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ROLE OF SEDIMENTARY PROCESSES AND ENVIRONMENTAL FACTORS IN DETERMINING THE DISTRIBUTION PATTERN OF DIATOMS AND MARINE/ TERRESTRIAL PALYNOMORPHS IN A TROPICAL COASTAL WETLAND

BISWAJEET THAKUR, JYOTI SRIVASTAVA, PREMRAJ UDDANDAM, MC MANOJ and **VANDANA PRASAD***

BIRBAL SAHNI INSTITUTE OF PALAEOBOTANY,
53 UNIVERSITY ROAD, LUCKNOW-226 007
INDIA
*CORRESPONDING AUTHOR, EMAIL ADDRESS: prasad.van@gmail.com

ABSTRACT

Factors controlling the distribution of marine and terrestrial palynomorphs in a coastal ecosystem were studied from surface sediments of 17 stations of Vembanad wetland, Kerala. Marine and terrestrial organic matter, mangrove and terrestrial pollen, dinoflagellate cysts, diatoms, Total organic carbon, percentage of sand, silt and clay, total dissolved solids and salinity were recorded in the sediment samples from each station. Based on the study, three depositional zones were identified in the Vembanad wetland i) flood tidal basin, ii) Central tidal basin, and iii) fluvial basin. The constant composition of terrestrial and mangrove pollen in the 8 stations of the northern Vembanad ecosystem from Munambaom-Barmouth points to tidal influence. Low percentage of dinocysts and pollen but high percentage of diatoms in Munambaom, Cherai beach, and Midway to Cherai stations of the central part of Vembanad is probably due to prevalence of high energy and an oxidizing environment of deposition. Abundance of terrestrial pollen as well as fresh water diatoms, but extremely low representatives of marine dinocyst in the southern stations Kochi Shipyard-Kumarakaom indicate high fluvial supply and proximal setting with respect to the terrestrial source. This study helped to elucidate the role of different factors, i.e. proximal-distal trend, tidal flushing, hydrodynamic conditions, climate and redox state of the depositional environment in determining the distribution of marine and terrestrial palynomorphs in a coastal environment.

Keywords: Vembanad wetland, Pollen, Diatoms, Palynofacies, Dinoflagellate cysts, Depositional environment

INTRODUCTION

Coastal waterways are among the most fragile, dynamic and productive ecosystems of the earth's surface in which geomorphic change is driven by the deposition and erosion of sediments (Cowell *et al.*, 2003; Kaiser *et al.*, 2005). These coastal landforms are predominantly depositional environments in which trapped sediments are laid down and shaped by the tidal and fresh-water surges (Pethick, 1984; French and Stoddart, 1992; Friedrichs, 1995; Schuttelaars and deSwart, 2000; Lanzoni and Seminara, 2002). Any sedimentary environment is a product of a unique combination of physical, chemical and biological setting in a geomorphic unit (Reineck and Singh, 1980). The variation (spatial and temporal) in these flow types gives rise to a complex distribution of coastal sediments resulting into various sedimentary environments. Coastal wetlands are the most vulnerable but economically important ecosystems on earth (Barbier, *et al.*, 2011; Kirwan and Megonigal, 2013). These wetlands aid in conditioning the sustainability of coastal biological populations due to their strong interaction with physical and chemical properties of the environment and offer clear evidences of the response of coastal habitats to abiotic factors such as tidal amplitude, sea-level rise/fall, climate, groundwater, accommodation space, water and sediment dynamics along with various anthropogenic activities (Pratolongo *et al.*, 2009). Hence, the major concern of a palynologist is to understand correctly the coastal morphology, characterization of sub-environments, together with its present-day dynamics and long-term evolution. There is a further need to develop modern analogues to understand correctly the process-driven changes, redox state, proximal- distal depositional environments, and vegetational pattern in wetland ecosystem, based on the distribution pattern of marine and terrestrial palynomorphs. Several conceptual models have been introduced to explain the differences in coastal morphology, sedimentary processes, and general sediment distribution (Boyd *et al.*, 1992; Dalrymple *et al.*, 1992) in order to provide a better basis for global and regional comparison of coastal ecosystems (Balsinha *et al.*, 2009; George *et al.*, 2012). In these models, the system is divided into a landward zone, dominated by riverine sedimentation; a seaward zone, dominated by wave and tidal processes; and an intermediate zone of mixed energy between the two. Roy *et al.* (2001) also recognized four geomorphic zones within a coastal wetland system: a marine flood-tidal delta, central mud basin, fluvial delta and riverine channel and alluvial plain. These zones correspond to mappable sedimentary environments and provide characteristic sedimentological, hydrological and biological attributes. A mutual co-adjustment of these coastal forms and their processes is termed the coastal morphodynamics (Wright and Thom, 1977) and these processes which drive a section of the coast are the function of climatic and oceanographic aspects, nature of hinterland and pre-existing topography (Woodroffe, 2002). Thus, a morphodynamic model, based on the studies of biological proxies and complemented by computer simulation would synthesize these relationships to produce a better perception of how the coasts operate (Cowell and Thom, 1994).

The distribution of sand, silt and clay in sediment samples relates to the availability of different sizes of sediment particles in the parent material and processes operating where the sediments are being deposited (Friedman and Sanders, 1978). Consequently, textural data are often used for the recognition of specific processes of sediment transport and deposition, and hence, used to characterise depositional environments. Variation in soil salinity in the coastal ecosystem is due to distance from the coast, tidal incursions and fresh water inputs. Anthropogenic pressures and sea-level changes influence the mechanism of salt water intrusion and freshwater run-off. The salinity of estuaries usually increases away from a fresh water source such as a river, although evaporation sometimes causes the salinity at the head of the estuary to exceed seawater. Freshwater discharges in a coastal wetland are mainly episodic, and are primarily controlled by conditions in the catchment including rainfall patterns, vegetation type and cover, topography, catchment area, and geology. The interaction between marine and freshwater generates hydrodynamics unique to a coastal wetland, in which both the natural variation in freshwater inputs as well as the flood and ebb tidal flows are vital for maintaining coastal health and mangroves in particular (Rao, 1975; Chapman, 1977). Mangrove forests with their exclusive ecological characteristics provide clues to ecological variability in the ecosystem (Ellison, 1989). These are closely associated and are influenced by the average sea-level position, therefore indicating its variability through a time period. Recurrent water runoffs in the coastal wetland favour mangrove growth (Naskar and Mandal, 1999) and, therefore, are good indicators of monsoon intensity. These respond opportunistically to habitat change induced by geomorphological processes that provide the basis for understanding the changes in the past and predict the possible trend in future.

Diatoms are unicellular eukaryotic algae with siliceous frustules which are a major source of primary productivity (Round *et al.*, 1990; Dixit *et al.*, 1992; Stoermer and Smol, 1999; Smol and Stoermer, 2010). Diatoms are sensitive to changes in pH, salinity, temperature, hydrodynamic conditions, and nutrient concentrations, and are useful proxies for the ecological analysis. They are particularly useful as environmental indicators as they have specific habitat preferences that are optimal for their growth and survival (Dixit *et al.*, 1992). Dinoflagellates are unicellular algal protists which occur in different aquatic environments from freshwater to marine (Taylor, 1987; Mertens, 2012). Production and preservation of dinoflagellate cysts is defined by the complex interaction of physicochemical properties such as salinity, temperature, nutrient availability, light penetration, turbulence, oxygen availability at the sediment water interface, hydrodynamics and sedimentary processes (Zonneveld *et al.*, 2013; Marret and Zonneveld, 2003). The dinoflagellate cysts serve as a suitable proxy for palaeoecology, palaeoproductivity and palaeoclimate reconstruction from all lattitdes. However, recent distribution of cysts has been utilised to demarcate the regional differences in trophic stages as well as different hydrodynamic and sedimentary processes on small spatial scales (Elshanwany *et al.*, 2010; Narale *et al.*, 2013). Cyst signals are also a good indicator of variation in marine and riverine processes, associated sedimentary processes and trophic status in an estuarine ecosystem (Pospelova and Kim, 2010; Pospelova *et al.*, 2005).

Pollen are useful indicator of past climatic conditions, however, quantitative estimation of pollen belonging to ecologically sensitive vegetation (mangrove, tropical rain forest, savanna grass land) in the surface sediments of coastal wetland can help in elucidating the proximal distal trends, vegetation pattern as well as climatic conditions in the continental region. Palynofacies is defined as a set of quantitative distinctive assemblages of various types of phytoclasts (recovered from sedimentary rocks after non-oxidizing palynological procedure-HCL and HF treatment), whose quantitative composition reflects specific depositional environment (Combaz, 1964; Powell, 1990; Tyson 1995). Since marine and freshwater phytoclasts are characteristically different, palynofacies study is a potentially useful tool to decipher proximal-distal trends in shallow marine depositional setting. Several studies have been carried out on palynofacies of pre-Quaternary sediments. However, in order to achieve a more reliable dataset, palynofacies study of modern wetland ecosystem is required.

The aim of this study is to develop a modern analogue based on distribution pattern of centric and pennate diatoms, autotrophic and heterotrophic dinoflagellate cysts, mangrove and terrestrial pollen and dispersed organic matter content in the different zones of Vembanad coastal wetland for the determination of process-driven changes and environmental factors such as proximal-distal trends, tidal flushing, fluvial activity, climate, redox state, change in the vegetation source pattern in tropical wetland ecosystem. The study will help to understand correctly the depositional setting and environment of the Vembanad coastal wetland ecosystem.

