

Chapter 2

Data and methodology

2.1 Remote sensing data and statistical analysis

Monthly averaged chlorophyll maps at 9 *km* spatial resolution derived from *Sea-viewing Wide Field of view Sensor (SeaWiFS)* satellite data for the period January 1998 to December 2006 was downloaded from the website of NASA ocean colour (<http://oceancolor.gsfc.nasa.gov/cgi/l3>) [Oceancolour, 2010]. The optically sensitive constituents such as suspended solids and yellow substance in *Case-2* waters in this region [Menon et al., 2005, 2006] often give undesirable chlorophyll values. This issue was solved during extraction of chlorophyll-a from the composite image using an algorithm for masking turbid waters [Bricaud and Morel, 1987]. A trend between sardine landing and chlorophyll-a has been found using the polynomial trend line, which gave the best fit. Coefficient of determinant was worked out for quantifying the variability in sardine landings and chlorophyll-a during the bloom initiation month.

2.2 Fish landing data

Data on marine fish landings in India for the period 1985-2006 published by the Central Marine Fisheries Research Institute [Srinath et al., 1969] have been used. We collected 316 samples of sardines from the major sardine landing centre at Cochin for length and weight measurements. Sardine catch is dominated by 0-group individuals, *viz.*, measuring ≤ 14 *cm* total length [Pauline and Jakob, 1986], spawned during the earlier spawning period starting from May (Table 2.1). The entire breeding activity of sardines is confined to coastal waters with an active artisanal fishery comprising of motorized and non-motorized crafts with operating gears such as ring, purse and shore seines. This artisanal fishery responds with vital fishing efforts depending on the fish availability. Mechanized trawlers in the coastal waters are restricted to a period of 45 days, starting from 15 June. De-

crease in sardine fishery within the study area did not result in heavy landings elsewhere, thus ruling out the possibility of migration of sardines from the study area. Hence, it is assumed that the sardine landings within the study area are representative of stock abundance [Longhurst and Wooster, 1990]. This assumption holds good since the present study is restricted to a time period, when there was relatively little change in the composition of fishing crafts and gears [Grinson George et al., 2011].

Table 2.1 Average length and weight measurements of 316 random sardine samples from a major landing centre

Total Length (cm)	Fork Length (cm)	Std Length (cm)	Gill Girth (cm)	Mouth Diameter (cm)	Weight (gm)
11.64±2.57	10.24±2.28	9.64±2.15	1.77±0.49	0.88±0.39	12.58±10.96

2.3 Field measurements

Measured data on tides, currents, meteorological and biological parameters are used for calibration of the model and validation of model results. Tides and currents were measured by Water Level Recorder (WLR) and mooring Recording Current Meters (RCM), respectively. Data on meteorological parameters have been collected by installing Autonomous Weather Station (AWS) at different coastal locations. The field data collected by the National Institute of Oceanography (NIO) for some of the major programmes formed the biological data set. The details of data (primary and secondary) collected for each study area are described below:

2.3.1 Gulf of Kachchh

NIO has been conducting general as well as site-specific studies in the GoK since 1981 as a part of several ongoing developments bordering the Gulf, particularly along the southern coast. The site-specific studies conducted by NIO from time to time have resulted in an extensive database for the concerned segments of the GoK. Various studies on coastal waters of the GoK often reveal significant seasonal changes in its ecology. The study region experiences three distinct seasons: pre monsoon, SW monsoon and NE monsoon. However, field observations are limited during SW monsoon due to rough sea conditions. Data compiled from various segments of the GoK includes off Okha, Salaya, Vadinar, Sikka, Bedi, Navlakhi, Kandla and Mundra (Figure 1.1).

Field measurements carried out in the GoK under the project "Integrated Coastal and Marine Area Management (ICMAM) plan for the Gulf of Kachchh" by NIO [Kankara et al., 2007] and the data in the report "Status of flora and fauna of Gulf of Kachchh" prepared by Vijayalakshmi [2002] are useful in addition to the data received from the NIO Data Centre. The data on the biota of the GoK has been prepared based on secondary data scattered over a wide array of technical reports, scientific reports and published papers. Among the scientific reports from sources other than NIO, the reports from Gujarat Ecological Society are significant as these are bench mark surveys consolidating the available data on geomorphology, marine ecology and threats, socioeconomic profile, agriculture, environmental problems etc. of the GoK [Gupta and Deshmukh, 1999; Gupta et al., 1999]. Issues and problems involved in managing protected areas and a detailed management plan for the Marine National Park and Sanctuary were reported by Singh [1994].

During the ICMAM programme, six sites, A, B, C, D, E and F representing mouth, mid and head of the GoK in the northern and southern boundaries of the GoK were surveyed for fish egg abundance to identify spawning sites (sites marked in Figure 5.3). Egg samples were collected using a 200 $\mu.m$ mesh size net attached with a pre-calibrated TS flow meter to determine the volume of water filtered. After each (surface-horizontal) haul, the samples were fixed in 5% buffered formaldehyde solution. In the laboratory, an aliquot with a volume of minimum 5 ml was analysed for enumeration of groups. When the total

quantity of egg sample was more than 5 *ml*, it was sub-sampled (Folsom plankton splitter) and only a fraction was counted. The samples were transferred to a counting chamber (petridish provided with a grid of 1 *cm*²) for numerically counting the eggs.

