Waste assimilative capacity studies of select regions of the west coast of India

A Thesis submitted to Goa University for the award of the Degree of

DOCTOR OF PHILOSOPHY

in

MARINE SCIENCES

By

Renjith V. R

Goa University,
Taleigao, Goa
2016

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Research Guide

Dr. P. Vethamony

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Dedicated to……………

My Parents and Sister

Statement

As required under the University Ordinance OB-9.9.(v-vi), I state that the present thesis entitled "**Waste assimilative capacity studies of select regions of the west coast of India**" is my original research work carried out at the CSIR-National Institute of Oceanography, Goa and that no part thereof has been submitted for any other degree or diploma in any University or Institution.

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

Renjith V. R

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September 2016

Certificate

This is to certify that the thesis entitled "**Waste assimilative capacity studies of select regions of the west coast of India**" submitted by **Renjith V. R** for the award of the degree of Doctor of Philosophy in the Department of Marine Sciences is based on his original studies carried out by him under my supervision. The thesis or any part thereof has not been previously submitted for any degree or diploma in any University or Institution.

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Preface

The coastal areas are under multi-dimensional menaces, resulting from both natural and anthropogenic causes, tied either directly or indirectly to human fossil fuel combustion, fertilizer use, industrial activities, overfishing, tourism activities, aquaculture farms, etc, which are vulnerable to environmental deterioration due to the upsurging anthropogenic activities. These factors are of primary relevance in waste assimilative capacity (WAC) studies. In the wake of present global scenarios, the WAC study is one of the most congruent factors for sustainable development. The improper release of pollutants results in the exceedance of the resilience of the receiving systems. There are ample instances of irreversible and indelible deterioration of coastal water quality around the globe due to unchecked and perpetual release of contaminants - one of the reasons is economic development and subsequent industrial boom. Industrial belts are mostly concentrated along the coastal areas due to their proximity to water fronts for various uses. The population growth in India and developments along the coastal zone led to major pollution impacts on creeks, estuarine and coastal environment. Three important water quality problems in the shallow high primary production water areas are eutrophication, toxic algal blooms and sediment linked contaminants. The major causative factors for such problems originate from land-based sources that reach estuaries and the coast via non-point sources, direct deposition of waste and atmospheric fall-out. Over the past few decades, mangrove swamps also have been deliberately used as convenient dumping sites for waste and sewage in many developing countries.

In the recent years, coastal water quality is a subject of serious concern due to its direct dynamic relationship with human as well as aquatic ecosystem health. The rapid change in the demographic trend of the coastal region has made many alterations. The area is prone to rapid industrialisation and economic growth. Coastal environmental modelling is a cost effective method to tackle problems related to coastal environment, as it is not possible to monitor the environmental variables very frequently. The numerical models play invaluable role in treating the chemical, biological and physical processes and the interrelations between them. This also provides an immense aid in the decision making processes for coastal environmental restoration, management efforts and infrastructural planning. Determination and assessment of WAC using water quality models and observational data requires a multi disciplinary approach. In this study, effort is taken to assess the general assimilative capacity of select locations along the west coast of India. This thesis summarizes the study carried out, and is organised as follows:

Chapter 1 describes the background of the work, literature review, objectives of the present work, brief description of hydrodynamics, water quality modeling, waste assimilative capacity and its significance. In the literature review, various works related to WAC are referred to. Water quality studies incorporating assimilative capacity assessments are referred in detail.

Chapter 2 describes the data and methodology. In this section, data collected and processed are described in detail with the adopted methodologies. This includes field measurements carried out off Goa, Mumbai and Gulf of Khambhat and other data sets such as UNEP population data. A complete description of hydrodynamic and water quality models is also given in this section along with a description of model domain and grid size, model calibration and validation.

Chapter 3 deals with assessment of WAC of Mandovi (Goa) estuarine environment and a description of the study area. The Mandovi estuary, Goa, lies along the west coast of India; Goa being a global tourist destination. Mandovi estuary is a tide dominated, coastal plain estuary and the tidal range is about 2.0 m. In addition to factor analysis of water quality data, the water quality index (WQI), trophic state index (TSI) and percentage of freshwater volume in the estuary are calculated to infer the general waste assimilative capacity and prevailing water quality conditions. The AOU (Apparent Oxygen Utilisation) in the estuary during the three seasons indicates that the assimilative capacity is comparatively good throughout the estuary. The freshwater runoff is high in the estuary during the monsoon season. This provide an additional advantage in diluting and flushing the contaminants out of the estuary and largely help to maintain a good acceptable quality of water in the estuary during the monsoon season, thus maintaining good assimilative capacity. The dominant parameters affecting the water quality over different seasons are deciphered using factor analysis. This will help in understanding the contaminants, which influence the water quality and assimilative capacity of the estuary, as the external loading of contaminants reduces the assimilative capacity. During SW monsoon, external loadings of fluoride, NO_2-N, PO_4-P, NH_3-N, TSS or TVC can affect the assimilative capacity of the estuary. The WQI and TSI indicate considerably good water quality and productivity suggesting a good assimilative capacity of the estuary during SW monsoon. During post-monsoon, the assimilative capacity of the estuary can be affected by fluoride, SO_{4-}, urea, TVC and TN. The WQI and TSI indicate a fairly good assimilative capacity of the estuary. The assimilative capacity during this season can be affected by SO_{4-}, fluoride, PO_4-P and NO_2-N. Though there are some high values at some stations, the general trend of WQI and TSI throughout the estuary indicates good to fairly good water quality and productivity and indicating a good assimilative capacity. The assimilative capacity of the estuary is also found to be in good to fairly good state in the order, pre-monsoon < SW monsoon < post-monsoon, considering the dominant contaminants, WQI and TSI.

Chapter 4 briefly describes the prevailing water quality conditions, water quality modeling and estimation of WAC of Mumbai coastal waters. This chapter also describes the impact of climate change on water quality and effects from coastal megacities. Mumbai region is taken as a case study for the coastal megacity. The calibrated model is validated with field data collected off Mumbai. The output from MIKE model is given as hydrodynamic input to WASP water quality model. WASP model is used for estimating WAC of Mumbai Coastal waters, which receives the organic waste materials generated by upstream cities and towns. This waste can cause dissolved oxygen depletion due to increased oxygen demand, affecting the natural ability of water bodies to withstand certain amount of pollution - the WAC. The pollution load (Biochemical Oxygen Demand) calculated using the Population Equivalent value of 0.225 m^3/day for the present Mumbai population of 13 million is 731,250 kg/day. Simulations carried out using MIKE-21 and WASP models indicate that the Mumbai coastal waters can withstand the present pollution load since the simulated biochemical oxygen demand is within the range of 0.2-1.5 mg/L, the national standard limits. In spite of the teeming population, the modeling exercise of the Mumbai region reveals that the coastal waters can assimilate the waste generated by the present population due to the specific hydrodynamic conditions prevailing in the region. The water quality of the Mumbai region balances the fluxes of pollutants received and the dispersion of the pollutants by tidal flushing and decay and removal from the water column by processes such as degradation, adsorption on suspended solids, sedimentation and biotic uptake. A projected population increase exceeded the target BOD value of 2 mg/L, indicating the deterioration of ambient quality of Mumbai coastal waters.

In the recent years, population increase and industrialization, the congruent factors contributing to coastal pollution and environmental stress, eventually lead to the rise of megacities in the coastal zones. Nearly half of the world population now lives within 200 km of the coast, and it is expected to reach 75% by 2025. It is likely that a substantial proportion of wastewater generated from this population will be discharged into the coastal environment with little or no treatment, and this can eventually lead to low oxygen zones, as evident from previous experiences around the globe. The population rise results in heavy input of organic materials to coastal waters. This will reduce the Dissolved Oxygen (DO) in the water column substantially. The warming coastal waters reduce the oxygen solubility and increase bacterial break down of organic matter, which further lower the DO in the water column. The SST change in the coastal waters of Mumbai megacity shows an increasing trend and the decadal change in SST is found to be 0.24 ± 0.01. In the present study, it is shown that the combined effect of anthropogenic effluent discharges and ocean warming scenario can be a potential threat to the sustainable health of the coastal ecosystem and its feedback to climate.

Chapter 5 deals with the present water quality conditions and physical settings of Gulf of Khambhat (GoK). This also includes water quality modelling and assessment of WAC in the GoK. The GoK is a south to north penetration of the Arabian Sea on the western shelf of India between Saurashtra peninsula and the mainland Gujarat. The region is under heavy anthropogenic activities of various kinds. Analysis of in-situ parameters indicated that Gulf waters show a variation from slightly polluted to polluted depending upon the area. Though there are considerable inputs of pollutants from the ongoing anthropogenic activities, simulations reveal that the assimilative capacity of the GoK is still good with high DO content. This DO can mitigate the effect of pollutants entering into the Gulf to a considerable extent. Throughout the simulation period, DO (of GoK) values are above 6 mg/L; high values upto 9.3 mg/L are obtained. Irrespective of the high DO values, high BOD values are also observed in the observed data. The range of BOD values is 1 to 4.7 mg/L. Simulated ammonia values indicate marginal contamination from ammonia. The hydrodynamic conditions prevailing in the gulf (flushing out by tidal currents) largely aid in the dispersal of pollutants. GoK has one of the highest tidal ranges in India. Even if the waste water is treated according to Central Pollution Control Board standards and disposed in the coastal waters, the increased number of industries can pose danger to the delicate ecological balance of the Gulf. Hence, it is essential to have regular water quality monitoring in the Gulf, and carrying capacity of the Gulf should be assessed before new industrial establishments are authorized.

Chapter 6 summarizes the salient findings of this study. In this chapter, overall conclusions of investigations on the WAC along the west coast of India as well as some suggested directions for future research are described.

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1. Vishnuradhan, R., Zainudin, Z., & Vethamony, P. (2012). Introduction to water quality modeling. *Jurutera*, *2012*(8), 12-16.

2. VishnuRadhan, R., Vethamony, P., Zainudin, Z., & Kumar, K. V. (2014). Waste Assimilative Capacity of Coastal Waters along Mumbai Mega City, West Coast of India Using MIKE-21 and WASP Simulation Models. *CLEAN–Soil, Air, Water*, *42*(3), 295-305.

3. VishnuRadhan, R., Sagayadoss, J., Seelan, E., Vethamony, P., Shirodkar, P., Zainudin, Z., & Shirodkar, S. (2015). Southwest monsoon influences the water quality and waste assimilative capacity in the Mandovi estuary (Goa state, India). *Chemistry and Ecology*, *31*(3), 217-234.

Chapter 1
Introduction

1.1. Environmental status of select coastal regions on the west coast of India

The coastal areas are under multi-dimensional menaces resulting from both natural and anthropogenic causes, tied either directly or indirectly to human fossil fuel combustion, fertilizer use, industrial activities, overfishing, tourism activities, aquaculture farms and marine traffic. Identification of regions which are vulnerable to environmental deterioration due to the upsurging anthropogenic activities is of primary relevance in waste assimilative capacity (WAC) studies. In the wake of present global scenarios, the WAC study is one of the most congruent factors for sustainable development. The improper release of pollutants results in the exceedance of the resilience of the receiving systems. There are ample instances of irreversible and indelible deterioration of coastal water quality around the globe due to unchecked and perpetual release of contaminants - one of the reasons is economic development and subsequent industrial boom. Industrial belts are mostly concentrated along the coastal areas due to the proximity to cheap resources. The population growth in India and uncontrolled development along the coastal zone has led to major pollution impacts on creeks, estuarine and coastal environment. Three important water quality problems in the shallow high primary production water areas are eutrophication, toxic algae blooms and sediment linked contaminants. The major causative factors for such problems originate from land-based sources that reach estuaries and the coast via non-point sources, direct deposit of waste and atmosphere fall-out. Over the past few decades, mangrove swamps also have been deliberately used as convenient dumping sites for waste and sewage in many developing countries [Clough et al., 1983; Dwivedi and Padmakumar, 1983]. Many eutrophication and organic loading problems in coastal regions throughout the world are linked to discharge of sewage effluent and dumping of sewage sludge. Pollution and water quality degradation interfere with vital and legitimate water uses at any scale, i.e. local, regional or international [Meybeck et al., 1990].

The coastal regions are very important for humanity for their survival and growth. Coastal water quality is a subject of serious concern due to its direct dynamic relationship with human as well as aquatic ecosystem health.

1.2. Hydrodynamics and water quality

1.2.1. Role of hydrodynamics in water quality

Several physical factors combine to make the coastal systems complex and unique in their hydrodynamics; the associated physical transport and dispersal processes of the coastal flow field are equally complex [Rao and Schwab, 2007]. Coastal waters are often characterized by their hydrodynamics and water quality (physico-chemistry/biology) characteristics. Hydrodynamics of a coastal sea depends on a wide range of factors such as coastal morphology, bathymetry, prevailing winds, waves, tides and other oceanographic conditions. Prevailing hydrodynamics in a region is the primary determinant of its sustainable health and it plays an important role in the waste loading, pathways and fate of pollutants reaching the coastal waters via point and non-point sources. The hydrodynamics of coastal water influences the reaeration of water column as the reaeration is directly proportional to the flow velocity. The natural reaeration mitigates the adverse effects in systems having anoxic/hypoxic environment and can alleviate the ill effects of anthropogenic waste water fluxes.

1.2.2. Modelling as a tool for hydrodynamics and water quality studies

The use of appropriate mathematical models can help to predict hydrodynamic water quality processes and response to natural driving variables or anthropogenic pressures. Models can guide management and policies, and help in the design of monitoring programmes. Coastal regions are hubs of intense anthropogenic activities and frequent environmental deterioration. Coastal environmental modelling is a cost effective method to tackle problems related to coastal environment as it is not possible to monitor the environmental variables on a daily basis. Models play invaluable role in understanding the chemical, biological and physical processes and the interrelations between them. This also provides immense aid in decision-making processes in coastal environment restoration, management efforts and infrastructural planning. The assimilative capacity of the receiving water body affects the optimal treatment levels for a given set of pollutant sources [Zainudin et al., 2011].

Therefore, a simulation model for the prediction of the steady-state water quality response for various possible combinations of waste loadings is required to find the optimal waste load allocation strategy [Murty et al., 2006]. Coastal ocean modelling plays a critical role in understanding how nutrients, contaminants, sediments and other water borne materials are transported [Blumberg et al., 1994]. Water quality modelling is increasingly recognized as a useful tool for acquiring valuable information for optimal water quality management [Fan et al., 2009]. They can be used to calculate watershed loads for existing conditions, relate loads to water quality response, and evaluate the effectiveness of proposed control alternatives in reducing loads and improving water quality to meet standards [DePinto et. al., 2004].

Water quality models have made the job of policy makers and researchers much more reliable and sustainable in recent years. Now it is possible to predict the water quality condition due to land use changes, surging population, effluent discharge and global climate situations. Often water quality models can fill data gaps, which is a major constraint in water quality assessment and management. It serves the purpose of identifying the pollution sources and help to decipher various complex biogeochemical processes in the water bodies simultaneously, which is otherwise difficult to assess with field monitoring alone. Water quality models make it possible to predict future water quality conditions with greater accuracy and are predictive tools for representing complex physical, chemical and biological processes.

1.2.3. Marine and meteorological parameters for coastal environmental modelling

Water quality models have many kinetic equations and each equation includes unknown parameters. The determination of unknown parameters generally requires a great deal of effort because they are dependent on complex physical and biochemical factors such as geological characteristics, temperature, tidal variation, freshwater inflows, point/non point nutrient loads, species of algae, nutrient concentrations at the sediment column, etc. Water quality model parameters are not a common environmental measurement and hence the values of model parameters are usually selected from a range of feasible values which are acquired from field observations, laboratory experiments, previous studies, etc. The popular method of parameter selection is the trial-and-error method that adjusts parameters continuously until there is an optimal agreement between predicted nutrient values and measured nutrient data [Kim and Sheng, 2010].

One of the preliminary processes in water quality modelling is the prediction of transport and dispersion processes using the respective ambient data. Prior to this, the water body of interest is divided into grids/elements/segments. The grid size and the time steps should comply with the stability of the mathematical solutions. The predicted hydrodynamic conditions are mostly used as input for the water quality model. The transport properties of water bodies are devised by numerical solutions of differential equations of motion and continuity. Generally, water quality models have the following components: movement of water bodies, dispersion, dilution of dissolved substances and its first order decay, water quality process and sediment transport. All these components are interdependent, and are usually represented by time varying partial differential equations in one, two or three dimensional spaces. In addition to these, initial and boundary conditions should be specified in order to solve these equations for respective water quality predictions. Once the model is calibrated for a particular region and task, the model results can be verified with measurements. If we find that the match is good between model and field data, the model can be used for simulating water quality parameters for varied conditions. Several constants and coefficients are needed for calibrating a water quality model, but, many of them are difficult to measure in the field. In such a situation, it is desirable to rely on available data or refer to standard manual such as United States Environmental Protection Agency (USEPA). Data requirement for running the models include ambient water quality, water body hydrography, pollution sources, point/non-point sources, long-term water quality and discharge data, sediment oxygen demand and topographic maps/GIS support. In addition to these datasets, bathymetry, current, wind and tide data are needed for marine applications.

1.3. Waste assimilative capacity of coastal/marine environment

1.3.1. Definition of WAC

WAC is the ability of a body of water to cleanse itself; its capacity to receive waste waters or toxic materials without deleterious effects to aquatic life or humans who consume the water. The time variability of pollutant release into the aquatic environment falls into four main categories. Sources can be considered as permanent or continuous (e.g. domestic wastes from a major city and many industrial wastes), periodic (e.g. seasonal variation associated with the influx of tourist populations or food processing wastes), occasional (e.g. certain industrial waste releases) and accidental (e.g. tanker accidents, pipeline bursts). The effects of these pollutants on receiving water bodies are rather different [Chapman, 1996]. The capacity to destroy residues or to insert them in natural cycles of matter does not only guarantee the protection of the ecosystem, it also provides society with valuable environmental functions. Environmental functions are commonly defined as the current and potential uses of an essential part of our biophysical environment [Serafy, 1998]. In many cases, there exist no technological substitutes yet for this crucial ecosystem service [Leandri, 2009].

1.3.2. Factors influencing WAC

WAC highly depends on location and site specific factors of the receiving waters. Coastal waters have distinct WAC for different pollutants depending on the chemical, physical and biological processes in the particular water body and the rate of pollutant input. The physical and chemical factors such as strength of the current, mixing characteristics, sedimentation, dispersion, resuspension and ambient water quality are also deterministic factors of WAC. Open ocean usually has high WAC compared to coastal waters as it can assimilate more oxygen demanding substances and nutrients than coastal waters. It is often difficult to estimate the exact WAC of receiving waters, as it is usually impacted by multiple pollutants. It is possible to understand the WAC process in coastal water bodies to a considerable extent by determining how much waste can be disposed of before oxygen is completely depleted or how fast the system will recover (for example, in terms of oxygen) after a waste disposal scenario. Nowadays, anthropogenic activities are the foremost factors affecting the efficient WAC mechanism in coastal waters around the globe, and natural environmental resilience is threatened to a substantial amount. The WAC of a coastal environment depends on the hydrodynamics, water quality and land use patterns of the region. Technically, water quality can deteriorate beyond WAC, and WAC becomes most evident when exceeded. Water quality criteria that define the limit of WAC often depend on the type of water body and its designated use based on water quality standards.

1.3.3. Estimation of WAC

Due to the complexity of factors determining water quality, large variations are found in coastal waters of different continents or hydro-climatic zones. Similarly, the response to anthropogenic impact is also highly variable. As a consequence, there is no universally applicable standard which can define the baseline chemical or biological quality of waters. At present, regulations for effluent control are concentration-based and do not have specified stringent volumetric discharge limits. Consequently, the Total Maximum Daily Load (TMDL) approach is not fully integrated into the current regulations. TMDL is a calculation of the maximum amount of a pollutant that a water body can receive and still safely meet water quality standards. TMDL approach is a real challenge in developing countries, where the economic development induced population surge and industrial pressure are critical factors. Water quality models can determine the maximum TMDL that can be released from a proposed development without exceeding the WAC of water bodies. Models are an integral part of the TMDL process, in that they provide a quantitative link between pollutant sources and receiving water quality. The estimation of WAC is done usually by determining the quantitative relationship between pollutant sources and water quality criteria.

1.3.4. Significance of WAC study

Insight into the relationships that exist between liquid wastes imposed upon a water resource and the ability of the water to assimilate the load is a basic requirement for the intelligent development of water quality management [Butts et al., 1970]. Coastal waters are complex and insufficiently known ecosystems, which have been perceived as playing a vital role in the global equilibrium of the biosphere. These are highly productive systems, which in many cases even export that productivity, and supply optimal conditions of reproduction and nursery for majority of marine fish species stock, contributing positively to replenish populations in the coastal region. The coastal regions also support economic activities, which is a causative factor for most of the waste material flux to coastal waters. Globally, the largest amount of pollution load discharged into the marine environment is sewage, which is also the major contaminant discharged to coastal region of India. This can bring about potential ill-effects on marine food webs and the availability of the marine resources which the coastal population depends on. The increased anthropogenic activities affect the sustainability of worldwide coastal ecosystems. In this regard, WAC studies are crucial in the present-day regional as well as global scenarios such as water shortage and climate change. Also, help in taking major decisions on maintaining sustainable resource utilization and a healthy coastal ecosystem.

1.4. Review of earlier studies

A detailed literature survey has been carried out to understand the water quality processes, their interactions and environmental impacts. As the subject is very vast, only relevant literature related to the specific work has been compiled and presented. Relevant publications are also referred in Chapters 3, 4 and 5, while discussing the WAC of the respective coastal regions.

Extensive scientific literature is available on water quality studies in rivers/streams/coastal ocean, but very few studies on WAC assessments. Some studies documented the influence of water quality in WAC. Krenkel et al. [1965] evaluated effect of impounding reservoirs on river waste assimilative capacity. Muñoz et al. [1969] evaluated self purification rates of polluted streams in Puerto Rico. They used correlations to relate the oxygenation rates of polluted streams with their hydraulic properties. The Illinois state water survey [Butts et al., 1970] carried out studies for the La- Grange Pool, Illinois River for dissolved oxygen resources and WAC in which a variety of methodologies were investigated to determine the best procedure for defining the waste assimilative capacity. Busch [1972] showed the relation between dissolved oxygen, reaeration and waste assimilative capacity. Campbell [1981] gave a detailed critical short coming in all the definitions of WAC. Liu and Fok [1983] analyzed stream WAC using reaeration coefficients. Krom [1986] gave a detailed definition for WAC, and proposed strategies for the implementation of the concept for marine waters. Juračić and Pravdić [1991] studied the role of suspended matter in assessing the waste assimilative capacity of estuaries. Bronfman [1992] enumerated self-purification in the context of the problems of anthropogenic ecology of the sea. Cairns [1998] viewed assimilative capacity as a key for sustainable use of the planet and the integrity of natural systems are maintained by not exceeding their assimilative capacity. Beaumont [2000] estimated the assimilative capacity of the Humber Estuary, North East England for total dissolved Copper. Using a non-steady advection-dispersion-reaction equation, Campolo et al.

[2002] examined the influence of different pollution control strategies on dissolved oxygen (DO). A study stressing the influence of physical forcing in estimating WAC was done by Yokoyama et al. [2007]. Oelofse et al. [2007] developed an operational policy providing the strategic view on marine disposal as well as the goal, basic principles, ground rules and management framework that will be applied to the discharge of land-derived wastewater to the marine environment. Ioannou et al. [2009] investigated the self-purification capacity along the different stretches of the Pinios River, Central Greece based on the responses of the benthic macro invertebrate community to municipal, industrial and agricultural pollution in the basin. Fitzpatrick [2008] estimated the Magherarney River orthophosphate assimilative capacity using observational data. Cairns [2008] questioned the continuing applicability of the assimilative capacity concept when global ecosystems were being stressed by climate change. He argued that present day waste disposal practices are no longer suitable. Boyacioglu and Alpaslan [2008] conducted a study focused on the development and application of TMDL (maximum amount of pollutant that a water body can receive and still safely meet water quality standards) based on sustainable basin growth and management strategy to give better insight for the management of surface waters. They validated the approach through a systematic study in Tahtali Basin, Turkey.

Pioneering work, which paved the way for development of water quality model was initiated way back in 1850s, with the concept of concentration by Mulvaney [1851]. Various pioneer works [Darcy, 1856; de Saint-Venant, 1871; Manning et al., 1890; Green and Ampt, 1911] which lay the foundation for water quality modelling were done till the development of Streeter and Phelps model in 1925**.** According to Thomann [1998], water quality modelling stages are divided into three stages with the third one being the recent developments. During the initial stages of water quality modelling (1920-1980), the emphasis was given to a free body domain, in which all sources were external to the model and only point sources were directly clubbed to the input. During this stage, only point source pollutants were addressed. First stream oxygen models were developed during this stage [Streeter and Phelps, 1958]. The model was improved by adding a theoretical basis for the reaeration coefficient in later years [O'Connor and Dobbins, 1958]. After 1958, the water quality modelling was extended to estuaries as well [O'Connor, 1960, 1967; O'Connor and Mueller, 1984]. During the end of the first stage, models of increased complexity, addressing eutrophication issues were emerged [Di Toro et al., 1971]. The need to address increasing non-point source pollution problems initialised the second stage (1980-1995). During this period, the number of state variables in the model had been increased. Studies were initiated to address non-point sources and eutrophication [Thomann and Di Toro, 1983; O'Connor et al., 1983; O'Connor, 1988; Di Toro et al., 1990; Donigian et al., 1991; Di Toro and Fitzpatrick, 1993]. During this time, models began to include sediment related factors also. The third stage started from 1995 and continuing till date with more complex models addressing components of atmospheric inputs, using air shed models coupled to water quality models. During this period, number of models increased enormously and models became inevitable in decision making processes.

Hansen and Rattray [1965] suggested that biochemical oxygen demand (BOD), sediment oxygen demand (SOD) and vertical DO profiles are mainly controlled by physical factors like surface reaeration, river flow and estuarine circulation. A water quality model for self-purification of small streams had been modified by Novotny and Krenkel [1975], and applied for the WAC determination of a shallow turbulent stream. Klose [1988] evaluated WAC of Kaministiquia River through BOD-DO modelling. Hathhorn and Tung [1989] used an optimization technique known as fuzzy linear programming in solving a multiple discharge, two-objective waste load allocation problem. Omori et al. [1994] estimated assimilative capacity with regard to organic loading in Uwajima Bay, southwest coast of Japan. They developed an one-dimensional numerical model of the material cycle, considering the DO balance for an analysis of the decomposition process in the bottom layer. Lung and Sobeck [1999] demonstrated that modelling continues to be the most cost-effective method of water quality planning and that water resource managers should apply water quality modelling on a regular basis to support the present and future needs. Wang et al. [1999] used the WASP water quality model to simulate and evaluate the relationship between the nutrient input and water quality of Tampa bay, USA. Ribeiro and Kjerfve [2002] documented the anthropogenic influence on the water quality in Guanabara Bay, Rio de Janeiro, Brazil.

Ribeiro and Araújo [2002] used numerical modelling as a management tool for water quality control of the tropical Beberibe estuary, NE Brazil. Stow et al. [2003] used estuarine water quality models for TMDL in the Neuse River Estuary, North Carolina. DePinto et al. [2004] detailed the modelling processes, which quantify the TMDL. They stated that mathematical models had been used for many years to assist in the management of water quality and models can represent the means by which the assimilative capacity of a water body can be quantified. Using WASP WQ model, Nikolaidis et al. [2006] modelled the hydrodynamics and nutrient cycling of Thermaikos gulf in Greece. Vellidis et al. [2006] described mathematical simulation tools for developing dissolved oxygen TMDLs. The effects of non-uniform flow due to: (i) inflow from tributaries and (ii) the presence of a downstream control structure (such as a weir or a barrage) on the optimal waste load allocation decision and the resulting cost-equity trade-off relationships had been investigated by Murty et al. [2006]. They used an embedded river water quality simulator with gradually varied flow and transport (BOD-DO) modules.

Imam and El Baradei [2009] elucidated the impact of water level control structures on self-assimilative capacity of rivers and on fish habitat using a mathematical model. The WASP/EUTRO model was used by Yang et al. [2009] to model a low DO stream in Taiwan as a part of the water quality management effort. Rucinski et al. [2009] proposed a dual discharge strategy for management of the effluent from the Syracuse Metropolitan Treatment Plant, New York. The approach involved routing the discharge to the Seneca River when assimilative capacity was available there and to Onondaga Lake when it was not. Application of a deterministic modelling approach demonstrated that the dual discharge strategy is effective in meeting water-quality standards/goals in both the river DO and the lake total phosphorus under summer average conditions of river flow. The integration of WASP with a geographical information system (GIS) was presented by Peng et al. [2010] and a case study of the Lower Charles River Basin (Massachusetts, USA) water quality model system was conducted to demonstrate the integration process. Huang et al. [2010] applied WASP model for studies dealing with delineation of reservoir-drinking water source**.** The study was conducted at Nanwan Reservoir, which is located 8.5 km southwest to the city of Xinyang, Henan, China. Tett et al. [2011] developed ACExR and LESV models that could be used to assess the capacity of Scottish lochs and voes to assimilate water from seacage farming of salmonids.

Considerable literature is available on water quality regarding surface water bodies of India, but WAC studies are very less and are mostly confined to rivers. Some of the available literature relevant to the proposed study is presented here. Studies regarding self-purification capacity of Vaigai River (Tamil Nadu) were done by Mahadevan and Krishnaswamy [1986]. A study had been carried out by ICMAM, Chennai [Anonymous, 2004] on the estimation of WAC for Ennore creek and north Chennai coastal waters. Kumar et al. [2000] did water quality modelling of municipal discharges from marine outfalls off Mumbai. DO is one of the important parameters influencing the WAC of water bodies. In this regard, Desa et al. [2005] highlighted the significance of DO as a target indicator to zone the Gulf of Kachchh for different water use. Assimilative capacity of the waters off Kochi in terms of BOD had been studied by Babu et al. [2006]. Vethamony et al. [2007] estimated the carrying capacity of the Gulf of Kachchh in relation to petroleum hydrocarbons through oil spill modelling. Rao et al. [2010] estimated assimilative and healing capacity of coastal waters against the sewage and effluents released along the coast of Visakhapatnam industrial belt. Shirodkar et al. [2012] used MIKE 21 and enumerated the assimilative capacity of Mormugao harbour water, Goa. WAC of a stretch of Periyar River (Kerala state) was estimated by Chandravathi and Resmi [2013] and Rasool et al. [2013] studied self purification capacity of Tawa River, Madhya Pradesh. Patel and Mishra [2013] studied the impact of anthropogenic and industrial activities on water quality and water-self-purification capacity of Subarnarekha River, Jharkhand. As such, it is found that very few works on WAC had been carried out in the coastal waters of India.

1.5 Selection of Research Scheme

Several nearshore regions on the west coast of India (WCI) are hubs of anthropogenic activities including industries, ports, fishing, tourism, urbanization, etc. The anthropogenic activities have made substantial alteration in the ambient environmental conditions in these regions, and these changes persist in the coastal waters for years. The major industrial establishments on the WCI are located at select regions along the Gujarat, Maharashtra and Karnataka coasts.

An important region of anthropogenic activities along the WCI is Goa state, which is a global tourist destination. This region has been an iron ore mining and shipping hub (drastically reduced now due to mining ban). Two major rivers, Mandovi and Zuari, drain through the Goa coastal region and form a major estuarine system. These estuaries receive substantial amount of waste water generated in the region.

Along the Maharashtra coast, the Mumbai region is heavily populated as well as industrialised. Major fraction of the population lives in squatter settlements and the waste water generated is directly discharged into the local rivers and waterways. This will ultimately reach the coastal waters. Sewage treatment plants are installed at specific locations but the soaring population is a serious challenge in managing wastewater in the region. According to the MPCB and the Municipal Corporation of Greater Mumbai, the total length of sewers in the region is 1500 km consisting of 3 ocean outfalls, 50 wastewater pumping stations and 7 wastewater treatment plants. The seven sewerage zones in the region are as follows: Zone 1 (Colaba), Zone 2 (Worli), Zone 3 (Bandra), Zone 4 (Versova), Zone 5 (Malad), Zone 6 (Bhandup) and Zone 7 (Ghatkopar). The Colaba zone covers an area of 6 km^2 consisting of six pumping stations and about 40 km of sewers leading to preliminary treatment and the 1.2 km short outfall to the harbor. The Worli zone that covers the main city area (39 km^2) has 16 pumping stations, about 355 km of sewers and a 3.4 km long outfall. The Bandra zone (77 km^2) has 16 pumping stations and about 350 km of sewers, leading to a 3.7 km long sea outfall. The Verzova zone (21 km^2) has a final pumping station and one small pumping station at Versova village. The total length of sewers is about 160 km leading to preliminary and aerated lagoon treatment and further discharge the treated effluents to the Malad Creek. Malad zone is the largest zone covering an area of 115 km^2 having 6 pumping stations and about 320 km of sewers. A large final pumping station receives the effluents from the Malad zone, and after preliminary treatment, the wastewater is discharged to the Malad Creek. Bhandup zone is a smaller zone (43 km^2) having 3 pumping stations and about 120 km of sewer. After preliminary and aerated lagoon treatment, the effluents are discharged into the Thane Creek. The Ghatkopar zone has 155 km of sewers with 3 pumping stations. The effluents are discharged into the Thane Creek after preliminary treatment by aerated lagoon. Mangroves along the Mumbai coast are also seriously threatened by several man-made changes including intense sewage and industrial pollution [Untawale, 1980].

Among the coastal regions of India, Gujarat has the longest coastline. The Gulf of Khambhat (GoK) and the Gulf of Kachchh are two ecologically fragile large semi-enclosed basins in the Arabian Sea, which are located on the Gujarat coast. Among these, the GoK is not well-studied for anthropogenic impacts and ecosystem response. Though treated, the continuous discharge of waste water from the industrial establishments into the Gulf over the years can pose serious threat to the environment. The Gulf also receives substantial amount of wastes generated by human settlements and port related activities. The main rivers draining into the GoK are Sabarmati, Mahi, Narmada, Tapti and Shetrujni. These rivers discharge large amounts of sediments into the Gulf. The pollutant generated from anthropogenic activities upstream also reaches the Gulf through these rivers.

All the three regions are impacted by anthropogenic activities in one way or other. A detailed literature survey pertaining to the present work, highlighting environmental/water quality scenario and anthropogenic influences in the study regions are compiled and presented in sections 1.5.1 - 1.5.3.

1.5.1. Mumbai region

Mumbai, located along the west coast of India, is the largest and one of the fastest growing urban agglomeration in India. The growing city generates substantial amount of effluents and these effluents find their way into the coastal waters through open drains which connect to rivers in the region, ultimately draining to the coastal ocean. Approximately 60% of residents of the region live in squatter settlements [Chinai, 2005; Surjan et al., 2009], where there is no provision for treatment of waste water, as of now. Lack of adequate sanitation facilities in the region also contribute to waste materials discharged into the coastal waters. Though sewage treatment plants (STPs) are installed in specific locations, they are inadequate to handle the present situation. The waste water deteriorates the ambient coastal environmental quality as reported in earlier studies [De Sherbinin et al., 2007].

The four major rivers draining in the city are Mithi, Oshiwara, Dahisar and Poisar. The Mithi River originates from the Vihar and Powai lakes, and drains into the Arabian Sea via Mahim Creek. The Oshiwara River begins in the Aarey Milk Colony and joins the Arabian Sea via Malad Creek. The Dahisar River empties into the Manori creek after originating from the Tulsi Lake. The Poisar River is now a contaminated urban stream which ends its journey after draining into the Marve Creek. The region also has two minor rivers named as Tasso (empties into the Vihar Lake) and Tansa (one of the Mumbai's major water source and embanked by one of the largest masonry dams in the world). Ulhas River is another major river near the region which splits near Thane into two branches leading to the formation of the Vasai and Thane Creeks. All these rivers carry substantial amount of industrial and urban wastes in their due course. Recently in 2015, as an effort to mitigate the growing pollution problems in the rivers, the MPCB issued closure notice to around 100 industrial establishments polluting the Mithi River.

The region receives substantial amount of domestic and industrial contaminants emanating from point and non point sources [NEERI, 1985; Lancelot Pereira, 1986; Rokade, 1994; NIO, 1999; Zingde and Govindan, 2000; Karn and Harada, 2002]. Many earlier studies extensively addressed the growing pollution problems resulting from various effluent discharges [Naidu and Shringapure, 1975; Zingde et al., 1979; Zingde and Desai, 1980; Deshmukh and Kagwade, 1987; Zingde et al., 1989; Ramaiah et al., 1992; Ramaiah and Nair, 1993; Ramaiah and Nair, 1997; Ramaiah and Nair, 1998; Swami et al., 2000; Zingde and Govindan, 2000]. Jha et al. [1999] used ^{210}Pb dating technique to study the history of mercury and nickel accumulation in the Thane Creek. The study indicated positive evidence for continued fresh inputs of mercury and nickel to the region. Ingole and Kadam [2003] assessed water and sediment qualities of major coasts in Mumbai and concluded that the environmental quality degradation off Dadar is due to the highly polluted discharges through Mahim Creek. The coliform counts were found to be abnormally high in the studied regions.

Substantial input of mercury and associated mercury pollution was identified in an earlier study in Thane Creek by Zingde and Desai [1980]. The study also pointed out mercury bioaccumulation in the region. Sediment core based study [Sharma et al., 1994] from the Thane Creek-Bombay harbour complex indicated that the inner creek acted as a sink for lead while active winnowing prevailed in the southern segment. The quantification [Singare et al., 2012] of accumulated toxic heavy metals in the sediments of Mithi River during 2009-2012, showed severe pollution of the region by heavy metals. Spatial and temporal variation in the accumulation of organic matter and trace metals in Manori Creek was investigated by Fernandes et al. [2011]. The study attributed the source of these contaminants as, erosion of terrestrial matters as well as domestic and industrial discharge. Menon and Mahajan [2010] concluded that the prime factor for elevated levels of mercury in water in Ulhas estuary and Thane Creek is due to the proximity to the source of discharge and, showed positive correlation with temperature and BOD. Ram et al. [2009] found that 80% of mercury settles in the vicinity of the discharge site and, once deposited in sediments, it is not affected to any substantial degree. The study dealt with post-depositional memory record of mercury in sediment near an effluent disposal site in Thane Creek. Jayasiri et al. [2014] studied the spatial and temporal variability of metals in beach sediment and concluded that beach sediments were polluted by heavy metals.

Chouksey et al. [2004] reported the accumulation of petroleum hydrocarbon residues in marine environment of Bassein. The higher concentration of petroleum hydrocarbon was observed in the bottom water of shallow waters, attributed to the contribution from sediment-associated petroleum residue. The study found no evidence regarding bioaccumulation of petroleum hydrocarbons. Marine water quality assessment off Mumbai was done by Dhage et al. [2006] and the study delineated the affected area around the Worli outfall. Spatial and temporal analyses were done [kamble et al., 2010] to assess the water quality of creeks and coastal regions. Most of the water quality parameters in the creeks exceeded the standards and was attributed to sewage disposal. Agrahari et al. [2006] found in a study conducted to assess the amount of heavy metals in commercially important finfish off Mahim that the concentration of heavy metals decreases from inshore to offshore. The study also observed a gradual increase in bioaccumulation of heavy metals with increase in average body weight and length of fishes. A comparison study [Sawant et al., 2007] between 1960s and 2000s to assess the eutrophication status of Mumbai and Jawaharlal Nehru ports found that the nitrate concentration has increased gradually over the years with a simultaneous decrease in DO. Based on the assessment using Estuarine Trophic Status Model, the study concluded that the current status is poor and may get worsen in future. Sukumaran and Sarala Devi [2009] used polychaete diversity and spatial patterns as a proxy for environmental assessment of Mumbai port. The study concluded that the dominant presence of *P. pinnata* with low species diversity indicates unhealthy environment in the Mumbai Port

Gupta et al. [2009] used multivariate statistical techniques to study the variation in water quality of Mumbai coast. Dhage et al. [2006] assessed the marine water quality along the Mumbai coast and highlighted the sewage problem in the region. Prabhu and Kulkarni [2009] assessed the water quality off Dadar, and found evidences for organic pollution in the region. Sardar et al. [2010] carried out an assessment regarding water quality of Malad Creek and suggested various options for improvement of water quality. Kamble and Vijay [2011] assessed water quality at 17 seafronts in Mumbai coastal region using statistical methods. It is found that the Mahim region was worst affected due to incoming organic load from the Mithi River and most of the water quality parameters exceeded the standards in the other regions also. Vijay et al. [2011] suggested that designated water quality at seafronts can be achieved by restricting nonpoint sources through improvement in waste water collection system, treatment and proper disposal. Environmental assessment of non-biodegradable solid wasted along the Vasai Creek [Singare, 2012] suggested the need to enforce strict control measures against the disposal of solid waste materials. Pollution impact assessment study [Singare et al., 2012] along the Vasai Creek concluded that the present high level of pollution will affect the aquatic life and the aesthetic beauty of the creek.

Sukumaran et al. [2014] studied the impact of collision between two merchant vessels in the mouth region of Mumbai harbour in August 2010 and the inter tidal regions of Colaba was found affected. Singare and Dhabarde [2014] studied the pollution discharge scenario of effluents released from chemicals manufacturing industries along Dombivali industrial belt of Mumbai. Assessment of toxic heavy metals in Mahim Creek [Singare and Ferns, 2014] showed that the average concentration of mercury and lead was above the permissible limit of 0.01 ppm and 0.1 ppm, respectively. Tidal and seasonal variation in water quality of Thane Creek [Vijay et al., 2015] showed that the creek water is more polluted in the upper stretch than the middle and lower stretches. Using object-based image analysis, Vijay et al. [2015] checked the extent of sewage pollution in coastal environments of Mumbai. Same methodology was used by Shirke et al. [2016] to study the impact of sewage pollution in Malad Creek. The study showed the impact of organic matter reaching the creek through discharge of sewage.

A water quality modeling study using a dispersion model [Kumar et al., 2000] to understand the effect of discharges from outfalls showed higher level of bacterial pollution near the diffuser location. A two dimensional numerical modeling [Gupta et al., 2004] study was conducted to determine the wastewater assimilative capacity of Thane Creek. The water quality of the creek was simulated for projected flows and loads for the year 2015 to develop wastewater management strategy. Gupta et al. [2006] used a two dimensional numerical model to study the dilution effects near Worli outfall. A dispersion model developed by NEERI and BARC was used to study [Vyas and Vyas, 2007] the effluent dispersion near sewage outfalls at Worli, Bandra, Versova and Malad. Using MIKE 21, hydrodynamic and water quality simulation were carried out [Vijay et al., 2010] to study the impact of sewage on water quality of Malad Creek. The study suggested that the upper section of the creek requires more dilution and flushing due to its small width and large inflow of discharges from open drains. Similar modeling exercise was carried out for Thane Creek [Vijay et al., 2014] to understand the impact of sewage discharges. Recently, Dhage et al. [2015] evaluated the domestic waste discharge from marine outfalls at Mumbai using tracer techniques.

1.5.2. Goa region (Mandovi Estuary)

The Mandovi River together with the Zuari River and its interconnecting Cumbarjua canal forms a major estuarine system along the west coast of India. The region is influenced by tourism, marine traffic, fishing and mining. Earlier studies [Qasim and Sen gupta, 1981] detailed the environmental characteristics of this estuarine system and classified it as a tide-dominated coastal plain estuary.

Fluoride concentration in the estuary was studied earlier by DeSouza and Dalal [1984]. Low dissolved aluminium is found throughout the estuary in an investigation on the behaviour of aluminium in waters of the Mandovi estuary [Upadhyay and SenGupta, 1995]. A study investigating the effect of mining rejects on the nutrient chemistry of the estuary found that the mining rejects increase the turbidity and metal contents in the estuary [De sousa, 1999]. Harkantra and Rodrigues [2004] showed the environmental influences on the species diversity, biomass and population density. In order to determine the extent of anthropogenic inputs from mining activities, a study was carried out regarding the concentration and distribution of selected trace metals in surface sediments of the Mandovi estuary [Alagarsamy, 2006]. The lowest metal concentrations were found during the monsoon. The distribution of tributyltin in the estuary was studied by Bhosle [2007] and the high concentrations at some stations were attributed to the berthing of barges and small fishing boats. An investigation carried out using sewage-pollution indicator bacteria [Rodrigues et al., 2007] found that the estuarine water is unfit for bathing as per USEPA standards probably due to the raw sewage effluents. In a study carried out to find the sources of hydrocarbons in the Mandovi estuary, terrestrial hydrocarbons were found in the estuarine sediments [Harji et al., 2008]. The benthic fluxes of nutrients show strong seasonality, higher in the pre-monsoon compared to the monsoon season [Pratihary et al., 2009]. The study pointed out that this may be the reason for high biological productivity during dry season in spite of less riverine nutrient inputs. An investigation done to enumerate spatial and temporal variation of limno-tolerant bacteria revealed that the nitrate concentration in the estuary is governed by limno-tolerant bacteria [Divya et al., 2009].

Using a hybrid network numerical model, Manoj et al. [2009] studied the tidal circulation and salinity distribution in the estuary and found that a small fresh water influx can affect the longitudinal distribution of salinity to a great extent. The incursion of saline waters deep into the river channel during dry season help in aggregation and settling of particulate-borne pollutants close to the discharge areas, keeping the estuarine waters free from major contaminations [Shynu et al., 2012]. The concentrations of suspended particulate matter are low at river-end regions and high at seaward side [Kessarkar et al., 2010] and an estuarine turbidity maxima prevailed at seaward side during monsoon period. Distribution patterns of dissolved carbohydrates and uronic acids were studied by Khodse et al. [2010]. The particulate organic matter was relatively more degraded during monsoon season and particulate organic matter from autochthonous sources was found during pre-monsoon [Fernandes, 2011]. Dilution, difference in sources, biodegradation and physiological state of phytoplankton influence the transport of particulate carbohydrates in the estuary. In the estuary, monsoon plays an important role in the occurrence and distribution of harmful algal species in addition to salinity variations and nutrient loading [Pednekar et al., 2012]. Siraswar and Nayak [2012] estimated the role of suspended particulate matter in metal distribution within the estuary. Parab et al. [2013] showed the effect of fresh water influx on phytoplankton in the estuary.

Veerasingam et al. [2015] recently investigated the sources, vertical fluxes and accumulation of petroleum hydrocarbons using sediment cores. A recent study carried out for the assessment of surface water quality characteristics of the estuary using water quality index method concluded that most of the water samples (total 36 surface samples) were found within good to moderate categories [Singh and Kamal, 2015]. The fate of iron ore pollution after the mining ban from September 2012 was investigated recently by Kessarkar et al. [2015]. The study concluded that, the mining ban reduced the input of iron ore material but more flushing of estuarine sediments is required for healthier environment. Pradhan et al.

[2015] investigated the seasonal nutrient chemistry of the estuary during 2011-2014. A very recent study assessed the ecological status of the estuary using the temperate benthic indices [Sivadas et al., 2016]. The study found that, although there are several activities (tourism, sewage disposal and fishing jetties) along the Mandovi estuary, the overall water quality remains considerably good. Further, the high freshwater runoff in the Mandovi estuary during the monsoon season dilutes and flushes the contaminants out of the estuary.

1.5.3. Gulf of Khambhat

Major rivers such as Narmada, Tapi, Mahi, Sabarmati and many minor rivers empty into the GoK. Though water quality studies concentrating the GoK are less, the estuaries formed by these rivers are investigated extensively. Zingde [1999] reported a five-fold increase in the level of $NO3^-$-N in the Gulf due to the influence of rivers. It was also noted that the chlorophyll a content remained static despite the availability of NO_3^--N and PO_4^{3-}-P. This was due to the hindrance of photosynthesis by high natural SPM (suspended particulate matter). The state of water quality in the three main estuaries of GoK (The Narmada, Mahi and Sabarmati) was investigated by Deshkar et al. [2012] using physico-chemical parameters, and concluded that the Narmada estuary is least polluted. The study also revealed high organic pollution in the Sabarmati estuary. Using satellite data, the spatial and temporal variation of SPM in the GoK was studied by Misra et al., 2014. The study pointed out that the large tidal range as well as the presence of major rivers influences the SPM dynamics in the region.

