DISCUSSION

An estuary has always been a complex ecosystems compared to their counterparts in terms of abiotic and biotic interactions. The complexity amplifies with interaction of abiotic fraction within themselves at very frequent intervals and their resultant counteraction on biota sustaining within the ecosystem. Looking to this multifaceted nature of the estuarine ecosystem it would be bias to study the ecosystem or any of its process from a single view. The more comprehensive idea of the problem can be validated by applying a holistic approach to the study. With this basic understanding an effort was made to understand the baseline status of Mahi river estuary and correlate the abiotic parameters with the prevailing habitat aspects especially the animal-habitat interaction. During the study following components were evaluated: i) General estuarine habitat characterization, ii) Estuarine water quality, iii) Sedimentological study, iv) Benthic faunal diversity study, v) Benthic fauna distribution profile and vii) Animal sediment relationship.

Geography and morphology of the river, river meandering, slope etc. defines the hydrodynamics of the estuary. Work by previous researchers has shown the role of habitat on the persistent hydrodynamics which in turn affects the physico chemical parameters of the estuary, sediment deposition, grain size sorting and finally the animal distribution on estuarine scale (Talley et al., 2000; Zajac, et al., 2000). The prominent part of the estuarine system i.e. regular mixing of freshwater and marine water serves as the foremost reason for spatial water quality change whereas the volume of the flow from both the sides (riverine and marine) regulates the temporal variation of water quality. The three major estuarine parameters viz. salinity, total hardness and total solids are the prime factors which show a predominant fluctuation due to the tidal mixing. These three parameters crucially demarcate the gradient and zoning in the estuary wherein their unit values increases prominently as moving from upstream to downstream respectively. Furthermore, the ratio of tidal and freshwater mixing; tidal force/amplitude, tidal volume, bed morphology etc. are few of the characteristic features governing the estuarine gradation pattern from downstream to upstream.

The geomorphology of gulf is very specific; steep narrowing of gulf from ~ 200 km at gulf mouth to ~6 km at tail i.e. mouth of Mahi estuary. As a rule, a large volume of tidal water enters gulf from mouth which narrows down exponentially causing high tidal amplitude and churning of water current. The churning of the ingressed water and thereby the upwelling of the bottom sediments eventually results in the suspended sediment load at the downstream which decreases gradually moving towards upstream. High level of total hardness at downstream showed the marine salts load as well as load due to Calcium and magnesium. The sedimentation pattern and the substratum composition are one of the important factors governing the animal distribution. The high meandering at mid-estuarine region prominently erodes one bank of the river while the opposite creating the depositional site with a flat land as a generalized rule. The bed structure with coarse grains and pebbles as well as shallow water level at upstream sites favours a good molluscan density as was the case in initial years of research which later on changed due to construction of wear at upstream. The estuarine salinity is mainly governed by freshwater discharge which decides the salinity levels. In most of the cases in estuaries like Mahi, marine tidal flow dominates the riverine inflow exceptionally during the monsoon season in which the high inflow of freshwater pushes the saline boundary more downstream towards the marine side. The basic interest of the study was to access the general habitat condition of the estuary and assessment of benthic fauna of estuary with their habitat interactions. With same reason, seasonal evaluation of estuary was avoided looking towards random sampling throughout the year and demarcating the range of selected water parameters with estuarine regime.

Habitat assessment has been an integral part of any study as it governs animal distribution and abiotic status to certain extent. In an estuarine ecosystem, the geomorphic alteration and thereby the resultant hydrodynamics roots a variety of habitat at different estuarine zones or even at point level. A mosaic of patches with different environmental characteristics, at different states of recovery, can contribute to the spatial heterogeneity within ecosystems (Thrush et al., 2008). The geomorphic study of Mahi River estuary has already been presented by Maurya et al. (1997). Moreover the upstream of Mahi estuary represents cliff storing levels of paleo deposits which has been very well studied to understand the past paleoclimatic events. The studies have shown the signatures of frequent flooding in Mahi River and the predominant sand deposits at the lower reaches of upstream giving evidence of flooding event (Sridhar, 2009).

