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Estuarine Mudflat and Mangrove Sedimentary Environments along Central West Coast of India

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Abstract

Estuaries are complex and dynamic aquatic environments, wherein fresh water mixes with rhythmically intruding seawater. Mudflats and mangroves are the important sedimentary sub-environments within estuaries which facilitate deposition of fine sediments, organic matter and metals from overlaying water. The cohesive sediments present in these environments protect the coast from erosion and the sediment column can be used to understand past depositional environments, sea level changes, changes in land use-land cover in the catchment area of the rivers and bioavailability of metals.

Keywords: Estuary; Mudflats; Mangroves; Environments

Introduction

The coastal zone is characterized by a variety of landforms out of which estuaries have received considerable attention due to large land-sea interaction mechanisms [1,2]. The word "Estuary" is derived from the Latin "aestus", meaning the tide [3] and Cameron and Pritchard [4] and Pritchard [5] defined an estuary as a semi-enclosed and coastal body of water, with free communication to the ocean, and within which ocean water is diluted by freshwater derived from land. Estuaries are complex and dynamic aquatic environments, where fresh water from river mixes with rhythmically intruding seawater of different physic-chemical composition. Estuaries are major nutrient suppliers to coastal oceans, breeding and nursery grounds for marine organisms and a potential fishery habitat. They act as transportation routes and also recreational places for humans [6,7].

Although all estuaries are analogous, in that they are semi-enclosed bodies of brackish water, a multiple criteria are used to classify them. According to their geological characteristics or geomorphology, estuaries are classified as coastal-plain estuaries, bar-built estuaries or lagoons, fjord-type estuaries, and tectonically caused estuaries [8,9]. Further, based on stratification and circulation, estuaries have also been classified as salt wedge estuaries, vertically homogeneous estuaries and partially mixed estuaries. Further, on the basis of water balance, estuaries are classified into three types: positive, inverse and low-in flow estuaries. Based on tidal range, Hayes [10] defined three types of estuaries: microtidal, mesotidal and macrotidal estuaries.

An estuary is divided into three zones (Figure 1) namely, marine or lower estuary, which has free connections with open sea; middle estuary subjected to strong salt and freshwater mixing and fluvial or an upper estuary, characterized by freshwater but subjected to tidal action. However, the boundaries or the transition zones between these sectors shift according to constantly changing tides and river discharge.

Freshwater inflow plays a key role in carrying continental material from the watershed to the estuary and in balancing effects of tidal inputs of saltwater. Physical, chemical, and biological interactions between terrestrial and coastal systems profoundly affect the transport and fate of material in to the estuary [12]. Material is carried in, from the land via rivers and from the sea by the tides (Figure 2).

Tidal currents provide the steady supply of energy that causes sediment movement into and out of estuaries. Waves and tides carry fine sediments from the mouth of an estuary leaving behind coarser ones. Fresh water from the land drainage adds varying size sediment material during monsoon months. In addition, suspended and particulate material is removed on changes of physicochemical properties on interaction of fresh water and seawater. The distribution of sediments within estuaries is often classified on the basis of grain size which in turn helps in understanding the hydrodynamic conditions prevailing in the area. Estuarine sediments retain large quantity of finer sediments and

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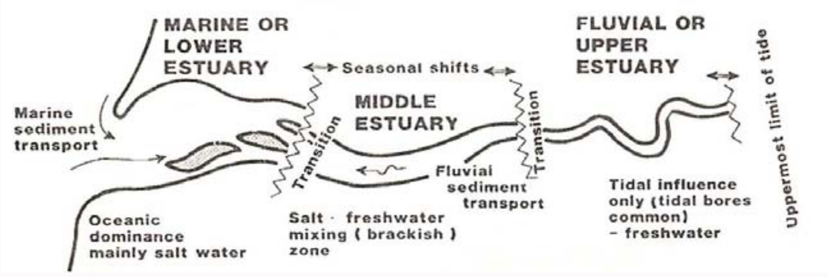

Figure 1: Estuary showing three divisions–Lower, middle and upper estuary: The boundaries are the transition zones that shift according to season, weather and tides [11].

organic matter and act as sink for a wide range of metals which show high affinity for fine grained sediments. These metals get adsorbed onto the suspended particulate matter and are transported through the water column which finally gets incorporated into the sediments. In this paper the work carried out along central west coast of India on estuarine mudflats and mangroves with an aim to understand past depositional environments, effect of land use-land cover in the catchment area of the rivers and bioavailability of metals and possible bioaccumulation was attempted.

