae and the Pennales or Pennatae, depending on the structure and sculpture on their cell walls (Tomas et al., 1997).

  **Centrales** - The valves of the centric diatoms has radiating sculpture either central or lateral, without raphe and without movement. Examples include *Coscinodiscus, Thalassiosira* etc.

  **Pennales** - The valves are arranged along median line. They are elongate and bilaterally symmetrical. Examples include *Navicula, Pleurosigma.*
• **Dinophyta:** Dinoflagellates are diversified group of organisms which move around in water with the help of their cilia or flagellae. The cells bear paired flagellae which arise in close proximity, usually with one flagellum trailing behind the cell and lying in a groove (sulcus) and the ribbon like transverse flagellum also lying in a groove (cingulum or girdle). Wing like extensions of the body probably assist floatation in some genera. The major pigment present is peridinin. Dinoflagellates are further divided depending on the mode of their nutrition as autotrophs, heterotrophs and mixotrophs (Stoecker 1999). Among the autotrophic planktonic organisms, Dinophyta come next in importance to the Bacillariophyta (Tomas et al., 1997).

• **Cyanophyta:** The members of this class are distinguished from all other algae in being the absence of an organized nucleus, lacking nuclear membrane and chromosome, instead a central body is present. They are known as cyanobacteria. Besides chlorophylls, the chloroplast contains a blue green pigment known as phycocyanin also present. Planktonic blue green algae are unicellular, colonial or filamentous in habit. In the inshore environments, blooming of one filamentous form, *Trichodesmium* spp. is a common phenomenon, causing discolouration of water and sometimes harmful affects to the aquatic organisms. Filamentous blue green algae possess specialized cells called Heterocyst. These are thought to be concerned with nitrogen fixation (Tomas et al., 1997).

• **Chlorophyta:** The members of this class are having grass green, pale yellow chromatophores. Starch is the customary form of storage of the products of photosynthesis. The motile cells exhibit the same features and possess a number of
equal flagella (commonly 2 or 4) which arise from the front end of the swarmers. Eg.: *Chlorella, Nannochloropsis* and *Tetraselmis* (Tomas *et al.*, 1997).

- **Chrysophyta:** This includes silicoflagellates, small star shaped organisms characterized by the possession of a skeleton taking the form of framework of silicious rods, arranged in diverse ways and with intervening spaces of definite shape. Outside this skeleton is a delicious layer of cytoplasm and containing a number of bright yellow to brownish yellow discoid chromatophores containing xanthophylls and carotene as accessory pigments. Representative genera are *Dictyocha, Distephanus* (Tomas *et al.*, 1997).

- **Haptophyta:** The members of this class are golden yellow or brown flagellates measuring less than 10 microns. The flagellates will have one to two flagella which arise from the front end. Carotene and xanthophylls pigments are dominant other than chlorophyll. Eg.: *Isochrysis* and *Chromulina* (Tomas *et al.*, 1997).

Growth of the phytoplankton is controlled by the physical and chemical environment and is very sensitive to the changes taking place in the environment. Because of the quick response to changing environmental conditions phytoplankton are considered as bioindicator. The major factors affecting phytoplankton growth in an estuary are the dynamic changes in salinity, tidal-flushing, pH, turbidity of the water column. Even the concentrations of dissolved gases, trace metal concentrations and nutrients so also various organic compounds are known to be affecting the photosynthesis by phytoplankton. Combination of some of these factors provides optimal conditions for this phytoplankton to transform into blooms (Tilstone *et al.*, 1997).
1994 and Tan et al., 2006). Process of bloom initiation and formation during the favorable conditions is shown in Fig. 2.

Figure 2. Environmental conditions that lead to harmful algal blooms (HABs) (Source: http://ian.umces.edu).

1.5. Harmful Algal Blooms (HABs)

Phytoplankton is very important component of marine food web contributing around 40% of the world’s primary productivity (Folkowisky 1984). About 7% of marine phytoplankton out of approximately 5,000 species are known for formation of algal blooms. This includes Dinoflagellates, Diatoms, Silicoflagellates Raphidophytes, Premensiophytes and (Sournia 1995). About ~ 2% of them are harmful or toxic (75%) contribution is by dinoflagellates (Smayda 1997). Algal
blooms are of two types harmful and non-harmful. Harmful algal blooms (HABs) occur when the algal cells in the marine or fresh water grow out of proportion causing economic loss and severe impacts on marine life and human health (Anderson and Garrison 1997 and Hallegraeff et al., 2003). Bloom forming species are divided into two types toxic species and non-toxic species which are shown schematically in Fig. 3.