Three prominent seasons namely, pre monsoon, SW monsoon and NE monsoon are prevalent in the GoK [Babu et al., 2005]. Hence, recording current meter (model: RCM7; make: Aanderaa, Norway) data measured off Okha, mid-central Gulf and off Kukadsar during April 2002 and November 2002, representing pre monsoon and NE monsoon seasons respectively, were used for model validation. The current speed and direction was resolved into *u*-velocity and *v*-velocity components representing currents in the east-west direction (east is considered as positive and west is negative) and north-south direction (north is considered as positive and south is negative), respectively.

Secondary data on fisheries of the GoK were collected from the Department of Fisheries, Gujarat. Trawl catch composition data were collected from the NIO Data Centre.

2.3.2 Goa

The simulated water levels and current velocities have been validated with predicted water levels and measured currents off Captain of Ports (COP), Panaji (location is marked in Figure 1.4). Currents were measured for every 10 minutes interval using Recording Current Meter (model: RCM7; make: Aanderaa, Norway) during 14 November to 10 December 2007. The current speed and direction was resolved into *u*-velocity and *v*-velocity components. The validated model has been used to simulate flow patterns for the entire model domain for the periods May 2007, October 2007 and December 2006.

The spawning sites for larval release were selected on the basis of an exploratory survey conducted in the study site. The spawning sites were Vengurla, Arambol, Anjuna, Singuirim, Dona Paula, Mormugao Port, Bogmalo and Galgibagh from north to south. The spawning sites were selected based on visual observations on the occurrence of barnacles in the rocky habitat. This rocky intertidal habitat is immersed on hourly basis for a period of 24 hours during 3 different sampling periods (December 2006, May 2007 and October 2007, representing the three different seasons. Samples were collected with the

help of Haron-Trantor net of mesh size $100 \mu m$. The net was towed horizontally with the help of a boat for about 10 minutes. The volume of water filtered was calculated using the number of revolutions obtained with a flow meter. The samples were preserved in 5% formaldehyde, and later sorted and counted under dissection microscope to determine their abundance.

2.3.3 Mangalore

The simulated water levels and current velocities have been validated with predicted water levels and measured currents at Suratkal and Mulki. Currents measured for every 10 minutes interval using Recording Current Meter during 14 November to 10 December 2007 are used for model validation. The current measurement location is marked in Figure 1.4. The current speed and direction was resolved into u -velocity and v -velocity components. The validated model has been used to simulate flow patterns for the study area.

Fish egg and larval studies carried out for assessing fishery, fish spawning grounds and ichthyoplankton studies in the coastal waters off Mangalore have been compiled [Verlecar et al., 1998] from the NIO Data Centre and used for interpreting the model results in the Mangalore region. In order to understand the distribution pattern of fish eggs and larvae, samples were taken from the coastal waters off Mangalore fishing harbour every month during September 1997 to May 1998 and in October 1998 by:

- (i) Vertical hauls by Hansen egg net (mesh size $60 \mu m$)
- (ii) Horizontal haul
- (iii) Oblique haul by Heron Tranter (HT) net (mouth area $0.25 m^2$; mesh size $330 \mu m$).

Zooplankton samples were collected by horizontal, oblique and vertical hauls using a HT in the coastal waters off Mangalore. The sampling was done at 3 water depths in the $5 m$, $10 m$ and $15 m$ depth contours. A calibrated flow meter was attached to the mouth of the net to record the volume of seawater filtered through the net.

For horizontal and oblique hauls, the net was towed for 10 minutes duration. The vertical hauls were made by lowering the net near to the bottom at each station and hauling it up slowly to the surface. All the samples were preserved onboard in 5% formaldehyde. The zooplankton samples were analysed for estimation of spatial and temporal variations in standing stock (biomass), distribution and abundance of different groups and their common species. The biomass was estimated by the displacement volume method and expressed as 100 ml.m^{-3} . The sub-samples or aliquots were taken by Folsom Plankton Splitter and examined under the stereoscopic binocular microscope for numerical counts of zooplankton groups and species. Fish eggs and larvae were separately picked up from the Hansen Egg Net and HT net hauls. The population density of zooplankton and fish eggs and larvae is expressed as numbers per 100 m^3 water filtered.

2.4 Modelling hydrodynamics

In general, estuarine and nearshore coastal waters are well mixed under the influence of strong tidal currents. Therefore, two dimensional depth averaged models have been used in the earlier studies (in the above 3 regions) to simulate tides and currents. The model results show good match with the observations [Moller, 1984; Unnikrishnan et al., 1999; Vethamony et al., 2004; Ramanamurthy et al., 2005; Babu et al., 2005; Kankara et al., 2007].

