Chapter 5

DISCUSSION

Estuaries are tidally influenced ecological systems where rivers meet the sea and freshwater mixes with seawater. Estuaries also form crucial transition zones between land and water that provide unique biological and geological functions like, they provide habitat to varieties of micro and macro organisms, nurseries to many marine organisms including commercially valuable fish species, filtration of nutrition and sediments from upland, flood control, etc.

Mangroves are unique coastal wetland ecosystems with complex associations of plant, animal and microorganisms adapted to inter-tidal zones and river mouths in the tropical and subtropical regions of the world. Moreover mangroves function as a natural reservoir of biodiversity constituting a bridge between the terrestrial and aquatic ecosystems. The inter-tidal flora and fauna found among the mangroves are rich and vary according to location, salinity level etc. The mangrove associated fauna and micro-organisms are highly interdependent and serve in controlling pH, leaching of metals and nutrient cycling (Ananthakrishnan, 1982). The mangrove ecosystem has a number of ecological functions. They harbour a rich community of plankton, which forms the source of food for crabs, prawns and fishes. They also form the breeding and nursery grounds for many marine and freshwater fishes. They recycle polluted water, prevent floods and bank erosion, reduce the fury of waves and wind and recharge ground water.

Estuaries and mangroves have for long been important to mankind, either as place of investigation, or as locations on their banks for towns and cities. Now-a-days, they are under pressure either as repositories for the effluent of industrial processes and domestic waste or as prime sites for land-claim to create sites for industry or urban development. Estuaries have been
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claimed to be amongst the most productive natural habitats in the world (McLusky & Elliott, 2004). The estuarine and mangrove environments are characterized by having a constantly changing mixture of salt and fresh water which differs from both biotic and abiotic conditions. The dynamic nature of these ecosystems proves to be a great challenge to the biotic community, which few are able to adapt to it (Deeley & Paling, 1999). The studies have shown that the change in nutrient status, whether due to pollution or natural cause can have a significant impact on distribution of estuarine organisms (Kimmerer, 2002; Paul et al., 2008). Anthropogenic inputs frequently cause changes in the chemical characteristics and water quality of ecosystem which ultimately can lead to various ecological consequences (Martin et al., 2008). The physico-chemical parameters of surface water and surface sediment with reference to biotic components of Mahi estuary and Vamleshwar mangrove were analysed in the present study. The results of this study are discussed under various subheadings such as: (1) Physical and chemical characteristics of the surface waters, (2) Physical and chemical characteristics of the surface sediments (3) The phytoplankton community, (4) The zooplankton community and (5) The benthic fauna.

5.1. PHYSICO-CHEMICAL CHARACTERISTICS OF THE SURFACE WATERS

The quality of an aquatic ecosystem is dependent on the physical and chemical qualities of water (Bhatt et al., 1999). The results of variations in all the physical and chemical characteristics of water in a lake at a particular place during different seasons and also the variations at different places during a particular season reveal some of the significant ecological tendencies of the aquatic system. The estuarine environments are subjected to various changes in physicochemical properties due to continuous mixing of fresh water with marine water. The estimation of water quality is very important in determining the quality of ecosystem (Chang, 2008).
The pH is one of the very significant chemical characteristics of all waters, which explains certain significant biotic and abiotic ecological characteristics of aquatic systems in general. The pH of a water body is a diurnally variable property according to temperature variation in the system (Ojha & Mandloi, 2004). The general trend of pH was observed in range of 6.8 to 8.5 during present study for two years. When pH is within the range of 5.5 to 8.5 a balance in an ecosystem is maintained (Chandrasekhar et al., 2003). Kaul & Handoo (1980) found that increased surface pH in water bodies is due to increased metabolic activities of autotrophs, because in general they utilize the CO$_2$ and liberate O$_2$ thus reducing H$^+$ ion concentration. Moreover, in the bottom of water bodies liberation of acids from decomposing organic matter under low O$_2$ concentration results in low pH. Due to the buffering capacity of the sea water, generally the pH ranges from 7.8 to 8.3 in estuaries (Millero, 1986). Significant changes in pH occur due to disposal of industrial wastes, acid mine drainage etc. Such changes can make many common pollutants more toxic. In natural waters pH also changes diurnally and seasonally due to variation in photosynthetic activity which increases the pH due to consumption of carbon dioxide in the process.

During the entire period of study the pH of surface waters showed below neutral value only at Gambhira of Mahi estuary. All the other three stations of estuary and the three stations of Vamleshwar mangrove have shown the pH values above 7. The pH values documented ranged between 6.8 to 8.6 in Mahi estuary and 7.3 to 8.6 in Vamleshwar mangrove. Similarly, Prakash et al. (2009) observed a wide range in pH change from 6.9 to 8.8 during monsoon to pre-monsoon period in tropical Cauvery river system. The other two study sites J.Point and Dhuvaran did not show much fluctuation and showed the pH values in narrow range of 8.0 to 8.4 throughout the seasons for the first year of study and from 7.5 to 8.0 during second year. Similarly Satpathy et al. (2009) also observed a pH range of 7.7 to 8.3 along the coastal waters of Kalpakkam, South east coast of India. The pH of water
also depends upon relative contents of free CO$_2$, carbonates, bicarbonates and calcium. The water tends to be more alkaline when it possesses carbonates, but lesser alkaline when it supports more bicarbonates, free CO$_2$ and calcium. 

**Omstedt et al. (2010)** reported that the marginal change in pH from one month to other month may be due to the excessive buffering activity of sea water. The high pH might be due to the marine water influence in the sites which was observed prominent during pre-monsoon period. The decrease in pH value in Gambhira of Mahi estuary can be attributed to the fresh water influence on these areas as reported by **Islam (2007)** while working in a pond of Rajshahi University, Begladesh.

**Kataria et al. (1995)** pointed out that a suitable range of pH is necessary for fish survival in water bodies and acid waters reduce the appetite of fish and their growth. They also emphasized that the suitable pH is above neutrality whereas the recommended range of pH for fresh water aquatic life is 6.5 to 6.9 as prescribed by Environment Protection Agency of United States. According to **ICMR (1975)** and **WHO (1985)** the safe pH limit for fresh water aquatic life is 7 to 8.5 but **ISI (1991)** has recommended the pH range 6.5 to 8.5 for aquatic life. Almost similar pH range of 6.0 to 8.5 is considered suitable for aquatic life according to the United States Public Health Association (De, 1999). Considering all these recommended standards, the pH observed in both the study area Mahi estuary and Vamleshwar mangrove waters were within the prescribed safe limits.

The water **temperature** is of enormous significance as it regulates various abiotic characteristics and biotic activities of an aquatic ecosystem (McCombie, 1953; Kataria et al., 1995; Sharma & Sarang, 2004; Radhika et al., 2004). **Stenseth et al. (2004)** suggested that variability in temperature may induce variations in marine and estuarine ecosystems at all levels of the food chain, from primary productivity to the top predators including fisheries. It is clear from the results obtained from the study that there were no significant
variations in surface water temperature across stations in both estuary and mangrove environments. A comparison of the average of surface water temperature of the two-year period showed that the variations in temperature across the different stations were insignificant but the differences in temperature over different seasons were very significant.

The surface water temperature at all the stations during a particular season throughout the period of study, showed a maximum fluctuation of 1-4 °C only. The lowest seasonal surface water temperature noticed in the Mahi estuary during the entire period of study was 18.9 °C, in the post-monsoon period of 2009 and the maximum noticed was 32.5 °C during the pre-monsoon of 2009. In mangrove the surface temperature ranged from 20.1 °C in the post-monsoon period of 2010 to 31.7 °C during the pre-monsoon of 2009. The results were found to be well agreed with investigations carried out by Martin et al. (2008) for Cochin estuary of south India where they reported a temperature variation of 28 °C to 32 °C during pre-monsoon period. Bhardwaj et al. (2010) also recorded a wide variation in temperature ranging from 29.7 °C to 38.7°C while estimating the water quality of the Chhoti Gandak river of Ganga Plain. Jayaraman et al. (2003) observed a difference in surface water temperature from 25 °C (post-monsoon or northeast monsoon) to 30.6 °C (pre-monsoon) in Karamana river near Thiruvananthapuram, in Kerala. Higher temperature was observed during summer due to clear atmosphere, greater solar radiation and low water level. The change in water temperature may be attributed to the change in solar radiation received at different seasons along the study sites (Ozaki et al., 2003).

