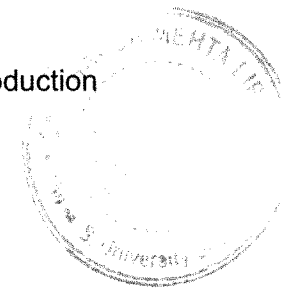
INTRODUCTION



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1. ESTUARINE ECOSYSTEM AND PROCESSES

Aquatic/marine ecosystems serve as one of the largest, diverse and highly functional ecologies on the planet. They are primarily divided into freshwater ecosystems and marine ecosystems. Estuaries are the intermittent ecosystems between riverine and marine systems. The word "estuary" is derived from the Latin word "aestuarium" meaning tidal inlet of the sea, which in itself is derived from the term aestus, meaning tide. Thus, estuaries can be illustrated as ecotone which is a system between two ecosystems. The most widely accepted definition of an estuary which was given by Pritchards (1967) states that "estuaries are *a semi-enclosed coastal body of water, which has a free connection with the open sea, and within which sea water is measurably diluted with freshwater derived from land drainage.*" Later on Wolanski (2007) coined a more thorough definition of estuary relevant to its processes and hydrolology stating estuaries as "*a semi-enclosed body of water connected to the sea as far as the tidal limit or the salt intrusion limit and receiving freshwater runoff; however the freshwater inflow may not be perennial, the connection to the sea may be closed for part of the year and tidal influence may be negligible.*"

Estuaries form a transition zone between river and ocean environments and are subject to both marine influences, such as tides, waves, and the influx of saline water; and riverine influences, such as flows of fresh water and sediments (Fig. 1). Being implicated by marine and riverine processes, estuaries are the dynamic ecosystems which are influenced by tidal rhythm and causes mixing of freshwater and sea water at various extents. The complexity of estuarine ecosystem thus creates dynamic critical mosaics which are challenges to understanding (Livingston, 1987; 1991). Salinity ingress resultant of tidal water ingress, waves and tidal volume serves as the marine critical factors; on the other hand, freshwater volume and sedimentation load represent the riverine influence acting upon the estuaries.

Apart from this natural stress, pace in human development has stressed the rivers and estuaries. At the end of the 20th century there were about 40,000 large dams in the world and on an average one new large dam

was commissioned daily (Dynesius and Nilsson, 1994). Considering the human benefit apart, the consequences may lead to the altered freshwater flow rate in estuaries. Moreover, many of the estuaries are highly ignored and being used as a dumping site for sewage or industrial effluent. This amplifies the harshness of the estuary apart from natural one and forces the benthic community to repel.

1.1. Importance of the Estuaries

Estuaries are important natural places. Since histories, estuaries have been of importance to humans and civilizations. Mankind has preferred to be settled on the river banks or near estuaries. An estuary provides settlements, food and transport to humans. Thus they have always been esthetically important. Of the 32 largest cities in the world, 22 are located on estuaries along with many more small cities and towns. They provide goods and services that are economically and ecologically indispensable.

Being receiving high amount of nutrients from marine as well fluvial sediments along with water drains, estuaries are known as one of the most productive natural ecosystem of the world. Estuaries harbor unique faunal and floral biota due to the constant water flux in terms of salinity and other water quality parameters. They are often called nurseries of the sea (USEPA, 1993) where especially adaptive biota sustains in these environments and they provide a shelter and food to marine animals. Moreover, it provides a breeding, feeding and nesting ground for many of the faunal groups. Estuaries produce very high amount of organic matter as well as provide variety of habitat and microhabitat which is the cause of attraction of many of the marine animals for feeding and breeding purpose. Many of the organisms make estuaries their permanent home while some of them pass only a part of their lifecycle in estuaries (Sumich, 1996). Many of the migratory birds use estuaries as a stopover during their migratory routes and feed on the estuarine fauna during their stay.

Being a buffer zone between land and water, estuaries endows protection from floods and storms. They act as an absorbing system which soaks over excess of flood water. Furthermore, they limit the coastal/shoreline erosion by lowering the force of the water. An estuary receives drains from the riverine flow as well as the catchment flow which possess very high amount of nutrients, thus making the estuarine ecosystem very rich in terms of productivity and nutrients. Concerning to the global development issues, along with nutrients the drains also carry huge amount of pollutants. An estuarine part such as marsh land or peat land with vegetation serves as a natural filter (matrix of roots, organic matter and fine sediments) for these pollutants as well as excess sediments and nutrients thus making the marine part more protected (USEPA, 1993).

2. THE GULF OF KHAMBHAT

India owes three gulfs on its coastal line viz. Gulf of Kachchh, Gulf of Khambhat and Gulf of Mannar; in which Gulf of Kutch and Khambhat are on the western end of the country and Gulf of Mannar on the southern end of the country. Amongst these, Gulf of Khambhat owes its own peculiarity in terms of its geomorphology, hydrodynamics and high tidal amplitude. Gulf, being funnel shaped with wide mouth and narrow head (width 200 km at mouth of Gulf terminating to 6 km at the extreme end of Gulf i.e. mouth of Mahi estuary, (Fig. 2a and b, Table 1) provides geo assistance to tidal amplitude and turbulence. The Gulf of Khambhat, which covers an area about 400,000 ha, has an extensive area of estuarine habitat around its periphery. The Tapi, Narmada, Mahi, Sabarmati, Shetrunji and several other rivers have deposited large volumes of alluvium which together with the marine recession have resulted in Saurashtra being joined to the mainland of Gujarat. Large quantities of silt are still being deposited and there are extensive areas of intertidal mud and sandflats, coastal salt marshes and degraded mangroves especially in the deltas of the Mahi and Sabarmati (Scott, 1989). There are several mud islands north of Bhavnagar and at the mouth of the Narmada but these are covered at high tides. Rocky, mile long Piram Island lies at the

mouth of the Gulf. A general tidal actions prevailing according to the moon days can be summarized in Fig. 3 wherein highest high water occurs at Full moon day and No moon day respectively. Since the lowest low tide is seen during no moon day these are the best days for intertidal study and were preferred in the present study also.

The Gulf receives the full force of monsoon waves so that there is little shelter for marine life, unlike the Gulf of Kutch. Its shape and orientation in relation to the southwest monsoon winds account for its high tidal range (40 feet [12 m]) and the high velocity of the entering tides. Thus Gulf of Khambhat shows high tidal amplitude, extreme water current and churning of bed material. Moreover, sediment input and drainage from major rivers like Narmada, Tapi and Mahi contribute to high turbidity. Owning to these peculiarities, the geomorphology and hydrodynamic of the Gulf of Khambhat makes the estuary very specific in terms of sedimentology as well as water quality. These features of gulf amplify the harshness of the estuary and challenge the life of the benthic animals within. Also, the low diversity of the benthic animals of Gulf and the estuary can be attributed to the featured harshness. Moreover, many of the major rivers like Narmada, Mahi, Sabarmati, Dhadhar and Tapi opens into the gulf contributing to high freshwater discharges in the gulf along with heavy sedimentation. Estuaries opening to Gulf of Khambhat can be taken as partially mixed or mixed estuaries due to high tidal influence which is not the case with the stratified estuaries.