The Tapi River forms a major permanent estuary in the vicinity of GoK. The course of the river is through major industrial cities such as Surat and Hazira, rendering it to carry the pollutants generated in these upstream cities. The strong tidal currents of the region make the estuary well mixed, most of the time. A study conducted for the period July 2008 to June 2009 [Kumar et al., 2009] found that the highest concentration of all the nutrients and DO prevailed during the monsoon and the dissolved inorganic nutrients were influenced by factors such as tidal currents, benthic invertebrates and drainage discharged from industries/cities located around the estuarine zone. The quality of Tapi River estuarine system was assessed by the relationship between physicochemical parameters and phytoplankton assemblages [George et al., 2013]. The study concluded that freshwater discharges through the river and rivulets include additions of nitrate, phosphate and silicate to the coastal water mainly during the monsoon season. Dubey and Ujjania [2013] concluded that the Tapi River is moderately polluted due to discharges of industrial waste, domestic sewage and agricultural run-off in river water. A recent study assessed the water quality based pollution status in estuarine environment of the Tapi River [Dubey and Ujjania, 2015]. The study concluded that the estuarine environment of Tapi River is polluted by point sources including industrial effluents and domestic sewage. A recent [Ujjania and Dubey, 2015] investigation was carried out on the pollution status of the Tapi estuary on the basis of physico-chemical parameters using water pollution index (WPI). The study found that low DO and high nitrate-N, turbidity and COD distribution prevails in the estuary and is influenced by discharges from industries and anthropogenic activities in and around the estuarine zone.

An investigation carried out during 1982 related the distribution of phytoplankton, chlorophyll *a* and phaeophytin to water pollution in the Mahi estuary [Jiyalal Ram., 1991]. The water quality at industrial discharge points were found to be polluted compared to far away regions. The distribution of water quality parameters studied using statistical methods during the monsoon and non-monsoon seasons in the Mahi estuary [Kumar et al., 2013] showed high deterioration in the physico-chemical quality of water during the non-monsoon season compared to that in the monsoon season.

In Narmada estuary, temporal changes in the fluxes of macronutrients (nitrate, nitrite, phosphate) during 2005-2010 revealed that the effluent flow, sewage drainage, catchment runoff and the tides influence the macronutrient fluxes [Sonal et al., 2014]. High load of inorganic nutrients at the middle and upper reaches of the Narmada estuary due to anthropogenic influence and low freshwater flow in this zone was highlighted in a study [George et al., 2014] conducted on the relationship between physicochemical parameters and phytoplankton assemblage in Narmada estuarine region. A recent study traced the spatio-temporal variation in water quality at Narmada estuarine region through solute concentration [Kumar et al., 2015]. The results indicated that spatiotemporal variation of water quality occurs because of the following main mechanisms: carbonate weathering, dilution and seawater–freshwater mixing. A recent study conducted in the Sabarmati River indicated that the river stretch from Ahmedabad-Vasana barriage to Vataman was highly polluted due to perennial waste discharges mainly from municipal drainage and industries [Haldar et al., 2014]. The investigation also recommended the implementation of sustainable management plan with proper treatment of both municipal and industrial effluents is essential to prevent further deterioration of the water quality of this river.

1.6. Objectives

Earlier studies showed that these regions are stressed by anthropogenic activity of various degrees. Though there are a number of studies addressing the anthropogenic activities and corresponding pollution problems in these regions, none of them could estimate the WAC or highlight the need for WAC studies. In this situation, as seen in the earlier studies of these regions, mitigation and adaptation strategies are required for the sustainability of our environment. This can be achieved through systematic WAC studies of these regions. As seen in the literature review section, there are knowledge gaps and lack of baseline WAC studies along the Indian coastal regions. Rather than comparing the water quality of three regions, the present research work use the modelling technology and methodologies to explore assimilative capacity of these unique coastal regions (an estuarine system, an open coastal region and a semi-enclosed bay) based on the specific anthropogenic activities. The study regions (Goa, Mumbai and GoK) addressed in the present research work are exposed to immense anthropogenic activities and it is high time that these issues are addressed for the sustainability of these regions.

As the recent climate change is projected to exacerbate in future [Nicholls et al., 2007] and the water bodies around the world start showing responses to the change in climate, WAC can also get affected. The two most important water quality parameters crucial for the determination of WAC are BOD and DO concentration [Thomann and Mueller, 1987]. Significant changes in DO concentration will affect the ambient water quality dynamics/mechanism. Specifically the BOD will rise with a consistent drop in DO, which affect the ecosystem dynamics and WAC. The dependence on coastal waters for anthropogenic activities such as industrial establishments, tourism, fishing, aquaculture farms, marine traffic and associated economic development, enhanced the population pressure in coastal regions in recent decades. Nearly 50 % of the world population now lives within 200 km of the coast and it is expected to reach 75 % by 2025 [Creel, 2003; UNESCO, 2009], eventually lead to the rise of megacities (cities having population > 10 million) in the coastal zones. Substantial proportion of wastewater generated is discharged directly into the coastal environment with little or no treatment [Islam and Tanaka, 2004], and this can eventually lead to the evolution of low oxygen zones, as evident from previous experiences around the globe [Rabalais et al., 2010]. An estimated 90 % of the untreated wastewater from urban areas in developing countries is discharged directly into the rivers, lakes or the oceans [Evans et al., 2012]. Such discharges, allied to run off, are part of the reasons why de-oxygenated dead zones are growing rapidly in the seas and oceans of the developed world and emerging now in developing countries [Corcoran et al., 2010]. As the majority of waste water entering the coastal zone is organic in nature [Islam and Tanaka, 2004; Foroughi et al., 2010], it can cause depletion in DO and affect the BOD mechanism. Globally, oxygen decline rates are more severe in a 30 km band near the coast than in the open ocean (> 100 km from the coast) [Gilbert et al., 2010] and 71 % of world's coastal waters are warming significantly [Lima and Wethey, 2012]. The warming effect will further decrease the DO content in the water column and contributes to the degeneration of basic WAC mechanism.

Keeping these background information in view, the objectives of the present research work are formulated as follows:

- To estimate the pollutant loadings, understand ongoing processes and the response of the receiving water bodies based on water quality of the three study regions (Mumbai, Goa and Gulf of Khambhat).

- To estimate the WAC of these select coastal waters through simulations and observations.

- To check the possible climatic impacts on WAC with respect to present climatic scenario (Mumbai mega city coastal region as an example).

Chapter 2
Data and Methodology

2.1. Measurements of temperature, salinity, currents and water quality parameters

A SBE-19 plus Conductivity-Temperature-Depth (CTD) was used for the vertical hydrography measurements of temperature and salinity. The conductivity and temperature are recorded continuously as the CTD is lowered through the water column. The salinity is derived from the conductivity measured by the passage of electric current through the water column.

Current measurements were carried out using Recording Current Meter model 9 (RCM-9) which is a self-recording current meter moored to measure and record the vector averaged speed and direction of ocean currents. The details of CTD, current and water quality measurements carried out off Mumbai, Mandovi estuary, Goa and GoK are given in Tables 2.1 to 2.6. CTD measurements for the Mandovi estuary were done synonymous to water quality data collection for three seasons, as detailed in Table 2.3. Data were collected during pre-monsoon (March), SW monsoon (August) and post-monsoon (November) seasons (2010-2011) and were collected for both low tide and high tide conditions. Water quality measurements were done in the Mumbai coastal region (October 2009) and GoK (March 2011), in order to validate the water quality model results. The current meters were deployed off Worli and Satpati (Mumbai) and off Dahej and Hazira (GoK) such that the current meter locations lie within the model domain of the study regions.

Date of Sampling	Station No.	Time(hrs)	Latitude (^oN)	Longitude (^oE)	Depth (m)	Distance from the coast (km)
24/10/2009	1	12.2	19 00.297	72 47.639	6.5	2
24/10/2009	2	11.3	19 00.077	72 45.596	13	5.6
24/10/2009	3	10.05	18 59.986	72 42.6	19	10.8
24/10/2009	4	13.43	19 05.096	72 48.096	6.5	2.5
24/10/2009	5	15.38	19 05.002	72 44.648	14.2	8.5
24/10/2009	6	16.18	19 04.591	72 43.380	15	10.8
25/10/2009	7	8.45	19 10.443	72 46.058	8	2.8
25/10/2009	8	9.45	19 10.639	72 41.945	14	9.9
25/10/2009	9	10.41	19 09.973	72 37.951	17	17
25/10/2009	10	14.1	19 15.051	72 45.607	8	2.3
25/10/2009	11	12.55	19 15.242	72 41.719	11	9.1
25/10/2009	12	11.35	19 15.072	72 37.402	16	16.7
25/10/2009	13	15.3	19 20.235	72 44.964	7	4.2
25/10/2009	14	16.2	19 20.171	72 40.384	12	12.2
25/10/2009	15	17.15	19 20.207	72 35.696	18	20.4
26/10/2009	16	13.1	19 25.052	72 44.028	6	2.7
26/10/2009	17	14	19 25.0	72 40.685	10	8.5
26/10/2009	18	15.2	19 25.0	72 35.811	15	17

Table 2.1. Details of CTD and water quality measurements off Mumbai during October 2009.

Location	Depth (m)	Latitude (^oN)	Longitude (^oE)	Deployment Date	Retrieval Date
off Satpati	5	19° 43’ 58.4”	72° 36’ 58.7”	26/10/2009	24/11/2009
	16				
off Worli	5	19° 3’ 31.6”	72° 43’ 35.1”	24/10/2009	25/11/2009
	15				

Table 2.2. Details of Recording Current Meter (RCM) deployment off Mumbai during October-November 2009.

Station No.	Latitude (^oN)	Longitude (^oE)	Depth (m)	Distance from the mouth (km)
M1	15.46465	73.75004	11	0
M2	15.48714	73.80672	9	7
M3	15.50397	73.82392	7	10
M4	15.50813	73.86615	6	15
M5	15.53647	73.92854	8	22
M6	15.54224	73.95971	7	25

Table 2.3. Details of CTD measurements and water quality sampling in Mandovi during 2010 - 2011.

Date of Sampling	Station No.	Time (h)	Latitude (°N)	Longitude(°E)	Depth (m)	Distance from the coast (km)
11/03/2011	D1	09:40	21.69696	72.47327	21	05.5
11/03/2011	D2	10:50	21.69592	72.4217	22	10.8
11/03/2011	D3	12:15	21.68949	72.36676	20	16.5
11/03/2011	D6	13:13	21.56158	72.40302	38	19.4
11/03/2011	D5	14:50	21.56423	72.4658	17	12.9
11/03/2011	D4	15:45	21.56509	72.52538	16	6.8
13/03/2011	D7	14:00	21.40253	72.48293	25	17.4
13/03/2011	D8	15:15	21.40927	72.40012	30	25.5
13/03/2011	D9	17:40	21.39804	72.56012	12	9.4
09/03/2011	D17	10:50	21.2271	72.57168	9	3.8
09/03/2011	D10	12:04	21.2405	72.52546	17	7.6
09/03/2011	D11	13.10	21.23759	72.45353	31	15
08/03/2011	D13	09:37	21.12077	72.54608	26.2	7.6
08/03/2011	D14	12:05	21.11706	72.46242	26.9	16.3
08/03/2011	D16	16:56	21.1121	72.59761	16	2.57
08/03/2011	D18	17:45	21.06589	72.65791	15	0.8

Table 2.4. Measurements of water quality parameters in the Gulf of Khambhat during March 2011.

Station	Depth (m)	Latitude (°N)	Longitude (°E)	Deployment date	Retrieval date
off Hazira	18	21.04	72.61	04/03/2011	04/04/2011
off Dahej	20	21.64	72.51	06/03/2011	06/04/2011

Table 2.5. Details of the deployment of current meters in the Gulf of Khambhat.

Location	In-situ water quality data	Current meter data
Mumbai	1980- 2008 Model validation data: 2009	October 2009–November 2009
Gulf of Khambhat	1980-2010 Model Validation data: 2011	March 2011 - April 2011

Table 2.6. Details of the data used in setting up the WASP modelling network.

2.2. Analysis of water quality parameters

The water samples collected for nutrients, chlorophyll *a*, Petroleum Hydrocarbons (PHc), trace metals and phenolic compounds were analysed as per standard methods [Strickland and Parsons, 1972; Grasshoff et al., 1983; APHA, 1992]. The microbiological analyses for total viable coliforms (TVC), total coliforms and total vibrios were carried out following APHA [1992]. Urea was determined by the modified diacetyl monoxide method [Grasshoff et al., 1983]. The sediment samples were collected using a Van-Veen grab. The detailed methodologies are discussed in the following sections. Samples were collected through boat and research vessels. Quantity of samples was collected according to the need and requirement of analysis. Mostly, 5L single samples were collected using a Niskin sampler for the analysis of various biological and chemical parameters. However, a few multiple samples were collected depending on need and weather conditions at that time, including currents.

2.2.1. pH, DO, BOD and suspended solids

pH was measured using a portable pH meter (Eutech Tutor). The instrument was first calibrated with standard pH buffers of pH 7.0 and pH 4.0 and then the measurements were done. DO was measured by Winkler's method [APHA, 1992]. The DO in a measured volume of seawater sample was first fixed onboard by adding the Winkler reagents A & B (manganese chloride and alkaline potassium iodide, respectively) immediately after collection. The precipitate so formed was then decomposed with concentrated hydrochloric acid (HCl) and the resulting analyses followed the iodometric titration method.

Samples for the determination of BOD were collected in triplicate. The dissolved oxygen concentration was determined first using one of the triplicate samples according to Winkler's method. The remaining bottles were then left for 5 days in the dark at 20°C. Dissolved oxygen in these samples was determined by Winkler's method after fixing the samples immediately on completion of incubation period (5 days). The BOD_5 was computed from the initial DO concentration.

For analysis of suspended solids, known volume (1L) of water was filtered through a pre-weighed 0.45 μm filter paper. This paper was dried till constant weight was obtained.

The difference in the original weight and the weight after filtering the water and drying was taken, and then the amount of suspended solids was calculated.

2.2.2 Nutrients

2.2.2.1. Nitrite - Nitrogen (NO_2^--N)

Nitrite was determined by the method of Bendschneider and Robinson [1952]. Nitrite in the samples was measured after diazotizing it with sulfanilamide and coupling with N (1-Naphthy)-ethylene diamine-dihydrochloride. The absorbance of the resultant azo dye was measured at 543 nm by a Shimadzu UV 1200 spectrophotometer.

2.2.2.2. Nitrate - Nitrogen (NO_3^--N)

Nitrate [Grasshoff et al., 1983] in the samples was first reduced quantitatively to nitrite by heterogeneous reduction by passing each buffered sample through an amalgamated cadmium reduction column and the resultant nitrite was analyzed as in section 2.2.2.1 [Mullin and Riley, 1955; Strickland and Parsons, 1972]. The measured absorbance was due to the initial nitrite in the sample as well as the nitrite obtained after the reduction of nitrate. Necessary correction was, therefore, made for any nitrite initially present in the sample.

2.2.2.3. Phosphate - Phosphorous (PO_4-P)

Dissolved reactive phosphate was measured by the method of Murphy and Riley [1962] in which the samples were made to react with acidified molybdate reagent and reduced using ascorbic acid. The absorbance of the resultant blue complex was measured at 880 nm using Shimadzu UV 1200 spectrophotometer.

2.2.2.4. Silicate (SiO_4^--Si)

The determination of silicate [Strickland and Parsons, 1972] in water was based on the formation of a yellow silicomolybdic acid when a nearly acidic sample was treated with a molybdate reagent. The yellow silicomolybdic acid was reduced to an intensely coloured blue complex using ascorbic acid as the reductant and the colour was measured spectrophotometrically at 820 nm.

2.2.2.5 Ammonia – Nitrogen (NH_3^--N)

Ammonia-nitrogen was determined by the Indo-phenol blue method [Strickland and Parsons, 1972] based on the principle that in a moderately alkaline medium, ammonia was allowed to react with hypochlorite in the presence of catalytic amounts of nitroprusside to form indophenols blue. The formation of monochloramine requires a pH between 8 and 11.5. The resultant blue complex was measured at 630 nm by spectrophotometer.

2.2.3. Trace Metals

Water samples for Cadmium (Cd), Lead (Pb), Copper (Cu) and Mercury (Hg) analyses [APHA, 1992] were collected along transects, filtered at the shore laboratory, and the dissolved and particulate metals were estimated. Hg was estimated as total Hg in the collected water samples. Sediment samples were also collected for the trace metals along transects using Van-Veen grab. Depth of sample collection at each location is mentioned in Tables 2.1 and 2.4 in the methodology section. Model of AAS used for trace metal analysis is GBC cold vapour analyser (Hg), and AA ANALYST 600GF AAS (Cu, Cd, Pb) in water. Detection limits of AAS are as follows: Cu- 0.014 µg/L, Cd- 0.002 µg/L, Pb-0.005, Hg-0.001 µg/L.

The metals were selected based on their toxicity and the damage it can impart to the ecosystem. Many previous studies suggested that these trace metals can impart substantial environmental damage and affect the water quality [Sultana and Rao, 1998; Desai et al., 2006; Shanmugam et al., 2007; Shirodkar et al., 2009; Rejomon et al., 2010; Sundaray et al., 2011; Al-Usmani et al., 2015; Jadhav and Singare, 2015; Jayaprakash et al., 2015; Veerasingam et al., 2015; Achary et al., 2016]. The harmful effect of these metals is widely known and is a matter of concern for the environmentalists because of its lasting effect on biota. Cadmium is not known to have any physiological function in the human body and is considered as a biohazardous metal causing several health hazards including kidney damage, bone damage, acute respiratory diseases, gastrointestinal problems and even cancer in humans [Linshy et al., 2013]. The anthropogenic source of cadmium is mainly industrial and is used as anticorrosive agent, stabilizer in PVC products, as colour pigment, in nickel cadmium batteries, in nuclear power plants as a neutron absorber and in phosphate fertilizers and various pesticides. Lead is a toxic metal which causes subtle neurological impairment in humans [Gloag, 1981]. The sources of lead in water are primarily due to marine paints, pipelines, mining rejects, petroleum products and industries utilising lead or discharging lead containing effluents. Copper is regarded as one of the earliest known toxic metals and is deleterious for health because of its non-biodegradability, biological magnification and long persistent in the environment [Shrivastava, 2009]. The main sources of copper in the environment are from alloy making industries, plumbing systems, electronic industries and ceramics and pesticide manufacturing units. Mercury is among the first elements discovered and utilized by humans, and its relationship with human society has been a topic of conundrum, controversy, and catastrophe over the past at least 2000 years [Wang and Zhang, 2013]. It is a non-essential element, and is not required by any known essential biochemical functions of any life form. The main sources of mercury are cement production, municipal and medical waste incineration, coal combustion, leaching from landfills and Chlor-alkali plants.

2.2.3.1. Dissolved Cadmium, Lead and Copper

Sample collection, filtration, treatment and analysis for dissolved metals were carried out according to protocols established for ultra-trace metal analysis. Pre-concentration of the metals was achieved by chelation with ammonium pyrrolidine dithiocarbamate (APDC) at an optimum pH < 2 followed by extraction of the metal chelates into methyl isobutyl ketone (MIBK). The organic extract was back extracted into the inorganic form using ultra pure acid. The final extract was made up to suitable volume and analysed on graphite furnace Atomic Absorption Spectrometer (AAS), calibrated with spiked standards and blanks extracted in a similar manner at wavelengths recommended for each metal.

2.2.3.2. Cadmium, Lead and Copper in sediment samples

Dried sediment samples were digested with hydrofluoric acid / nitric acid / perchloric acid.

The residue after evaporation dissolved in diluted HCl and metal concentration determined by AAS.

2.2.3.3. Total mercury in water

Sea water samples for Hg were collected in acid washed glass bottles, and acidified to a pH below 2. Pre concentration of Hg was carried out by complexing with dithizone and the complex was extracted into carbon tetra chloride and back extracted into 5M HCl. The acid extract was shaken with sodium nitrite to decompose the dithizone and revert Hg to the aqueous phase. Inorganic forms of the metal in the final solution were reduced to the elemental form and measured by cold vapor AAS.

2.2.3.4. Total mercury in sediment samples

Sediment samples were oven dried at 40°C and crushed to fine powder. Sediments were digested with Aqua Regia / potassium permanganate ($KMnO_4$) in a water bath for 30 min. On cooling, the excess $KMnO_4$ was reduced by sodium chloride – hydroxylamine reagent and made upto a known volume. Blanks and standards were treated in a similar manner. Mercury compounds in the final solution were reduced to the elemental form and measured by cold vapour AAS at the indicated wavelength 253.7 nm. 1000 ppm $HgCl_2$ was used as stock; subsequent dilutions were made by spiking. MESS-3 was used as reference material from NRC Canada.

2.2.4. Oil Compounds

2.2.4.1. Petroleum Hydrocarbons (PHc)

Dissolved / dispersed petroleum hydrocarbons were extracted from seawater with double distilled hexane and quantified by using Shimadzu RF-5301PC fluorescence spectrophotometer with excitation at 310 nm and emission at 360 nm [Ehrhardt and Burns, 1993]. The model is RF-5301. The high-throughput optical system in RF-5301PC employs a blazed holographic grating, photomultiplier and digital circuit to provide the highest level S/N ratio attainable. The band pass on the RF-5301 can be set as narrow as 1.5 nm, and the

the accuracy is ± 1.5 nm. Reference material used for quantifying hydrocarbons was the Bombay High Crude Oil.

2.2.4.2. Phenols

Phenols [Grasshoff et al., 1983] in a known quantity of water sample (500 ml) were converted to organic coloured antipyrene complex by adding 4-amino-antipyrene. The complex was extracted in 25 ml chloroform and its absorbance was measured at 460 nm using phenol as a standard (US-EPA Method # 9065).

2.2.4.3. Petroleum hydrocarbons

Hydrocarbons [Grasshoff et al., 1983] in the sediment samples were extracted with triple distilled n-Hexane and the concentration of the PHc was determined by spectrofluorometry with excitation at 310 nm and an emission at 360 nm.

2.2.5. Analysis of biological parameters

2.2.5.1. Primary productivity

Water samples were collected from the surface region using 300 ml polycarbonate bottles (Nalgene, Germany) as per the JGOFS protocols. One ampoule of $NaH^{14}CO_3$ (Board of Radiation and Isotope Technology, Mumbai; Specific activity 185 kBq) was added to each 300 ml bottle (two light and one dark bottle) and incubated in a tub containing seawater for a period of 12 hrs. Fresh seawater was added to maintain ambient temperature. Samples were filtered through GF/F filters (47 mm diameter, 0.7 µm pore size, Whatman, USA) and the filter papers were exposed to concentrated HCl fumes to drive off any inorganic ^{14}C adhering to samples. 10 ml liquid scintillation cocktail (Spectrochem Pvt Ltd, Mumbai) was added to each vial and the radioactivity was measured by scintillation counter (Wallac 1409DSA, Perkin Elmer, USA). PP rate was expressed as $mgC/m^3/day$ [UNESCO, 1974].

2.2.5.2. Chlorophyll *a*

For the estimation of chlorophyll *a*, 500 ml of water sample was filtered through GF/F glass fibre filter paper and extracted in 90% acetone overnight. The extracts were used for the estimation of fluorescence before and after acidification using Turner Designs Fluorometer. The fluorescence values were converted to chlorophyll *a* and phaeophytin using appropriate calibration factor. All the analysis was carried out as per procedure described in Parsons et al. [1984].

2.2.5.3. Phytoplankton

Surface and bottom water samples were collected using a 5 L Niskin sampler. For phytoplankton counts, 250 ml of water was transferred to a plastic bottle and was preserved in Lugol's Iodine and formalin solution. The Phytoplankton was enumerated and identified using an inverted microscope by transferring 1 ml cell concentrates into Sedgewick Rafter counting chamber [UNESCO, 1974].

2.2.5.4. Zooplankton

Zooplankton samples were collected by surface tow for 5-10 minutes using a Heron-Tranter net of 200 micron mesh size having a mouth area of 0.25 m^2. The volume of the water filtered through the net was recorded from the calibrated flowmeter attached to the net during the tow. The samples thus collected from the net, were fixed and preserved in 10 % formaldehyde solution. The zooplankton biomass was estimated by displacement volume method [Madhupratap et al., 1996]. Values were converted to 100 m^3. The concentrated samples were diluted to an aliquot of 6.25 % using a Folson plankton splitter and then were examined under the stereoscopic binocular microscope for numerical counts and group identification.

2.2.5.5. Microbiology

Water samples for microbiological analyses [APHA, 1992] were collected from surface and bottom to represent the water column at each sampling location. Small portions of the sediment samples obtained by Van-Veen grab were removed aseptically for microbiological analysis. Immediately after collection, all samples were stored in iceboxes. They were transported to an adequately clean room (field laboratory) for microbiological analysis. Samples were kept in ice until they were processed for enumeration of various groups of bacteria.

To find out the abundance of general heterotrophic and indicator bacteria, the following microbial populations were enumerated. Bacteriological media used for enumerating the group(s) is mentioned against respective group:

Total viable (culturable) aerobic bacteria (TVC) – Seawater Nutrient agar
Total coliforms (TC) – McConkey agar
Total vibrios (VLO) – Thiosulphate citrate bile salts sucrose agar

All the media used were from Hi-Media (Mumbai) and prepared as per manufacturer's protocol. Spread plating technique was followed for enumerating all the microbial groups listed above. One milliliter of water or one gram of sediment sample was serially diluted using 0.8% sterile saline to 10^{-2} to 10^{-4}. Sample (100 µl) was surface plated using micropipette in replicates in appropriate media - Nutrient agar (M001) for total viable counts (TVC), MacConkey agar (M081) for total coliforms (TC) and M-FC Agar base (M1122) for total faecal coliforms (TFC). All plates were incubated at 28°C for 48 to 72 hrs and final counts of colony forming units (CFU) on all the media were counted and average counts were determined.

2.3. Other data sets

Population data from the 2011 Indian national census is used for the present study (for Mumbai region). In addition to this, the Mumbai population data from Taubenböck et al. [2009] was used to project annual population growth per year and percentage growth for the years 2020, 2050 and 2100. Megacity population (past and projected) data was taken from the United Nations, Department of Economic and Social Affairs, Population Division [UNDESA, 2012]. BOD data from sewage treatment plant (STP) generated load from Maharashtra Pollution Control Board is also used to find the waste water load. High resolution coastal Sea Surface Temperature (SST) data from Lima and Wethey [2012] and the World Ocean Atlas (WOA, 2009) [Garcia et al., 2010] data was used for understanding the annual climatological distribution of surface oxygen in the global ocean.

The long term water quality data is used to setup modelling networks off Mumbai and Gulf of Khambhat. Mandovi region is studied using primary and secondary data. The primary and secondary hydrography as well as water quality data available from IODC, CSIR-NIO were (from 1980s) used to set up modelling networks (Table 2.6) for the Mumbai and GoK coastal regions. The calibrated model was validated with field data available during the model simulation period. The output from MIKE model (section 2.4.1) was given as hydrodynamic input for water quality modelling off Mumbai. The water quality model for GoK was driven by the measured current data. The field data collected off Mumbai, Mandovi estuary and GoK was utilised to evaluate the Trophic State Index (TSI) and Water Quality Index (WQI). Factor analysis was performed using the software program STATISTICA to evaluate the water quality status of the Mandovi estuary and GoK and also to identify the dominant variables. Temporal DO data (4 hourly data starting from 29 October (0800 h) to 30 October (0800 h)) for Mahim region was specifically collected to understand the effect of effluents from the Mumbai city on the coastal water quality.

2.4. Models used in the study

2.4.1. MIKE hydrodynamic model

MIKE21 HD is a hydrodynamic model developed by Danish Hydraulic Institute, Water & Environment [DHI, 2008]. The model uses equations of conservation of mass and momentum, integrated over the vertical to describe the flow and water level variations. MIKE21 has been regularly used as a tool to model hydrodynamic problems of various complexities [George et al., 2009]. The model has been used earlier to study the circulation characteristics off Mumbai during an extreme weather event [Kumar et al., 2012], modelling the tide driven currents and eddies [Babu et al., 2005] and to estimate residence time of pollutants in the Gulf of Kachchh [Patgaonkar et al., 2012] along the west coast of India.

2.4.2. WASP water quality model

The Water Quality Analysis and Simulation Program (WASP) model [Ambrose, 1987; James and Bierman, 1995; Wool et al., 2001; US EPA, 2006] is a validated water quality model, the development of which was supported by United States Environmental Protection Agency (US-EPA). WASP has been utilized in addressing major water quality problems around the globe [Nikolaidis et al., 1996; Wang et al., 1999; Tufford et al., 1999; Burian et al., 2002; Peng et al., 2010; Romeiro et al., 2011; Boutilier et al., 2011].

After many versions [Di Toro et al., 1983; Connolly et al., 1984; Ambrose et al., 1988; Ambrose et al., 1993; Wool et al., 2003], the latest enhanced version of the model WASP 7 has come into practice; it includes kinetic algorithms for eutrophication, conventional pollutants, organics, chemicals/metals, mercury, temperature, fecal coliform and conservative pollutants. The model helps users in interpreting and predicting water quality responses to natural phenomena and man-made pollution of fresh water and marine environments. WASP 7 is a dynamic compartment modelling program and can be one, two or three dimensional depending on the complexity of the intended use. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model [Cerucci et al., 2007]. The WASP model follows the box modelling approach. The boxes can be fitted to any morphometry. The two kinetic sub-models simulate two of the major classes of water quality problems: (i) conventional pollution which involves dissolved oxygen, biochemical oxygen demand, nutrients, eutrophication and (ii) toxic pollution which involves organic chemicals, metals and sediment [Carroll et al., 2000].

The basic principle of the water-quality model is the conservation of mass. The water volume and water-quality constituent masses being studied are tracked and accounted for over time and space using a series of mass balancing equations [Lung, 2001]. To perform these mass balance computations, seven important characteristics that define the data should be given as input to the WASP model, namely, i) simulation and output control, ii) model segmentation, iii) advective and dispersive transport, iv) boundary concentrations, v) point and diffuse source waste loads, vi) kinetic parameters, constants, and time functions and vii) initial concentrations [Doytsher et al., 2010]. The input data, together with the general mass balance equations and the specific chemical kinetics equations, uniquely define a special set of water quality equations and are numerically integrated by WASP as the simulation proceeds in time. At user-specified print intervals, the model saves the values of all display variables for subsequent retrieval by the post-processor program. These programs allow the user to interactively produce graphs and tables of variables of all display variables [US EPA, 2006]. The WASP modelling frame work is found to be suitable for DO/BOD applications and WAC studies [Lung, 2001]. The present study used eutrophication module of the WASP model.

2.4.3. Model calibration

Model calibration to observed data is needed to provide plausible model predictions. WAC studies for planning and remedial actions rely on these types of predictions. The modified Streeter-Phelps equations in the WASP model divide BOD into carbonaceous and nitrogenous fractions, and allow time-variable temperatures to be specified. This allows for more realistic calibration to observed data. During calibration, the user can select "constant" or "bypass" for any selected variables. Model calibration is the first stage testing or tuning of the model to a set of field data not used in the original construction of the model [Nair, 2002]. Such tuning is to include consistent and rational set of theoretically defensible parameters and inputs [Thomann, 1982; Himesh et al., 2000].

Calibration process is based on field measurements that help in choosing the empirical coefficients in water quality models and also in the verification of the consistency of the model's initial and boundary conditions with that of the in-stream measurements. Calibration of the hydrodynamic part of the model was first carried out by comparing simulated hydrodynamic variables (depth and velocity) with the measured ones. Next, the calibration of the process compartment of the model was carried out sequentially by using transformation kinetic parameters. The order of calibration is: temperature, BOD, DO and related parameters. During calibration of water quality process, estimated parameters are fixed, few parameters are extracted from literature and the remaining parameters are obtained by tuning them till the observed and predicted results closely matched [Himesh et al., 2000].

2.4.4. Model validation

It is the testing of the calibrated model against the additional set of field data preferably under different environmental conditions (river flow, waste load, etc.) further examines the range of validity of the calibrated model. Validation data is to be collected in such a way that they are fully independent of the calibration data. The model so verified can be used for forecasting water quality under a variety of perturbed environmental conditions. It is nothing but the subsequent examination and verification of the model's predictive ability following the implementation of environmental control program [Himesh et al., 2000].

2.4.5. Model Evaluation

A wide variety of model evaluation techniques are used in order to check the model reliability. The model evaluation statistics (sections a - d) are selected based on the following factors: (i) robustness in terms of applicability to various constituents, models and climatic conditions, (ii) commonly used, accepted and recommended in published literature and (iii) identified strengths in model evaluation [Moriasi et al., 2007].

a. Pearson's correlation coefficient (r) and coefficient of determination (R^2):

Pearson's correlation coefficient (r) and coefficient of determination (R^2) describe the degree of collinearity between simulated and measured data. The correlation coefficient, which ranges from −1 to 1, is an index of the degree of linear relationship between observed and simulated data. If $r = 0$, no linear relationship exists. If $r = 1$ or -1, a perfect positive or negative linear relationship exists. Similarly, R^2 describes the proportion of the variance in measured data explained by the model. R^2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable [Santhi et al., 2001; Van Liew et al., 2007]. Although r and R^2 have been widely used for model evaluation, these statistics are oversensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data [Legates and McCabe, 1999].

b. Nash-Sutcliffe efficiency (NSE)

NSE is a normalized statistics that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") [Nash and Sutcliffe, 1970]. NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in the following equation:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(y_i^{obs} - y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(y_i^{obs} - y_i^{mean} \right)^2} \right]$$

Where, *Yi obs* is the *i*th observation for the constituent being evaluated, *Yi sim* is the *i*th simulated value for the constituent being evaluated, *Ymean* is the mean of observed data for the constituent being evaluated, and *n* is the total number of observations. NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE =1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance. Values <0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance.

c. Percent bias (PBIAS):

Percent bias (PBIAS) measures the average tendency of the simulated data, which is larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias [Gupta et al., 1999]. PBIAS is calculated using the following equation and is expressed as a percentage.

$$PBIAS = \left[\frac{\sum_{i=1}^{n} \left(y_i^{obs} - y_i^{sim} \right) \times (100)}{\sum_{i=1}^{n} \left(y_i^{obs} \right)} \right]$$

d. Root mean square error (RMSE)-observations standard deviation ratio (RSR):

RMSE is one of the commonly used error index statistics [Chu and Shirmohammadi, 2004; Singh et al., 2004; Vazquez-Amábile and Engel, 2005]. Although it is commonly accepted that the lower the RMSE the better the model performance, only Singh et al. [2004] have published a guideline to qualify what is considered “a low RMSE” based on the standard deviation of the observed data. RSR standardizes RMSE using the observations standard deviation, and it combines both an error index and the additional information recommended by Legates and McCabe, [1999]. RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor so that the resulting statistics and reported values can apply to various constituents. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. Lower the RSR and RMSE, better the model simulation performance. RSR is calculated as the ratio of the RMSE and standard deviation of measured data as shown in the following equation:

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(y_i^{obs} - y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(y_i^{obs} - y^{mean}\right)^2}\right]}$$

2.5. Factor Analysis

Factor analysis is one of the multivariate statistical approaches widely used for deriving the significance of specific parameters among the data. In this study, the Principal Component Analysis (PCA) was used for evaluating water quality status of Mandovi estuary during different seasons in order to identify the dominant variables. To generate the principal components (PCs), the R-mode (sorted) factor analysis was used, which resulted in eigen values, percentage of variance and cumulative percentage of the data set, allowing inter-parameter relation and the variation in water quality [Vega et al., 1998; Singh et al., 2004].

A varimax normalized different varifactors with factor loading was calculated using eigen values greater than 1 and sorted by the results having values greater than 0.4 based on significant influence. Rotation of the axis as defined by factor analyses produced a new set of factors, each one involving primarily a subset of the original variables with a little overlap as possible so that original variables could be divided into groups. The factor loadings were classified based on absolute loading values and were categorized corresponding to absolute loading values: > 0.75 as “strong”, 0.75-0.5 as “moderate” and of 0.50-0.40 as “weak” [Liu et al., 2003].

2.6. Water Quality Index (WQI)

Water quality is a multi-parameter attribute, influenced by large number of physical, chemical, biological and bacteriological factors. WQI is a mathematical tool, which transforms the bulk water quality data into a single digit, cumulatively derived numerical expression indicating the level of water quality. This can be used to infer the assimilative capacity by utilizing the observational data. For example, high WQI values indicate polluted waters because the polluted waters have low assimilative capacity. In the present study, for calculating WQI, the following nine parameters have been considered: DO, BOD, pH, temperature change, total phosphates, nitrates, turbidity, total solids and fecal coliform. All these parameters are selected as per the classification scheme of inland surface water in India for classification of the types of water, and the scheme is accepted by the Central Pollution Control Board (CPCB) for recommending suitability of water for specific use. Thus, for each water quality parameter, the WQI is first computed individually by using the equation obtained from the value function curve in which, the concentration of the parameter is taken on Y-axis and the index value on X-axis [Sargaonkar et al., 2003]. These measured values are then transformed into a single number called the Overall Index of Pollution (OIP) (Table 2.6), representing the overall quality of water at that particular location. The OIP values are estimated as the average of all the pollution indices (Pi) for individual water quality parameters considered in this study as per the mathematical expression $OIP = \Sigma_i Pi / n$, where Pi = pollution index for i^{th} parameter, where, i = 1, 2. . . n and n = number of parameters. The coastal water is then categorized as excellent, acceptable, slightly polluted, polluted and heavily polluted based on these OIP values. The WQI index in the present study is developed following Abbasi and Abbassi [2012].

OIP Values	**Type of water**
0 – 1	Excellent
1 – 2	Acceptable
2 - 4	Slightly polluted
4 - 8	Polluted
8 - 16	Heavily polluted

Table 2.7. Classification of water bodies based on OIP.

2.7. Trophic State Index (TSI)

Trophic State Index (TSI) is a classification system designed to "rate" individual water bodies based on the amount of biological productivity occurring in water [Montes et al., 2011]. The quantities of nitrogen, phosphorus and other biologically useful nutrients are the primary determinants of a water body's TSI. Nutrients such as nitrogen and phosphorus tend to be limiting resources in standing water bodies, so increased concentrations tend to result in increased plant growth, followed by corollary increase in subsequent levels. Although the term "trophic index" is commonly applied to lakes, any surface water body can be indexed. Carlson's index is one of the most commonly used trophic indices and is the trophic index used by the United States Environmental Protection Agency (USEPA). Using this index, one can gain a quick idea about how productive a water body is by its assigned TSI number. TSI classification ranges from 1 to 100. A water body is usually classified as one of the three possible classes: oligotrophic, mesotrophic or eutrophic. Water bodies with extreme trophic indices may also be considered hyperoligotrophic or hypereutrophic as shown in Table 2.7. Oligotrophic water bodies host very little or no aquatic vegetation and are relatively clear, while eutrophic water bodies tend to host large quantities of organisms. In mesotrophic water bodies, the water is moderately clear. When the productivity is high or very high (high trophic state), it reduces the available dissolved oxygen in the water column, as the available dissolved oxygen in the water column is utilized for the photosynthetic process. Thus, the high TSI indicates low assimilative capacity and low TSI indicates high assimilative capacity.

Chl(µg/L)	P(µg/L)	Secchi Depth (m)	Trophic Class	TSI
0—2.6	0—12	>8—4	Oligotrophic	<30—40
2.6—20	12—24	4—2	Mesotrophic	40—50
20—56	24—96	2—0.5	Eutrophic	50—70
56—155+	96—384+	0.5—<0.25	Hypereutrophic	70—100+

Table 2.8. Classification of water bodies based on TSI.

In general practice, the water bodies with TSI values from 30 - 45 are considered to have mid-range nutrients and reasonable productivity. Those with TSI values from 46 - 70 are considered to have good or sufficient nutrients and fairly high productivity. Water bodies with TSI values from 71 - 100 are considered to have over abundance of nutrients and are the most productive trophic class of water bodies.

Chapter 3
WAC assessment of an estuarine regime: Mandovi estuary, Goa

3.1. Major estuaries of Goa

Among the coastal water bodies, estuaries act as filters or exporters of both organic and inorganic material [Montes et al., 2011], and transport large quantities of natural and anthropogenic materials to the coastal water. The estuaries are peculiar ecosystems exhibiting mixed characteristics of both fresh and marine water and are the most productive ecosystems around the globe [Meire et al., 2005]. A large number of estuaries located along the coast of the Indian subcontinent are influenced by the Indian Summer Monsoon (ISM) and are therefore referred to as the ''monsoonal estuaries'' [Vijith et al., 2009]. In these monsoonal estuaries, the physical and chemical properties swing between pre-monsoon, monsoon and the post-monsoon seasons as per the run-off and river discharge from the catchment areas. The ecosystem and natural habitats associated with these estuaries routinely adjust to these seasonal changes [Shetye, 2011]. Furthermore, the influence of anthropogenic waste, land runoff and the riverine discharge in these estuaries affect the water quality and productivity. Mandovi and Zuari are the major estuaries of Goa.

The Mandovi River (Fig. 3.1) is about 50 km long and 5 m deep (average). It is connected to the other major river, the Zuari River through a canal, called the Cumburjua canal, forming the major estuarine system called the Mandovi - Zuari estuarine system, which acts as a lifeline of Goa [Desousa, 1999]. The Mandovi estuary is a tide dominated estuary and the tidal range is about 2.0 m [Manoj et al., 2009]. Tidal reversal and seasonal changes bring about large variations in the physico-chemical and biological properties of the estuary. The estuary has a large number of tributaries, which bring in freshwater from its catchment areas. Heavy precipitation during the monsoon season reduces the salinity, and brings about near freshwater conditions in the estuary. Consequently, the estuary remains stratified during the monsoon season with a salt wedge formed upto 10 km upstream [Qasim and Sen Gupta, 1981]. The physical, chemical and biological features of this estuary are determined by the annual cycle of the ISM. During the south west (SW) monsoon (July–September), the estuarine characteristics are predominantly freshwater in nature. The SW monsoon is followed by a recovery period during the post-monsoon season (October–January) and thereafter a stable pre-monsoon (February–May) - a hot and dry season when the estuary becomes marine dominated. During pre-monsoon, the estuary remains well mixed with an intrusion of salt water high up in the upstream as far as Ganjem, whereas, during the SW monsoon season, stratified conditions prevail with a salt wedge and the estuarine system can be classified as a tide-dominated coastal plain estuary [Qasim and Sen Gupta, 1981]. The rainfall during SW monsoon results in heavy run-off into the Arabian Sea. The volume of Mandovi (excluding the Aguada Bay) is about 70 million cubic meters and the volume of freshwater flowing through the Mandovi exceeds the volume of the estuary by a factor of about 20 if the Ganjem (gauging station located 50 km from the mouth of the Mandovi) runoff is used and 40 if the Panaji (the Mandovi drains into the Arabian Sea in the vicinity of Panaji) runoff is used [Shetye et al., 2007].

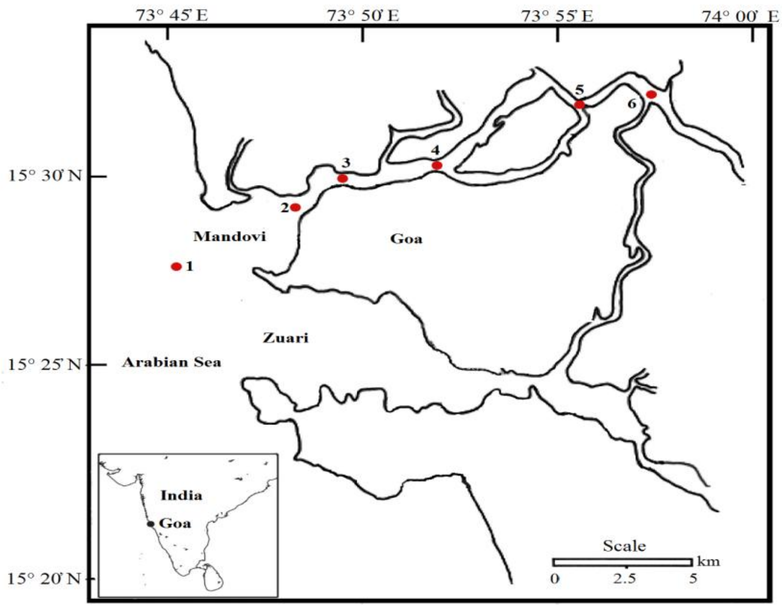


Fig. 3.1. Study area and station locations: Mandovi estuarine regime.

3.1.1. Mandovi estuary as a case study

The settlements along the estuary discharge raw waste (a common practice) including the septic waste directly into the estuary. The daily discharges of untreated sewage effluents are either deliberate or incidental at most of the locations along the estuary, which often exceed the seaward flow of effluents during the low tide [Rodrigues et al., 2011]. Though the treated sewage from Panaji city is discharged at a location 3.93 km upstream from the estuarine mouth, both the channel and the bay region receive untreated sewage as well [Maya et al., 2011]. The sewage treatment in the region was initialized in 1976, which had great difficulties in smooth functioning; hence, mostly sulfidic conditions prevailed throughout the sewage channel due to periodic stagnancy. Subsequently, a new technologically improvised system was installed in 2005 with a sewage treatment capacity of 12.5 million litres day^{-1} for handling 7-8 million litres only, in a region where intense monsoon activity can cause floods [Nanajkar and Ingole, 2010]. The raw sewage effluents (Table 3.1) (Public Works Department, Govt. of Goa) from Panaji city indicated strong effluent type as per the conventional classification of sewage types (strong [400 mg/L BOD], medium [250 mg/L BOD] and weak [110 mg/L BOD] classes of sewage). The seasonal variability in the Mandovi estuary coupled with the input of large contaminants from various anthropogenic sources can change the quality of the estuarine water due to the dominance of influencing contaminants, which in turn affects its productivity and assimilative capacity. The high land run-off during the SW monsoon contributes to large quantities of suspended matter-transport from land derived and the riverine organic derived material from the upstream region to the estuarine region.

Sl. No	Parameters	Raw Sewage			Treated Sewage		
		pre-monsoon	SW monsoon	post-monsoon	pre-monsoon	SW monsoon	post-monsoon
1	pH	6.8	6.8	6.9	7.1	7	7
2	Temperature (°C)	30	29	28.8	30	29	28.4
3	Total solids (mg/L)	1099.90	494.69	1118.35	951.93	326.88	716.49
4	Total dissolved solids(mg/L)	640.30	307.88	849.29	941.12	307.60	695.93
5	Suspended solids (mg/L)	876.65	186.94	269.16	21.04	17.25	20.45
6	Volatile solids (mg/L)	349.65	214.05	293.76	61.64	57.49	61.80
7	Chloride (mg/L)	265.54	60.18	305.90	383.70	67.90	263.04
8	BOD (mg/L)	384.76	197.38	279.93	5.13	2.65	4.09
9	COD (mg/L)	761.17	402.80	601.55	26.72	18.51	25.32
10	E.Coli count (MPN/100 ml)	33.17×10^6	568×10^6	149×10^6	49.13	19.29	43.65

Table 3.1. Water quality of untreated and treated sewage reaching Mandovi averaged during different seasons (source: Public Works Department, Govt. of Goa).

3.2. Dissolved Oxygen and freshwater volume in the estuary

In estuaries, the most important factors affecting the oxygen saturation are temperature, salinity and partial pressure variations due to elevation [Chapra, 2008]. The Mandovi meanders over the coastal plain and the elevation from the mouth to 50 km upstream is small

[Shetye, 2011], so the pressure effect on saturation can be neglected for this study. A FORTRAN program has been developed to compute the dissolved oxygen saturation and percentage of freshwater volume in the estuary over three seasons as given by Chapra [2008].

a. Temperature effect

The following equation [Chapra,2008] was used to establish the dependency of oxygen saturation on temperature.

$$\ln O_{sf} = -139.34411 + \frac{(1.575701\times10^{5})}{T_a} - \frac{(6.642308\times10^{7})}{T_a^{\ 2}} + \frac{(1.243800\times10^{10})}{T_a^{\ 3}} - \frac{(8.621949\times10^{11})}{T_a^{\ 4}} \qquad (1)$$

where,

O_{sf} = saturation concentration of DO in freshwater at 1atm (mg L^{-1})

$T_a = T + 273.5$

T_a = absolute temperature (K)

T = water temperature in °C

b. Salinity effect

The following equation [Chapra, 2008] was used to establish the dependency of oxygen saturation on salinity.

$$\ln O_{ss} = \ln O_{sf} - S\left\{1.7674\times10^{-2} - \frac{\left(1.0754\times10^{1}\right)}{T_a} + \frac{\left(2.1407\times10^{3}\right)}{T_a^{\ 2}}\right\} \qquad (2)$$

where,

O_{ss} = saturation concentration of DO in seawater at 1 atm (mg L^{-1})

S = salinity (g L^{-1} =practical salinity unit)

c. Salt water saturation value

The following equation [Chapra, 2008] was used to calculate salt water saturation value.

$$SS = e^{(O_{SS})} \qquad (3)$$

where,

SS = salt water saturation value

d. Percentage of freshwater

The following equation [Chapra, 2008] was used to calculate percentage of freshwater.

$$PF_w = \left\{ \frac{SS}{e^{(O_{sf})}} \right\} \times 100 \qquad (4)$$

where,

PF_W = Percentage of freshwater

The assimilative capacity of a water body primarily depends upon the DO concentration. Since DO is utilized for the oxidization of the organic matter in water, it is taken an indicator of the health of a water body. Thus, the high DO concentration in the water column indicates higher assimilative capacity of a water body. The observed surface DO values at various stations in the Mandovi estuary were compared with the calculated oxygen saturation values to get the general status of oxygen utilization in the estuary. The observed DO and calculated oxygen saturation values during the high tide, irrespective of seasons, are shown in Fig. 3.2. It is noticed that during the pre-monsoon season (low tide), the observed DO values in the mid estuary are lower compared to the calculated oxygen saturation values. This is due to high BOD content as compared to other regions of the estuary. Similarly, the observed DO and calculated DO saturation values show much difference in the upstream stations during the low tide of monsoon season. This is also attributed to relatively high BOD values encountered at these stations (around 3 mg/L) as compared to very low values (as low as 0.35 mg/L) at the remaining stations. The samples for BOD were collected at surface and bottom. The vertical profile is obtained by interpolation of surface and bottom values. During the post monsoon period, the observed and calculated DO values do not show much difference. The BOD values (Fig. 3.3) are typically low as compared to the pre-monsoon period. The apparent oxygen utilisation in the estuary over the three seasons indicates that the assimilative capacity is comparatively good throughout the estuary.