In the present study, for the simulation of flow and water level in the coastal waters of GoK, Goa and Mangalore, a two dimensional hydrodynamic model MIKE 21 HD, developed by the Danish Hydraulic Institute, [DHI, 2010] has been used. MIKE21 HD is a depth averaged (vertically homogeneous), two-dimensional (2-D) model that simulates unsteady 2-D flows in one layer. The distribution of currents and water levels are replicated by taking into account the hydraulic characteristics governed by the bed topography, surface wind effects and boundary conditions.

The flow in x and y direction changes the water level according to vertically integrated equations of continuity and conservation of momentum. The governing equations are

fully 2-D in the horizontal plane. The HD module uses implicit finite difference method to solve the equations of continuity and conservation of momentum [Chubarenko and Tchepikova., 2001; Babu et al., 2005; Babu, 2005].

$$\frac{\partial \eta}{\partial t} + \frac{\partial uH}{\partial x} + \frac{\partial vH}{\partial y} = 0 \quad (2.1)$$

The two depth-averaged momentum equations can be written as:

$$\frac{\partial uH}{\partial t} + \frac{\partial u^2H}{\partial x} + \frac{\partial uvH}{\partial y} = fvH - gH \frac{\partial \eta}{\partial x} + H \frac{\partial}{\partial x} (K_x \frac{\partial u}{\partial x}) + H \frac{\partial}{\partial y} (K_y \frac{\partial u}{\partial y}) + \tau_{wx} - \tau_{bx} \quad (2.2)$$

$$\frac{\partial vH}{\partial t} + \frac{\partial uvH}{\partial x} + \frac{\partial v^2H}{\partial y} = -fuH - gH \frac{\partial \eta}{\partial y} + H \frac{\partial}{\partial x} (K_x \frac{\partial v}{\partial x}) + H \frac{\partial}{\partial y} (K_y \frac{\partial v}{\partial y}) + \tau_{wy} - \tau_{by} \quad (2.3)$$

where t -time; x, y -Cartesian coordinates; u, v -depth averaged velocity components in the x and y directions, respectively; f -Coriolis parameter; g -acceleration due to gravity; K_x, K_y -diffusion coefficients in the x and y directions; τ_{wx}, τ_{wy} -wind stress in x and y directions; τ_{bx}, τ_{by} -bottom stress in x and y directions. The basic assumption behind these equations is that the water column is well mixed without any stratification.

The flow model can include bottom shear stress, wind shear stress, barometric pressure gradients, Coriolis force, momentum dispersion, sources and sinks, evaporation, flooding and drying and wave radiation stresses. The initial data essential for the HD model includes the orientation of water body to be modelled, latitude and longitude, bathymetry, wind (speed and direction), wave parameters, time step and duration of modelling. The resultant HD gives water level, current speed and direction that has vital importance in larval transport.

Depth averaged assumption is based on shallow water equations by which two average horizontal velocity components (u-component and v-component) can represent the vertical distribution of horizontal velocities. The model uses Alternating Direction Implicit (ADI) techniques to integrate the equations for mass and momentum conservation in the

space-time domain [DHI, 2003]. Water levels and flows are resolved on a square or rectangular grid covering the area of interest. The equations for each individual grid line are resolved by a Double Sweep (DS) algorithm. The main inputs to the model are bathymetry, bed resistance coefficients, wind fields, water level and flux boundary conditions [DHI, 2001].

2.4.1 Model domain, bathymetry and grid size

One of the key parameters which resolve the accuracy of model output is bathymetry data. Bathymetry is imperative in the hydraulic behaviour of water body. Setting up of bathymetry includes selection of the area, grid spacing, location and type of boundaries. In a bathymetry file, the study area is defined by the UTM (Universal Transverse Mercator), its geographical position of origin, width and height. Horizontal coordinates are given in easting and northing projected in UTM Zone 43. The UTM zone is found out by the UTM Zone formula [DHI, 2003] given by

$$UTM = \frac{180 + \lambda}{6} + 1 \quad (2.4)$$

where, λ is the geographical longitude of the origin in degrees.

The bathymetry file has been created by digitising the depth values given in the Naval Hydrographic chart (Naval Hydrographic office, Dehra Dun). After digitisation, the depth values are interpolated for the whole domain.

To simulate the flow pattern in the study area, structured numerical grids have been used. In areas where the flow is very complex due to bathymetry, high resolution grids were used for a better representation of the flow. Model domain for each case study is discussed in detail in chapter 4, while discussing the hydrodynamics of respective study region.