**Salinity** is a direct measure of the amount of salts in the water. Salinity influences several processes such as dissolution, dispersion and dilution in seawater due to high dissolved salt content and higher density. Shiel et al. (2006) stated that biotic communities present in estuarine regions are acclimatized for certain range of salinity where they thrive. The wide range in
salinity can result in adoption with modification and dominance of selected species in the lower order while higher order biota may migrate. Any sudden change in salinity can cause high mortality including fish due to salinity shock.

In both the ecosystems higher concentrations of salinity were recorded mostly during pre-monsoon periods which signify the role of tidal influence on increased salinity. The lowest recorded salinity value was 1.4‰ and the highest was 34.5‰ for Mahi estuary. The salinity values in accordance with present result of Mahi estuary have been registered by Martin et al. (2008) from Cochin estuaries in which the salinity was in the range of 0‰ to 30‰ in pre-monsoon & monsoon season. Satpathy et al. (2009) recorded the salinity ranging from 23.4‰ to 35.9‰ in Kalpakkam Coast of South east India and the highest being recorded during pre-monsoon season which is in accordance with the results of Vamleshwar mangrove showing salinity values from 25.7‰ to 34.1‰. The concentration of chlorinity is closely related to salinity and the amount of chlorinity gives a direct measure of salinity in water. During monsoon high freshwater inflow can lead to a decrease in salinity along the estuarine regions (Froneman, 2002) and this might be the reason for low salinity range observed during monsoon season.

**Electrical Conductivity (EC)** is a basic index to select the suitability of water for agricultural purposes (Kataria et al., 1995). The EC in water is due to ionization of dissolved inorganic solids and is a measure of total dissolved solids and salinity (Bhatt et al., 1999). The area around the estuarine and mangrove environments represents zone of interaction and transition between the two systems where dissolved constituents such as pollutants are diluted, exchanged, transformed or destroyed. The more total dissolved solids in water, particularly salts, the greater is its electrical conductivity (Westbrook et al., 2006). The average EC values ranged between 29.3 mS and 53 mS in Vamleshwar mangrove in present study, a similar pattern was
revealed at Pichavaram mangrove ecosystem of South east India with the range of 32 mS to 57 mS by Kathiresan (2002). The average EC values ranged from 19.1 mS to 46 mS in Mahi estuary which were comparatively lower than EC values of mangrove ecosystem. This might be due to the influence of fresh water in some of the study sites of Mahi estuary. The high conductivity values were observed at lower reaches of Mahi estuary and all sites of Vamleshwar mangrove. The rise in EC during summer months suggests the influence of marine water on contributing dissolved ions like Na, K and Cl into estuarine and mangrove environments and enhanced precipitation (Satheeshkumar & Anisakhan, 2009).

**Dissolved Oxygen (DO)** is the sole source of oxygen for all the aerobic aquatic life and hence it is considered as an important measure of purity for all waters. Oxygen content is important for direct need of many organisms and affects the solubility and availability of many nutrients and therefore the most significant parameter affecting the productivity of aquatic systems (Wetzel, 1983). The DO reflects the water quality status and physical and biological processes in waters and shows the metabolic balance of a water body. The DO is an important water quality parameter in assessing water pollution (Laluraj et al., 2002). The factors affecting oxygen content in natural waters include input due to atmosphere and photosynthesis and output from respiration, decomposition and mineralization of organic matter as well as losses to atmosphere. Hence, the oxygen balances in water bodies become poorer as the input of oxygen at the surface and photosynthetic activity decreases and as the metabolic activities of heterotrophs are enhanced.

The influx of anthropogenic discharges containing oxidisable organic matter and certain pollutants consume more DO than the water body can replenish, thereby degrading the ecological quality. However, in a dynamic coastal environment the impact is considerably lowered because of tidal action and turbulence (Pena et al., 2010). In the present investigation the
average values of DO ranged between 0.6 mgL\(^{-1}\) and 7.0 mgL\(^{-1}\) for Mahi estuary. In Vamleshwar mangrove it was in the range of 0.7 mgL\(^{-1}\) to 6.0 mgL\(^{-1}\). The DO values of present study are comparable with the values reported by Sundaramanickam et al. (2008) while studying in Parangipettai and Cuddalore coast. They reported the values of DO in the range of 3.14 to 7.02 mgL\(^{-1}\). Similarly, Sankar et al. (2010) while working on coastal waters of Uppanar estuary reported dissolved oxygen level of 2.8 to 5.5 mgL\(^{-1}\). The higher dissolved oxygen present in the upper reaches of Mahi estuary might be due to the freshwater influence in these areas. The DO in lower estuarine mouth of Mahi estuary was recorded 0.6 mgL\(^{-1}\) only. Similar observation was recorded by Roegner et al. (2011) while working on Columbia river estuary. They suggested that low concentration of dissolved oxygen at the estuarine mouth may be attributed to wind stress, tidal stress and ocean forcing. The lowest DO values were observed during the pre-monsoon period of present study. High biological activity during pre-monsoon period may be responsible for low dissolved oxygen concentration in estuaries as observed in Chesapeake Bay (Levinton, 2001). The lower dissolved oxygen concentration reported at lower reaches of Mahi estuary and Vamleshwar mangrove during pre-monsoon might also be due to the domestic as well as industrial effluent released into the region as these are the main source of oxidisable organic matter (Abdullahi et al., 2008).

**Total Alkalinity (TA)** is caused by bicarbonates, carbonates, OH ions, borates, silicates and phosphates. Alkalinity is a measure of buffering capacity of water and is important for aquatic life in a freshwater system because it equilibrates the pH changes that occur naturally as a result of photosynthetic activity of phytoplankton (Kaushik & Saksera, 1989). Alkalinity of water is its capacity to neutralize a strong acid and is characterized by presence of all hydroxyl ions capable of combining with hydrogen ions (Koshy & Nayar, 2000). Alkalinity is used as criteria for determining the nutrient status of waters (Moyle, 1949).
The minimum value of TA reported during the entire study period at Mahi estuary was 49 mgL⁻¹ and the maximum value of 310 mgL⁻¹ whereas in Vamleshwar mangrove the TA ranged from 69 mgL⁻¹ to 241 mgL⁻¹. The higher values of TA observed at lower reaches and that too during pre-monsoon season was an indicative of marine water influence on alkalinity. The results obtained were similar to studies carried out by Shaikh & Mandre (2009) in Khed (Lote) Industrial water, Ratnagiri, Western India where they reported 350 mgL⁻¹ alkalinity during summer season and a minimum of 120 mgL⁻¹ during monsoon season. Saksena et al. (2006) in their study on certain saline ponds of Ratnagiri also emphasized the role of marine water intrusion affecting the alkalinity of water. Meera & Nandan (2010) on their study on Valanthakad backwaters of Kerala suggested that low alkalinity value at post-monsoon may be attributed to increased uptake or release of carbon dioxide by organisms there by changing the proportion of carbonate and bicarbonate ions in water.