STUDY AREA

The Kerala coast in India encompasses long and irregular coastal wetlands behind the coastal barriers. Amongst these, Vembanad wetland (9°50'N, 76°45'E) is the largest brackish water, humid tropical ecosystem on the southwest coast of India (Fig. 1). The topography of the Vembanad wetland is divisible into two zones; the southern zone and the northern zone. The northern zone is well connected to the Arabian Sea at Cochin and Azhikode, 16 miles apart. The wetland lies parallel to the coastline, extending between Thannermukkam in the south and Azheekode in the north. The seven rivers entering into the wetland system on either side of the mouth are Periyar, Pamba, Manimala, Achankovil, Meenachil, Muvattupuzha and Chalakudi (Abdulla Bava, 1996). The wetland region is majorly associated with short, fast-flowing, monsoon-fed rivers and experiences a wet and maritime tropical climate influenced by seasonal heavy southwest (SW) summer monsoon and northeast (NE) winter monsoon with around 120–140 rainy days per year (Planning commission, 2008). Most of the precipitation occurs from June to August corresponding to the southwest monsoon (Thorpe *et al.*, 2012), while the rest falls between September to December as a result of the northeast monsoon. The mean daily temperature ranges from 19.8 °C to 36.7 °C, while the mean annual temperature varies from 25.0–27.5 °C in the coastal

EXPLANATION OF PLATE I

Diatoms, pollen, dinoflagellate cysts and organic matter identified in the assemblage from Vembanad wetland.

1,2. ***Rhizophora mucronata***; 3. ***Sonneratia***; 4. ***Combretum***; 5. ***Artemisia***; 6. ***Avicennia***; 7. ***Bruguiera***; 8. ***Terminalia***; 9. ***Alternanthera***; 10. ***Desmodium***; 11. ***Poaceae***; 12. ***Eugenia***; 13. ***Nitzschia separanda***; 14. ***Nitzschia panduriformis***; 15. ***Surirella***; 16. ***Stauroneis***; 17. ***Cyclotella meneghiana***; 18. ***Nitzschia gracilis***; 19. ***Asteromphalus***; 20. ***Diploneis***; 21. ***Gyrosigma***; 22. ***Melosira***; 23. ***Baccilaria***; 24. ***Diploneis*** 25, 26 ***Bitectatodinium spongium*** 27,28 ***Operculodinium centrocarpum*** 29. ***Lingulodinium machaerophorum*** 30. ***Tubercuodinium vancompoae*** 31,32,33,34, ***Spiniferites*** spp. 35. ***Lejeunecysta*** spp. 36. ***Polykrikos*** spp. 37. **Concentricystis?** 38. **Copepod** egg shell; 39. **Structured degraded debris**; 40. Foraminifera lining; 41. Black oxydized; 42. Brown degraded.

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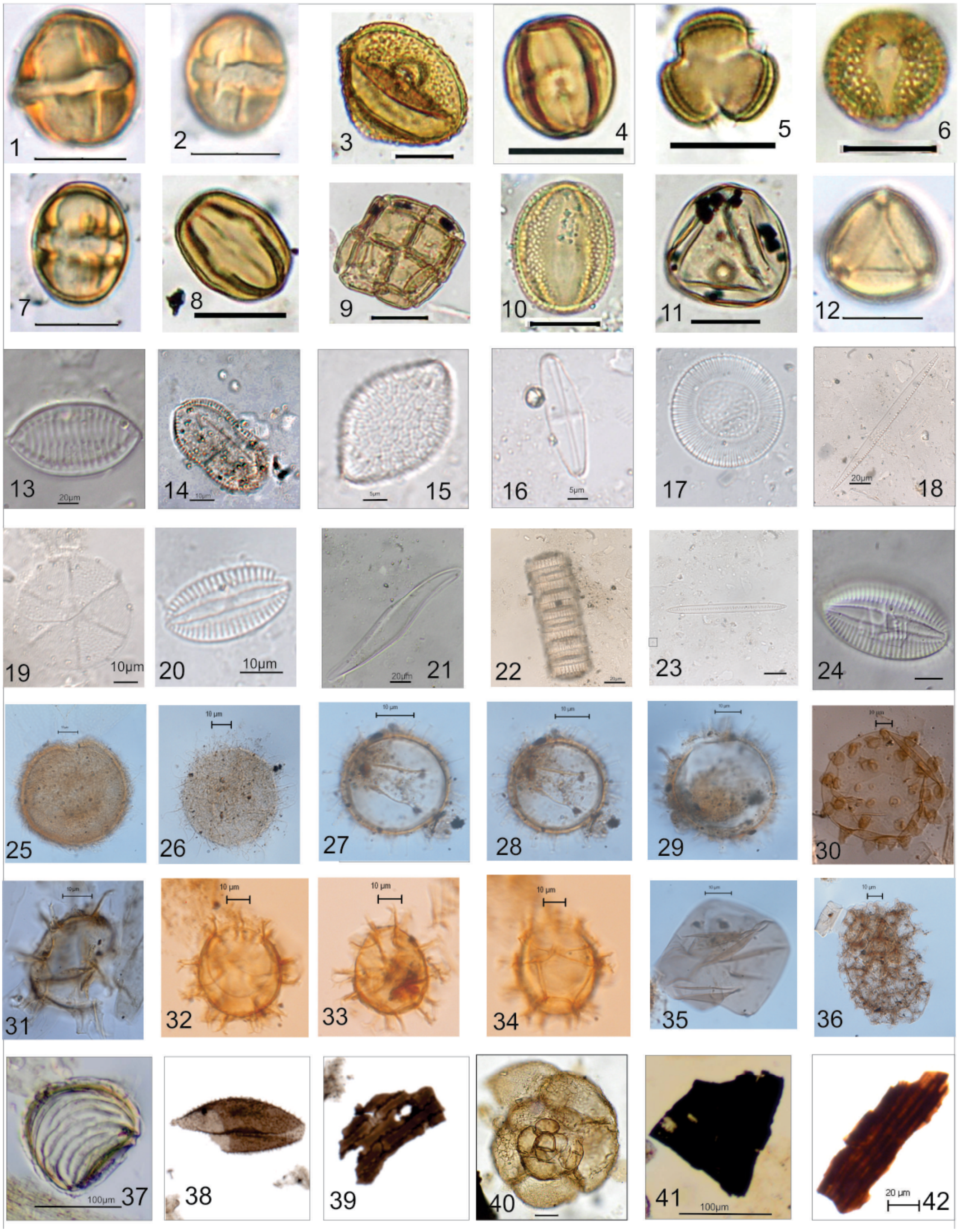
Plate I



lowlands (Brenkert and Malone, 2003). The wetland holds an extensively rich biodiversity with 24 species of green algae, 10 species of blue green algae, one species of yellow brown algae, 13 species of desmids and 19 species of diatoms (Planning Commission Report, 2008). The major aquatic plants found includes *Eichhornia crassipes*, *Salvania molestsa*, *Nymphaea stellata*, *N. Nouchali*, *Nymphoides cristatum*, *N. indica*, *Hydrilla verticellata*, *Najas minor*, *Limnophila heterophyll*, *Aponogeton crispium*, *Potamogeton pectinatus*, *Scripus validus*, *Cyperus corymbosus* and *Ischaemum barbatum* (Kumaran *et al*., 2008). Along with these, 8 pteridophytes and 202 angiosperms, of which 68 arboreal species are recorded and this also includes 14 mangrove species with rare true mangroves-like *Excoecaria agallocha* and *Bruguiera sexangula* and more than 30 mangrove associate species. Vembanad wetland also supports diverse faunal assemblages which include a large variety of fish, prawns and clams, reptiles and birds and provides a conducive environment for different individuals. Almost all of the 20 groups of zooplankton recorded from Kerala backwaters are present in the Vembanad wetland system. These outstanding qualities of the Vembanad wetland system suggests that a morphodynamic study of the coastal processes and its control on the depositional pattern of sediments as well as other biotic and abiotic forms may serve as a suitable model to understand the larger coastal deposits of the Quaternary and pre-Quaternary times.

Hydrography of the Vembanad wetland has been well studied by several researchers (Qasim and Reddy, 1967; Qasim *et al*., 1968; Josanto, 1971a; Laxmanan *et al*., 1982; Sankaranarayanan *et al*., 1986; Anirudhan, 1988; Joseph, 1989). The geochemistry and sedimentology of the wetland has also been well documented by Sankaranarayanan and Panampunnayil (1979), Saraladevi *et al*. (1991), Ansari and Rajagopal (1974), Verma *et al*. (2002), and Venkatachala *et al*., (1992). The bathymetric and terrain characteristics have been explored by Gopakumar and Takara (2009) with the aid of GIS technology in the Vembanad wetland.

MATERIALS AND METHOD

Sampling for palaeontological and sedimentary analysis was undertaken along the coastline covering the entire Vembanad wetland system (Fig. 1). Sediment surface samples were collected using a Van Veen grab sampler at regular intervals while moving from the northern zone (Munambaom; Station 1) towards the southern zone (Kumarakaom; Station 17). The sediment sampling stations for the present study are given in Table 1. Grain-size distribution was determined by laser scattering (Cilas 1190 Particle Size Analyzer) and relative percentages of sand, silt and clay contents were computed. Sediment salinity was measured in 10 g of air dried soil sample dissolved in 100 ml of deionized water. Prior to measuring, the soil solution was kept overnight after rigorous shaking for an hour. The samples were homogenized for 30 minutes before measuring the salinity using 'Orion-5 star (Thermo-Orion, Scientific Equipment, USA) at a standardized 25ºC temperature (Farooqui and Naidu, 2010; Srivastava and Farooqui, 2012).