2.4.2 Stability criterion

In the numerical integration of geophysical fluids, it is necessary to follow a constraint in the time step of integration. Courant-Friedrichs-Lewy condition (CFL) is a stability criterion, which is a measure of stability. The Courant number is an important dimensionless flow parameter that describes how many grid points the celerity propagates within one time step. Courant number is defined as:

$$C_R = c \frac{\Delta t}{\Delta x} \quad (2.5)$$

where, c is the celerity, Δt is the time step and Δx is the grid spacing, where the celerity c is given by

$$c = \sqrt{gh} \quad (2.6)$$

where, g is the gravity and h is the water depth. The maximum value of Courant number which can be used without stability problems is calculated based on the bathymetry. The Courant number should be kept ≤ 2 in cases like flow simulation of coastal waters where the bathymetry gradient is high. The maximum Courant number that can be used is determined by the grid size (Δx) and the time step (Δt). By adjusting the time step, Δt , the Courant number is set within the recommended range. This means that in order to be accurate, the integration must be done with a time step, Δt , small enough such that a fluid particle moves only a fraction of the mesh spacing Δx in each step.

Length of simulation is decided specific to each case-study. It varies from days, weeks, months and years depending upon the data required to be simulated for resolving each study.

2.4.3 Calibration parameters

Model calibration is defined as fine tuning of parameters until the numerical model results and the field measurements are within an acceptable tolerance by modifying the boundary conditions and improving the hydro-meteorological forcing input. In the hydrodynamic model calibration, model parameters are chosen such that the model reproduces currents

and water level close to the observations. The two parameters adjusted during calibration are:

- (i) Roughness coefficient-used in the bottom friction formulation: Bed roughness is considered as a primary calibration parameter. Bed roughness can be applied as spatial roughness coefficient reflecting the surface characteristics of the sea bottom. Bottom friction is an important parameter in shallow water which can act significantly to retard current flow. The roughness of the sea floor varies with sediment variation. The sea sediment bed is usually mobile and its roughness in turn may impact the flow, which acts as a feedback between the sea floor and overlying flows. The bottom shear is described as:

$$\tau_b = \rho C_d U^2 \quad (2.7)$$

where, C_d is the drag coefficient, ρ is the density seawater and U is the depth averaged velocity. The drag coefficient can be specified in one of the following ways: (a) Manning number (M) and (b) Chezy number (C). Manning and Chezy numbers are inter-convertible using the following equation:

$$C = M h^{\frac{1}{5}} \quad (2.8)$$

Hence, in the present study, Manning number is used for carrying out simulations. Larger the bed resistance value, smaller will be the resultant bed friction. The model determines hydraulic friction losses based on a derivative of the Mannings equation. Sediment characteristics of the respective domains are provided to the model.

- (ii) Eddy viscosity-parameterizes horizontal mixing of momentum: Viscosity refers to the measure of the resistance of a fluid which is being deformed by some stress, and eddy viscosity refers to the internal friction generated as laminar flow becomes non-linear and turbulent. Therefore, we have to account for friction in the ocean so that the dissipation of motion can be accounted. Eddy viscosity or turbulent viscosity is the coefficient relating the average shear stress within a turbulent flow

of water. The eddy viscosity depends on the fluid density and distance from the sea bed. The eddy viscosity can be specified in one of the three different ways:

Smagorinsky formulae has been used to calculate the eddy viscosity in the present study. The Smagorinsky formulation calculates the eddy viscosity as a time-varying function of the local velocity gradients multiplied by the Smagorinsky constant [DHI, 2001]. The Smagorinsky factor was used mainly to damp out numerical oscillations and stabilize the model. The model allows choosing velocity-based or flux-based eddy viscosity formulations, and velocity-based constant eddy viscosity has been used in the present task. The eddy viscosity can be calculated by using the relation,

$$E \approx K \frac{\Delta x^2}{\Delta t} \quad (2.9)$$

where, E is eddy viscosity, K is an empirical constant that typically ranges between 0.01 and 0.06 [DHI, 2001], Δx is the grid spacing, and Δt is the computational time step.

2.4.4 Wind data and wind friction factor

The wind field over GoK undergoes seasonal changes coinciding with the change of seasons in the Indian Ocean. Since GoK is a semi-enclosed basin, the horizontal variation in the wind field from mouth to head is assumed to be insignificant. Therefore, mean winds are applied (Table 2.2) in the simulations for different seasons based on a previous study by Babu et al. [2005].

Table 2.2 Seasonal variability of mean wind speed and predominant direction in the GoK based on Babu et al. [2005]

Period	Wind speed ($m.s^{-1}$)	Wind direction ($^{\circ}$)
Pre monsoon	4.5	WNW(292)
SW monsoon	6.5	SSW(247)
NE monsoon	3.5	NNE(337)

In Goa and Mangalore region, the pre monsoon period represents a transition period from winter to summer characterized with very sluggish winds. But in the NE monsoon period winds are stronger. The AWS winds (direction and speed) are used in the hydrodynamic model as one of the input parameter for studying the seasonal variation of wind effect on the surface currents (Figure 2.1).