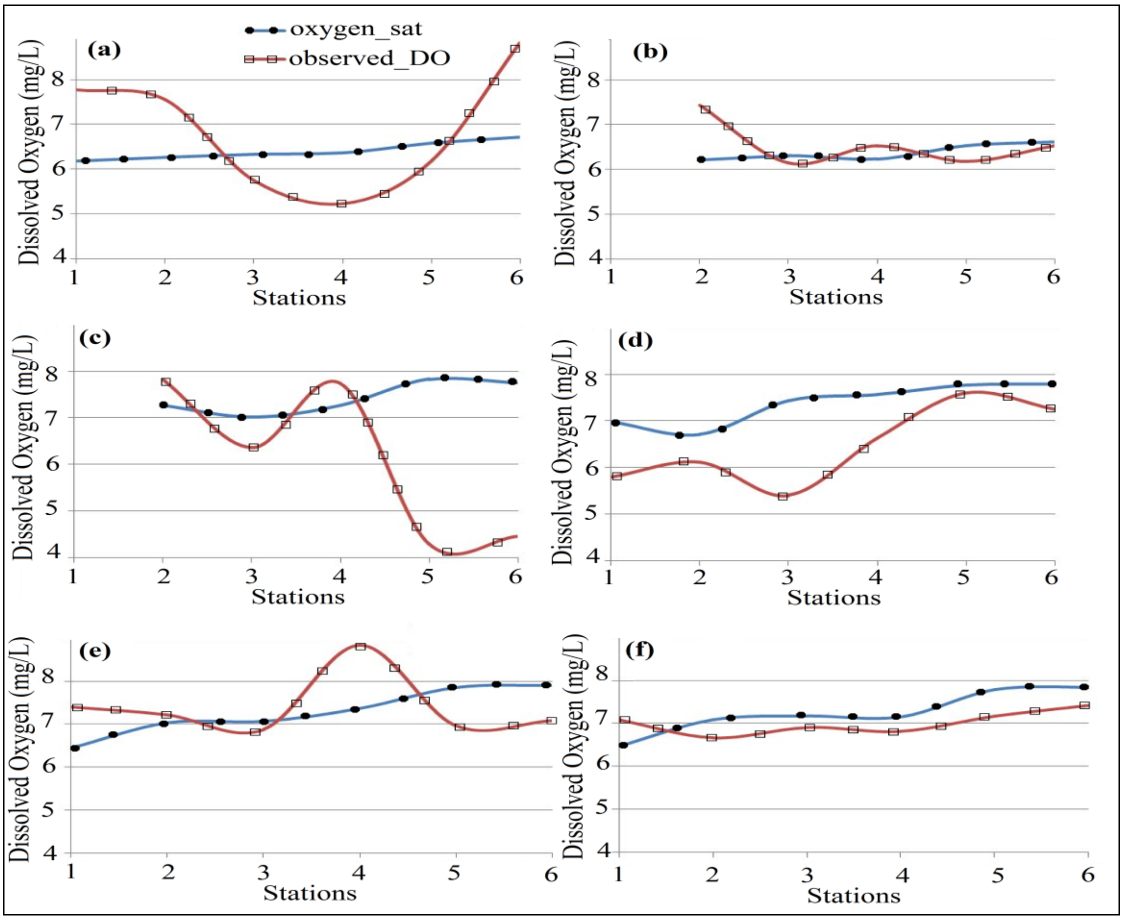


Fig. 3.2. Calculated oxygen saturation and observed DO values: a) pre-monsoon-low tide, b) pre-monsoon-high tide, c) SW monsoon-low tide, d) SW monsoon-high tide, e) post-monsoon-low tide and f) post-monsoon- high tide.

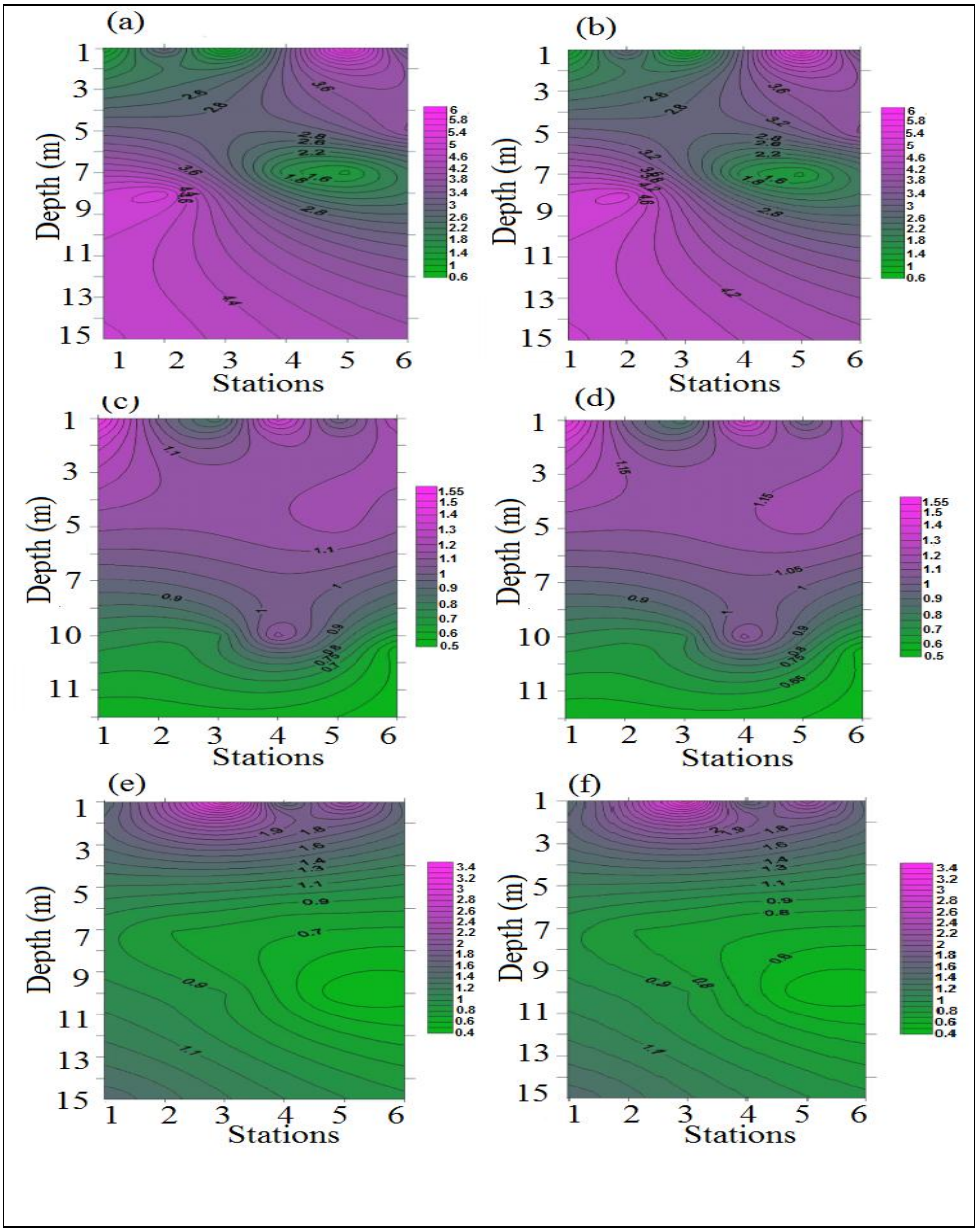


Fig. 3.3. BOD during three seasons: a) pre-monsoon low tide, b) pre-monsoon high tide, c) SW monsoon low tide d) SW monsoon high tide e) post-monsoon low tide and f) post-monsoon high tide.

The freshwater runoff is high in the estuary during the monsoon season**,** providing an additional advantage in diluting and flushing the contaminants out of the estuary and largely helping to maintain a good and acceptable quality of water in the estuary during the monsoon season and thus providing good assimilative capacity. The percentage of freshwater influx to the estuary was calculated at each station, and it was found to follow the river discharge pattern (Fig. 3.4 a and b). Fig. 3.5 presents the typical discharge pattern of the Mandovi estuary. The maximum volume of freshwater in the estuary is found during the SW monsoon season and it is slightly high during the low tide (av.96.0%) as compared to the high tide (av.94.7%). Following the SW monsoon, the next higher volume is observed during the post-monsoon season and it is nearly similar during low tide and high tide (av. 93.0%). The lowest volume, however, is observed in the pre-monsoon season, which is 87.7% during high tide and 86.2% during the low tide. The maximum volume during the SW monsoon season is due to rainfall and land drainage, which brings in large amount of freshwater from its catchment areas through the tributaries, and the estuary becomes freshwater dominated. Similarly, the lowest volume during the pre-monsoon season is due to reduced freshwater flow to the estuary when the estuary becomes nearly marine dominated. The high seasonal run-off flushes the estuary on a regular basis, thereby getting rid of land generated pollutants. This also increases the general assimilative capacity of the estuarine environment.

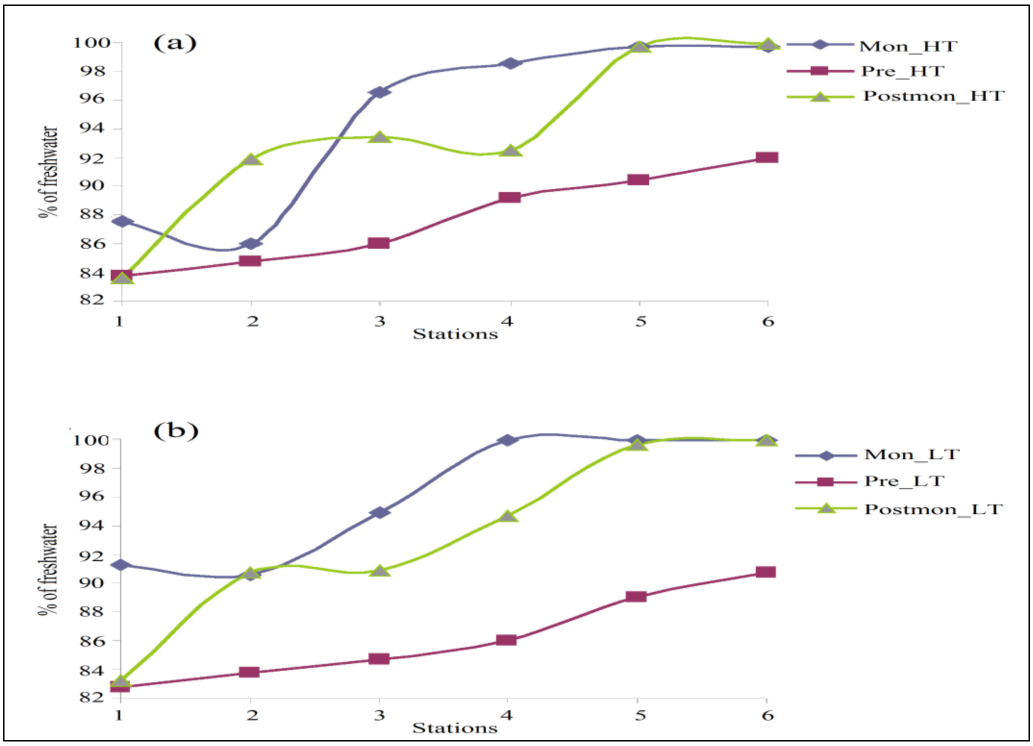


Fig. 3.4. Percentage of freshwater volume during SW monsoon (Mon), pre-monsoon (Pre) and post-monsoon (Postmon) seasons during: (a) high tide and (b) low tide.

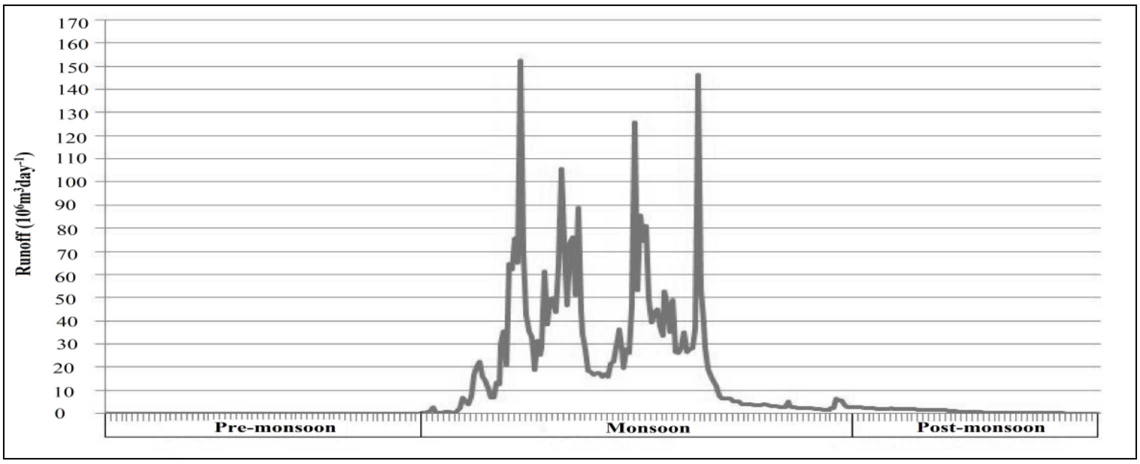


Fig 3.5. Typical discharge pattern over different seasons in Mandovi estuary (Source: Central Water Commission).

3.3. Factor analysis of water quality

3.3.1. SW monsoon season

The dominant parameters affecting the water quality over different seasons can be deciphered using factor analysis. This will help in understanding the contaminants, which influence the water quality and assimilative capacity of the estuary. The factor analysis showed that during the SW monsoon season (Table 3.2), fluoride (0.94) and nutrients such as NO_2-N (0.93), PO_4-P (0.82) and NH_3-N (0.78) along with TSS (0.82) and TVC (0.81) are strongly loaded in factor 1, indicating their dominance in the estuary. This is followed by moderate loadings of turbidity (0.68), TP (0.61) and SO_4- (0.57).

3.3.2. Post-monsoon season

During the post-monsoon, the factor analysis (Table 3.3) showed strong positive loadings of fluoride (0.84) and SO_{4-} (0.76) and moderate loading of TVC (0.57) in factor 1, indicating their dominance in the water. This is followed by strong positive loadings of urea (0.82) and TN (0.78) in factor 2. Thus, during post-monsoon season, the assimilative capacity of the estuary can be affected by fluoride, SO_{4-}, urea, TVC and TN. The WQI and TSI indicate a fairly good assimilative capacity of the estuary.

3.3.3. Pre-monsoon season

During the pre-monsoon season, the factor analysis (Table 3.4) showed strong positive loadings of salinity (0.94), total hardness (0.90), Ca-hardness (0.96), Mg-hardness (0.88) and SO_4— (0.92), with negative loadings of nutrients and moderate positive loading of fluoride (0.69) in factor 1, indicating their impact on water quality. This is followed by moderate positive loading of phenol (0.52) in factor 2 and of PO_4-P (0.51), NO_2-N (0.53) and silicate (0.58) in factor 3, respectively. The assimilative capacity during this season can be affected by increasing salinity, hardness (Ca, Mg & SO_4) and fluoride. Though there are few high values at some stations, the general trend of WQI and TSI throughout the estuary indicates good to fairly good assimilative capacity.

Parameters	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Temp	-0.499	0.319	-0.235	-0.005	-0.274
pH	-0.155	-0.069	0.218	**-0.804**	-0.025
DO	**-0.798**	-0.096	0.026	-0.080	-0.094
BOD	-0.392	-0.157	-0.203	**0.558**	0.026
Salinity	**0.741**	-0.081	0.362	0.399	0.213
SS	**0.823**	0.059	-0.161	-0.276	-0.326
Turbidity	**0.680**	**0.409**	-0.285	-0.106	-0.397
PO_4	**0.820**	**-0.422**	0.054	-0.095	-0.126
NO_2	**0.935**	-0.163	0.052	0.074	-0.010
NO_3	**-0.625**	0.244	-0.216	-0.325	**0.430**
NH_3	**0.780**	-0.044	0.188	0.314	-0.361
Si	-0.197	-0.154	0.060	-0.050	**-0.861**
Urea	-0.135	**0.680**	-0.088	-0.353	0.322
TP	**0.606**	-0.363	-0.166	-0.350	0.017
TN	-0.104	-0.117	**-0.609**	0.102	0.171

PHc	-0.190	-0.059	-0.100	-0.318	0.007
Phenol	-0.122	0.183	**-0.761**	0.055	0.043
Chla	-0.075	0.199	**0.708**	0.009	0.150
TH	**0.939**	0.124	0.063	0.180	0.142
Ca Hardness	**0.922**	0.131	0.073	0.211	0.182
Mg Hardness	**0.940**	0.123	0.062	0.176	0.137
F	**0.944**	0.172	0.033	0.133	0.165
SO_4	**0.573**	**0.421**	0.070	**0.518**	0.057
TVC	**0.808**	0.246	0.188	-0.101	-0.332
TC	**0.395**	**0.779**	0.166	0.224	0.053
FC	-0.035	**0.566**	**0.454**	0.187	-0.034
Expl.Var	10.436	2.536	2.259	2.284	1.841
Prp.Totl	0.401	0.098	0.087	0.088	0.071
	Eigen value	**% Total variance**	**Cumulative Eigen value**	**Cumulative %**	
1	10.79	41.48	10.79	41.48	
2	2.82	10.83	13.60	52.31	
3	2.10	8.06	15.70	60.37	
4	2.00	7.70	17.70	68.07	
5	1.66	6.37	19.36	74.45	

Table 3.2. Factor analysis of the data during the SW monsoon season in Mandovi estuary.

Parameters	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Temp	0.098	0.184	-0.247	0.206	**0.766**
pH	**0.592**	-0.291	0.149	-0.352	0.370
DO	-0.427	-0.138	**-0.778**	0.061	-0.149
BOD	0.166	0.210	**-0.779**	0.150	0.092
Salinity	**0.874**	0.172	0.135	0.121	0.292
SS	**-0.528**	0.072	0.369	-0.613	0.125
Turbidity	-0.046	-0.627	0.404	0.139	-0.017
PO_4	0.214	0.295	0.495	0.438	0.075
NO_2	0.382	**0.567**	0.103	-0.037	0.386
NO_3	**-0.719**	-0.025	0.394	-0.201	-0.273
NH_3	0.154	0.070	0.332	0.050	**0.690**
Si	**-0.807**	0.124	-0.047	0.071	0.167
Urea	-0.154	**0.816**	-0.047	-0.138	0.211
TP	0.377	0.315	0.027	0.675	-0.139
TN	-0.096	**0.783**	0.315	0.143	0.105
PHc	-0.127	0.189	0.004	**-0.715**	-0.498
Phenol	0.334	0.098	0.032	-0.052	**0.730**
Chla	0.190	0.227	0.048	**-0.760**	0.057
TH	**0.939**	0.062	0.176	0.126	0.110
Ca Hardness	**0.910**	-0.041	0.171	0.036	0.100
MgHardness	**0.896**	0.044	0.288	0.063	0.142
F	**0.845**	-0.035	0.054	0.030	0.238
SO_4	**0.764**	0.044	0.141	-0.029	0.402
TVC	**0.570**	0.046	-0.137	0.180	0.096
TC	0.067	0.118	0.036	-0.100	**0.505**

FC	0.387	0.092	**0.594**	-0.015	0.149
Expl.Var	7.630	2.549	2.781	2.496	2.996
Prp.Totl	0.293	0.098	0.107	0.096	0.115

	Eigen value	**% Total variance**	**Cumulative Eigen value**	**Cumulative %**
1	8.84	34.00	8.84	34.00
2	3.00	11.55	11.84	45.55
3	2.80	10.77	14.64	56.33
4	2.06	7.92	16.70	64.25
5	1.75	6.72	18.45	70.97

Table 3.3. Factor analysis of the data during the post-monsoon season in Mandovi estuary.

Parameters	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**
Temp	**-0.63**	-0.13	-0.15	-0.16	-0.37
pH	**0.73**	0.04	0.23	0.11	0.00
DO	-0.09	**-0.65**	-0.13	-0.09	-0.02
BOD	0.07	-0.07	0.04	**0.77**	0.10
Salinity	**0.94**	-0.01	-0.08	0.02	0.26
SS	-0.05	**0.70**	-0.10	-0.24	0.16
Turbidity	0.28	-0.24	0.23	**-0.41**	0.07
PO_4	0.00	0.04	-0.17	**0.51**	**0.68**
NO_2	**-0.70**	-0.06	0.12	**0.53**	0.01
NO_3	**-0.48**	0.01	-0.05	-0.04	**-0.78**
NH_3	**-0.53**	0.14	-0.35	**-0.53**	0.05
Si	**-0.63**	-0.12	0.15	**0.58**	0.17
Urea	-0.04	**-0.50**	0.35	0.11	0.38
TP	0.26	-0.37	-0.36	0.15	0.13

TN	-0.10	0.38	0.03	0.05	**-0.56**
PHc	-0.31	**0.49**	**-0.45**	-0.22	**0.41**
Phenol	0.33	**0.52**	0.02	0.12	-0.24
Chla	0.15	**0.46**	0.05	0.03	-0.11
TH	**0.90**	0.09	-0.04	-0.08	0.08
Ca Hardness	**0.96**	-0.02	-0.12	0.01	0.07
Mg Hardness	**0.88**	0.09	-0.04	-0.08	0.08
F	**0.69**	0.35	0.08	-0.10	-0.24
SO_4	**0.92**	-0.06	0.06	0.05	0.03
TVC	**-0.48**	-0.30	**0.47**	-0.32	0.35
TC	0.02	0.07	**0.89**	0.29	0.09
FC	0.06	0.08	**0.85**	-0.14	-0.11
Expl.Var	7.67	2.53	2.57	2.34	2.29
Prp.Totl	0.30	0.10	0.10	0.09	0.09

	Eigen value	**Total Variance %**	**Cumulative Eigen value**	**Cumulative %**
1	7.77	29.89	7.77	29.89
2	3.31	12.74	11.08	42.63
3	2.51	9.67	13.60	52.30
4	2.14	8.22	15.74	60.52
5	1.67	6.43	17.41	66.95

Table 3.4. Factor analysis of the data during the pre-monsoon season in Mandovi estuary.

3.4. WQI and TSI

The primary data (Total Phosphate (μmol/L), Total Nitrogen(μmol/L)) of TSI is converted to units used for TSI calculation. For TSI calculation, unit used for Total Phosphate is μg/L and unit used for Total Nitrogen is mg/L. This is the reason for expressing the same parameters in different units in Tables 3.6, 3.8 and 3.10.

3.4.1. SW monsoon season

To understand the effect of dominant parameters on the quality of water in the estuary during the SW monsoon season, the WQI was used; wherein the variation in WQI values depends upon the extent of parameter loadings. At station M1, data could not be collected during high tide as the sea was rough. Hence, WQI of adjacent station was considered for that station. Also, WQI is an average value for the entire estuary, having a range of values. The variation in WQI values was found to be very minimum when all the station data were considered. The calculated WQI values were then converted to OIP which showed a variation from 2.04 to 3.32 in the bottom water layers of the first 3 stations from mouth to near mouth stations in the estuary (M1 to M3) relative to surface. The average OIP values of surface and bottom water layers at these 3 stations (M1 to M3) show a variation from 1.91 to 2.46, suggesting that water at M2 remains slightly polluted (Table 3.5). During low tide of the SW monsoon season, the OIP values at the surface layer range from 1.36 to 2.25 whereas at the bottom water layer it ranges from 1.69 to 2.48. The higher value of 2.25 is observed at the surface layer at M3, and this value is above the OIP value of 2 and therefore suggested slightly polluted condition of water at this station. All the other stations show acceptable quality of water with OIP values remaining below 2. Mandovi is a monsoonal estuary and during SW monsoon the entire estuary is filled with freshwater especially during low tide. The dilution effect of freshwater causes similar OIP values in the entire water column during low tide, as the influence of saline water is less. The effect of changes in water quality on productivity potential of the estuary was evaluated using TSI. The TSI values calculated for each water sample at these 6 stations in Mandovi estuary during the monsoon season indicated a variation from 32.94 to 56.57, with higher values at stations M1 to M3 (mouth to near mouth). However, the average TSI value calculated for all the 6 stations is 46.95 (Table 3.6), suggesting a mesotrophic condition of the estuary during the SW monsoon season.

3.4.2. Post-monsoon season

The impact of dominant parameters on water quality evaluated by calculating the WQI values showed OIP values ranging from 1.02 to 1.46 in surface water and from 1.16 to 1.87

in the bottom water (Table 3.7) during the low tide of post-monsoon. All these values are found to be much below the OIP value of 2, and thereby indicated good and acceptable quality of water during the post-monsoon season. Similarly, during the high tide, the OIP values vary from 1.01 to 1.83 at the surface and from 1.17 to 2.33 at the bottom. Table 3.7 shows that except an OIP value of 2.33 observed at the bottom water layer at station M3, all the other OIP values are well below 2. This indicated acceptable quality of water at all the other stations in the estuary during the post-monsoon season. The higher value of 2.33 observed in the bottom layer at M3 could be due to re-suspension of sediment due to disturbance. The TSI values calculated for the water samples collected at 6 stations in the estuary during the post-monsoon season indicated a variation of 29.47 to 44.47, with no fixed trend of higher values. However, the overall TSI value calculated for all the stations shows a value of 42.43 (Table 3.8), which is much lower than the one observed during the monsoon season, also suggesting a mesotrophic condition of the estuary during the post-monsoon season. This suggested the input of low nutrients to the estuary during the post-monsoon season relative to the monsoon season.

3.4.3. Pre-monsoon season

The impact of dominant parameters on water quality of the estuary, evaluated by calculating the WQI values, showed OIP values ranging from 2.01 to 2.69 at the surface water layer and from 2.04 to 2.48 at the bottom water layer (Table 3.9) during the low tide. All these values are found to be higher and remain above 2, indicating slightly polluted water all over the estuary during the low tide of pre-monsoon season. Similarly, during the high tide, the OIP values varied from 1.82 to 2.63 in the surface water layer and from 1.91 to 2.82 in the bottom water layer. This showed that except for one last station M6 towards upstream showing low OIP values of 1.82 to 1.91, all the other stations showed OIP values above 2. This indicates a slightly polluted water condition at the other stations (M1-M5) during the pre-monsoon season, which is due to high BOD, total phosphates, nitrates, fecal coliform and negligible river run off. . At station M1for high tide, data was not available due to rough weather condition. Even if the WQI for M1 data is missing, WQI of other nearby stations could be representative of the condition in the entire estuary as the water quality index is a range of values. The variation in WQI values is very minimum when all the station data are considered. The TSI values calculated for each of the water depth sample at these 6 stations during the pre-monsoon season indicated a variation in TSI values from 43.47 to 54.66. The overall TSI value calculated for the stations is 48.42 (Table 3.10), which is slightly higher than the values observed during the SW monsoon and post-monsoon seasons, and suggests a mesotrophic condition of the Mandovi estuary during the pre-monsoon season.

Low Tide			
Station	**Surface**	**Bottom**	**OIP**
M1	1.77	2.19	1.98
M2	1.61	3.32	2.46
M3	1.78	2.04	1.91
M4	1.47	1.96	1.71
M5	1.48	1.33	1.40
M6	1.33	1.40	1.36
Average			1.80
High Tide			
M2	1.66	1.85	1.75
M3	2.25	1.94	2.09
M4	1.36	1.77	1.56
M5	1.40	2.48	1.94
M6	1.68	1.69	1.68
Average			1.80

Table 3.5. Water Quality Index during the SW monsoon season in Mandovi estuary.

Station no.	**Secchi depth (m)**	**TSI**	**Chl a (µg/L)**		**TSI**	**TP (µmol/L)**	**TP (µg/L)**	**TP TSI**	**TN (µmol/L)**	**TN (mg/L)**	**TN TSI**	**Avg. TSI**
Low Tide												
M1	1	60.00	S	0.79	28.49	0.54	16.82	44.85	21.47	0.30	57.29	**47.66**
			B	0.65	26.70	2.32	71.88	65.80	32.68	0.46	58.22	**50.24**
M2	0.5	69.77	S	3.68	42.57	0.59	18.35	46.11	26.84	0.38	67.83	**56.57**
			B	0.75	27.93	1.04	32.12	54.18	22.41	0.31	68.58	**50.23**
M3	1	60.00	S	0.40	22.11	1.68	52.00	61.13	106.43	1.49	48.45	**47.92**
			B	0.61	26.01	0.79	24.47	50.26	30.34	0.42	48.61	**41.63**
M4	0.7	65.03	S	1.65	35.18	0.40	12.23	40.26	13.77	0.19	57.02	**49.37**
			B	0.51	24.47	0.30	9.18	36.11	45.75	0.64	53.22	**37.94**
M5	1	60.00	S	0.73	27.77	0.20	6.12	30.27	42.01	0.59	56.69	**43.68**
			B	0.97	30.29	0.20	6.12	30.27	31.51	0.44	56.69	**39.09**
M6	0.5	69.77	S	0.83	28.89	0.54	16.82	44.85	36.18	0.51	59.07	**50.65**
			B	0.60	25.83	0.40	12.23	40.26	29.64	0.41	56.09	**40.73**

High Tide												
M2	1	60.00	S	2.37	38.50	0.59	18.35	46.11	46.68	0.65	43.80	**47.10**
			B	0.69	27.18	0.15	4.59	26.12	34.31	0.48	45.51	**32.94**
M3	1.5	54.28	S	1.87	36.36	0.35	10.71	38.34	19.84	0.28	64.04	**48.26**
			B	0.55	25.08	0.79	24.47	50.26	32.68	0.46	49.36	**41.57**
M4	1	60.00	S	0.75	27.93	0.05	1.53	10.28	65.59	0.92	55.56	**38.44**
			B	0.72	27.64	0.20	6.12	30.27	33.38	0.47	42.81	**33.57**
M5	1	60.00	S	1.62	35.01	0.44	13.76	41.96	54.85	0.77	54.86	**47.96**
			B	0.32	20.02	0.20	6.12	30.27	50.18	0.70	55.51	**35.27**
M6	1	60.00	S	0.60	25.84	1.04	32.12	54.18	33.38	0.47	56.69	**49.18**
			B	1.02	30.76	0.64	19.88	47.26	37.11	0.52	57.82	**45.28**
Average		**61.71**			**29.12**			**41.79**			**55.17**	**46.95**

Table 3.6. Trophic State Index during the SW monsoon season in Mandovi estuary.

Low Tide			
Station	**Surface**	**Bottom**	**OIP**
M1	1.08	1.70	1.39
M2	1.36	1.87	1.61
M3	1.46	1.66	1.56
M4	1.05	1.68	1.36
M5	1.25	1.53	1.39
M6	1.02	1.16	1.09
Average			1.40
High Tide			
M1	1.62	1.49	1.55
M2	1.83	1.52	1.67
M3	1.36	2.33	1.84
M4	1.18	1.61	1.4
M5	1.14	1.17	1.15
M6	1.01	1.47	1.24
Average			1.47

Table 3.7. Water Quality Index during the post-monsoon season in Mandovi estuary

Station no.	Secchi depth m	TSI		TN (µmol/L)	TN (mg/L)	TN TSI	TP (µmol/L)	TP (µg/L)	TP TSI	Chl a (µg/L)	Chl a TSI	Avg. TSI
Low Tide												
M1	0.5	69.77	S	30.11	0.42	41.99	0.94	29.24	52.83	0.17	14.59	**36.47**
			B	27.19	0.38	40.51	0.79	24.52	50.29	0.11	10.62	**42.80**
M2	0.7	65.03	S	29.66	0.42	41.77	1.15	35.53	55.63	0.15	13.28	**36.89**
			B	27.87	0.39	40.87	0.94	29.24	52.83	0.23	17.08	**43.95**
M3	0.7	65.03	S	31.69	0.44	42.72	0.64	19.81	47.21	0.11	10.39	**33.44**
			B	33.26	0.47	43.42	0.89	27.67	52.03	0.14	12.78	**43.31**
M4	0.5	69.77	S	33.71	0.47	43.61	1.35	41.82	57.98	0.10	9.30	**36.96**
			B	35.96	0.50	44.54	0.79	24.52	50.29	0.15	13.28	**44.47**
M5	0.3	76.98	S	30.56	0.43	42.2	0.74	22.95	49.33	0.05	2.41	**31.31**
			B	26.07	0.36	39.9	0.23	7.23	32.68	0.08	7.64	**39.30**
M6	0.5	69.77	S	26.29	0.37	40.03	0.44	13.52	41.7	0.07	6.67	**29.47**
			B	31.46	0.44	42.62	0.39	11.95	39.92	0.54	25.03	**44.33**

High Tide												
M1	1	60.00	S	31.01	0.43	42.41	0.94	29.24	52.83	0.15	13.28	**36.17**
			B	26.52	0.37	40.15	0.79	24.52	50.29	0.13	12.13	**40.64**
M2	1	60.00	S	27.87	0.39	40.87	0.54	16.66	44.72	0.48	23.82	**36.47**
			B	32.13	0.45	42.92	0.89	27.67	52.03	0.22	16.52	**42.87**
M3	1	60.00	S	32.36	0.45	43.02	0.69	21.38	48.31	0.12	11.16	**34.16**
			B	35.73	0.50	44.45	0.79	24.52	50.29	0.27	18.73	**43.37**
M4	1	60.00	S	28.54	0.40	41.21	0.49	15.09	43.29	0.15	13.11	**32.54**
			B	36.63	0.51	44.81	0.74	22.95	49.33	0.11	10.28	**41.10**
M5	0.5	69.77	S	35.06	0.49	44.18	0.49	15.09	43.29	0.07	6.51	**31.33**
			B	31.91	0.45	42.82	0.69	21.38	48.31	0.13	11.75	**43.16**
M6	-	-	S	31.24	0.44	42.51	0.94	29.24	52.83	0.08	7.34	**34.23**
			B	26.52	0.37	40.15	0.69	21.38	48.31	0.07	5.89	**31.45**
Average		**66.01**				**42.33**			**48.91**		**12.47**	**42.43**

Table 3.8. Trophic State Index during the post-monsoon season in Mandovi estuary

Low Tide			
Station	**Surface**	**Bottom**	**OIP**
M1	2.69	2.36	2.52
M2	2.1	2.33	2.21
M3	2.01	2.18	2.09
M4	2.07	2.04	2.05
M5	2.52	2.32	2.42
M6	2.42	2.48	2.45
Average			**2.29**
High Tide			
M2	2.63	2.82	2.72
M3	2.15	2.21	2.18
M4	2.19	2.12	2.15
M5	2.04	2.06	2.05
M6	1.82	1.91	1.86
Average			**2.19**

Table 3.9. Water Quality Index during the pre-monsoon season in Mandovi estuary.

Station no.	Secchi depth (m)	TSI	TN (µmol/L)		TN (mg/L)	TN TSI	TP (µmol/L)	TP (µg/L)	TP TSI	Chl a (µg/L)	Chl a TSI	Avg. TSI
Low Tide												
M1	2.3	48.26	S	22.61	0.32	37.85	3.96	122.74	73.51	0.34	20.81	45.11
			B	27.66	0.39	40.76	0.51	15.70	43.86	0.20	15.92	37.20
M2	1.2	57.43	S	36.44	0.51	44.74	5.35	165.55	77.83	0.37	21.41	50.35
			B	39.10	0.55	45.75	3.13	97.05	70.12	0.45	23.23	49.13
M3	1	60.00	S	44.68	0.63	47.68	3.09	95.62	69.91	0.74	27.89	51.37
			B	37.50	0.52	45.15	1.98	61.37	63.52	0.42	22.65	47.83
M4	1	60.00	S	42.82	0.60	47.07	5.48	169.84	78.19	0.68	27.10	53.09
			B	34.84	0.49	44.09	1.47	45.67	59.26	0.70	27.32	47.67
M5	1	60.00	S	40.69	0.57	46.33	1.43	44.24	58.80	0.45	23.20	47.08
			B	38.83	0.54	45.65	4.47	138.44	75.25	0.44	23.09	51.00
M6	1.1	58.66	S	42.02	0.59	46.79	0.88	27.12	51.74	0.43	22.80	45.00
			B	31.91	0.45	42.82	3.04	94.19	69.69	0.38	21.78	48.24
High Tide												
M2	1.2	57.43	S	31.38	0.44	42.58	3.78	117.03	72.82	0.51	24.36	49.30

			B	35.64	0.50	44.42	4.01	124.17	73.68	0.57	25.45	50.24
M3	1.1	58.66	S	41.76	0.58	46.70	4.10	127.02	74.01	0.57	25.37	51.18
			B	45.48	0.64	47.94	1.20	37.11	56.26	**SL**	**SL**	54.28
M4	0.5	69.77	S	44.15	0.62	47.51	3.36	104.18	71.15	0.96	30.21	54.66
			B	40.43	0.57	46.24	1.61	49.95	60.55	0.70	27.35	50.98
M5	0.5	69.77	S	41.76	0.58	46.70	1.47	45.67	59.26	0.48	23.88	49.90
			B	42.55	0.60	46.98	0.23	7.14	32.49	0.52	24.63	43.47
M6	0.7	65.03	S	31.38	0.44	42.58	1.29	39.96	57.33	0.50	24.26	47.30
			B	33.24	0.47	43.41	2.12	65.65	64.49	0.34	20.58	48.38
Average		**60.45**				**44.99**			**64.26**		**23.97**	**48.42**

Table 3.10. Trophic state index during the pre-monsoon season in Mandovi estuary.

Region/Water body	**Major sources of pollution**	**Water quality conditions**	**References**
South Saurashtra (South western part of Gujarat state)	Industry, Seasonal tourism, Fish landing.	Ideal conditions at south, deteriorating at north	Badja and Kundu, 2012 [1]
Estuaries of Gulf of Khambhat (The Narmada, Mahi and Sabarmati)	Chemical industry, Agriculture	Sabarmati, Mahi (north); High pollutant load Narmada (south); less pollution load	Deshkar et al., 2012 [2]
Kandla Creek, Gulf of Kutch	Port activities, discharge of suspended solids from little Raan	Slightly polluted to polluted	Shirodkar et al., 2010 [3]
Mumbai, Maharashtra state	Industry, Urbanisation, Population pressure, Port activities	highly polluted, Hypoxic	Kamble and Vijay, 2011 [4] Shirodkar et al., 2012 [5] Sawant et al., 2007 [6]
Mangalore, Karnataka state	Industry, Port activities and domestic waste.	Acceptable to Slightly polluted	Shirodkar et al., 2009 [7] Andrade et al., 2011 [8]
Zuari estuary, Goa state	Port activities, industry, tourism, domestic waste.	Acceptable (monsoon) Polluted (post-monsoon) Slightly polluted (pre-monsoon)	Shirodkar et al., 2012 [9]
Cochin estuary, Kerala state	Industry, Port activities, Population pressure	Moderately polluted to eutrophic	Balachandran et al., 2008 [10] Abhilash et al., 2012 [11]

			Martin et al., 2011 [12]
Ashtamudi estuarine system, Kerala state	Solid waste dumping in banks, coconut husk retting, fish processing units	Moderately polluted	Karim 2012 [13] Sujatha et al., 2009 [14]
Akkulam–Veli coastal lake system, Kerala state	Population pressure, tourism	Organic pollution (pre-monsoon)	Sheela et al., 2012 [15]

Table 3.11. Water quality conditions of coastal water bodies along the west coast of India.

3.5. WAC of the Mandovi estuary

During SW monsoon, the external loadings of fluoride, NO_2-N, PO_4-P, NH_3-N, TSS or TVC can affect the assimilative capacity of the estuary. The WQI and TSI indicate considerably good assimilative capacity of the estuarine water during the SW monsoon. During post-monsoon, the assimilative capacity of the estuary can be affected by fluoride, SO_{4-}, urea, TVC and TN as the WQI and TSI indicate a fairly good assimilative capacity of the estuary. The assimilative capacity during this season can be affected by SO_{4-}, fluoride, PO_4-P and NO_2-N. Though there are some high values at some stations, the general trend of WQI and TSI throughout the estuary indicates good to fairly good assimilative capacity. The assimilative capacity of the estuary is also found to be in good to fairly good state (pre-monsoon < SW monsoon < post-monsoon) considering the dominant contaminants, WQI and TSI. The water quality conditions of other estuaries/coastal water bodies (Table 3.11) situated on the west coast of India is compared with that of the Mandovi estuary. The range of water quality parameters for these regions are compiled and presented in Table 3.12. The prevailing estuarine water quality of the Mandovi estuary is found to be good and acceptable as compared to most of the other regions along the west coast of India.

References →	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**	**[9]**	**[10]**	**[11]**	**[12]**	**[13]**	**[14]**	**[15]**
Parameters ↓	South Saurashtra (South western part of Gujarat state)	Estuaries of Gulf of Khambhat (The Narmada, Mahi and Sabarmati	Kandla Creek, Gulf of Kachchh	Mumbai, Maharashtra state			Mangalore, Karnataka state		Zuari estuary, Goa state	Cochin estuary, Kerala state			Ashtamudi estuarine system, Kerala state		Akkulam–Veli coastal lake system, Kerala state
Temperature (°C)	21.09 - 25.79	27.00 - 30.00	21.00 - 32.50--	-	26.00 - 30.50-	29.00 - 30.00-	30.10 - 32.10-	28.00 - 34.75-	-	-	28.00 - 32.00-	30.00 -33.00	-	26.00 - 32.50	26.60 - 30.50 -
Salinity	32.22 - 35.58	0.20 - 33.27	24.00 - 33.00-	-	29.00 - 36.00-	34.80 35.80	12.40 - 35.50	-	22.20 - 34.90-	-	0 - 30.00	8.00 - 32.00	-	24.82 - 36.68	0.06 - 2.67
pH	8.14 - 8.39	7.60 - 10.70	7.50 - 8.30	-	8.40 - 8.80--	7.90 8.10	7.70 - 7.80-	6.87 - 8.25-	7.80 - 8.20-	-	6.80 -7.90	6.4 0 - 7.80	7.00 - 7.80	7.30 - 8.10	6.30 - 7.80
Dissolved Oxygen (mg/L)	5.62 - 6.38	1.14 - 5.03	5.20 -7.30	0 -7.50	0.67 - 7.17--	2.70 - 5.30-	3.60 - 7.70-	2.60 - 7.30-	1.50 - 7.90-	-	3.90 - 5.80	-	5.60 - 6.00	1.90 - 6.30	0.13 - 6.48
BOD (mg/ L)	0.48 - 0.95	0.22 - 3.77	0.20 - 1.90	1.00 - 38.00-	0.30 - 2.10--	-	0.20 - 3.20-	0.70 - 14.40-	0.10 - 4.60 -	-	-	-	0.40 - 0.60	-	0.78 - 12.25
Nitrate (mg/L)	-	0.07 - 0.40	0.13 -0.81	-	0.06 - 1.20--	0.68 - 2.24-	0.04 - 0.26-	3.35 - 23.02-	0 - 0.39	-	-	0 .00 - 4.40	-	-	0.61 - 6.73
Nitrite (mg/L)	-	0.01 - 0.05	0.02 - 0.27	-	0.01 - 0.11--	0.01 - 0.30-	0.01 - 0.07-	-	0 - 0.12	-	-	-	-	0.00 - 0.04	0.00 - 0.24
Phosphate (mg/L)	0.06 - 0.08	0.052 - 0.36	0.18 - 0.56	-	0.12 - 0.76--	1.07 - 2.27-	0.03 - 0.16-	-	0 - 1.31	-	-	0.00 - 0.66	-	0.00 - 0.30	0.14 - 0.43

Table 3.12. Range of water quality parameters of coastal water bodies along the west coast of India.

Chapter 4

WAC of Mumbai coastal waters: coastal region surrounded by a megacity

4.1. Area of study

4.1.1. Mumbai coastal region

Mumbai (Fig. 4.1), a mega city (urban areas with a population of 10 million or more) of India is located on the west coast of India. It is designated as one of the global cities, which are engines of economic growth, centres of innovation for the global economy and the hinterlands of nations. Mumbai, known as Bombay in the past, was a cluster of seven tiny islands until the end of eighteenth century. It now forms a collected mass of islands, trapezoid in shape and occupies an area of 437 km^2. Mumbai city has rich natural resources of lakes, wetlands and mangroves. Nearly 8% of industries in the country are located around Mumbai in three large industrial clusters namely, Chembur–Thane–Belapur belt [Gupta et al., 2004; Krishna and Govil, 2005], Kalyan–Ulhasnagar–Ambarnath belt and Patalganga–Amba belt. About 11,494 industries are located in the city and 24,554 industries in the suburbs. The coastline is indented with large and small creeks. Although majority of the population in Mumbai is provided with houses and sanitary facilities, many of the slum dwellers use coastal area in and around the city as a natural sanitary facility, resulting in the release of huge amount of sewage directly into the Arabian Sea. Coastal region around Mumbai has deteriorated due to the discharge of wastewater through creeks, rivers, drains, and various non-point sources [Yedla and Kansal, 2003; Dhage et al., 2006]. The region suffers from the depletion in coastal habitats like mangroves and wetlands and severe coastal pollution. The foul smell and deteriorated aesthetics made the coastal areas unsuitable for recreation and tourism development [Murthy et al., 2001]. Previous studies [Vyas and Vyas, 2007] indicated that Mumbai city generates about 2000 million litres per day (MLD) of sewage from the seven service areas of the city sewerage network and discharges it into the adjoining coast and the creeks.

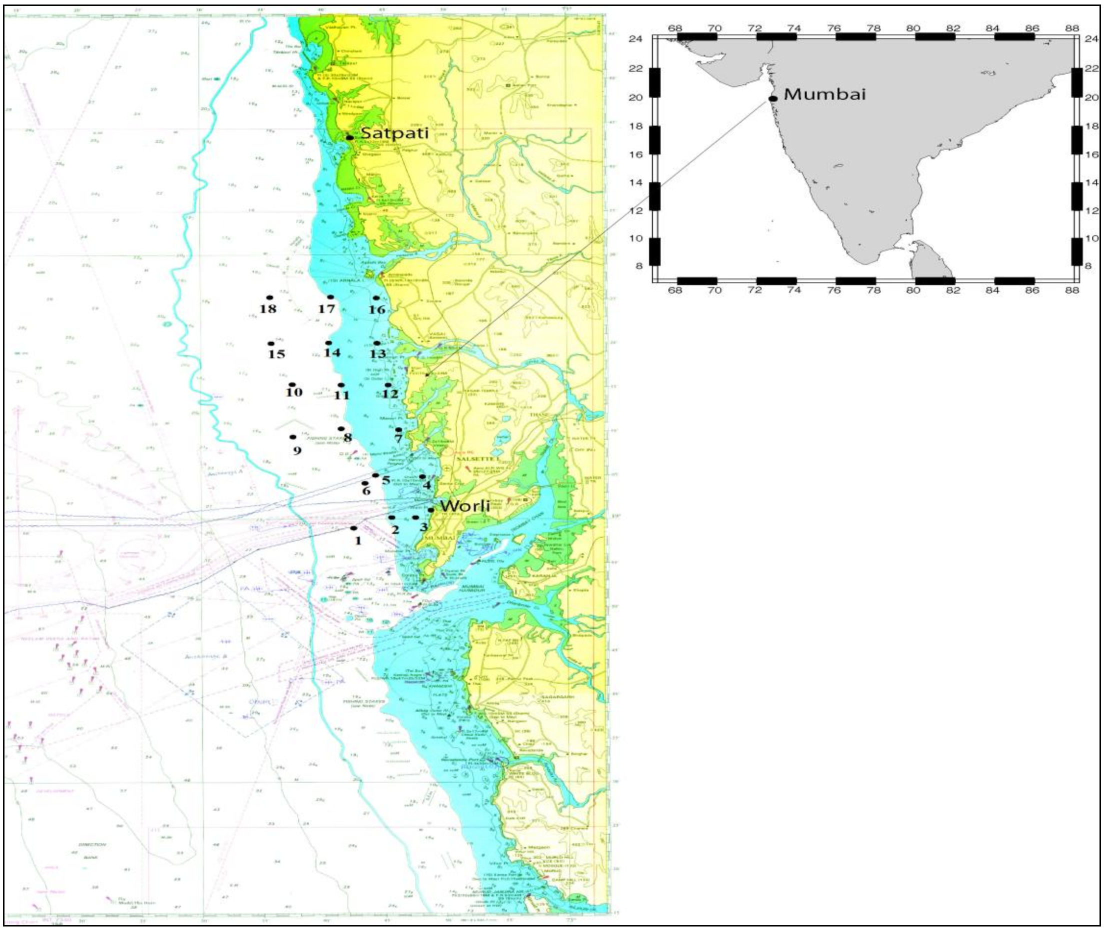


Fig. 4.1. Study area: station locations off Mumbai megacity (selected for sampling).