Table 1: Station sampling locations from Vembanad wetland system.

St No.	Station Name	St No.	Station Name
1	Munambaom	9	Kochi Shipyard
2	Midway to Munambaom	10	Thevara
3	Cherai Beach	11	Arookutty
4	Midway to Cherai	12	Panapally
5	Kadakkara	13	Murinpuzha
6	Elemkunnapuzha	14	Vaikom
7	Barmouth	15	TVpuram
8	Bougatty	16	Thaneermukkam
		17	Kumarakaom

For diatom study, sediment samples were prepared using standard digestion procedures (Battarbee and Kneen 1982; Battarbee 1986; Renberg 1990). Diatom frustules were identified from Round *et al*., (1990). The identification was carried out using light microscopy (Olympus BH-2) with x100 oil immersion objective. In total, 300-500 frustules per sample were counted for statistical and graphical representations. Identification and counting of diatom frustules was done as per Round *et al*. (1990).

Pollen analysis was done on 10g of dried soil samples, treated with KOH followed by HF to dissolve the silica. The residue was acetolysed following Erdtman (1943). Residue obtained after passing through 10 µm mesh size was studied under high power light microscope (Olympus BX-51). The qualitative and quantitative study of pollen/spores has been documented as percentage values of more than 200 counts. Identifications were made to the narrowest taxonomic category possible with the aid of pollen atlases of Thanikaimoni (1966), Thanikaimoni *et al*. (1973), Pollen flora of Western Ghats (Tissot *et al*., 1994) and flora of Maharashtra (Nayar, 1990).

For dinoflagellate cysts and palynofacies, the concentration of organic matter in the sediment samples was prepared according to standard palynological methods (Traverse, 1988). HCl and HF were used to remove carbonates and silicates, respectively. No oxidizing agent was used to avoid the degradation of sensitive dinoflagellate cysts. The organic matter was further concentrated by sieving of samples through 20 µm mesh. The fixation of the samples was done with polyvinyl alcohol and mounted in Canada Balsam for better reflection under light microscope. The identification of the dinoflagellate cysts is done using published literature from Marret and Zonneveld (2003).

The organic and inorganic carbon content was determined through Loss-on-ignition method (Dean, 1974; Heiri *et al*., 2001). Dried samples were heated in a drying oven at 110°C for 12 hours, 550°C for 2 hours and 950°C for 2 hours. LOI in the samples was calculated by adding all the weight loss due to ignition and taking out its percentages (Dean, 1974; Bengtsson and Enell, 1986). The distribution chart of different biotic and abiotic proxies are shown in Fig. 2 and the photomicrographs displaying the palynomorphs and non-palynomorphs are shown in Plate I. Figs. 3–9 showing the distribution of data across the Vembanad wetland were made using IDW interpolation method in 3D analyst (ArcGIS 9.3). A Principal Component Analysis (PCA) was carried out using XLsoftware 2013, for the entire dataset (Fig. 10) to distinguish different depositional environments based on biotic and abiotic proxies.

RESULTS

The distribution of sediments, salinity, palynofacies, total organic carbon, diatom, dinoflagellate cysts and pollen has been used to describe the riverbed environments, by the identification of sedimentary processes and palynoflora/fauna ecological zones. The distribution of these environments/zones can then be related to the various physical and chemical factors within the coastal wetland (Fig. 2).

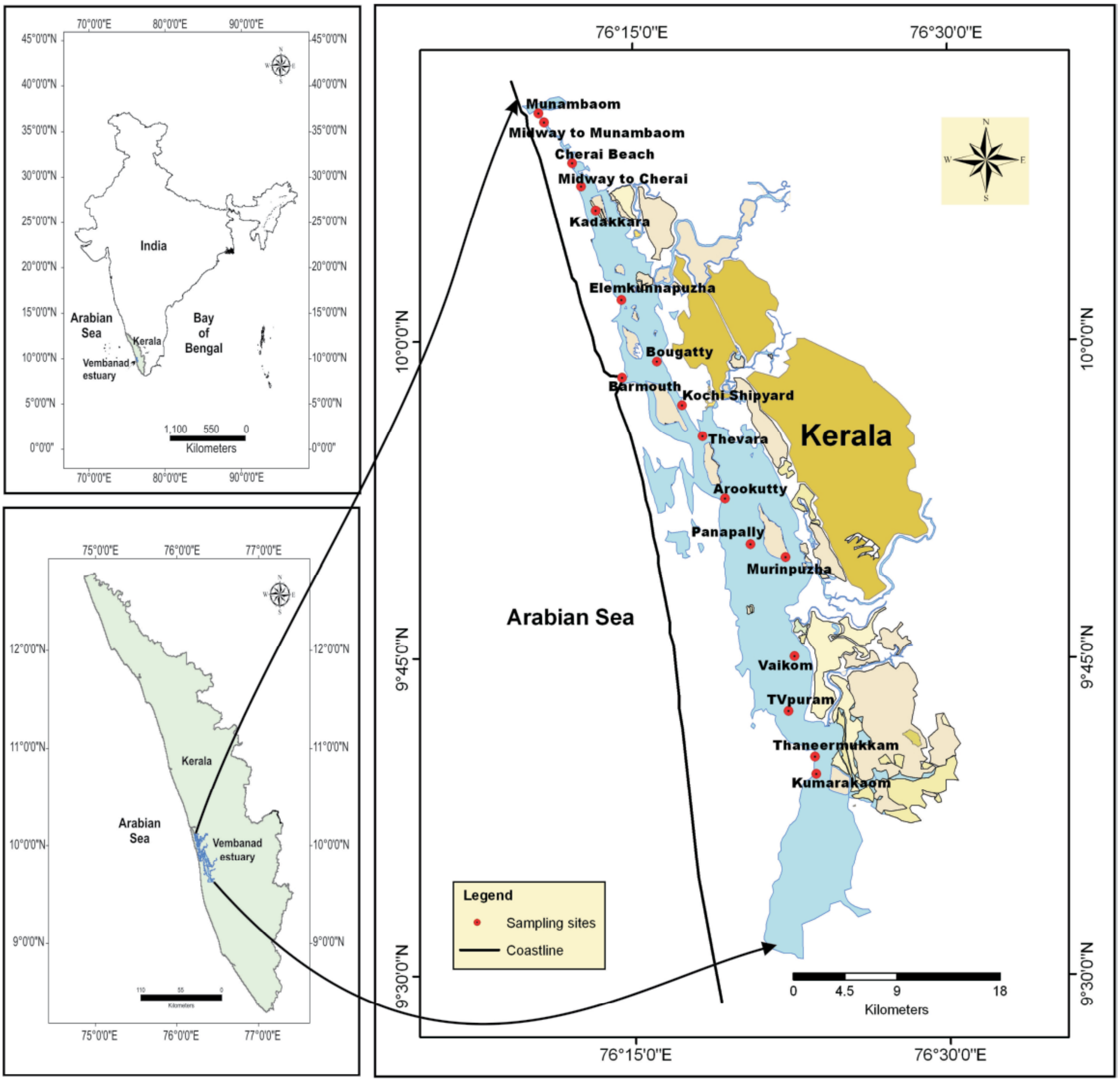


Fig. 1. Location map of Vembanad wetland system, west coast of India.

Sediment texture and salinity status

The sediment texture was quite variable along the wetland course. Minimum value of sand was found in Viakom (Station-14) (22.19 %) followed by Midway to Cherai (Station-4) and Kadakkara (Station-5) having 32% sand. Maximum stations from the wetland show sand content ranging from 60-85% while Kochi shipyard (Station-9) and Panapally (Station-12) display moderate sand composition (55%) (Fig. 3). Highest sand content was observed in Murinpuzha (Station-13). Clay distribution was dominant in Midway to Cherai, Kadakkara and Vaikom with values around 4-5% but a constant reduction was observed in other stations (1.0-2.8%). Lowest clay content (0.73%) was found in Murinpuzha (Station-13). The percentage of silt was variable throughout the wetland ranging from 7.02% in Murinpuzha to highest in Vaikom (73.04%). The entire wetland is characterized by silty sand to sandy silt sediment.

Salinity status in the aqueous soil solution also shows a marked gradient from 8.7 in Midway to Cherai (Station-16), followed by Kadakkara (Station-4) and Kochi Shipyard (Station-9) to 0.7 in Murinpuzha (Station-5) dominated by sandy sediment (Fig. 4). Major stations from the wetland show an oligosaline condition with salinity ranging from 1.2 to 5 whereas Munambaom (Station-1), Barmouth (Station-7) and Bougatty (Station-8) exhibit higher salinity gradient from 5.6 to 6.8.