Study area

The west coast of India extends from border with Pakistan in Gujarat to Kanyakumari in Tamil Nadu. It is surrounded by the Arabian Sea. Maharashtra, Goa and Karnataka together comprise the central portion of the west coast of India. This region is highly diverse with respect to coastal environmental features such as estuaries, creeks, lagoons, bays etc. A large number of fast flowing and mostly perennial rivers originate in the Western Ghats and drain into the Arabian Sea. The characteristic of the rivers is the formation of estuaries rather than deltas. Estuaries receive material from multiple sources such as natural weathering of rocks, domestic and industrial sewage outfalls, effluents from mines, and agricultural runoff. The growing population and associated rapid industrialization in and around central west coast of India has increased anthropogenic inputs. Therefore, estuaries are under increasing stress from the human activities.

The catchment area of the rivers in Maharashtra consists of Deccan trap basalts [14] having tholeiitic composition [15]. The catchment area of estuaries in Goa comprises of Western Dharwar Craton (WDC) containing meta-volcanic and meta-sedimentary rocks [16]. The catchment area of estuaries in Karnataka consists of Dharwar system and peninsular gneiss containing metamorphic and crystalline rocks which are made up of granites and granitic-gneisses. The coastline receives the southwest monsoon (June to September) with rainfall decreasing from South (3900mm) to North (2000mm), while the tidal range is in the micro-tidal scale in Karnataka, meso-tidal in Goa and meso to macro tidal in Maharashtra.

Materials and Methods

Sampling is the process or technique of selecting a representative part of a field site in a particular environment for the purpose of determining parameters or characteristics of the entire environment. The sediment cores were collected from mudflat and mangrove environments from almost all the estuaries along central west coast of India covering the coast of Maharashtra, Goa and Karnataka states representing lower, lower middle and upper middle regions estuaries. Precautions were taken to avoid contamination of sediment samples during collection and handling and a systematic procedure for the analysis of the sediments was followed. The sampling locations were positioned using a hand held Global positioning system (GPS). The sediment cores were collected during the low tide when the intertidal region was well exposed using a pre-cleaned handheld PVC corer. The sediment cores were then sub-sampled at 2cm intervals with the help of plastic knife and transferred into clean and labeled plastic bags with care taken to avoid metal contamination. The packed sub samples were then store in an ice box and transported to the laboratory.

The parameters studied for each sub-sample are pH; sand, silt, clay percentage [17]; clay minerals [18] and were identified and quantified following the semi-quantitative method of Biscaye [19]; total organic carbon (TOC) was determined following the wet oxidation method [20]; Magnetic susceptibility measurements of sediments were carried out and various parameters were calculated in terms of magnetic concentration, mineralogy and grain size as summarized by Thomson and Oldfied [21] and Oldfield [22]; total/bulk metal concentrations in sediments, sediment samples were digested following the procedure given by [23] and analyzed using an Atomic Absorption spectrophotometer (Flame AAS). Sediment standard reference 2702 was used to compute percentage recovery. Further, analysis of speciation of metals was carried out following the procedure developed by Tessier et al. [24] involving sequential chemical extractions of sediments. Five fractions namely exchangeable, bound to carbonates, bound to Fe-Mn oxides, bound to organic matter/ sulfides, and residual was employed. Metals in sediment associated organisms and mangrove pneumatophores collected from the specified sampling locations were also studied. Al, Fe, Mn , Cr, Co, Ni, Cu and Zn were studied for total sediment, speciation and bioaccumulation. Statistical analysis and sediment quality assessment were applied to understand level of metal concentration. Selected sediment cores were dated using lead dating method.