**Total Hardness (TH)** is governed by the contents of Ca and Mg, and the major contribution to hardness is usually Ca. It may be due to other ions such as Fe⁺⁺ as well. Practically hardness is a measure of the capacity of water to precipitate soap. The total hardness is defined as the sum of Ca and Mg concentrations, both expressed as CaCO₃ in mgL⁻¹. The carbonates and bicarbonates of Ca and Mg cause temporary hardness whereas sulfates and chlorides cause permanent hardness. Comparison of the two-year average of TH of surface waters showed that fluctuations in hardness were significant over different seasons whereas such fluctuations were insignificant across stations. The highest hardness in surface water noticed was during the pre-monsoon season (6198 mgL⁻¹ at J.Point in April, 2010) and lowest during the monsoon season (784 mgL⁻¹ at Gambhira August, 2009). In Vamleshwar mangrove the TH ranged from 3019 mgL⁻¹ at Station 3 in September, 2008 to 6547 mgL⁻¹ at Station 1 in May 2009. Similar observations were reported by
Prasanna & Ranjan (2010) in Dhamra estuary with the TH values of 969.68 mgL\(^{-1}\) to 5655.24 mgL\(^{-1}\).

**Total Solids (TS)** is a direct measure of all the dissolved and suspended matters in water. It comprises dissolved salts, suspended particles, soil particles, discharged effluents and decomposed organic matter. In Mahi estuary the TS of surface water varied from 3448 mgL\(^{-1}\) to 23748 mgL\(^{-1}\). In Vamleshwar mangrove it was observed in the range of 11350 mgL\(^{-1}\) to 24384 mgL\(^{-1}\). The present findings are in concordance with the studies carried out by Prasanna & Ranjan (2010) in Dhamra estuary of western India in which they reported 63850 mgL\(^{-1}\) of total solids during pre-monsoon period and 12550 mgL\(^{-1}\) in monsoon period. The total concentration of TS was observed higher during pre-monsoon period which may be because of the high tidal influence and low freshwater inflow. Soundarapandian *et al.* (2009) suggested that tidal current forms the main factor influencing the TS concentration by constant turbulence of bed sediments. The heavy tidal influence experienced at study sites might be the reason of higher TS concentration particularly along the lower reaches of both Mahi estuary and Vamleshwar mangrove.

All forms of **phosphates** such as orthophosphates, condensed phosphates, and organically bound phosphates are found in waters. The phosphate is added to land through different ways; phosphate containing fertilizers (manufactured from mined phosphate), animal manures, and waste products from animals supplemented with phosphate enriched feed. In natural waters phosphate exists as soluble phosphates. Phosphate is the nutrient considered to be the critical limiting nutrient, causing eutrophication of fresh water systems (*Rabalais, 2002*). It is a major nutrient that triggers eutrophication and required by algae in small quantities (*Bandela et al.*, 1999). The phosphate concentration in coastal waters depends upon its concentration in the freshwater that mixed with the seawater within the sea-land interaction zone, phytoplankton-uptake addition through localized
upwelling, and replenishment as a result of microbial decomposition of organic matters (Paytan & Mclaughlin, 2007). Phosphate constitutes the most important inorganic nutrient that can limit the phytoplankton production in tropical coastal marine ecosystems and thereby the overall ecological processes (Cole & Sanford, 1989).

In the present study, phosphate at surface waters of Mahi estuary ranged from 0.12 mgL\(^{-1}\) to 1.99 mgL\(^{-1}\). Phosphate concentrations ranging from 0.07 mgL\(^{-1}\) to 0.45 mgL\(^{-1}\) were reported from Vamleshwar mangrove. In both estuarine and mangrove ecosystems the fluctuations in phosphate content during the different seasons and different years were random. The fluctuations in the phosphate of water were significant across different stations in all the seasons. In the present study phosphate concentration was reported higher at middle reaches and upper reaches of estuaries during post-monsoon period. Silveira & Ojeda (2009) emphasized the role of urban release on phosphate concentration on their study on Yucatan Coast and their results found to be corroborated with the present studies. Liu et al. (2009) reported that sea water serves as the main source of phosphate in estuarine and coastal waters except those receiving freshwater contaminated with domestic wastes containing detergents as well as wastes from agro field rich with phosphate-phosphorous fertilizers and pesticides. Gabche & Smith (2002) while working on two estuaries of Cameron concluded that the increased concentration of phosphate after monsoon was the result of agricultural run-off along with city drainage which in-turn will serve as important phosphate contributors to the coastal environment.

**Nitrate** is considered as the most stable form of nitrogen, in presence of oxygen in sea water (Sillen, 1961; Grasshoff, 1983). Nitrate is one of the most important indicators of pollution of water which represents the highest oxidized form of nitrogen. The observed minimum and maximum values of nitrate in Mahi estuary were 0.03 mgL\(^{-1}\) and 3.34 mgL\(^{-1}\) respectively. The
minimum and maximum values of nitrate in Vamleshwar mangrove were 0.06 mgL\(^{-1}\) and 0.52 mgL\(^{-1}\) respectively. The higher values of nitrate content were observed during monsoon season which indicates the source of run-off water in adding this nutrient into both ecosystems studied. Similar results were obtained by Prasannakumar et al. (2002) during their study on eastern Arabian Sea in which they reported 1-2 mgL\(^{-1}\) of nitrates during pre-monsoon period. Satpathy et al. (2009) also reported the range of nitrate from 0-4.28 mgL\(^{-1}\) in the coastal waters of Kalpakkam. The most important source of the nitrogen is biological oxidation of organic nitrogenous substances, which is derived from sewage and industrial waste or produced indigenously in the water (Sharma et al., 2008). Zepp (1997) observed that variation in nitrate and its reduced inorganic compounds are predominantly the result of biologically activated reactions. Quick assimilation by phytoplankton and enhancement by surface run-off results in large scale spatial-temporal variation of nitrate in the coastal regions. Edokpayi et al. (2010) observed a negative correlation of nitrate with salinity and also concluded that freshwater influx is the main source of nitrate in coastal waters which corroborated with results of present study.

The Ammoniacal Nitrogen (AN) in water is produced by microbiological degradation of organic nitrogenous matter. Free NH\(_4^+\) is an important parameter indicating pollution. Surface waters generally have lesser NH\(_4^+\) than bottom waters because it is liberated often from the decomposing organic matter of the lakes and its release in the deep layers is governed by anoxic conditions (Kaul & Handoo, 1980). Moreover, in surface layers the low NH\(_4^+\) concentrations results through its utilization by plankton and other plants (Prochazkova et al., 1970). Ammonia, the chief excretory product of the marine invertebrates, is also well known as a nutrient, which is preferred over nitrate by the phytoplankton community in certain environmental conditions which significantly affects the concentration of ammonia.
In the present study AN concentration was observed in the range from 0.16 to 2.92 mgL\(^{-1}\) in Mahi estuary and 0.10 to 0.75 mgL\(^{-1}\) in Vamleshwar mangrove. Satpathy et al. (2009) also observed AN concentration ranging from 0.09 to 0.20 mgL\(^{-1}\) along Kalpakam coastal water which supports the present study. Increased amount of AN present in the surface waters of Mahi estuary could be due to the discharge of effluent in the lower reaches of this estuary. Similarly Damotharan et al. (2010b) also recorded maximum concentration of AN at the lower reaches during their study on Point Calimere coastal waters of south east coast of India. Sankaranarayanan & Qasim (1969) suggested that the spatial and temporal variation in AN concentration might also be due to its oxidation to other forms or reduction of nitrates to lower forms in coastal waters.

Sulfate is a major component in natural water and has a sea origin in the estuary. It seeks its entry during tidal ingression and as a result, the lower reaches of the estuaries are found to be rich in sulfate content in summer months. In the present study there is a distinct spatial variation in sulfate concentration along the study sites. It showed a declining trend from lower reaches to middle reaches and upper reaches. The present investigation revealed that the concentration of sulfate was higher during pre-monsoon season (2376 mgL\(^{-1}\) in Mahi estuary and 2314 mgL\(^{-1}\) in Vamleshwar mangrove) followed by post-monsoon season and the lowest during monsoon season (150 mgL\(^{-1}\) in Mahi estuary and 1515 mgL\(^{-1}\) in Vamleshwar mangrove). The ratios of freshwater flow directly influence the sulfate concentration by its diluting nature (Rosenbauer et al., 1979). Similar sulfate concentration ranging from 497 mgL\(^{-1}\) to 1200 mgL\(^{-1}\) was reported by Mitra et al. (2011) from the lower Gangentic plains of West Bengal. The positive correlation of sulfate with salinity, pH and chlorinity indicates the marine water influence on this nutrient (Matson & Brinson, 1985). Beck et al. (2008) suggested that heavy fresh water inflow during monsoon might have lowered the concentration of sulfate whereas less inflow and increased transpiration rate
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from estuarine zone resulted in increased concentration during pre and post-monsoon periods.