Wind data measured at Dona Paula (Goa) coastal station at 43.5 *m* height, were reduced to 10 *m* height using power law- a method for extrapolating the wind speeds between two heights [Peterson and Hennessey, 1978]. The reduced wind is represented by the following equation:

$$\frac{U}{U_r} = \left[\frac{Z}{Z_r} \right]^m \quad (2.10)$$

where, U_r and U are the wind speeds at the reference height Z_r (10 *m*) and the height Z (43.5 *m*), respectively. The exponent, m depends on the values of surface roughness and stability. As AWS is located in a relatively flat terrain area, m is assumed as 1/7. The reduced wind speed becomes:

$$U_{10} = 0.8106U_{43.5} \quad (2.11)$$

2.4.5 Initial and boundary conditions

For a realistic simulation, coastal ocean models need to be initialised and constrained at lateral boundaries of the domain. The hydrodynamics at the model's open boundaries must be accurately specified initially to get accurate current flow inside the model domain. The open boundaries should allow a consistent specification of physical properties at the interface between the interior and the exterior of the computational domain. In general, disturbances generated inside the domain should be able to travel outward across the open boundaries without spurious reflection that would affect internal water flow conditions. Boundary conditions for the model are defined by water levels along the open boundaries. This is to represent flow entering or leaving the system due to some process that may alter the flow rate inside the system. Since the offshore boundary is set only a few tens

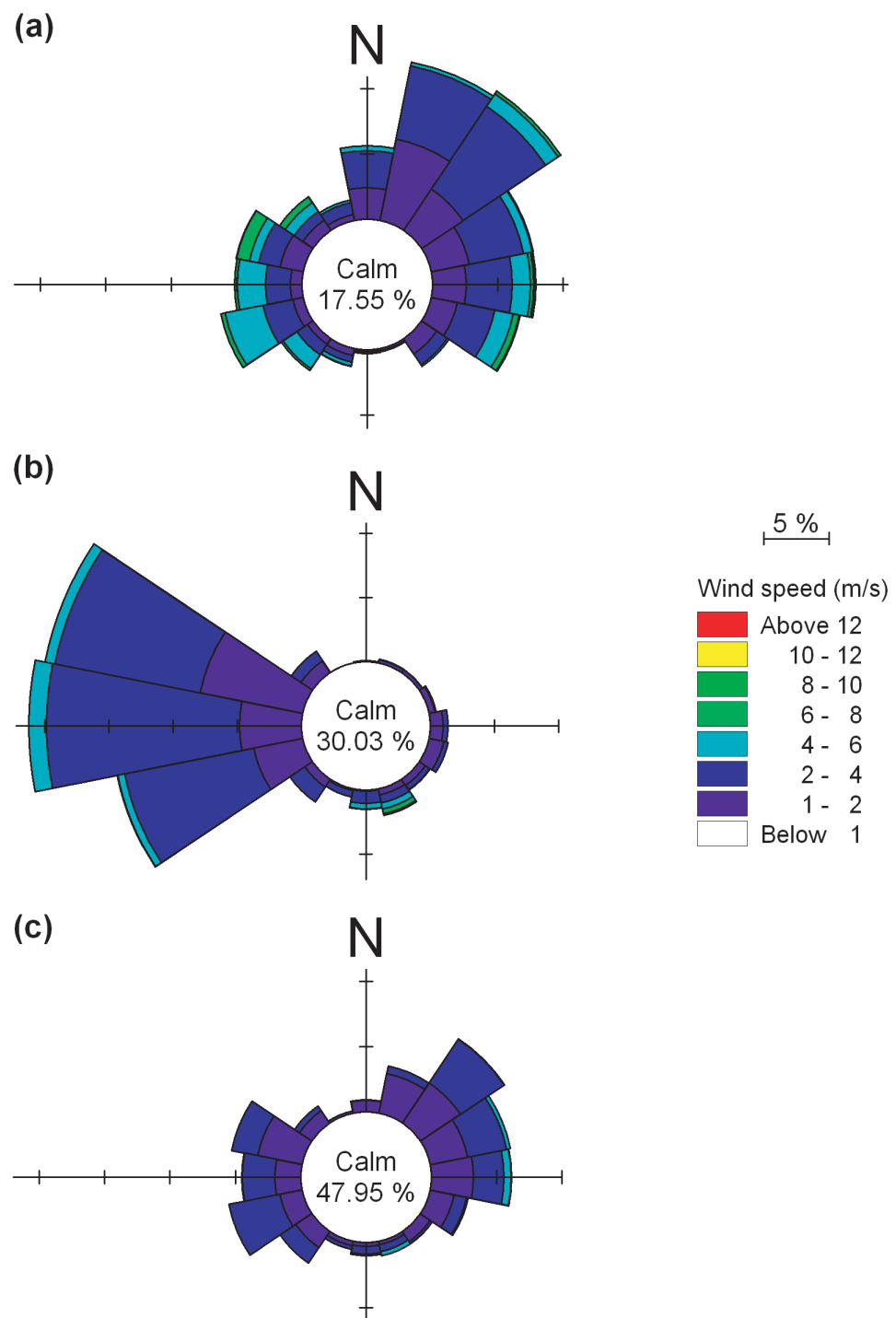


Figure 2.1: Wind rose plot: (a) December 2006 (b) May 2007 and (c) October 2007

of kilometers from the closed land boundary, the water level is assumed to be the same as that of the tidal stations throughout the particular latitude.