Total Organic Carbon (TOC)

The total organic matter (TOC) comprising volatile components (Dw), organic carbon (IC) and inorganic carbon (CO_3) is an important abiotic proxy to represent the variation of volatile matter, distribution of organic matter and carbonate components in a sediment record. In the Vembanad wetland

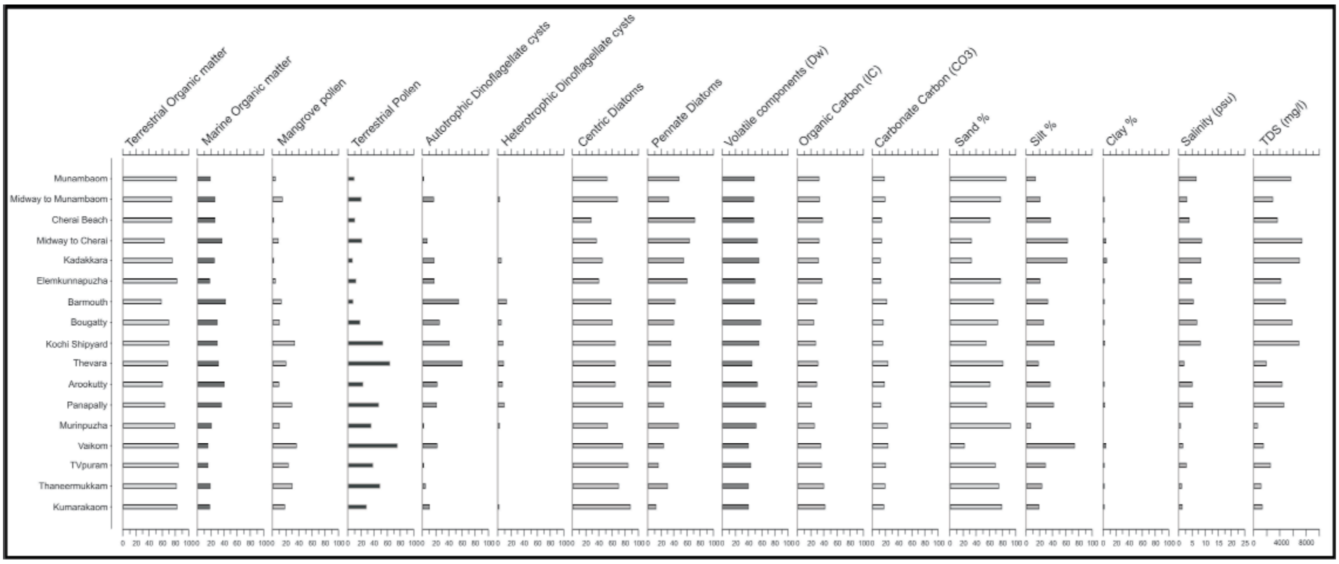


Fig. 2. Bar diagram showing distribution of biotic and abiotic proxies in Vembanad wetland, west coast of India.

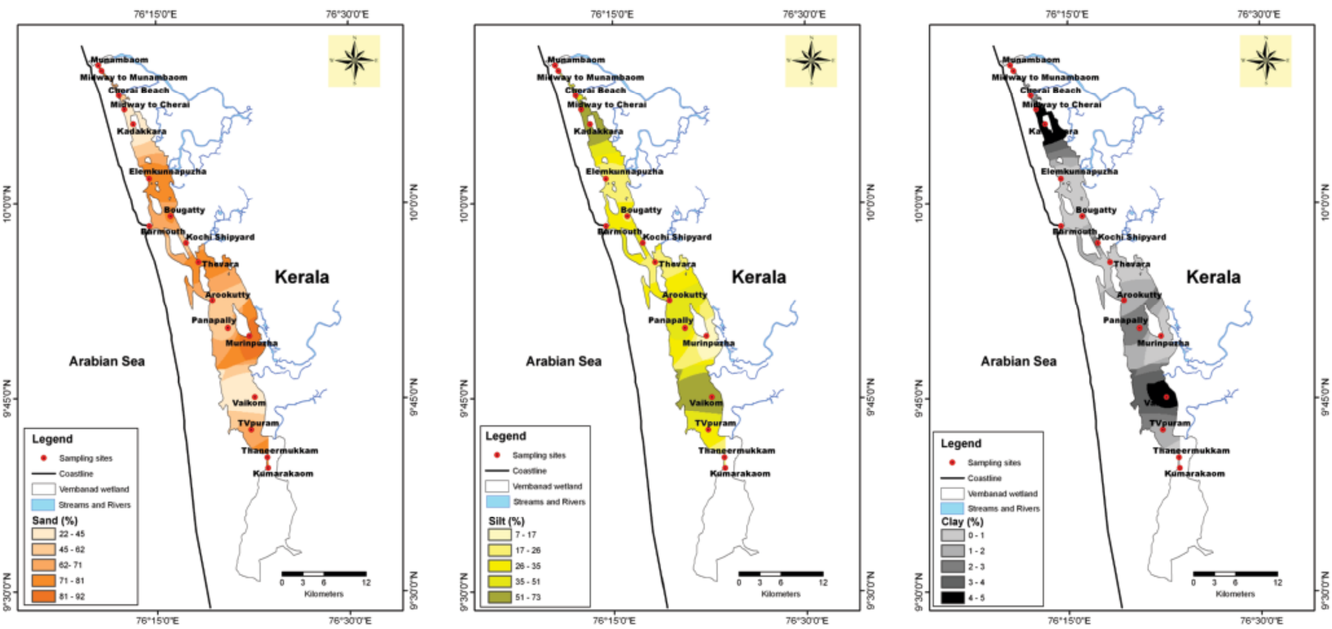


Fig. 3. Spatial variation of Sand/Silt/Clay using IDW method.

ecosystem due to the variable nature of the depositional environment in a tropical system the TOC can be well-documentd. The volatile components range from 40–65 per cent in all the stations with lowest percentage at Kumarakoam station (~40 %) and highest at Panapally (~65 %). Similarly, the variation of the organic matter ranges from 20 to 42 per cent in the wetland with lowest record at Panapally (~21 %) and highest variation in Kumarakoam (~42 %). The inorganic carbon content varies from 12 to 25 per cent with lowest in Kadakkara (~12 %) and highest in Vaikom station (~24 %) (Fig. 5). The variation in the organic carbon shows decrease from the Barmouth to the Murinpuzha station which may be due to the dominace of marine incursion and this differentiates the northern and southern arms of the Vembanad wetland.

Pollen assemblage

Stations from Kochi Shipyard (Station-9) to Kumarakaom (Station-17) show high percentage of mangrove and terrestrial pollen with *Rhizophora mucronata, Rhizophora apiculata, Bruguiera* sp, *Lumnitzera racemosa, Justicia* sp and *Acrostichum aureum* as the dominant mangrove and their associate species (19 to 36 per cent) with measurable variation in terrestrial pollen like that of *Selaginella* spore, *Terminalia*, *Artemisia*, *Alternanthera* sp., *Crotalaria, Desmodium, Combretum, Zizyphus* and Poaceae (19 to 75 per cent) except for Arookutty (Station-11) and Murinpuzha (Station-13) which reveal a lower pollen concentration. Munambaom (Station-1) to Elemkunnapuzha (Station-6) also display comparatively low pollen assemblage with less abundance of mangrove as well as

