

Fish larval transport in the coastal waters through ecological modelling

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To my teachers who moulded my academic zeal

Statement

As required under the University ordinance 0.19.8.(vi), I state that this thesis entitled *Fish larval transport in the coastal waters through ecological modelling* is my original contribution, and it has not been submitted on any previous occasion.

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

Grinson George

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Certificate

This is to certify that the thesis entitled *Fish larval transport in the coastal waters through ecological modelling* , submitted by Grinson George to Goa University for the degree of Doctor of Philosophy, is based on his original studies carried out under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any university or institution.

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Abstract

The coastal waters of India are rich in diverse marine larval population, and fish larvae form the major commercial group. Larval phase of marine organisms is very important in deciding their future stock and abundance. There are a few obnoxious bioinvasive barnacle larvae, which spread in the coastal waters and form a biofouling agent disturbing harbour, jetties, navigation and recreational activities. Larvae of marine organisms are passively drifted along with the ambient currents from their spawning sites to nursery areas where they develop into juveniles. It is imperative to protect such nursery areas of economically important species, and restrict the areas of dispersion of larvae in the case of obnoxious or bio-invasive species. There are several techniques employed for determining the larval transport in the marine environment. They include extensive field surveys, screening the larval samples using molecular tools (to distinguish endemic larvae spreading to different locations from their natal sites), attaching markers/ tags and releasing larvae (to find out their extent of retention/ dispersion), quantifying physical parameters like winds, tides and currents to relate the possible passive transport of larval biomass and numerical model as a tool for simulating the larval transport processes. Numerical simulations give a synoptic scale information for a larger area on the larval transport of marine organisms, compared to other techniques, which provide point data. Further, numerical models once validated for a region can act as a decision support system. Hence, the present study is carried out using numerical modelling techniques, utilising measured / sampled data.

There is a greater influence of environmental parameters deciding the biology of marine larvae, and it is possible to track the actively swimming juveniles based on their ambient conditions, especially food. Therefore, this thesis examines the influence of ambient food factors in sardine (a major pelagic fish in the western coastal waters of India) larval survival. The aggregation response and inter-annual variability in sardine is explored using satellite-derived chlorophyll. Further, the larval transport of fish and shell-fish in three unique marine ecosystems along the west coast of India is carried out with the help of

numerical modelling. With this background, the objectives of the study are framed as follows:

- (i) to find out the influence of environmental parameters on the biology of the given ecosystem
- (ii) to track larval transport and biological abundance in relation to environmental variables
- (iii) to compare biological abundance and fish larval transport in three different marine ecosystems, namely, the Gulf of Kachchh (a semi-enclosed basin), Mandovi-Zuari (major estuarine system of Goa), and off Mangalore (an open coast with seasonal variability)

Introduction to this thesis describes background of the work, followed by thesis outline, literature review, objectives and scope of the present work and regional oceanography and ecology. The literature review covers the importance of larval phase in marine organisms, methodologies adopted and larval transport (in corals, echinoderms, shell-fish and fish). Data collected and analyzed is described along with a complete description on modelling of hydrodynamics and larval transport. The data includes satellite derived chlorophyll, fish landing and wind, tide and current measurements carried out in the Gulf of Kachchh (GoK), Goa and Mangalore. Numerical simulation includes a description on model domain, grid size, time step and length of simulation, bathymetry, calibration, sensitivity analysis and validation experiments. Validated results are used for describing the larval transport.

The survival, migration and aggregation pattern of Indian oil sardine larvae has been studied using satellite-derived chlorophyll. The biology, migratory pattern of sardine and the importance of satellite chlorophyll in sardine fisheries, relationship of sardine and chlorophyll variability, seasonal appearance of sardine in association with the progressing or receding chlorophyll and the response of chlorophyll during bloom initiation month with the fishery are discussed. Monthly averaged surface phytoplankton biomass has been estimated along the waters of southwest coast of India from the shoreline upto 200 *m* isobath

for ten years (1997-2007) using *SeaWiFS* ocean colour data. This estimation is compared with the biological calendar of Indian oil sardine. The average chlorophyll-a for the bloom initiation month (1998-2006) matches very well with sardine landings. The results imply that the concentration of chlorophyll-a during the bloom initiation month can be used to assess the quantum of fish that recruit into the population. Finer scale spatial variations in the chlorophyll along the coastal waters help in deciphering the migratory pattern of sardines during their active breeding phase. This study shows that 39 % variability in fish landings is related to availability of chlorophyll-a during the bloom initiation month. But, larval abundance in a region depends not only on the biological processes, but also on the physical processes (air-sea interactions and processes driven by tides and currents). In this context, larval transport is modelled in three different regions (Gulf of Kachchh, Goa and off Mangalore) along the west coast of India to explore the significance of physical processes in the larvae abundance. The results reveal different patterns of aggregation response in temporal and spatial scales.

Current pattern/ circulation of an area influences the larval transport processes for passive swimmers, like most of the marine larvae immediately after their spawning. So it is important to have an understanding of the current pattern for studying the larval dispersion processes from spawning sites. In the present study, the focus is on regional oceanographic processes which influence the larval transport of fishes and shell-fishes. For this purpose, a two dimensional hydrodynamic model is used to generate flow pattern of select coastal regions. Simulated currents are validated with measured currents (speed and direction), and the match is very good (correlation coefficient is ≥ 0.84). In the GoK, tidal circulation controls the hydrodynamics. Even though currents along the Goa region (Mandovi-Zuari estuary) and Mangalore coastal waters are tide dominated seasonal winds have a significant role in controlling the hydrodynamics.

Further, larval transport in these different marine ecosystems has been studied utilizing the hydrodynamic model results as input. During numerical simulations, fish and barnacle larvae are defined as particles with a specific mass based on observations and released at specific spawning sites. Lagrangian random-walk technique is used in the model to track the movement of the particles released. For the GoK, six spawning sites have been

identified for larval release based on field surveys and particle trajectory pattern. The model results and field observations indicate a larval aggregation towards the southern Gulf. Experimental trawling in the gulf several years confirms the better abundance of fish in the southern Gulf. In the numerical simulations it is evident that 10-20% of the larval particles released from spawning sites exited from the Gulf along the northern boundary. Thus, the numerical simulations carried out in the GoK reiterates the fact that fish larval abundance is higher in the southern gulf. Therefore, proper demarcation of the nursery areas of fishes based on the model data may be an effective management measure to sustain the local fishery in the Gulf. Similarly, release of fish larvae from the three major spawning areas off Mangalore (Malpe, Mulki and Netravati) indicates aggregation of fish larvae at Mangalore fishing ground. Thus, it could be inferred that better fish abundance in the traditional fishing ground off Mangalore is primarily due to the current pattern which supports larval accumulation. Based on the numerical simulation results it is possible to improve the fishery management measures in the GoK and Mangalore coastal regions.