Silicates are any mineral that contain silica, and include quartz (SiO$_2$), feldspars, clays, and others. Silicon dioxide occurs in all natural waters in various forms. Much of the silica in water comes from the dissolution of silicate minerals. Silicate is one of the important nutrients which regulate the phytoplankton distribution in estuaries. The variation of silicate in coastal water is influenced by physical mixing of seawater with freshwater, adsorption in to sedimentary particles, chemical interaction with clay minerals, co-precipitation with humic components, and biological removal by phytoplankton, especially by diatoms and silicoflagellates (Satpathy et al., 2009). In the present study, freshwater discharge from the backwaters rich in silicate into the coastal water could be the reason for higher value during post-monsoon period. The higher post-monsoon values of silicate could also be due to heavy influx of freshwater derived from land drainage carrying silicate leached out from rocks and also from bottom sediments exchanging with overlying water because of turbulent nature of water in the estuaries as reported by Saravanakumar et al. (2008b).

Concentrations of silicate were observed in the range from 0.73 to 9.79 mgL$^{-1}$ in Mahi estuary and 0.80 to 9.60 mgL$^{-1}$ in mangrove region. The highest concentration was reported from the upper reaches during post-monsoon period. The silicate showed negative correlation with salinity and positive correlation with DO. This showed that freshwater, which is rich in DO could be the main source of silicate in these coastal water regions as entry of silicate mainly takes place through land drainage rich with weathered silicate material (Lal, 1978). The results obtained in the present study were found to correlate with the results obtained by Martin et al. (2008) in Cochin estuary, west coast of India where they reported silicate ranging from 2 to 9.5 mgL$^{-1}$. Sridhar et al. (2006) also reported a low silicate concentration of 0.5 to
1.5mgL\(^{-1}\) in Palk Bay, southeast coast of India which showed similarity with the results of present study in lower reaches. The low concentration of silicate observed during pre-monsoon might be because of adsorption of reactive silicate into suspended sedimentary particles, chemical interaction with clay minerals, co-precipitation of soluble silicon with humic compounds and iron, and biological removal by phytoplankton, especially by diatoms and silicoflagellates (Satpathy et al., 2009 & Rajasegar, 2003).

Sodium and Potassium are the two major nutrients entering into estuarine ecosystem through sea water sources. They play a major role in directing the distribution of marine organisms and in supporting their existence in a particular saline habitat by osmoregulation. The estuarine area experiences high sodium and potassium concentration as compared with freshwater zones and less concentration than marine water. The negative correlation of sodium and potassium with DO and significant positive correlation with salinity indicates the marine water influence of these nutrients in water. The concentration of sodium and potassium was observed high during pre-monsoon period as 7427 mgL\(^{-1}\) sodium in Mahi estuary and 9368 mgL\(^{-1}\) in Vamleshwar mangrove whereas 347 mgL\(^{-1}\) potassium in Mahi estuary and 421 mgL\(^{-1}\) in Vamleshwar mangrove. Solai et al. (2010) obtained similar type of results while working in surface water of Pondicherry, Bay of Bengal, South East Coast of India. This might be attributed to the increased tidal influence and low freshwater inflow during this period. In the present study the higher concentration of sodium and potassium were found at lower reaches followed by middle and upper reaches in both of the ecosystems. Hoz et al. (2003) also observed similar spatial variation in sodium and potassium concentration in Coatzacoalcos River of Southeast Mexico. The proximity of lower reaches towards the sea and tidal influence at this zone contribute sodium and potassium at higher concentration.
The various physico-chemical parameters of surface waters in both the estuarine as well as mangrove ecosystems exhibited large seasonal fluctuations. In the monsoon season, freshwater flow was dominated from upstream river and land runoff; while in the pre and post-monsoon season, saline characteristics were predominant. Similar conformity of controlling effects of freshwater runoff on various parameters in monsoon season was carried out by Balachandran et al. (2008) in the Cochin estuary. The observations of varying concentrations of various parameters were governed by river water flow, seawater intrusion, and other inputs from different human activities, urban sewage, industrial effluents, etc. which were also confirmed by the study of Joseph & Ouseph, (2010).

Multivariate statistical techniques have been applied to characterize and evaluate surface water quality, since they are useful in verifying temporal and spatial variations caused by natural and anthropogenic factors linked to seasonality (Kowalkowski et al., 2006). The application of multivariable statistical methods offers a better understanding of water quality for interpreting the complicated data sets (Pradhan et al., 2009). Principal Component Analysis (PCA) is one of the best statistical techniques for extracting linear relationships among a set of variables. Principal components are the linear combinations of original variables and the eigenvectors (Iyer et al., 2003).

In the present study a total of three principal components were obtained after analysis, each explained the variation in hydro-chemical properties of both estuarine and mangrove ecosystem. In Mahi estuary, the three principal components explained 86.57% of variation observed during 2008-09 and 85.87% variation during 2009-10. In Vamleshwar mangrove, the principal components explained more than 76.49% of variation during 2008-09 period and 73.20% of variation during 2009-10. In both the ecosystems, principal component 1 explained more than 50% of the cumulative variance.
In Mahi estuary principal component 1 explained the variance with strong positive loading by pH, chlorinity, salinity, sodium, potassium, sulfate and EC indicating the marine water influence in contributing these nutrients. Component 2 was positively loaded with temperature, DO and sodium indicating release of these nutrients through urban, industrial run-off and riverine influence on this component. Study on the water quality of Reconquista river by Castane et al. (2006) revealed the river water influence on contributing ammonia and phosphate into principal components. The clustered occurrence of closely related groups in component plot diagram indicated the close association between each parameters as well as the source of these nutrients (Pradhan et al., 2009). This is further supported by correlation analysis which revealed a close association between parameters like DO, phosphate, nitrate, silicate and ammoniacal nitrogen in fresh water dominated sites and sulfate, chloride, salinity, sodium and potassium in marine water influential regions.

5.2. PHYSICO-CHEMICAL CHARACTERISTICS OF THE SURFACE SEDIMENTS

Sedimentary deposits or muds are the most characteristic features of estuaries. Sedimentary materials are transported into the estuary from rivers or the sea or are washed in from the land surrounding the estuary (McLusky & Elliott, 2004). Estuaries are generally rich in nutrients and the presence of suspended sediments in estuaries may cause substantial modifications to supply of nutrients which results in increased overall recycling efficiency of nutrients (Corbett, 2010). The exchange of nutrients between sediment and water depends upon the sediment type, aerobic and anaerobic conditions, biotic community of water, temperature and tidal influences (Golterman, 2005). Analysis of geochemical properties such as temperature, phosphate, organic carbon, organic matter, sodium, potassium and chloride helps to evaluate the anthropogenic impact on aquatic ecosystems as they have
significant role in accumulation of contaminants and nutrients for bioavailability in aquatic systems (Golterman, 2000).

**Temperature** plays a major role in controlling various physicochemical processes, distribution of organisms, nutrient cycling, etc. (Tabuchi et al., 2010; Gudasz et al., 2010. In the present study sediment temperature was observed high during pre-monsoon period followed by monsoon and post-monsoon period. The temperature was reported in the range from 18.4 °C to 30.4 °C in Mahi estuary and 18.5 °C to 30.5 °C in Vamleshwar mangrove. The different study sites recorded minor difference of 1 to 3 °C. Jackson & Richardson (2002) proposed that seasonal variation in reception of solar radiation is the main factor behind observed spatial and temporal change of temperature while working on Fort Walton Beach of Florida.