The water levels of a particular tidal station at the north and south boundary of the model are specified using MIKE21 tide prediction tool. Tidal constituents from the master tide chart *M2, S2, K1* and *O1* (Table 2.3) provided by the International Hydrographic Bureau, Spec. Pub, Monaco (Anonymous 1930) are used for predicting these water levels using Admiralty method. The water level along the open boundary in the north-south direction is linearly interpolated. The east boundary is closed by land so that it can be considered as a no flow boundary, except for the small domain simulations of Mandovi-Zuari estuarine systems where tides are predicted for the eastern open boundaries also (Figure 1.4).

A constant water level and zero velocity is used as initial conditions at all grid points. The water level at the open boundaries is used as the boundary condition and the flow direction at the open boundary is considered to be perpendicular to the boundary.

For the GoK domain (Figure 1.2), tide elevations at Okha and Godia creek in the south and northwest boundaries, respectively have been predicted for different periods and the tide elevations between Okha and Godia creek have been spatially interpolated in all grid points along west boundary. East boundary of the GoK between Navlakhi and Kandla is closed as there is no significant fresh water run-off into the GoK [Desa et al., 2002].

For the Goa domain, tide elevations are predicted at Karwar and Vengurla in the south and north boundaries, respectively. The tide elevations between Karwar and Vengurla have been spatially interpolated in all grid points along the west boundary. The east boundary is closed. For the smaller domain (Figure 1.4), tide elevations predicted at Panjim Bridge and Borim using tidal constituents, are used as the boundary conditions in the east boundary. The water levels and fluxes from the large domain simulations are applied as boundary conditions to the smaller domain.

For the Mangalore domain (Figure 1.5), tide elevations are predicted at Mangalore and Malpe in the south and north boundaries, respectively. Tide elevations between Mangalore and Malpe have been spatially interpolated in all the grid points along the west boundary. The east boundary is closed.

Table 2.3 Four major tidal constituents used in the Admiralty method of tidal prediction at the boundary stations.

Sl.No.	Location	Tidal constituents							
		M2		S2		K1		o1	
		Amp (m)	Phase (deg)	Amp (m)	Phase (deg)	Amp (m)	Phase (deg)	Amp (m)	Phase (deg)
1	Godia creek	0.864	338.8	0.333	15.6	0.418	63.9	0.211	58.4
2	Dwarka	0.823	325	0.293	359	0.399	54	0.195	53
3	Vengurla	0.553	310	0.193	347	0.313	0.53	0.16	50.8
4	Karwar	0.52	325	0.18	4	0.3	61	0.15	59
5	Malpe	0.43	317	0.15	1	0.3	59	0.13	53
6	Mangalore	0.36	328	0.12	15	0.25	59	0.12	55

2.5 Model parameters evaluation

The quality indices used for comparing model results with measurements are *bias* (mean error), *RMS* (Root Mean Square Error) and the *correlation coefficient* r . For each measurement, me_{ij} measured at time t_{ij} , the corresponding model value, mo_{ij} , is extracted from the model results using linear interpolation between the model time steps before and after t_i . The quality indices are calculated as follows:

$$dif_i = mo_i - me_i \quad (2.12)$$

$$\overline{me} = \frac{1}{N} \sum_{i=1}^n dif_i \quad (2.13)$$

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^n dif_i^2} \quad (2.14)$$

$$r = \frac{\sum_{i=1}^n (me_i - \overline{me})(mo_i - \overline{mo})}{\sqrt{\sum_{i=1}^n (me_i - \overline{me})^2 \sum_{i=1}^n (mo_i - \overline{mo})^2}} \quad (2.15)$$

Where, me_i is the measured value and mo_i is the model value.

The modelled HD gives water level, current speed and direction that has vital importance in larval transport. The evaluation of these parameters confirms the extent to which the model reproduces the observed hydrodynamic conditions.

2.6 Modelling larval transport

The Particle Analysis (PA) module of the MIKE21 [DHI, 2003] has been used to simulate the larval transport in the study regions. The model simulates transport and fate of dissolved and suspended substances in the aquatic environment under the influence of fluid transport and associated dispersion processes. It uses the Lagrangian random-walk technique to track the movement of the particles released, and the model has been effectively utilized for tracking the retention or dispersion of hypothetical abalone larvae *Haliotis iris* [Stephens et al., 2006].

Fish and barnacle larvae are treated like neutrally buoyant particles with a definite mass. Selecting dispersion coefficients for them is a difficult process. This is done by calibration of transport processes. The eddy viscosity varies parabolically over the vertical [Deigaard and Hansen, 1994] as given below:

$$v_t(z) = ku_f \left(1 - \frac{z}{D}\right).z \quad (2.16)$$

where k Von karman's constant(0.42), u_f bottom friction velocity, D water depth and z vertical position in the water column.