The Bay of Fundy (New Brunswick, Canada) has the world's highest tides and **the Gulf of Khambhat ranks second** (max. tide 40 feet [12 m]). The average tide at Bay of Fundy is about 45 feet (14 meters) high in the northern part of the bay, far surpassing the world average of 2.5 feet (0.8 meter). The height of the tide difference ranges from 3.5 meters (11 ft) along the southwest shore of Nova Scotia and steadily increases as the flood waters travel up the 280 km (174 miles) of shoreline to the head of the Bay where, in the Minas Basin, the height of the tide is incredible (53 ft [16 meters]).

3. THE BENTHIC FAUNA

Benthos are the organisms associated with the sediments of the water body living on or in the sediments. They are further divided into various sub groups;

I. Based on their size:

- Macrobenthos: Greater than 0.5 mm in size.
- Meiobenthos: Less than 0.5 mm but greater than 32 µm.
- Microbenthos: Microscopic and less than 32 µm in size.

II. Based on their location:

- Epifauna: Benthos living on the top of the sediments.
- Seminfauna: Partially outside the sediment.
- Infauna: Benthos living inside the sediments.

III. Based on feeding:

- *Suspension feeder:* This particular group feed by straining suspended matter and food particles from water, typically by passing the water over a specialized filtering structure.
- *Deposit feeder/Scavengers*: Deposit feeders or scavengers, also known as detritus feeders or saprophages, are heterotrophs that obtain nutrients by consuming detritus (decomposing organic matter).
- *Herbivorous/microalgal grazers:* These organisms usually feed on the algal cover or bed.
- *Carnivores:* This group of benthos are predators which feed on other organisms either representing their own community or other benthic species.
- *Scavengers:* Scavenging is a carnivorous feeding behaviour in which a predator consumes corpses or carrion that were not killed to be eaten by the predator or others of its species. Scavengers play an important role in the ecosystem by contributing to the decomposition of dead animal remains. Decomposers complete this process, by consuming the remains left by scavengers.

Benthic fauna are the vital component of the estuarine food chain. Most of the benthos feed on either detritus or the organic matter thus controlling the

ecological functioning. In estuary, these organisms work as a super creatures adapting to the harshness of the environment. On the estuarine intertidal mudflats, they are acted upon by variety of environmental factors like desiccation stress, temperature, predation and change in salinity etc. Moreover, the daily tidal fluctuations imply flux in water quality and sediment depositions. These are probable causes of broad scale community pattern variations spatially and temporally. The sediment deposition, grain composition and variations on a diurnal, seasonal and annual basis define the micro habitat conditions (Johannesson et al., 2000). In an estuary, these variations are noted vertically, horizontally and laterally. Depending upon the length of the transitional zone from freshwater to salt water, the salinity gradient makes the conditions of an estuary moderate to harsh longitudinally (Levin et al., 2001). Tidal fluctuation and changes in water quality influence diversity and distribution of pelagic larval stages of benthic forms (Levin et al., 2001). Tidal variations induce site selection and abundance of benthic forms along the estuary (Talley and Dayton, 2000).

3.1. Animal Sediment Relationship

Animal sediment relationship deals with the interaction of an animal with the substrata which inturn modifies the existing sediments in terms of their physical and to some extent chemical constitution. These interactions can be due to the result/pre-cause of animal routine like feeding, breeding, environmental adaptation etc. Benthic fauna being entirely dependent on the sediment throughout their life are involved in variety of sediment modifications. Bioturbation, one of the resultant outcomes of sediment processing by benthic animals, over churns substratum by variety of displays. Bioturbation by the benthos may be in terms of burrowing and feeding; the extents of burrowing to various depths, feeding on the upper sediment layer by crabs etc. are few of the important bioturbatory activities and depend on the size of an animal and its physiological condition. These bioturbation activities process the sediments to generate micro-habitat variations, modify micro-topography, sediment chemistry, sediment transport and drainage.

Moreover, several benthic forms mark their presence by cryptic behavioral patterns, typical burrow patterns; burrowing/feeding/excretory pellets or even by leaving their trail marks (Chakrabarti et al., 2006). The dominant species usually alter recruitment patterns, site selection, survival/ mortality of settling larvae, control food availability, predation etc. of other species also and thus regulate the community composition (Quinn, 1982). Benthic fauna mark their presence on the intertidal mudflat/coast by peculiar burrows, track and trail marks. These marks are species specific and keen study of these biogenic structures may unveil the presence of an animal in the habitat. Unlike mammalian studies less work has been done on the indirect evidences of these organisms. Further, these biogenic structures and markings preserved in the form of ichnophysis serves as a very strong paleo-evidence describing the paleoenvironment and climate. In such instances, sediment depending on its composition, acts as a casting agent. As a whole, the animal sediment interaction scripts a record of temporary and permanent evidences on and under the sediment surface which narrates the prevailing ecological conditions.

3.2. Burrowing

Burrowing on the intertidal area represents the activity of an organism within the sediment. This is an integral part of animal sediment relationship and because of this temporal relationship, burrows normally cross cut other deposition – related sedimentary structures like bedding and lamination. This process of disruption of deposited sedimentary structures is known as bioturbation which in layman language can be taken as upwelling of the sediments. Each animal represents its distinct and specific fashion of burrowing which are the best indirect evidences of their presence as well identification. Burrow morphologies are amazingly diverse and include variety of markings on inner walls known as bioglymps. Burrow geometry is one of the important parts of burrowing which refer to branching, horizontal or vertical orientation, curvatures and shapes etc. On the basis of whether the sediment

is upwelled and transported or it is compressed on the adjacent surfaces, the burrowing/penetration style of an animal can be named as;

i. Intrusion: Wherein the animal merely pushes the sediment aside temporally displacing with its body. It buries itself in the medium. This process is usually a predatory behavior or a hiding behavior. The substratum usually is soft ground or sandy for easy penetration of animal. It is seen in few of the crab species.

ii. Compression: Herein the animal penetrates in the sediment by pushing and compressing the sediment aside and compacting. Thus it forms a burrow with a compacted wall which may be smooth or marked with animal impression which is mostly preserved as trace fossils. This is usually seen in polychetes and several other annelids.

iii. Excavation: It represents a common process seen in most of the macrofauna and represents the typical bioturbatory activity of an animal. The process involves excavating the sediments while burrowing and transporting to the adjacent surfaces. It's a common practice seen in many crabs.

Benthos like crabs are usually the dominant species on the intertidal, coastal and estuarine mudflats. The bioturbatory processes by crabs on the intertidal area results into variety of biogenic structures and markings. These structures and processes control variety of following processes which are important for health of an ecosystem. These activities by crabs and their forthcoming benefits are summarized in Fig. 4. Even a routine activity of burrowing facilitates series of chemical and physical alterations in the original sediment quality. The facilitation of oxygen to the subsurface depth allows microbial diversity and sediment oxic-anoxic zoning. The feeding activity by scraping the upper organic rich layer of the sediments regulates the organic content and the algal covering and on the contrary byproducts from gut enriches the sediments with few minerals (Fig. 5).