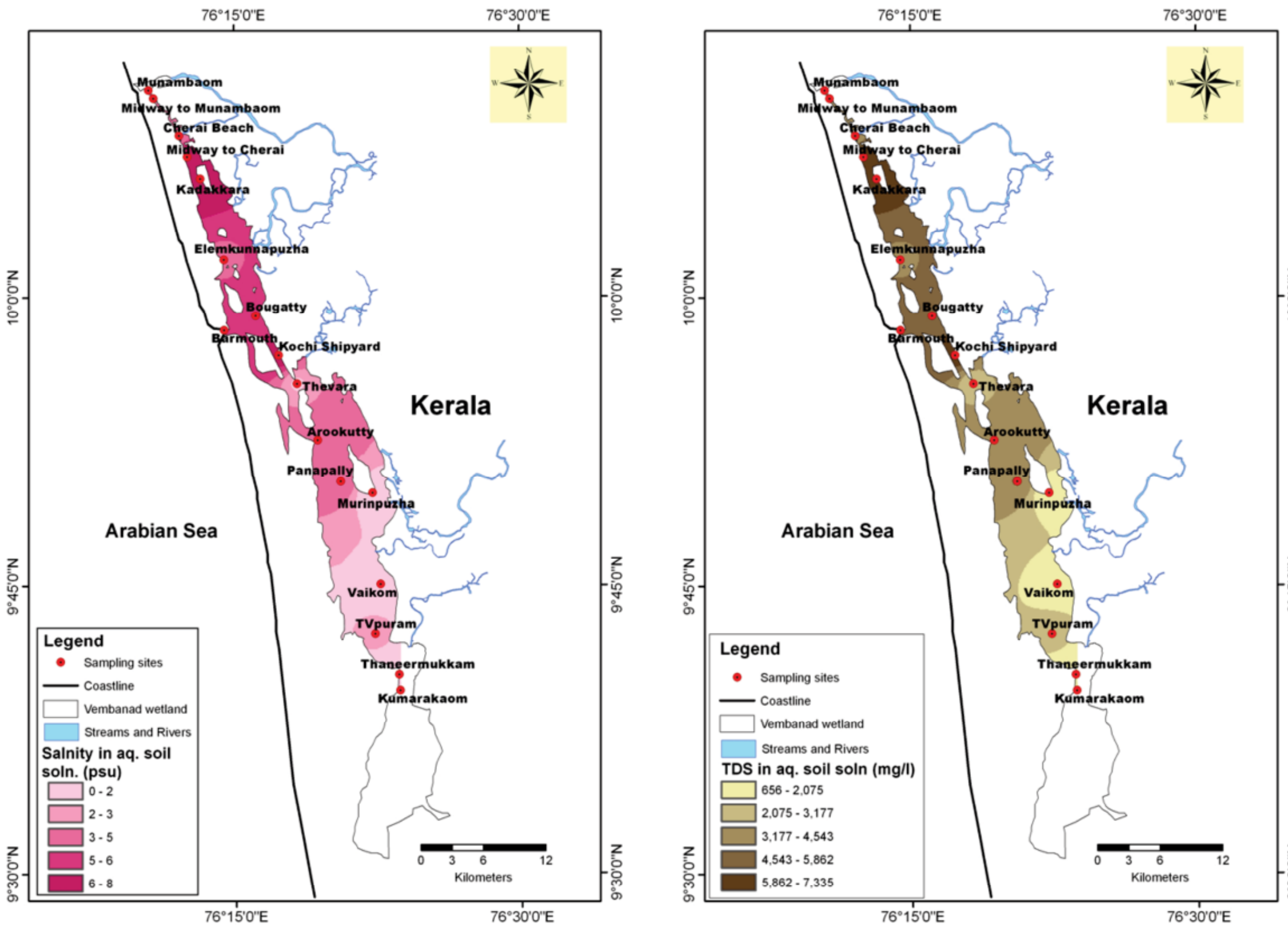


Fig. 4. Spatial variation of salinity gradient (psu) and Total dissolved solid (mg/l) content.

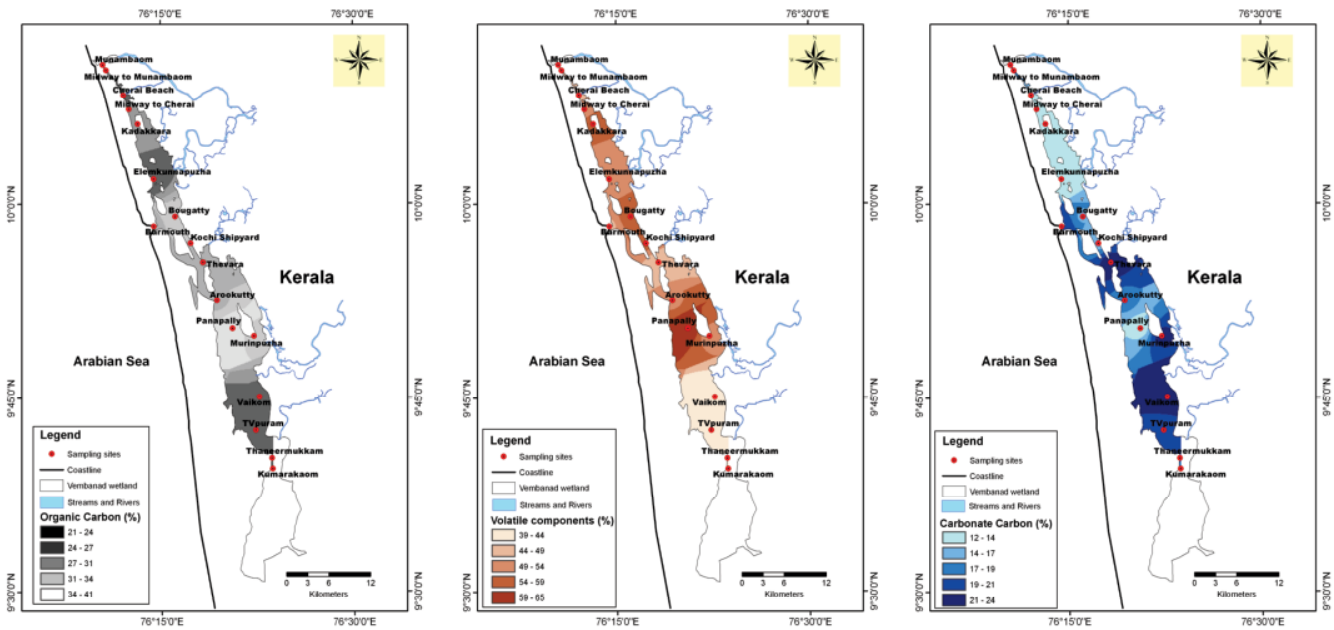


Fig. 5. Spatial variation of Total organic matter (TOC) comprising volatile component, organic carbon and inorganic carbon.

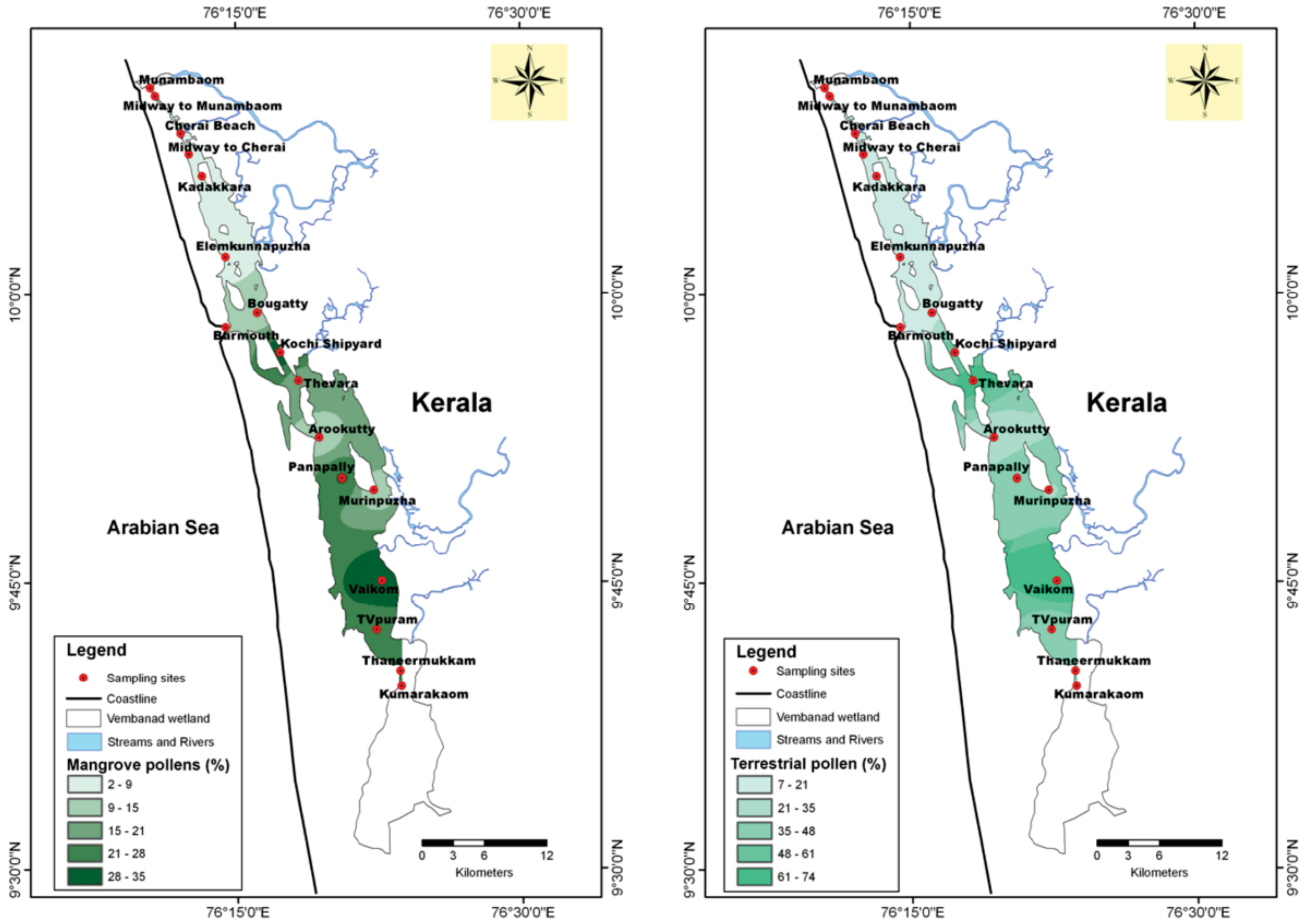


Fig. 6. Spatial variation of modern (mangrove and terrestrial) pollen assemblage.

terrestrial pollen with true mangrove pollen such as *Rhizophora mucronata, Bruguiera* sp and *Ceriops decandra* (< 13 per cent) and terrestrial pollen like that of *Terminalia, Syzygium, Artemisia* and *Alternanthera* sp. (8 to 20 per cent) except at Midway to Munambaom (Station-2) which shows a moderate abundance of mangrove as well as terrestrial pollen (15 to 20 per cent) (Fig. 6).