**Toxic:** Toxins of certain algal species reach humans through food chain and cause several gastrointestinal as well as neurological sicknesses which are detailed in Table 1.

**Non-toxic:** This includes two types

Species that produce harmless water discolorations are capable of forming dense blooms resulting into sever fish kill and invertebrates due to oxygen depletion (*Gonyaulax polygramma, Scrippsiella trochoidea, Akashiwo sanguinea, Trichodesmium erythraeum* and *Noctiluca scintillans*).

Species that are harmful to invertebrates and fish as they damage or clog the gills however these are non-toxic to humans (*Chaetoceros convolutes, C. concavicorn*, *Chattonella marina* and *Prymnesium parvum*).

First International Conference (1974) addressed the research related to the Toxic Dinoflagellate Blooms. However the Fourth International Conference (1989) concluded that the increase in the global bloom distribution is due to human activities. So many international programmes were created to study the harmful algal blooms (Hallegraeff et al., 2003).
The occurrences of HAB species are linked to impact of weather conditions on water parameters like temperature, salinity, nutrient concentrations, currents, monsoonal pattern and geomorphology of the place (Tilstone et al., 1994 and Tan et al., 2006). The frequency of harmful algal blooms (HABs) is increasing across the world and their effects are noticed by ecosystems managers, scientists and the general public. Understanding of the bloom dynamics requires interdisciplinary studies (Hallegraeff et al., 2003)
Table 1. HAB species producing type of toxin, syndromes and symptoms associated with it in human beings

<table>
<thead>
<tr>
<th>Phytoplankton species</th>
<th>Type of toxin</th>
<th>Type of toxic effect/ Syndrome</th>
<th>Associated foods (transvectors)</th>
<th>Symptoms in Human beings</th>
<th>References</th>
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<tr>
<td><em>Alexandrium catenella, Alexandrium tamarense, Alexandrium fundyense Pyrodinium bahamense var. compressum</em></td>
<td>Neurotoxin (Saxitoxin)</td>
<td>Paralytic shellfish poisoning (PSP)</td>
<td>Bivalve shellfish, primarily scallops, mussels, clams, oysters and certain herbivour fish and crabs</td>
<td>Diarrhoea, nausea, vomiting leading to paraesthesia of mouth and lips</td>
<td>Cembella, A.D. (1998); Taylor, F.J.R., 2003 and Azanza et al., 2001</td>
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<th>Phytoplankton species</th>
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<tr>
<td><em>Pseudo-nitzschia australis</em>, <em>P. delicatissima</em>, <em>P. multiseries</em>, <em>P. pseudodelicatissima</em>, <em>P. pungens</em> and <em>P. seriata</em></td>
<td>Domoic acid</td>
<td>Amnesic shellfish Poisoning (ASP)</td>
<td>Bivalve shellfish, primarily scallops, mussels, clams, oysters and fish</td>
<td>Diarrhoea, vomiting, abdominal pain and neurological problems such as confusion, memory loss and coma</td>
<td>Bates, S.S and Trainer, V.L. 2006; Trainer et al., 2008 and Lefebvre and Robertson, 2010</td>
</tr>
<tr>
<td><em>Gambierdiscus toxicus</em>, <em>Coolia</em> spp., <em>Ostreopsis</em> spp., <em>Prorocentrum</em> spp.</td>
<td>Ciguatoxin, Maitotoxin, Scaritoxin</td>
<td>Ciguatera Fish Poisoning (CFP)</td>
<td>Large reef fish eg. grouper, red snapper, barracuda</td>
<td>2-6 hrs: abdominal pain, Nausea, vomiting, Diarrhoea, 3 hrs paraesthesia</td>
<td>Swift A and Swift T, 1993; Schep et al., 2010</td>
</tr>
<tr>
<td><em>Anabena circinalis</em>, <em>Microcystis aeruginosa</em>, <em>Nodularia spumigena</em></td>
<td>Anatoxin, Microcystin and Nodularin</td>
<td>Cyanobacterial toxin poisoning</td>
<td>Fish and Shellfish</td>
<td>gastro-intestinal and hay fever symptoms or pruritic skin rashes</td>
<td>Stewart et al., 2008 and Stewart et al., 2006</td>
</tr>
<tr>
<td><em>Pfiesteria piscicida</em> and <em>P. shumwayae</em> <em>Ptychodiscus brevis</em></td>
<td>Aerosolized Brevetoxin</td>
<td>Estuarine associated syndrome (Through aerosol)</td>
<td>Aerosolized seawater</td>
<td>Acute eye irritation, acute respiratory distress (non-productive cough, rhinorrhea)</td>
<td>Fleming et al., 2007 and Baden DG, Mende TJ., 1982</td>
</tr>
</tbody>
</table>