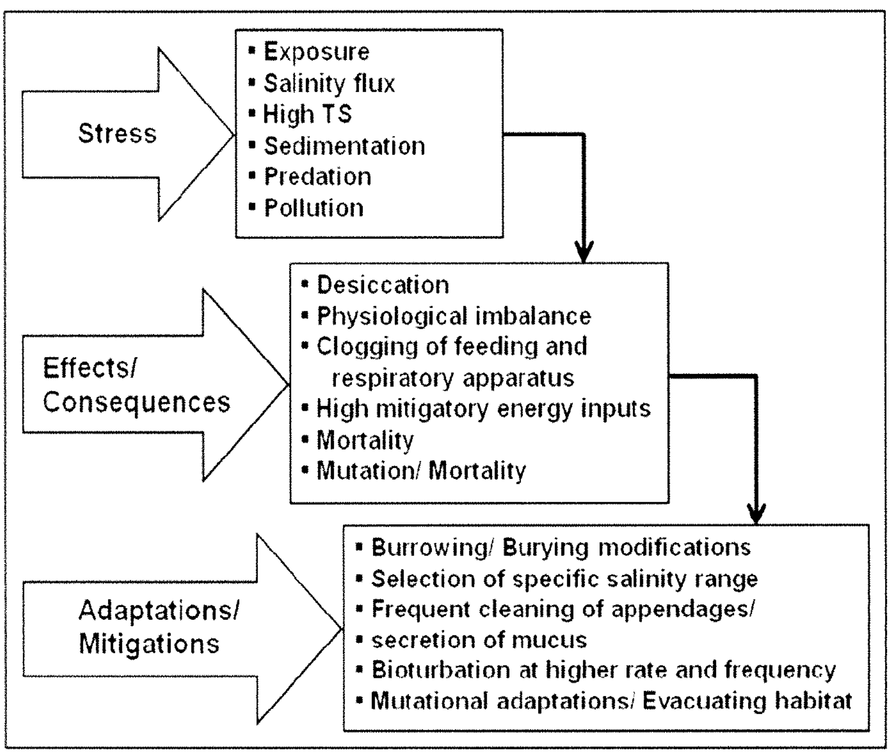
Apart from the effect of geomorphology and hydrodynamics on estuarine water quality and gradation, the meandering water current results into an erosional site and depositional site on the estuarine back as a rule. A generalized rule of sediment sorting applies to the deposition theory which can be reflected by sediment grain size and composition. Sediment and bed composition at different levels in estuary reflects prevailing present and past records of hydrodynamic fluctuations and events. A similar case can be observed at upstream and midstream site of Mahi, wherein the upstream is represented by coarse sand and gravel bed reflecting the flowing nature of river which eventually on construction of a wear changed to accumulation of sand and vanishing of shallow habitat. The midstream sites (Dabka) shows predominant sand beds deposited on the bank which are the result of the flooding event where in there is a sudden arrival and drop in water column with current causes sand deposition. The lower estuarine mudflats and intertidal flats show a characteristic depositional nature and dynamic interactions of freshwater with marine sediments creating a mosaic of sediment zones at different levels from high tide line to low tide line which is best seen at Kamboi. Sediment deposition and sorting at macro and micro level is an important phenomenon creating a diverse macro and microhabitats. The present investigation suggests that the downstream estuarine part dominates in silt and clay while upstream dominates in sandy nature. The silt-clay deposits in downstream evident the possible fluvial and marine deposition spread over tidal flats. Looking at a point level, a gradient of sediment sorting is clearly seen at the downstream (Kamboi) with a distinct zonation from high tide line to the low tide line on estuarine intertidal area. The muddy sediments (silt/clay) towards the upper intertidal zones represent the sediments deposited on the bank side and are mostly the fluvial sediments mixed with marine inputs. The fine sandy sediment composition dominating the lower intertidal zones (Zone 5) represents the marine sand mixed with settling silt. A study of Tasmanian estuaries indicated that silt loading had a widespread and detrimental effect on estuarine communities (Edgar and Barrett, 2000).

During the study it was clearly seen that different macrofaunal groups exhibited a sediment specific distribution pattern and a strong affinity to particular type of substrata. In case of Mollusca high diversity was seen at upstream followed by downstream while the lowest was seen at the midstream. High diversity at the upstream site can be due to the favourable bed material available as well as the less turbid conditions as compared to the lower estuarine portions. Lower diversity at midstream site Dabka, can be attributed to the critical transitional zone which always acts as a highly fluctuating environment and checks the animal acclimatizing limits. The low diversity area can also be best fitted to a two-ecocline model proposed by Attrill and Rundle (2002) and by Sousa et al. (2008) which shows overlapping of gradients at mid-estuarine environment. Though, during the course of study eventually a decline in few of the molluscan species was seen (the change was not documented) due to the wear construction, rise in water column and the stagnancy which was not the case earlier.

