

**Numerical modelling of tidal circulation  
and studies on salinity distribution in  
Mandovi and Zuari estuaries**

**Thesis**

*submitted to*

**Goa University**

*for the Degree of*

**Doctor of Philosophy**

*in*

**Marine Sciences**

**by**

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November 2008

*to my mother*

# Statement

As required under the University ordinance 0.19.8.(vi), I state that this thesis entitled *Numerical modelling of tidal circulation and studies on salinity distribution in Mandovi and Zuari estuaries* 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.

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*November 2008*

# Certificate

This is to certify that the thesis entitled *Numerical modelling of tidal circulation and studies on salinity distribution in Mandovi and Zuari estuaries*, submitted by N. T. Manoj 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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## Publications

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<sup>1</sup>L<sup>A</sup>T<sub>E</sub>X 2<sub>ε</sub> is an extension of L<sup>A</sup>T<sub>E</sub>X, a collection of macros for T<sub>E</sub>X. T<sub>E</sub>X is a trademark of the American Mathematical Society.

# Synopsis

The estuaries on the west coast of India are unique in their physical and bio-geochemical features and the Mandovi and Zuari estuaries are two of these estuaries. Monsoon is a typical feature of this region. The south westerly winds blowing from the Indian Ocean bring heavy rainfall into the Indian subcontinent during June to September and these estuaries receive heavy river discharge during this period. Hence they are often called as “monsoonal estuaries”. Rainfall and subsequent discharge flushes out salinity very fast from these estuaries into the sea during southwest monsoon. Salinity in these estuaries undergoes intraseasonal variations during this period. Tidal dynamics, salinity distribution, flushing time etc. in an estuary are to be studied in detail for navigation, fishing, dredging and recreation purposes and also to determine the effects of oil spills, disposal of sewage and other potentially harmful wastes.

For the present study, the Mandovi and Zuari estuaries were chosen. These estuaries represent the other estuarine systems on the west coast of India in terms of tidal characteristics, channel convergence, heavy fresh water discharge etc. In addition, the Mandovi and Zuari estuaries play a vital role on the regional economy as these channels are exclusively used for the transportation of iron and manganese ores from their upstream regions to the nearest Port, Mormugao, which is one of the major ports along the west coast of India. The Mandovi and Zuari estuaries are connected by a narrow canal called Cumbarjua at their upstream regions. A number of tributaries also join the Mandovi and Zuari estuaries. Previous studies on tides and salinity in the Mandovi and Zuari estuaries

were limited to observations [Thomas et al., 1975; Varma et al., 1975; DeSousa, 1977; DeSousa et al., 1981; Qasim and Sengupta, 1981; Shetye et al., 1995; DeSousa, 1999b]. Shetye and Murty [1987] used a one dimensional numerical model for the simulation of salinity in the Zuari estuary. Unnikrishnan et al. [1997] used a one dimensional network model for the simulation of tidal decay during southwest monsoon at the upstream regions in the Mandovi and Zuari estuaries. Tide is major driving force in an estuary and tidal asymmetry can change the duration of flood and ebb in an estuary. Though many studies [Unnikrishnan et al., 1999a; Shetye, 1999; Unnikrishnan and Luick, 2003; Sundar and Shetye, 2005] were conducted to understand the variation of major diurnal and semidiurnal constituents in the gulfs and estuaries on the west coast of India, no detailed study was undertaken to know the variations of overtides ( $M_4$ ,  $M_6$ ) and compound tides ( $MSf$ ,  $MK_3$ ,  $MN_4$ ,  $MS_4$ ) inside an estuary. The overtides and compound tides have major role on tidal asymmetry inside the estuaries. Tidal asymmetry has important effects on both the geological evolution of shallow estuaries and the navigability of estuarine channels [Aubrey and Speer, 1985; Speer and Aubrey, 1985]. The aim of the present thesis is to simulate tides and salinity distribution in the Mandovi and Zuari estuaries using a hybrid network numerical model. The main objectives are (i) to study the tidal characteristics such as the longitudinal variation of tidal amplitudes during dry and wet seasons, freshwater influence on tides and the tidal asymmetry caused by overtides and compound tides (ii) to study the longitudinal variation of salinity distribution and freshwater influence on salinity distribution and (iii) to study the intraseasonal variations of salinity in the Mandovi estuary during southwest monsoon with the help of salinity measurements made in the estuary.

Chapter 1 of the thesis presents an introduction to the study area, the previous studies by earlier researchers and the objectives of the present study. Chapter 2 deals with the data and methodology. A hybrid network numerical model was developed to simulate tidal elevation, tidal currents and salinity distribution in the Mandovi and Zuari estuaries.