(Adopted from Hallegraeff et al., 2003)
Figure 3. Schematic representation of different types of HABs (adopted from http://products.coastalscience.noaa.gov/pmn/_images/habdiagramlg.gif)
1.6. Literature Review

Study on the algal blooms is gaining more importance day by day as this phenomenon is increasing all over the world. Usually phytoplankton blooms appear depending on the health of the estuarine system and oceans in which they are present (Francis et al., 1878; Clarke et al., 2006 and Acharyya et al., 2012). Extensive work has been carried out on different aspects of estuarine ecosystem around the world. Phytoplankton population, distribution, composition, abundance and variations with respect to its ecology is well studied for the east coast of India. Achuthankutty et al., 1981 studied the plankton composition along Shastri and Kajvi estuaries observed more phytoplankton composition during pre-monsoon period. Study on the phytoplankton variation in respect to seasonal and tidal influence was carried out by Chandran 1985 in gradient zone of Vellar estuary. Phytoplankton bloom study along the east coast of India was carried out by Mani et al., 1986 in Vellar estuary and De et al., 1991 in Hoogly estuary. Diurnal variations in phytoplankton along Rushikulya estuary were studied by Gouda et al., 1989. Work on phytoplankton community was reported along the Gopalpur estuary by Padhi M. and Padhi S., 1999. Study on the diversity of phytoplankton was undertaken in the Vellar estuary by Rajasega et al., 2003. Seasonal variations in phytoplankton distribution was undertaken along the east coast in Maipura estuary by Panigrahi et al., 2005 and Palleyi et al., 2008 showed seasonal variations in phytoplankton abundance in Brahmani estuary of Orissa. In the case of Mahanadi estuary highest phytoplankton biomass and cell density was
reported during post-monsoon season Naik et al., 2009. Periyanayagi et al., 2007 studied the phytoplankton relation with respect to environmental pollution in Uppanar estuary. Work on biodiversity of phytoplankton by Palleyi et al., 2011 was reported along the Dharma river estuary. The study on the distribution and occurrence of diatom community was done by Shashikumar et al., 2002 in the Dakshina Kannada estuary in Karnataka. Eswari et al., 2002 reported the distribution and abundance of phytoplankton in the Chennai estuarine waters.

Pattern of phytoplankton distribution and composition with respect to seasonality is well studied along the west coast India considerable work has reported the distribution pattern and composition of phytoplankton with respect to seasonality. Gopinathan et al., 1974 studied the seasonal abundance of phytoplankton in Cochin back waters. Another study by Devassy and Bhattathiri 1974 was in relation with ecology of phytoplankton. Work on distribution of phytoplankton in Cochin back waters was carried out by Jayalakshmy et al., 1986 and Gopinathan et al., 1994. Seasonal variations in phytoplankton distribution were undertaken along the east coast in Netravathi estuary by Gowda et al., 2001. Monsoonal effect on the phytoplankton distribution in presence of fresh water influx been studied by Jyothibabu et al., 2006 and Madhu et al., during 2007 in Cochin back waters. Study on the influence of hydro chemical parameters on phytoplankton distribution was carried out in the Tapi estuary by George et al., 2012. Work on the dinoflagellate community along the Mumbai Jawaharlal Nehru port was done
by D'costa et al., 2008 and also studied diatom community dynamics in the year 2010.