This model also simulates the spreading and weathering of suspended substance in an aquatic environment under the influence of the fluid transport and the associated dispersion processes. Since the model uses the Lagrangian random-walk technique to track the movement of the particles defined, the same can be effectively utilized for tracking the retention/ dispersion of hypothetical fish and barnacle larvae released within the domain. The model recovers the Lagrangian information from Eulerian velocities obtained through the hydrodynamic model, determining the trajectory of the advected particles from this velocity field throughout time. Larval movement between horizontal grid cells

is calculated as

$$V_{l,t} = [R]_{-1}^1 \sqrt{6D_{l,t}\Delta t} \quad (2.17)$$

where $[R]_{-1}^1$ is a random number in the interval -1 to 1, D_l and D_t are the horizontal diffusion coefficients in the longitudinal and transverse directions relative to the current flow, respectively, and Δt is the model time step. The particles that move out of the computational domain through the open boundary are assumed to lose their identity and do not return.

2.7 Larvae- defined based on regional variations and dominating species

2.7.1 Gulf of Kachchh

During 2007-2008, total fish landing for Gujarat was $6.77 \times 10^5 t$, contributing 22.37% to the total Indian production of $30.27 \times 10^5 t$. The major share is from Jamnagar and Kachchh districts. Though there are fluctuations in total fish landings, there has been a steady growth in fish production from 1983-84 onwards, except minor fluctuations in 1995-1996 and 1998-1999 (Figure 2.2).

A total of 27 categories of fish were recorded from the GoK (Figure 2.3) during 1999-2000 with sciaenid (34%) dominating the catch [Vijayalakshmi, 2002]. Since croakers belonging to sciaenidae family formed the major component of fishery in the GoK, sciaenid is considered as the bench mark in deciding the larval transport model parameters. Therefore, in the present study, for the simulation of fish larval transport, the following assumptions are proposed:

- (i) period of simulation: based on planktonic larval duration of the sciaenid, which is similar to other tropical fish species too.

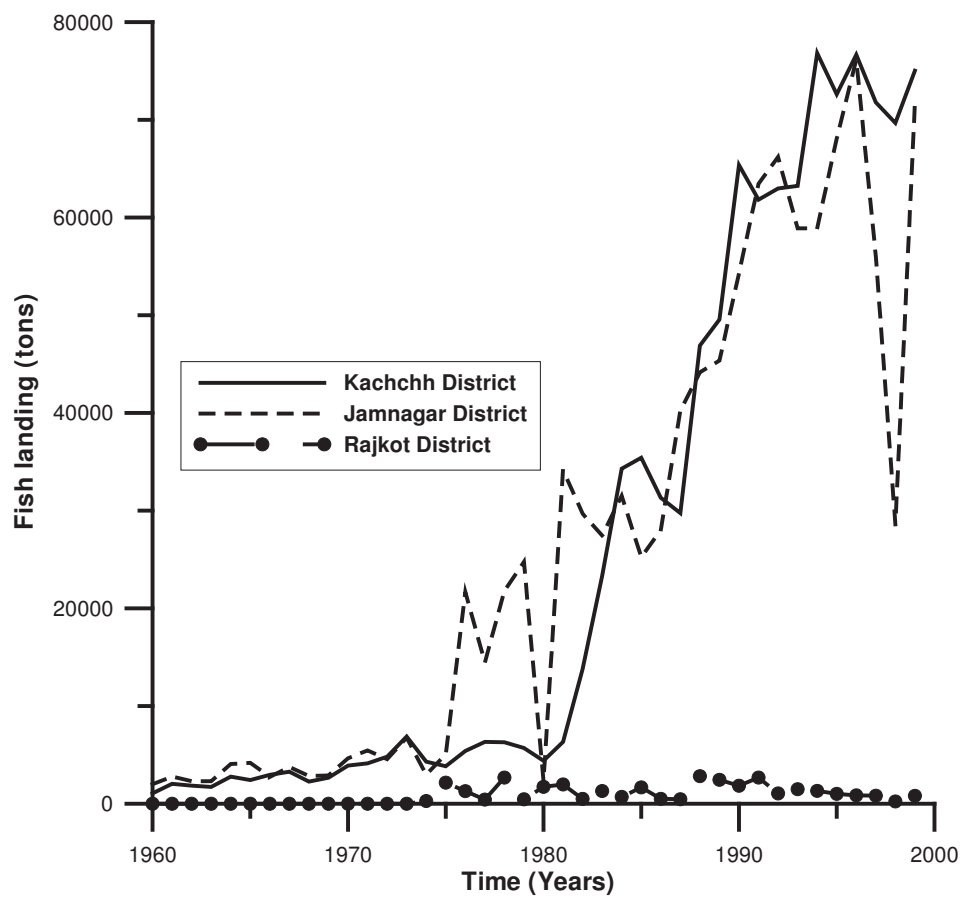


Figure 2.2: Marine fish landing in the three districts of Gulf of Kachchh during 1960-2000