3.3. Role of Sediment Sorting in Benthic Fauna Distribution

The geometry and the resultant hydrodynamics of the gulf cause high churning of water during the tidal cycles and resultant upwelling of loose bed material. This has made the gulf very prominent in terms of levels of total and suspended solids (TS and SS) being very high at the lower estuarine regions. Also the deposition of fluvial and marine sediments, especially at the estuarine mouth, forms variable habitat depending on the hydrodynamic forces. These mosaics of habitat with different sedimentology thus are ideal habitat for varied benthic animals and each supports its unique diversity. The Mahi River channel is filled with deposits ranging from non marine (fluvial), through estuarine (tidal) to open marine making the sediment composition quite complex. Moreover, there is an established correlation between physical properties of habitat and macro benthos distribution (Flint, 1981; Bolam, 2003). Small-scale textural properties of the sediment grain may affect stability of sediment patches and hence the spatial patchiness of the benthos (Peter et al., 2001; Snelgrove and Butman, 1994). Hydrodynamic regime and physico - chemical factors play pivotal role in determining the complexity and dynamics of the system, and in determining the sediment characteristics. These cause gradients on one hand and patchy structure on the other (Attrill and Rundle, 2002) and can be considered as the ultimate cause of broad scale community pattern spatially and temporally. Benthic forms depend on the sediments and use them as a tool in various ways to overcome the ecological stress. Sediment type and strata formation are some of the important features of habitat selection by different animals (Snelgrove and Butman, 1994) and thus habitat specific distribution/occupancy by different species along the intertidal area (Shin and Choi, 2000; Chakrabarti et al., 2006).

3.4. Salinity Gradient: Active Controller of Animal Distribution

The role of certain abiotic factors particularly salinity and sediment type have been discussed earlier by few authors (Barash and Danin, 1982; Sousa et al., 2005; 2007) which states clear profiled distribution of certain benthic taxa. Peculiarly due to the geomorphology, Mahi estuary shows extended

salinity ingress during the tides. Based on this salinity profile, any estuary can be divided into upstream, midstream and downstream (Cowardin et al., 1979). Molluscs were the prominent taxa of Mahi estuary showing salinity based distribution form upstream to downstream while other taxa illustrated a restricted distribution favouring limited salinity tolerance.

3.5. Benthic Animals and Their Mitigatory Behavioural Patterns

Benthic forms are one of the evitable components of the estuarine ecosystem. They potentially control the bioavailability of organic matter and balance the food chain (Sobczak et al., 2002). Benthic fauna are prone to various ecological and human imposed stresses which pose a high risk factor to their life. In turn, they respond to this risk by their varied behavioural displays and habitat selection. These adaptations are displayed either in terms of their behaviour patterns or their physiological attributes. Looking into the Mahi estuarine system and factors prevailing there, Figure 5 briefly describes different sediment processes, their consequences to benthos and the mitigatory adaptations by these animals. Further, bioturbatory activities by benthic forms at the interface contribute to the behaviour of an organism and grain size distribution (Pearson, 2001). Most of the benthic macrofauna found at Mahi estuary were active burrowers with dominant community of brachyuran crabs. However, there is a significant difference in various benthic species in terms of their specialized feeding and walking appendages, cheliped, burrowing pattern, burrow morphometry etc. which are one or the other ways to overcome the ecological stress. The depth of the burrow is generally highly variable which can be hypothetically accredited to the hydrodynamics and the prevailing sediment physical parameters. Chan et al. (2006) described different type of burrowing patterns in crab *Ocypode ceratophthalma* (Pallas) at different age intervals and in different sedimentological conditions.

4. REVIEW OF NATIONAL LITERATURE

As discussed above, estuaries though being harsh ecosystem are under high anthropogenic pressure. This has made the human community aware to think and work in direction of estuarine ecosystem, its physical and biological processes and its biota. Considerable amount of work has been done internationally specially from developed countries on various estuaries probing various aspects. Compared to this, very less work has been done from Indian estuaries and that too on benthic fauna and habitat correlations. The information on the estuarine ecosystem in India is scattered and sparse. In most of the cases, very small region of the estuary is studied. Usually, the characteristic features of estuary do not deviate much within the restricted stretch or the adjoining regions and therefore the dynamic nature of estuary and biotic variations cannot be evaluated significantly. More work is done on the estuaries from southern and south-western India. Majority of the work done includes a single dimensional study specially water quality or sedimentological aspect or diversity study or the distribution. Literature review from National Institute of Oceanography (Goa, India) database of Indian marine/estuarine research from 1990 to 2010 and from Indian Journal of Marine Sciences catalogue supports the above statement. The review states that 31% studies deals with benthic fauna followed by studies on different estuarine physical/chemical processes (28%) (Fig. 6). Within benthic faunal studies, only 10% of wok has been done on crabs, 12% deals with animal-sediment relationship while most of the other scatters for either a single animal, their distribution etc. (Fig. 7). Benthic faunal studies have been carried out in various estuaries on different aspects viz. diversity, distribution, experimental study, larval settlement etc. A study pertaining to benthic community structure has been done by Murugesan et al. (2007) on Vellar estuary and a similar kind of work focusing on macrofaunal community structure has been investigated on estuarine beaches of Goa (Harkantha and Parulekar, 1985). Very few studies are done investigating brachyuran crab diversity from estuarine or coastal regions of India. Notable pioneering work regarding the brachyuran diversity of south eastern estuaries has been carried out by workers from Annamalai University (Ajmal khan et al., 2005;

Manokaran et al., 2008). A comparison of scattered work on brachyuran crabs and existing lacunae along Indian coast is presented in Fig. 8.

Animal sediment relationship which can be better talked as an interaction of benthos with the sediments is an important tool in assessment of ecology of an animal and its responses to the environment. Macrofauna like brachyuran crabs are the best animals for studying animal sediment relationship in the estuarine system as they are the major bioturbators. Very little work has been done in India on the animal sediment relationship especially on burrowing pattern, tracking and trailing and feeding of sand bubbler crabs (Chakrabarti et al., 2006). A similar kind of work on animal sediment relationship has been carried out in detail on Mandvi coast of Gulf of Kachchh, Gujarat (Desai, 2002). Comparatively very sparse published data exists on the benthic diversity from estuaries of Gujarat. Earlier Nanda and Vachhrajani (2002) have reported the planktonic diversity and distribution in Mahi river estuary.

Geological processes and depositional environment of Mahi river has been extensively studied by Maurya (1997a, b) and Shridhar (2009) examining the depositional pattern and paleoenviromental evidences. Estuaries from Central west coast of India (Singh and Nayak, 2009); Poorna estuary from south western India (Anilakumari, 2001) and estuaries of eastern India (Chakrabarti, 2005) have been investigated for their sedimentary and the bed form characteristics. Hande and Madhyastha (2003) have investigated the hydrological and sediementological aspects of Malpe and Gangolli estuaries from eastern India. Few studies deal with water quality of an estuary (8%); mostly the studies are single dimensional focusing on particular aspect. Moreover, physico-chemical characteristics of estuaries from South Gujarat have been studied by Zingde et al. (1980, 1981). Studies have been carried out for the water quality of the south eastern estuary (Kumary et al., 2007). Few of the estuaries from southern and western India have been studies using modeling and statistical formulations for their physical and hydrological processes like flushing and mixing (Jyothi et al., 2000, Dineshkumar et al., 1999; Pylee et al., 1990). A critical study involving

sea water intrusion and behavior of trace metals has been carried out for Vashisthi estuary by Zingde et al. (1995).