Diatoms

The primary productivity in terms of diatoms shows a marked variation in the present study. The total cell counts is recorded maximum at (Panapally – 804 cell counts), while the minimum are observed in the Munambaom (218 cells counts). However, separating the centric and pennate forms the highest pennate cell counts are recorded in Murinpuzha (Station 13 - 374 cells counts) while the lowest counts are recorded in Kumarakaom (53 cells counts). The centric forms show highest abundance in Panapally (551 cell counts) while the lowest record are in the Cherai beach (106 cell counts). The diatoms assemblage in the Vembanad wetland is mainly dominated by *Cyclotella meneghiniana*, *Thalassiosira*, *Nitzschia*, *Navicula*, *Aulacoseira, Diploneis* followed by *Actinophytus*, *Actinocyclus*, *Asteromphalus*, *Cocconeis*, *Triceratium favus*, *Biddulphia*, *Campylodiscus*, *Chaetoceros*, *Grammatophora*, *Thalassionema*, *Eunotia*, *Anomoeoneis*, *Tabularia*, *Tabellaria*, *Synedra*, *Brachysira*, *Achnanthes*, *Melosira*, *Pinnularia*, *Gomphonema*, *Amphora*, *Gyrosigma*, *Cymbella*, *Bacillaria*, *Achnanthidium*, *Encyonema*, *Caloneis*, *Surirella*, *Tryblionella*, *Mastogloia*, *Hantzchia*, *Neidium*. The overall assemblage in the wetland shows differential primary productivity in terms of centric and pennate diatoms. The stations Munambaom to Barmouth (station 1 – 7) shows dominance of *Cyclotella meneghiniana*, *Thalassiosira*; however in the station Elemkunnapuzha (station 6) the centric diatoms are low as compared to pennate forms and this may be due to the high fresh water supply with fairly large accommodation space.

The region from Bougatty to Murinpuzha (stations 8 - 13) very high marine centric and pennate forms dominated by *Cyclotella meneghiniana*, *Thalassiosira*, *Diploneis*, *Actinophytus*, *Actinocyclus*, *Asteromphalus*. The freshwater pennate diatoms are very low in frequency, however; the brackish diatom *Nitzschia panduriformis* is dominating the pennate diatom assemblage in the stations. The stations Vaikom to Kumarakaom show dominance of fresh water centric forms viz. species of *Melosira*, *Cyclotella* and *Aulacoseira* indicating higher water depths in these stations (Fig. 7).

Dinoflagellate cysts

Dinoflagellate cyst assemblage shows a low diversity of dinoflagellate cysts. In total, 16 taxa belonging to gonyaulacoides, protoperidinioides and gymnodinoides were documented. Lowest cyst count was recorded at Munambaom (Station-1) while the highest abundance was at Thevera (Station-10). Gonyaulacoide

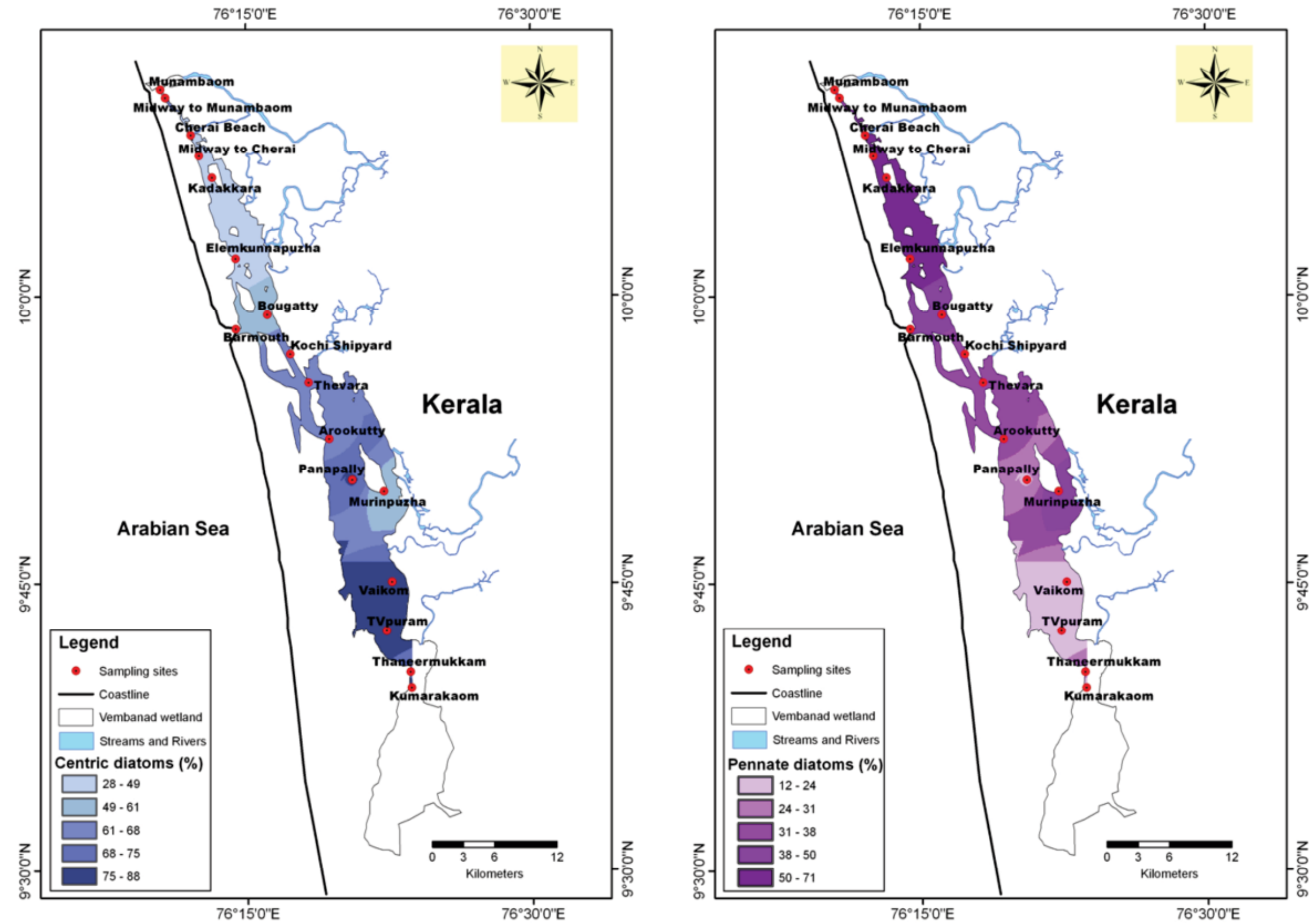


Fig. 7. Spatial variation of diatom assemblage (Centric and Pennate).

taxa were represented by the species *Bitectatodinium spongium, Tuberculodinium vancompoae, Spiniferites membranaceus, Spiniferites* spp., *Operculodinium centrocarpum, Lingulodinium machaerophorum*. Protoperidinioid taxa were represented by *Brigantedinium simplex, Selenopemphix quanta, Selenopemphix nephroides, Stelladinium stellatum, Lejeunecysta oliva, Quinquecuspis concreta,* Cyst of *Protoperidinium latissinum* and *Votadinium calvum*, while gymnodinoid cyst represented by *Polykrikos schwartzii*. Autotrophic Gonyalaucoid taxa dominated the assemblages in all studied stations. *Bitectatodinium spongium* is the dominant taxa in most of the stations except from Murinpuzha (Station 13) to Kumarakaom (Station-17) in which *Spiniferites* spp. is the dominant taxa (Fig. 8). In Munambaom (Station-1), Cherai beach (Station-3), Midway to Cherai (Station-4), Murinpuzha (Station-13), TVpuram (Station-15), Thaneermukkam (Station-16) lowest abundance was observed with less than 8 counts of species such as *Bitectatodinium spongium*, *Spiniferites* spp., *Quinquecuspis concreta*, *Tuberculodinium vancompoae* and *Trinovantedinium applanatum.*

Palynofacies analysis

The palynofacies components comprising terrestrial and marine organic matter are indicative of runoff-related changes and monsoonal activities. In the Vembanad wetland system, the distribution of the palynofacies components is not clear. The terrestrial matter in all the stations vary in abundance comprising degraded brown, well-preserved structured organic matter, algal remains, fungal spores, woody trachieds, etc. The distribution of the terrestrial organic matter is very high in most of the stations, however, there is a slight lowering of the terrestrial matter from Barmouth to Panapally stations ranging from 60–70 per cent of the total organic mass (Fig. 9). The marine organic matter viz. amorphous organic matter (AOM), animal remains, foraminiferal test linings, copepod egg envelopes, scolecodonts, tintinnids and labile organic matter form another important palynofacies derivatives for marine incursion. The rise in the marine organic matter from Barmouth to Panapally shows high dominace of marine organic matter giving evidence of marine incursion from the Barmouth station and its extend up to Panapally.