For the Goa region, distribution and abundance pattern of a bioinvasive barnacle, *Balanus amphiprite* is studied with the help of numerical modelling and observations. For studying the coastal dispersal of barnacle larvae eight spawning sites are selected based on an exploratory survey. The results indicate that the barnacle species is a part of a well mixed population, and there is a seasonal pattern of recruitment in their stock in Mandovi-Zuari estuary from different spawning sites along the coast. The dispersal distances varied from a few kilometers to 78 km stretch in the study domain. Field observations indicate that there is higher abundance of larvae in the estuary during October. The abundance significantly differed between all the three sampling periods (Analysis of Variance (ANOVA) : $p \leq 0.0005$). There was an hourly variation in the larval abundance during May 2007 and October 2007 samplings. Further, the naupliar density increased with the tidal amplitude. Numerical simulations and wind data support these observations as the larvae tend to move into the estuary from open coastal waters with the flood currents. During northeast monsoon season, the mouth of the Mandovi-Zuari estuarine system is more exposed to northeast winds, and hence, a net offshore particle transport has been observed for the larvae at Singuirim and Dona Paula. Major amount of particles has been settled

along the coastal belt south of Bogmalo for the spawning locations southward from Singuirim. The magnitude of southward spread of particles is in the increasing order from Arambol to Galgibagh during pre-monsoon season. However, the quantum of particles reaching the sampling point at Zuari estuary is in the increasing order from spawning locations at Anjuna, Singuirim and Arambol. During the study period it was observed that in the first half of October, there existed southwest winds with low magnitude and in the second half, northeast winds prevailed due to the onset of northeast monsoon. Therefore, in October dispersal of particle occurred northward predominantly in the first half and reversed later in the second half. The numerical simulation data thus indicate that it may be resorted for the management of bioinvasive species like barnacles. In areas like ports and harbours, where ballast water release from vessels also contributes to the larval release, the ideal sites for ballast water release can be effectively managed based on the numerical simulations for the region.

Finally, it could be inferred from the study that ambient environmental parameters and food are major factors for larval survival and transport. This study further indicates that the chlorophyll abundance in the dwelling habitats of sardine at the initiation of their active breeding phase acts like a precursor of their annual biomass. In the case of passive swimmers and fish larvae numerical modelling is an effective tool in explaining the larval transport processes. There are initiatives globally to model the larval transport of marine organisms, and the present study is an attempt in that direction to explore the larval transport processes in the western coastal waters of India. Sparse reports and data sets on early life history stages of the marine organisms is a major lacunae in the study. This emphasizes the importance of generating long term datasets for the larvae of marine organisms in the Indian coastal waters. The future scope for this study is to improve the numerical model by incorporating the biological variables like prey-predation, food abundance and natural mortality. This can be achieved by carrying out the simulations for different regions and comparing them with longer time series data set. Remote Sensing and Geographical Information System (RS-GIS) can be largely used for demarcating potentially rich larval nursery areas based on modelling and observations. This can be a useful decision support system for the managers of fishery. Similarly, the release point of ballast

waters and regulations for controlling the spread of obnoxious species like barnacles can also be identified. This present work suggests the relevance of applying remote-sensing and numerical model data as a surrogate for biological data sets in deriving scientific conclusions for management of marine ecosystems.

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Chapter 1

Introduction

1.1 Background

Fisheries form one of the means of sustenance for the coastal rural population in India [Thomson, 2009]. The major share of fish landing in India comes from the west coast. The nursery areas for fish along the west coast are located in the unique marine ecosystems consisting of coral reefs (*e.g.* the Gulf of Kachchh (GoK)) and mangroves (*e.g.* major estuarine areas). For effective management of these nursery areas along the coast, regulations are enforced in the form of closed areas and seasons [Singh, 1994]. The concept of closed area is followed by creating Marine National Parks and Marine Sanctuaries (*e.g.* GoK) at some ecologically relevant sites consisting of reefs and mangroves. These areas are closed for fishing on the belief that ecologically sensitive areas form nursery for most of the fishes. But, there are conflicting issues with respect to this concept [Singh, 1994]. Demarcating areas of aggregation of fish larvae will be helpful in rightly deciding a closed area. In case of obnoxious species like certain bio-fouling shell-fishes and barnacles, the extent of bio-invasion is relevant in taking management measures near harbour areas, where ballast water forms a means of transport for barnacles. Hence, we need to understand the mechanisms underlined in the fish or shell-fish larval distribution, both spatially and temporally.

There are various physical (driven by winds, tides and currents) and biological processes controlling the fisheries in an ecosystem [Dickey, 1990]. Seasonally changing monsoon is the major physical forcing which controls the biological abundance and fisheries along the west coast of India. There are excellent reports from this region not only on the variability of monsoon winds but also on their oceanographic and biological consequences in relationship to fisheries [Longhurst and Wooster, 1990]. However, these seasonal changes in monsoon, reflecting in the abundance on fish, were not examined as a trophic response to the reproductive cycle of fishes [Madhupratap et al., 1994]. This suspected trophic

link for sardine fisheries forms part of the present study by exploring the remotely sensed chlorophyll as a putative trophic link to explain the survival of sardine larvae, their migration and aggregation pattern.

Fish larvae show variability in their abundance due to factors other than the monsoon driven seasonal trophic conditions. It is possible to model the larval transport and its bionomics through ecological models (hydrodynamics coupled with ecosystem). Various efforts were done in the Indian coastal waters to predict the abundance of fish landings with accuracy so that better management of capture fisheries could be done [Srinath, 1997; Sathianandan, 2002; Grinson George, 2002]. But, this was not sufficient enough to enforce a fishery management measure like closed area or season as these studies reveal only a cyclical trend in the fish landing data. The motivation for the present study is derived from the work of researchers such as Sammarco and Andrews [1988, 1989]; Pineda [2000]; Paris et al. [2005] and Cowen et al. [2006], who worked on numerical-models globally incorporating ambient conditions influencing fish larval transport to demarcate zones of larval aggregation.

Fish larvae are ichthyo-plankton with no or less swimming ability. A proper information on hydrodynamics will improve our understanding of fish larval transport and their aggregation pattern along the coast. There are distinct regions along the west coast of India which show the presence of mangroves and abundance of fish larvae. These include semi-enclosed basins like the GoK and Gulf of Kambhat, estuaries such as Mandovi-Zuari, Netravati, Vembanad and Ashtamudi and dynamic areas where the coastal stretch is least obstructed (for *e.g.* open coast such as Mangalore). Numerical modelling provides an opportunity to reproduce the flow patterns at desired coastal regions and helps to study the fish/shell-fish larval transport during specific periods.