Present study interpretations corroborate with the findings of Sousa et al. (2008) regarding high diversity of animals in upstream area followed by downstream which was also the case in River Minho estuary, Europe. The spatial distribution in similar fashion against gradient has been discussed by several authors (Mortensen and Høsæter, 1993; Underwood and Chapman, 1996).

Looking over the brachyuran group, the highest congregation of crabs in the Zones 3 and 4 suggested substratum preference of the species. A substrate-based microhabitat selection has been reported for *Uca uruguayensis* Nobili, 1906 (cf. Ribeiro et al., 2005). Thus, the density of and preference for Zones 3 and 4 can be attributed to the sediment characteristics as well as to the slope, which together make the ground firm and suitable for easy burrow construction. At Zone 5, the alluvial substratum is exposed and devoid of sufficient silt/clay covering, which makes it unfavourable for the animals to make deep burrows, and thus is less occupied. Since Zone 2 is well hydrated only during spring tides, the distribution of *M. depressus* is sparse. The probable reason behind the selection of silty/clayey sediments can be the facilitation of burrow formation, which is otherwise difficult in the fine sandy substratum of Zone 5. Moreover, it was seen that *M. depressus* and *Uca lactea* were the active burrowers which hindered their movement to lower intertidal sandy and watery zones which do not facilitate sustainable burrowing. In case of *D. crepsydrodactyla,* the species used to build superficial burrow which can be build even in fine sandy substrata. Similar was the case with *M. dilatatus* which being inhabitation Zone 5 sandy substrata used to build a shallow and vertical burrow.

Interestingly, during the course of study one of the hypotheses was to check whether selected benthic species follow any specific rule of distribution. A species specific habitat preference was seen. Sediment type and strata formation are some of the important features of habitat selection by different animals (Sunelgrove, 1999; Middelburg and Heip, 2001; Stefan, 2003). Studies suggest habitat specific distribution/occupancy by different crab species along the intertidal area (Shin and Choi, 2000; Chakrabarti et al., 2006). This phenomenon was clearly observed in the present study. Brachyuran crabs were the dominant and focal species which show close and notable sediment relationship. The extent and type of burrowing by crabs reflects their adaptation to the habitat and prevailing habitat conditions. As an example, in case of *Uca lactea*, the burrow cast obtained from Zone 2 were double in depth as compared to the same in Zone 3. The most viable reason for this can be the hydration condition i.e. the required moist condition available in Zone 2 would be at more depth due to upper being an intertidal zone not frequently hydrated. Zone 3 gets regular tidal current and is much hydrated thus giving a required moisture and microhabitat at lesser depth as compared to Zone 2. Moreover, the number of resting chambers importantly was more in Zone 2 which can be hypothetically the effect of water levels at different moon days which was not the case in Zone 3. The variety and number of resting chambers may be used for resting, moulting, and breeding. Supporting this, previous worker has stated that brachyuran crabs use their habitat variably for burrowing to overcome harsh estuarine conditions, for protection from predation, and for feeding, moulting, mating, etc. (Leme, 2002). Moreover, to overcome the ecological stress specially seen in estuarine ecosystem, benthos form various adaptive measures. The male *Uca lactea* sp. forms typical mudball which differ sex wise as discussed in results section, Chapter 4. The mudballs formed by males are bulky and round as compared to those formed by female which are spindle shaped and small. This is due to the presence of large chela in male which is used for digging and carrying mudballs. Moreover, the mudball placement follows a specific pattern in case of male and female. The same fact has been observed by Burford et al. (2000) who discussed similar experience in case of *Uca tangeri.* It is opined that the distance of mudball placement may display the territory of male crab. Looking into the Mahi estuarine system and factors prevailing there, the figure below briefly describes different stress factors, their consequences to benthos and the mitigatory adaptations by these animals:



The extent of habitat exploration by crabs is influenced by ecological factors, salinity being one of the major controlling factors (Frusher et al., 1994). The distribution and abundance of crabs depend on their ability to make and maintain their burrows in a given habitat. Other important physical factors are tidal variations, slope, sorting, composition, and compactness of the sediments and the ease of excavation (Bertness and Miller, 1984; Weissburg, 1992). Additionally few of *the* researchers have also reported availability of nutrients, larval recruitment, community composition, and interactions as other such factors (Travis, 1996; Bradshaw and Scoffin, 1999) influencing animal distribution. At present, no information is available for Mahi estuary on the larval recruitment, preferences of juveniles or adults, predation pressure, or factors determining community composition and, therefore, it is difficult to interpret the heterogeneity of the distribution of *M. depressus.* Few of the authors have described different *Uca sp.* forming a dome or a chimney effectively as part of their mating display (Crane, 1975; George and Jones, 1982; Wada and Murata, 2000) though in present study neither of the *Uca sp.* displayed such type of behaviour.