Principal Components Analysis (PCA)

Principal components analysis of various biotic and abiotic components clearly defines three zones of different ecological and environmental conditions in the Vembanad estuary (Fig. 10). Stations in the Group I belong to the northern zone, which includes- Munambom, Cherai, midway to Cherai, Kadakkara and Elamkunnapuzha associated with a marine environment. This zone was characterized by relatively high salinity, high percent of silt and sand, and low values of mangrove and terrestrial pollen. The northern sites are connected with the shelf waters by two openings which is affected by the tidal variations. However, in the northern zone, midway to Munambom, is an exception as this station lies in the central region of norther zone where the

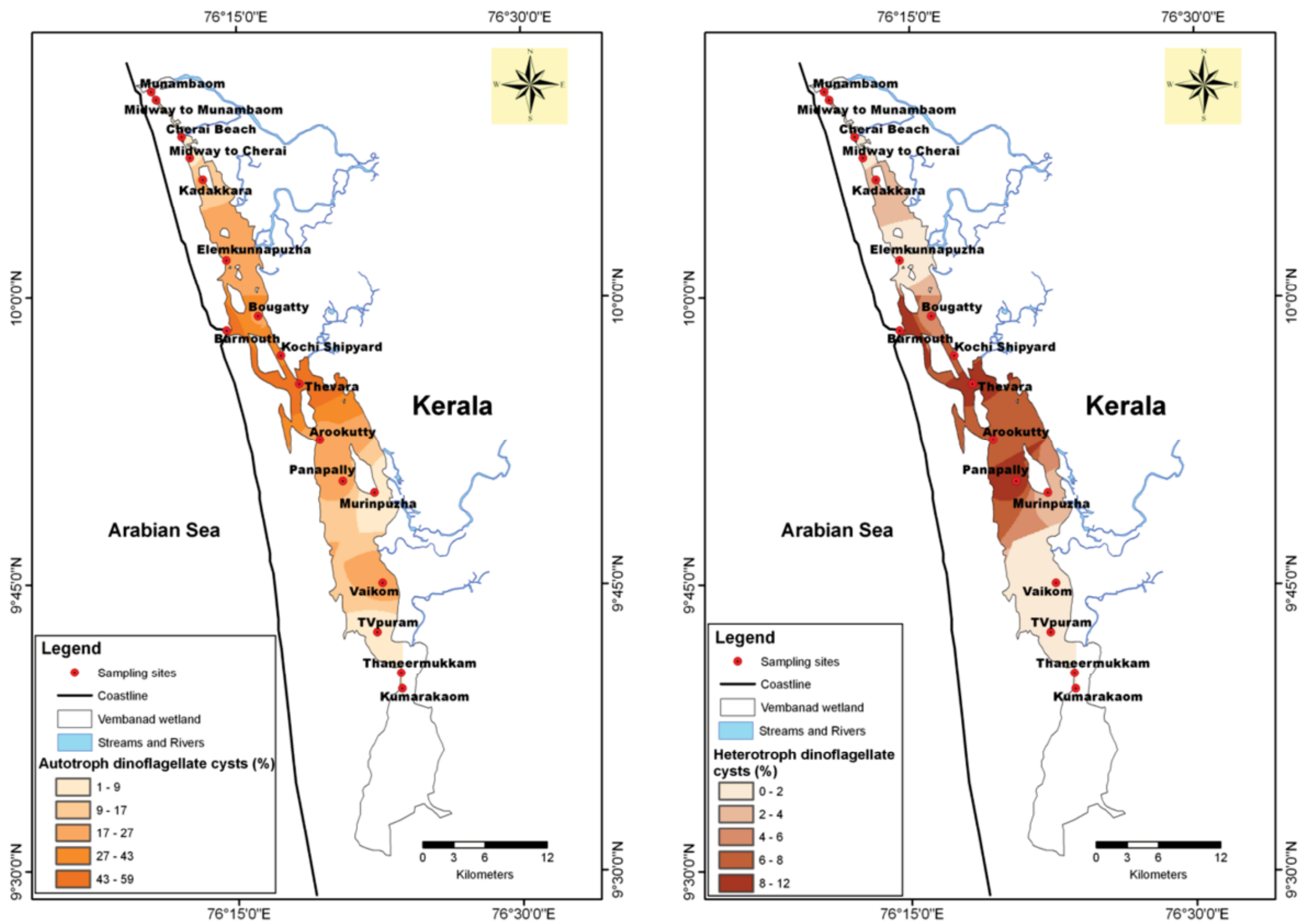


Fig. 8. Spatial variation of dinoflagellate cysts composition (autotrophs and heterotrophs).

tidal effect does not give well defined observations from proxy records as compared to rest of the stations. Stations in Group II includes the central zone- Bougatty, Barmouth, Kochi Shipyard, Thevara, Arrokkutty, Parapallly and midway to Munambom. This zone shows high percent of sand and silt along with optimum salinity, terrestrial organic matter and carbonate values. High percent of mangrove and terrestrial pollen, diatom and dinoflagellate cysts are also recorded for the stations in central zone. Station Murinpuzha shows the differential behaviour in this zone and find its place in Group III. This may be probably due to the extreme extent of the tidal inlet in the central region that prevents the influence of tidal variations in this station. Stations in Group-III includes the southern zone- Murinpuzha, Vaikom, TVPuram, Thaneerkukkam and Kumarakom which are mainly associated with a fluvial environment. Due to the presence of islets and shoals in the central and southern zone of this complex wetland system, good freshwater discharge through rivers during the monsoon season will limit the tidal influence. Altogether, the results suggest varying environmental conditions which lead to differential productivity in the Vembanad wetland system.

DISCUSSIONS: DEPOSITIONAL ENVIRONMENTS IN VEMBANAD WETLAND

The wetland displays a unique and complex system in its entire north-south flow regime and identifies two well demarcated estuarine complexes: in the north due to Periyar River mouth and at the Cochin Barmouth due to small riverine inlets and one purely terrestrial setting due to the absence of tidal influence. This is also reflected in the distribution of different proxies that comprise of textural analysis (sand, silt and clay), total organic carbon (volatile components, organic carbon and inorganic carbon), physico-chemical parameters (salinity and TDS), primary productivity (centric and pennate diatoms), pollens (terrestrial taxa and mangroves), dinoflagellate cysts (autotroph and heterotrophs) and palynofacies (terrestrial and marine organic matter). In the light of these proxies, the process-based changes in the ecosystem can firmly be laid down. The three depositional zones that have been identified in the Vembanad wetland estuary are (1) Flood-tidal basin (2) Central tidal basin and (3) Fluvial basin.

Flood-tidal Basin

Flood tidal basins are subtidal to supratidal channels, typically found at the entrance of wetlands and are formed by the redistribution of sediment through tidal incursions (Dalrymple, 1992). In Zone I (from Station 1: Munambaom to Station 7: Barmouth) almost constant number of the marine and terrestrial palynomorphs were recorded. The homogeneous behavior of pollen and dinoflagellate cysts in this stretch of the wetland ecosystem can mainly be attributed to the mixing of marine and fresh waters. Munambaom mouth is shallower than the Cochin mouth, hence the influence of the marine waters from the Arabian Sea on the northern part is less, both in terms of magnitude and extent, as compared to the Cochin Barmouth (Ramamirtham and

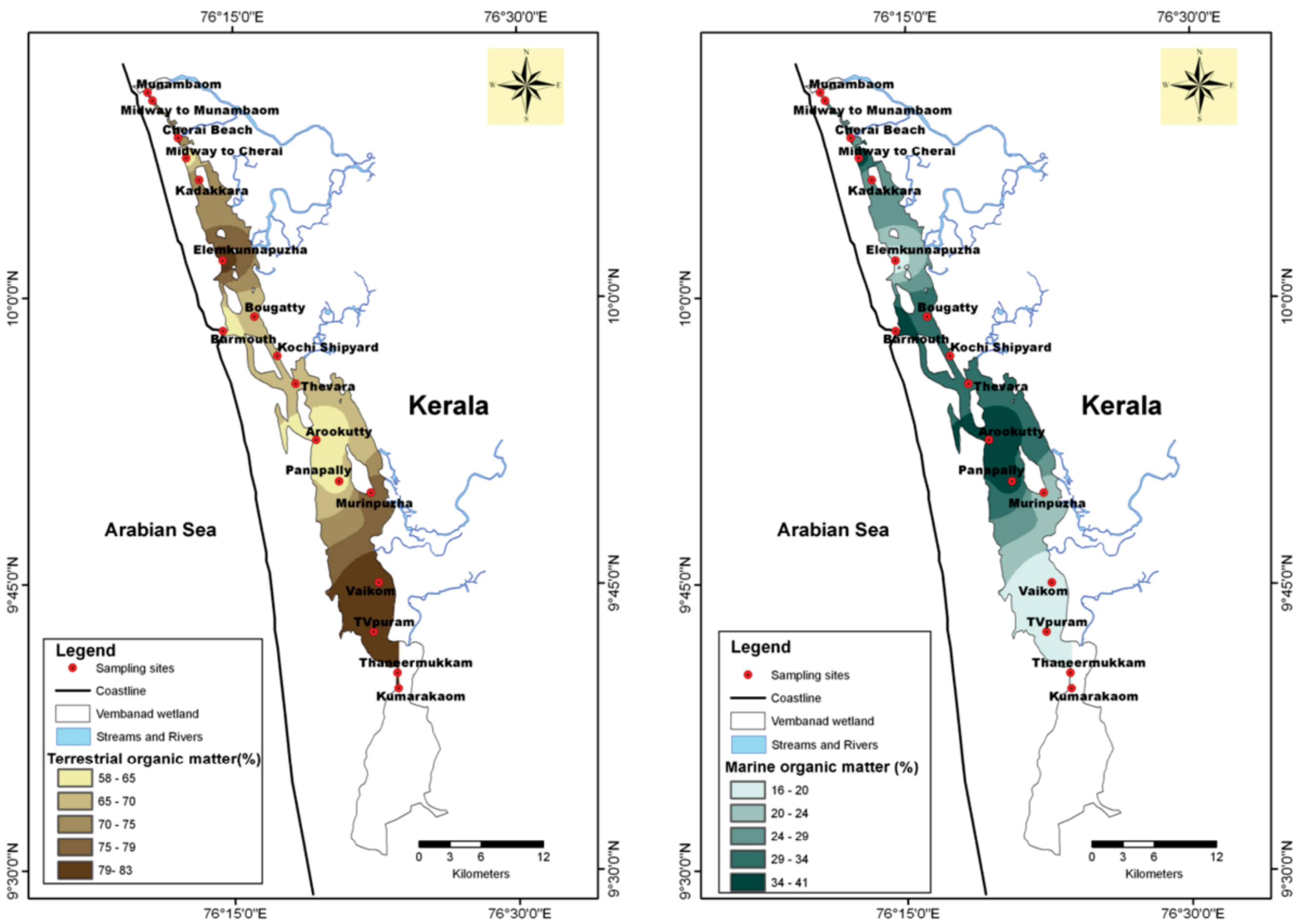


Fig. 9. Spatial variation of palynofacies composition.