The present study is an effort to explain the mechanism of fish and shell-fish larval transport along the west coast of India (WCI) by coastal oceanographic processes using measurements and modelling. Since larvae remain planktonic during its initial phase of development, simulation and quantification of flow patterns prevailing along the coast for different seasons will apparently elucidate the possible larval spread from major spawning sites. Therefore, the following regions have been selected to study larval transport

through numerical modelling:

- (i) the GoK- a semi enclosed basin off Gujarat coast,
- (ii) the Mandovi-Zuari estuarine system off Goa and
- (iii) the Mangalore-Malpe stretch, an open region off Karnataka coast.

The modelling results were verified using measured and published data available for select locations.

1.2 Literature review

Fish and shell-fish larval transport is a multi-disciplinary subject. Various authors tried to explain the dispersion of larvae in aquatic environment [Cowen et al., 2000] using different tools. They attempted to describe larval transport based on the nature of their study, uniqueness of the area as well as species [Pineda, 2000; Paris et al., 2005; Cowen et al., 2006]. In this review, effort is taken to describe the larval dispersal, the factors influencing their dispersal, the methodologies adopted for describing dispersal pattern and the relevance of bio-physical link between various aquatic species.

1.2.1 Importance of larval phase of marine organisms

The life cycles of most marine organisms include a planktonic larval phase, usually lasting from weeks to months [Brothers et al., 1983; Moser and Boehlert, 1991]. Larval phase is important in marine ecology as marine invertebrates and fishes have a life cycle involving a demersal/nektonic adult and a Pelagic Larval Duration (PLD) phase or pelagic eggs which could be transported to long distances [Grosberg and Levitan, 1992]. There are four major reasons suggested for this PLD phase [Swearer et al., 2002]:

- (i) A long PLD phase can help a species to break its parasite cycles: Larvae of some species metamorphose in response to chemical cues associated with a particular

hostile species [Hadfield and Scheuer, 1985; Lambert et al., 1997]. In the absence of specific environmental cues, larvae postpone their metamorphosis and prolong larval life [Pechenik, 1990; Morgan, 1995].

- (ii) Pelagic larvae avoid predators: Lengthy PLD phase and low probability of successful recruitment leads to larval release in huge numbers so that the chances increase for the survival of at least one larva [Thorson, 1950; Roughgarden et al., 1985; Caley et al., 1996]. However, studies on larval behaviour and ecology show that this is not true always [Kingsford et al., 2002]. Larvae are small in size and plentiful, and many animals take advantage of this food source. Some larvae have direct defense like large spines and other protective structures [Morgan, 1989]. Some larvae avoid predators by simply sinking when they are approached by a predator and certain larvae are nocturnal undertaking diel vertical migrations, as most larvivorous fishes are visual predators and need light to hunt. Marine larvae (and other zooplankton) can significantly decrease their risk of predation by withdrawing to areas of low light during the day [Zaret and Suffern, 1976]. In reverse tidal vertical migrations, larvae use the tidal cycle and coastal flow pattern to aid their departure to the ocean [Cronin and Forward-Jr., 1979; Tankersley and Forward-Jr., 1994; Zeng and Naylor, 1996; Di-Bacco et al., 2001].
- (iii) Larvae have the potential to disperse long distances, invade new area, and move away from congested or incompatible location: Sluggish demersal marine organisms like barnacles, tunicates, mussels and crabs need some mechanism to shift their juveniles into new territory since they cannot traverse long distances as adults. These species have relatively long PLD phase of the order of weeks or months [Brothers et al., 1983]. During the PLD phase, larvae feed, grow and undergo stages of development. Some larvae are able to delay their final metamorphosis for a few days or weeks and some species cannot delay it [Gebauer et al., 2004]. If these larvae metamorphose too far from a suitable settlement site, they perish. Such species exhibit swimming rhythms of reverse tidal vertical migration to aid in their transport away from their hatching site, the same species can exhibit tidal vertical migrations to re-enter the estuary when they metamorphose and are competent to settle

[Christy and Morgan, 1998]. Many larvae become more tactile, clinging to larger objects than themselves. These objects along with the larvae can be transported towards shore due to oceanographic forces such as internal waves, which carry the floating debris shoreward regardless of the prevailing currents [Alan, 1985]. If they are able to successfully return to shore, settlers encounter a new suite of problems concerning their actual settlement and successful recruitment into the population. Space is a limiting factor for sessile invertebrates on rocky shores, and larvae might not find any open habitat. Additionally, settlers must be wary of adult filter feeders, which usually cover the rocks at settlement sites and eat particles similar to the size of larvae. Settlers must also avoid becoming stranded out of water by waves, and must select a settlement site at the proper tidal height to prevent desiccation and avoid competition and predation. To overcome many of these difficulties, some species rely on chemical cues to assist them in selecting an appropriate settlement site. These cues are usually emitted by adult conspecifics, but some species cue on specific bacterial mats or other qualities of the substrate [Crisp and Meadows, 1962; Pawlik, 1986].

- (iv) Dissimilar food source of larvae may decrease competition between adults: Fish larvae are characterized by digestive systems and diets that differ from adults [Govoni et al., 1986]. Most barnacles molt through six naupliar stages before molting to a ciprid, the stage at which they seek an appropriate settlement substrate. This allows the larvae to use different food resources than the adults and gives them time to disperse.

1.2.2 Methodologies adopted to explain larval transport

While reviewing the literature, it was observed that researchers have used several techniques to resolve the larval transport processes. These observations helped in broadly categorizing these approaches into five methodologies, and these are described below:

- (i) Field surveys to determine the pattern and extent of larval transport: Larval fish composition and abundance were determined based on field sampling at different

parts of the world like Eastern Australia [Smith and Suthers, 1999], the Agulhas Current off South Africa [Beckley and Ballegooyen, 1992], the Western Irish Sea [Dickey-Collas et al., 1996], the English Channel [Giroche et al., 1999], southwestern Africa [Oliver and Shelton, 1993], Peru [Velez et al., 2005], California Current [Loeb et al., 1983] and Canary Islands [Rodriguez et al., 2004]. Fish larval samples from International Indian Ocean Expedition (IIOE) [Peter, 1967] form the major larval data set for the Indian Ocean region.