During the present investigation, only a single species *Dotilla crepsydrodactyla* was seen forming a chimney over the burrow. The chimney was build up by placing the mudballs staked over each other. Though the proper function of chimney was not clear but it can be hypothesized that the size and length of chimney may be the form of courtship display for attracting the female species. Moreover, the chimney may function as a barricade against the predators and the ecological factors protecting the animal in a shallow burrow. Based on the field observations and data available few of the possible hypothesis can be proposed and discussed regarding chimney formation by *Dotilla crepsydrodactyla* and its functions as under;

i). ***The sexual attraction hypothesis:*** The species forms a chimney of variety of length and width as stated in results. This may be the viable reason of attracting female by building more pronounced chimney. The same has been also discussed and worked by Christy et al. (1988, 2003) for *Uca sp.*

ii). ***Protection from abiotic factors:*** This can be one of the potential hypotheses for creation of chimney by an animal. The large chimney of *D. crepsydrodactyla* not only protects the animal from desiccation stress by direct sunlight but also keeps the inner burrow temperature lowered and moist. This is the most useful utilization as the burrows of the species are mostly shallow and prone to direct heat. Further, it is well observed that the crab constructs chimney after actively feeding and later plugs the chimney from inside which can be best correlated to the present hypothesis.

iii). ***Hypotheses of Ventilation and aeration:*** Though the present hypotheses contradicts the previously discussed one, the specific amount of aeration is required by the animal to be within the small and plugged burrow for longer time. The chimney of *D. crepsydrodactyla* is generally loosely constructed with mudballs, and many large gaps remain in the walls of the chimney; thus, the wind can easily ventilate the burrow through these gaps. However, after the chimney construction is finished, the burrow entrances can become plugged (Refer Plate 12 a and b in Chapter 4), a similar behavior also seen in *Uca sp.* (Salmon and Zucker, 1988).

iv). ***Hypotheses of territoriality.*** The 4th important function of the chimney can be protection from the intruder as well display of territoriality through chimneys. The chimney can not only act as first line of defence against the direct intruders but also virtually increase the actual depth of the burrow. McCann (1938) proposed that the function of the castle built by the terrestrial (freshwater) crab, *Paratelphusa (Barytelphusa) guerini* (H. Milne Edwards) on Salsette I., India, was to keep intruders away during estivation, as it acted as a bluff which is mistaken for a clod of earth to the predators. Silas and Sankarankutty (1960) also cited McCann's opinion to explain the castle built by the land crab, *Cardisoma carnifex* (Herbst). Wada and Mutata (2000) also considered that the function of the chimney of *U. arcuata* was to protect the burrow from usurpation by wandering crabs.

A similar observation was made for *D. crepsydrodactyla* wherein the species is seen to make burrow in groups showing a type of social grouping. A group of individuals occupies a whole ripple crest forming superficial burrows in close vicinity (Fig. 2). It is believed that this may be due to the water logging as well unavailability of proper substrata in the trough of the ripples, the habitat available for burrow construction would be much less against the density of the species in an area which force them to make a close grouping in particular microhabitat.

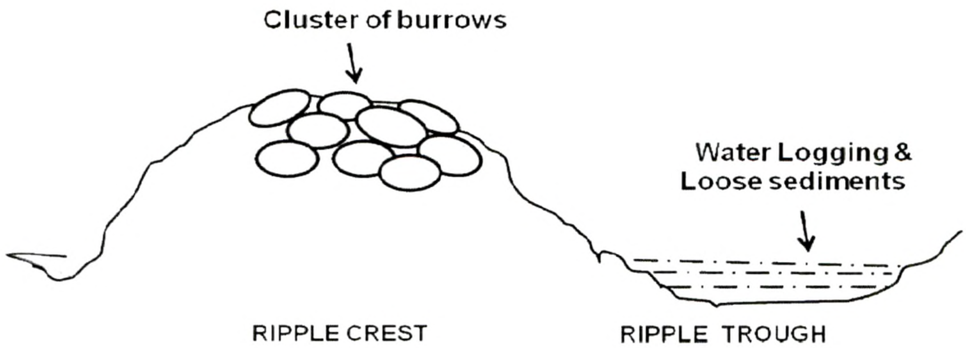


Fig. 2: Diagrammatic representation of close proximity burrowing by *D. crepsydrodactyla* in specific microhabitat.