The study of distribution and behaviour of phosphates in sediments is significant to understand the dynamic cycling of phosphorous in estuary and bay water areas, induced by wastewater discharge and the phosphate exchange across the sediment-water interface (Min et al., 2003). Mesnage & Picot (1995) observed that sediments act as reservoir for various nutrients like phosphate or as a source when this phosphate is released under certain conditions. In the present study, sediment phosphate concentration was observed maximum at middle and lower reaches particularly during pre-monsoon and post-monsoon periods. Mean phosphate concentration obtained in Mahi estuary was 0.66 mgKg⁻¹ and in Vamleshwar mangrove it was 0.59 mgKg⁻¹. Comparable results were reported by Pant & Reddy (2001) from Indian river lagoon, Florida, USA where mean phosphate concentration was 0.75 mgKg⁻¹. Organic effluents released from industrial and domestic purposes followed by its accumulation might be the reason for higher phosphate concentration especially during pre-monsoon and post-monsoon period (Howell, 2010). Salinity plays a major role in adsorption-desorption properties of phosphate along with tidal forces have a major role in release of
phosphate ions in to water (Millero et al., 2001) which might be the cause of low phosphate concentration during pre-monsoon period and in the lower reaches.

The knowledge of the sources of organic matter in estuarine and mangrove sediments and factors controlling their distribution are important in understanding of global biogeochemical cycles. In these transitional systems, primary production generates large amounts of organic matter of which a significant portion sinks and ultimately gets preserved in sediments (Hu et al., 2006). In Mahi estuary and Vamleshwar mangrove higher concentration of organic carbon was encountered from lower reaches where more anthropogenic activities including diverse inputs from fall, stream flow, inappropriate animal waste applications and disposals, agricultural practices, etc. occur. In the present study the organic carbon was observed in the range of 0.17 mgKg$^{-1}$ to 0.86 mgKg$^{-1}$ in Mahi estuary and 0.09 mgKg$^{-1}$ to 0.95 mgKg$^{-1}$ in mangrove regions. During the present study the sediment samples from the lower reaches of estuary especially in pre-monsoon season carried higher amounts organic carbon with effluents. Bragadeeswaran et al. (2007) also observed high concentration (0.53 mgKg$^{-1}$ to 1.12 mgKg$^{-1}$) of organic carbon during pre-monsoon period while studying sediment texture and nutrients of Arasalar estuary, Karaikkal, south-east coast of India. Ghosh & Choudhury (1989) explained that sediment texture also plays a major role in retaining the organic components. As the texture decreases it can hold more organic matter which probably explains the higher percentage of organic carbon in upper reaches. Kumary et al. (2001) on basis of study on Poonthura estuary reported that the level of organic carbon in sediments is a reliable index of nutrient regeneration and the productivity of a water body. They also suggested that oxidation-reduction activities at the sediment-water interface bear marked influence upon the estuarine chemistry and upon the type of organism present in the sediment.
The concentrations of sodium, potassium and chloride were observed higher at lower reaches, which possibly explains the role of marine water influence in contributing these nutrients in sediments. Mackereth (1965) suggested that the increased concentration of these nutrients during summer season may be due to the low fresh water inflow followed by high transpiration rate in both the ecosystems studied. Sodium, potassium and chloride were found to be positively correlated with each other indicating the marine water influence on contributing these nutrients into estuarine sediments (Jordan et al., 2000). Ramanathan et al. (1988) reported that due to mixing of sea water with estuarine water, saline water gets enriched in interstices of sediments and gets precipitated in pre-monsoon months resulting in increased concentration during pre-monsoon and post-monsoon seasons.

Principal component analysis of geochemical properties revealed that two principal components were responsible for variation among the estuarine and mangrove regions. In Mahi estuary two principal components were found to be responsible for 89.38% and 87.97% during 2008-09 and 2009-10 respectively, in Vamleshwar it was observed 74.70% and 70.87% respectively during 2008-09 and 2009-10. As observed in water analysis, the influence of marine water on PC1 for sediment is evident from the strong positive loadings of chloride, phosphate, organic carbon, organic matter, sodium and potassium. In the present study PC2 explains strong positive load of temperature. Vaalgamaa & Conley (2008) carrying out PCA analysis of nutrient status of estuaries in Finland, stated that the concentration of phosphate, organic matter can be better correlated with the urban land-use type and industry together with the anthropogenic discharges. The study carried out by Wenchuan et al. (2001) also revealed the influence of anthropogenic influence in contributing nutrients into estuarine sediments by multivariate analysis studies of Taihu Lake in China. Rajasegar et al. (2002)
suggested positive correlation of sodium, potassium, indicated the strong association between these parameters in the sediments.

5.3. PHYTOPLANKTON COMMUNITY

The phytoplankton is an important biological indicator of the water quality, important primary producers forming the basis of the food chain in aquatic ecosystem. Some phytoplankton can be harmful to human and other vertebrates by releasing toxic substances, hence, should be monitored regularly and seasonally. Phytoplankton studies are useful for identification of the physico-chemical and other biological conditions of the water in any aquatic ecosystem. Certain groups of phytoplankton can hamper recreational value of surface water, particularly by forming thick surface scum, which reduces the use of amenities for contact sports or large growth, which cause deoxygenation of the water leading to fish death (Whitton & Pattis, 2000).

Over the last few decades, there has been found more concern about the processes influencing the development of phytoplankton communities, primarily in relation to physico-chemical factors (Peerapornpisal et al., 1999; Elliott et al., 2002).

There are many detailed descriptions of phytoplankton succession being correlated with changes in environmental parameters particularly temperature, light, nutrients availability and mortality factors such as grazing and parasitism. The dynamics of phytoplankton are a function of some environmental processes that affect species diversity (Morais et al., 2003). Further, eutrophication can be described through a number of abiotic as well as biotic parameters. Among the abiotic parameters, nutrients and oxygen concentration are usually used for assessing trophic levels, whereas, chlorophyll-a concentration, phytoplankton cell number and ecological indices are among the biotic parameters often employed to assess trophic conditions of the aquatic ecosystem (Krivokapic, 2008).
In estuaries, phytoplankton assemblage, structure and growth are affected by the different environmental factors that include salinity, nutrient, temperature etc. (Gasiunaite et al., 2005). Phytoplankton and their growth depend on several environmental factors, which are variable in different seasons and regions. In both the ecosystems studied, maximum density of phytoplankton was recorded during post-monsoon followed by pre-monsoon whereas it was noticed minimum during monsoon. The high density of phytoplankton could be attributed to the neritic element domination, clear water condition and availability of nutrients. As the hydrological parameters were in stable condition during post-monsoon months, the phytoplankton production was registered higher (Nayar & Gowda, 1999; Rajesh et al., 2002). Besides, more occurrence of phytoplankton during post-monsoon could be due to increased radiation or light intensity (Mani, 1992). Perumal et al. (2009) noticed higher density of phytoplankton during post-monsoon months and lower in monsoon months while studying on Kaduviyar estuary, India which corroborated very well with present investigation.