- (ii) Biotechnological approach to determine larval transport: The production of monoclonal antibodies for use as probes in the identification of northern Australian crown-of-thorns starfish (*Acanthaster planci*) and commercial prawn larvae [Feller, 1986; Hanna et al., 1994] is a manner in which biotechnological applications also made a foray into larval transport. A major difficulty experienced in marine ecological studies is an inability to distinguish between species at early larval stages, especially among crustacean and soft-bodied in-vertebrate larvae. The larvae of penaeid prawns and crown-of-thorns starfish are no exception, and as a consequence, studies of larval dispersion and recruitment into adult populations are difficult. An approach to this problem has been to produce monoclonal antibodies against preserved specimens of particular species and then select, through screening a range of different larvae, those that show species-specificity.
- (iii) Marker assisted sampling design: Twenty-four fishes fitted with 300 *k.Hz* transponding acoustic tags were tracked by sector-scanning sonar in the southern North Sea for periods up to 52 *h* and over distances up to 72 *km* [Arnold et al., 1994]. Jones et al. [1999] and Swearer et al. [1999] found that a proportion of reef fish larvae was returning to their natal reef, after their maturation in the water column, with the help of markers. They found higher than expected (approximately 60%) self-recruitment in these populations, using variations of a typical mark, release, recapture sampling design. These studies were the first to provide conclusive evidence of self-recruitment in a species with the potential to disperse far from its natal site, and laid the groundwork for numerous future studies [Levin, 2006].

- (iv) Larval transport as a manifestation of bio-physical processes: Different physical oceanographic processes influence the distribution of larval fish on a variety of scales, ranging from a few meters to thousands of kilometres, therefore, larval distribution is likely to be determined by their interaction with a number of concurrent features [Bruce et al., 2001; Hare et al., 2002]. The physical process relevant to the mixing and dispersion of marine organisms was explored with emphasis to the role of diffusion and related physical processes in dispersal and recruitment of marine populations [A.Okubo, 1994]. These processes include advection and diffusion occurring over a broad range of temporal and spatial scales of oceanic motion. Diffusion in the sea has customarily been treated as a stochastic process; but a chaos-induced or deterministic, diffusion, is necessary in order to improve our understanding of larval dispersal and recruitment. Tidal flows can move larvae passively in peak tidal velocities [Levin, 1990; Gross et al., 1992]. As the relevance of oceanographic features in explaining larval transport has been realised, numerous studies on these topics have been conducted, covering most of the world's coastal waters [Moser and Smith, 1993; Oliver and Shelton, 1993; Grothues and Cowen, 1999; Hare et al., 2001]. Physical processes not only affect the magnitude of the plankton biomass, but also the species composition [Huntsman et al., 1981], which may in turn affect larval fish feeding and survival [Lasker, 1975; Simpson, 1987].
- (v) Numerical modelling as a tool to explain larval transport processes: Globally, various researchers have utilized different bio-physical numerical models to study the hydrodynamic pattern and further, the larval transport process. Numerical simulations give a synoptic scale data on the larval transport of marine organisms. Numerical experiments could be easily altered/ repeated for different scenarios by changing the variables acting on the larval transport, unlike other methods mentioned earlier. Other techniques could be a supporting tool in the quest for larval transport, providing point data. Further, numerical models once validated for a region can act as a decision support system. It works out to be a feasible option providing quick results without affecting the quality and level of interpretation.

The following subsection (1.2.3) describes in detail some of the major larval trans-

port studies carried out globally using numerical models for different marine organisms.

1.2.3 Global studies on larval transport scenarios

This section illustrates larval transport of corals, echinoderms, shell fish and fish primarily through modelling.

(i) Corals-fertilization and dispersal pattern

Larval dispersal and recruitment processes in corals [Heyward and Negri, 2006], their analysis and synthesis [Sammarco, 1991] were done for Scleractinian corals, which reproduce via external fertilization and exhibit broader recruitment patterns than their brooding counterparts. Numerical simulations of coral dispersal [Galindo et al., 2006] have shown that particles occurring in different layers in shallow water produce different dispersal patterns. Normal trade winds in the central Great Barrier Reef region (15 *knots*) produce a wide dispersal pattern in eggs and larvae associated with the surface layer [Sammarco, 1991]. Coral recruits on a reef may be derived from both the near and far fields. Most recruits recorded in a large-scale experiment on the Great Barrier Reef (The Helix Experiment) [Sammarco and Andrews, 1988, 1989], were derived from the natal reef. The effects of recruitment strategies on coral larvae settlement distribution at Helix reef was also studied [Andrews and Gay, 1988]. A review on physical oceanographic aspects of the dispersal of coral spawn slicks [Pattiaratchi, 1994] reveals that the annual spawning of corals is limited to a brief period in which enormous quantities of eggs and larvae are injected into the reef systems. There are several factors affecting larval dispersion which is reported in a case study carried out in the central Great Barrier Reef [Parslow and Gabric, 1989].

(ii) Echinoderms with special emphasis on crown-of-thorns starfish

Black [1993] has studied dispersal on the Great Barrier Reef through multidisciplinary approach. Investigations of the dispersal of crown-of-thorns starfish (*Acan-*

thaster planci) larvae have provided new insights into the dynamics of larval dispersal of Australia's Barrier Reef. Further, physical aspects of large-scale dispersal in the crown-of-thorns starfish *Acanthaster planci* [Dight et al., 1990] got into an in-depth analysis with numerical models.

(iii) Shell-fish dispersal

Various processes control the larval dispersal and post larval recruitment of penaeid prawns [Rothlisberg et al., 1983]. In the shallow Gulf of Carpentaria, tidal currents combine with the larval vertical migration to advect *Penaeus merguensis* larvae up to 160 km over a 20 days period. Changes in tidal phase with respect to constant diurnal larval behaviour result in seasonal changes in advance direction, which are consistent with the observed spatial and seasonal recruitment patterns. In contrast tidal currents are not responsible for appreciable across-shelf advection of *P. plebejus* larvae on the open shelf of southeastern Australia. Similarly, transport processes affecting banana prawn post larvae in the estuaries of the Gulf of Carpentaria were explored [Heron et al., 1994]. Miyake et al. [2009] used a coupled particle-tracking and hydrodynamic model to simulate larval dispersal of large abalone *Haliotis discus discus*, *H. gigantea*, *H. madaka* in Sagami Bay, Japan. In the case of barnacles, large-scale offshore oceanographic processes operate first over higher abundances than the small scale nearshore processes that operate last over fewer individuals [Pineda, 1994, 2000]. In the present study, an attempt has been made to investigate the relevance of coastal processes in the distribution of barnacle larvae in the coastal waters off Goa.