Differential weathering of the inter-layered soft tuffs and resistant basaltic flows (Deccan Traps) has created several bays and creeks around Mumbai, namely, Thane-Mumbai harbour, Mahim, Versova, Malad and Bassein creeks. Mahim creek, which is wide and shallow in the inland extension of the Mahim Bay, separated by a narrow constriction at the Mahim Causeway. The Mahim creek receives overflow of the Vihar and the Powai lakes during monsoon via the Mithi River. The annual flushing induced by heavy precipitation associated with monsoon increases the environmental quality of the creek and adjacent areas. The river run-off decreases during the post-monsoon period leading to stagnant conditions in the Mithi River and the Mahim creek [NIO, 2006]. Mahim creek sustains vast stretches of mangroves, which have been degraded severely due to the pressure of development. Mangrove species have been reduced from 14 to 2 species at present [Kamble, 2014]. On 19 August 2006, water in the near shore zone of the Mahim Bay in the vicinity of Shivaji Park was reported to have turned to freshwater. The associated studies [NIO, 2006] indicated that this was due to low salinity water primarily formed due to density differences between the Bay and Creek waters and sluggish tidal movements at or around neap tide. The Bay water was severely degraded with low DO, high concentrations of nitrate, nitrite and phosphate, probably due to contamination by sewage.

The Mumbai harbour region is a land-locked mass connected with the Arabian Sea to the south. At the head is the Thane creek through which opens in one arm of the Ulhas River after traversing the Thana-Kalyan mainland belt [Srinivasan, 1990]. The other arm opens into the Arabian Sea through the Bassein creek on the northern reaches of the island. The Ulhas water flows into the Thane creek only when there is a high flood during the monsoon months. The harbour is thus subject to ingress of waters from the Arabian Sea during most of the year. The Thane creek is a major sink for wastes from fertilizer, petrochemical, thermal power station, nuclear and other allied industries in and around Trombay. Malad creek receives wastewater and sewage from open drains and partially treated sewage from Malad and Versova treatment plants. The creeks of Mumbai in the western waterfront, i.e., Malad and Manori, are affected by heavy siltation due to the flushing of the polluted waters from the nearby industrial and residential areas and slums.

4.1.2. Physical settings

The climate of Mumbai is tropical, with temperature ranging between 16 ^{O}C and 33 ^{O}C. Temperature and rainfall are strongly affected by the Indian monsoon, which normally starts in June and ends around the middle of September. Mumbai receives approximately 2,500 mm of annual rainfall, with flooding when spells of heavy rainfall coincide with high tides or storm surges. On 26 July 2005, the city received an unprecedented 944 mm of rainfall in a 24 hrs period, resulting in the most devastating urban floods in recent history.

The coastal current along the west coast of India, the West India Coastal Current (WICC), one of the two eastern boundary currents which flow against the winds is southward during June to September and northward during November to January. Currents along the west coast of India are dominated by tides, which are mixed with dominant semi-diurnal constituents [Shetye et al., 1991; Unnikrishnan et al., 1999]. The wind-forced changes along the Indian west coast are largely forced remotely by winds in the Bay of Bengal [McCreary et al., 1993; Shankar et al., 2002]. The maximum tidal elevations are of about 5 m [Unnikrishnan, 2010]. Being a coastal city, the region is also prone to tropical cyclones which form predominantly during pre-monsoon/spring-summer transition (May-June) and post-monsoon/fall-winter transition (October-November) periods. Kumar et al. [2009] speculated that the Arabian Sea is experiencing a regional climate shift since 1995, which is accompanied by a five-fold increase in the occurrence of the most intense cyclones. Tropical cyclones often augment life in the ocean through upward pumping of nutrients into the euphotic zone [Byju and Prasanna Kumar, 2011].

4.1.3. Wastewater influx and water quality

The inshore and coastal areas of Maharashtra receive a variety of contaminants through point and non point sources emanating from domestic and industrial establishments located in the narrow coastal belt [NEERI report, 1985; Lancelot Pereira, 1986; Rokade, 1994; NIO report, 1999; Zingde and Govindan, 2000; Karn and Harada, 2002]. According to Kumar et al. [2000], more than 5000 metric tons of solid waste is generated every day in Mumbai. The domestic wastewater is generally released to nearby inshore waters wherever sewage collection network has been laid. The total domestic wastewater generated from 22 Municipal corporations is estimated to be 5399 MLD, but some kind of treatment facility is available with only 17 corporations.

The major manufacturing industries in Maharashtra are textiles, chemicals, metallurgical industries, transport equipment, automobiles and machinery machine tools, each of which account for more than one-fourth of the country’s production in those industries. Most of the industrial estates of Maharashtra Industrial Development Corporation (MIDC) are located a few kilometres inland from the coast and release their effluents in nearby creeks and estuaries.

Based on the information made available by MPCB as well as that gathered from other sources, the domestic and industrial effluents entering in inshore and coastal waters are as follows: in Thane District a 500 MW thermal power plant consisting of two 250 MW units has been commissioned in 1999. The thermal power plant discharges 528 MLD of warm return seawater to the nearby creek. The inputs to the sea in terms of pollution are heat, additional salinity and sulphates. Dahanu is a major commercial and industrial town in the Thane District. Dahanu creek receives about 4 MLD of untreated domestic wastes from Dahanu Town. Around 1891 medium and small scale industries are largely located in MIDC- Tarapur and Industrial Estate. Almost 2.6 MLD treated effluent generated in Tharapur is discharged to the coastal waters. The atomic power plant also uses the sea water for cooling and lets out the thermal effluent to the coastal waters. Bassein creek receives 425 MLD of domestic sewage apart from industrial waste. A variety of industries located in Ambernath-Kalyan-Dombivli-Mumbra industrial belt release their effluents into the creek. The industries in and around Manori feeding their waste into Manori creek include Metlab industries, fair Pent plastic, Dip Chemical, SA industry, Madam Agro Food Industry, Gei Haman Industry, etc. Domestic wastewater generated in the catchment of the creek is also pumped to the creek. The Versova creek receives wastewater and sewage from open drains and partially treated sewage from Malad (23 MLD) and Versova (260 MLD) treatment plants. The Mahim Creek receives overflow of the Vihar and the Powai Lakes during monsoon via the 14 km long Mithi River. During its course, the Mithi River carries wastewater discharged from several small scale industries and urban settlements. The total effluent load retained in the Mahim creek has been estimated to be 93,000 m^3. From Worli, the Arabian Sea receives around 725 MLD of sewage through a short channel. An outfall for disposal of sewage several kilometres in the sea was commissioned during 1999-2000. Untreated sewage is released through this outfall [MPCB, 2009].

The water quality of Thane Creek is a result of the balance between the anthropogenic fluxes of pollutants emanating from domestic wastewater and variety of industries located along its eastern/western shores and removal of contaminants by natural processes [Zingde and Govindan, 2000]. The number of industrial establishments and vehicles in Thane district has increased by 350% from 1987 to 1995 [Thane district report, 1995]. The Mumbai metropolis waste, which is discharged through various points, influences the Bombay harbour- Thana and Bassein Creek region [Naidu and Shringapure, 1975; Zingde et al., 1979; Zingde and Desai, 1980; Deshmukh and Kagwade, 1987; Zingde et al., 1989; Ramaiah et al., 1992; Ramaiah and Nair, 1993; Ramaiah and Nair, 1997; Ramaiah and Nair, 1998; Swami et al., 2000; Zingde and Govindan, 2000]. Domestic wastewater, often untreated or partially treated, is released as point discharges along the western shores. The major releases are through a subsurface outfall off Colaba and through pipelines and/or natural tributaries off Tank Bandar, Wadala, Ghatkopar, Bhandup and Thane on the western part of the creek, whereas the eastern part of the creek receives sewage from Koparkhairane, Nehrul, Belapur, Vashi and Airoli. Altogether the creek receives around 1260 MLD of sewage; the information available on the domestic and industrial effluents entering the inshore and coastal waters is often fragmentary and is by no means complete.

4.2. Water quality of Mumbai coastal waters: measurements and simulations

4.2.1. Water quality of Mumbai coastal waters

The field data collected during 2007 and 2008 (Source: NIO - Indian Oceanographic Data Center) specifically for the creeks, which bring in large amount of urban effluents to the coastal waters (Tables 4.1 - 4.6) was used to infer the influence of city effluents on the water quality of the region in and around Mumbai coastal region. The small creeks are divided into upper and lower creeks, while the large creeks into upper, middle and lower creeks for clear analysis. The division of creeks (into segments) facilitates easy interpretation of effluent effects (mostly confined to the upper segments) and also help in specifying the impact zones in the water quality modelling network. These data are used to infer the influence of city effluents on the water quality of Mumbai coastal waters, and also for the estimation of boundary conditions in the water quality modelling network. The field data collected during 2009 at 18 stations are used for validating the water quality model results.

Location: Dahanu (Lat:19.97°N; Long:72.73°E)								
Parameter	**February 2007 (post-monsoon)**				**March 2008 (pre-monsoon)**			
	Coastal	Lower creek	Middle creek	Upper creek	Coastal	Lower creek	Middle creek	Upper creek
Temperature (°C)	27.6	29.3	30	28.7	25	27	29.5	29.4
pH	8	8	8	8.1	8	8.1	8	8
SS (mg/L)	124	103	133	118	101	104	125	149
Salinity (ppt)	34.6	35.9	35.4	35.5	34.7	36	35.3	34.1

DO (mg/L)	5	4.8	4.8	5	4.4	3.9	4.2	3.5
BOD (mg/L)	2	0.8	2.9	2.3	0.7	-	2.6	1.7
PO_4^{3-}-P (µmol/L)	2.9	1.5	4.9	6	1.7	0.9	4.7	4.2
NO_3^--N (µmol/L)	14.7	11	11.4	12	13.8	12	10	5.7
NO_2^--N (µmol/L)	1	1.0	2	2.6	0.7	1.2	1.5	1.4
NH_4^+-N (µmol/L)	0.8	0.9	1.6	0.9	0.6	0.9	0.7	0.4
PHc (µg/L)	20	13	82	15	12	9	27	5
Phenols ((µg/L)	65	22	17	31	66	103	58	50

Table.4.1. Water quality results off Dahanu.

Location: Tarapur (Lat:19.85°N; Long:72.7°E)								
Parameter	**February 2007 (post-monsoon)**				**March 2008 (pre-monsoon)**			
	Coastal	Lower creek	Middle creek	Upper creek	Coastal	Lower creek	Middle creek	Upper creek
Temperature (°C)	28.1	28.7	29.4	30.5	25.9	-	27	27.5
pH	7.7	-	8.2	8.1	7.8	8	8	8
SS (mg/L)	40	25	31	20	66	48	37	23
Salinity (ppt)	35	35.2	35.6	35.7	35.2	35.3	35	34.3
DO (mg/L)	5.3	5.0	5.8	4.8	3.1	1.1	2.9	3.3
BOD (mg/L)	2.9	1.3	4.6	1.6	2.1	4.1	1.9	2.8
PO_4^{3-}-P (µmol/L)	1.1	1.3	0.5	1.2	2.2	1.3	1.6	1.8

NO_3^--N (µmol/L)	12.7	16.4	23.2	37.3	12.5	22	10	13
NO_2^--N (µmol/L)	0.7	0.7	5.8	5.8	0.7	2.7	2.2	1.3
NH_4^+-N (µmol/L)	3.1	10.3	22.1	24.3	2.1	8.5	21.4	24.5
PHc (µg/L)	11	37	20	17	16	21	25	38
Phenols ((µg/L)	21	7	37	77	27	31	76	106

Table.4.2. Water quality results off Tarapur.

Location: Bassein (Lat:19.47°N; Long:72.8°E)								
Parameter	**April 2007 (pre-monsoon)**				**February 2008 (post-monsoon)**			
	Coastal	Lower creek	Middle creek	Upper creek	Coastal	Lower creek	Middle creek	Upper creek
Temperature (°C)	31.6	30.5	32.5	32.5	23.0	25.2	25.7	26
pH	8	7.6	7.5	7.4	7.8	7.4	7.4	7.2
SS (mg/L)	126	152	90	42	174	148	68	60
Salinity (ppt)	34.7	27.3	20.6	16.4	30.6	21.1	10.2	3.8
DO (mg/L)	4.7	3.2	2.6	2.6	3.0	2.5	2.1	2.1
BOD (mg/L)	3.8	2.7	2.9	1.6	4.2	2.7	1.4	2.6
PO_4^{3-}-P (µmol/L)	2.5	3.0	2.5	3.0	3.5	2.9	9.6	6.1
NO_3^--N (µmol/L)	5.3	8.3	24.8	2.9	30.9	32.8	34.8	23.6
NO_2^--N	0.7	3.5	38.2	57.3	0.87	7.7	25.0	25

(µmol/L)								
NH_4^+-N (µmol/L)	1.3	1.7	10.2	23	1.1	3.3	6.8	13.4
PHc (µg/L)	41	30	10	12	7	9	-	-
Phenols ((µg/L)	21	10	27	29	50	35	49	71

Table.4.3. Water quality results off Bassein/Vasai.

Location: Manori (Lat:19.21°N; Long:72.79°E)				
Parameter	**April2007 (pre-monsoon)**		**February 2008 (post-monsoon)**	
	Lower creek	Upper creek	Lower creek	Upper creek
Temperature (°C)	31.7	32.8	24.4	25.3
pH	7.6	7.5	7.9	7.3
SS (mg/L)	37	38	103	23
Salinity (ppt)	33.1	35.4	34.1	31.5
DO (mg/L)	4.7	4.1	3.8	1.7
BOD (mg/L)	-	-	2.2	-
PO_4^{3-}-P (µmol/L)	20.7	33.7	9.8	17.7
NO_3^--N (µmol/L)	15.8	7	21	8.4
NO_2^--N (µmol/L)	47.2	17.7	1.9	3.2
NH_4^+-N (µmol/L)	56.7	88.2	4.0	10.4
PHc (µg/L)	7	10	12	9
Phenols ((µg/L)	21	38	8.5	20

Table.4.4. Water quality results off Manori.

Location: Versova (Lat:19.14°N; Long:72.79°E)				
Parameter	**April2007 (pre-monsoon)**		**February 2008 (post-monsoon)**	
	Lower creek	Upper creek	Lower creek	Upper creek
Temperature (°C)	30.5	30.3	30.5	26
pH	8	7.8	8	7.5
SS (mg/L)	33	51	33	61
Salinity (ppt)	33.4	31.7	33.4	30.2
DO (mg/L)	3.1	2.1	1.7	0.8
BOD (mg/L)	2.9	1.8	-	-
PO_4^{3-}-P (µmol/L)	3.2	10	0.7	18.2
NO_3^--N (µmol/L)	17.1	13.8	6.5	4.3
NO_2^--N (µmol/L)	4.1	4	7	1.3
NH_4^+-N (µmol/L)	4.4	25.3	19.5	29.2
PHc (µg/L)	8	21	-	-
Phenols ((µg/L)	12	16	-	58

Table.4.5. Water quality results off Versova.

Location: Mahim (Lat:19.036°N; Long:72.83°E)				
Parameter	**April 2007 (pre-monsoon)**		**February 2008 (post-monsoon)**	
	Lower creek	Upper creek	Lower creek	Upper creek
Temperature (°C)	29.5	30.5	24.2	24.6
pH	8	7.8	8.1	7.6
SS (mg/L)	36	45	18	18

Salinity (ppt)	35.1	32.8	35.4	33.1
DO (mg/L)	4.3	2.8	4.5	1.7
BOD (mg/L)	2.3	1.8	3.3	-
PO_4^{3-}-P (µmol/L)	4.2	11	4.5	14.6
NO_3^--N (µmol/L)	10.8	12.9	8.6	9.9
NO_2^--N (µmol/L)	.4	2.6	1	1.9
NH_4^+-N (µmol/L)	2.7	31.5	7	12
PHc (µg/L)	10	24	14	34
Phenols ((µg/L)	31	61	65	92

Table.4.6. Water quality results off Mahim.

Dahanu Creek is an ecologically sensitive region and investigations [Kadam and Tiwari, 2011] show that the creek is fully rich with phytoplankton and supports a diverse community. The Reliance Power unit at Dahanu uses the creek system for intake of seawater for cooling and FGD facilities. The return water enters the creek through a long channel with a weir over flow. It was found that a small area around the release would witness marginally higher temperature and sulphates [NIO, 2010]. Recently, NEERI recommended a 25 km industry free buffer zone around Dahanu Creek. During 2007-2008, the pH varied in a narrow range (8.0 to 8.1) and without significant trend in Dahanu creek. DO in Dahanu creek (Table 4.1) is generally good, varying from 3.5-5.0 mg/L. Low values of March 2008 indicate the presence of some external organic inputs. High BOD values prevailed in the middle creek compared to other segments. The levels of phosphate in Dhahanu coastal region varied from 0.9 to 6.0 µmol/L, which were sometimes high without any trend. Other water quality parameters were within the expected ranges. The existing effluent releases had not grossly deteriorated the creek ecology except for relatively high temperature in the immediate vicinity of the outfall location [NIO, 2010].

The waters off Tarapur also showed normal and stable pH range of 8.0 to 8.1. DO values varied from 1.1 to 5.8 mg/L in the creek waters of Tarapur (Table 4.2) with marginally low values during March 2008. The creek waters also showed BOD values varying from 1.3 to 4.6 mg/L. High BOD value prevailed in the middle segment of the creek. Phosphate varied from 0.5 to 2.2 µmol/L and nitrate from 10.0 to 37.3 µmol/L. The value of nitrite ranges between 0.7 and 5.8 µmol/L and ammonia between 2.1 and 24.5 µmol/L. The unusually high concentrations of nitrate and ammonia in February 2007 and very high levels of phosphate in March 2008 were probably associated with the sewage entering the creek. The creek transporting effluents to the coastal waters was highly degraded and resembled a sewer during low tide. The effluents entering the creek had caused severe deterioration of the creek ecology with low DO and pH and high SS and nutrients in water [NIO, 2010]. In May 2014, hundreds of dead fish wash ashore near the Tarapur MIDC chemical zone. As a mitigation measure, the MPCB had served closure orders to 57 industrial units for violating pollution norms near Tarapur.

The Bassein creek is formed by the Ulhas estuary. The creek receives a large amount of industrial and urban effluents. During the study period, in the Bassein creek, pH shows low values (7.2-8.0), especially in the upper creek. This low value of pH in the creek may be due to high microbial activity supported by organic wastes entering the system from urban areas. DO varied from 2.1 to 4.7 mg/L (Table 4.3) with a decrease towards land direction due to its consumption for oxidation of anthropogenic organic matter. During February 2008, the value of phosphate varied from 2.9 to 9.6 µmol/L; nitrate was higher in the lower creek and coastal waters, compared to rest of the estuary. The higher values of nitrite and ammonia in the creek suggest the stress associated with the release of sewage in the inner creek. A recent study [Singare et al., 2012] observed higher level of pollution in the creek during 2010-2011 compared to 2009-10 and is attributed to sewage and industrial effluent discharges.

Manori Creek is drained by the Dahisagar River and receive substantial amount of sewage effluents. The pH range varied from 7.3 to 7.9 in the Manori creek, suggesting high rate of bacterial break-down of anthropogenically introduced organic matter. In February 2008, the mean DO of Manori creek (Table 4.4) showed a fairly good oxidizing condition except in the upper creek. In April 2007, at the surface, particularly during flood, high value of DO was observed, which may be associated with high primary production. In Manori creek, during April 2007, a tremendous increase in phosphate and high concentrations of nutrients were observed; this is expected for a creek, which receives sewage in excess of their capacity to assimilate organic matter.

Versova Creek which received voluminous domestic wastewater is under environmental stress [NIO, 2010]. pH varied from 7.5 to 8.0 in the upper Versova creek and due to the impact of organic loading, the average DO levels were invariably low in the Versova creek (Table 4.5), and the value sometimes reached zero at low tides, typical of inshore tidal waters receiving oxidizable organic waste in excess of their assimilative capacity. The temporal measurements during 2007-2008 indicated that the Versova Creek was characterized by abnormally high levels of Phosphate, nitrite and ammonia, which may be due to inshore tidal waters receiving oxidizable organic waste.

The Mithi River drains into the Mahim Creek and the creek forms the boundary between the city and suburbs. The 2006 Mumbai sweet water incident was observed in this region. It is the only creek which balances the water level of Mumbai during heavy rainfall and during Mumbai monsoon time [Singare et al., 2014]. In Mahim creek, the pH was in the normal range with a decrease in the upper creek as compared to the lower creek and it is probably associated with wastewater release. In the upper creek of Mahim (Table 4.6) there was a reduction in DO associated with the entrance of organic load into the creek system. But, the lower creek sustained better DO concentrations. High values of nitrate and phosphate was also observed in the creek. High ammonia value (31.5 μmol/L) was observed in the upper creek during pre-monsoon period.

The Coastal Ocean Monitoring and Prediction System (COMAPS) under the Ministry of Earth Sciences observed that the Mahim and Versova creeks are the most degraded water bodies of Maharashtra due to the release of untreated industrial effluents and sewage. The water quality of all the creeks showed some amount of stress from the effluents as revealed by the distribution of DO, BOD and nutrients. Topography and water circulation pattern along Mumbai coast suggest that effluents brought in through the creeks can influence the beach environments (MSGB, 1979).

Sn no	Depth	Temp (°C)	pH	DO (mg/L)	BOD (mg/L)	PO_4 (umol/L)	NO_2 (umol/L)	NO_3 (umol/L)	NH_4 (umol/L)	SiO_4 (umol/L)	F (mg/L)	PHc (ug/l)	Phenol (ug/l)
1	S	28.3	8.53	2.79	1.79	3.16	0.62	11.56	15.76	22.96	1.786	15.33	0.24
	B	27.3	8.6	1.48	1.14	2.14	0.60	11.81	12.48	22.01	1.753	114.15	13.93
2	S	28.6	8.63	3.12	1.79	4.44	0.58	9.59	36.42	30.32	1.719	42.02	ND
	B	27.6	8.64	2.63	1.63	2.76	0.62	1.83	20.24	21.11	1.698	30.16	ND
3	S	27.8	8.67	4.43	1.27	1.94	0.50	3.45	15.39	19.26	1.761	37.97	2.13
	B	26.7	8.68	1.31	0.65	1.63	0.29	7.09	12.18	15.77	1.740	33.80	ND
4	S	27.4	8.64	1.48	0.31	3.67	0.58	5.73	14.18	25.61	1.904	177.13	ND
	B	27.1	8.65	0.82	0.32	5.87	0.48	12.66	13.33	26.98	1.753	14.77	ND
5	S	28.5	8.65	3.78	0.94	2.76	0.56	3.11	17.70	25.71	1.727	10.99	ND
	B	27.5	8.68	4.27	1.10	2.45	0.54	9.31	11.21	26.77	1.820	72.76	12.28
6	S	28.1	8.68	4.76	1.26	2.14	0.44	5.34	12.48	20.79	1.782	20.97	ND
	B	27.1	8.67	1.97	0.14	1.84	0.32	8.50	12.67	17.20	1.723	105.64	11.57
7	S	26.6	8.42	2.50	0.83	2.60	1.47	8.56	2.12	25.08	1.837	21.87	ND
	B	26.6	8.54	3.17	1.83	2.35	1.62	13.50	2.06	23.49	1.765	68.40	ND
8	S	27.1	8.63	3.33	0.17	2.86	0.62	14.96	2.00	28.78	1.909	26.74	ND
	B	26.3	8.67	2.00	0.67	2.60	1.60	9.71	1.58	21.32	1.786	236.94	ND
9	S	27.7	8.71	5.83	0.67	2.19	0.71	1.35	1.03	26.88	1.534	34.89	ND
	B	26.3	8.66	0.67	0.33	2.96	1.93	0.93	2.00	18.73	1.694	23.82	3.07
10	S	28.7	8.68	5.50	1.33	2.14	0.47	3.37	2.00	33.07	2.107	23.03	ND
	B	27.8	8.67	0.83	0.50	2.55	1.20	3.85	1.45	18.20	1.563	16.59	22.20
11	S	28.3	8.68	5.00	1.00	2.45	0.38	14.23	2.55	33.49	1.778	80.82	1.42
	B	26.1	8.64	1.33	0.33	4.39	1.04	2.91	4.00	25.93	1.744	15.14	6.61
12	S	27.3	8.68	4.50	0.67	3.62	0.91	13.12	0.97	36.72	1.866	36.05	12.28
	B	26.1	8.65	4.67	0.83	5.82	2.33	7.96	4.97	37.94	1.841	52.21	3.07
13	S	29.2	8.66	6.17	1.17	3.32	0.93	19.33	2.48	62.08	2.237	26.10	ND
	B	27.3	8.67	1.50	0.33	7.81	2.24	4.99	10.00	33.44	1.719	12.65	Lost
14	S	27.8	8.68	5.50	1.00	2.04	0.44	12.37	2.24	32.97	1.791	22.12	ND
	B	26.6	8.6	1.33	0.67	2.65	0.36	10.76	5.76	23.49	1.45	79.7	4.25

			6								8	9	
15	S	28.4	8.79	7.17	2.00	1.28	0.24	4.56	7.09	12.97	1.782	152.21	ND
	B	26	8.68	0.67	0.00	1.99	0.27	7.28	3.70	20.99	1.390	14.70	ND
16	S	29.6	8.6	5.33	1.00	2.35	1.11	13.84	5.52	72.71	1.791	22.43	ND
	B	27.3	8.62	1.50	0.00	3.37	1.22	13.05	7.94	35.73	1.677	50.35	ND
17	S	30.5	8.69	5.33	1.50	2.14	0.93	11.98	13.58	53.96	1.727	43.86	1.65
	B	27.9	8.64	1.00	0.17	2.65	0.78	10.44	3.82	33.80	1.799	25.14	7.56
18	S	29.7	8.76	6.50	1.17	1.73	1.82	8.88	3.27	35.99	1.841	171.70	ND
	B	27	8.66	1.17	0.00	2.30	0.80	13.40	14.36	24.22	1.770	105.10	ND

Table.4.7. Water quality results from 18 stations off Mumbai during October 2009.

During 2009 October, pH in the surface waters of almost all the stations ranged from 8.42 to 8.79, and in the bottom from 8.54 to 8.68; average pH values remain the same (8.65) both in surface and bottom layers. During 2009 (Table 4.7), DO ranged from a low of 1.48 to a high of 7.17 mg/L (av.4.61 mg/L) in surface, while from 0.67 to 4.67 mg/L (av.1.79 mg/L) in the bottom, indicating significantly low values in bottom water layer. The lower DO could be due to sewage pollution, whereas higher DO could be due to the photosynthetic activity of the algal blooms. The coastal waters of Maharashtra indicated average DO of > 3 mg/L suggesting good oxidizing potential in spite of organic pollutants reaching the coastal system from urban and industrial areas. Persistently, low DO was observed in Manori, Versova, Mahim and Thane creeks, where huge sewage outfalls are located

Consumption of DO during heterotrophic degradation of oxidisable organic matter creates oxygen demand popularly termed as the Biochemical Oxygen Demand (BOD). Presence of sufficient DO through replenishment keeps this demand low. However, input of oxidisable organic matter, more than that a water body can assimilate enhance the BOD - an indicator of unfavorable conditions. The BOD of 1-3 mg/L is common for coastal and inshore water and can be up to 5 mg/L in areas of high biological productivity such as the estuarine zones. This is because all natural waters contain some oxidisable organic matter of natural origin that includes a variety of organic compounds in minute quantities, some of which are derived from the land through drainage. In 2009, the Mumbai coastal waters occasionally showed BOD > 3 mg/L. BOD remains low throughout the study period and indicates a variation from a low of 0.17 to 2 mg/L (av.1.1 mg/L) in surface and from 0.0 to 1.83 mg/L (av. 0.55 mg/L) in the bottom water, suggesting higher BOD in surface water relative to bottom. This shows that the waste contributing to BOD is brought by the Creek water and added to the coastal waters of Mumbai. Turbidity showed low values in the surface (9.50 to 62.90 NTU) relative to bottom (10.3 to 271 NTU).

Water quality observations during 2009, indicate that almost all the nutrients show high values in the coastal waters of Mumbai and the values are higher for bottom water relative to surface (Phosphate exceeds the limit of 2 µmol/L in both the layers). In surface, Phosphate varies from 1.28 to 4.44 µmol/L (av. 2.60 µmol/L), whereas in bottom it varies from 1.63 to 7.81 µmol/L (av.3.23 µmol/L), which could be due to regeneration of phosphate from sediments. Nitrite shows low values in surface ranging from 0.24 to 1.82 µmol/L (av.0.74 µmol/L), relative to bottom, where it varies from 0.27 to 2.33 µmol/L (av.1.01 µmol/L). Nitrate, however, shows a reverse trend as compared to phosphate and nitrite (remains high in surface varying from 1.35 to 19.33 µmol/L (av.9.19 µmol/L) and low in bottom, where it varies from 0.93 to 13.5 µmol/L (av.8.33 µmol/L)). Ammonia also follows a similar trend of nitrate and remains high in surface relative to bottom. The observed ammonia values are very high both in surface and bottom layers. In surface, ammonia varies from 0.97 to 36.42 µmol/l (av.8.71 µmol/L), while in bottom water, it varies from 1.45 to 20.24 µmol/L (av. 7.99 µmol/L). Silicates remain high in surface and low in bottom layer (vary from 12.97 to 72.71 µmol/L in surface and 15.77 to 37.94 µmol/L in bottom). This shows that silicates are brought by the creek water into the coastal waters of Mumbai. Fluoride also shows high values in surface layer and low in bottom (in surface it varies from 1.53 to 2.24 mg/L, while in bottom it varies from 1.39 to 1.84 mg/L). This also indicates that fluoride is added to the coastal waters through creek. TP shows high values in surface varying from 0.92 to 5.11 µmol/L (av.1.46 µmol/L) and low values in bottom, varying from 0.58 to 2.07 µmol/L (av. 1.21 µmol/L). On the contrary, TN shows a reverse trend and remains low in surface (10.85 to 57.69 µmol/L) and high in bottom water (11.08 to 66 µmol/L).

Further to understand the long term effect of water quality in the region, particularly DO and BOD, these parameters from the reports published by the Maharashtra Pollution Control Board have been compiled and presented in Table 4.8. Also, simulations have been attempted for DO and BOD only. The locations (Table 4.8) were selected after considering the influence of anthropogenic impacts. The results showed considerable improvement in the DO concentration and subsequent decrease in the BOD in recent years, possibly due to the stringent regulations by MPCB in recent years.

Station	2002-03			2007-11			2011-12			2013-14		
	pH	BOD	DO	pH	BOD	DO	pH	BOD	DO	pH	BOD	DO
Mahim Creek	7	38.6	4.2	7.8	28.3	4	7.7	13.1	4.2	7.7	7.7	4.7
Worli Sea Face	7.2	13.5	-	7.7	12.5	4.9	7.7	12	4.5	7.8	8.2	4.8
Near Gate- Way of India	7.2	16.2	-	7.7	10.6	4.6	7.7	12.5	4.4	7.8	7.9	5.2
Near Nariman Point	7.1	14.4	-	7.8	11	4.4	7.8	12.5	4.8	7.7	9.9	4.9
Dadar Chowpaty	7	23.5	-	7.7	10.3	4.6	7.8	11.2	4.8	7.7	9	4.3
Near Malabar Hill	6.7	224	-	7.8	11.3	4.5	7.8	10.6	4.9	7.8	7.9	5.1
Near Haji Ali Bridge	7.2	28	2.7	7.8	10.7	4.4	7.5	9.8	4.6	7.8	8.3	4.8
Vashi Creek	7.1	33.3	-	7.6	10.9	4.4	7.7	10.2	4.8	7.6	8	4.6
Bassein Creek	-	-	-	7.9	9	5	7.9	9.3	5.4	7.6	6.4	5.3
Dahanu Creek	-	-	-	8	10.9	4.9	8.1	9.4	5.4	8	7.5	5
Versova	-	-	-	7.8	11.1	4.4	7.9	13	4.5	7.8	7.5	5.1
Juhu beach	-	-	-	7.9	11	4.6	7.8	13.1	4.6	7.9	8.1	4.9

Table.4.8. Water quality parameters (DO in mg/L, BOD in mg/L) at selected locations along Mumbai coastal region during 2002 - 14.

4.2.2. Trace metals

The observed concentrations of suspended solids, Cd, Pb, Cu & Hg (during October 2009) in water and sediments are presented in Figs 4.2, 4.3, 4.4 and 4.5, respectively. The highest range of TSS (20-105 mg/L) was observed off Vasai followed by that at Santa Cruz, Manori and Arnala especially at bottom waters. A significant decrease in range was observed from

Mahim to Versova. The spatial distribution of TSS (Fig. 4.6) indicated a decrease from nearshore stations to offshore stations. In general, all the metals exhibited higher concentrations in the nearshore stations. Cd concentrations were higher in the surface than the bottom at some stations with a reverse trend at many other stations. The highest dissolved Cd concentrations in water samples were observed at Vasai in the bottom water concentrations (av. 0.47 µg/L and range 0.11-1.13 µg/L). The dissolved Pb concentrations in both surface and bottom were low. The maximum surface dissolved Pb range, 0.03-0.07 µg/L, was observed at Arnala nearshore stations and bottom dissolved range 0.03-0.2 µg/L along transect off Santa Cruz.

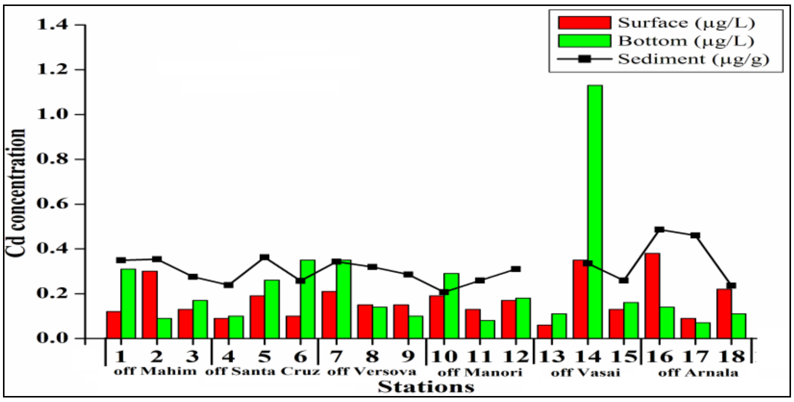


Fig. 4.2. Concentration of Cd in water and sediment.

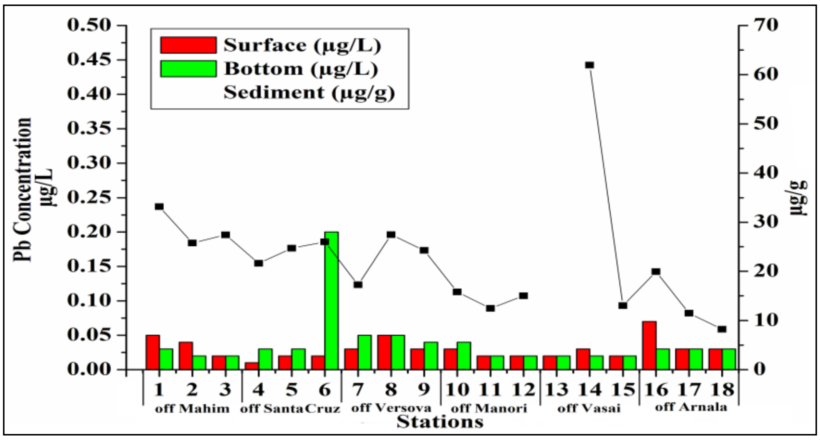


Fig. 4.3. Concentration of Pb in water and sediment .

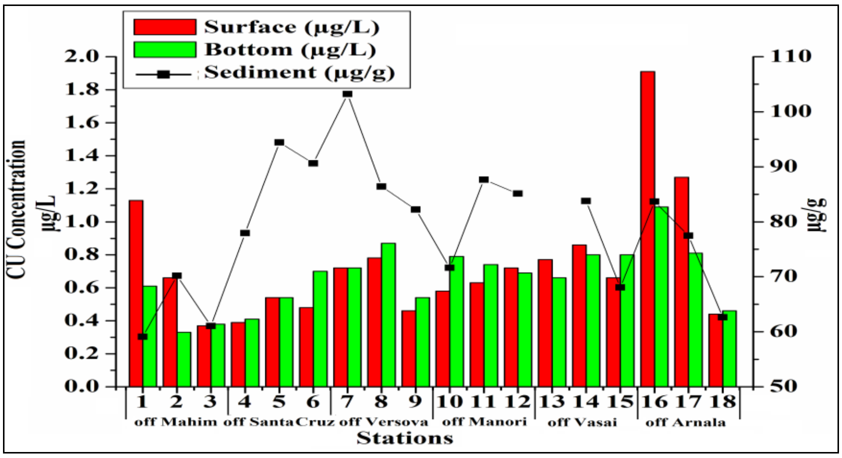


Fig 4.4. Concentration of Cu in water and sediment.

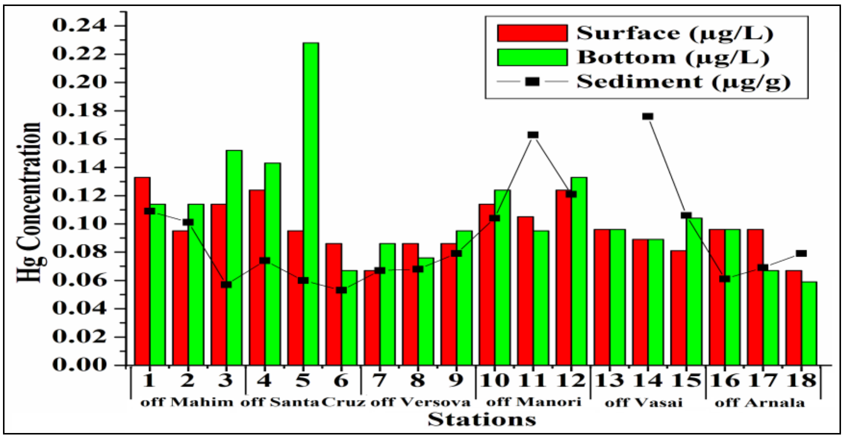


Fig. 4.5. Concentration of Hg in water and sediment .

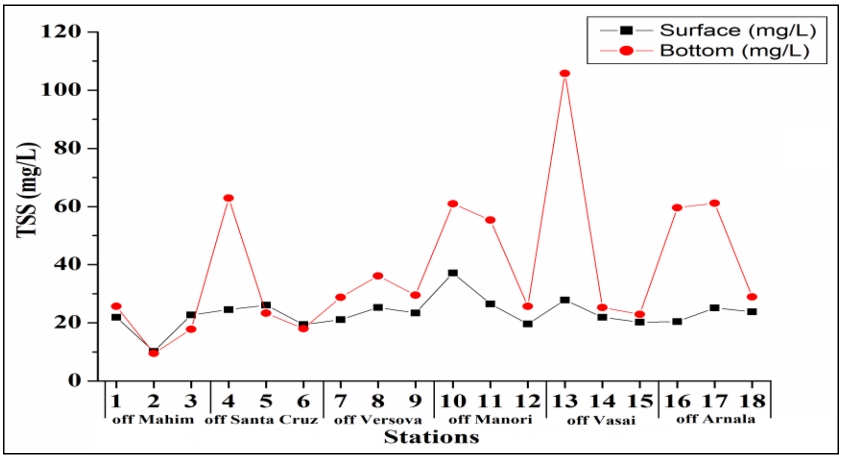


Fig. 4.6. Concentration of TSS in surface and bottom water samples.

Cu showed a unique pattern of distribution with the surface dissolved fraction exhibiting higher concentration than the bottom dissolved fraction in water at transects I, V and VI. The highest dissolved concentration of surface and bottom water samples, 1.91 and 1.09 µg/L, respectively were observed off Arnala in the near shore station where surface Pb was also high. Total Hg concentrations varied from 0.07 to 0.13 µg/L in surface samples and 0.06-0.23 µg/L in bottom samples. In general, the distribution of Hg was similar at all the six transects, but with marginally higher surface concentrations (0.10-0.13 µg/L) off Mahim and in bottom samples (0.07-0.23 µg/L) off Santa Cruz lighthouse. The pathway of Pb to these regions could be from the small scale industries of painting, dyeing, battery manufacturing and oil refineries located near the coastal region. At most of the stations, Cd shows an inverse relation with Cu as Cd is known to reduce copper toxicity. Cd is found to be comparatively higher at the nearshore station off Arnala due to its proximity to battery manufacturing industries, cement and ceramic plants, paint and enamel industries, etc. Maximum Pb and Cu concentration was observed at this station. Cu pathway to the coastal water is due to its proximity to marine traffic and marine vessel maintenance as the antifouling paint is the primary contributor of Cu in water. The maximum Hg concentration was observed off Mahim and Santa Cruz. Hg usually reaches the coastal waters from industrial establishments in the region which require either Hg as raw material or as a catalyst (Eg: plastic industries, chlorine and alkali plants). Though some values are high, the metal concentrations are within the limit, prescribed by CPCB. The CPCB metal standards prescribed in water quality criteria for healthy aquatic life and aesthetic quality of coastal waters are as follows: 10 µg/L for Cd, 100 µg/L for Pb, 10 µg/L for Hg and 20 µg/L for Cu as per the environmental protection rules of 1986 [CPCB, 1986].

Trace metals in sediment samples at the six transects showed a distinct spatial variation with the nearshore sediment indicating higher concentrations of all the metals analysed. Cd varies from 0.21 - 0.49 µg/g in surface water with the highest concentration av. 0.39 µg/g and range 0.24-0.49 µg/g off Arnala. Pb varies from 8.22-61.96 µg/g with the highest average values of 37.48 µg/g and range of 13 - 61.96 µg/g off Vasai. Cu concentration varies from 59.10 to103.24 µg/g in the sediment with the highest concentration observed off Versova (av. 90.63 µg/g; range 82.24-103.24 µg/g). The highest concentration of Hg was off Vasai (av.0.14 µg/g; range 0.11-0.18 µg/g). Enhanced levels of trace metals (Cr, Ni, Cu, Zn and Pb) both in water and sediment, especially in the creek/bay regions, together with a relatively high concentration of these trace metals in zooplankton, benthos and fish/shell fishes of the creek/bay regions was reported by Sabnis [1984]. Patel et al. [1985] found that the concentration of the major trace metals in Bombay harbor ecosystem- water, sediment, shellfish and fish – have remained practically unaltered for atleast in the last few years. This suggests that the effluents containing these metals have not so far affected the sediments significantly in the bay environment. The metals from the industrial sector in Mumbai [Bhanarkar et al., 2005] and the marine area of Bassein have been extensively investigated with respect to changes in the concentrations of heavy metals in water and sediment [Bhosale and Sahu, 1991]. High Cd values were observed in the sediment samples off Arnala, synonymous to that in water samples suggesting direct input of Cd to this region. The highest values for Pb and Hg were also observed off Vasai indicating that there can be a breach in threshold values in near future. Possible sources of these metals in sediment can be same as those discussed for water samples.

4.2.3. Biological parameters

During October 2009 (18 stations off Mumbai), Total viable counts were in the range of 10 x 10^3 to 94 x 10^4 cells/ml, minimum is recorded in the surface water at station 5 (off Santa Cruz) and the maximum in the bottom water at station 16 (transect VI; 10 m) (Fig. 4.7). In sediment samples, an increase of two to three orders in bacterial populations was noticed. High counts in sediments were obtained (45 x 10^7 cells/g) at station 5 in transect II (10 m) (Fig. 4.7). The coastal and creek/estuary along the coastal Maharashtra revealed high variations in bacterial counts (TVC, TC and FC in surface water). In general, the bacterial counts in the creek/estuary segments were broadly comparable with open coastal waters of the respective segments of north and south Maharashtra [CPCB, 2010]. But, the coastal and creek/estuary of north Maharashtra indicated much higher counts of TVC, TC and FC than that of south Maharashtra. Peak values are mostly observed at near shore stations indicating land based inputs. The maximum count was observed off Arnala (station 17), that too in surface due to the effect of effluent outfalls present in the area. The minimum count was observed in surface water at station 1 off Mahim which is an offshore station as the effluents are diluted in the nearshore regions.

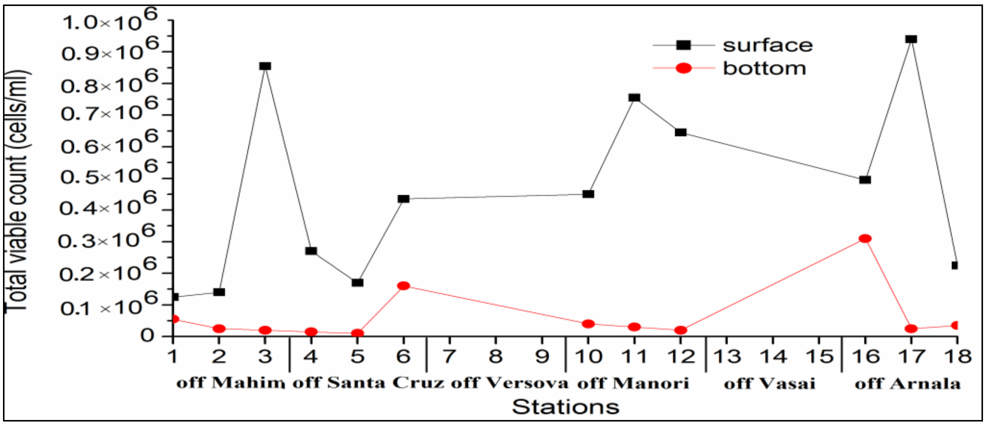


Fig. 4.7. Total Viable Count in water samples.

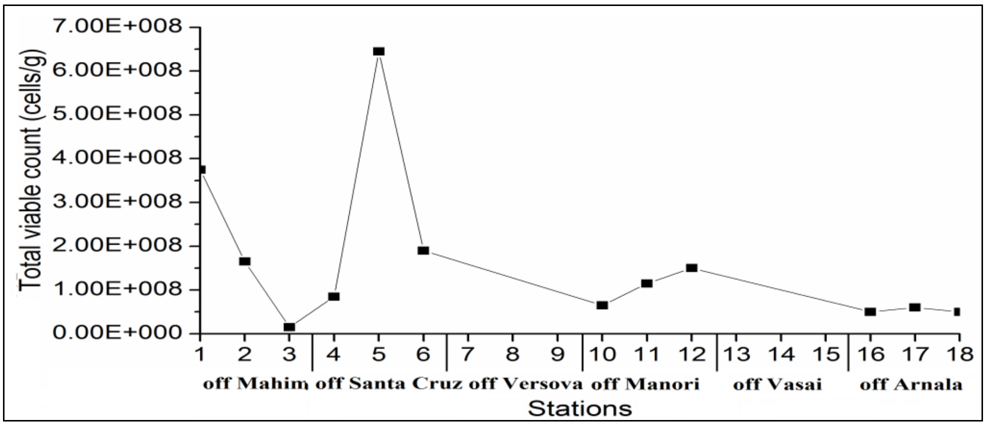


Fig. 4.8. Total Viable Count in sediment samples.

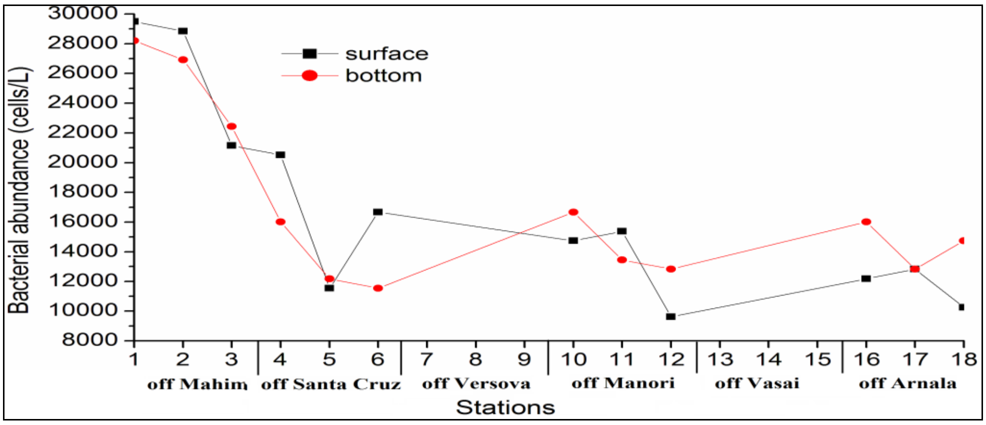


Fig. 4.9. Bacterial Abundance (AODC) in water samples.