As far as the Goa coast (west coast, India) is concerned, considerable studies have been carried out with respect to phytoplankton distribution, diversity, primary production and community structure. Bhargava and Dwivedi 1974 reported diurnal variations in phytoplankton pigments. Goswami and Singbal 1974 studied the ecology of phytoplankton in the Mandovi and Zuari estuaries. The seasonal distribution of phytoplankton pigments was studied by Bhargava and Dwivedi 1976 along Mandovi and Zuari estuarine complex of Goa. Bhattathiri et al., 1976 worked on the primary production at different trophic levels in Mandovi and Zuari estuaries. Study on the phytoplankton production is also carried out by (Devassy 1983 and Krishna Kumari et al., 2002). Bhargava et al., 1977 recognized contribution of nanoplankton to primary production in the Mandovi and Zuari estuaries. Diel changes in phytoplankton population were carried out by Devassy and Bhargava 1978 in Mandovi and Zuari estuarine complex. Devassy and Goes 1988 studied the phytoplankton structure in the same estuaries. Garg and Bhaskar 2000 and Redekar and Wagh 2000, studied the diatom fluxes. Mitbavkar and Anil 2002 worked on the temporal and spatial variations in the diatoms of microphytobenthic community in Mandovi estuary. Matondkar et al., 2007 studied the phytoplankton for their diversity, biomass and primary production in Zuari and Mandovi estuaries of Goa. Temporal variations in benthic propagules along Zuari estuary was studied by
Patil and Anil 2008. Mitbavkar and Anil 2008 and Patil and Anil 2011, deal with the seasonal variations in phytoplankton community with respect to fouling diatoms in the Zuari estuary.

The events of HABs are reported all around the world. The first HAB event was by *Noctiluca scintillans* and *Skeletonema costatum* in 1933, reporting the death of Razor clams and some shellfish in China (Fei 1952). Allen 1946 reported red tide waters in La Jolla Bay. Bell 1961, reported the blooms of *Coscinodiscus convolutus* and *C. concavicornis* along the west coast of U.S. and also noticed the penetration of setae into the gills causing fish death due to suffocation from excessive mucus production.

Bloom of *Prorocentrum minimus* was observed in the Bohai sea of China in 1977 which lasted for twenty days covering 560 Km$^2$ area caused mass mortality of fish, causing losses to the local fishery (Hua 1989). During 1952 – 1998 around 322 HAB events were documented along China (Yan et al., 2000). PSP outbreak was caused by bloom of *Alexandrium minutum* leading to the mortality of fish and bivalve in the southern Chile (Koray Tufan 1992). Bates et al., 1989 observed the bloom of *Pseudo-nitzschia pungens* in Prince Edward Island which produced potent neurotoxin called Domoic acid (DA) leading to the series of human illness and deaths after consumption of mussels contaminated by DA. Fish mortality caused by bloom of *Cerataulina pelagic* (diatom) was reported in New Zealand by Taylor et al., 1985. Dundas et al., 1989 reported mortality of wild and caged fish due to massive and unpredicted bloom of *Chrysochromulina polylepis* in the Scandinavian waters.
The outbreaks of *Dinophysis cf. acutum* in Thermaikos Gulf in Greece reported by Mouratidou et al. 2004 where he detected the presence of DSP toxin in mussels. Ichthyotoxic dinoflagellate bloom by *Karlodinium veneficum* was reported in the River estuary, North Carolina in October 2006 (Hall *et al.*, 2008). Naz and Siddiqui 2012 reported bloom of potentially harmful diatom *Coscinodiscus wailesii* in Pakistan.

Saxitoxin produced by dinoflagellate *Pyrodinium bahamense* var. *bahamense* was found in the fish tissues in the IRL (India River Lagoon) Florida USA (Landsberg *et al.*, 2006 and Abbott *et al.*, 2009). Paralytic Shellfish Poisoning (PSP) associated with unknown toxin produced by *Alexandrium tamarense* was detected from seafood in 2003, Korea (Shin *et al.*, 2008).

Anthropogenic disturbances are found to be often associated with HAB events which are mainly due to nutrient loading (Pearl 1997; Smayda 1990 & 2005; Anderson *et al.*, 2002 and Verity 2010). Jennifer *et al.*, 2010 reported bloom of Cyanobacteria in the Florida bay as result of due to nutrient loading. Fresh water discharge during monsoon season enhances the nutrients loading which promotes the phytoplankton blooms (Admiraal *et al.*, 1990; Yan *et al.*, 2000; Scavia and Bricker 2006 and Bricker *et al.*, 2008).