(iv) Fish larval transport

Dispersal and advection of *Macruronus novaezealandiae* (*Gadiformes: Merlucciidae*) larvae off Tasmania with simulation of the effects of physical forcing on larval distribution was studied [Lyne and Thresher, 1994]. The hypothesis that passive drift alone of *Macruronus novaezealandiae* is sufficient to account for its distribution off the Tasmanian coast is tested with a Lagrangian model of larval drift. Dispersal of the larval stage of southern blue fin tuna *Thunnus maccoyii* in the East

Indian Ocean [Davis et al., 1991] is significant in the recruitment of fishery. Numerical modelling of fish eggs dispersion at the Patos Lagoon estuary in Brazil utilized a two dimensional hydrodynamic model-SIMSYS2D and a Lagrangian particle tracking model [Martins et al., 2007]. Since wind fields are influential in the strength and position of oceanographic features, climatic cycles like *El Nino* also influence larval fish transport and survival [Tsai et al., 1997; Cubillos and Arcos, 2002]. Fish larval transport is affected by a variety of physical and biological factors, operating over a wide range of temporal and spatial scales. However, the domain at which larval fish transport are studied will affect the processes that are ultimately deemed to be relevant. Potentially influential physical and biological factors may vary in time as well as space, therefore recent meteorological and oceanographic events, as well as regional seasonal and climatic cycles may also be significant.

1.3 Scope and limitation of larval transport studies in the Indian coastal waters

Successful fisheries management relies heavily on understanding population connectivity and dispersal distances, and these processes are driven by larvae. Dispersal and connectivity must also be considered when designing natural reserves, both on land and in the water; if populations are not self-recruiting, then solitary reserves may lose their species assemblages. Additionally, many invasive species are able to disperse long distances during an early life stage, such as seeds in land plants or larvae in marine invasives. Understanding the factors influencing their dispersal is the key to control their spread and managing pre-established populations. Through the continued study of the ecology of these microscopic creatures, we can understand better and manage more effectively the myriad populations in the sea. No attempt is made so far for studying larval transport of marine population in the coastal waters of India. The limitation for such study is the lack of continuous larval data set to compare with the model output.

1.4 Objectives of the present work

The present task is to study the fish larval transport along the WCI through ecological modelling. The influence of ambient food factors in fish larval survival and their aggregation response is explored using satellite chlorophyll for studying the interannual variability in sardine landing. A proper understanding of physical, biological and chemical processes in the region will help in studying larval transport along the coast. Taking into account of all these factors, the objectives of the study are framed as follows:

- (i) to find out the influence of environmental parameters on the biology of the given ecosystem
- (ii) to track larval transport and biological abundance in relation to environmental variables
- (iii) to compare biological abundance and fish larval transport in three different marine ecosystems namely, the GoK (a semi-enclosed basin), Mandovi-Zuari (estuarine system of Goa), and Mangalore coastal region (an open coast with seasonal variability).

1.5 Study area

The study area lies along the WCI. The WCI comprises of the continental shelf of western India (5 to $25^{\circ}N$) which widens from south to north, reaching about 300 km between $18^{\circ}N$ and $25^{\circ}N$. The shelf break on this coast is approximately along the 200 m depth contour [Chandramohan et al., 1993; Shetye et al., 1991].

1.5.1 Regional oceanography

The currents along the WCI are primarily driven by semi-diurnal tides and seasonal wind systems prevailing over the region. Regional circulation responds both to local and remotely forced effects of the southwest (SW) and northeast (NE) monsoon winds. Onset

of the SW monsoon occurs first in the south Indian Ocean in May or June, then spreads northward, and continues till October. From November to May, the coast is influenced by lighter, drier NE winds and some cooling and mixing of shelf water occurs. During this season, the cyclonic circulation of the Arabian Sea causes downwelling of isopleths near the coast. Sea breeze is also prevalent along the westcoast of India during this season. Coastal currents respond to local wind forcing with equatorward flow along the coast from February to September/ October and poleward during the rest of the year [Longhurst, 1998]. Broadly four seasons are prevalent in the region:

- (i) pre monsoon from March to May
- (ii) SW monsoon from June to September
- (iii) post monsoon during October
- (iv) NE monsoon from November to February

1.5.2 Regional ecology

Upwelling along the coastal waters is pronounced in the regional biological response of the waters. Nutrient levels are low during pre-upwelling period. The mixed layer is thin and subsurface low oxygen water starts to appear on the shelf. When Ekman upwelling begins the nutrient levels increase, the mixed layer becomes even thinner, and very low oxygen concentrations ($\leq 0.5 \text{ ml.l}^{-1}$) characterize shelf waters below the thermocline. The upwelling period is reflected with heavy algal blooms ($8.0 \text{ mg.chl.m}^{-3}$) in response to the nutrient advection in the upwelled water and remineralization of nutrients locked in the mobile mudbanks. Blooms result in low water clarity (chlorophyll maximum $\leq 5 \text{ m}$; water column chlorophyll $\leq 200 \text{ mg.m}^{-3}$; Secchi disc, 2 or 3 m) with diatom cells at high concentrations of $< 2.9 \times 10^5 \text{ cells.l}^{-1}$ [Shah, 1973]. Areas with strong seasonal diatom blooms may support a pelagic clupeid fish which depends almost entirely on medium to large diatoms for food, obtained by active filtration on gill-rakers: for example, *Brevoortia* in the western Atlantic, *Ethmalosa* in the eastern Atlantic, and *Sardinella longiceps* of the Indian Ocean [Longhurst, 1998].

The abundant Indian oil sardine along the WCI (Figure 1.1) have strong interannual variability and their arrival and departure along the coastal waters coincides with the upwelling bloom [Grinson George et al., 2011]. The putative trophic link of sardine interannual variability is explored as a manifestation of the productivity of the planktonic ecosystem using remote sensing. This is discussed in Chapter 3, in which time series remotely-sensed chlorophyll data representing the food is compared with the biology, migration and landing of sardine.