Observations and Discussion

Our investigations on the estuaries along central west coast of India with special references to sediment components and metal content in the sediment with an aim to understand the depositional environment in estuarine mangrove and mudflat sediments along with source, behavior, contamination and bioavailability of metals [25-41] have provided significant results. Also, an attempt was made to study on bioaccumulation and bioremediation potential in an estuary [42,43]. Further, analyses have also been carried out using different proxies namely diatoms, sediment grain size, isotopes to understand the recent past climate variations [44,45].

From our studies along central west coast of India it was clear that

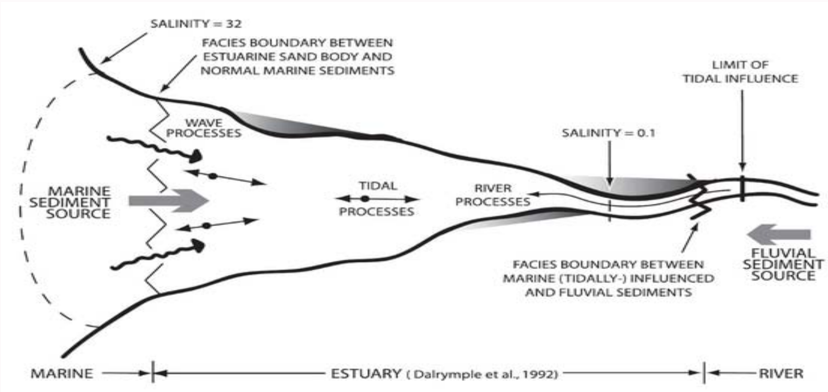

Figure 2: Classic estuarine zonation depicted from the head region where fluvial processes dominate, to the mid- and mouth regions where tidal and wave processes are dominant controlling physical forces, respectively. Differences in the intensities and sources of physical forcing throughout the estuary also result in the formation of distinct sediment facies [1,13].

there were considerable variations in the depositional environment with time. The geomorphology of the estuaries, rainfall, river runoff, construction of dams, bridges and other anthropogenic activities have considerably influenced the depositional environment. It is prominently noted that there is a strong transition in the estuarine environment from fresh water dominated in the past to marine inundated in recent times. These changes were mainly attributed to the rise in sea level, rainfall pattern, decrease in runoff due to the construction of dams in recent times etc. Several estuaries such as Vaitarna, Rajapur, Mandovi, Sharavathi are dammed in the upstream regions for diversion of river water and irrigational purposes in the recent years that resulted in reduced fresh water runoff. This in turn enhanced the tidal surge into the estuary and hence more saline water intrusion towards the upper reaches of the estuaries in recent times. Thus, the mixing processes were affected leading to increased flocculation and deposition of fine grained sediments in the recent years. Further, anthropogenic activities in the catchment areas of the estuaries have considerably affected sedimentation. Activities like mining and transportation of ores add considerable amount of material in to the estuaries.

The characteristics of an estuary are determined by the dynamics of various processes and the sediment sources. Material is imported from the river and its catchments, and sea into the estuary where the transformation of material takes place. Post transformation, a part of the material such as a particulate matter is retained in the estuary in sediments whereas the dissolved material is exported to the sea [46]. The main sediment sources of an estuary are from existing base material, terrigenous material held in the catchment and sand transported from the open-coast marine environment. In addition particulate and dissolved matter composed of organic and inorganic material is added in to the estuary that may be supplied naturally or from anthropogenic sources. The distribution of the sediments within an estuary is regulated by interactions between the available sediments, bottom morphology and flow hydrodynamics [47]. The dynamics of sediment transport depend on the water circulation, salinity, biological interaction, and sediment type [48]. The interaction among cohesive sediments (mud) is different from that of non-cohesive sediments (sand). Cohesive sediments may aggregate, forming flocs by the flocculation process caused by chemical or biological interaction. Flocculation increases the settling velocity of sediment particles. Chemical flocculation is started by salinity, ions that attach to the small mud particles, cause electronic forces between the particles, which start aggregating and thus forming a larger mud floc. In contrast, "Biological flocculation" is caused by bacteria and plankton that produce exopolymer and binds mud particles leading to formation of extremely large flocs of ~1000 µm in size [49].