- (ii) particle size of released eggs: based on the egg size, weight and fecundity of sciaenids. The estimated time of hatch based on the sampling point time was controlled using a source flux defining the mass and release of larvae at selected spawning sites.
- (iii) possibility of passive drifting: based on swimming speed of the sciaenid
- (iv) total particles released: eggs were estimated based on the fecundity of the sciaenid. Particle release time is based on the spawning time of sciaenid. One particle released in the model is estimated to be equivalent to 100 eggs as fecundity of tropical fishes tend to vary from 0.1 to 1 million [Pandian, 2003]. Release of 10 million eggs is achieved by assuming that a minimum of 10 fishes are spawning in a site during the active breeding phase with each egg weighing 0.02 *mg* weight [Gustavo et al., 2003] as estimated for sciaenid in tropical waters (the most dominant group of fish found in the GoK).
- (v) virtual fish eggs are simulated as neutrally buoyant passive particles. Released eggs form larvae in a day in tropical conditions as their hatching time is reported to be less than a day [Pauly and Pullin, 1988]. For a smooth illustration of events during larval transport, the tracer particles used in the model are termed as eggs at the spawning site, and larvae thereafter as eggs develop into larvae in a day in sciaenid fishes. Hence, hypothetical larvae were allowed to disperse following the egg release from two major spawning sites identified from the six survey sites for each season.
- (vi) active fish larvae tend to migrate vertically. But, a well mixed current regime similar to the GoK tends to carry forward the larvae. The difference in trajectory may result in a shift in their distribution to the order of hundreds of meters, but limitations of a 2-D depth averaged model in a 500 *m* grid spacing make it difficult to consider this possibility, and it is assumed that the changes in distribution of larvae due to vertical migration is negligible for the study.

To visualize the movement of fish larvae, particle-tracking was simulated for the 6 spawning locations surveyed for egg abundance in the GoK and tracked for 30

days. Final site selection for egg release in the PA model was decided based on the egg abundance and dispersal pattern observed from the particle tracking results.

In this study, we assume that fish larvae are transported with the flow without being settled. The assumption of a purely pelagic phase is supported in some systems, but lab/field observations sometimes contradict the assumption that the larval component is completely passive [Leis, 2006]. In a macro-tidal regime like the GoK, weak swimmers will not contribute to dispersal trajectories because of strong currents. Tropical sciaenid fishes have a swimming speed of 0.6 to 1.4 $cm.s^{-1}$ [Leis et al., 2006b], but the current speed is of the order of 150-200 $cm.s^{-1}$. The larvae complete their Planktonic Larval Duration (PLD) in approximately 20 days, as for most tropical fish larvae [Wellington and Victor, 1989]. The larvae are tracked hourly in this experiment to identify their patterns of dispersal and retention. Dispersed patterns are presented as snap shots in the results at different time steps (day 1, day 5, day 10 and day 16). The larval abundance in a region is affected by predation, mortality and behaviour. In this study, these aspects were neglected as the variation in these parameters in the study domain is not known, and it is difficult to interpolate the same in spatial scales in the numerical model.

2.7.2 Goa

Barnacle larvae are defined as neutrally buoyant, and they follow the prevailing flow without being settled. But its PLD phase is approximated as 10 days for the study after which they are treated as settled. On completion of its PLD phase (610 days), the larvae will settle down if a suitable rocky substratum is available; else it will continue its PLD phase for few more days in search of a viable substratum and finally perishes if it fails to settle in a hard substratum. In the numerical simulations, it is defined that one particle is equivalent to 1000 larvae as it is difficult to model larval transport with huge number of particles. At each time step 4000 number of larvae are released making it into 11.92 million hypothetical larvae over 2980 time steps (with a time step interval of 30 s). The release is so continued for 24 hours and 50 minutes covering 2 tidal cycles as the source



Figure 2.3: Species composition of fish in the GoK

flux. Assuming a mass of $5 \mu g$ for each larva, $0.2 mg$ of larvae per second was released in each time step. The simulations have been carried out for 15 days duration in each season, considering the release of larvae on 6th day and observed the larval transport for next 9 days after the release. Dispersion of the larvae according to the prevailing flow was analysed for each season. The dispersal pattern at the beginning (after complete release of the larva), middle and end of the simulation has been plotted to visualize the larval dispersion.

The concentration, viz., number of hypothetical larvae for each unique hydrodynamic situation is also extracted at various sampling stations to assess the intensity of retention or dispersal under the influence of flow and associated dispersion processes.

2.7.3 Mangalore

One million fish larvae is defined as one particle. Two particles were released simultaneously as pelagic species with high fecundity like sardine dominates the fishery of Mangalore region. The release (source flux) is continued for 24 hours and 50 minutes covering 2 tidal cycles. Larvae were allowed to disperse in the currents following their release. The dispersal or retention pattern of the larvae has been estimated every 30 s. This time step is reasonable to calculate the larval transport in the prevailing flow.