Salinity is a primary candidate in the list of potential regulating factors for phytoplankton composition. Frankovich et al. (2006) noted salinity as one of the major factors influencing phytoplankton zonation and distribution within estuaries, both in terms of range of values and rate of variations. The positive correlation for phytoplankton density and the salinity was also revealed from the present investigation in both the ecosystems. Adaptation to osmotic stress is a major factor indicating the success of specific species in estuarine environments and can have broad impacts on phytoplankton composition and standing crops (Kennish, 1990). Phytoplankton communities in marine tropical areas are known to be less dynamic than in temperate waters, from an annual perspective, with smaller seasonal variation in net phytoplankton growth (Qasim et al., 1972).
In the present study, phytoplankton assemblage was observed higher at upper and middle reaches in both Mahi estuary and mangrove regions where there is a dominance of fresh water. In Mahi estuary a total of 87 species belonging to 53 genera were recorded during the entire study period. The phytoplankton was represented by five dominant groups viz. Cyanophyceae, Chlorophyceae, Bacillariophyceae, Euglenophyceae and Dinophyceae. The genera present in different groups were Cyanophyceae (7 genera), Chlorophyceae (13 genera), Bacillariophyceae (26 genera), Euglenophyceae (2 genera) and Dinophyceae (5 genera). In Vamleshwar mangrove 64 species belonging to 38 genera were observed during the entire study period. The genera present in different groups were Cyanophyceae (6 genera), Chlorophyceae (9 genera), Bacillariophyceae (19 genera) and Dinophyceae (4 genera). The group Bacillariophyceae was found to be the most dominant group followed by Chlorophyceae, Cyanophyceae, Dinophyceae and Euglenophyceae.

Nabout et al. (2006) also observed the predominance of Bacillariopycean members followed by Chlorophyceae and Cyanophyceae members during his study on phytoplankton community of Brazilian lakes which was in relevance with our present study. Redekar & Wagh (2000) from their studies on Bacillariophyceans of Zuari coast of India concluded that salinity has a direct influence on distribution of Bacillariophyceae members which supports the predominance the group than other groups in our study. Palleyi et al. (2011) observed that in Dhamra Estuary phytoplankton of Bacillariophyceae appeared throughout the year and represented in majority of population (75-94%) at all the sampling stations, followed by Dinophyceae (3-14%), Cyanophyceae (3-8%) and Chlorophyceae (0-4%) classes, these results very well corroborated with the present study. Seasonal variations of phytoplankton in Mahanadi estuary, east coast of India was worked out by Naik et al. (2009) which revealed Bacillariophyceae to be the most dominant group followed by Dinophyceae and Cyanophyceae as observed in our
present study. The maximum phytoplankton count was observed during post-monsoon season by Naik et al. (2009) which was also found in similar trend with the results of present investigation.

Bacillariophyceae emerged as the most dominant group in both the ecosystems comprising of 46 species in Mahi estuary and 43 species in Vamleshwar mangrove. Ekeh & Sikoki (2004) also reported class Bacillariophyceae to be the most abundant group of phytoplankton among many tropical estuaries. Perumal et al. (2009) also recorded more than 50 percent of Bacillariophyceae members in their studies of phytoplankton diversity of Kaduviyar estuary. Bacillariophyceae members can be used as suitable bio-indicators for water quality assessments as they have short generation time and many species have a specific sensitivity to ecological characteristics (Stevenson & Pan, 1999; Goma et al., 2005). During present study, both the ecosystems showed higher density and diversity of Bacillariophyceae members at middle reaches and lower reaches. This may be due to the role of salinity in their distribution (Redekar & Wagh, 2000). Salomoni et al. (2006) working on phytoplankton of Gravatai river recorded the presence of Bacillariophyceae such as Nitzschia, Eunotia, Pinnularia and described them as indicators of organic pollution. They also reported them as pollution tolerant species. Palleyi et al. (2011) observed that nutrients like phosphate, nitrate and silicate have significant role in distribution of Bacillariophyceae group in estuarine environment. Thessen et al. (2005) reported diatoms to be prominent during the pre-monsoon and post-monsoon where there was a dominance of marine water in the estuarine region and their results were found to be corroborated with the present study. Tiwari & Nair (1998) and Senthilkumar et al. (2002) supported the dominance of diatoms in near coastal waters in west coast of India. This was reflected during the present study too, diatoms were found to flourish at lower reaches of both the ecosystems due to hydro-chemical conditions.
Chlorophyceae is the second largest and important group of phytoplankton documented from both Mahi estuary and Vamleshwar mangrove. Members of Chlorophyceae were represented by 20 species in Mahi estuary and 12 species in Vamleshwar mangrove. In the present study the dominance of Chlorophyceae members was found in the upper and middle reaches of estuary. Similar results in cross river Estuary of Nigeria were reported by Ekwu & Sikoki (2006) where the dominance of Chlorophyceae was observed in middle and upper reaches of estuary. In present study the density of Chlorophyceae members was found higher in upper reaches of Mahi estuary than in Vamleshwar mangrove might be due to freshwater dominance and less saline water intrusion in some stations of Mahi estuary. Dissolved oxygen, pH, alkalinity play a significant role in distribution of Chlorophyceae members in freshwater zones (Rajagopal, 2010). Rao & Pragada (2010) reported that the absence of Chlorophyceae forms in the lower reaches indicated the influence of salinity on the distribution of Chlorophyceae members. The Chlorophyceae were reported to be dominant during winter season, as also reported by Tiwari & Chauhan (2006), that might be due to high DO, high nutrient status and slow water current during this period. The growth of certain green algae (Scenedesmus, Ankistrodesmus falcatus and Chlorella vulgaris) is favored by higher concentration of nitrate and phosphate in water (Thomas et al., 2006) and hence these species are designated as pollution indicators (Nagarathna & Hosmani, 2002).

The past and recent studies on Cyanobacteria have emphasized their important role in ecosystem. They grow at any place and any environment where moisture and sunlight are available. The average population density of Cyanophyceae members was encountered greater in post-monsoon followed by monsoon months at freshwater dominated sites of both Mahi estuary and mangrove ecosystems. This could be attributed to the high temperature, slightly alkaline conditions and nutrient rich freshwater discharge, turbidity
due to suspended sediment which favors the growth of Cyanophyceae members (Harsha & Malammanavar, 2004). The present findings were in agreement with Sarojini (1994) who observed that Chlorophyceae and Cyanophyceae were usually favored by increased nutrients and dissolved organic material characterizing areas subjected to freshwater discharge. Besides, salinity has been suggested as controlling factor for blooms of N2-fixing cyanobacteria in the estuaries. Moreover, Moisander et al. (2002) suggested that direct effect of salinity on cyanobacteria physiology does not alone explain the low frequency and magnitude of blooms of N2-fixing cyanobacteria in estuaries. Cyanophyceae members were found to be less dominant than other groups like Bacillariophyceae in both the studied ecosystems. Several studies have recorded high abundance of cyanobacteria, but their contribution to the total phytoplankton community is usually relatively small in estuaries (Pinckney et al., 1998; Ning et al., 2000) which was well corroborated in the current findings.

Most of the members of Dinophyceae are marine plankton, but they are common in fresh water habitats as well. Their population is distributed depending on temperature, salinity or depth. The distribution of dinoflagellates is regulated by salinity, temperature and pH as their occurrence is more in areas having significant marine water influence (Cremer et al., 2007). The studies carried out at Cross river estuary of Nigeria by Ekwu & Sikoki (2006) revealed Dinophyceae to be the least dominant group and mostly reported from lower reaches which supports our results. Dinoflagellates community appeared relatively less in abundance in both the ecosystems throughout the year as compared to the diatoms and other groups. This might be due to the preferential oligotrophic nature of dinoflagellates and their competition with diatoms (Cushing, 1989).

The abundance of Euglenophyceae members in a water body can be attributed to the entry of nutrients through the influx of domestic sewage
which is an indication of organic pollution (Kumar & Hosmani, 2006; Laskar & Gupta, 2009). In the present study the group Euglenophyceae was represented by Euglena and Phacus genera. The members of Euglenophyceae were recorded from Mahi estuary only. The representatives of class Euglenophyceae inhabit freshwater basins as well as marine waters. It is established that macro-algae of this class develop widely in waters with high concentration of organic matter and basins subjected to anthropogenic eutrophication (Lee, 1999). In Mahi estuary, Euglenophyceae members were observed at upper and middle reaches where anthropogenic pollution is more as compared to lower reaches. Their occurrence and distribution is mostly reported during post-monsoon and pre-monsoon period. Tiwari & Chauhan (2006) also observed similar temporal variation in Euglenophyceae distribution at Kitham lake, Agra.