Pollution has become a critical issue in India and the leaping industrialization is still intensifying the issue. As per the Ocean Monitoring and Prediction Systems (COMAPS) programme launched by Central Pollution Control Board, Gujarat and Maharashtra, reports nearly 24 CETPs (Common Effluent Treatment Plants) discharging the treated effluent to the coastal waters. These CETPs deal about 2500 SSI units in Gujarat and 2000 SSI units in Maharashtra. Gujarat ranks 2nd in number of CEPTs, which evidences its industrial development. Estuaries have become an ideal site for dumping of industrial effluent and domestic waste as they are the neglected intermediate ecosystems between marine and freshwater zones. The effluent released contains high amount of heavy metals and organicals. Heavy metals from the effluent eventually biomagnifies in the estuarine system and deposits in sediments and benthic animal tissues. Work has been done on deposition of heavy metals in the estuaries and estuarine sediments of India (Balachandran, 2005, Chakraborty, et al., 2009; Kumar and Patterson, 2009; Ram et al., 2009,). Narmada and Sabarmati estuaries along with few other south Gujarat estuaries have been studied for pollution aspects (Sharma, 2006). Preliminary study on pollutants in Mahi estuary has been carried put by Pandya (2000) describing reproductive toxicological potentials of such industrial effluent in laboratory rats. Due to the present industrial belt at Vadodara, Mahi estuary suffers from pollution load. A rivulet (Mini river) with high industrial effluent input merges with Mahi estuary at upstream while common Industrial effluent channel opens at donstream (Sarod) pouring effluent in the Mahi estuary (Plate 1) and its amplification in vicinity. Sharma (1995) has investigated the amount of pollutant accumulated in the vegetation and farm products of adjacent areas of the Mahi estuary and the industrial effluent channel. However, there is lack of information on the biomagnifications of the pollutants in the benthic fauna.

The review of literature suggests that multifaceted approach is needed for the research on the estuaries of India. Countable work on pollution aspect of estuaries has been carried out. However, looking to the bulk of estuarine

pollution in Gujarat, more work is required integrating the pollutant transfer and biomagnifications rate. Very less published date occurs on benthic fauna and especially on crabs of Gujarat except the work done by Chappgar (1957) on past Bombay state and few records by Desai et al. (2002) on Mandvi coast, Gulf of Kachchh.

5. REVIEW OF INTERNATIONAL LITERATURE

During last couple of decades the anthropogenic activities have induced changes in varied aspects of estuarine ecosystem. Estuaries have been studied with reference to their hydrodynamics, oceanographic influences, migratory avifauna and other biotic diversity by researchers of different disciplines (Steffens et al., 2006). Much work has been carried out on the general hydrological processes of an estuary. Turbidity and salinity are the chief governing parameters of an estuary responsible for the gradients and extent of estuarine conditions. Effect of morphodynamics on the tidal regulation of Australian estuaries has been studies in detail by Lessa (2000) stating the direct correlation of tidal processes and its extent with the geomorphology of estuary. Moreover, physics of turbidity and salinity has been studied influencing the gradation of an estuary (Sanford, 2001). Several reports demonstrated dependence of estuarine faunal diversity and distribution on physical and physico chemical features such as sediments and salinity, respectively (MacFarlane and Booth, 2001; Attrill and Rundle, 2002). There exists an established correlation between physical properties of habitat and macrobenthos distribution (Flint, 1981; Bolam, 2003). Studies have suggested that macrobenthic communities could be distinguished on the basis of sediment composition (Sanders, 1958; Glēmarec, 1973; Buchanan et al., 1978).

Among benthos, brachyuran crabs are the interesting macrofauna highly distributed and imparting greatly to the bioturabtion of sediments. Botto and Iribarne (1999) supported the previous research narrating crab as an important habitat modifier influencing the microtopography and sediment chemistry to some extent. Literature survey says that work has been carried

out for behavior of individual fiddler crab species mainly focusing on their burrowing activity and reproductive strategies (Christy 1982; Christy, 1987; Burford et al., 2000; Shih et al., 2005). Population densities of the soft-sediment infuana are difficult to estimate, due to the cryptic burrowing of the inhabitants and the nature of the sediments (Morrisey et al., 1998), thus several studies have used the number of burrow openings (hole count) to estimate macrofaunal density looking to the reliability of the method (Butler and Bird, 2007). Sediment composition is an important variable for the distribution of macrofauna. Considerable international literature exists on distribution pattern of crabs and molluscs. The literature states about the distribution in mangrove habitat, spatial distribution in saltpans and distributional change of a community based on the patchiness of sediment texture (Bezerra et al., 2006; Frusher et al., 1994; Flores and Paula, 2001).

Leaping industrialization has made the ecosystems of the world prone to pollutants, especially the aquatic environments. Estuaries are the prime target worldwide for release of effluents and sewage. The agricultural drainage via rivers is carried into estuaries along with surface runoffs which carries pesticide concentration. Work has been done on the invertebrate diversity of polluted estuaries (Rosenberg and Olundh, 1973; Nagvenkar and Ramaiah, 2009). Researchers have been investigating how these pollutants passes through the ecosystem components like water and leaches into the sediments (Barrett, 1972;, Ferrer et al., 2000; Kumar et al., 2001; Fang and Lin, 2002). Many of these heavy metals biomagnifies and part of them gets congregated in the tissues of invertebrates inhabiting the system. Studies with mudskippers as a target of bioaccumulation and its extent have been carried out by few researchers (Kruitwagen et al., 2005; Olayan and Thomas, 2008).

6. INTERDISCIPLINARY APPROACHES OF THE STUDY

Environmental biology/science is a field encompassing wide range of scientific disciplines to understand interactions among physical, chemical, biological and human components. The magnitude and complexity of these environmental aspects have necessitated multidisciplinary training in

environmental sciences. Interaction, interconnections and integration are the need of time. The super specialized knowledge is finely fragmented and hence is of little applied value since the environment is not a nano entity but a comprehensive and complex system. The discussion so far has highlighted various abiotic and biotic components of the estuarine ecosystem. An integration of these is presented in the following section.

6.1. Hydrodynamics

Hydrodynamics serves as one of the crucial factor in estuarine condition. Tidal fluctuation is one of the important elements governing the hydrodynamics of an area. The extent of tidal variation depends on the geomorphology of the area as well as the celestial conditions and gravitation. Further, the daily and seasonal tidal difference on different moon days results in generated tidal amplitude, resultant current and wave generation. Estuaries fit best to the hydrodynamics theory wherein a complex interaction of tidal fluctuations with riverine dynamics occurs which is not seen in purely marine and freshwater system. Moreover, the state of interaction and the hydrodynamics in estuary highly depends on riverine discharges as well as the coherent marine inflow. Over and above these implications there are certain obvious changes in distribution and diversity of benthic animals governed by hydrodynamics.