Around 101 cases of HABs have been reported from both the coasts of India during 1908 to 2009 and their predominant in the west coast of India. It was observed that majority of the blooms appeared just after the withdrawal of South West monsoon (D'Silva *et al.*, 2012). Blooms of dinoflagellates
dominated towards west coast and diatoms towards east coast (D'Silva et al., 2012). Aiyar 1936 reported pink colouration to water due to *Noctiluca miliaris* with no fish mortality along the Madras coast, Tamil Nadu. Chacko 1942 reported bloom of cyanobacteria *Trichodesmium erythraeum* along Krusadai Island where as mortality of fishes and *Holothuria atra* was reported from Southern coast of Pamban Tamil Nadu. Gulf of Mannar, Chidambaram and Unny 1944, reported bloom of *Trichodesmium erythraeum* along with fish and crabs mortality. Blooms of diatom *Rhizosolenia alata* and *Rhizosolenia imbricata* were observed along inshore waters off Mandapam, by Raghu Prasad 1956. Raghu Prasad 1953 and 1958 reported bloom of *Noctiluca miliaris* in Palk Bay, Mandapam–Tamil Nadu. Bloom of *Trichodesmium erythraeum* was reported by Ramamurthy 1968, 1970 and 1973 along Porto Novo, Tamil Nadu. Bloom of diatom *Asterionella japonica* was observed with greenish–brown discolouration of coastal waters along Off Vishakhapatnam, Andhra Pradesh (Subba Rao 1969).

Joseph 1975 reported bloom of *Noctiluca miliaris* in Vellar Estuary, Tamil Nadu. Blooms of *Trichodesmium thiebautii* was observed with Fish mortality along the Gulf of Mannar, Tamil Nadu (Chellam and Alagarswami 1978). Silas et al., 1982 reported one death and several hospitalizations due to the consumption of *Meretrix casta* in Vayalar village, Tamil Nadu. Mani et al., 1986 found bloom of along Vellar Estuary, Tamil Nadu. Choudhury and Panigrahy 1989 observed greenish-brown patch of *Asterionella glacialis* bloom along Gopalpur, Orissa coast. Sargunam and Rao 1989 in Kalpakkam,
Tamil Nadu reported bloom of *Noctiluca miliaris*. Panigrahy and Gouda 1990 observed bloom in Rushikulya estuary caused by *Asterionella glacialis* Orissa coast. Blooms of *Asterionella glacialis, Coscinodiscus centralis, Coscinodiscus excentricus* and *Thalassiothrix fraunfeldii* were found in Bahuda estuary, Orissa coast by Mishra and Panigrah y 1995. Satpathy and Nair 1996, Off Kalpakam, Tamil Nadu reported bloom of *A. glacialis* but no fish mortality was found. Blooms of *Noctiluca scintillans* imparted green colouration to water along Port Blair Bay, Andamans (Eashwar et al., 2001). Jyothibabu et al., 2003 observed blooms of *T. erythraeum* with brownish-yellow colouration of water with no fish mortality along Tamil Nadu and Off Kolkata. In Minnie bay, Port Blair–Andamans, green colouration was observed to Water, due to bloom of *Noctiluca scintillans* by Dharani et al., 2004. Sasamal et al., 2005 observed dark-brown discolouration of water due to the bloom of *Asterionella glacialis* in the Gopalpur estuary. Blooms of *Noctiluca scintillans* was reported by Mohanty et al., 2007 caused red discolouration and oxygen depletion in water column. Bloom of *Trichodesmium erythraeum* imparted yellow-green colouration of water however fish mortality was not reported (Satpathy et al., 2007) Bloom caused by *Noctiluca scintillans* in the Gulf of Mannar was dark-green in colour and due to lack of oxygen there was bleaching of corals and death of marine fauna (Gopakumar et al., 2009).

In India along the west coast massive fish mortality was observed along the Malabar to south Kanara (Hornell J., 1908, 1917 and Hornell and
Nayudu 1923) and also observed discoloration of water due to blooms of *Ditylum* sp., *Thalassiosira* sp. and Dinoflagellate species. Bhimachar and George (1950) reported that although there was no fish death fishes avoided the area. Which lead to the break and sudden setback for the fisheries industry. Subrahmanyan (1954) in Calicut, North Kerala found bloom of *Hornellia marina*, giving green discolouration, along with fish and faunal mortality. Prakash and Sarma 1964 reported bloom of dinoflagellate *Gonyaulax polygramma* which observed virtual exclusion of zooplankton. Blooms of *Trichodesmium erythraeum* and *T. hildebrontii* were observed in Ullal, off Mangalore by Prabhu et al., 1965. *Trichodesmium erythraeum* bloom was reported in Laccadive Island by Qasim 1970. However Nagabhushanam 1967 observed the adverse effects of *Trichodesmium erythraeum* bloom were on Tuna fisheries in Minicoy Island, Lakshadweep. Devasssy 1974 reported bloom of diatom of *Fragilaria oceanica* Off Kaikani, Mangalore. Deavssy and Bhattachthiri 1974, observed blooms of *Nitzschia sigma* and *Skeletonema costatum* in Cochin backwaters, Kerala. Verlancar 1978 associated the bloom of *T. erythraeum*, with the swarming of *Physalia* along Ratnagiri–Mangalore.