The minimum number of total coliforms ($1x10^3$ cells/mL) was observed off Manori in the bottom waters of station 10, and the maximum (80×10^3 cells/mL) in the surface water of station 16 off Arnala (Fig. 4.10). Sediment investigation on total coliforms revealed the lowest (33×10^6 cells/g) in station 4 and the highest (28×10^7 cells/g) from off Santa Cruz (station 5) (Fig. 4.10). The lowest no. of fecal coliforms, one per ml is seen at three stations from the bottom waters at station 18 (off Arnala); station16 (off Arnala) and in station 11 (off Manori), while the highest being 110 cfu/mL from the surface water of station 16, off Arnala (Fig. 4.11). In sediments, the fecal coliforms were in the range of 1333 to 16×10^3 cfu/g, the lowest is at station 1 off Mahim and the highest at station 16 off Arnala (Fig. 4.13). Earlier observations indicated that the sewage dispersion is north-south with a much longer and wider waste field. Malad and Versova discharges if combined and discharged, into the sea at 3 km from the coast, will result in fecal coliforms patch near the shore [Vyas and Vyas, 2007].

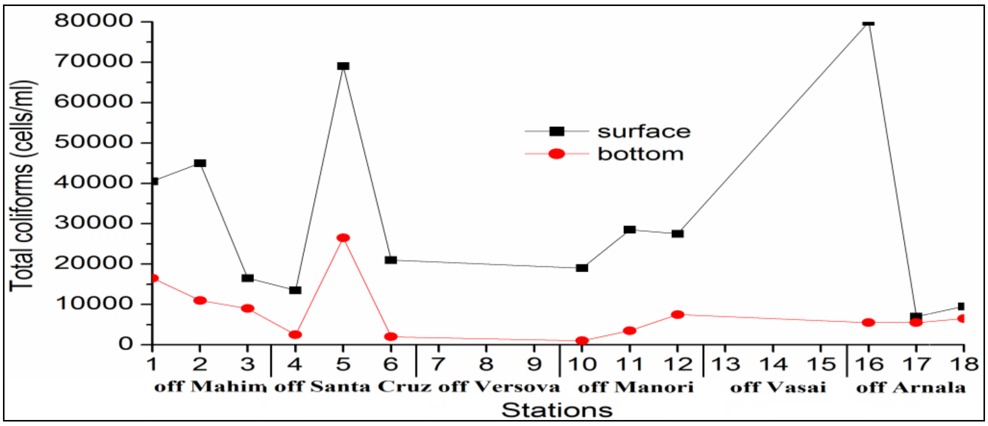


Fig. 4.10. Total coliforms in water samples.

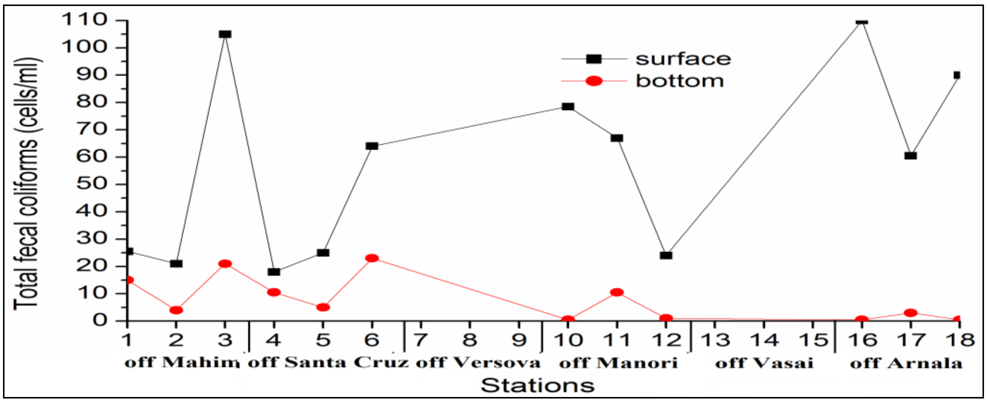


Fig. 4.11. Total fecal coliforms in water samples.

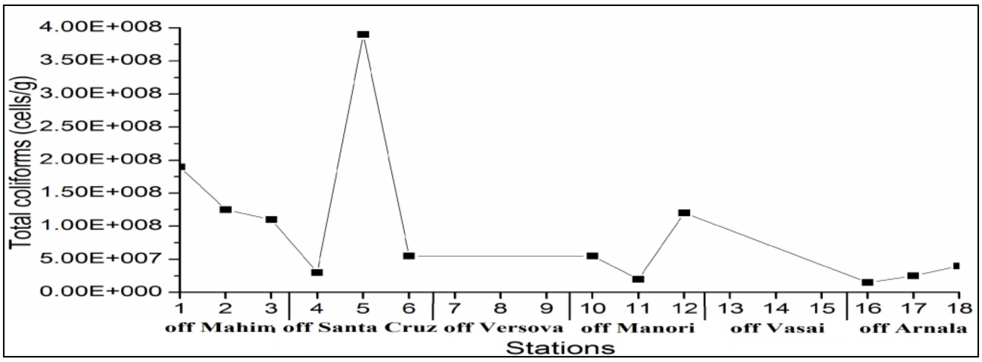


Fig 4.12. Total coliforms in sediment samples.

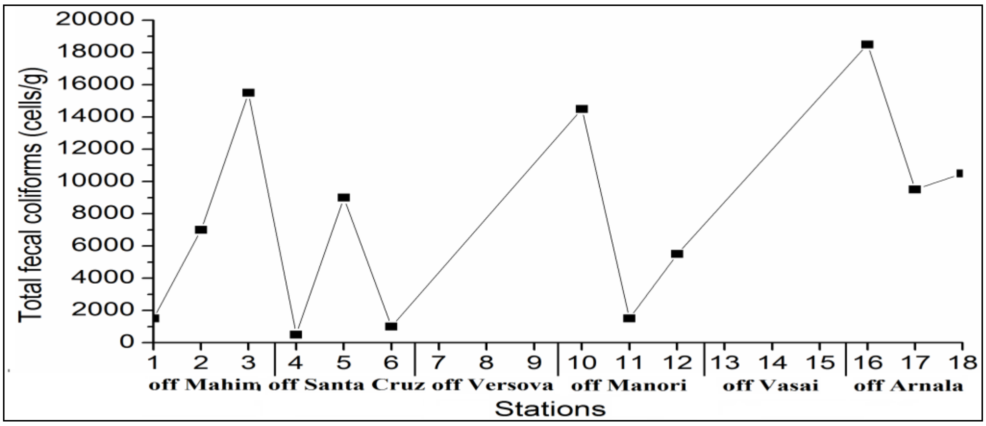


Fig. 4.13. Total fecal coliforms in sediment samples.

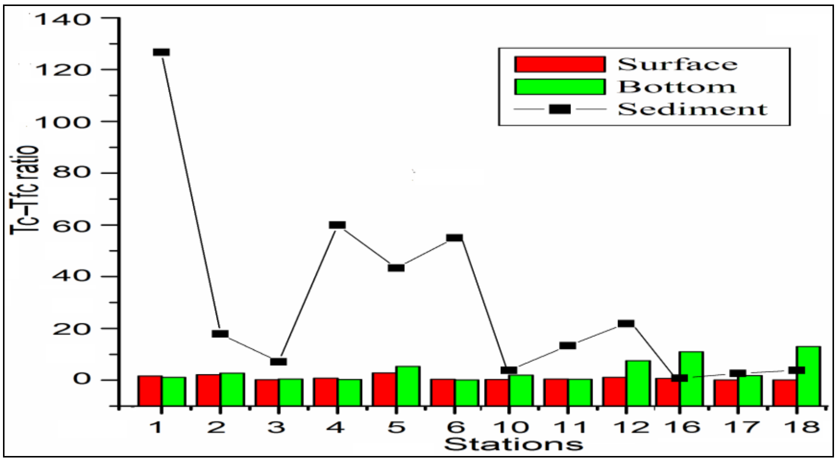


Fig. 4.14. Ratio between Total coliforms and Total fecal coliforms.

Among all the stations, maximum productivity was observed from the surface water of station 6 (0.001474 mg C/m^3/day) off Santa Cruz and the lowest productivity (0.00001 mg C/m^3/day) in the bottom water of station 17 off Arnala (Fig. 4.15). Comparisons were made with the previous and the recent data. Bacteriological studies conducted from the coastal waters of Mumbai and Mahim recorded 7.60 x 10^4 - 2.96 x 10^5 in surface water and 3.30 x 10^4 - 2.84 x 10^5 in bottom water, and in sediments 2.38 x 10^5 -7.89 x 10^5 . The Mumbai Harbour- Thane Creek – Bassein Creek consisting of over 75 km stretch forming the eastern edge of the Mumbai Metropolis is understood to have high microbial activity [Ramaiah et al., 1997], abundance [Ramaiah, 1994; Neelam et al., 1995] and ecologically versatile bacterial types [Ramaiah and De, 2003].

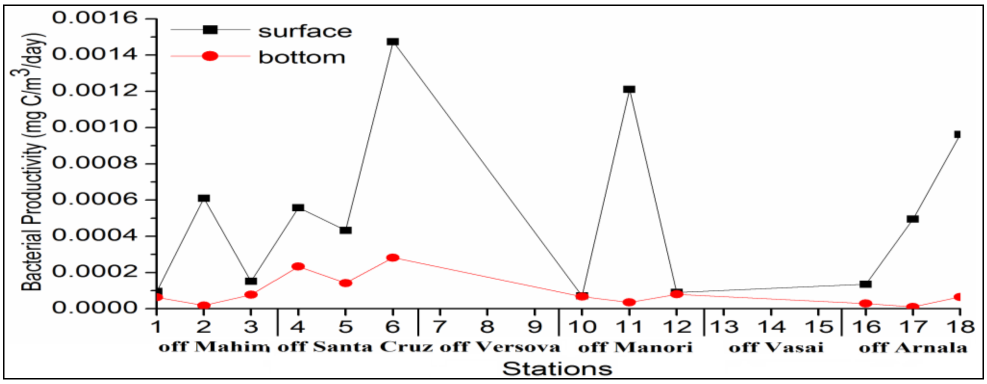


Fig. 4.15. Bacterial productivity in surface and bottom samples.

The primary productivity was observed minimum at the surface water at station 17 in off Arnala (38.39 mg C/m^3/day) and maximum production at station 2 off Mahim (1041.19 mg C/m^3/day) (Fig. 4.16).

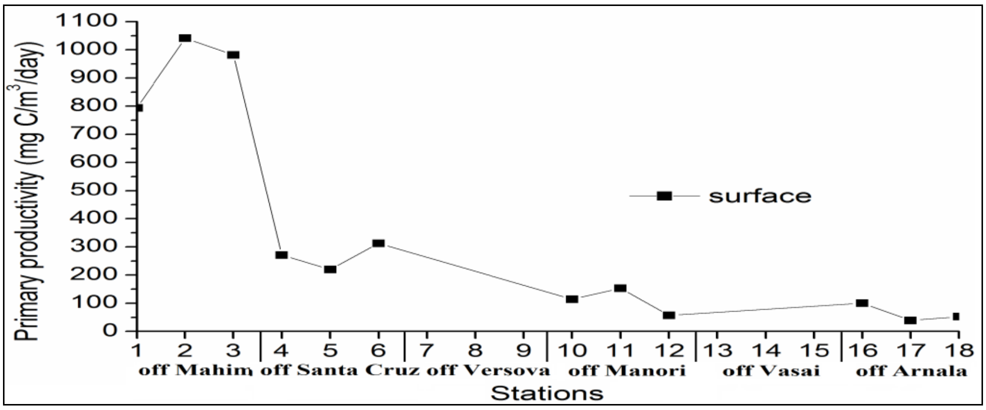


Fig. 4.16. Primary productivity in surface samples.

Maximum amount of chlorophyll (3.014 µg/L) was observed at the surface water at station 2 off Mahim, and the lowest (0.228 µg/L) at the bottom waters at station 12 off Manori (Fig. 4.17). Phaeopigments yielded the highest value of 0.944 µg/L in the bottom water at station 2, off Mahim, and the lowest value of 0.080 µg/L at the surface water at station 12, off Manori.

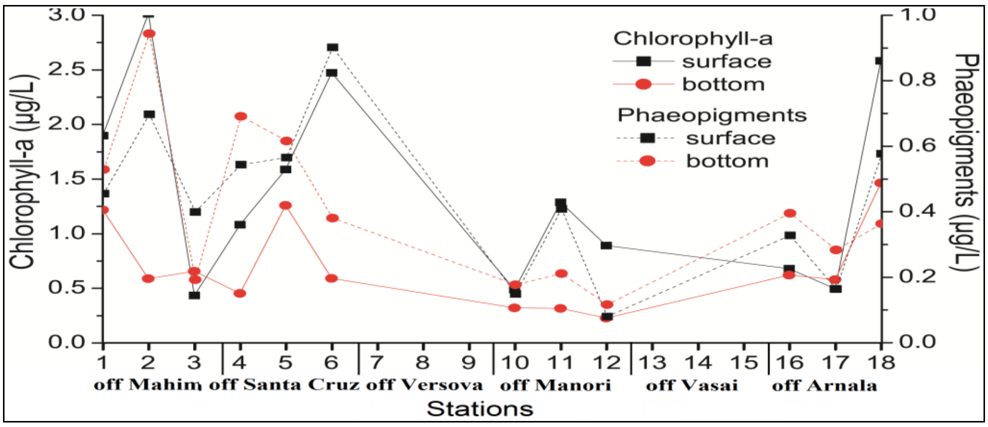


Fig 4.17. Chlorophyll-a and Phaeopigments in surface and bottom samples.

Thalassiosira, Skeletonema costatum, *Odontella mobiliensis*, *Protoperidium steinii,Cyclotella striata*, *Nitzschia closterium,Chaetoceros*, *Navicula*, *Leptocylindrus danicus*, *Asterionellopis glacialis* and *Pleurosigma elongatum phytoplakton species* were commonly observed in most of the stations. *Thalassiosira* and *Nitzschia closterium* were the two dominant species in this area. *Thalassiosira* observed to be predominant species in the surface water of station 3 off Mahim, was overtaken by *Nitzschia closterium* in the bottom waters of the same site. The phytoplankton number varied from 7788 cells/L to $23 x 10^4$ cells/L in these waters (Fig. 4.18).

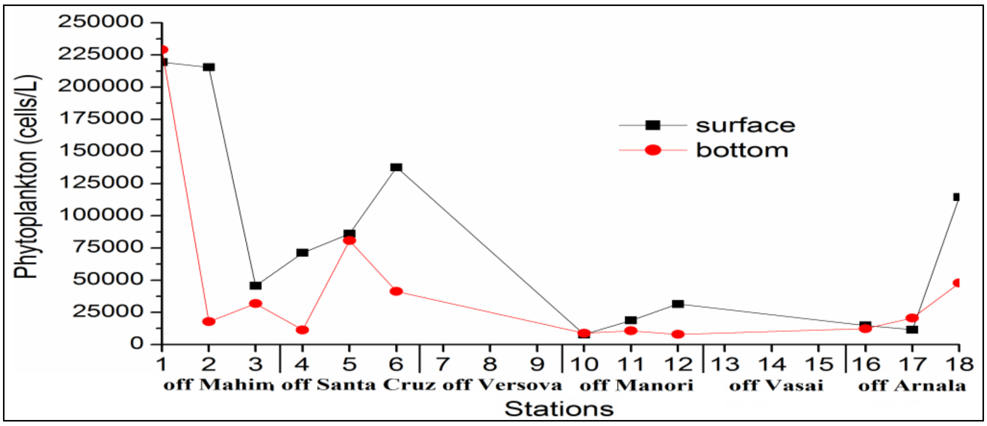


Fig. 4.18. Phytoplankton distribution in surface and bottom samples.

The biomass of zooplankton varied from 2.0 mL/100 m^3 to 4.5 mL/100 m^3. Copepods formed the largest group of zooplankton. Copepods are in the range of 135 to 1732 cells/m^3. *Chaetognath and Luciferae* are next to *Copepods* in counts. *Polychete, gastropods, Cladocera, Siphanophores, Foraminifera* and Fish larvae are the other groups of zooplankton seen in this area.

4.2.4. WQI

The minimum and maximum water quality indices are 2.14 and 4.53 (Fig. 4.19), respectively with an average value of 2.99. This indicates that water quality is slightly polluted to polluted state. The calculated TSI shows a value of 50.15. As the values ranging from 50-60 indicate eutrophic state, the Mumbai coastal waters are observed to be eutrophic.

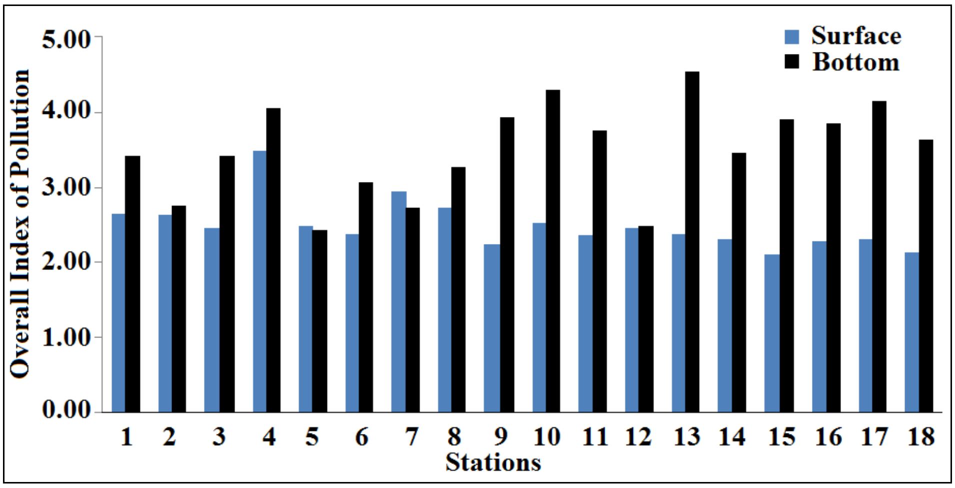


Fig. 4.19. Water Quality Index of Mumbai coastal waters.

4.3. WASP model setup and validation

The hydrodynamic input for the water quality model is taken from the output of MIKE21 HD. The hydrodynamic model domain covers the Mumbai coastal region (18º 30′ N - 20º N and 71º 45′ E - 73º 15′ E) of 330 x 330 grids having a resolution of 500 m x 500 m (Fig 4.20). The model bathymetry was generated using ETOPO5 data obtained from the National Geophysical Data Center, USA for deep water and digitized hydrographic chart data [Sindhu et al., 2007] for the nearshore region. The south, west and north boundaries of the domain were driven by the tidal elevations predicted using the Global Tide Model [Anderson, 1994; Anderson, 1995; Anderson et al., 1995]. The six hourly blended wind data of QuikSCAT and operational European Centre for Medium-Range Weather Forecasts (0.25º x 0.25º) [Ebuchi et al., 2002] obtained from IFREMER/CERSAT [Bentamy et al., 2007] was used for hydrodynamic simulation. The wind vectors were linearly interpolated to each grid cell. The model output was validated with the zonal and meridional current velocities derived from the surface current speed and direction measured using Aanderaa Recording Current Meters (RCM 9 LW) at two nearshore locations off Satpati and Worli along the Mumbai coast at 15 m water depth during 22 October – 22 November, 2009 at 10 minute interval.

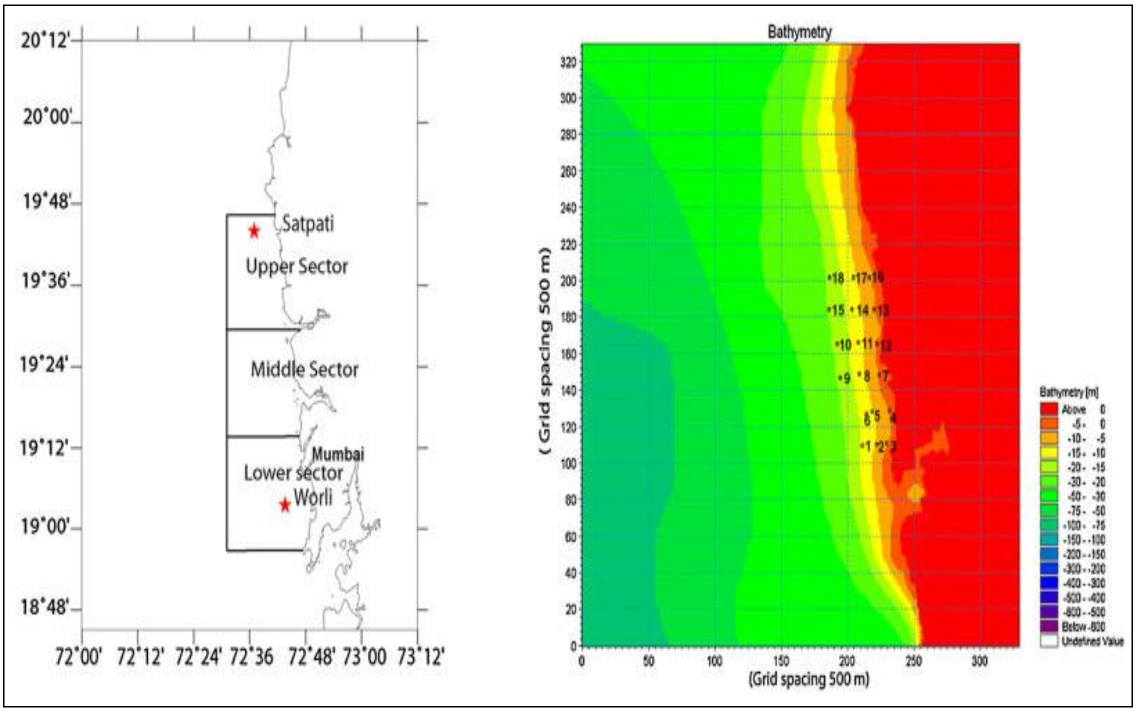


Fig. 4.20. Study area bathymetry and station locations.

The RCM 9 LW has an accuracy of ± 0.15 cm/s for current speed and ± 7.5º for current direction. The output parameters of fluxes, water levels and current velocities were obtained for every 10 minutes. The output parameters of MIKE21 (hydrodynamics) have been used as input for the water quality model.

The WASP model domain covers an area of 1215 km^2 with 135 grids of 3km x 3 km resolution. The region is divided into upper, middle and lower sectors, each having an extension of 27 km. The present area of study, Mumbai, comes in the lower sector of the model domain. The model was initiated using observed values for boundary conditions (DO, BOD, nutrients). After quality checking and analysis of long term water quality data, the boundary conditions were set as follows: salinity-36.8, DO-6.9 mg/L, BOD- 3.5 mg/L primary productivity- 1150 mg C/m^3/day, nitrite- 2.5 µmol/L, nitrate- 20 µmol/L, ammonia- 39.5 µmol/L, Turbidity- 300 NTU. At the eastern boundary, considering the influence of city effluents reaching the coastal water, water quality parameters with varying user defined concentrations were assigned as boundary condition. The limit is kept within the above mentioned parameter values. BOD, Currents, temperature and salinity were specified as forcing functions. The kinetic rates, constants and other formulations were obtained from

Bowie et al. (1985). An open boundary condition is specified for the east, west and north boundaries. At the eastern boundary, a land boundary is specified with user defined inflow in order to represent the creeks and other effluent inflows to the domain. First order decay rate was assigned for various parameters. Meteorological parameters used in the modelling network were obtained from Regional Meteorological Centre, Mumbai. Sensitivity analysis was carried out in order to find out the effect of different model inputs on model output variability.

A second set of sensitivity analysis was carried out on the calibrated model parameters to estimate the model sensitivity. The procedure for sensitivity analysis was carried out by changing the value of each uncertain parameter. The analysis was carried out for one parameter at a time or in groups. The model sensitivity was assessed by simulations with altered values and estimating the relative change of the outputs. When there were large changes in the outputs, the model is more sensitive to the alteration of parameter values. Initially the inputs were altered individually and then in groups. 789 alterations were made for the Mumbai model domain which consist of 200 perturbations related to hydrodynamics, 396 perturbations related to parameters such as BOD, DO, temperature, salinity and concentration of nutrients at the boundary and 193 perturbations related to various kinetic constants and coefficients (Table 4.9). After testing different parameter inputs using sensitivity analysis, calibration runs were carried out to estimate the range of values which were expected for the calibrated parameters. The model was calibrated using measured temperature, salinity, currents and water quality data, as well as the coefficients and constants relevant to the study area (Table 4.9). The model was utilized for the simulation of BOD during October 2009-January 2010. Further, the model results were validated with the DO and BOD data collected at 18 stations along the Mumbai coast during October 2009.

The validation results of the zonal and meridional currents are shown in Figs. 4.21 and 4.22. The scatter plot between measured and simulated current velocities (Fig. 4.23) shows that the parameters are least scattered, indicating less variations between observed and modelled values. The correlation coefficient, r.m.s. error and bias estimated for u-velocity are 0.63, 0.07 and 0.01, respectively off Satpati and 0.73, 0.10 and 0.00, respectively off Worli, whereas those estimated for v-velocity are 0.89, 0.28 and 0.00, respectively off Satpati and 0.86, 0.17 and 0.04, respectively off Worli. The correlation coefficient for u-velocity is less compared to that of v-velocity, and the zonal velocity component is much lower compared to meridional components. Model validation is presented in Fig. 4.24 for BOD and DO; validation was carried out only for Oct 2009, for which measured values were available. Model parameter evaluation for the water quality model to check the model reliability is presented in Table 4.10.

Model Coefficient	**Model value range**	**Calibrated/ Estimated**
Global Reaeration Rate Constant @ 20 °C (per day)	0-10	8
Minimum Reaeration Rate, per day	0-24	19
Theta -- Reaeration Temperature Correction	0-1.03	0.8
BOD Decay Rate Constant @20 °C (per day)	0-5.6	3.8
BOD Decay Rate Temperature Correction Coefficient	0-1.07	1
BOD Decay Rate Constant in Sediments @20 °C (per day)	0-0.0004	0.0003
BOD Decay Rate in Sediments Temperature Correction Coefficient	0-1.08	1
BOD Half Saturation Oxygen Limit (mg O/L)	0-0.5	0.45
Fraction of Detritus Dissolution to BOD	0-1.000	0.9
Fraction of BOD Carbon Source for Denitrification	0-1.000	0.7
Atmospheric Deposition of BOD1 (Ultimate) (mg/m2-day)	0-1000	700
Denitrification Rate Constant @20 °C (per day)	0-0.09	0.07
Calc Reaeration Option (0=Covar, 1=O'Connor, 2=Owens, 3=Churchill, 4=Tsivoglou)	0-4.000	1
Use (1 - On, 0 - Off) Total Depth of Vertical Segments in Reaeration Calculation	0-1	1

Table 4.9. Model coefficients used in modelling network.

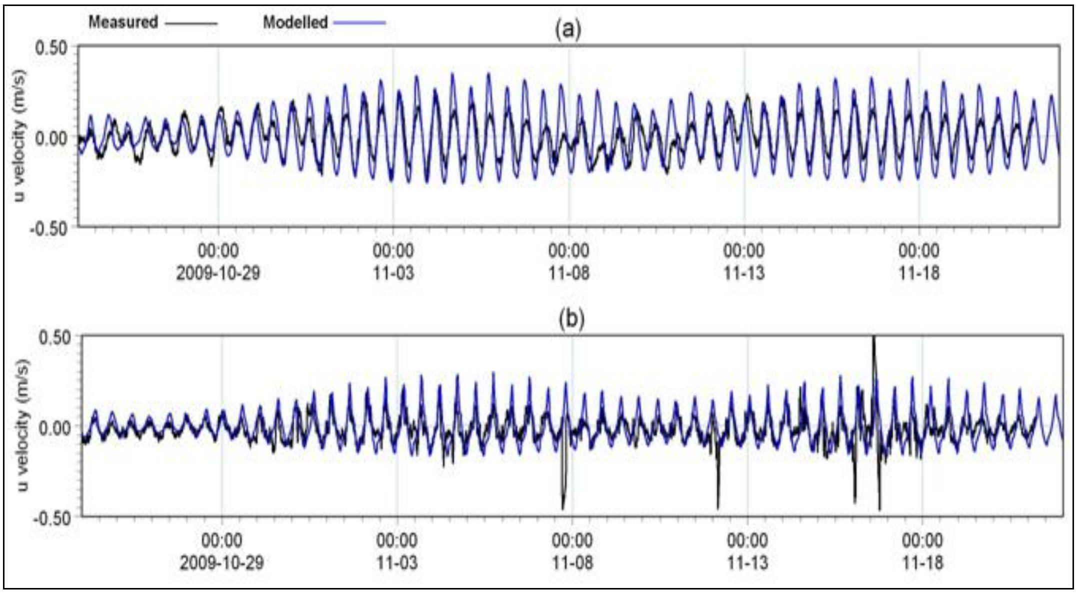


Fig. 4.21. Validation of u component (zonal) of currents: (a) off Worli and (b) off Satpati.

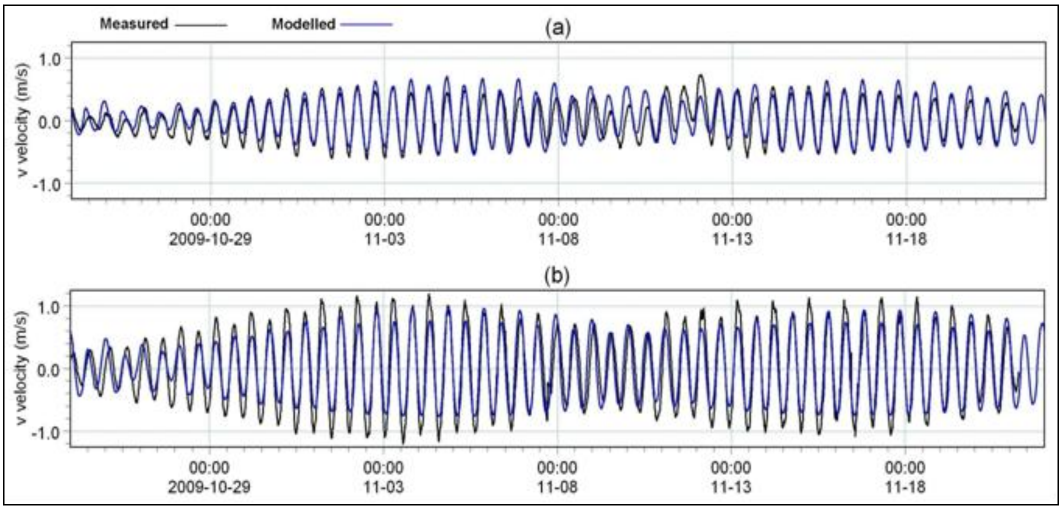


Fig. 4.22. Validation of v component (meridional) of currents: (a) off Worli and (b) off Satpati.

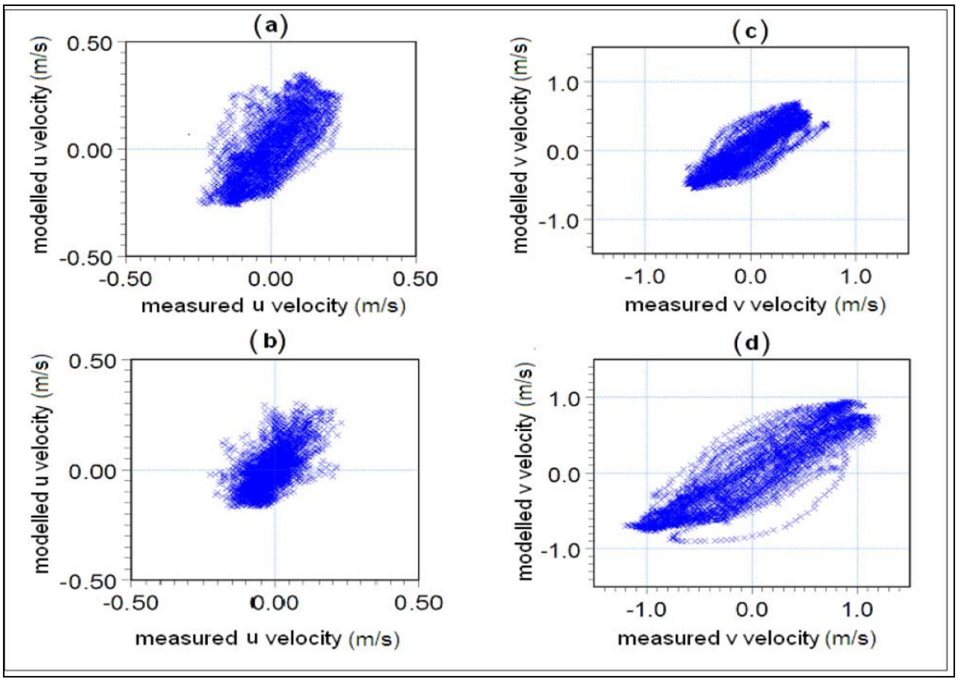


Fig. 4.23. Scatter of measured and modelled current velocities: (a) u- velocity off Satpati, (b) u-velocity off Worli, (c) v-velocity off Satpati and (d) v-velocity off Worli.

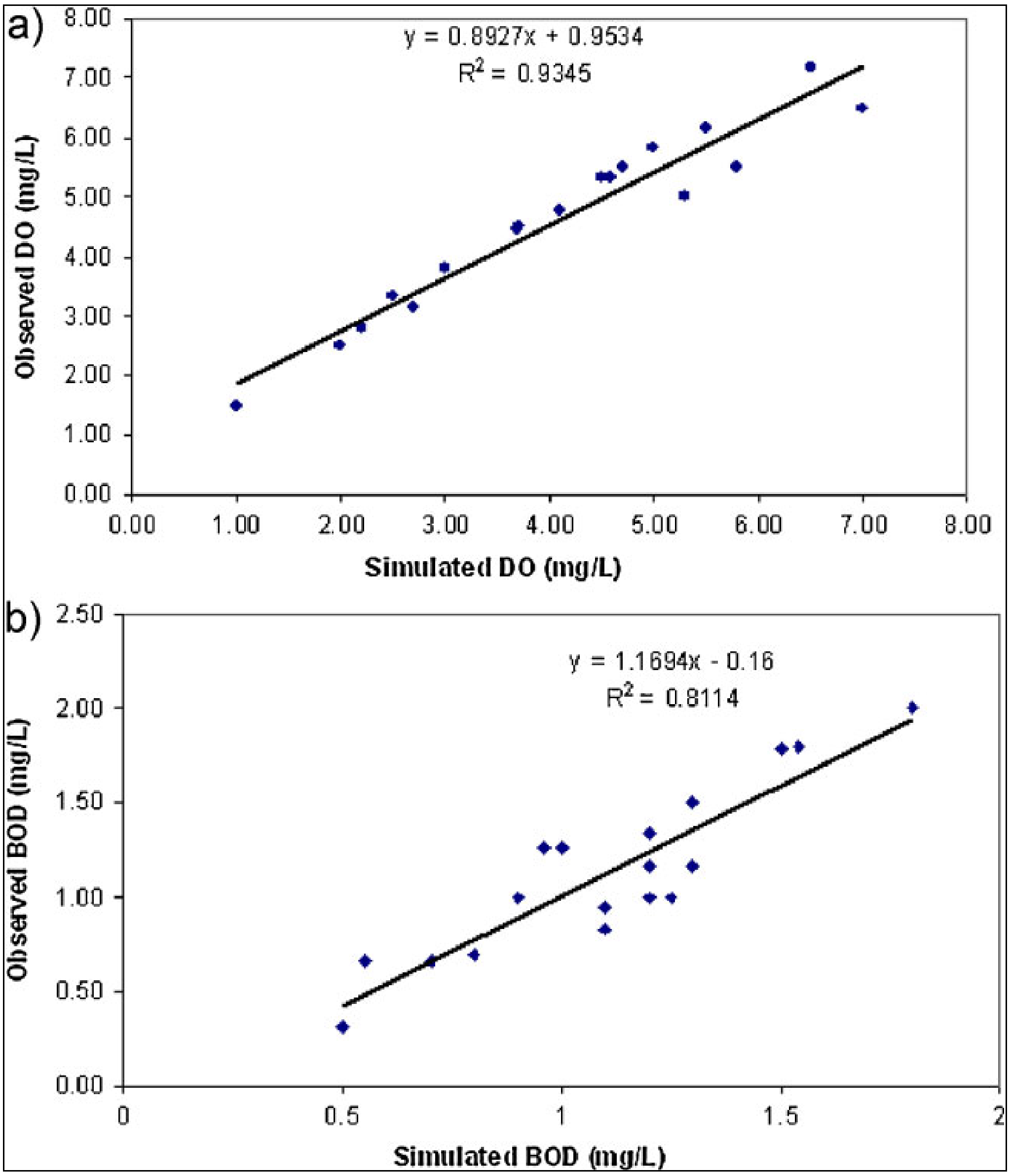


Fig. 4.24. Regression analysis of model values with measurements: (a) DO and (b) BOD.

Model parameter evaluation	Dissolved Oxygen (mg/L)	Biochemical Oxygen Demand (mg/L)
Pearson's correlation coefficient (r)	0.97	0.90
coefficient of determination (R^2)	0.94	0.81
Nash-Sutcliffe efficiency (NSE)	0.89	0.79
Percent bias (PBIAS)	6.89	2.4
RMSE-observations standard deviation ratio (RSR)	0.34	0.25

Table 4.10. Model parameter evaluation for the Mumbai WASP water quality modelling network.

4.4. Simulation of BOD

The waste-water load of the study area was calculated in terms of BOD using a Population Equivalent (PE) value of 0.225 m^3/day [SIRIM, 1991]. This value is conventionally used for developing countries, considering that the whole effluents ultimately reach the coastal waters. PE is the hydraulic or flow equivalent to the contribution from one person per day. The standard PE of the US-EPA is 0.284-0.378 m^3/day, while a 0.19 m^3/day was suggested [Chapra, 2008] for the developing countries. It is reported that 75% of the waste-water in Mumbai is untreated [De Sherbinin et al., 2007], and the remaining 25% is fully treated or partially treated by STPs. The flow weighted average of treated effluents is estimated in terms of BOD from STPs, and the final effluent load is calculated by summing the PE and STP generated loads. The effluent loads for the strong (400 mg O_2/L), medium (250 mg O_2/L) and weak (110 mg O_2/L) classes of sewage are calculated (Table 4.11), which are the conventional classification of sewage types [Tchobanoglous et al., 2003]. The three cases are incorporated into the model separately to cross check the class of sewage, which shows compatibility with the observed BOD values. The effluent load is calculated using the following equations.

$$Effluentload = \{TotalPopulation * P.E * (1Day / 24hours) * (1hour / 3600\sec) * (EffluentQuality) * 86.4\} Kg / day \quad \text{----------- (1)}$$

$$TotalEffluentload = 75\%(UntreatedEffluents) + 25\%(Treatment) \quad \text{----------- (2)}$$

The calculated load was given as input to the model in specific locations where the effluents are released into coastal waters in real time to understand the prevailing assimilative capacity behavior of the region. It may be noted that we considered only the domestic sewage generated in the area. Domestic waste-water generated in and around Mumbai enters the Arabian Sea, directly or via creeks, bays and estuaries.

From literature, it is evident that effluents from Mumbai region have medium quality and the incorporation of three cases of effluent quality (weak, medium, strong) also show results which are in par with the earlier studies [Zingde and Govindan, 2000; UNEP 2004] indicating medium sewage quality. The model BOD output for the medium quality effluents shows good comparison with observed BOD values in the region. The model underestimates the BOD values in the case of weak effluents and overestimates in the case of strong effluents, when compared to observed BOD values. The flow weighted average BOD after effluent treatment (by STPs) is calculated as 113.5 mg/L. The effluent load, calculated for different classes of sewage, generated by the total population, is given in Table 4.11. The total untreated effluent load in terms of BOD for the present population is 731,250 kg/day BOD for sewage having medium quality and after considering the treatment by STPs the effluent load assumed is 631,391 kg/day BOD. The simulated BOD attributed to the present population in the coastal waters of Mumbai is presented in Fig. 4.25. Though the region is documented for heavy metal pollution [Bhosale and Sahu, 1991] and Petroleum Hydrocarbons (PHCs) [Chouskey et al., 2004], our results indicate that Mumbai coastal region can assimilate the waste generated by present population since the BOD values (0.2 – 1.5 mg/L) are within the limit proposed by Central Pollution Control Board (CPCB), India.

Classification of sewage contamination	**Concentration of BOD (mg/L)**	**Pollutant Load (Kg/day)**	**Pollutant Load (Kg/day) after treatment**
Strong	400	1170001.15	960453.86
Medium	250	731250	631391
Weak	110	321750.32	-

Table 4.11. Sewage classification and pollution load.

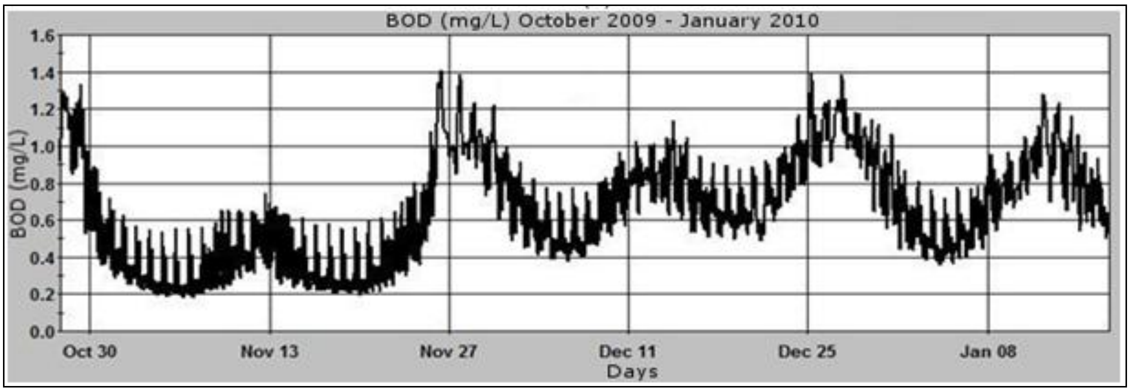


Fig. 4.25. Simulated BOD for the present Mumbai population.

During the simulation period, the temporal changes in water quality pattern reveal interesting features. The Mumbai coastal region encountered the tropical cyclone, Phyan (9-11 November 2009) within the simulation period. The physical and biological response of the Arabian Sea due to the cyclone [Byju and Prasannakumar, 2011] and coastal circulation during the event [Joseph et al., 2011; Kumar et al., 2012] were investigated by other researchers. The detailed analysis of current structure in the model domain is represented by Fig 4.26 and the effect of cyclone is clearly seen in the residual currents of the region. Modelled BOD values were higher during the pre-cyclone with a maximum value of 1.4 mg/L, then decreased to a minimum of 0.2 mg/L during the cyclone and increased thereafter showing that decrease in BOD may be due to the enhanced mixing induced by the increased wind stress. The occurrence of high rainfall during the cyclone period could also dilute the BOD concentration. Other phenomenon such as decrease in sea surface temperature during cyclone can also induce lower BOD values, since oxygen solubility is higher for cold water. This will enhance the availability of oxygen in the water column and corresponding increase in WAC. The indication is that extreme events can increase the WAC of marine environment, however only for a short period. The high primary productivity during post-cyclone can have a negative effect on WAC, due to consumption of the available oxygen for the subsequent decay of organic detritus as well as introduction of more organic detritus. The tidal currents dominate [Unnikrishnan, 2010] over the wind driven currents around the Mumbai coastal waters. Simulations done by incorporating the pollutant load calculated from present population of the region show that the BOD values respond inversely to the tidal variations (Fig. 4.27). Tides are predicted using tidal constituents of the mumbai coastal waters. For predicting tides in the present work, the south, west and north boundaries of the model domain were kept open; east is closed (land) boundary. The tidal elevations along the open boundaries have been predicted using the Global Tide Model (Andersen 1994, 1995; Andersen et al. 1995). These predicted tides have been applied as boundary conditions for model simulations. After the cyclone, BOD follows the tidal variations; during high tides, BOD values exhibit a decrease in concentration. The BOD values simulated for the middle sector in the model domain also shows the same response as that of the lower sector. This effect of the pollutant load is not visible in the upper sector. The reason could be that the hydrodynamic conditions are such that pollutant loads get dispersed before reaching the upper sector.

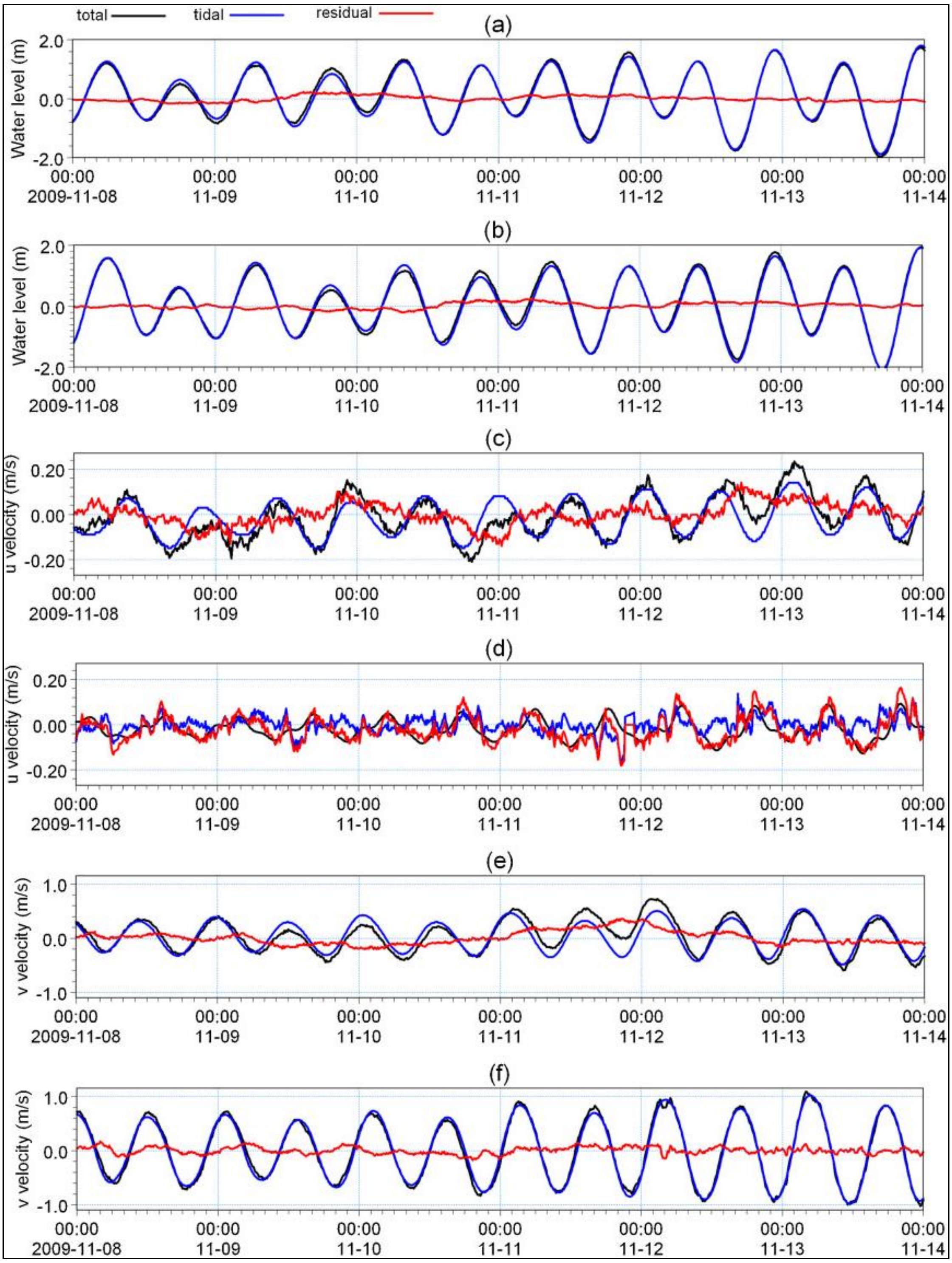


Fig. 4.26. Tidal, residual and total water levels and current velocities measured off Mumbai: (a) water levels off Worli, (b) water levels off Satpati, (c) u-velocity off Worli, (d) u-velocity off Satpati, (e) v-velocity off Worli and (f) v-velocity off Satpati.