6.2. Habitat characteristics

Profiling of diverse habitat features, distinctly the abiotic parameters can be termed as habitat characteristics. In estuarine case, there is always a fragile overlapping of different ecosystems or habitats which can be compared to ecotone which is usually applicable to terrestrial system. Sediment compositions, beach slope, estuarine gradients etc. resultant of hydrodynamics are few of the important aspects which distinctly characterize the estuarine habitat. Sediment composition, consequential of sediment sorting during the hydrological fluctuations is an important factor which determines the distribution of benthic flora and fauna. Additionally, the counter geological actions like creation of channel bars, terrace formations, sediment

layering and the beach morphology formed by the estuarine interactions are closely interrelated which too controls the benthic assemblage.

6.3. Community association patterns

Community can be termed as a mass of species occupying a particular area/place. In estuarine ecosystem, benthic communities hold a strong part in biotic – abiotic interactions. As discussed in para 6.2 and 6.3, the abiotic variables strongly generate different habitats/microhabitats which inturn regulates the community structure prevailing in the region. Moreover, a species specific preference of habitat is evident which limits the distribution of particular group in an area. The species in a particular community show close associations wherein the association can be between two animal species or between faunal and floral species as prey predatory mechanism or a mutualistic interaction. In case of burrowing animals, a fine case of commensalism can be seen wherein a common burrow is shared by two benthic forms. During present study, *Neries sp.* was seen inhabiting the burrow of crab or mudskipper. More to this, *Isopod sp.* (*Spheroma sp.*) and Amphipod sp. was seen sharing a same microhabitat without overlapping each other's life form. Interestingly, in case of active burrowing forms like crabs, role of microbial diversity within the sediment at different depth affects the burrowing features specially the depth of the burrow and the same follows vice-versa. This particular aspect is governed by the oxic-anoxic layering facilitated by the microbes.

Further, the above described biotic and abiotic features impact the adaptiveness of the species in a given habitat which is best seen in form of the behavioural displays exhibited by an animal. In nutshell, the tiny benthic fauna holds an evitable position in the estuarine food chain and food web taking hand in hand the healthiness of an ecosystem and sustainable ecological functioning.

7. INITIATION OF RESEARCH IDEA

7.1. The Thought

Estuaries are one of the vital ecosystems on the planet and a challenging environment for the animals within. Probably, being a transition zone between freshwater and marine ecosystems, they are highly neglected and scantly studied as compared to other aquatic ecosystems. Mahi River is one of the major rivers of Gujarat and bears a year round live estuarine region. There is very scarce literature on the Mahi estuary and no literature/study dealing with the benthic fauna, which are one of the important components of the estuarine food chain and play pivotal role in ecosystem health. This lacuna motivated me to investigate the benthic faunal diversity of the Mahi estuary and to characterize estuarine habitat.

Other than benthic diversity study, the subsequent field visits and time spend in the field attracted me to look more keenly to these super creatures. More I learnt from field more the questions aroused which finally droved me to investigate animal-sediment relationship: an interesting fact of nature, how these tiny animals mitigate ecological harshness and behave in their niche. Detail characterization of habitat/microhabitat helped me to probe the like and dislike of the animals interms of their niche. Further, it was my interest to step down to taxonomy of benthos especially the brachyuran crabs which is not studied well. Looking to the modern trend and needs, gradually I incorporated few interdisciplinary aspects to clearly understand the classical ecology with recent tools and to have a broader view.

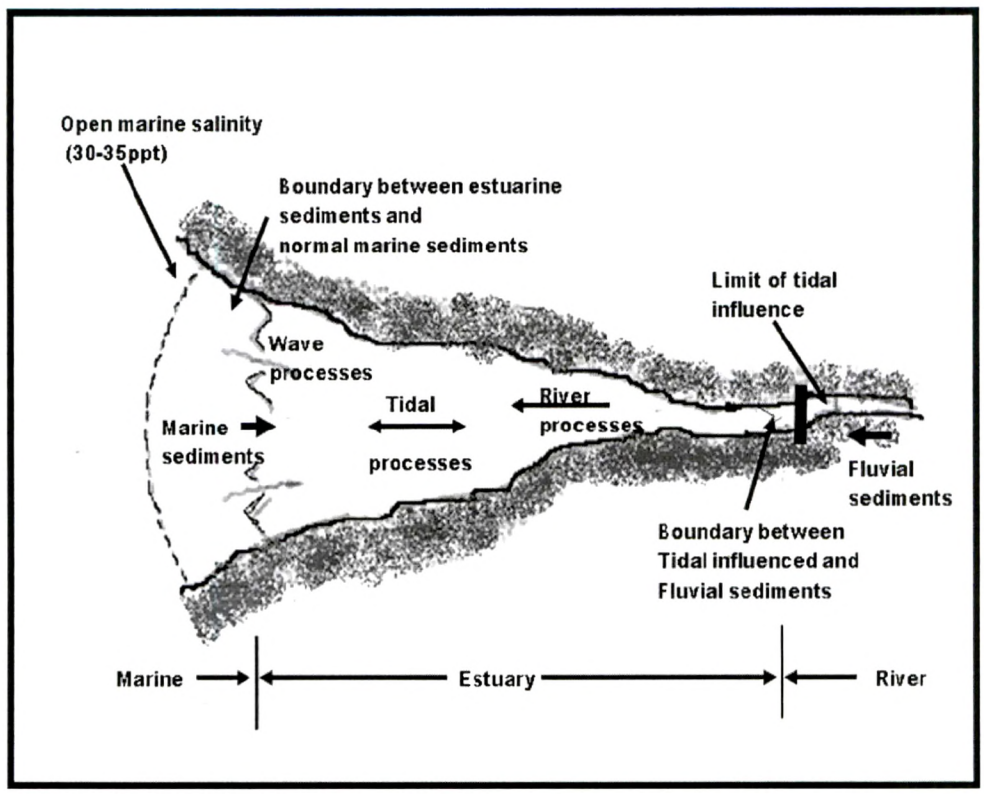


Fig.1: Shows generalized physical processes at the estuarine scale with marine and riverine influences.

Table 1: Description of characteristic features of Gulf of Khambhat briefing width of Gulf from head to tail with respective distance.