**Chlorophyll-a** is an important determinant of the phytoplankton standing stock and organic productivity of an aquatic system. Chlorophyll-a has often been utilized to assess the overall health of estuarine and mangrove ecosystem and in management strategies to ensure sustainable use of these ecosystems. A higher value of chlorophyll-a was recorded during post-monsoon and the lower value was observed during monsoon in both Mahi estuary and Vamleshwar mangrove. The low monsoonal values could be due to anthropogenic effects in addition to freshwater discharges during runoff from the rivers (dilution), causing turbidity and less availability of light (Kawabata et al., 1993; Godhantaraman, 2002). Furthermore, the presence of a prominent community of freshwater phytoplankton was also evident from the high values of chlorophyll-a associated with low-salinity waters at upper reaches in the Mahi estuary and Vamleshwar mangrove. The study confirmed the similar trend of chlorophyll-a by the observations of Perumal et al. (2009) in Kaduviyar estuary.
Palmer (1969) made the first major attempt to identify and prepared a list of genera and species of algae tolerant to organic pollution. He reported that the genera like Oscillatoria, Euglena, Scenedesmus, Navicula, Nitzschia, and Ankistrodesmus are found in organically polluted waters. Ratnasabapathy (1975) reported that Oscillatoria, Euglena, Chlorella and Ankistrodesmus are typical inhabitants of heavily polluted waters. Patrick (1965) concluded that Euglena and Oscillatoria are highly pollution tolerant genera and, therefore, reliable indicators of Eutrophication. In present study similar genera with very high grade points of Palmer’s scale accounted >20 at all sites of Mahi estuary which confirms the high organic stress and pollution in Mahi estuary from the nearby industrial set up. In Vamleshwar mangrove, station 2 and 3 were found to be moderately organic polluted. But station 3 was highly organic polluted which might be due to the discharge of domestic sewage into this region.

Diversity index is a statistics, which is applied to measure the species biodiversity in an ecosystem. A stressed environment typically has a lower number of species with one or two dominant species (those adapted to the stress) having many more individuals than the other species (Gao & Song, 2005). During the post monsoon season, as a result of fresh water flushing and changes in salinity, both the estuarine and mangrove regions experienced the most dramatic change in phytoplankton species composition, as is evident from the diversity index data. In the present study the diversity of phytoplankton community among four sites in Mahi estuary and three sites in Vamleshwar mangrove were estimated by Shannon's diversity index (H’). In upper reaches of both the estuaries the diversity index ranged from 2.33 to 4.15 in Mahi estuary and from 0.97 to 3.57 in Vamleshwar mangrove that revealed high species biodiversity among the study sites of both the estuarine and mangrove ecosystems. Harnstrom et al. (2009) suggested that tidal influence experienced in the estuarine region acts as a major factor in distribution of species along the salinity gradient.
5.4. ZOOPLANKTON COMMUNITY

The distribution of zooplankton community depends on a complex of factors such as change of climatic conditions, physico-chemical parameters and vegetation cover (Neves et al., 2003). The stability of zooplankton in any aquatic body of water is of profound importance because they represent important and unique food source for fish and many aquatic vertebrates (Ochang et al., 2005). The estuarine zooplankton species have to be highly adaptive and are reported to show mechanisms to detect changes in salinity and DO. The physico-chemical boundaries play a significant role in the distribution of zooplankton in the sea as there are strong gradients in the terms of light, temperature and salinity from surface to bottom layers (Colebrook, 1982). The zooplankton exhibited uneven distribution along the horizontal and vertical planes. The zooplankton are dispersed according to the scale of water turbulence. The intensity of zooplankton aggregation depends on their ability to counter dispersion, phytoplankton growth, grazing rates, predatory/prey relationship and reproduction strategies of zooplankton (Robin et al., 2009). Zooplankton also play an integral role by serving as bio indicators and is a well-suited tool for understanding water pollution status (Contreras et al., 2009).

The Zooplankton density was reported maximum during post-monsoon period in both Mahi estuary and Vamleshwar mangrove. The upper reaches were found to harbour maximum population density than middle and lower reaches. In the present study the low density of zooplankton occurred during monsoon period that might be due to the mixing and dilution effect of run-off water along with change in environmental variables like salinity, temperature and nutrient concentration (Madhu et al., 2007). Multivariate analysis of Mission Bay hyper saline estuary was carried out by Elliot & Kaufmann (2007) which revealed that variation in zooplankton species composition was best related to measured abiotic factors.
(temperature, salinity, rainfall and tidal velocity) that shows resemblance with the results of present study. Salinity is the key factor influencing the distribution and abundance of zooplankton (Padmavathi & Goswami, 1996). This was also evidenced by the positive correlation of the salinity with the dominant group copepoda in both the ecosystems studied. Besides, in post-monsoon months zooplankton density was greater in all the study sites of Mahi estuary and Vamleshwar mangrove. Similar observations were made by Govindasamy & Kannan (1991); Perumal et al. (2009) and Mulani et al. (2009) which may be due to easy availability of food.

The studies on zooplankton communities, especially copepods are very important in assessing the health of coastal ecosystems (Ramaiah & Nair, 1997). The abundance and variation in zooplankton of estuaries are mainly related with salinity regime. Among the crustacean zooplankton, Copepoda was represented as the dominant group. This may be due to their continuous breeding behavior, quick larval development and probably they adapt well to the widely changing environmental conditions of the estuary. Further, among the calanoids, Acartia dominated other forms throughout study period (Madhupratap, 1987).

The maximum density of copepods was observed during post-monsoon period and minimum density during monsoon period. The dominance of species suggests the significant role in trophic food web and studies showed that most of the copepods are either herbivorous or omnivorous (Madhupratap, 1979). The increase in copepod density during post-monsoon season could be also suggestive of their active grazing of phytoplankton independently or in combination with microzooplankton because the herbivorous copepods are capable of grazing up to 75% of the phytoplankton in a tropical estuary (Tan et al., 2004). Similar results were also obtained by Padmavathi & Goswami (1996) in Mandovi and Zuari estuaries and Sastry & Chandramohan (1990) in Godavari estuary.
Cladocera is a crucial group among zooplankton and forms the most useful and nutritive group of crustaceans in higher members for fishes in the food chain which feed on smaller zooplankton like bacterioplankton and algae (Murugan et al., 1998) and is highly responsive against pollutants; thus reacts against the low concentration of contaminants. In present study Daphnia sp. and Bosmina sp. and Moina sp. were reported from all the study sites of both Mahi estuary and Vamleshwar mangrove. Jha & Barat (2003) stated that the presence of Daphnia, Bosmina and Moina indicates the high pH of water. In the present study the highest density of Cladocera population was observed at lower reaches and middle reaches of both the ecosystems. Moreover, the highest density was observed during post-monsoon period. Ojha et al. (2007) reported that dominance of Cladocera among zooplankton during post-monsoon which might be due to optimal thermal and nutritional conditions. The species like Daphnia and Keratella were positively influenced by salinity whereas species like Bosmina was regulated by changes in fresh water. Mikhailova & Isupova (2007) stated that spatial variation was influenced mainly by morphometrical characteristics of the estuary while temporal variation by climatic changes. The studies of seasonal and temporal variation of species richness and population densities described in this study could be due to alterations in the hydrological and biological characteristics of the ecosystems studied.

Rotifers are the most sensitive bio-indicators of water quality and their presence may be used as a reference to the physico-chemical characteristics of water (Saksena, 1987). The members of this group were represented mainly by Brachionus, Keratella, Ploesoma and Rotaria in the present study. Kruger & Strydom (2011) have reported that salinity has a prominent role in determining the distribution of Rotifers along salinity gradient. Nogueira (2001) reported Brachionus calyciflorus as indicators of sewage and industrial pollution. The present study reported Brachionus calyciflorus in all waters of Mahi estuary and Vamleshwar mangrove which suggests that these sites are
polluted by direct contamination of sewage and other industrial effluents. Rotifers like *Brachionus* and *Keratella* were observed at all the study sites of both the ecosystems that reveal the eutrophic condition and also indicate the presence of high suspended sediment load as per the findings of Ferdous & Muktadir (2009).