The entire sardine fishing ground off the southwest coast of India, extending from $5^{\circ}N$ to $15^{\circ}N$ was considered for the study. The seaward limit of the study area extends upto the outward edge of the continental shelf (200 *m* isobaths) (Figure 1.1). Figure 1.1 explains the schematic representation of sardine movement, but the actual dwelling area of sardines is segregated in the satellite image by following the depth contour. The spatial extent of the study area was determined in concurrence with earlier observations [Longhurst and Wooster, 1990]. Characteristics of the coastal currents and environmental setting described in the earlier study [Dineshkumar and Srinivas, 2007] also define this study area as a narrow continental shelf domain with strong upwelling and downwelling signatures. For imbibing specialised features to compare biological abundance and larval transport in different marine ecosystems three unique domains were selected for the study as mentioned earlier:

- (a) Gulf of Kachchh: The GoK is located on the northwest coast of India, between $22^{\circ}15'N$ - $23^{\circ}00'N$ and $69^{\circ}00'E$ - $70^{\circ}15'E$ (Figure 1.2) and is approximately 170 *km* long and 75 *km* wide at the mouth. Tidal range varies from 3 *m* at the mouth to 7 *m* in the upstream and tidal currents reach upto 2 m.s^{-1} . The collective contribution of fish production in the GoK during 2007-08 was 18.80% to the total production of Gujarat State. The northern GoK, which is predominantly sandy or muddy and confronted by shoals and creeks, also has large stretches of mangroves. The southern GoK has numerous islands and inlets that has vast areas of mangroves and reefs with living corals. The southern GoK is a productive spawning ground for fishes with mangroves, coral reefs, sea grass, sea weeds and many species of red, green and brown algae. A variety of marine wealth that exists in the

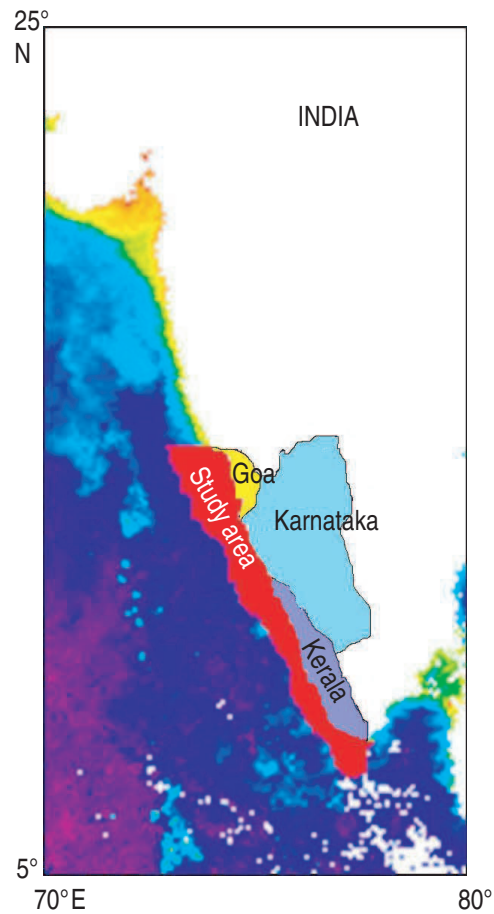


Figure 1.1: Study area of occurrence of Indian oil sardine

GoK includes algae, mangroves, corals, sponges, molluscs, prawns, fishes, reptiles, birds and mammals. In order to protect the rich biodiversity of GoK, several long stretches of intertidal mudflats and coral reefs along its southern GoK are Marine National Park and Marine Sanctuary (Figure 1.3). A variety of exposed and sheltered sites are present in the GoK and previous studies show the existence of three distinct eddies with diameters varying between 10 and 20 *km* in the western half of the GoK [Desa et al., 2002; Vethamony et al., 2004; Babu et al., 2005; Kankara et al., 2007]. The high tidal influx covers vast low lying areas of about 1500 *km*², comprising of creeks, marshy tidal flats and rocky regions which provide congenial