Cross Section		X- Co-ordinate (km)	Width (km)
No.	Location		
1	Diu-Umargam	0	200
2	Pipavav-Valsad	45	150
3	Methla-Hazira	90	66
4	Alang-Mor	120	50
5	Ghogha-Dahej	1150	27
6	Mouth of Mahi River	210	06

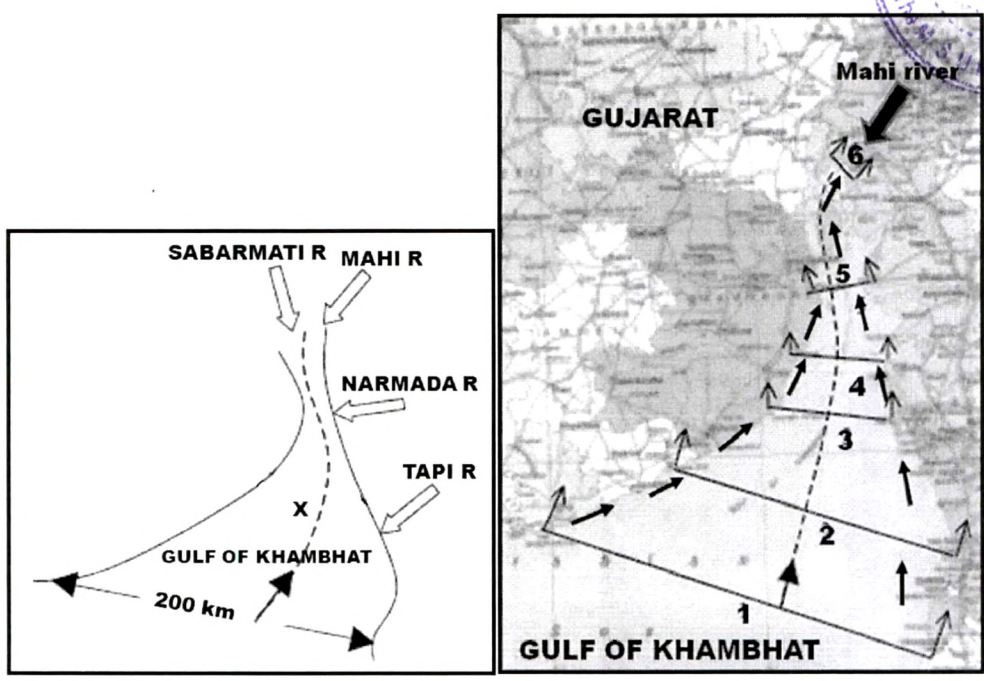


Fig. 2 a and b: Geometry of the Gulf of Khambhat having broad mouth and narrow end with the sharp decline in distance (Source: Modified from Timmermans, 2002).

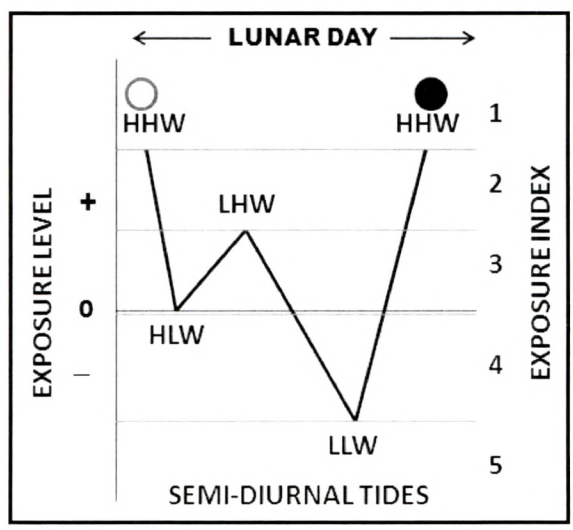


Fig. 3: Represents tidal actions on different moon days

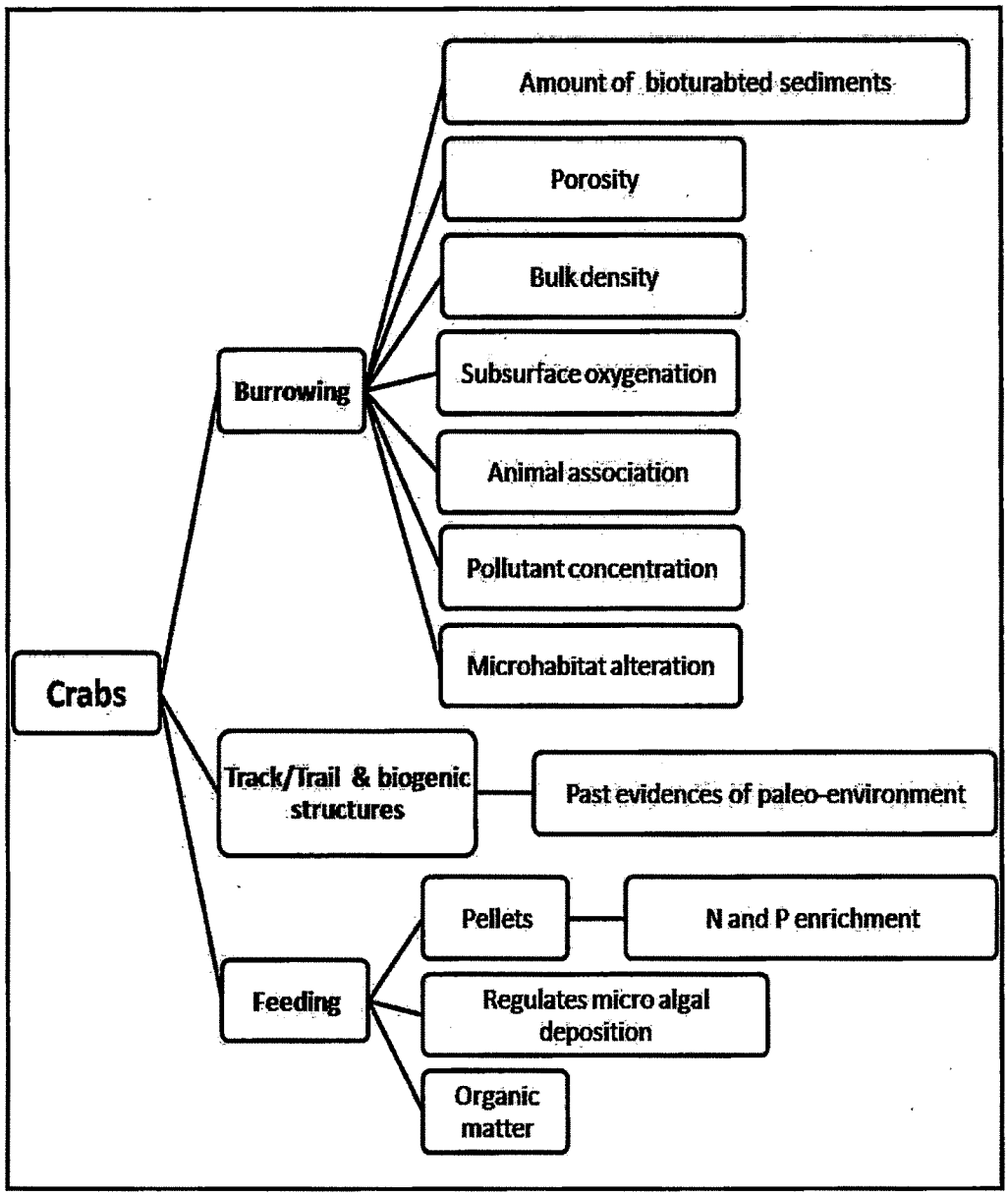


Fig. 4: Flow chart shows major bioturbatory activities performed by crabs on the exposed estuarine beach. The secondary blocks mention the resultant alterations/facilitations to the substrata/sediments.