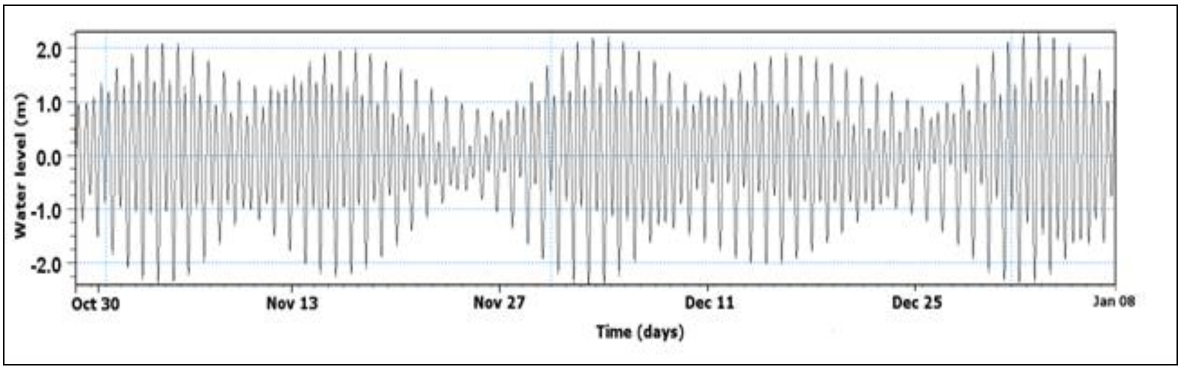


Fig. 4.27. Predicted tidal levels of Mumbai coastal region.

4.5. Demographic trends of Mumbai city

The Mumbai city and suburb are one of the most heavily populated coastal regions on earth. The total population according to the latest national census in Mumbai region is around 13 million. The number of megacities in the world has increased from 3 in 1975 to 19 in 2007. Future projections predict this figure to go upto 24 in 2015 and 27 in 2025 [Parrish and Zhu, 2009]. According to the United Nations Department of Economic and Social Affairs [UNDESA, 2012], Mumbai ranked 7th in terms of population in 2011. Future projections for the year 2025 indicate that the region is ranked 4th, ahead of New York, Mexico City and Sao Paulo with Tokyo, Delhi and Shanghai occupying first, second and third place in the list, respectively. According to the projections, we can speculate that the population difference between Tokyo and Mumbai decreases from 17.5 million in 2011 to 12.1 million in 2025, indicating higher rate of population growth in Mumbai than the most populous city. As the cities grow and flourish, the demand of water for domestic, industrial purposes surges and the issue of waste water and sewage treatment and release rise up.

Population pressure causes changes in the surface water dynamics and decline in the extent of open water [Prigent et al., 2012], which are pathways of waste materials to coastal waters. Though it is reported that population increase is responsible for the degradation of coastal ecosystems inducing serious environmental consequences [Jorge et al., 2002; Agardy et al., 2005; McGranahan et al., 2007], when we look at very closely we find that it is not population increase, but improper management of the ecosystem environment is the serious issue. Though many studies [MCGM, 2010] attribute a future population explosion in the region, the recent Government of India census indicates a negative population growth (-

5.75%) for the Mumbai city. Since the population of Mumbai region has almost doubled in a short span of past 20 years [Acharya and Nangia, 2004], it is expected that the trend may continue in future as well [Ranger et al., 2011]. The annual population growth per year and percentage growth for the years 2020, 2050 and 2100 are shown in Table 4.12. The annual and percentage population growth rate is presented in Fig. 4.28a and the projected future population growth in Fig. 4.28b. Though the projection shows decrease in both growth per year and percentage growth, population seems to double by 2050.

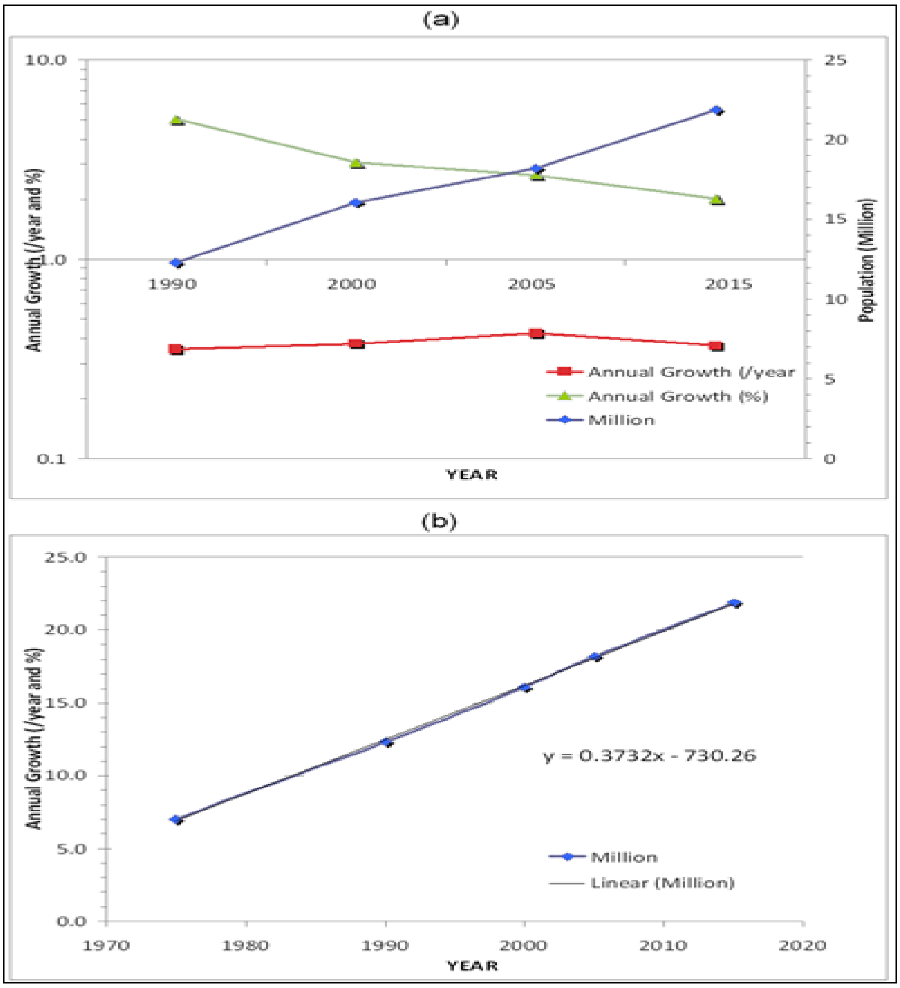


Fig. 4.28. Population growth: (a) annual growth per year and percentage growth and (b) future population growth.

Year	% Growth rate		Linear extrapolation	Average Population (in millions)
	Mean increase in population	Projected population (in millions)	Projected population (in millions)	
2020	0.16	25.36	23.61	24.48
2050	1.12	46.28	34.80	40.54
2100	2.71	81.15	53.46	67.31

Table 4.12. Population growth: average projected population growth.

4.6. Simulation of BOD for an increase in population

As a second case study, a typical scenario is considered when the present population is doubled to check whether an increase in population will adversely affect the WAC of the coastal waters or not (keeping the present hydrodynamic conditions). The scenario is considered by keeping a target value of 2 mg/L BOD. However, it may be noted that the Arabian Sea is experiencing a regional climate shift [Kumar et al., 2009; Sriver, 2011] that can potentially alter the circulation and hydrodynamics of the region in future, which we did not address in this model. Fig. 4.29 presents the simulated BOD values for the doubled population. The BOD values show substantial increase (upto 3 mg/L) when the pollutant load is increased. Though a basic process, it has been successfully brought out by a water quality model. The results show that environmental conditions/hydrodynamics cannot be that effective in diluting the pollution if the population rises to a huge surge. From the results obtained we can decipher that the BOD load is exceeding the target value of 2 mg/L. This clearly indicates that population increase can result in the exceedance of pollutants if not handled properly, and subsequently, surpasses the WAC of coastal waters. This will exert additional pressure to already pressurized coastal zone, implying its severe vulnerability in near future.

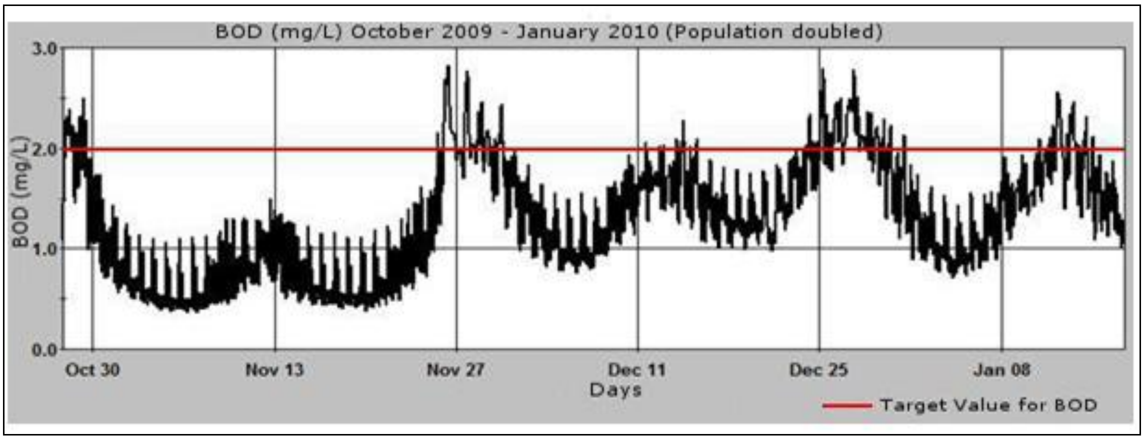


Fig. 4.29. Simulated BOD for an increase in population with the present coastal hydrodynamics.

4.7. Waste assimilative capacity of Mumbai coastal waters

Coastal waters are the ultimate receivers of the organic waste materials generated by upstream cities and towns. This waste can cause dissolved oxygen depletion due to increased oxygen demand, affecting the natural ability of water bodies to withstand certain amount of pollution - the Waste Assimilative Capacity. The pollution load (BOD) calculated using the Population Equivalent value of 0.225 m^3/day for the present Mumbai population of 13 million is 731,250 kg/day. Simulations using MIKE-21 and WASP models along with the observed water quality data as well as current meter data indicated that the coastal waters can withstand the present pollution load since the simulated BOD was within the range of 0.2-1.5 mg/L, the National Standard limits. In spite of the teeming population, the modelling exercise of the Mumbai region reveals that the coastal waters can assimilate the waste generated by the present population due to the specific hydrodynamic conditions prevailing in the region. The water quality of the Mumbai region balances the fluxes of pollutants received and their dispersion by tidal flushing as well as their decay and removal from the water column by processes such as degradation, adsorption on suspended solids, sedimentation and biotic uptake [NIO, 2010]. A projected population increase exceeded the target BOD value of 2 mg/L, indicating the deterioration of ambient quality of coastal waters. In addition to these changes, the WAC of coastal waters around India can change intra-annually as the coastal currents change direction with season [Shankar 2000]. The coastal current along the west coast of India, the WICC, one of the two eastern boundary currents which flow against the winds [Shetye et al., 1991] is southward during June to

September and northward during November to January. The uniqueness in the current regime will have many implications regarding the WAC of the region compared to other coastal areas.

4.8. Climate change and waste assimilative capacity

4.8.1. Climate change and WAC along global coastal megacities – a review

In recent decades, population increase and industrialization, the congruent factors contributing to coastal pollution and environmental stress, eventually lead to the rise of megacities (cities having population more than 10 million) in the coastal zones. They are important drivers for socio-economic development as well as sources of environmental challenges [von Glasow et al., 2012]. Nearly half of the world population now lives within 200 km of the coast, and it is expected to reach 75% by 2025 [Creel, 2003; UNESCO, 2009]. It is likely that a substantial proportion of wastewater generated from this population will directly be discharged into the coastal environment with little or no treatment [Islam and Tanaka, 2004], and this can eventually lead to the evolution of low oxygen zones, as evident from previous experiences around the globe [Rabalais et al., 2010]. An estimated 90% of the untreated wastewater from urban areas in developing countries is discharged directly into the rivers, lakes or the oceans [Evans et al., 2012]. Such discharges, allied to run off, are part of the reasons why de-oxygenated dead zones are growing rapidly in the seas and oceans of the developed world and emerging now in developing countries [Corcoran et al., 2010].

The deliberate or undeliberate discharge of wastes into the coastal environment primarily affects the WAC of coastal waters. Majority of the pollutants reaching the coastal waters through point and non-point sources are organic in nature. By far, the maximum volume of waste discharged into the marine environment is sewage [Islam and Tanaka, 2004; Foroughi et al., 2010] and the high organic loading is the primary cause of oxygen depletion in the coastal waters [Naqvi et al., 2006]. The high organic loading can significantly reduce the amount of dissolved oxygen in water, a natural mechanism for the degradation of pollutants and the basic working principle of WAC. The decrease in the dissolved oxygen content in coastal waters can be further amplified as a result of present ocean temperature increase. Recent studies by Jaccard and Galbraith [2012] showed that the climate driven changes are responsible for decreased oceanic dissolved oxygen concentration in the past. Over the past 40 years, nearly 84% of the increase in the earth's heat budget has been absorbed by the surface oceans that increased the average temperature of the upper 700 m of water column by 0.1°C [Wohlers et al., 2009]**.** This process is likely to accelerate in the next few decades, with a predicted increase in global mean sea surface temperature between 1.1°C and 6.4°C, until the end of the 21st century [Wohlers et al., 2009]. One of the impacts of ocean warming is a decrease in dissolved oxygen content of waters [Stramma et al., 2012] as solubility of oxygen is less in warm waters compared to cold waters. The potential of dissolved oxygen in establishing healthy ecosystems is very well documented **[**Stramma et al., 2010; Conley et al., 2011]. Numerous biological and physiological processes have oxygen thresholds that restrict the activity and habitat of marine organisms from microbes to macrofauna [Deutsch et al., 2011].

Ocean deoxygenation is bound to occur in a warming and more stratified ocean [Gruber, 2011]. Deoxygenation is predicted, not just because oxygen is less soluble in warm water, but global warming may increase upper ocean stratification, thereby reducing the oxygen supply to the ocean interior. Ocean models predict decline of 1 to 7% in the global ocean oxygen inventory over the next century, with decline continuing over thousands of years or more into the future [Keeling et al., 2010]. Median oxygen decline rates are more severe in a 30 km band near the coast than in the open ocean (>100 km from the coast) and the percentages of oxygen time series with negative oxygen trends are also greater in the coastal ocean than in the open ocean [Gilbert et al., 2010]. A recent study by Lima and Wethey [2012] reveals significant warming of 71% in the world's coastal waters by quantitative estimates of changes in coastal Sea Surface Temperature (SST) with unprecedented levels of spatial and temporal resolution worldwide. The decadal to multi-decadal variation in SST is part of the global warming [Dai, 2013].

The global coastal megacities (hereinafter referred to as CMCs) are generators of waste materials of all types. The major contributor of this waste is the sewage, discharged directly or after primary treatment into the coastal waters. The number of global increasing since the last 3 decades and it has increased from 3 in 1975 to 19 in 2007. Future projections predict this figure to go upto 24 in 2015 and 27 in 2025 [Parrish and Zhu, 2009; UNDESA, 2012]. The existing 18 CMCs delineated based on the study of Klein et al. [2003] are listed in Table 4.13. The SST changes in coastal waters of megacities computed from high resolution SST data set available in open domain [Lima and Wethey, 2012] are useful to determine the trend of SST. Though, the cities like Dhaka, Kolkata and Cairo are situated away from the sea, yet they are considered as coastal cities because of their deltaic setting. Coastal cities contrive to spread their transformative influence both into the hinterland, along the coastline, and into the coastal waters themselves [Timmerman and White, 1997]. Thus, Sao Paulo, which is situated 800 m above sea level, is considered here as a CMC, because as of now, the city is situated less than 50 km away from the coastline but it seems that the city is growing continuously; Sao Paulo will eventually reach the coast [Nicholls, 1997] as in the case of other CMCs in the recent past.

Rank according to Megacity population	**Country**	**city**	**Population (millions)**	**SST change**	**SST-increase /decade (°C)**
1	Japan	Tokyo	37.22	Increasing	0.29± 0.012
4	United States of America	New York	20.35	Increasing	0.2± 0.01
5	China	Shanghai	20.21	Increasing	0.46± 0.01
6	Brazil	São Paulo	19.92	Increasing	0.29± 0.01
7	India	Mumbai	19.74	Increasing	0.24± 0.01
9	Bangladesh	Dhaka	15.39	No significant trend	0
10	India	Kolkata	14.40	No significant trend	0
11	Pakistan	Karachi	13.88	Increasing	0.27± 0.01
12	Argentina	Buenos Aires	13.53	Increasing	0.614± 0.01
13	United States	Los Angeles	13.40	Decreasing	- 0.34± 0.01

	of America				
14	Brazil	Rio de Janeiro	11.96	Increasing	0.23± 0.01
15	Philippines	Manila	11.86	Slight increase	0.05± 0.01
17	Japan	Osaka-Kobe	11.49	Increasing	0.17± 0.01
18	Turkey	Istanbul	11.25	Increasing	0.44± 0.01
19	Nigeria	Lagos	11.22	Increasing	0.33± 0.01
20	Egypt	Al-Qahirah (Cairo)	11.17	Increasing	0.36± 0.01
21	China	Guangzhou, Guangdong	10.85	Increasing	0.24± 0.01
22	China	Shenzhen	10.63	Increasing	0.24± 0.01

Table 4.13. List of coastal megacities and occupying country with population (in millions) and SST changes (°C) in their coastal waters.

The majority of CMCs are located in the developing and under-developed world, where technologies and infrastructures are not sufficient enough to meet the growing need of soaring population. Even though the need is satisfied presently in some of these CMCs, the future of waste water problems and management is whimsical. The clustering of megacities in the coastal zone is due to the simple fact that access to water is facile and is a foremost player in social and economic development. The most populous continent Asia alone has 10 CMCs. As the cities grow and flourish, the demand of water for domestic and industrial purposes increases and subsequently, the problem of waste water and sewage discharge/management also arise. The majority of urban sewage being organic in nature, the DO in receiving water column decreases due to the oxidation of organic material and bacterial decomposition. DO is the most critical water quality parameter essential for the sustainable health of the coastal waters and survival of aquatic flora and fauna. The build-up of organic pollutants in coastal waters through effluent discharges has a deleterious effect on the dissolved oxygen content due to its utilization.

Once the discharged pollutants reach a critical threshold value of the ecosystem, any further discharge is undesirable. In coastal waters, the oxygen utilized by bacteria for the decomposition of organic waste is compensated through diffusion of atmospheric oxygen. The overall partitioning of oxygen between the atmosphere and ocean, are sensitive to the rate of surface-to-deep ocean circulation and mixing, temperature and salinity as well as the biological production [Joos et al., 2003] through photosynthesis. There is always a time lag between the oxygen replenishment and its utilization in oceanic environment. If more and more organic wastes find their way to coastal waters, there is a possibility for the time lag to stretch beyond normal limits and result in concomitant rise of Biochemical Oxygen Demand, which is the amount of oxygen utilized by bacteria in decomposition of organic wastes. The replenishment of utilized DO primarily depends on oxygen saturation by re-aeration and primary production, which keep the healthy status of coastal waters.

4.8.2. Climate change effects on WAC: Mumbai region as a case study

Projected future population [UNDESA, 2012] indicates a steady population growth in all the major coastal megacities with increase in the number of CMCs around the globe. More countries are transforming from underdeveloped to developing and developing to the developed. The growth of CMCs over the past years is presented in Fig. 4.30, which shows that majority of the megacities are located in the coastal zone. With the soaring population, the growth of new CMCs will ultimately lead to an enormous influx of effluents to the coastal waters. The organic materials in the water body received through city effluents will contribute to the decrease in DO in the water column. The temperature increase can significantly reduce the DO saturation in coastal waters. This implies that changes in water temperature can affect the basic oxygen solubility mechanism in sea water. A slight increase in temperature, however, does not immediately affect the mechanism. If the temperature rises consistently for a long time, there is a possibility of DO and BOD mechanisms to get affected. Table 4.13 indicates the SST change and SST increase per decade along the coastal waters of CMCs.

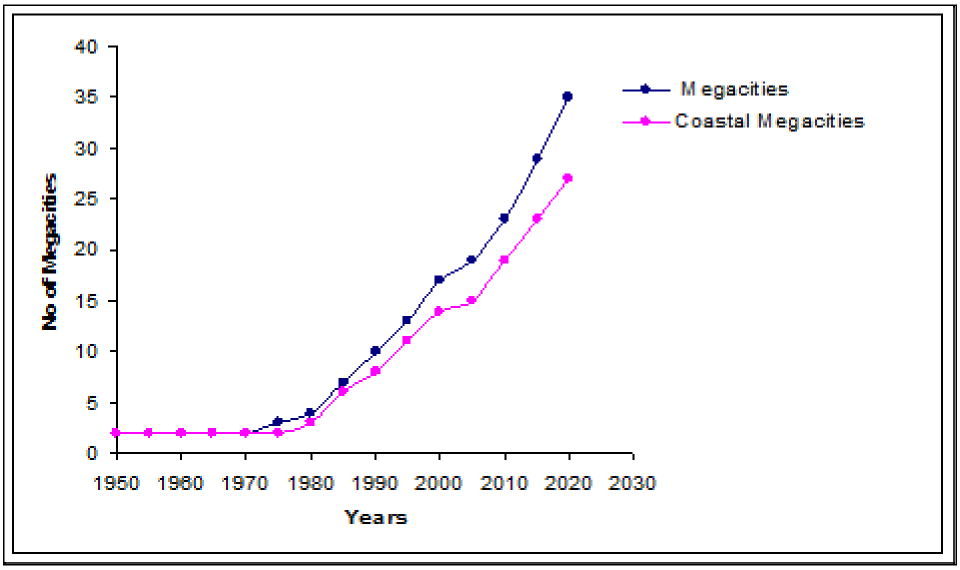


Fig 4.30. Temporal growth of megacities and coastal megacities.

Moreover, increased temperature in the water column also promotes increased bacterial breakdown of organic matter and will further deplete the oxygen level. Hence, the overall effect of low oxygen solubility and increased bacterial decomposition of organic matter due to increased temperature can reduce the oxygen levels to a very low value. When the effluents are discharged into the warming areas (where oxygen solubility is less due to increased temperature), the potential of these effluents to further deplete the DO is high. Thus, the combined aftermath of high effluent discharge and increased temperature can alter the normal oxygen content of the water column. The low oxygen values can first lead to hypoxic condition and then to anoxic condition in the water column, ultimately decreasing the WAC of coastal waters.

An example is the coastal waters of Mumbai megacity, which receives substantial amount of sewage load per day which is around 2300 MLD (million litres per day) [CPCB, 2005]; Mumbai population generates about 731,250 kg/day BOD. The waste water generated by the city is discharged into the coastal water, and this has given rise to hypoxic condition in the subsurface coastal waters of Mumbai. Sampling at 18 stations have been carried out in the coastal waters of Mumbai (Fig. 4.31) in 2009, and the results show hypoxia (DO concentration is below 1 mg/L) in the subsurface layers (Fig. 4.32). The temporal variation in DO (Fig. 4.33) off Mahim also indicates hypoxic layers. Mahim area is an impact zone of sewage outfalls [Vijay et al., 2010]. The SST change in the coastal waters of Mumbai megacity shows an increasing trend. The decadal change in SST is found to be 0.24 ± 0.01in the present analysis. It can be seen that coastal waters along most of the megacities experience an increasing decadal trend in SST, with the highest changes in the coastal waters of Buenos Aires (0.614 ± 0.01°C), Shanghai (0.46 ± 0.01°C) and Istanbul (0.44 ± 0.01°C). The coastal waters of Los Angeles, USA is an exception, which shows a decrease (-0.34 ± 0.01) in the SST pattern. The increasing trend can affect the oxygen solubility along the coastal waters. Similarly, most of the populous CMCs are located in regions already vulnerable to ocean deoxygenation (Fig. 4.34).

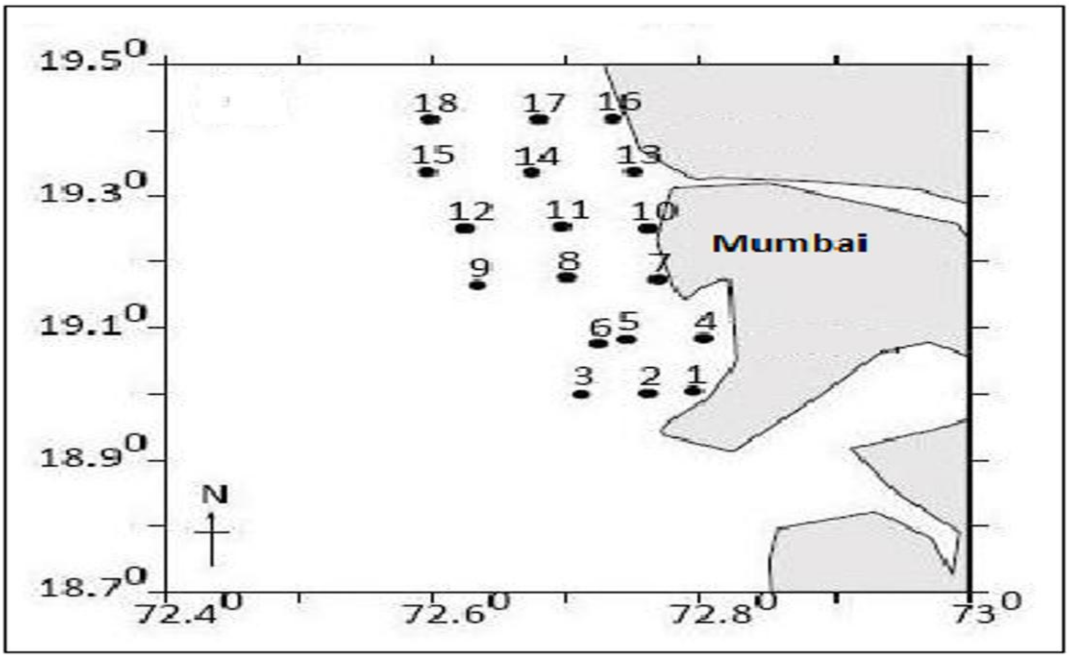


Fig. 4.31. Location of sampling stations in the coastal waters of Mumbai.

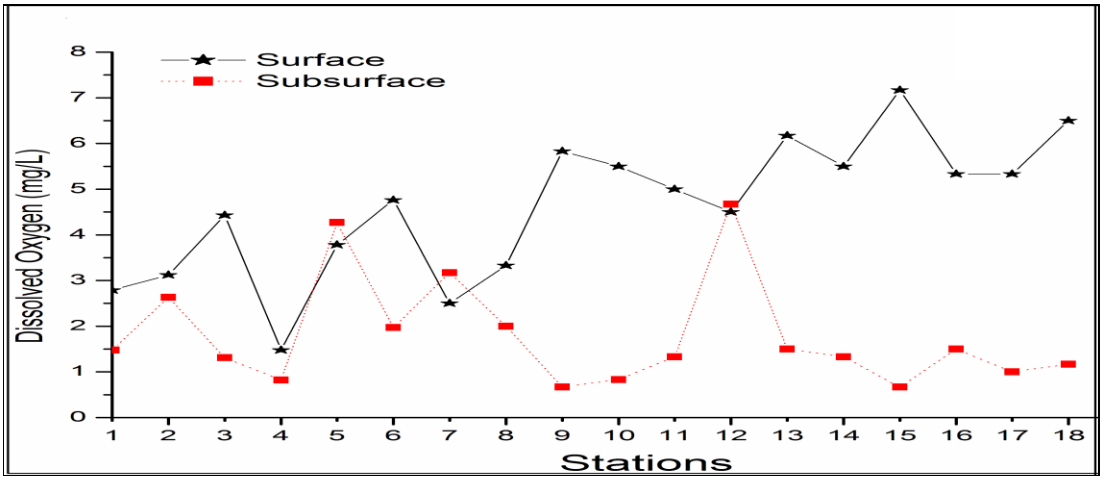


Fig. 4.32. DO variation in surface and subsurface layers in the coastal waters of Mumbai.

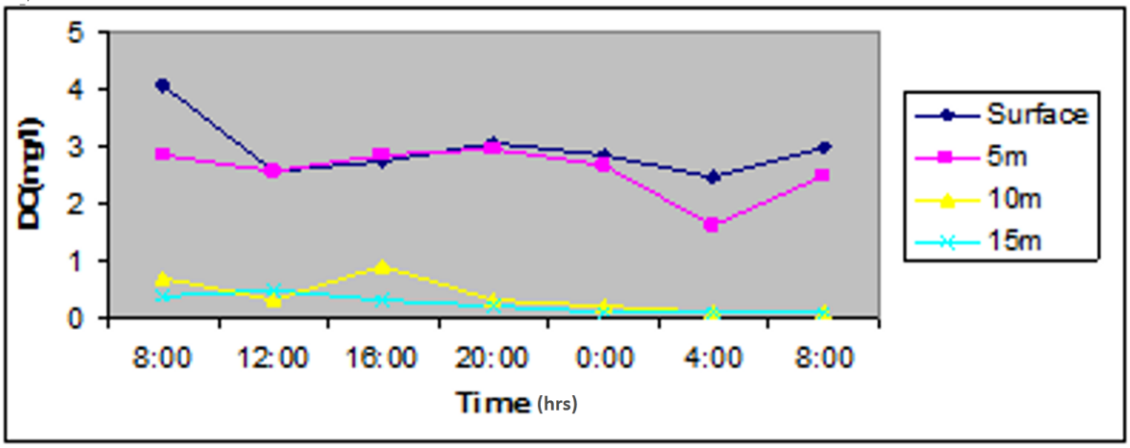


Fig. 4.33. Temporal variation in DO levels off Mumbai at various depths.

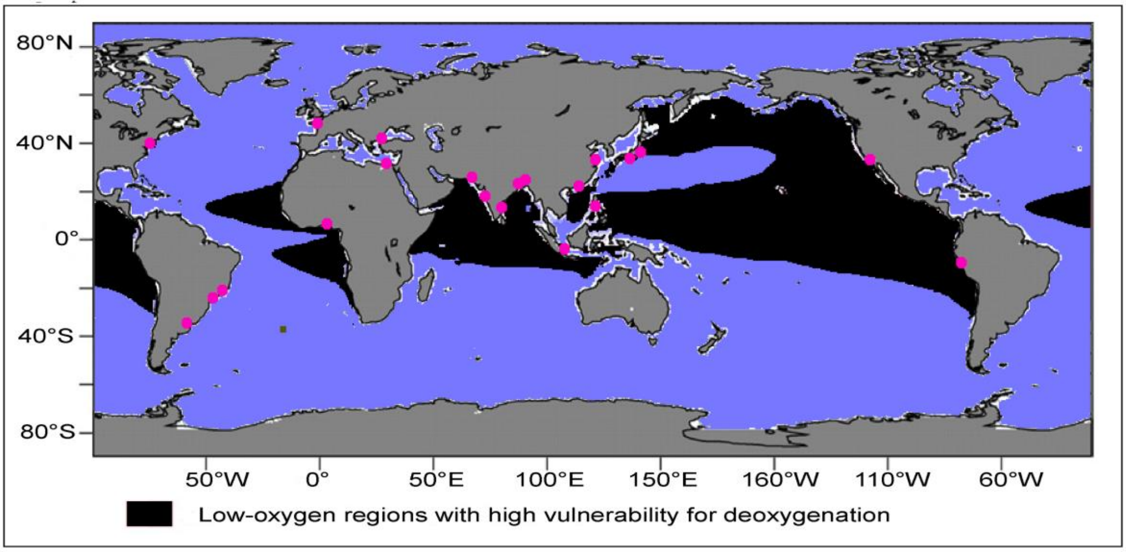


Fig. 4.34. Global map showing regions vulnerable to ocean deoxygenation (adapted from Gruber 2011) and coastal megacities (pink circles).

When the locations of CMCs coincide with the zones already vulnerable to deoxygenation and warming regions, the result will be detrimental. In addition to this, the annual climatological oxygen distribution (Fig. 4.35) also indicates the criticality of the location of CMCs. The combined effect of anthropogenic effluent discharge and present climate change has the potential to reduce the WAC of the coastal waters, and thereby worsening the situation further. A disquieting aspect of oxygen depletion in coastal waters is that it promotes the production of nitrous oxide (N_2O), a highly potent green house gas due to denitrification in oxygen depleted regions [Naqvi and Unnikrishnan, 2009]. In addition to this, the high organic inputs also produce CH_4. The high organic inputs to the hypoxic coastal waters also promote production of CH_4 [Naqvi et al., 2010], again a highly potent green house gas. The Global Warming Potential (GWP) [Shine et al., 2005] of CH_4 (72) and N_2O (289) is higher than that of CO_2. This implies that rising number of CMCs can have a significant effect on the projected global warming.

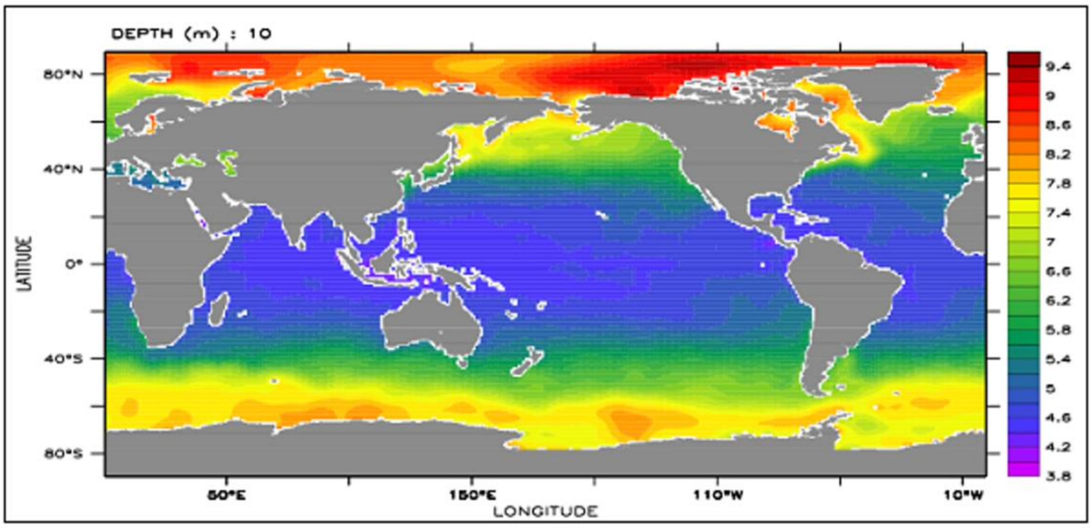


Fig.4.35. Annual climatological distribution of oxygen (WOA, 2009).

A mechanism is proposed as revealed in the present study that (Fig. 4.36) that the CMCs can induce positive feedback on the projected global warming. The increase in the number and size of coastal megacities with corresponding increase in population results in heavy input of organic materials to coastal waters. This will reduce the DO in the water column substantially. The warming coastal waters reduce the oxygen solubility and increase bacterial break down of organic matter, which further lower the DO in the water column. This can cause an overall reduction in DO available for the sustainable survival of the ecosystem. Thus, the low DO can trigger the production of highly potent green house gases, by shifting the oxic water to hypoxic and then to anoxic state, implying a positive feedback to projected global warming and the synoptic decrease in waste assimilative capacity (WAC) of coastal water. The decrease in WAC is due to the facts that DO is the basic driving factor for the successful operation of WAC mechanism. This decreased WAC has far reaching consequences as it affects the sustainable ecosystem health and prevailing pollutant dispersal mechanism.

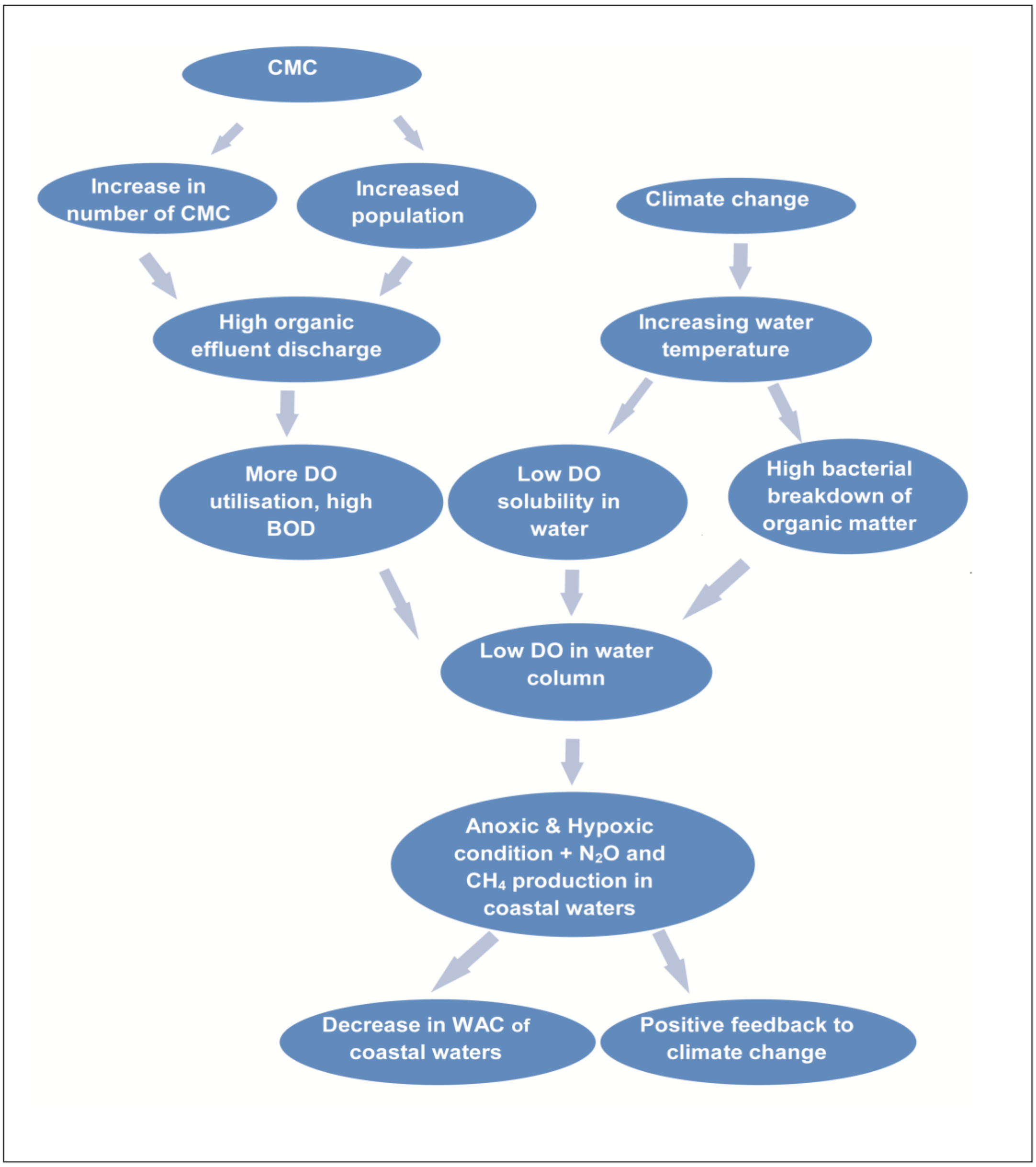


Fig. 4.36. Schematic diagram of processes driven by coastal megacities contributing to climate change.

4.8.3. Future implications along the coast of India

In the present study, it is shown that the combined effect of anthropogenic effluent discharges and ocean warming scenario can be a potential threat to the sustainable health of the global coastal ecosystem and its feedback to global climate. The present domestic and industrial effluents in India and around the globe are more complex and their copious discharges in the recent decades due to life style changes and technological advances. Though, each CMC has its own particular cultural, economic and social anchorage, they have synonymic water problems. The analyses of hypoxic systems around the globe revealed that [Kemp et al., 2009] oxygen conditions improved rapidly and linearly in systems where remediation focused on organic inputs from Sewage Treatment Plants (STPs), since STPs are the primary drivers of low oxygen conditions. The results are in agreement with IPCC Fourth Assessment report, AR4: Climate Change 2007 [Nicholls et al., 2007], which states that the impact of climate change on the coasts is exacerbated by increase in human-induced pressures. In the present study, an attempt is made to decipher the primary effect of CMCs on coastal waters and its feedback to climate scenario. The present climate scenario can lower the oxygen solubility in sea water. This is exacerbated due to the rising number of CMCs and population, ultimately resulting in the decrease of WAC along the coastal waters of CMCs around the globe. There are other growing megacities along the Indian coast such as Kolkata and Chennai. Other coastal cities are also in the race for potential future megacities. These clustering of megacities along the coast of India can adversely affect the assimilative capacity of adjacent coastal waters and the effect can be exacerbated in the wake of climate change.

Chapter 5

Waste Assimilative Capacity of Gulf of Khambhat (GoK)

5.1. Gulf of Khambhat (GoK): a heavily industrialized belt

5.1.1. Industrial wastewater contribution to GoK

The GoK (Fig. 5.1) is a south to north penetration of the Arabian Sea on the western shelf of India between Saurashtra peninsula and the mainland Gujarat. It is located approximately between 20°30' N to 22°20' N latitude and 71°45' E to 72°53' E longitude. At its northern end between Sabarmati and Mahi river mouths, the Gulf is barely 5 km wide and it opens out southwards like a funnel, reaching a maximum width at Gopnath in the south. Its north-south length is approximately 115 km and covers an area of about 3,120 km^2 consisting mainly of mudflats with some rocky (sandstone) intertidal areas. A few sandy patches are also observed intermittently. The Gulf is intercepted by several inlets of the sea and creeks formed by the confluence of rivers. All the major rivers form estuaries and their inflow carries heavy load of suspended sediments into the GoK. These rivers discharge an average of 4 mg/L of sediment load at the surface and 8 mg/L at the bottom into the Gulf [Vora et al., 1980]; the average monthly water discharge into the Gulf exceeds 2000 m^3. A medium sized delta is formed near Shetrunji River between Gopnath and Ghoga.

The Gujarat Industrial Development Corporation (GIDC) has developed 8 industrial estates around the GoK (3 in Bhavnagar, 1 in Kheda, 2 in Bharuch and 2 in Surat; Fig. 5.2 a-b), of which, the major one is in Ankaleshwar. The Bharuch district along the Narmada River coast has around 2000 units of chemicals and pharmaceutical plants. Majority of large scale industries around the Gulf are located in Surat and Bharuch districts. The Narmada River receives pollution load from industrial centers like Ankaleshwar, Panoli, Jhagadiya and various other establishments in Dahej, and all of which finally release the wastewater into the GoK. Industries that contribute significantly to water pollution are chemical, fertilizers, pharmaceuticals, dye and petro products, and all these are situated around Narmada estuary in the Bharuch district. An estimated quantity of 5000 million m^3 of wastewater is being discharged annually by these industries into the Gulf. The Bhavnagar district on the other coast of the Gulf has most of the small scale industries (SSI) concentrated in the Bhavnagar Taluka, while rest of the talukas are industrially backward (Fig. 5.2 b).

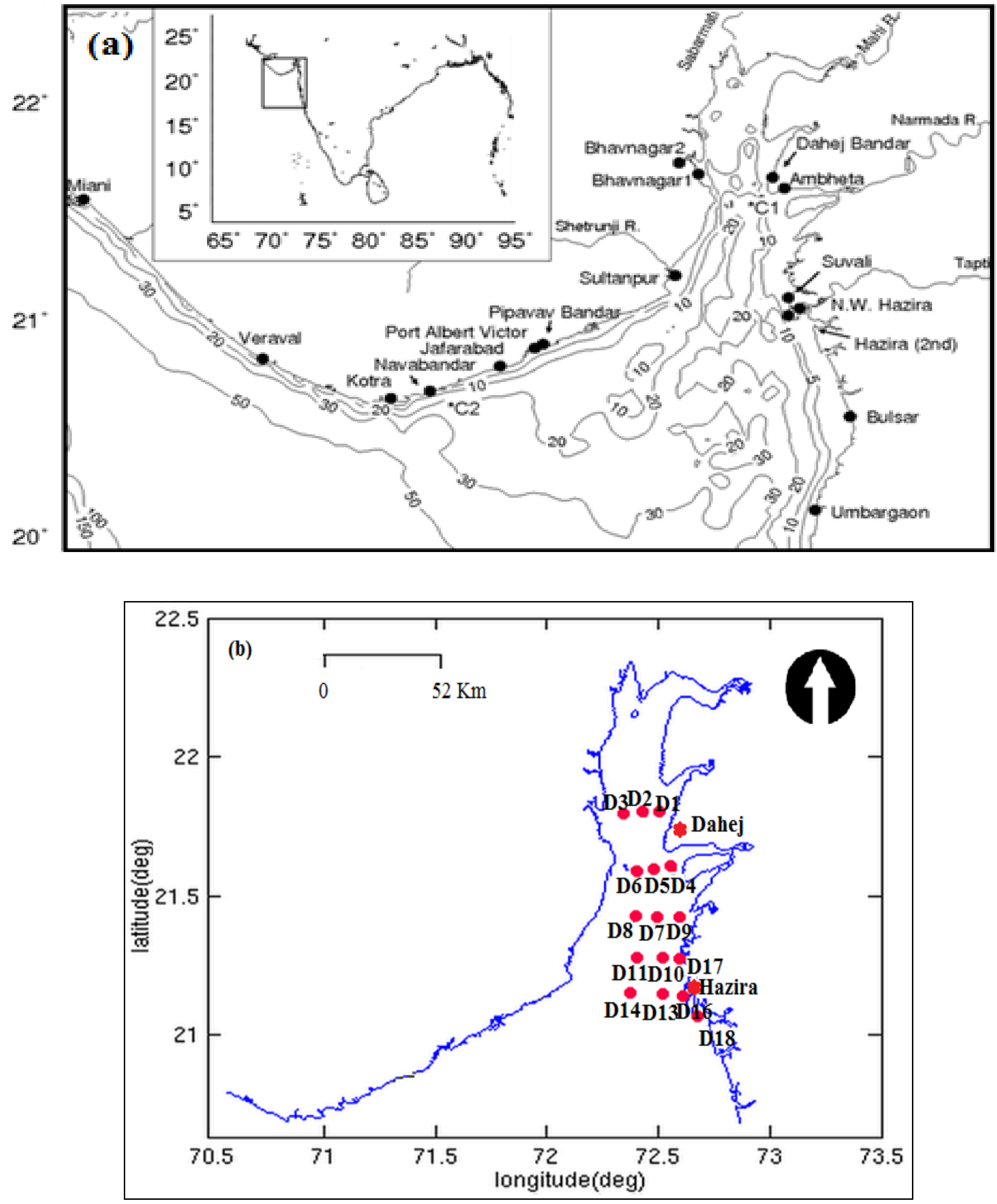


Fig. 5.1. a) Map of GoK with the major rivers flowing into GoK and b) station locations in the study area.

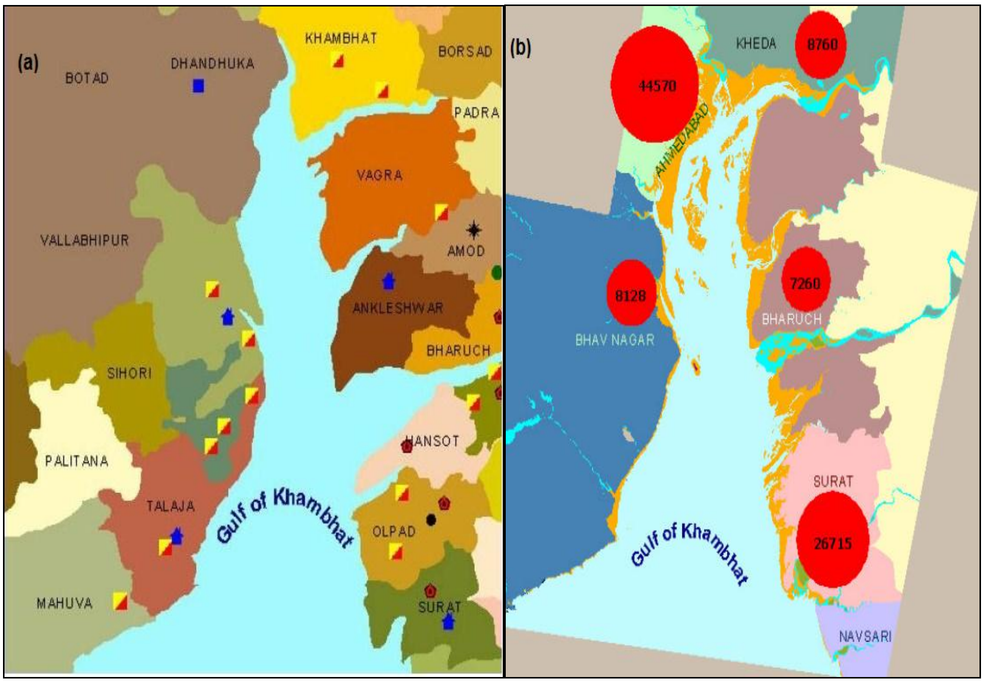


Fig. 5.2. a) Districts and b) Number of industrial units in different districts around GoK.