Estuaries contain many different habitats such as shallow open waters, sandy beaches, salt marshes mud and sand flats, rocky shores, mangrove forests, seagrass beds, river deltas and tidal pools. Out of these, mangrove and mudflats have received considerable attention as they are very effective in coastal protection, respond to sea level changes and offer an important habitat for wildlife, food and recreation. Mangroves are a diverse group of trees, palms, shrubs, vines and ferns that have the ability to thrive in waterlogged saline soils that are subjected to regular flooding by tides. Mangrove forests are typically found in the tropical and sub-tropical latitudes, lying between the land and the sea in sheltered coastal areas that are subjected to tidal influence and are among the most productive ecosystems [50,51]. The mangrove ecosystems play an important role in carbon, nitrogen, phosphorus, and sulfur cycles, in addition to providing protection to coastal areas from waves and storms [52]. Mangroves are known for being sites for sediment deposition and are associated carbon and nutrients [53,54]. The mangroves trap sediment by their complex aerial root structure and are an important sink for suspended sediments and thus function as land builders [42,55-59].

Mudflats are coastal wetlands formed in sheltered shores where greater amounts of sediments, detritus are deposited by the rivers or tides. They are frequently associated with estuaries, and are usually situated adjacent to mangroves and comprise around 7 % of total coastal shelf areas [60]. Intertidal mudflats play a critical role in the estuarine exchange of marine and continental supplies of nutrients and sediments. The sediments consist mainly of fine particles, mostly in the silt and clay fraction. Little oxygen penetrates through the cohesive sediments, and an anoxic layer is often present within millimeters of the sediment surface. Mudflats generally support very little vegetation other than green algae. Their biodiversity centers on the range of invertebrates living in the sediment which are biologically productive. The intertidal mudflats support communities characterized by polychaetes, bivalves and oligochaetes and large numbers of birds and fish. Mudflats provide an important nursery and feeding ground for many fish species.

Sediments that are transported by the estuarine waters typically cover a range of sizes from less than 0.002mm to more than 4mm, with the finer sizes dominant in most estuaries. Estuarine sand is typically composed of quartz, although other minerals such as feldspar or various heavy minerals such as magnetite may be present depending on the sediment source. The fine sediments in estuaries are mixtures of inorganic minerals, organic materials, and biochemicals. Mineral grains usually consist of clays such as montmorillonite, illite, and kaolinite and chlorite, and non-clay minerals like quartz and carbonate. Organic materials comprise of biogenic detritus and microorganisms [61].

The estuarine system is mainly an area of deposition and acts as an important sink for metals in the environment. Metals are supplied to the estuary by natural factors such as chemical leaching of bedrocks, water drainage basins, and runoff from banks while the discharge of urban and industrial waste water, combustion of fossil fuels, mining and smelting operations, waste disposal and transportation activities are the important anthropogenic sources of the metal pollutants [25,27,28,30,34,37,62-66]. Metals brought into the estuary are transferred from solution to sediments by adsorption onto suspended particulate matter, and are deposited with relatively short lag times and tend to get trapped and accumulate in the sediments [67]
. The distribution and accumulation of metals are influenced by the sediment texture, mineralogical components and physical transport [68,69]. The metals get assimilated in the sediment along with organic matter, Fe/Mn oxides, sulphide, and clay and thus undergo alterations in their speciation due to geochemical modifications by processes such as dissolution, precipitation, sorption and complexation when discharged into the estuary and form several reactive components [70]. The sediment characteristics such as pH, cation exchange capacity, organic matter content, redox conditions, chloride content and salinity determine metal sorption and precipitation processes, which are associated to the metal mobility, bioavailability and potential toxicity [71]. The organic matter content in the sediments leads to relatively higher metal accumulation [72]. In addition, sediment grain size substantially influences the metal concentration in the estuarine sediments as the clay fractions that have a high specific surface area, favor adsorption processes [73]. Following deposition and burial, metals become subject to a variety of physical, chemical and biological processes which may mix and remobilize the metals into the water column [74] or may be immobilized in the sediments for long periods of time and undergo compaction and diagenesis.