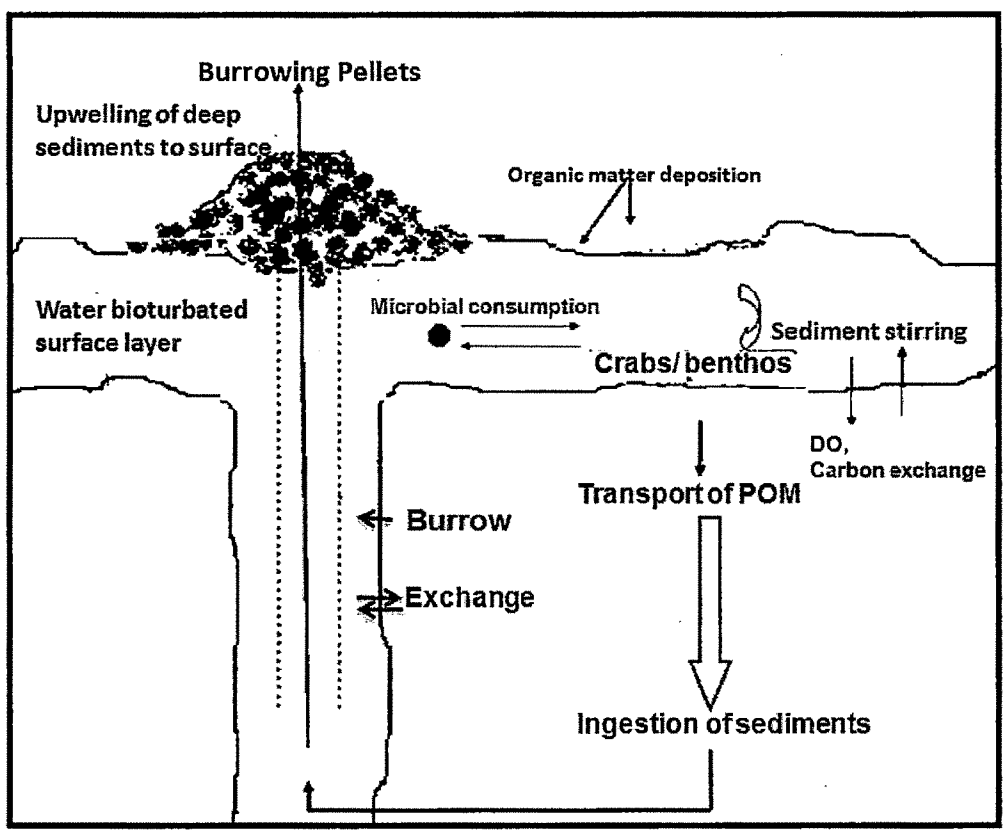


Fig. 5: Diagrammatic representation of surfaces and subsurface processes facilitated by benthic animals.

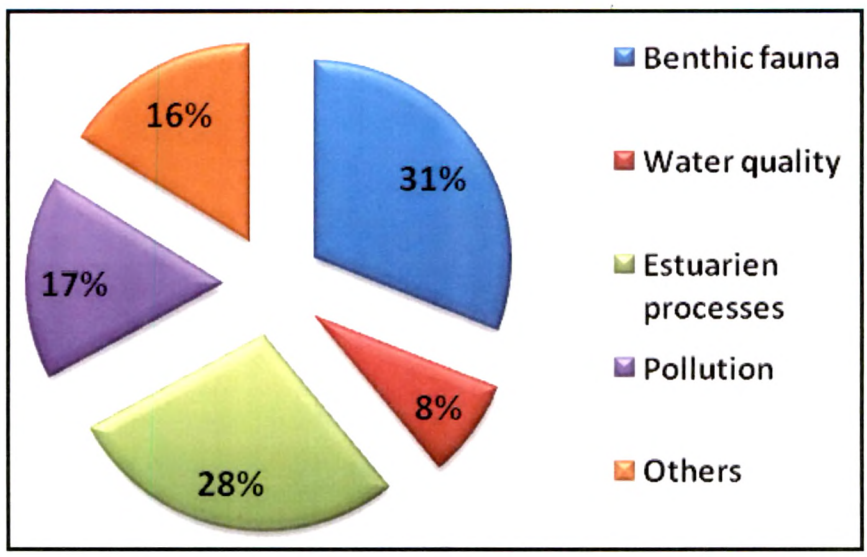


Fig. 6: Showing work done in different aspects of estuarine ecosystem from different estuaries of India . (Papers reviewed from National Institute of Oceanography database and Indian Journal of Marine Science. N=210, 10 years).

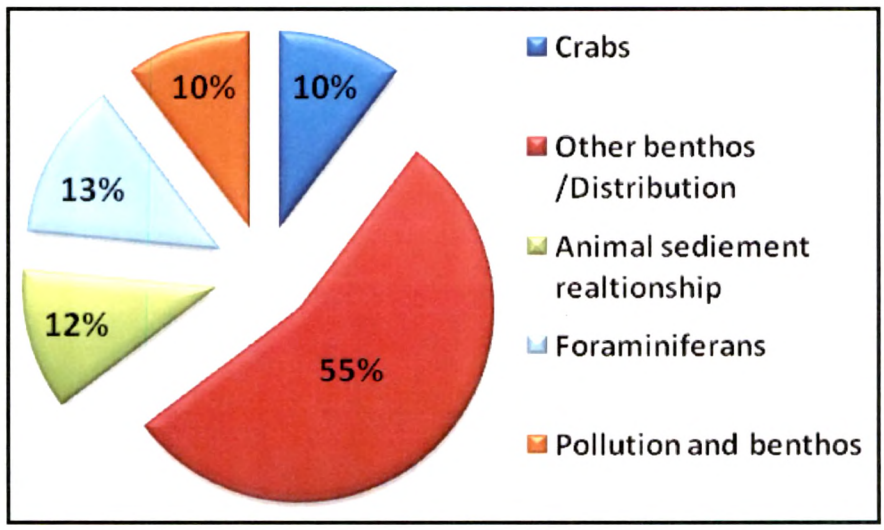


Fig. 7: Showing work categorization of benthic fauna from different estuaries of India.