The Sabarmati estuary receives the waste from Ahmedabad city and industrial effluents from Naroda Vatwa effluent channel. Mahi River receives industrial wastes from Vadodara Industrial Estate, viz., Indian Petrochemicals Corporation Limited (IPCL), Gujarat State Fertilizer & Chemicals Limited (GSFC), Gujarat refinery, Gujarat Industrial Development Corporation (GIDC) and Indian Dye stuff (P) Ltd. The effluent channel also receives treated effluents from Dhanora (CPCB). ONGC also discharges large quantities of waste from the two major oil fields in Ankaleshwar and Kalol, which enters the GoK. Sabarmati River receives more domestic sewage (1168.4 MLD) than Mahi and Narmada Rivers combined (160.20 MLD) [Anonymous, 2010].

5.1.2. Physical settings

The GoK receives rain during the SW monsoon (from June to September). The average annual rainfall varies from 600 mm (on the western side) to 800 mm (on the eastern side). The Gulf has a positive water balance, mainly due to high river runoff. Temperature in the Gulf is extreme, the lowest being 8.4^{o}C during January, and the highest 43.7^{o}C during May.

The depth of the Gulf ranges from 18 to 27 m and it is less than 20 m over most of its length. However, the depth at the head is as low as 5 m and in the channel on the eastern side of the Piram Bet, it is about 50 m. The tides are of mixed semi-diurnal type, with large diurnal inequality and varying amplitude, which decrease from north to south. Due to the funnel shape and the semi-enclosed nature at the head, the tidal height increases tremendously in the upstream. The semi-diurnal tides in the GoK amplify about threefold from mouth to head, whereas the amplification of diurnal tides is much smaller [Nayak and Shetye, 2003]. The maximum spring tide recorded at Bhavnagar is 12.5 m. Due to the large tidal range, strong currents, of the order of 2 to 3m/s are observed in the Gulf. Currents were predominantly tide induced and the direction is towards north-northwest during flood tide and towards south-southeast during ebb tide [Kumar and Kumar, 2010].

5.2. Water quality of Gulf of Khambhat

The GoK is a dynamic and complex environment. This unique marine environment is endowed with marked terrestrial influence from 16 major and minor rivers. The 5 major rivers emptying into the Gulf are Sabarmati, Mahi, Narmada, Tapti and Shetrunji. Large scale urbanization and industrialization along the banks of these rivers has resulted in the discharge of huge amounts of domestic and industrial wastes into the rivers, which ultimately reach the Gulf [Jiyalal Ram, 1991; Shraddha et al., 2008; Kumar et al., 2009; Jiyalal Ram et al., 2011; Kumar et al., 2012; Deshkar et al., 2012; Isaiah et al., 2013]. Besides this, the seasonal runoff from the agricultural land, which contains mostly the nitrogenous and phosphatic material, also enters the Gulf. The contaminants received by the Gulf are so enormous that they can degrade the water quality and affect its ecology. A recent study in the three main estuaries, viz., Narmada, Mahi and Sabarmati indicated that Narmada estuary has the least pollution load in terms of nutrients among the three estuaries. BOD and phosphate were high in Sabarmati estuary [Deshkar et al., 2012]. Haldar et al. [2014] observed that the Sabarmati River stretch from Ahmedabad-Vasana barrage to Vataman is highly polluted due to perennial waste discharges mainly from municipal drainage and industries.

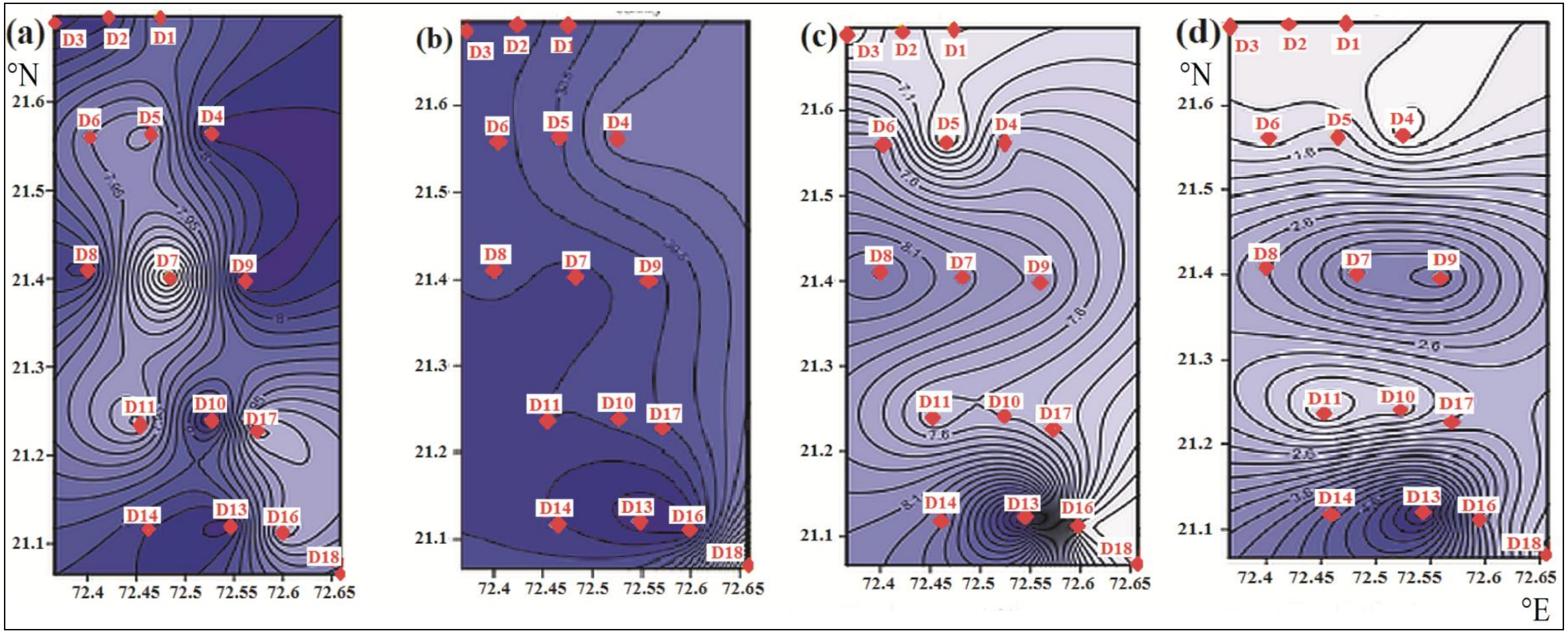
5.2.1. Variation of water quality

The spatial variation of various physico-chemical parameters at 16 different stations in the GoK is shown in Fig. 5.3 (a-n). pH ranges from 7.7 to 8.1 (av. 8.0), with higher surface pH off transects 1 to 3, starting from the coast to stns. D1, D4 and D9. Towards south, the low pH is seen between transects 3 to 5. Away from the shore, and beyond stations D1, D4 and D9, low pH is seen right from transect 1 to 4 (Fig. 5.3 a). Salinity shows a variation from 14.32 to 32.79 psu (av. 31.07 psu), with lower values near to the shore, while it increases away from the shore from transect 1 to 5 (Fig. 5.3 b). DO varies from 5.10 to 9.55 mg/L (av. 7.51 mg/L) and shows nearly uniform values all over, except, pockets of high DO in two regions (stns. 7 & 8) along transect 3, protruding as a tongue in the Gulf (Fig. 5.3 c). BOD varies from 0.08 to 6.21 mg/L (av. 2.06 mg/L) and shows uniformly low values all over, except at two regions where, higher BOD ($>$ 4 mg/L) is seen (at stns. 7 and 9 along transect 3, and at stns. 13 and 14 along transect 5), apparently coinciding with higher DO values (Fig. 5.3 d). The turbidity varies from 36.30 to 903 NTU (av. 634.82 NTU), and the northern region from transect 1 to 3 shows low turbidity and southern region from transect 4 to 5 shows very high turbidity (Fig. 5.3 e). The TSS varies from 46 to 2995 mg/L (av. 1102.2 mg/L) and shows uniform values, with very high values in patches as seen in Fig. 5.3 f. These high values are seen at stns. D2 and D3 along transect 1 and at stn. 4 along transect 2, with apparent higher values at stns. D10 and D17 along transect 4, and at stns. D16 and D18 along transect 5.

The contours of nutrients show very interesting features. The PO_4-P varies from 0.84 to 21.37 µmol/L (av. 3.12 µmol/L) and shows uniformly high values all over, with exceptionally higher values in a patch at stn. 9 along transect 3 (as a tongue protruding into the Gulf) (Fig. 5.3 g). The NO_2-N varies from 0.31 to 5.02 µmol/L (av. 1.07 µmol/L), whereas the NO_3-N varies from 19.80 to 34.26 µmol/L (av. 29.17 µmol/L) and shows high values at all the stations from transect 1 to 4, with very high values in the north at all the stations from transect 1 to 2, and a patch of higher values at stations D10 and D17 along transect 4 (Fig. 5.3 i). The NH_3-N varies from 0.53 to 44.56 µmol/L (av. 13.78 µmol/L) and also shows high values at all the stations with very high values seen as a tongue protruding into the Gulf at stations 7, 8 and 9 along Transect 3 (Fig. 5.3 j). Silicate varies from 37.45 to 85.61 µmol/L (av. 61.74 µmol/L) and shows high values at all the stations from Transect 2 to Transect 4, except Transect 1 in the north and Transect 5 in the south (Fig. 5.3 k). This shows that silicate is coming into the GoK from Narmada River. Phenols vary from 1.18 to

84.77 μg/L (av. 14.87 μg/L) and show uniform values at all the stations, except a patch of higher concentration at station D5 (mid of Transect 2) in the north (Fig. 5.3 l), which indicates a source of phenol in the Gulf. The PHc varies from 0.92 to 40.46 μg/L (av. 16.35 μg/L) and shows moderate values at almost all stations along Transect 1 to Transect 3 (Fig. 5.3 m).

The TC varies from 4000 to 83,000 CFU (av. 29,625 CFU) and shows higher values in two patches, one at station D6 along transect 2 and the other big patch at stations from D11 along transect 4 to station D14 along transect 5, which is seen as a tongue protruding inside the Gulf from the west direction (Fig. 5.3 n). This big patch indicates that the TC is coming from Shetrunji River, whereas, a smaller patch at stn. D6 on transect 2 indicates that TC is coming into the GoK from the Bhavnagar Creek.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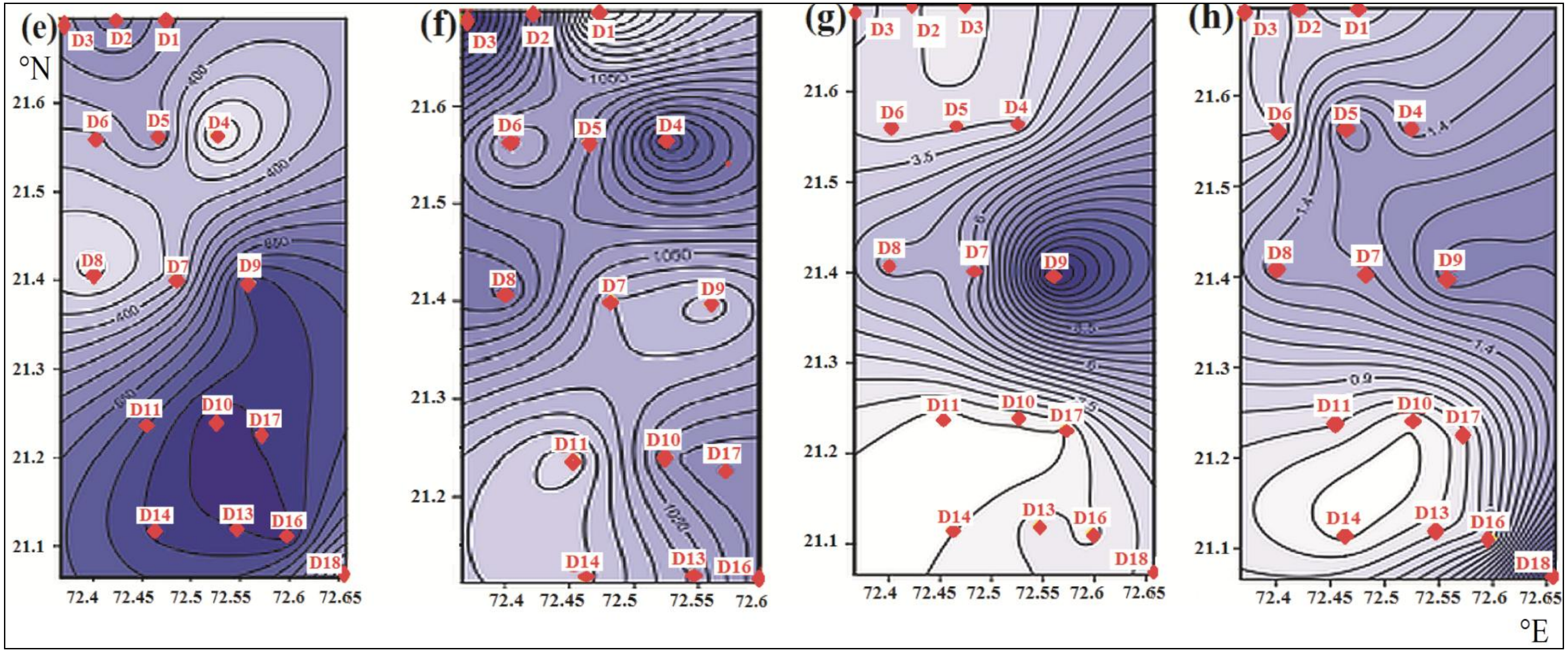
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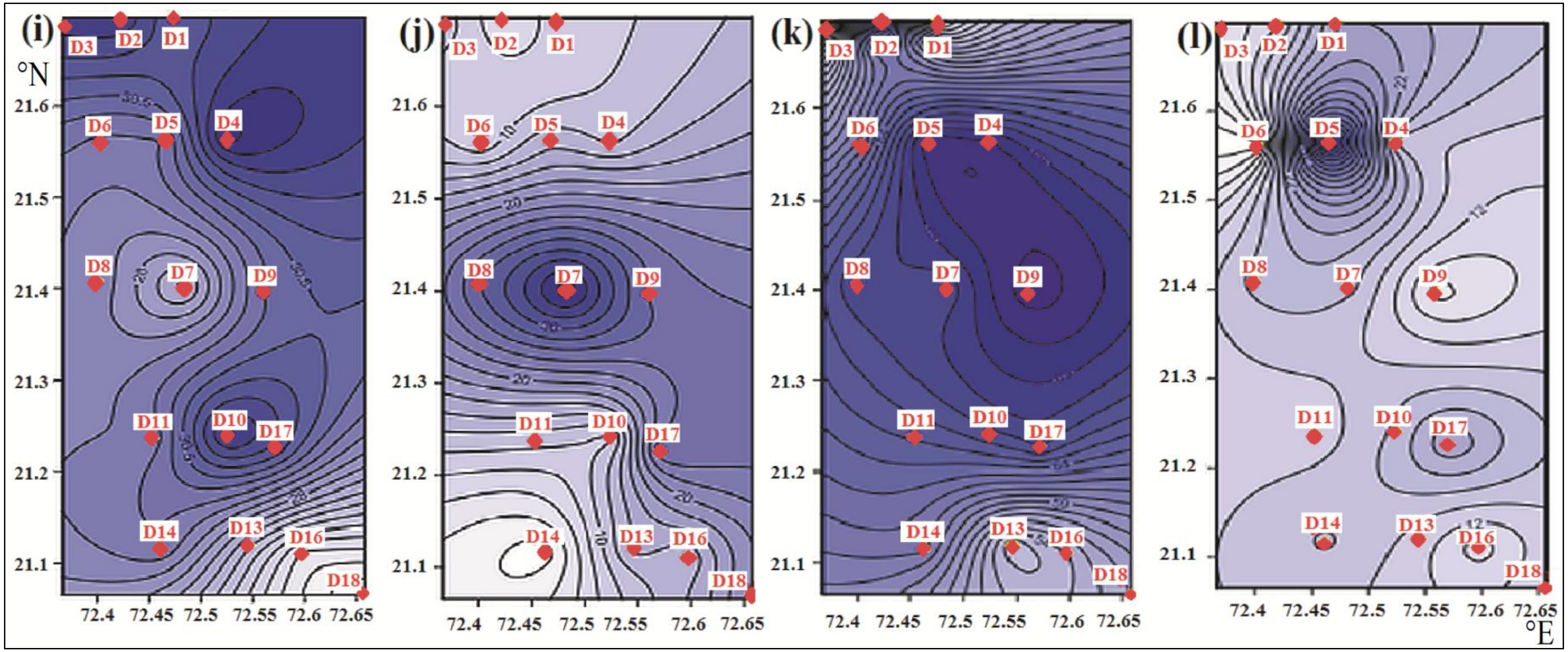
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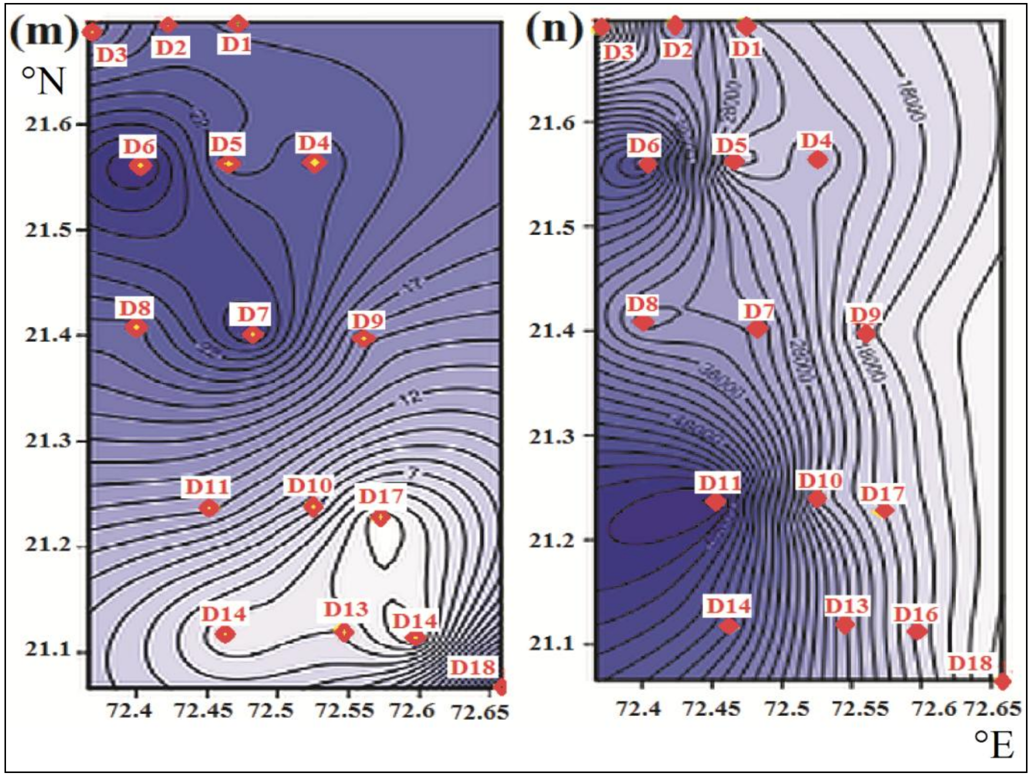

Fig. 5.3. Contours of various physico-chemical parameters at 16 stations in the GoK: .a) pH; b) salinity (psu); c) DO (mg/L); d)BOD (mg/L); e) Turbidity (NTU); f) TSS (mg/L); g) PO_4; h)NO_2 (µmol/L); i)NO_3 (µmol/L); j) NH_4 (µmol/L) ; k) SO_4 (µmol/L); l) Phenol (µg/L) ; m) PHc (µg/L); n) TC (CFU).

Trace metals (Fig. 5.4) show uniform mercury concentration in the water column, except for one high value of 0.43 µg/L in the surface layer at stn.14 off Hazira. Hg in surface water ranges from 0.07-0.43 µg/L, with an average value of 0.12 µg/L, and in bottom water from 0.07-0.18 µg/L, with an average of 0.11 µg/L. No significant variation is observed depthwise. Cadmium exhibited higher values all over, ranging from 0.05 to 1.75 µg/L in surface and 0.06-0.85 µg/L in bottom, with relatively lower values at transect III. Depthwise variation showed higher values in surface (av. 0.67 µg/L), relative to bottom (avg. 0.27 µg/L). Similarly, Lead showed higher values at transect III, relative to other transects. The variation showed a range of 0.08 - 0.84 µg/L, with an average of 0.35 µg/L in surface and a range of 0.08 - 0.69 µg/L, with an average of 0.24 µg/L in the bottom layer. The peak values in metal concentration at some stations could be due to the effect of industrial effluents.

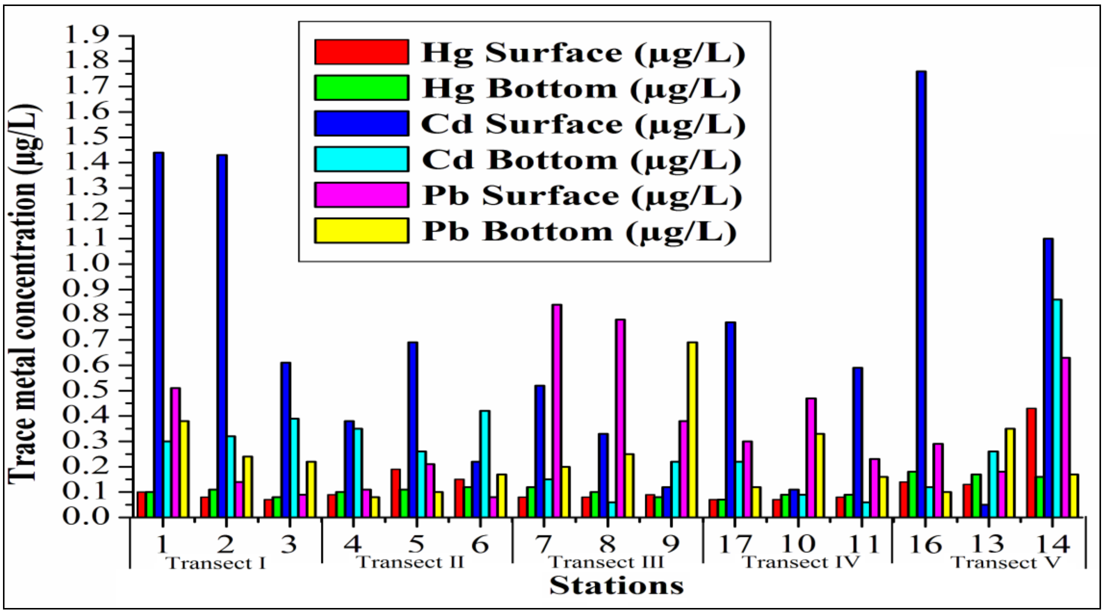

Fig. 5.4. Spatial variation of trace metals (Hg, Cd and Pb) in surface and bottom water.

Total viable count was in the range of 2-43 $x10^4$ cfu/mL, minimum count was recorded in the bottom water of D8 and the maximum, 43 x 10^4 cfu/mL from the bottom water of D6. In sediment samples an increase of two to three orders in bacterial numbers was noticed. The highest count (17.5 x 10^7 cfu/g) was obtained at D9 and the lowest (1.5 x 10^7 cfu/g) at Tapi. Bacterial abundance varied in the range of 1.99 x 10^8 cells/L to 30.96 x 10^8 cells/L. Maximum abundance is seen in the surface water of D6 and the minimum in bottom water of D18.

Minimum counts of coliforms were recorded in the surface waters of station D5, D17 and bottom waters of D18 (4 x 10^3 cfu/mL) and the maximum at bottom water of D6 (83 x 10^3 cfu/mL). Sediment samples collected from Tapi River showed the lowest coliform counts of 1.5 x 10^5 cfu/g and the highest being at D10 (31.5 x 10^5 cfu/g). The lowest no. of fecal coliforms was seen at D18 in both surface and bottom waters (5 x 10 cfu/ml), while the highest no. 425 x 10 cfu/mL was observed at bottom water of D6. In sediment samples the fecal coliforms were in the range of 1 x 10^3 cfu/g to 75.5 x 10^3 cfu/g: the lowest at D16 and the highest at D8. Among all the stations, maximum amount of productivity is observed (0.000506 mgC/m^3/day) at the surface water of D8 and the lowest at (0.000019 mg C/m^3/day) the surface water of D14. Primary productivity was minimum at the surface water at D9 (1.39 mg C/m^3/day) and maximum at the surface water of D6 (18.99 mg C/m^3/day). The maximum amount of chlorophyll was observed in the surface water at D8 (0.668 µg/L) and the lowest (0.202 µg/L) in the bottom waters at D7. While the highest phaeopigments value 0.488 µg/L was observed in the surface water at D4, the lowest value (0.109 µg/L) was observed at the surface water of D11.

Alexandrium, Centrodinium, Coscinodiscus, Gyrodinium, Gymnodinium, Gonolauyx, Ostreopsis, Polykrikos and *Warnowia* were commonly observed phytoplankton species in most of the stations. *Gymnodinium* and *Gyrodinium* are the two dominant species in this area. *Gymnodinium* was the highest in number among all the stations. Phytoplankton abundance varied from 2479 cells/L to 8179 cells/L at bottom waters of D10 and surface waters of D8, respectively. Gymnodinium was maximum at surface waters of D14 (4240 cells/L) and minimum at bottom waters of D5 (1093 cells/L). *Gyrodinium* number varied from 15 to 827 cells/L. The biomass of zooplankton varied from 0.86 mL/m^3 to 1.22 mL/m^3. Copepods formed the largest group of zooplankton. Copepods were in the range from 8148 no./m^3 at D16 to 68687 no./m^3 at D7. Chaetognaths were next to Copepods and their numbers varied from 750 no./m^3 at D13 to 16150 no./m^3 at D7. Decapod larvae, Gastropods, Siphonophores, Polychaetes, Cladocera, Fish larvae, Foraminiferans, Amphipods, Isopods, Appendicularians, Fish eggs and jellyfish were the other groups of zooplankton seen in this area. Percentage of Copepods ranged from 53.38 at station D13 to 90.83 at D11. Chaetognaths were the second highest in percentage and they ranged from 3.02 at D6 to 23.96 at D5.

5.2.2. WQI

The water quality data generated from stations off Dahej and Hazira in the GoK showed some contamination from nutrients, phenols, bacteria and turbidity. To understand the quality and type of water at these sampling locations in the GoK, water quality indices were computed.WQI for each water quality parameter is first computed individually by using the equation obtained from the value function curve in which, the concentration of the parameter is taken on Y-axis and the index value on X axis and plotted. These measured values are then transformed into a single number called the Overall Index of Pollution (OIP). The WQI index for each parameter is presented in Table 5.1, for more clarity in interpreting the OIP values. For example, in the GoK region, OIP values show polluted state mostly due the high turbidity or TSS values. It is found that a gradual increase in WQI and OIP values from north to south falling in the range of 4 - 8, suggesting slightly polluted to polluted at these stations off Dahej and Hazira. Thus, the study shows some amount of anthropogenic contamination, making the water at stations off Dahej and Hazira slightly polluted to polluted water.

	Station no.	Depth (m)	pH	WQI	DO Sat (%)	WQI	BOD (mg/L)	WQI	Turbidity (NTU)	WQI	NO_3 (umol/L)	WQI	TC	WQI	OIP
Transect 1	D1														
		S	7.96	2.43	89.12	1.26	2.31	1.54	667.00	20.61	29.16	1	27000	17.80	6.02
		MD	8.02	2.57	96.34	0.77	0.72	1.00	756.00	23.19	26.30	1	-	-	
		B	7.98	2.47	82.62	1.70	0.08	1.00	365.00	11.85	32.99	1	18000	17.20	
	D2	S	8.00	2.52	91.37	1.11	2.15	1.43	745.00	22.87	32.63	1	6500	4.98	5.50
		MD	8.00	2.52	91.4	1.10	0.80	1.00	495.00	15.62	34.26	1	-	-	
		B	8.03	2.59	85.44	1.51	0.08	1.00	546.00	17.10	32.33	1	69000	20.60	
	D3	S	8.04	2.61	87.47	1.37	1.19	1.00	665.00	20.55	31.75	1	12500	12.44	5.47
		MD	7.95	2.41	91.36	1.11	0.80	1.00	819.00	25.01	23.81	1	-	-	

		B	8.01	2.54	82.42	1.72	0.80	1.00	372.00	12.06	32.68	1	11000	10.58	
Transect 2	D6	S	7.93	2.36	96.4	0.76	2.15	1.43	204.00	7.19	26.39	1	32500	18.17	5.92
		MD	7.96	2.43	77.49	2.05	0.24	1.00	800.00	24.46	25.65	1	-	-	
		B	7.97	2.45	96.32	0.77	0.40	1.00	577.00	18.00	32.35	1	83000	21.53	
	D5	S	7.84	2.17	82.73	1.69	2.87	1.91	387.00	12.49	28.51	1	4000	3.74	4.8
		MD	7.80	2.09	101.53	1.15	1.19	1.00	471.00	14.92	25.54	1	-	-	
		B	8.03	2.59	87.47	1.37	0.16	1.00	609.00	18.92	30.60	1	37500	18.50	
	D4	S	8.03	2.59	92.21	1.05	0.80	1.00	201.00	7.10	33.92	1	32000	18.13	4.32
		MD	8.00	2.52	89.48	1.23	0.16	1.00	368.00	11.94	32.28	1	-	-	
		B	8.02	2.57	95.55	0.82	0.56	1.00	180.00	6.49	32.40	1	19500	17.30	

Tran sect 3	D7	S	7.68	1.87	107.51	1.47	4.86	3.24	45.50	2.59	22.90	1	27500	17.83	5.05
		MD	8.08	2.71	93.17	0.98	1.91	1.00	340.00	11.13	29.64	1	-	-	
		B	8.02	2.57	96.13	0.78	2.39	1.59	698.00	21.50	30.80	1	39500	18.63	
	D8	S	8.00	2.52	105.24	1.35	2.55	1.70	36.30	2.32	32.45	1	60000	20.00	4.58
		MD	8.06	2.66	92.41	0.08	1.99	1.00	775.00	23.74	31.45	1	-	-	
		B	8.03	2.59	106.38	1.41	3.03	2.02	430.00	13.74	25.30	1	6000	4.36	
	D9	S	8.00	2.52	93.57	0.96	4.78	3.18	815.00	24.90	28.96	1	4500	3.87	6.49
		MD	8.00	2.52	95.58	0.82	1.75	1.00	812.00	24.81	31.78	1	-	-	
		B	8.06	2.66	103.57	1.26	2.71	1.80	839.00	25.59	31.06	1	28500	17.90	
Tran	D17	S	7.79	2.08	107.52	1.47	3.82	2.55	903.00	27.45	31.40	1	4000	3.74	7.24

sect 4		B	8.02	2.57	79.38	1.92	0.64	1.00	772.00	23.65	31.48	1	36500	18.43	
	D10	S	8.04	2.61	83.1	1.67	1.04	1.00	901.00	27.39	32.19	1	28500	17.90	7.54
		MD	8.01	2.54	77.04	2.08	0.32	1.00	889.00	27.04	31.85	1	-	-	
		B	8.03	2.59	105.06	1.34	2.31	1.54	870.00	26.49	33.15	1	22500	17.50	
	D11	S	7.88	2.26	93.96	0.93	1.51	1.00	664.00	20.52	30.17	1	80000	21.33	7.24
		MD	8.00	2.52	112.84	1.75	3.66	2.44	839.00	25.59	29.90	1	-	-	
		B	7.95	2.41	91.05	1.13	1.19	1.00	824.00	25.16	28.13	1	49000	19.27	
	D13	S	8.02	2.57	119.69	2.11	6.21	4.14	800.00	24.46	27.02	1	36000	18.40	7.73
		MD	8.04	2.61	103.7	1.27	3.34	2.23	838.00	25.56	26.53	1	-	-	
		B	8.03	2.59	117.67	2.00	5.41	3.61	897.00	27.27	26.22	1	20000	17.33	

Tran sect 5	D14	S	8.00	2.52	102.34	1.20	4.78	3.18	862.00	26.26	29.31	1	59500	19.97	7.57
		MD	8.03	2.59	63.44	3.01	0.40	1.00	822.00	25.10	29.84	1	-	-	
		B	8.02	2.57	104.08	1.29	3.90	2.60	757.00	23.21	29.54	1	41500	18.77	
	D16	S	7.86	2.21	77.2	2.07	2.39	1.59	855.00	26.06	21.16	1	5000	3.11	6.72
		MD	8.03	2.59	115.22	1.87	4.14	2.76	829.00	25.30	23.64	1	-	-	
		B	7.97	2.45	95.17	0.85	3.42	2.28	881.00	26.81	27.68	1	29500	17.97	
	D18	S	7.99	2.50	89.03	1.26	1.83	1.00	76.90	3.50	26.27	1	13500	13.69	4.71
		MD	7.88	2.26	98.85	0.60	1.75	1.00	870.00	26.49	27.95	1	-	-	
		B	7.94	2.38	82.29	1.72	1.43	1.00	669.00	20.66	19.80	1	4000	3.74	

Table 5.1. WQI and OIP values of waters off Dahej and Hazira in the GoK.

The OIP values at stations in the horizontal transects are presented in Fig. 5.5 (a-e) and the values in the longitudinal transects in Fig. 5.6 (a-c). The N-S variation in water quality shows a gradual increase in integrated OIP values towards south (5.02 to 7.26; average OIP values of S, MD and B water sample at each station), whereas the E-W variation in OIP values showed an increase in OIP from near shore (5.87) to away from the shore (6.16).

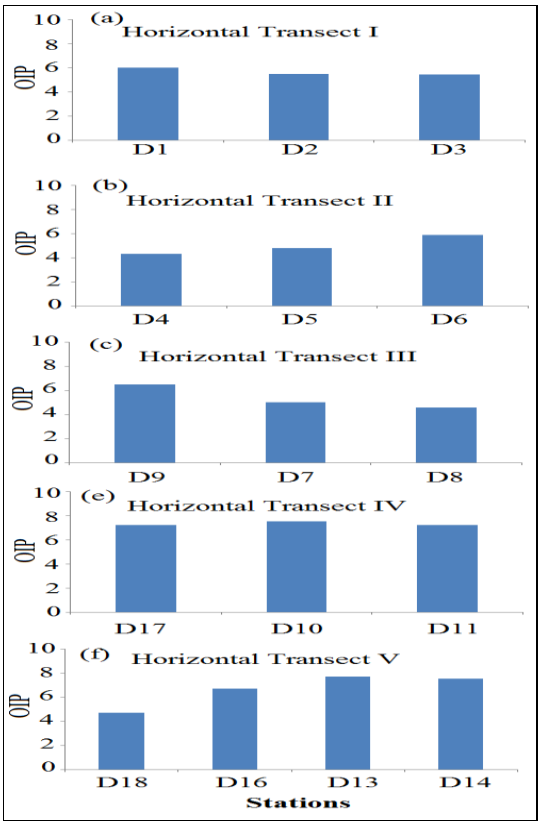

Fig.5.5. OIP values at stations in horizontal transects in the GoK (D1 - D16 are the water quality observation stations in the GoK).

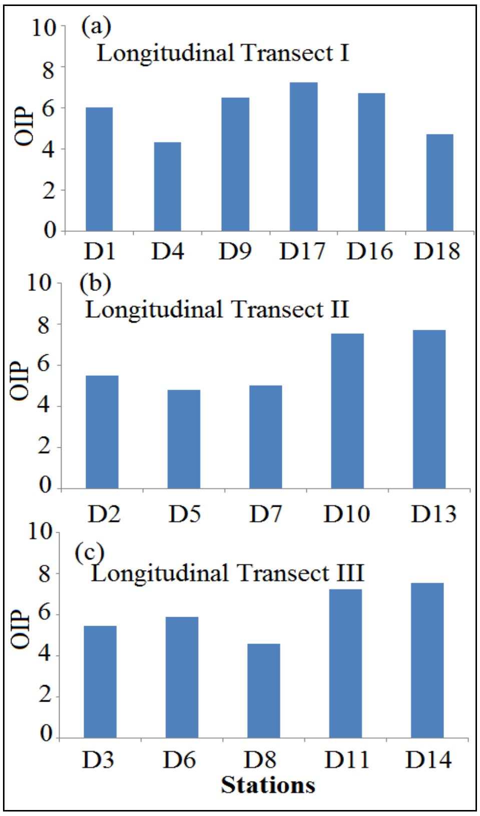

Fig. 5.6. OIP values at stations in longitudinal transects in the GoK.

The data on primary water quality parameters from stations off Dahej and Hazira in the Gulf of Khambhat showed well oxygenated water, rich in nutrients. The high phosphates, nitrates and ammonia indicated anthropogenic additions to the Gulf water. Similarly, the high turbidity and addition of high phenolic substances to the water from the riverine sources along with high bacterial content renders the Gulf water not healthy.

5.2.3. Factor and Cluster analysis

Water quality parameters from the surface, mid depth and bottom were integrated and were subject to factor analysis. The factor analysis procedure is done by integrating all the data available for the region (at all the depths) and not by averaging. This can be done using a

Fortran program or any statistical packages where the data for each depth is provided as a separate CSV file. The factor analysis (Table 5.2) showed a total of 6 factors explaining 86.25% of the variation. The correlation matrix of water quality parameters at 16 stations in the Gulf of Khambhat is presented in Table. 5.3.

Factor 1 explains 25.63% of the variation and indicates strong positive loadings of DO (0.91) and BOD (0.87) and moderate positive loading of salinity (0.71) and moderate negative loading of NO_3 (-0.57). DO and BOD correlate significantly with each other (r = 0.82), whereas salinity correlates positively with DO (r = 0.52) and BOD (0.79) and negatively with NO_3 (r = - 0.69). This shows that the addition of BOD to the Gulf water is associated with well oxygenated high salinity water and NO_3 with low salinity water. This is evident from Figs. 5.3 b, 5.3 c, 5.3 d and 5.3 j, i.e. high BOD and high DO areas in the region marked by high salinity and that of NO_3 in the region of slightly lower salinity. Studies [Deshkar et al., 2012] in the estuarine regions of the major rivers emptying into the GoK show that Narmada estuary is bringing in well oxygenated, high salinity water with low NO_3 to the Gulf, whereas the waters of Mahi and Sabarmati estuaries are of low salinity with relatively low oxygen content but very rich in NO_3. The contour of NO_3 shows high NO_3 at all the stations along Transect 1 with much higher values extending towards stn. D5 along Transect 2. The contours give an impression that large quantity of NO_3 is coming to the Gulf from Narmada, and high organic load from Shetrunji River (high values of BOD are observed at stations D13 and D14 along Transect 5).

Factor 2 explains 48.56% of the cumulative variation and indicates strong positive loadings of PO_4 (0.94), urea (0.91), NO_2 (0.82) and NH_3 (0.79) with weak negative loading of TC (-0.47). The PO_4 correlates significantly with NO_2 (r = 0.81), Urea (r = 0.81) and NH_3 (r = 0.66), and NO_2 correlates significantly with urea (r = 0.71) and NH_3 (r = 0.48), whereas, TC did not show any correlation with any of these loadings. This indicates an association or rather a common source for PO_4, NO_2, urea and NH_3, but not TC in the Gulf water. This is evident from Figs. 5.3 g and 5.3 j, which show high PO_4 at stations in areas marked by high NH_3 and apparently high NO_2 along Transect 3. It is found that these high contaminants are coming from the southern bank of Narmada River. Mahi estuarine water entering the Gulf is high in NO_2 relative to Sabarmati, whereas it has moderate PO_4 with the highest PO_4 concentration in Sabarmati water [Deshkar et al., 2012]. However, high PO_4 and NO_2 concentrations do not appear to be coming from Sabarmati or Mahi River but from Narmada River. Factor 3 explains 61.17% of the cumulative variation and indicates strong positive loading of silicates (0.90), moderate positive loading of NO_3 (0.58) and weak positive loading of TC (0.49). Silicate correlates significantly with NO_3 (r = 0.69) but not with TC, whereas, TC does not correlate with NO_3, indicating that along with NO_3, silicate is also added by the low salinity water, which is present in the north of transect 1 to 2. The silicate contour (Fig. 5.3 k) shows high concentrations of silicates at transect 2 relative to other transects, indicating addition of silicates by Narmada River water along with NO_3. The contour of TC (Fig. 5.3 n) shows additional input from the opposite side, indicating inputs from other sources and not from Narmada. The region of high TC coincides with the discharge areas of Shetrunji River, and therefore suggests addition of TC from Shetrunji River.

Factor 4 explains 72.53% of the cumulative variation and indicates strong positive loading of pH (0.93) and weak positive loading of NO_3 (0.44) with strong negative loading of phenol (-0.79). The NO_3 correlates significantly with pH (r = 0.41), but not with phenol, whereas phenol correlates negatively with pH (r = - 0.61). The pH contours show high pH in the north towards Narmada River side and low pH in the south. Factor 1 show that NO_3 is added to the Gulf water by high pH water from the north (not phenols). This is because, the area where high phenols observed as a patch at stn. D5 along transect 2 in the north is marked by low pH in the north (Figs. 4.32l and 4.32a). Factor 5 explains 79.89% of cumulative variation and indicates strong positive loading of PHc (0.88) and strong negative loading of turbidity (-0.85) and TP (-0.75) and moderate negative loading of salinity (-0.51). The PHc correlates negatively with salinity (r = - 0.46), turbidity (r = - 0.72) and TP (r = - 0.65), whereas salinity correlates positively with turbidity (r = 0.63) and TP (r = 0.59). This indicates addition of PHc by low saline and turbid waters and TP by high saline water (Figs. 5.3 b, 5.3 e and 5.3 m). These figures show that high turbidity is extending from the region where there is low salinity and high PHc; this region is marked by salinity stratification. Higher turbidity appears to be coming from the Narmada River. Factor 6 explains 86.25% of cumulative variation and indicates strong positive loading of water temperature (0.78), moderate positive loading of TSS (0.68) and strong negative loading of TN (- 0.81) with weak negative loading of TC (-0.48). Water temperature correlates negatively with TN (r = - 0.60) and not with other loadings, whereas, TSS correlates negatively with TC (r = - 0.41) and with no other loadings. The negative correlation of TN with temperature indicates that TN is being added to the GoK by water from Sabarmati and to some extent by Mahi. This is because, the Sabarmati estuary receives wastes from Ahmedabad city and industrial effluents from Naroda Vatwa effluent channel. Sabarmati also receives large quantities of domestic sewage as compared to Mahi and Narmada [GPCB, 2010]. The cluster analysis (Fig. 5.7) shows various groups of stations with similarities and dissimilarities, with major two groups, the smallest group with 3 stations (Nos. 6, 11 and 14). This smaller group in turn shows 2 groups with stns. 6 and 11 with similar characteristics to stn. 14.

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Factor 6**
Temp	0.36	0.19	0.21	-0.29	0.03	**0.78**
pH	0.08	-0.09	0.08	**0.93**	0.02	0.04
Salinity	**0.71**	-0.13	-0.30	0.08	**-0.51**	-0.04
DO	**0.91**	0.13	0.01	0.09	0.07	-0.02
BOD	**0.87**	0.19	-0.09	0.03	-0.37	-0.05
SS	-0.28	-0.12	-0.21	0.29	0.30	**0.68**
Turbidity	0.19	-0.08	-0.05	0.22	**-0.85**	-0.23
PO4	-0.04	**0.94**	0.09	0.02	0.02	0.03
NO2	-0.10	**0.82**	0.17	-0.31	0.35	0.03
NO3	**-0.57**	0.08	**0.58**	**0.44**	0.23	-0.06
NH3	0.35	**0.79**	0.10	-0.26	0.08	0.20
Si	-0.17	0.31	**0.90**	0.05	0.09	0.08
Urea	0.18	**0.91**	0.05	0.03	0.03	0.10

TP	0.23	-0.02	-0.37	-0.18	**-0.75**	0.24
TN	0.07	-0.18	-0.02	0.02	0.26	**-0.81**
PHc	-0.04	0.18	-0.04	-0.13	**0.88**	-0.18
Phenol	-0.02	0.10	-0.01	**-0.79**	0.24	0.05
TC	0.22	**-0.47**	**0.49**	-0.13	0.17	**-0.48**
Expl.Var	2.99	3.55	1.78	2.14	2.88	2.18
Prp.Totl	0.17	0.20	0.10	0.12	0.16	0.12
Eigenvalue	4.61	4.13	2.27	2.04	1.33	1.15
% Total variance	25.63	22.93	12.60	11.36	7.36	6.36
Cumulative Eigenvalue	4.61	8.74	11.01	13.05	14.38	15.53
Cumulative %	25.63	48.56	61.17	72.53	79.89	86.25

Table 5.2. Factor analysis of the data from 16 stations in the GoK.

	Temp	**pH**	**Salinity**	**DO**	**BOD**	**SS**	**Turbidity**	**PO4**	**NO2**	**NO3**	**NH3**	**Si**	**Urea**	**TP**	**TN**	**PHc**	**Phenol**	**TC**
Temp	1.00																	
pH	-0.16	1.00																
Salinity	0.11	0.08	1.00															
DO	0.27	0.14	**0.52**	1.00														
BOD	0.26	0.09	**0.79**	**0.82**	1.00													
SS	0.22	0.21	-0.24	-0.21	-0.33	1.00												
Turbidity	-0.19	0.17	**0.63**	0.16	**0.47**	-0.35	1.00											
PO4	0.21	-0.03	-0.21	0.11	0.15	-0.06	-0.09	1.00										
NO2	0.21	-0.37	**-0.42**	0.03	-0.08	0.00	**-0.48**	**0.81**	1.00									
NO3	-0.22	**0.41**	**-0.69**	**-0.41**	**-0.57**	0.22	-0.18	0.13	0.14	1.00								
NH3	**0.53**	-0.33	0.06	0.39	0.39	-0.12	-0.17	**0.66**	**0.70**	-0.16	1.00							
Si	0.20	0.08	**-0.48**	-0.07	-0.17	-0.04	-0.21	0.39	**0.48**	**0.69**	0.26	1.00						
Urea	0.35	-0.03	0.05	0.17	0.26	-0.12	-0.11	**0.81**	**0.71**	-0.04	**0.83**	0.27	1.00					
TP	0.15	-0.15	**0.59**	0.19	**0.50**	-0.10	**0.53**	-0.04	-0.25	**-0.64**	-0.01	-0.38	-0.05	1.00				
TN	**-0.60**	0.06	-0.03	0.11	0.06	-0.35	0.02	-0.20	-0.12	0.15	-0.25	-0.11	-0.26	**-0.40**	1.00			
PHc	-0.06	-0.16	**-0.46**	0.03	-0.37	0.02	**-0.72**	0.21	**0.49**	0.12	0.16	0.08	0.16	**-0.65**	0.18	1.00		
Phenol	0.36	**-0.61**	-0.25	0.00	-0.03	-0.08	-0.35	0.12	**0.40**	-0.18	0.25	0.04	0.01	-0.06	0.21	0.21	1.00	
TC	-0.28	-0.10	0.06	0.08	-0.03	**-0.41**	-0.05	-0.39	-0.19	0.02	-0.33	0.22	-0.33	-0.31	0.38	0.19	-0.13	1.00

Table 5.3. Correlation matrix of water quality parameters at 16 stations in the GoK.

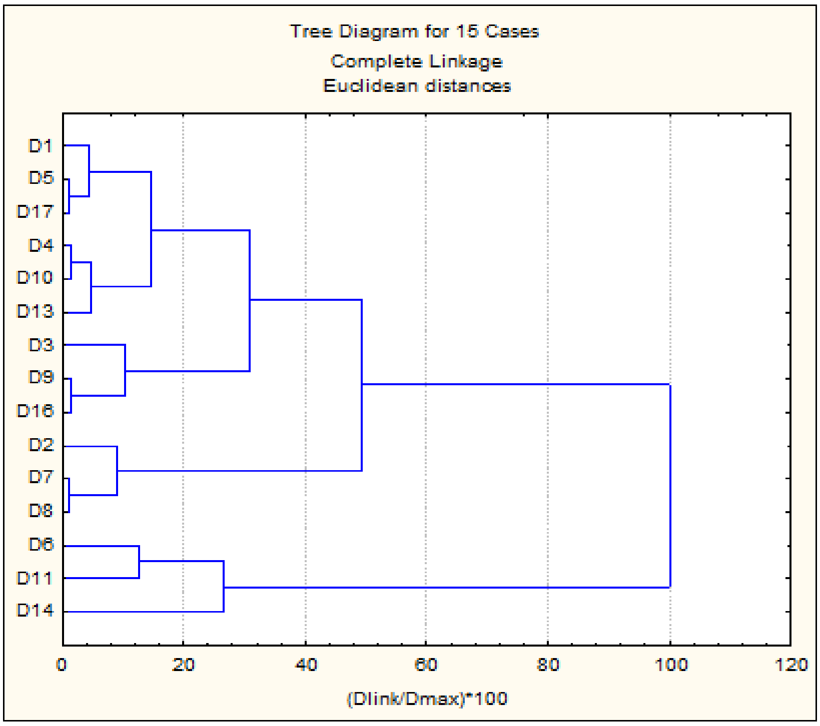

Fig. 5.7. Cluster analysis of stations in the GoK

5.3. Current regime of the region

The RCM current meter data for the period 4 March 2011 to 6 April 2011 was utilised to understand the surface and bottom current patterns prevailing in the area. The RCMs were moored in the western side of the GoK, off Dahej and off Hazira, one each at surface and bottom. The zonal (u) and meridional (v) components were resolved from the measured current speed. Subsequently, Tidal Analysis Software Kit (TASK) analysis was carried out to separate the residual currents from the tidal currents.

a) off Dahej

A very strong surface current regime is prevailing in this area (Fig. 5.8). The current speed varied between and 0.29 m/s and 2.14 m/s with mean direction towards SSW (south south-west). The task analysis shows the exceedence of residual currents over the tidal currents, both on the surface and at the bottom. The mean zonal flow is towards west and the mean meridional flow is towards north. The bottom current speed (Fig. 5.9) varied between 0.21

m/s and 1.6 m/s. The mean direction is towards SSW. The mean zonal flow is towards west and the mean meridional flow is towards north.