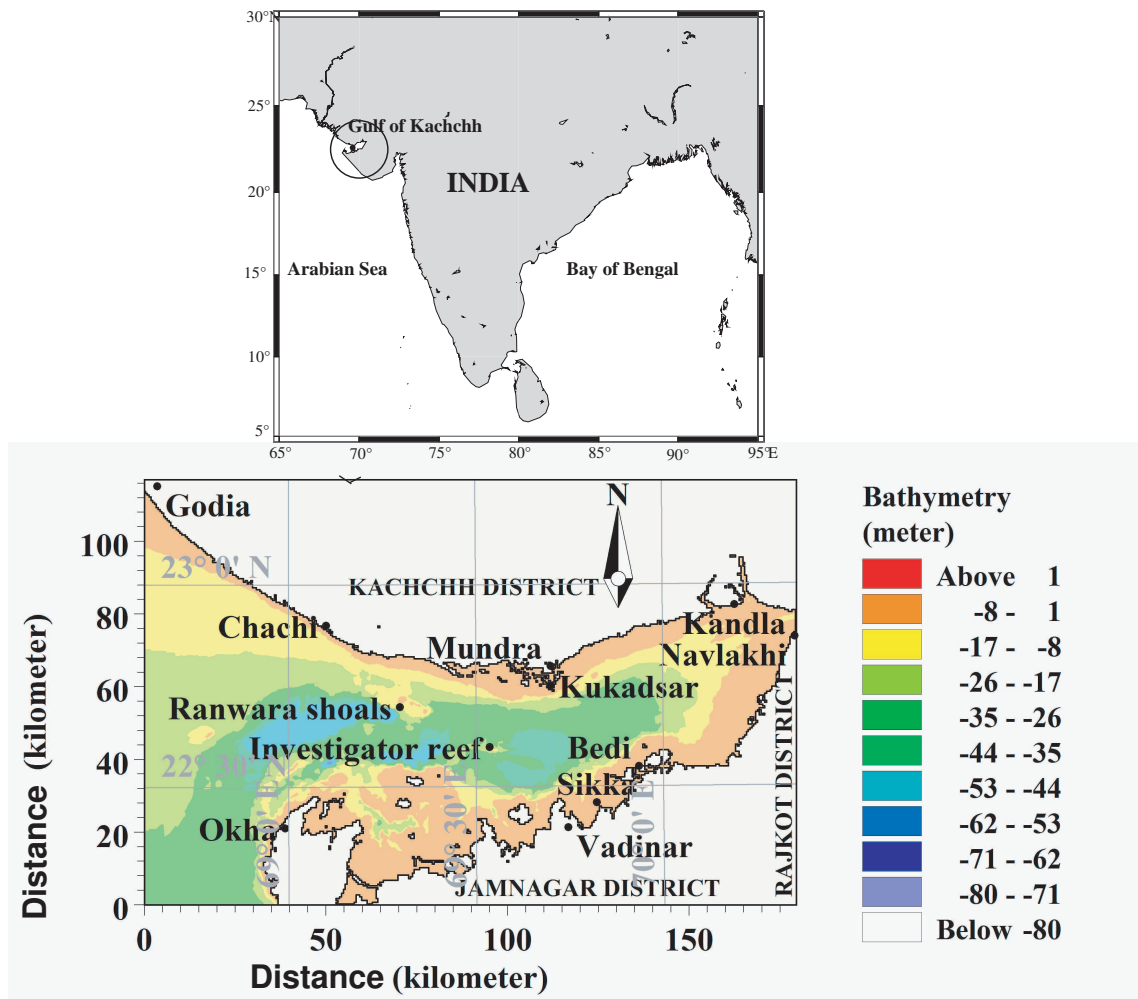


Figure 1.2: GoK and its topographic features with relevant study sites

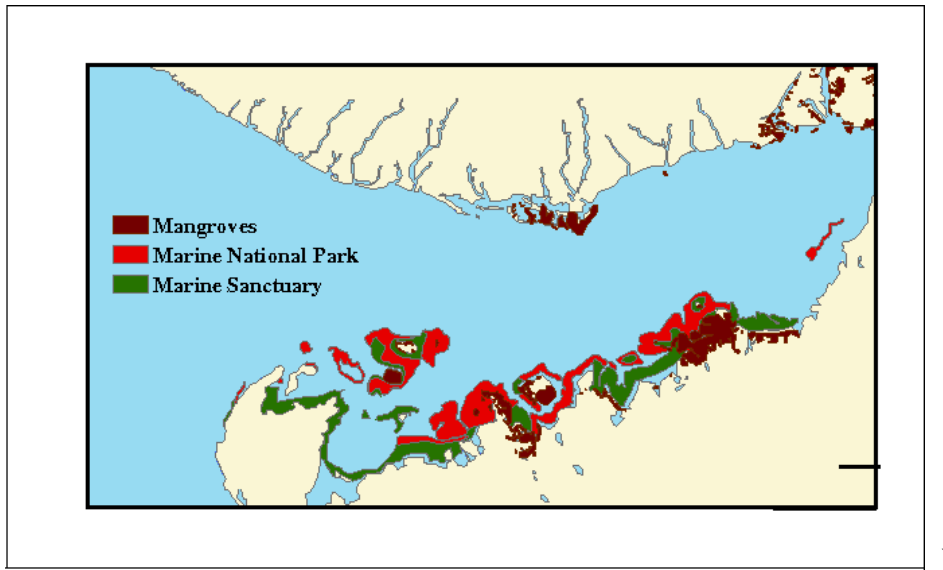


Figure 1.3: Distribution of ecologically sensitive areas along the GoK (reconstructed from Desa et al. [2002])

environment to a wide variety of marine biota.

No study has been carried out so far in the coastal waters of India to determine the influence of physical forcing on fish larvae under which they are widely dispersed or locally retained. We want to assess whether the abundant fish population in the GoK is a manifestation of self recruitment by fishes trapped due to hydrodynamics of the region or geographical barrier. We have released fish eggs as inert conservative particles from their representative spawning sites under a range of hydrodynamic conditions and associated dispersion processes, unique to the GoK to simulate the spreading of eggs and transport of larvae.

- (b) Goa coastal region: Goa is located along the central west coast of India, between the latitudes $14^{\circ}53'54''N$ and $15^{\circ}40'00''N$ and longitudes $73^{\circ}40'33''E$ and $74^{\circ}20'13''E$. It is flanked by the Arabian Sea with a coastline of 103 km. Mandovi and Zuari, the two major rivers in Goa, form their estuary which is typically a well mixed water body with an average depth of 5 m at the mouth. Throughout the course of these rivers an intricate system of wetlands, tidal marshes and cultivated paddy lands are

found which are interconnected by canals, inland water bodies and creeks governed by regular tides. A luxuriant growth of mangroves is found bordering the estuaries thereby, playing a major role in protecting the coast. There are rocky shores and tidal pools in between these sandy stretches which are relevant in the life cycle of many shell fishes. The specific study region (Dona Paula bay, Zuari estuary $15^{\circ}26'18.44''N$ and $73^{\circ}47'53.9''E$) is shown in Figure 1.4. Rocky shores at Arambol, Anjuna, Singuirim, Dona Paula, Mormugao, Bogmalo, Palolem and Galgibagh are the locations chosen for the model study in the Goa coastal region .

The coastal areas surrounding the Mandovi-Zuari estuarine system are areas of active fishing, practically throughout the year. The quantity of freshwater discharge in Zuari during pre and post monsoon period is negligible (about $0.03 \text{ km}^3 \cdot \text{year}^{-1}$) and therefore, their flow during these seasons is regulated by semi-diurnal tides. Similarly, in Mandovi also, the freshwater discharge during pre and post monsoon period is negligible (about $0.06 \text{ km}^3 \cdot \text{year}^{-1}$). The estuarine system turned out to be an ideal habitat for the barnacle, *Balanus amphitrite*, an important component of the intertidal community, and also of the marine macrofouling community. The cosmopolitan distribution of this organism along the waters off Goa made it an interesting feature to be studied. A coupled two dimensional hydrodynamic and particle tracking model is used to estimate dispersion and retention of barnacle larvae from their possible spawning sites. This is attempted using an Eulerian hydrodynamic model as well as a Lagrangian particle analysis model to simulate the barnacle larval transport. Larvae were released as inert conservative particles from their representative spawning sites under a range of hydrodynamic conditions, unique to the estuary to simulate spreading and weathering of larvae under the influence of prevailing flow and associated processes. An effort is made to validate the modelled larval dispersion using field data. This case-study identifies suitable time and location for larval dispersal and settlement, and accordingly, the maximum and minimum distance the larvae can disperse in different seasons has been calculated.

- (c) Mangalore coastal region: This coastal stretch is located along the SW coast of India, between the latitudes $12^{\circ}48'00''N$ and $13^{\circ}21'00''N$ and longitudes $74^{\circ}36'00''E$