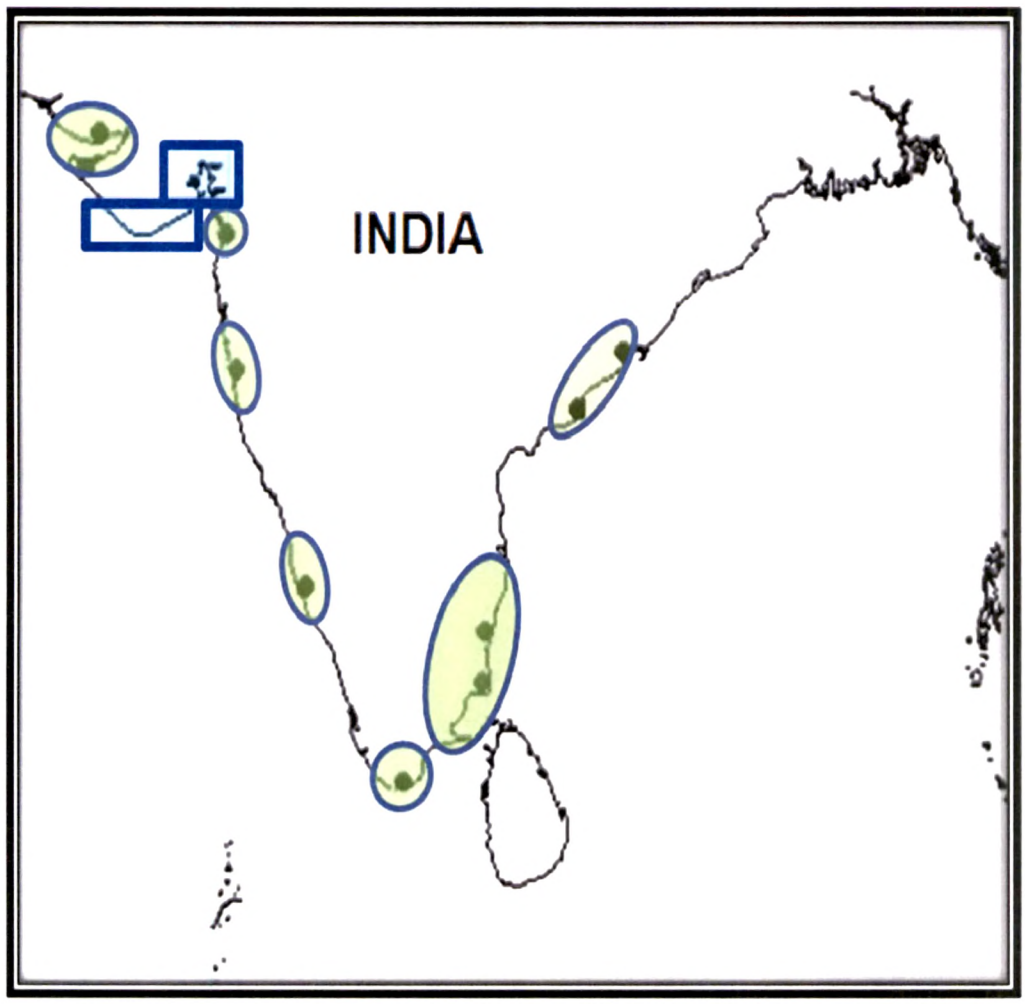
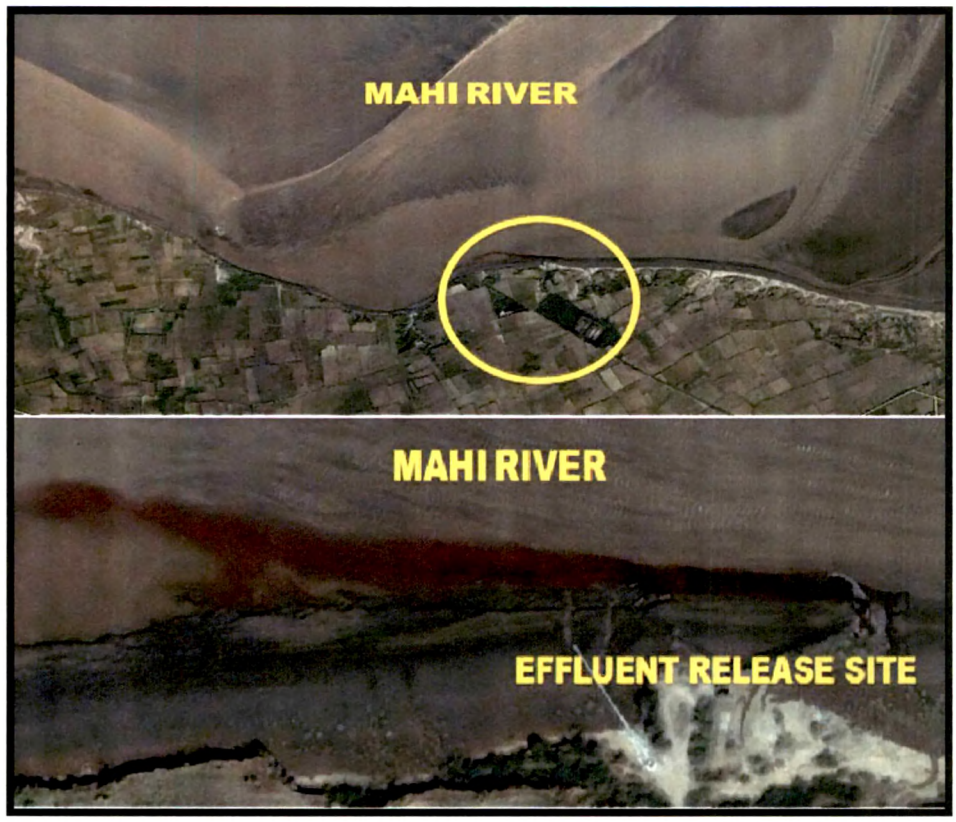


Fig. 8: Figure shows the scattered work done on brachyuran crabs in green pockets while blue window represents no work done in Gulf of Khambhat and Saurashtra coast.

Plate 1



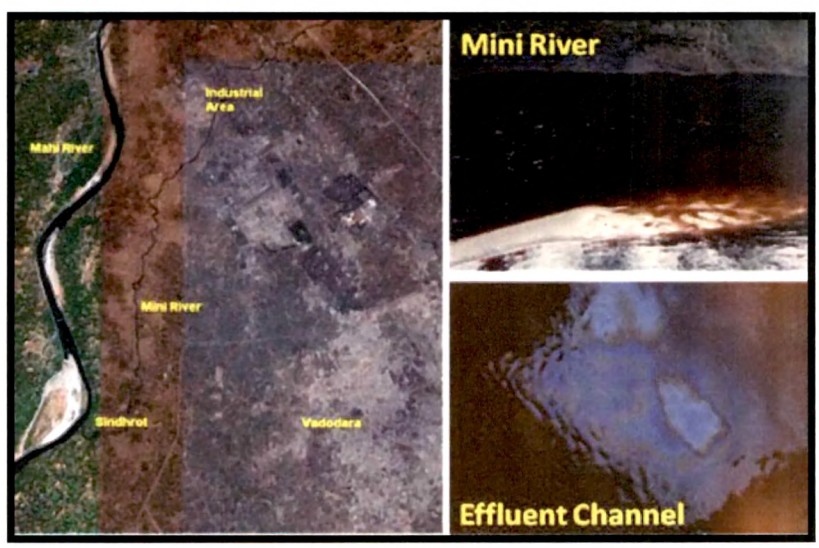


Plate 1: Glimpse to pollution load on Mahi river estuary, with first half showing Common industrial effluent channel opening at downstream Sarod while lower half shows a rivulet (Mini river) with effluent load merging to Mahi on Upstream.