The chemical speciation of metals in sediments involves the identification and quantification of the different forms or phases of the metal present in the sediments and provides advanced information on the potential availability of metals to biota under various environmental conditions [75-78]. The fractionation procedure can indicate the propensity for metals to be remobilized and can help distinguish those metals having a lithogenic origin from those with an anthropogenic origin [79,80]. Tessier et al. [24] devised a fractionation procedure which defined the desired partitioning of trace metals into fractions that are likely to be affected by various environmental conditions i.e. exchangeable, bound to carbonates, bound to iron and manganese oxides, organic matter/sulfide bound and the residual fraction. The metals in the exchangeable fraction are likely to be affected by sorption-desorption processes such as weakly bound to clays, hydrated oxides of iron and manganese and humic acids while the metals in the carbonate fractions can be associated with sediment carbonates and this fraction is susceptible to changes of pH. Together the exchangeable and carbonate fractions are known as the labile fraction [81]. The third fraction of sediment consists of metals bound to iron and manganese oxides and these oxides are excellent scavengers for trace metals [82] and are thermodynamically unstable under anoxic conditions. The fourth fraction consists of trace metals bound to various forms of organic matter such as detritus, humic and fulvic acids etc, through complexation and peptization phenomenon. A large amount of sulfides are also leached into this fraction. Under oxidizing conditions in natural waters, the degradation of organic matter leads to the release of soluble trace metals. The residual fraction of the sediments consists of primary and secondary minerals which may retain trace metals within their crystal structure and are not released easily into solution. The first four fractions are known as the bioavailable fraction as they exhibit mobility and are potentially available for uptake by organisms. The mobile fractions introduced by anthropogenic activities remain bound to the exchangeable, the carbonate and the easily reducible phases [83]. The sediment-associated metals have the potential to be ecotoxic due to their mobility and bioavailability, and this in turn affects both ecosystems and life through a process of bioaccumulation and biomagnification, respectively [12,68]. Thus, evaluating metal speciation can provide detailed information about the origin, mobilization, contamination risks, biological availability and toxicity of metals [84].

As sediments are often the final repository of metals, accumulation of high concentrations of metals can present a risk to organisms [85]. Metals normally occurring in nature are not harmful to the environment, because they play an essential role in tissue metabolism and growth of plants and animals [86]. However, metals like Cu, Zn, Fe, Co, Mo, Ni, Si, and Sn become predominantly toxic when their level exceeds the limit, and V, Cd, Pb, and Hg are prominently classified as toxic because of their detrimental effect even at low concentrations [87]. Marine organisms can accumulate metals in their tissues that may threaten the health of organisms higher in the food chain through trophic transfer to terrestrial, estuarine and eventually coastal species that become prey for oceanic predators and humans [88,89]. Metals are ingested of metal-enriched sediment and suspended particles during feeding, and by uptake from solution [90]. The ecological risk posed by metal-contaminated sediments depends strongly on the sediment characteristics, specific chemical forms of the metals, influencing their availability to aquatic organisms (bioavailability) and the ability of these organisms to accumulate (bioaccumulation) or remove metals. The efficiency of bioaccumulation via sediment ingestion is dependent on geochemical characteristics of the sediment. Various accumulation patterns have been described regulating the uptake of metals defined by the balance between uptake and excretion rates [91,92] and by detoxification processes usually involving proteins such as metallothioneins [93-95].

Conclusion

Study carried out on estuarine mudflats and mangroves sedimentary sub-environments along central west coast of India revealed that geomorphology, rainfall, river runoff, construction of dams, bridges and other anthropogenic activities have considerably influenced the depositional environment. The cohesive sediments present in these environments protect the coast from erosion and the sediment column can be used to understand past depositional environments, sea level changes, changes in land use-land cover in the catchment area of the rivers and bioavailability of metals in addition to depositional environments.

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