**Protozoans** are the group of unicellular ciliated or flagellated organisms that feed on either picoplankton or nanoflagellates and small nanophytoplankton according to their size. In the present study *Arcella*, *Globigerina* and *Vorticella* were the dominant protozoan species documented from both Mahi estuary and Vamleshwar mangrove. *Amoeba* and *Euglena* species were found at middle reaches of Mahi estuary which receive heavy dose of sewage. This suggests that these species are polluted water species (Saxena & Mishra, 1990).

The members of **Chaetognatha** play an important role in marine food webs, being active predators. Their diet includes a variety of pelagic organisms, consisting mainly of copepods, but they may also prey on fish larvae thus impacting the zooplankton and Ichthyoplankton communities (Casanova, 1999). The current study revealed the occurrence of *Sagitta* along the study sites of both the ecosystems. Chaetognaths are mainly found in zones where marine water influence is higher. In the present study the species belonging to this group was reported only from lower and middle reaches in Mahi estuary and from all sites of Vamleshwar mangrove. The results obtained in the present study showed that the presence of Chaetognatha species found in the estuarine area is due to the tidal effect (Casanova, 1999). The dominance of this group was observed at pre-monsoon season which is very well corroborated with the studies of Fernandes et al. (2005) in a tropical estuary of southern Brazil.

Diversity indices like Shannon-Weaver species diversity (H’), Margalef species richness (d) and Pielou’s evenness (J) for zooplankton analysis were
recorded higher at lower reaches followed by middle and upper reaches. **Wang et al. (2011)** conducted studies in Zhanjiang harbour water and observed the maximum Shannon-Weaver diversity during post-monsoon and pre-monsoon periods which corroborated with the results of present investigation. **Khalil & Rahman (1997)** on their studies on zooplankton of Gulf of Aqaba, Egypt also registered higher diversity index and spatial distribution as evident from present study.

### 5.5. BENTHIC FAUNA

Benthic organisms play a vital and precious role in the transfer of materials from primary producers through the detritus pool into higher trophic levels, including commercially exploitable fish (**Ingole et al., 2002**). Further, majority of the benthic fauna are sedentary and sessile and thus, cannot avoid any environmental perturbation (**Danulat et al., 2002**), hence are considered sensitive indicator of changes in the environment caused by natural and anthropogenic disturbances. The relationship between macro faunal assemblages and the effect of pollution in the sediment has been worked out by **Pearson & Rosenberg (1978)** and **Morrisey et al. (2003)**.

The spatial differences in the composition of the benthic communities along estuarine gradients are distinct and mainly related to changes in salinity, depth, sediment grain size and organic content (**Day et al., 1989**). This fact is supported by the present work where spatial difference of benthic communities for different study sites was noteworthy. Generally the estuarine communities are subjected to greater natural stress than those in non-polluted coastal waters and are expected to show lower benthic composition. Spatial and temporal variations in abiotic and biotic parameters in these estuarine systems are affected by tropical southwest monsoon, riverine and tidal flows contributing to the ecological complexity of the estuarine ecosystem of the west coast of India (**Parulekar et al., 1980; Qasim & Sengupta, 1981; Parulekar et al., 1986**).
Salinity is the major natural environmental factor controlling regional distributional patterns of the estuarine benthos. Differences in sediment characteristics and levels of bottom dissolved oxygen concentrations that occur from shallow to deep habitats control local benthic distributions. Sediment nutrient compositions like phosphate, organic carbon have a positive role in determining the distribution of benthic organisms (Martin, 2011). In the present investigation, Mahi estuary was found to be dominated with the members of Mollusca followed by the members of Crustacea. The Nematoda group was the least represented group with only 6% of total faunal population. In Vamleshwar mangrove Crustacea was encountered to be the most dominant group contributing about 28% of the total benthic organisms followed by Mollusca (25%). Similar results were obtained by studies conducted by Kastoro et al. (1989) in the estuarine waters of East Java and Giberto et al. (2007) in the Río de la Plata system.

The group Mollusca have assumed to have a major role in monitoring contaminants worldwide (Feldstein et al., 2003). Bresler et al. (2003) reported molluscs to be abundant, sedentary and easy to collect, which makes them ideal for bio-monitoring. Bivalve and molluscs are among the most useful organisms for environmental monitoring (Boening, 1999). In the present investigation, benthic forms were found to occur on mud banks, mud flats, mangrove forest, sandy area, swamps and hard substratum such as wooden blogs, poles and pillars. The maximum species were collected from estuary banks and mud flats which might have deposited mainly by tidal waves. Peeters et al. (2000) from their studies on distribution of macro-invertebrate community along salinity gradient suggested that the sediment grain size, together with salinity and depth, acts as an important factor to explain the dominance of Molluscan community at lower reaches in the present study. Mucha et al. (2003) also observed similar results showing higher diversity of Molluscs in sediment rich zones.
Crustaceans are a very successful group of animals, distributed in a number of different habitats including marine, terrestrial and freshwater environments. The dominant species comprising the crustacean group includes Acetes sp., Gammarus sp., Hemigrapsus sp., Uca annulipes and Uca lactea. In both the marine and freshwater environment, crustaceans may live in the benthic as well as in the pelagic zone (Akbulut et al., 2009). The distribution of crustaceans was encountered throughout the study sites with majority of organisms reported from lower and middle reaches. The extreme diversity of adaptations in morphology, physiology, and way of life and reproduction to the different conditions probably enable crustaceans to establish themselves in almost any water body (Vernberg & Vernberg, 1983). The variety of adaptations of crustaceans to different habitats is also reflected in a variety of feeding mechanisms (Dorit et al., 1991; Ruppert & Barnes, 1994). The micro-distribution of various species depends on particular ecological preferences, such as habitat structure (including water flow, substrate and food) as well as differences in physiological tolerance to oxygen content, temperature and water quality. Besides, the presence or absence of predators also plays an important role (Rinderhagen et al., 2000).

Species of Polychaeta are an important component of benthic communities, because of their high species richness, their high biomass and density and their high level of tolerance to adverse effects (pollution and natural disturbance). Polychaeta are usually the most abundant taxa in benthic communities and have been most often utilized as indicator species of environmental conditions (Dean, 2008). In the present study the presence of species belonging to Neries and Nerita along the lower and middle reaches are indicative of the pollution load experienced at these regions. Tomassetti & Porrello (2005) had reported that the organic content percentage in sediment has a positive role in distribution of Polychaeta species and their results were found to be corroborated with present findings. Jegadeesan & Ayyakannu (1992) also evaluated the seasonal variation of benthic fauna in marine zone of
Coleroon estuary of south east coast of India and suggested that the occurrence of Polychaeta in upper reaches might also be due to the higher percentage of silt and clay along with organic matter in these sites.

**Nematoda** is the most representative meiofaunal group found in almost all aquatic environments. Current study has revealed the occurrence of Juvenile forms and nematode worms from the study sites of both Mahi estuary and Vamleshwar mangrove. The taxonomic diversity and sensitivity to pollutants makes it an important tool in studies (Platt et al., 1984). In estuarine and mangrove environments, salinity is an important factor determining the structure of Nematode communities (Soetaert et al., 1995). In the present study the occurrence of this group was observed at all sites of both the ecosystems studied. Communities found on sandy bottoms are more resilient to natural physical disturbances, such as those created by currents and waves, than those found on muddy bottoms (Schratzberger & Warwick, 1998). In the present study nematodes were mostly recorded during monsoon and post-monsoon seasons. The environmental conditions found in the estuarine regions with lower hydrodynamics, a predominance of fine sand, a higher level of organic matter, higher mean levels of oxygen and pH, and total transparency, associated with shallow water, could favour the establishment of Nematodes (Kapusta et al., 2006).