The hybrid network model consisting of a vertically averaged 2D model for the downstream regions in the Mandovi and Zuari estuaries and an area averaged 1D model for the upstream regions in the Mandovi, Zuari and for the Cumbarjua canal are described. The finite difference numerical scheme was used for solving partial differential equations of motion, continuity and advection-diffusion equation of salinity. The bathymetry data of the Mandovi, Zuari and Cumbarjua channels were obtained by digitizing the bathymetry maps (1968-1969) of minor ports survey organization, Ministry of Shipping and Transport, Government of India. The monthly mean averaged discharge data (1993) at Ganjem, an upstream station in the Mandovi estuary were used for prescribing river discharge at the upstream end boundaries of the model domain. The continuous measurements of tides and salinity in April and August, 1993 were used for the validation of the model and tidal measurements in March–April, 2003 were used to study the tidal asymmetry in these estuaries. Salinity measurements made along the longitudinal sections in the Mandovi during the selected days of 2005–2007 were analysed to study the intraseasonal variations of salinity during southwest monsoon.

Chapter 3 describes the simulation of tides, freshwater influence on tides, tidal currents and harmonic analysis of observed and simulated tides. The simulation of tidal currents were carried out using the numerical model described in Chapter 2. To simulate the tidal constituents and to study tidal asymmetry in the Mandovi and Zuari estuaries, the 35-days measurements of sea level were used for the harmonic analysis, and this one-month data was sufficient to resolve major diurnal and semidiurnal constituents, overtides and compound tides. Thereafter, the harmonic analysis of both observed and simulated tides was done. To find the difference between observation and model simulation, the complex difference module was calculated. The complex difference module gives synthetic information of the difference in both amplitude and phase of the observation and simulation. It was found that the model simulated tides successfully during dry and wet seasons in the Mandovi and Zuari estuaries. The results from the study show that fairly

strong tidal currents in the absence of river discharge mix the water column vertically in the Mandovi and Zuari estuaries during dry season. During wet season, the velocity associated with river discharge prevents upstream propagation of tides. The rapid increase of the first and second harmonics of  $M_2$  and compound tides inside these estuaries show the non-linear response of the Mandovi and Zuari estuarine systems to the tidal forcing. The  $M_4/M_2$  amplitude ratio indicates that the tide is subjected to more asymmetry in the Zuari than that in the Mandovi. The increase of the first harmonic of  $M_2$  and decrease of relative surface phase ( $2M_2 - M_4$ ) inside the Mandovi and Zuari estuaries show that these estuaries are flood dominant.

Chapter 4 deals with the salinity distribution in these estuaries. The simulation of the longitudinal variation of salinity during dry and wet seasons, freshwater effect on the salinity distribution and the intraseasonal variations of salinity during wet season are described in this Chapter. The analysis of salinity measured during the selected days of 2005–2007 in the Mandovi estuary shows the intraseasonal variation of salinity during southwest monsoon. The residual circulation and flushing time in the Mandovi and Zuari estuaries were also determined.

The results described above are summarized in Chapter 5.

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# Chapter 1

## Introduction

### 1.1 Definition

Estuaries are semi enclosed bodies of water where freshwater from the river mix with saline water from the sea. The widely used definition of an estuary states that an estuary “is a semi enclosed body of water which has a free connection with sea and within which seawater is measurably diluted with freshwater derived from land drainage” [Cameron and Pritchard, 1963]. The action of tides, winds and other physical processes in an estuary make it a complex system.

#### 1.1.1 Classification of estuaries

Estuaries can be classified based on geomorphology, tidal range and salinity distribution. Based on geomorphology [Pritchard, 1952, 1967; Russell, 1967], estuaries are classified into Coastal plain estuaries, Fjords and Bar-built estuaries. Estuary geomorphology strongly affect the transport of pollutants and ultimately impacts water quality characteristics [Martin and McCutcheon, 1999; Dyer, 1973]. There are other types of estuaries which are formed by tectonic activity, volcanic eruptions etc.

Based on tidal range, if the tidal range is less than 2 *m* in an estuary then it is called

micro-tidal estuary. The tidal ranges are between 2 to 4 *m* in the meso-tidal estuaries and those estuaries, where tidal range is higher than 4 *m* are called macro-tidal estuaries [McCann, 1980; Dyer et al., 2000].

Salinity distribution in an estuary varies from place to place due to their geographical locations, prevailing climate systems and tidal range. The estuaries, based on salinity, are classified into stratified estuaries, partially mixed estuaries and well mixed estuaries [Pritchard, 1955, 1967; Bowden, 1967; Fischer, 1972; Dyer, 1973, 1997]. Hansen and Rattray [1966] classified an estuary based on the salinity variations in the vertical direction and the circulation due to the difference in density. Tidal currents are weak in stratified estuaries because of large river discharge. The low density freshwater from the river side flow above seawater and a sharp boundary is created between these two water masses. In partially mixed estuaries, saline water and freshwater mix partially due to increased tidal activity. Tidal activities generate turbulence and partial mixing take place between freshwater and saline water. Differential pressure forces due to landward moving saline water and seaward moving freshwater from the upstream end give rise to longitudinal density currents and consequent mixing both longitudinally and vertically [Fischer, 1972]. If tides are large, freshwater and saline water mix from surface to bottom and these type of estuaries are called well mixed estuaries.