Muthusamy, 1986b). This zone experiences a slightly higher salinity value due to the narrow width and shallow depth of the wetland bringing in higher mixing efficiency. Further, it is noteworthy to mention that the sand content is high in the upper region of zone-I, but decreases in Midway to Cherai (Station-4) and Kaddakara (Station-5), showing a decrease in the energy conditions due to distant location of the stations from tidal and riverine inlets. Total Organic Carbon (TOC) does not show any prevalent nature of variation, however, autotroph dinoflagellate cysts show increased abundance in Kaddakara station which may probably be due to the increased fine sediment leading to high preservation in this region. High silt content in the sediment can be explained by the fact that the water drained by Periyar River and the Arabian Sea occupies a greater part contributing to the central region of zone I which may offer much resistance to the tidal flows causing turbulence and mixing (Ramamirtham and Muthusamy, 1986b). The low abundance of mangrove pollen in this zone can be well-correlated to the high-energy conditions and turbulence which is unsuitable for the survival of true mangroves. Presence of terrestrial pollen and terrestrial organic matter reflects freshwater runoff conditions. It is also noticed that due to mixing, the variations between centric and pennate diatoms become insignificant as the contribution of both the forms in the assemblage are nearly equal. Thus, in totality it can be observed that the present zone operates as a two-channel system where the tidal flows are in opposite directions (one from Periyar side and another from Barmouth side). The presence of numerous islets and shoals in the central region of this zone creates a low-energy condition and high monsoonal discharge through Periyar River along with tidal variations in the northern and southern part of this zone lead to complex behaviour of the Vembanad wetland ecosystem.

Central tidal Basin

Central basins are uniform, lower energy environments in the deeper and quieter parts of the wetland. In the present study, Zone II (from Station 8: Bougatty to Station 13: Murinpuzha) comprises the widest and deepest region of the wetland. Prominent salinity variation in the sediments of this region has been observed moving towards N-S direction in the wetland (Ramamirtham *et al.*, 1986a; Balachandran *et al.*, 1996). Grain size distribution shows high sand content in this zone, but the lateral stretch of the wetland also plays a major role in distribution of sediment discharge and sediment transport. Large sediment accommodation space in this zone, well-drained water conditions also help to regulate the tidal variations. The salinity overall shows a decreasing trend from river mouth towards south in the zone, while at Thevara (Station 10) the salinity is low because of riverine inflow increasing the freshwater supply with high-energy conditions as expressed by the sand content. TOC also shows a high volatile content owing to pronounced wet conditions in the sediment which may be due to high silt and clay per cent of the sediment which causes less down percolation of water (Hiller, 2003). High percent of true mangrove pollen

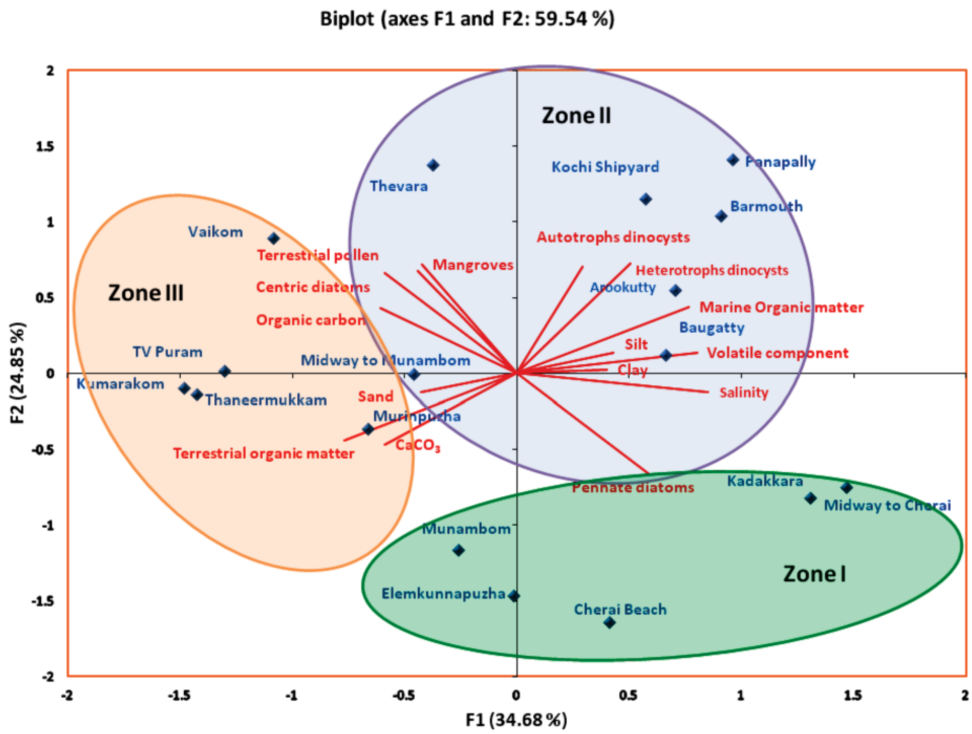


Fig. 10. Results of the Principal Component Analysis (PCA) for the proxies and studied stations.

could be due to the broader width of the wetland with widely distributed low saline environment and stratified water column enhancing the habitation of true mangroves in the vicinity. The terrestrial pollen also shows good percentage and this is contributed through the small channels that flush sediments, mainly during the south-west monsoonal periods and gets deposited accordingly. Dinoflagellate cyst assemblage shows high autotrophic forms from Bougatty to Thevara and then decreases from Arookutty to Murinpuzha which directly suggests high tidal influence up to Thevara and thereafter diminishing the effect of the tides, as indicated by the lowered values of dinocysts further south. The slight increase in heterotrophic dinocyst abundance further indicates a rise in nutrient levels from the land in this zone. The high terrestrial organic matter with slight marine components also indicates regular flushing from the marine regions. The diatoms in this reference also give a significant base for marine incursion as the rise in the marine centric diatoms in the stretch from Bougatty to Panapally also indicates marine influence. At the Murinpuzha station, the brackish water pennate diatom (*Nitzschia panduriformis*) shows high counts. The close proximity of this station to island barriers within the wetland ecosystem can be attributed to the near freshwater regime in the stretch and also the diminishing effect of the tides in the down south as a result of regular fresh water supply in the river channels from the adjacent land.

Fluvial Basin

A fluvial basin is formed at a point where freshwater source enters a coastal water body through intertidal and terrestrial levees. In zone III (from Station Viakom to Kumarakaom), the lowest tidal ranges are observed (Balachandran *et al*., 2008; Revichandran *et al*., 2012). The construction of a salt barrage at Thaneermukkam prevents the salt water intrusion beyond this station. In this stretch, it is observed that the clay and silt contents are higher than sand at Viakom, while at the rest of the stations down south the sand per cent is extremely high. The high runoff conditions and fresh water supply from numerous small rivulets from the terrestrial regime can be supportive for energy conditions. The high prevalence of sand has allowed for low volatile components and slightly high organic carbon content with lowered organic carbon proportion. The salinity in the stretch is also very low, indicating a very high freshwater region in the depositional site. The presence of pollen in this stretch is expressed by increased proportion of mangroves, but on the whole terrestrial pollen dominates the total pollen counts. The high back mangrove pollens are present mainly in Vaikom and TVpuram stations which may be due to the presence of relict salt pans, but decreases significantly at Thaneermukkam and Kumarakaom stations; this is due to the presence of the salt barrage (Thaneermukkam) that effectively restricts the flow of salt water further downwards. The runoff-related changes derived from the terrestrial organic matter shows indication of enhanced precipitation due to the SW monsoonal activity. The lowered marine organic matter in this zone may be attributed to both weakening of the tidal forces and also the high freshwater regime. The variations in the primary productivity measured from the diatoms show high freshwater centric diatoms with lowered pennate forms. The high freshwater centric forms are indicative of increased water level and deeper water conditions. The increased water levels and high accommodation space within the wetland also restricts the tidal influence to a great extent with farther distance from the coastline.

CONCLUSIONS

1. The distribution of marine and terrestrial palynomorphs and different types of organic matter and diatoms in Vembanad wetland are important parameters to determine the role of sedimentary processes and environmental factors in a coastal wetland ecosystem.
2. Based on the study, three depositional zones have been identified, i.e. (i) Flood tidal basin in the northern end of the wetland characterized by both marine and freshwater palynomorphs and diatoms, (ii) Central tidal basin spanning the middle region which relates to a stable estuarine ecosystem and (iii) Fluvial basin in the southern end with abundant terrestrial forms showing less tidal influence and high freshwater influence.
3. Based on the present study, proximal-distal trends and various subenvironments of the wetland ecosystem can be recognized. These studies can have a wider application in deteremining the palaeoenvironment of pre-Quaternary successions.

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