Off Quilon, Kerala, Venugopal et al., 1979, found bloom of *Noctiluca milliari* associated with red discoloration of water. In Kumble estuary, Mangalore coast Paralytic Shellfish Poisoning outbreak was observed where the causative organism was not known (Karunasagar et al., 1984), which leading to one deaths and hospitalization after intake of clams *Meretrix casta*. Intense green colouration of water was observed due to *N. milliari* bloom.
along Mangalore by Katti et al., 1988. Segar et al., 1989 in Mangalore reported unknown causative species, with lowest levels of PSP found in shellfish. Karunasar, 1993, reported bloom of Gymnodinium nagasakiiense in fish farm Kodi, Karnataka he also reported the fish mortality. Dharamtar Creek, Mumbai found bloom of Skeletonema costatum by Tiwari and Nair 1998. Karunasar et al., 1998 reported the deaths of seven persons as well as hospitalization of around 500 people due to the Outbreak of PSP after the consumption of bloom affected Peridinium indica in Vizhinjam, Kerala coast.

Naqvi et al., 1998, reported Noctiluca sp. bloom, causing severe mortality of fish due to oxygen depletion in Cochin–Calicut, off Kerala coast. Nayak and Karunasar, (2000) reported Moraxella like bacteria associated with bloom of N. milliaris along off Mangalore. Green colouration to water by N. scintillans was also reported by Matondkar et al., 2004 in Porbander (Gujarat) coast. HABs of Cochlodinium polykreikoides and Karenia brevis were observed along Kerala coast (The Hindu and, The Hindustan Times, 2004). Sahayak et al., 2005, off south Thiruvananthapuram, Kerala coast reported N. miliaris, causing red discolouration of water. The Stench of Cochlodinium polykreikoides was observed along the southern Malabar Coast by (Ramaiah et al., 2005). Brownish-red discolouration of water due to Coscinodiscus asteromphalus var. centralis bloom was reported along Off Kodikkal–Calicut, Kerala coast by Padmakumar et al., 2007. A bloom of some dinoflagellates includes Karenia mikimotoi during which mass mortality of fish was observed (Iyer et al., 2008 and Madhu et al., 2011) along Kerala
coast. Deep-green colouration of water due to *N. miliaris* Off Gujarat was observed by Padmakumar *et al.*, 2008a. *Microcystis aeruginosa* bloom was observed along Chalakudy River in Central Kerala by Padmakumar *et al.*, 2008b. Santhosh Kumar *et al.*, 2010 another bloom of same species was found with discolouration of water causing skin irritation and itching.

Non-harmful bloom of *Protoperidinium* sp. was reported Mangalore coast (Sanilkumar *et al.*, 2009). Bloom of Raphidophyte *Chattonella marina* was observed with effect on fishery along Calicut to Tellicherry, Kerala (Jugnu and Kripa 2009). Bloom adding Brick red discoloured water with no fish mortality was reported Off Kochi, Kerala caused by *N. scintillans* (Padmakumar *et al.*, 2010a). *T. erythraeum* bloom was found Off Kollam, Kochi and Kannur, Kerala coast (Padmakumar *et al.*, 2010b). *Karenia mikimotoi* imparted intense brownish colouration to water in Cochin bar mouth, Kerala by Madhu *et al.*, 2011. Rusty brownish-red discolouration of water due to *Coscinodiscus marina* in Off Kochi, Kerala reported by Padmakumar *et al.*, 2011. Many cysts of toxic dinoflagellate species has been reported in the sediments along south west of India during the Southwest monsoon period (Godhe *et al.*, 2000; Karunasagar *et al.*, 1990 and D’costa *et al.*, 2008).
1.7. Mandovi-Zuari estuarine complex of Goa