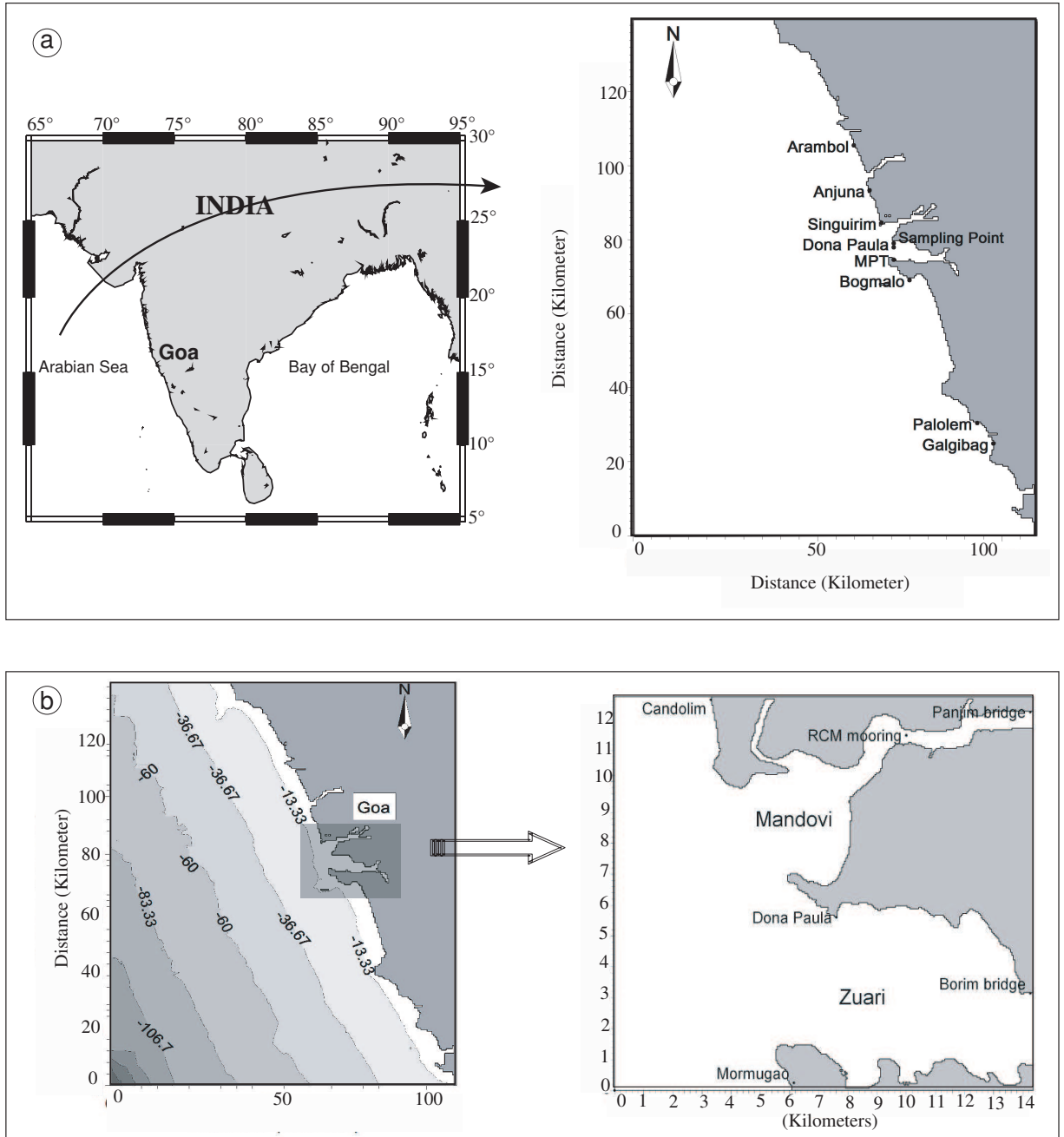


Figure 1.4: Goa study region with (a) large domain and (b) small domain

and $74^{\circ}55'00''E$ (Figure 1.5). This dynamic coastal stretch with a well defined Malabar upwelling zone is characterized by diverse fishing and industrial activities. Surveys indicate a clear presence of fishing ground in this region. This region is very dynamic with tidal currents and seasonal wind driven current systems. The river runoff is maximum during the SW monsoon season. The seasonal heavy precipitation is carried into the Arabian Sea through numerous streams and rivers in addition to the land run off. Major river in the study area is Netravati, which contributes to the coastal waters with considerable amount of nutrients and organic matter. These characteristics are likely to influence the fishery potential in the region. The region off Mulki in the coastal waters off Karnataka is an important area with high fishing activity. Therefore, off Mangalore forms an ideal location for studying the larval transport and dispersion of fish larvae.

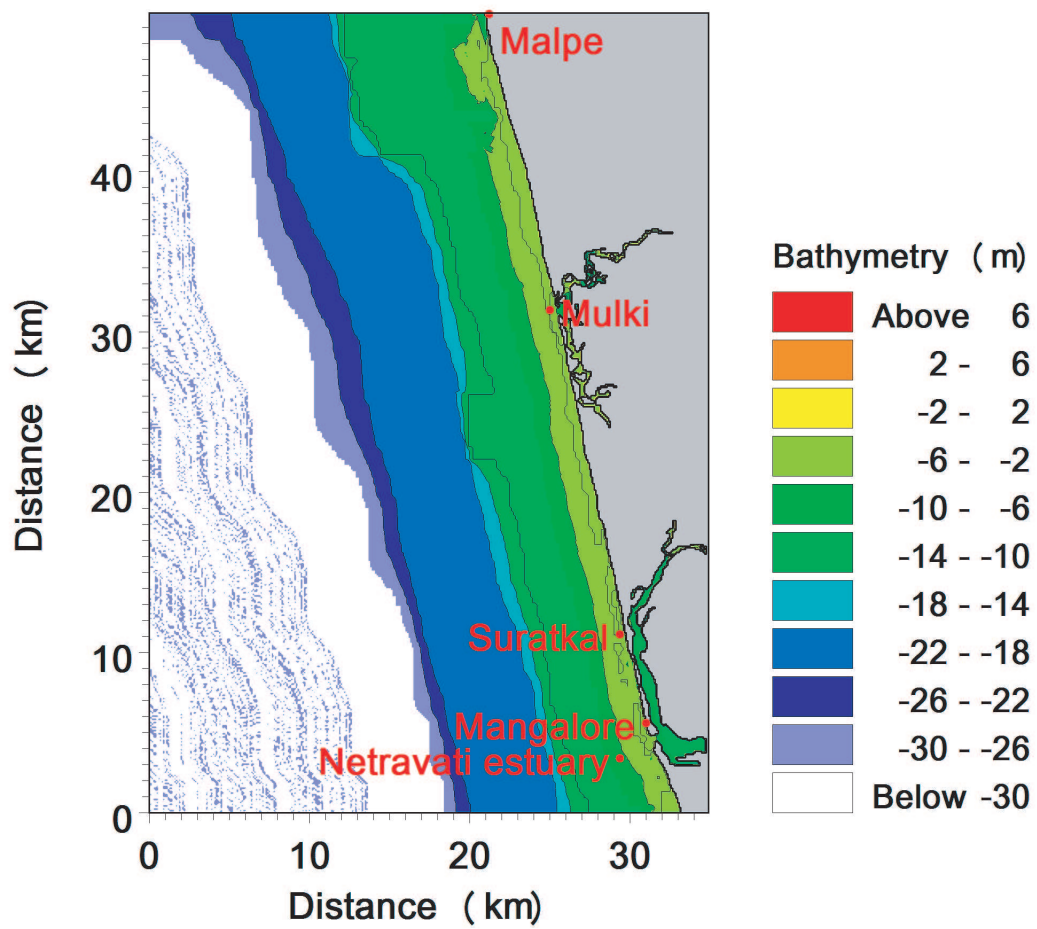


Figure 1.5: Mangalore study region with relevant study sites