Dotillid species moreover had been an interesting animal for the behavioural investigations during the study as the species allowed their observations at very close proximity which was not the case with other species. The species though being the tiniest of all obtained crabs was giving the highest bioturbatory input to the ecosystem as a group. One of the reasons for this other than their density is the activeness of the animal during feeding as well as the area exploration. The species shows highly adapted claws ranging much to their total body which are very effectively used in scooping the sediments. This typical feeding exploration leave fine traces of the feeding marks which in a few cases can be preserved as ichnofabrics. These are the only species which leave their grazing traces. The same statement has been supported by Chakrabarti et al. (2006) stating that species of bubbler crab effectively produce ichnofabrics which is not seen in Ocypodid crabs.

Mudskipper sp. tends to be one of the important macrofauna on Kamboi mudflat and one of the foremost bioturbator and forager. Immediately after low tide the species were seen very actively feeding and foraging on the watery mudflat. As the time passes the activity of the species was seen lowered. This may be due to the water and soup ground loving nature of the species. Further the smooth and watery ground enables easy and swift movement of the species. Even after the interval of low tide the species remains confined to loose watery substrata with depression around burrow and the burrow completely filled with water. The burrows are long, complex and horizontally spread instead of being vertically deep. The species is known to store oxygen in their burrow and timely peep out of the burrow to gulp air in their buccal cavity (Ishimatsu et al., 1998).

A community distribution zone wise was carried out species confined to a specific zone and species overlapping different zones. Though most of the species remained very much confined to their zones while few of them showed movement between adjacent zones. This was due to the availability of similar type of habitat to the species.

Few of the species confined to the hard substratum like amphipod, isopod, Sipuncula etc. showed a very restricted distribution and remained confined to their niche. These animals highly perforated the sediment block which were soft and organic matter rich. The CT scan study has revealed that these animals preferred boring the sediment with less density and avoided an intermediate places in the block where there was a compaction and calcrete formation.

Overall it can be said that most of the benthic forms tend to overcome the harsh environment and roll on their bodily processes. The Uca species by forming the simple burrow instead of branched one tends to minimize the energy needs. Similar case is seen in isopods and amphipods also wherein by sharing a common microhabitat and selecting a soft part of the sediment the species tries to overcome and save the energy inputs.

Anthropogenic pressure

Habitat destructions and fragmentation are well discussed as threat in terrestrial studies. Yet such an attention is not yet paid to marine and coastal/estuarine studies which are nowadays heavily impacted by human activities and utilizations. Human activity (e.g., habitat modification/destruction, pollution, and eutrophication) increases the frequency and extent of disturbance to the estuaries and estuarine communities. A wear has been raised at upstream to limit the ingress of marine water which eventually resulted in stagnancy of freshwater, eutrophication as well as lower freshwater input shifting the saline water more towards the river. A similar observation has been reported in Tanshuai estuary in Taiwan wherein the author has described manmade construction across river lowering freshwater flow and moving the salinity gradient (Liu et al., 2001). This distribution pattern as well density of animal at upstream, midstream and downstream is governed by these abiotic factors. Habitat loss, fragmentation, and disturbance of natural communities alter the patterns of connectivity, potentially isolating populations and communities and limiting them to their required habitats (Tilman et al., 1994; Fahrig, 2003; Holyoak et al. 2005b; Crooks and Sanjayan, 2006). Considering the human benefit apart, the consequences of damming or polluting the estuary may lead to the altered freshwater flow rate in estuaries. The pollution load yet not very well discussed in the study has a detrimental effect on the estuarine biota which was visible. A steep vanishing/decline of benthic and aquatic fauna on the adjacent areas of the effluent release point marks the evidence of negative impact of pollution. Moreover the anthropogenic pressure in terms of pilgrims at religious sites, vehicular transport, artificial constructions, constructions and modifications of river banks etc. may severely alter the habitat.