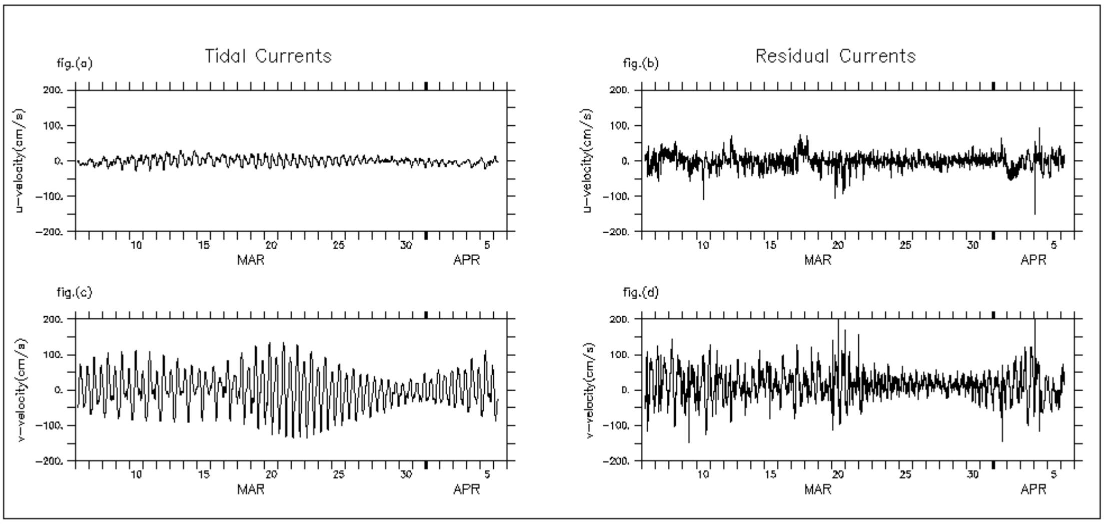

Fig. 5.8. Measured surface currents off Dahej: a & b represent the zonal component of tidal and residual current velocities while c & d represent the meridional component of tidal and residual current velocity, respectively.

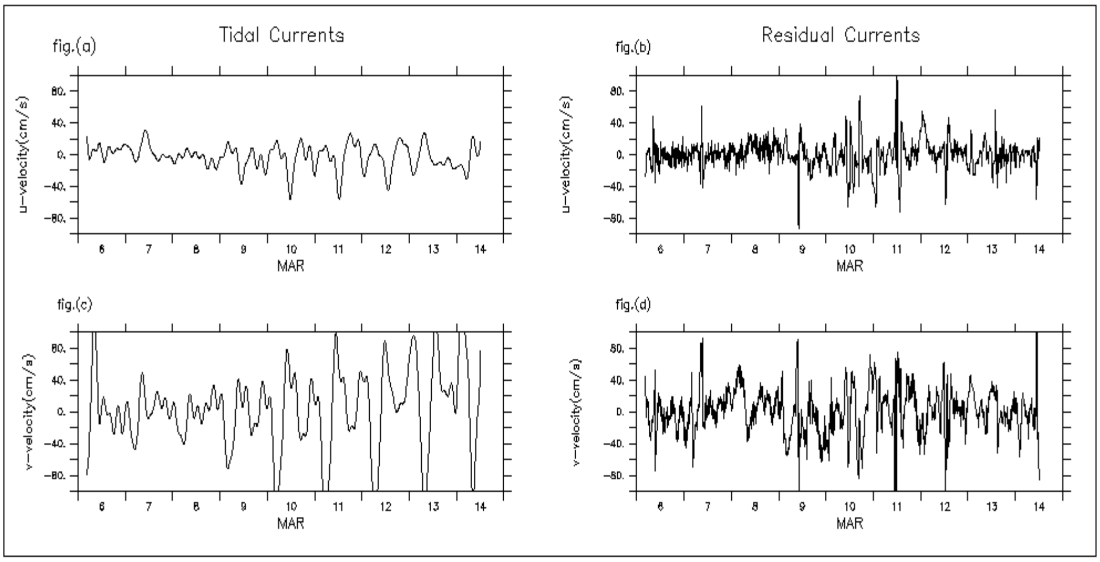

Fig. 5.9. Measured bottom currents off Dahej: a & b represent the zonal component of tidal and residual current velocities and c & d represent the meridional component of tidal and residual currents, respectively.

b) off Hazira

The surface currents off Hazira (Fig. 5.10) have a mean direction towards WSW and the tidal currents are more pronounced than the residual currents, which is typical for semi-enclosed tide dominated regimes. The mean zonal flow is towards west and the mean meridional flow is towards north. The bottom currents (Fig. 5.11) show a similar trend as surface currents; the tidal current dominates over the residual currents. The current speed varies between 0.25 m/s and 0.72 m/s and the mean current speed is towards WSW. The bottom residual current follows the same pattern as that of the surface. The scatter plots of the u and v components and time series of both surface and bottom currents are represented in Figs. 5.12 and 5.13. The surface currents are measured at 1 m depth from the surface. During spring time, the easterly component of the surface current reaches upto 0.8 m/s and the westerly component 1.0 m/s. The maximum observed northerly component is 1.08 m/s and that of southerly component 1.0 m/s during the same period. From the scatter plot, it is clear that surface currents are predominantly in the NW-SE direction, oscillating semi-diurnally. The bottom currents measured at 19 m depth are similar to surface currents. During spring period, the eastward bottom currents show a maximum value of 0.9 m/s and the westward current 1.0 m/s. The northerly and southerly components of bottom currents vary upto 1.2 m/s and 1.1 m/s, respectively. During neap time, the maximum observed eastward flowing bottom current is only 0.3 m/s and westward current is 0.2 m/s. However, the respective maximum ranges of northerly and southerly components of bottom currents are 0.8 m/s and 0.5 m/s, respectively. It is noticed from the plot that the bottom currents are in the NNW-SSE direction.

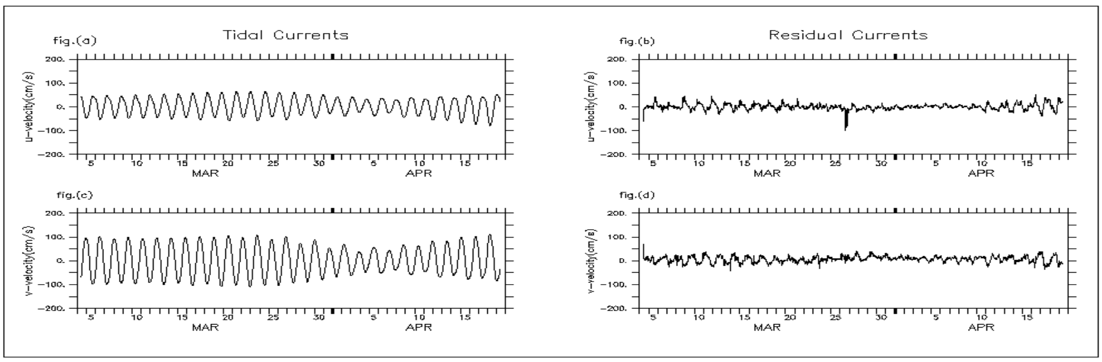

Fig. 5.10. Measured surface currents off Hazira: a & b represent the zonal component of tidal and residual current velocities and c & d represent the meridional component of tidal and residual current, respectively.

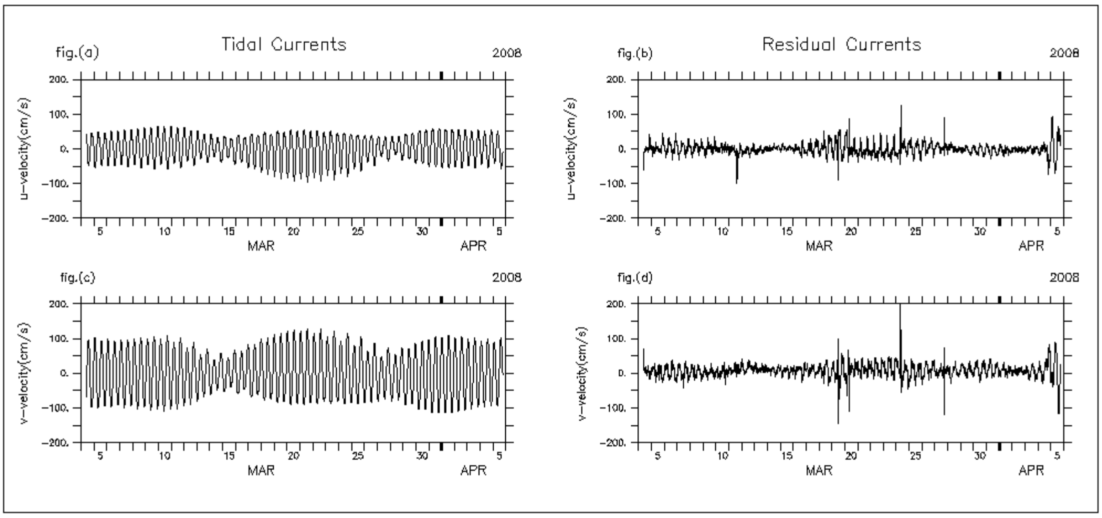

Fig. 5.11. Measured bottom currents off Hazira: a & b represent the zonal component of tidal and residual current velocities and c & d represent the meridional component of tidal and residual current, respectively.

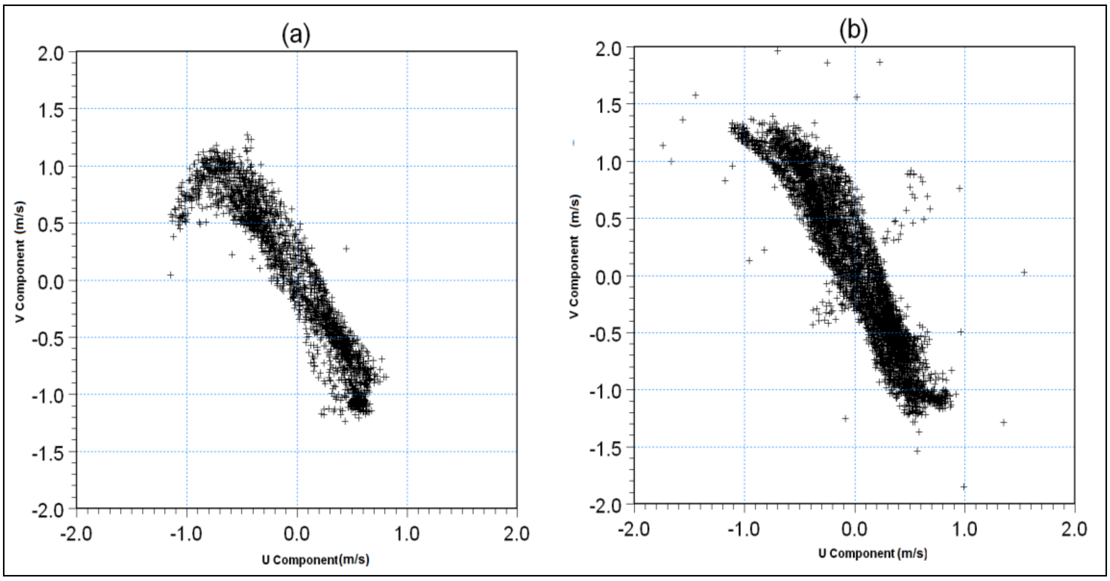

Fig. 5.12. Scatter plots of u and v current components at (a) surface and (b) bottom.

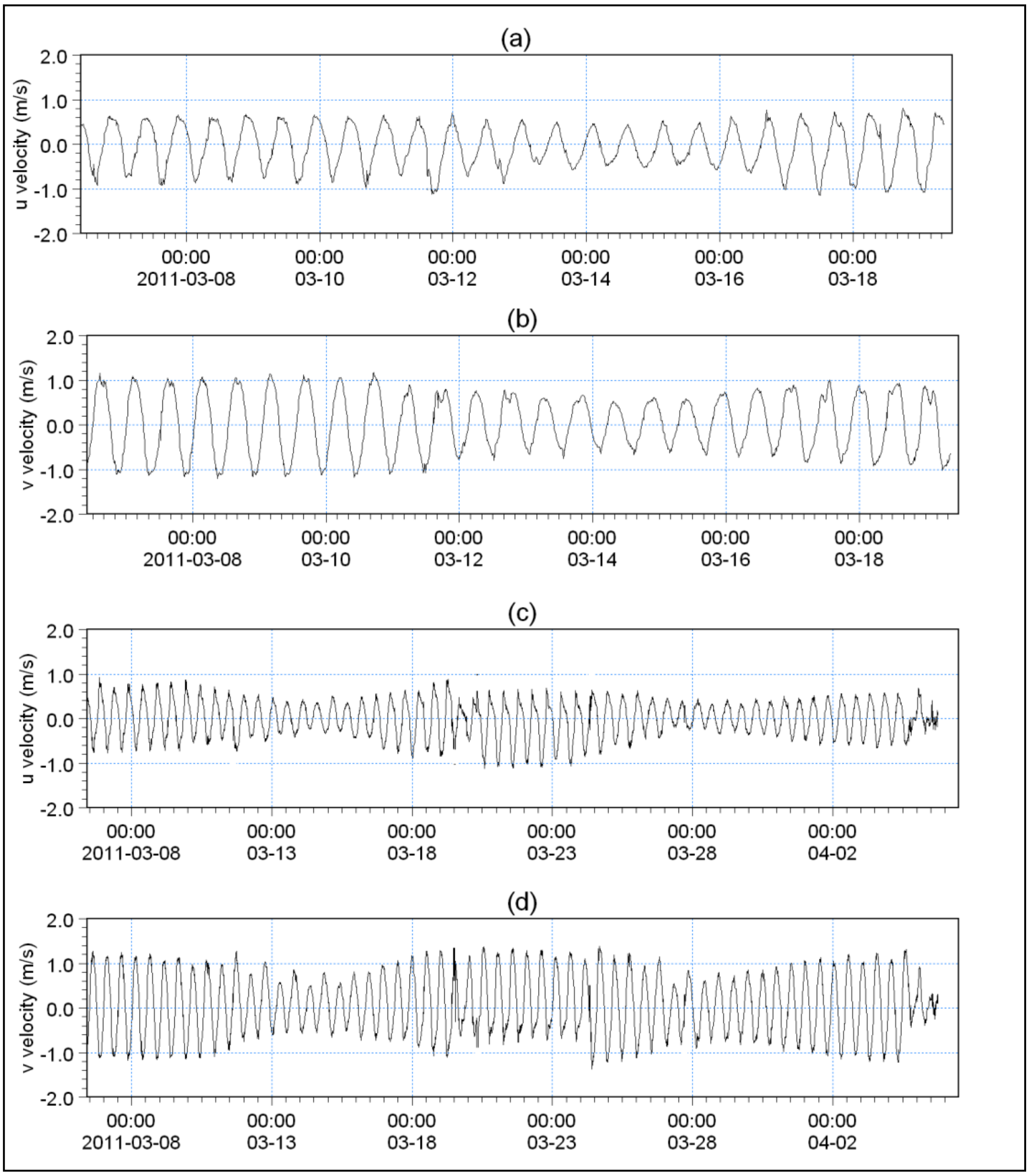

Fig. 5.13. Time series plots of the currents off Hazira during March 2011at surface (a & b) and bottom (c &d).

5.4. Water quality simulations off Gulf of Khambhat

5.4.1. Model set up and validation

The WASP model domain covers an area of 3120 km^2 with 803 grids of 2km x 2km resolution. The region (Fig. 5.14) is divided into upper, middle and lower sections; the upper section has a length of 44 km, the middle section has a length of 52 km and the lower section 84 km. The model bathymetry was generated using ETOPO5 data obtained from the National Geophysical Data Center, USA and digitized hydrographic chart data. The model was initiated using observed values for boundary conditions (DO, BOD, nutrients). After quality checking and analysis of long term water quality data, boundary conditions were set as follows: salinity- 33 (12 at the eastern boundary), DO- 9.6 mg/L, BOD- 6.2 mg/L, primary productivity- 20 mg C/m^3/day, nitrite- 5.4 μmol/L, nitrate- 34.5 μmol/L, ammonia-46 μmol/L, Turbidity- 950 NTU. At the eastern boundary, considering the influence of river water, water quality parameters with varying user defined concentrations were assigned as boundary conditions. The limit was kept within the above mentioned parameter values. BOD, Currents, temperature and salinity were specified as forcing functions. The kinetic rates, constants and other formulations were obtained from Bowie et al, 1985. An open boundary condition is specified for the south, west and north boundaries. At the eastern boundary, a land boundary is specified with user defined inflow. First order decay rate was assigned for various parameters. Sensitivity analysis was carried out in order to find out the effect of different model inputs on model output variability. A second set of sensitivity analysis was carried out on the calibrated model parameters to estimate the model sensitivity. The procedure for sensitivity analysis was done by changing the value of each uncertain parameter. The analysis was carried out for one parameter at a time or in groups. The model sensitivity was assessed by simulations with altered values and estimating the relative change of the outputs. When there was large change in the outputs, the model was more sensitive to the alteration of parameter values. Initially the model inputs were altered individually and in groups. 1204 alterations were made for the GoK region which consisted of 454 perturbations related to hydrodynamics, 410 perturbations related to parameters such as DO, BOD, temperature and concentration of nutrients at the boundary and 340 perturbations related to various kinetic constants and coefficients (Table 5.4). After testing different parameter inputs using sensitivity analysis, calibration runs were carried out to estimate the range of values which were expected for the calibrated parameters.

The model is calibrated using measured temperature, salinity, currents water quality parameters as well as coefficients and constants relevant to the study area. The details of calibrated model coefficients are given in Table 5.4. The model was utilized for the simulation of BOD, DO and NH_3 during January 2011-April 2011. Further, the model results are validated with the DO, BOD and NH_3 data collected at 16 stations along the GoK during March 2011. The regression analysis between the observed and modelled DO, BOD and NH_3 for surface water is presented in Figs. 5.15 (a-c) and the model parameter evaluation are given in Table 5.5.

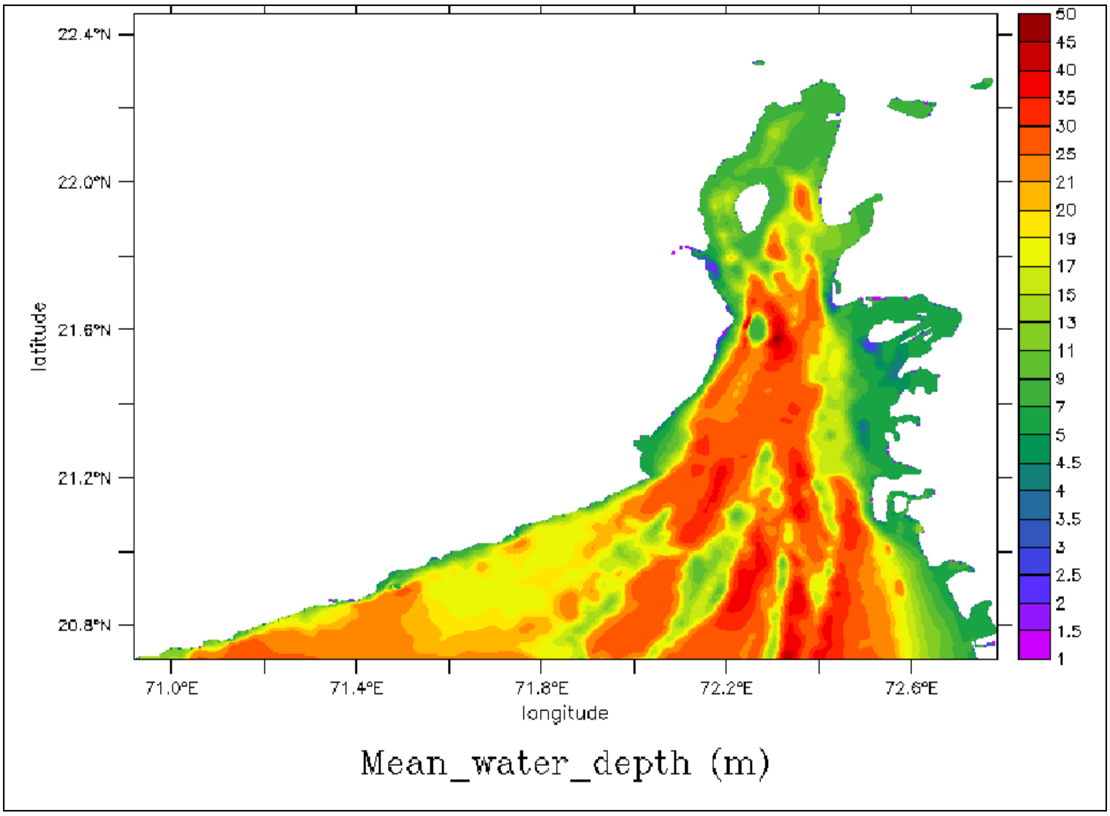

Fig. 5.14. Bathymetry of the study area.

Model Coefficient	Model value range	Calibrated/ Estimated
Global Reaeration Rate Constant @ 20 °C (per day)	0-10	8
Minimum Reaeration Rate, per day	0-24	22
Theta -- Reaeration Temperature Correction	0-1.03	0.7
BOD Decay Rate Constant @20 °C (per day)	0-5.6	4.8
BOD Decay Rate Temperature Correction Coefficient	0-1.07	1
BOD Decay Rate Constant in Sediments @20 °C (per day)	0-0.0004	0.0003
BOD Decay Rate in Sediments Temperature Correction Coefficient	0-1.08	1
BOD Half Saturation Oxygen Limit (mg O/L)	0-0.5	0.48
Fraction of Detritus Dissolution to BOD	0-1.000	0.9
Fraction of BOD Carbon Source for Denitrification	0-1.000	0.7
Atmospheric Deposition of BOD(Ultimate) (mg/m2-day)	0-1000	800
Denitrification Rate Constant @20 °C (per day)	0-0.09	0.08
Calc Reaeration Option (0=Covar, 1=O'Connor, 2=Owens, 3=Churchill, 4=Tsivoglou)	0-4.000	1
Use (1 - On, 0 - Off) Total Depth of Vertical Segments in Reaeration Calculation	0-1	1
Atmospheric Deposition of Ammonia (mg/m^2/day)	0-1000	default
Nitrification Rate Constant @20 °C (per day)	0-10	5
Nitrification Temperature Coefficient	0-1.07	1
Half Saturation Constant for Nitrification Oxygen Limit (mg O/L)	0-2.00	1
Minimum Temperature for Nitrification Reaction, deg C	0-20	12
Ammonia Partition Coefficient to Water Column Solids, L/kg	0-1000	600
Ammonia Partition Coefficient to Benthic Solids, L/kg	0-1000	700

Table 5.4. Constants and coefficients used in the WASP model.

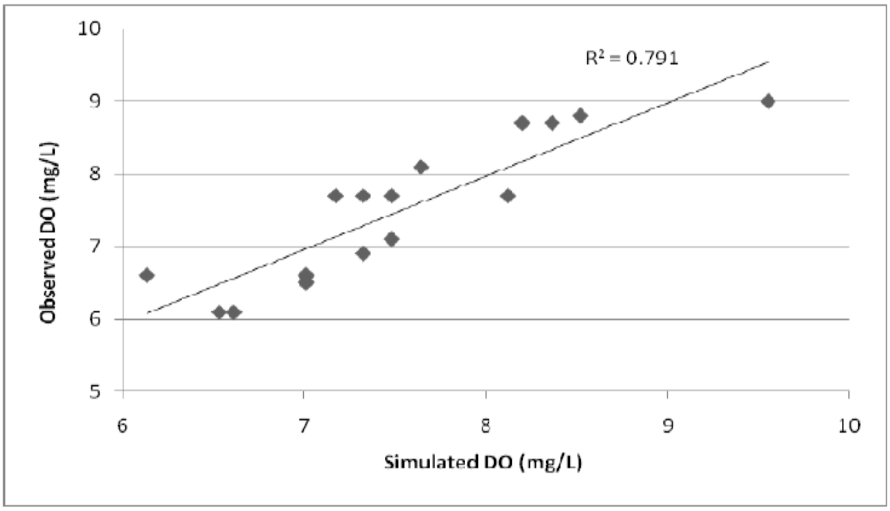

Fig. 5.15 a. Regression analysis of model values of DO with measurements.

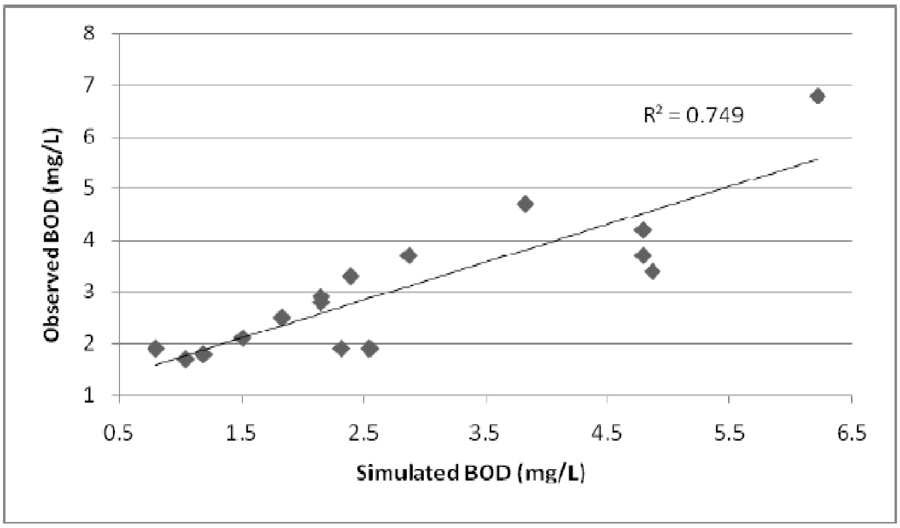

Fig. 5.15 b. Regression analysis of model values of BOD with measurements.

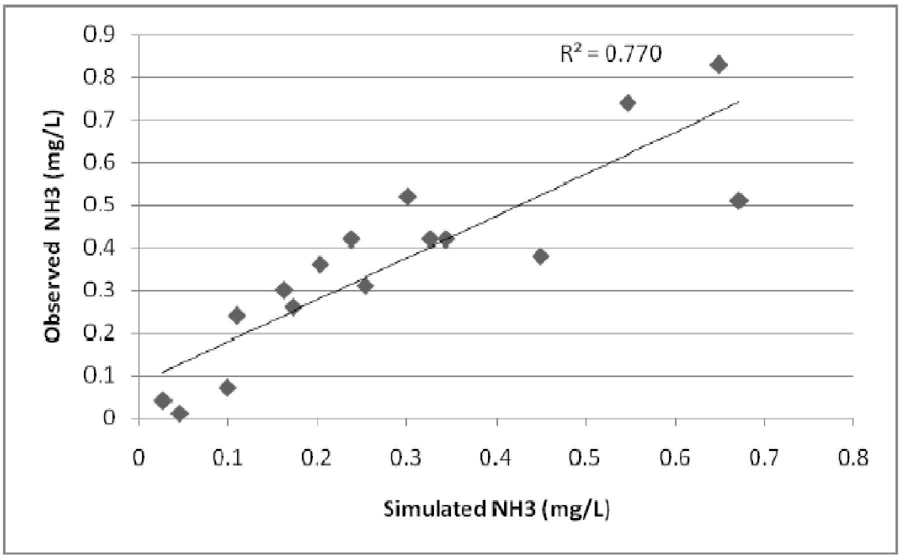

Fig. 5.15 c. Regression analysis of model values of NH_3 with measurements.

Model parameter evaluation	Dissolved Oxygen	Biochemical Oxygen Demand	Ammonia
Pearson's correlation coefficient (r)	0.89	0.87	0.88
coefficient of determination (R^2)	0.79	0.75	0.77
Nash-Sutcliffe efficiency (NSE)	0.73	0.71	0.56
Percent bias (PBIAS)	0.37	-8.9	-23.8
RMSE-observations standard deviation ratio (RSR)	0.16	0.53	0.66

Table 5.5. Model parameter evaluation for the GoK modelling network.

5.4.2. Simulations of DO, BOD and NH_3

The simulations also reveal well oxygenated water column in the Gulf. Throughout the simulation period, DO (of Gulf of Khambhat) (Fig. 5.16) values are above 6 mg/L. High values upto 9.3 mg/L are seen during the simulation period. Irrespective of the high DO values, high BOD values are also seen in the observed data. The range of BOD values (Fig.

5.17) is 1 to 4.7 mg/L. Simulated ammonia values (Fig. 5.18) indicate marginal contamination from ammonia. The high BOD and ammonia values are probably due to the effect of industrial clusters in the area. The maximum simulated NH_3 value is 0.95 mg/L. Though the simulation shows occasional high values for BOD and NH_3, the Gulf water is highly oxygenated as revealed by both observations and simulations.

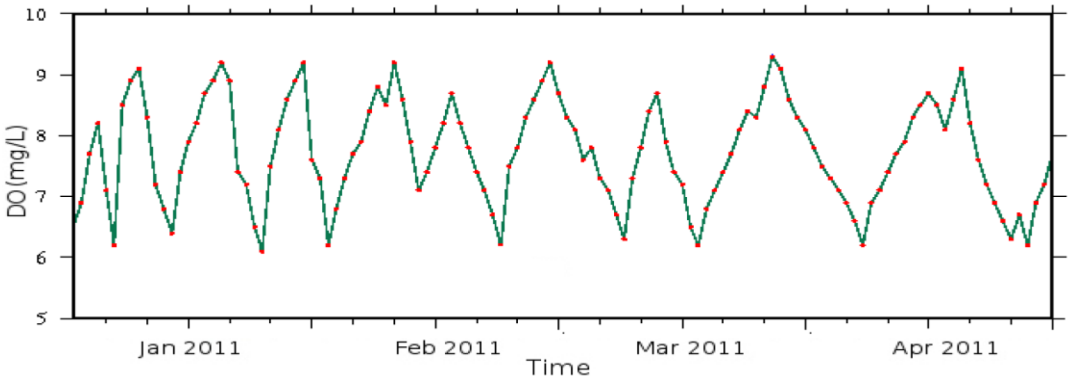

Fig. 5.16. Simulated DO for the period January 2011 – April 2011 in GoK.

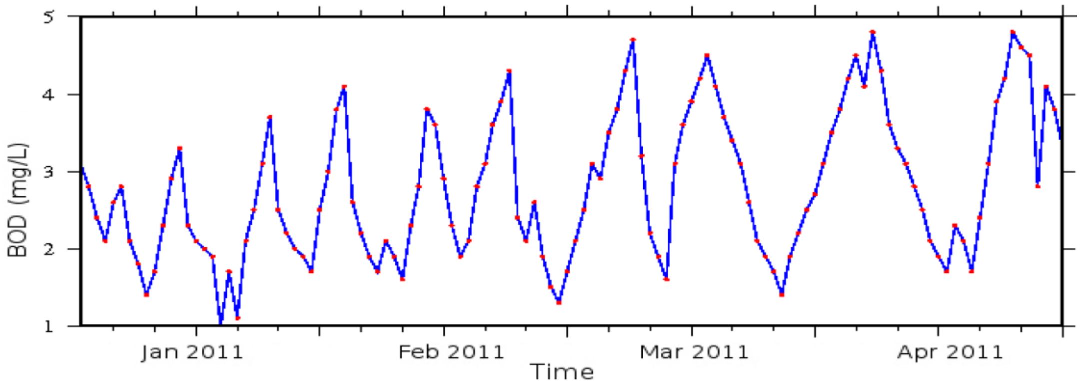

Fig. 5.17. Simulated BOD for the period January 2011 – April 2011 in GoK.

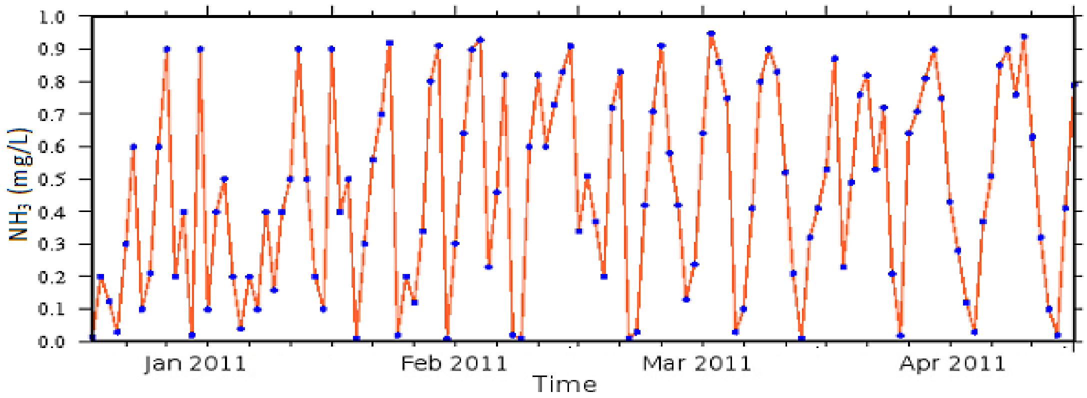

Fig. 5.18. Simulated NH_3 for the period January 2011 – April 2011in GoK.

5.4.3. Simulation of water quality parameters with open and closed boundaries

The major rivers emptying into the Gulf bring in a lot of contaminants in addition to the inputs from industrial establishments along the coast. In order to find the extent of riverine influence in contaminating the Gulf, simulations (Fig. 5.19) were carried out by closing the river boundary and the results were compared with that of open river boundary conditions. The results indicate that rivers play a major role in polluting the Gulf as revealed by the simulations. Among the parameters, phosphate (Fig. 5.19d) shows the maximum changes when the river boundary is closed, compared to ammonia (Fig. 5.19b). Results show that majority of ammonia pollution is caused by the industrial establishments and other anthropogenic activities going along the Gulf. The rivers also bring in considerable amount of nitrate and BOD into the Gulf.

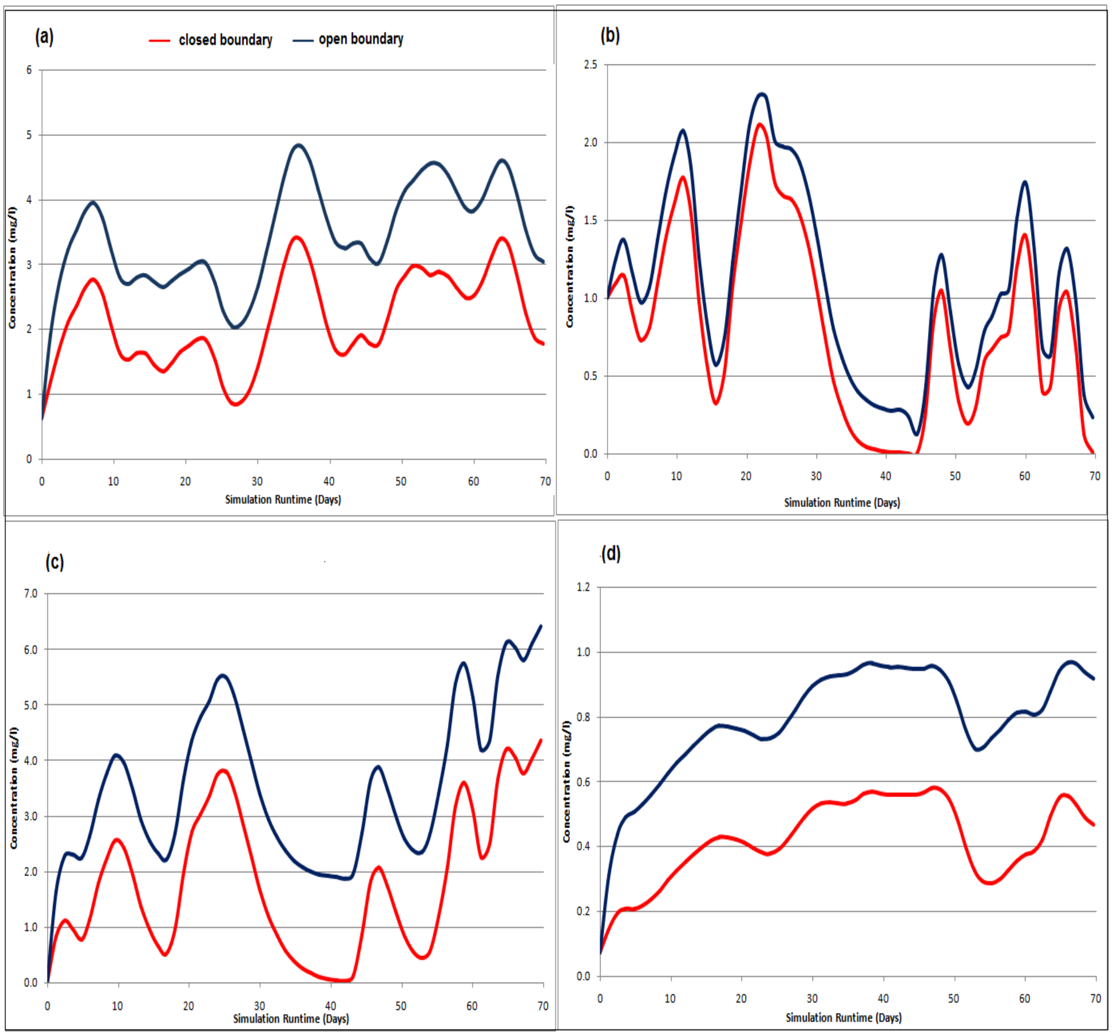

Fig. 5.19. Simulated water quality parameters using closed and open river boundaries: a) BOD, b) ammonia, c) nitrate and d) phosphate.

5.5. Waste assimilative capacity of GoK

Analysis of in-situ parameters indicated that Gulf waters are slightly polluted with respect to the calculated OIP values. Though there are considerable inputs of pollutants from the ongoing anthropogenic activities, simulations reveal that the assimilative capacity of the GoK is still good with high dissolved oxygen content. This DO can mitigate the effect of pollutants entering into the Gulf to a considerable extent. The hydrodynamic conditions prevailing in the gulf (flushing out by tidal currents) also aid in the dispersal of pollutants. GoK has one of the highest tidal ranges in India. Even if the waste water is treated according to CPCB standards (CPCB, 1986) and disposed in the coastal waters, the increased number of industries can pose danger to the delicate ecological balance of the Gulf. Hence, it is essential to have regular water quality monitoring in the Gulf, and carrying capacity of the Gulf should be assessed before new industrial establishments are authorized.

Chapter 6
Summary

6.1. Summary

Coastal regions are hubs of intense anthropogenic activities and frequent environmental deterioration. Industrial belts are mostly concentrated along the coastal areas due to their proximity to water front for various uses. The population growth in India and the developmental activities along the coastal zone have led to major pollution impacts on creeks, estuarine and coastal environments. The anthropogenic activities have made substantial alterations in the ambient environmental conditions of these regions, and the changes persist in the environment for years. This not only affects the aquatic life but also affect the human health, if not remedied properly. Insight into the relationships that exist between liquid wastes imposed upon a water resource and the ability of the water to assimilate the load is a basic requirement for the intelligent development of water quality management. Coastal waters are dynamic, complex and insufficiently known ecosystems, which have been perceived as playing a vital role in the global equilibrium of the biosphere. WAC is the ability of a waterbody to cleanse itself of. It is the capacity of a waterbody to receive waste waters or toxic materials without deleterious effects to aquatic life or humans who consume the water.WAC studies are crucial in the present-day regional as well as global scenarios such as water shortage and climate change. Also, help in taking major decisions on maintaining sustainable resource utilization and a healthy coastal ecosystem.

The three study regions (Goa, Mumbai and Gulf of Khambhat) addressed in the present research work have immense anthropogenic activities (Goa though has a less degree, anthropogenic activities are on the rise) and the present research work provides a general assessment of WAC along these coastal regions. CTD, water quality and current measurements were used in order to assess the prevailing water quality conditions along these regions. Water samples from selected locations in these regions were analysed using standard methodologies for chemical and biological parameters. Overall index of pollution and TSI were used in the present study to find out the prevailing conditions in the study.

areas. In addition, the hydrodynamic model, MIKE- 21 and the water quality model, WASP were used in the present study. The primary and the secondary data of hydrography as well as water quality parameters available from IODC, CSIR-NIO was (from 1980s) used to set up the modelling network. The model that is calibrated and validated with the field data from the study areas is then evaluated with standard evaluation techniques.

The Mandovi estuary in Goa is found to be comparatively clean irrespective of tourism activities, probably due to the flushing effect of the sea. During SW monsoon, external loadings of fluoride, NO_2-N, PO_4-P, NH_3-N, TSS or TVC can affect the assimilative capacity of the estuary. However, the WQI and TSI indicate considerably good water quality and productivity, with good assimilative capacity of the estuary during SW monsoon. During post-monsoon, the assimilative capacity of the estuary can be affected by fluoride, SO_{4-}, urea, TVC and TN. The assimilative capacity during this season can be affected by SO_{4-}, fluoride, PO_4-P and NO_2-N. Though there are some high values at some stations, the general trend of WQI and TSI throughout the estuary indicates good to fairly good assimilative capacity. In the present study, water quality conditions of other estuaries/coastal water bodies situated on the west coast of India were compared with that of the Mandovi estuary. The prevailing estuarine water quality of the Mandovi estuary is found to be good and acceptable as compared to most of the other regions along the west coast of India. The assimilative capacity of the estuary is also found to be in good to fairly good state over different seasons (pre-monsoon < SW monsoon < post-monsoon) as per the effective dominant contaminants, observed WQI and TSI.

The prevailing water quality conditions designate Mumbai coastal waters as polluted and are also observed to be reaching near to eutrophic. In spite of the teeming population, the modelling exercise of the Mumbai region reveals that the coastal waters can assimilate the waste generated by the present population due to the specific hydrodynamic conditions prevailing in the region. A projected population increase exceeded the target BOD value of 2 mg/L, indicating the deterioration of ambient quality of coastal waters. The BOD values show substantial increase (upto 3 mg/L) when the pollutant load is increased. A case study is also done for Mumbai region to identify the possible climatic effects on assimilative capacity of coastal waters. The study proposed the coastal megacities can induce positive feedback on the projected global warming.

The data on primary water quality parameters from the stations off Dahej and Hazira in the Gulf of Khambhat show well oxygenated water, rich in nutrients. The high phosphates, nitrates and ammonia indicate anthropogenic additions to the Gulf water. The simulations reveal well oxygenated water column in the Gulf. Though the simulation shows occasional high values for BOD and NH_3, the Gulf water is highly oxygenated as revealed by both observations and simulations. The results indicate that rivers play a major role in polluting the Gulf as revealed by the simulations. Among the parameters, phosphate shows the maximum changes when the river boundary is closed, compared to ammonia. Results show that majority of ammonia pollution is caused by the industrial establishments and other anthropogenic activities going around the Gulf. The rivers also bring in considerable amount of nitrate and BOD into the Gulf. Though there are significant inputs of pollutants from the ongoing anthropogenic activities, simulations reveal that the assimilative capacity of the Gulf of Khambhat is still good and the water maintains appreciable dissolved oxygen content. This DO can mitigate the effect of pollutants entering into the Gulf to a considerable extent. The hydrodynamic conditions prevailing in the Gulf (flushing out by tidal currents) also aid in the dispersal of pollutants.

The study also identifies major constraints and lacunae in WAC studies. In the present study, parameters such as BOD, DO and NH_3 were simulated and validated with field data. Future studies should focus on the measurements of other water quality parameters too; so that one can improvise the estimation of the prevailing total assimilative capacity. Time series and good quality data is a prerequisite for WAC studies as the estimate depend on the measured parameters. In this regard, regular monitoring should be conducted in the areas intended for WAC studies. The modelling network developed for the present study can be further improved by adding more modules for parameters other than BOD, DO and NH_3.

6.2 Importance of the study and future prospective

Water pollution in coastal areas is a global problem with considerable inputs from anthropogenic activities. The pollution and associated assimilative capacity reduction can affect the basic ecosystem dynamics prevailing in the environment. The present study is an attempt to identify the extent of pollution problems and associated processes. The present study, especially the one at Mumbai coastal sea can be extended to other coastal megacities around the globe. The study revealed possible climatic impacts on assimilative capacity of coastal waters. These climatic influences will be exacerbated in the wake of present anthropogenic activities. The impact of climate variability on WAC can be further investigated by studying the role of monsoons, Indian Ocean Dipole and El-Nino, utilising long term reanalysis data sets.

Decision support systems relying only on observational data have some drawbacks, especially sampling cost and difficulty in data collection during rough seasons. The combination of simulations with observational data can lead to robust conclusions in environmental problems. In this regard, time series water quality data will be required to estimate and determine the prevailing assimilative capacity with less errors and biases. Water quality model provides an essential link to predict concentration as a function of loadings in the process of water quality management. Water quality modelling in the present study is an attempt to understand the prevailing assimilative capacity of the area. The technique can also be utilised to identify other major pollutants in the ecosystem and its assimilative capacity dynamics. The findings of this thesis signify the usage of water quality modelling in environmental management and decision making. The continuous improvement of the modelling network is critical in ensuring the production of sustainable, comprehensive, adaptable, relevant and cost-effective outputs. The present study used eutrophication module of the WASP model. Future studies can consider using other modules in the model such as simple toxicants, organic toxicants, non-ionic organic toxicants, mercury and heat. Waste assimilative capacity of coastal waters is a very complex problem, which involves lot of uncertainties, and therefore deserves further investigations with long term time series data sets and better numerical modelling networks.

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Appendix A

Abbrevations

- WAC - Waste Assimilative Capacity
- UNEP - United Nations Environmental Program
- WQI - Water Quality Index
- TSI - Trophic State Index
- AOU - Apparent Oxygen Utilisation
- TSS - Total Suspended Sediments
- TVC - Total Viable Coliforms
- SW monsoon - South West monsoon
- WASP - Water Quality Analysis and Simulation Program
- BOD - Biochemical Oxygen Demand
- DO - Dissolved Oxygen
- SST - Sea Surface Temperature
- GoK - Gulf of Khambhat
- WCI - West Coast of India
- USEPA - United States Environmental Protection Agency
- GIS - Geographical Information Systems
- TMDL - Total Maximum Daily Load
- SOD - Sediment Oxygen Demand
- ICMAM - Integrated Coastal and Marine Area management Project Directorate
- SBE - Sea Bird Electronics
- CTD - Conductivity Temperature Depth
- RCM - Recording Current Meter
- APHA - American Public Health Association
- APDC - Ammonium Pyrrolidine DithioCarbamate
- MIBK - Methyl Isobutyl Ketone
- AAS - Atomic Absorption Spectrometer
- HCl - Hydro Chloric Acid
- GF/F - Glass Fibre Filter
- TFC - Total Faecal Coliforms
- CFU - Colony Forming Units
- STP - Sewage Treatment Plant
- WOA - World Ocean Atlas
- IODC - Indian Ocean Data Centre
- NSE - Nash-Sutcliffe efficiency
- PBIAS - Percent Bias
- RSR - Root mean square error (RMSE)-observations standard deviation ratio
- PCA - Principal Component Analysis
- CPCB - Central Pollution Control Board

- OIP - Overall Index of Pollution
- Pi - pollution indices
- ISM - Indian Summer Monsoon
- TN - Total Nitrogen
- WICC - West India Coastal Current
- MLD - Million Litres per Day
- MIDC - Maharashtra Industrial Development Corporation
- MPCB - Maharashtra Pollution Control Board
- MW - Mega Watt
- NTU - Nephelometric Turbidity Units
- PE - Population Equivalent
- CMC- Coastal Megacity
- GWP - Global Warming Potential
- GIDC - Gujarat Industrial Development Corporation
- IPCL - Indian Petrochemicals Corporation Limited
- GSFC - Gujarat State Fertilizer & Chemicals Limited
- GIDC - Gujarat Industrial Development Corporation
- ONGC - Oil and Natural Gas Commission
- TASK - Tidal Analysis Software Kit
- SSW - South South West
- WSW - West South West
- NW - North West
- SE - South East
- NNW - North North west
- SSE - South South East
- CSIR-NIO - Council of Scientific and Industrial Research- National Institute of Oceanography