Mandovi and Zuari rivers together with Cumbarjua canal form the major estuarine system of Goa. They are located between 15° 21’ and 15° 31’N and 73° 45’ and 73° 49’E. Both the rivers originate in Sahyadri hills in Western Ghats and come under the influence of South West monsoon. These estuarine systems receive large amount of runoff from June to September (south west monsoon). As a result these estuaries become fresh water dominated during monsoon. Goa receives 80% of its total rainfall from June to August. Mandovi gets freshwater throughout the year through its tributaries while Zuari receives most of its fresh water during the monsoon. Summer and monsoon are the two distinct seasons that determine the extent of saline and freshwater (Shetye et al., 2007). During peak monsoon season, the estuary is predominantly freshwater, which later slowly becomes saline. Salinity is an important factor governing the growth of phytoplankton (Qasim et al., 1972). The decline in salinity is accompanied by an increase in nutrients during the onset of monsoon season, which is an important factor controlling the distribution, abundance, and productivity of phytoplankton (Devassy and Goes 1988 and Krishna Kumari et al., 2002). Generally, tropical estuaries with moderately low salinities support a greater phytoplankton population than those with a higher salinity (Desikachary and Rao 1972 and Qasim et al., 1972).

Another unique feature of the rivers along the west coast of India is the phenomenal tides that they are subjected to. As a consequence, these rivers
experience large influxes of seawater which have a significant impact on circulation, salinity as well as water column turbidity caused by the disturbance of bottom sediments (Devassy and Goes 1988; Shetye et al., 2007 and Vijith et al., 2009). On account of this free mixing of coastal seawater with freshwater, these rivers represent a stressing habitat for phytoplankton growth defined by large fluctuations in salinity, nutrients, light and temperature (Devassy and Goes 1988).

With rapid increase in population and in industrialization during the last few decades, the estuarine channels have come under increasing stress due to anthropogenic activities. It is suspected that these activities could be causing irreversible changes in the chemistry and biology of the estuaries. In recent years the anthropogenic activities have increased in these estuaries (Goldar and Benerjee 2004; Alagarsamy Rengasamy 2006; Sawant et al., 2007; and Maya et al., 2011). This has lead to the increase in the macro-micro nutrients concentration specially nitrate and phosphate, suspended particulate matter, and trace elements (Pradhan and Shirodkar 2009). Such conditions are known to promote the algal blooms. Following are the reports of algal blooms in coastal and near-shore waters of Goa.

*Trichodesmium erythraeum* (Cyanobacterium) bloom was reported with no fish mortality in the coastal and near-shore waters of Goa (Ramamurthy et al., 1972 and Devassy et al., 1978). Dinoflagellate bloom by *Noctiluca miliaris* was reported imparting green colouration to water followed by decrease in fish catch in the estuarine waters of Mandovi and Zuari and
also along the off Goa coast (Devassy and Nair 1987; Matondkar et al., 2004 and Sanilkumar et al., 2009). Bloom of coccolithophore *C. polykrikoides* occurred which coincided with fish mortality in the off Goa region (O’Herald 2001).

Another important characteristic feature of these estuaries is the presence of thick mangrove vegetation along their banks which makes this area high in biological productivity (Selvakumar et al., 1980; Parulekar et al., 1982 and Devassy 1983). As discussed earlier there is considerable increase in the anthropogenic activities like construction of jetties, ship building and boat traffic (cruising), mining activities, sewage discharge, agricultural runoff which is known to alter the phytoplankton composition and production of blooms.
1.8. Objectives of the present study

Phytoplankton flora of Mandovi and Zuari estuary is well studied for its diversity, distribution and ecology. Studies also provide some information on primary production and biomass of phytoplankton. But HAB producing species did not receive the required attention. No study reveals a complete picture on Inter and Intra variability in the distribution of HAB species. No study has monitored exact effect of salinity and nutrients on temporal dynamics of HAB species based on regular and frequent field studies which are actually required for getting exact floristic picture and to know bloom events. There is no laboratory evidence to prove the effect of environmental factors on the production of toxins by HAB species from Goa. So to fill up these gaps present study is focused at following objectives

1. Distribution of Phytoplankton with respect to HABs in Mandovi – Zuari complex
2. Ecology of Phytoplankton with respect to HABs in Mandovi – Zuari complex
3. Laboratory Experiments on Toxic species of *Pseudo-nitzschia pungens*
4. Prediction of HABs in Mandovi – Zuari estuarine system

Based on the field study, laboratory analysis and experiments conducted the present thesis is divided into Five Chapters. Summary and bibliography is also given.