### **1.1.2 Physical processes in an estuary**

Ocean tides often dominate the mixing in estuaries [Gross, 1972]. Ocean tides are defined as the periodic rise and fall of sea surface caused by the gravitational attraction of moon and sun on earth. The gravitational attraction of other planets on earth are negligible because of their distant locations. Tide created in the ocean penetrates into rivers as a disturbance, the shape and size of rivers being such that they do not respond directly to the tidal forces. The disturbance takes the form of a progressive wave, markedly affected by friction and completely damped eventually [Godin, 1988]. Tide, river discharge,

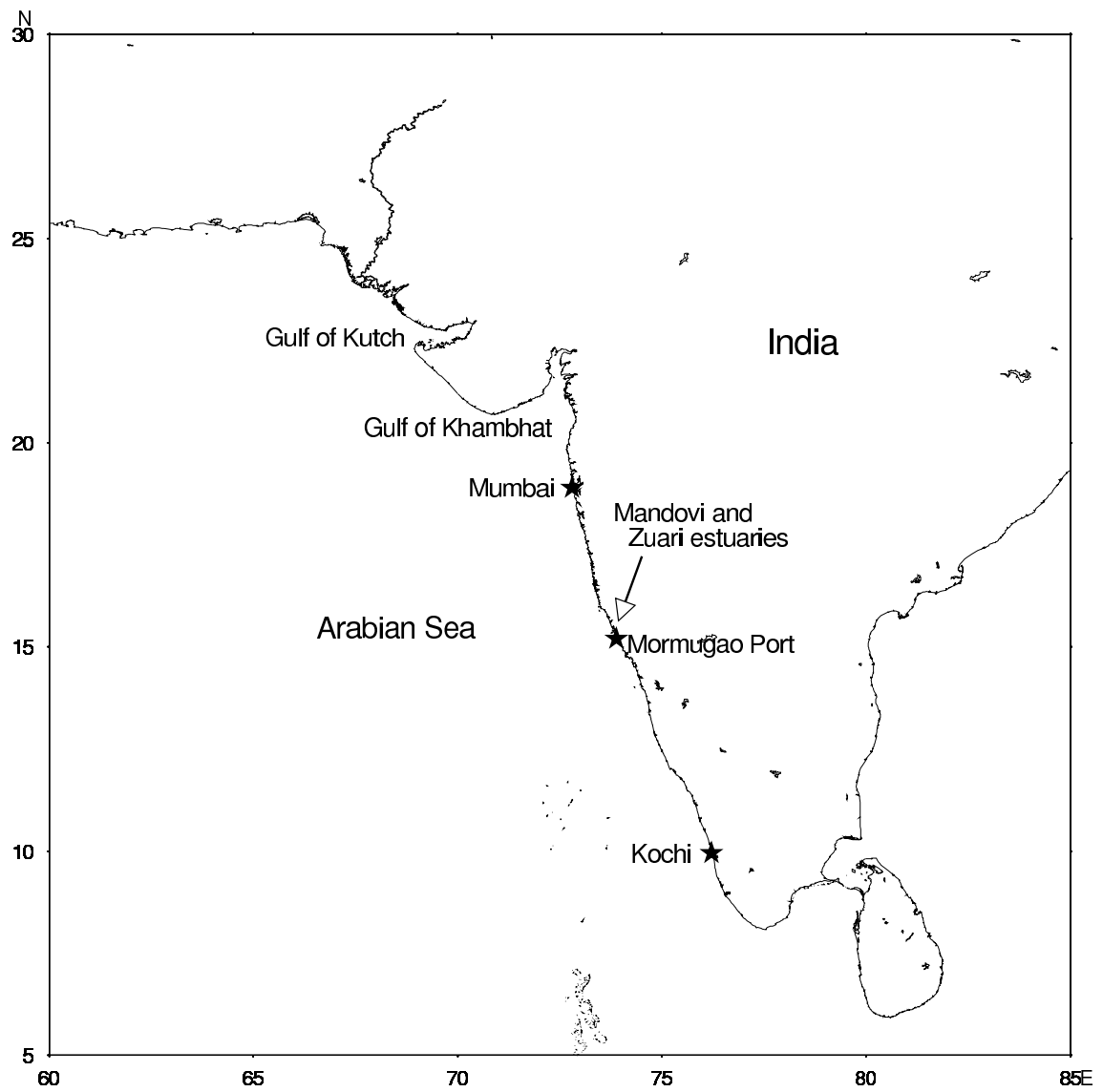
bathymetry, wind, Coriolis force etc. control the processes in an estuary [Fischer et al., 1979]. Circulation and transport mechanisms in estuaries are complex and subject to a large spatial and temporal variability derived from the interaction of river discharge, tides and winds. These forces drive the gravitational circulation and turbulent diffusion which are the main processes controlling the transport of properties in estuaries [Mantovanelli et al., 2004]. Bathymetry in an estuary regulate the speed of propagation of tides. Shallow regions of estuaries enable vertical mixing more effective than that of deeper regions. Freshwater inflow into an estuary normally has a significant impact on mixing and the increased freshwater inflow can change the character of an estuary from well mixed to partially mixed or stratified [Martin and McCutcheon, 1999].

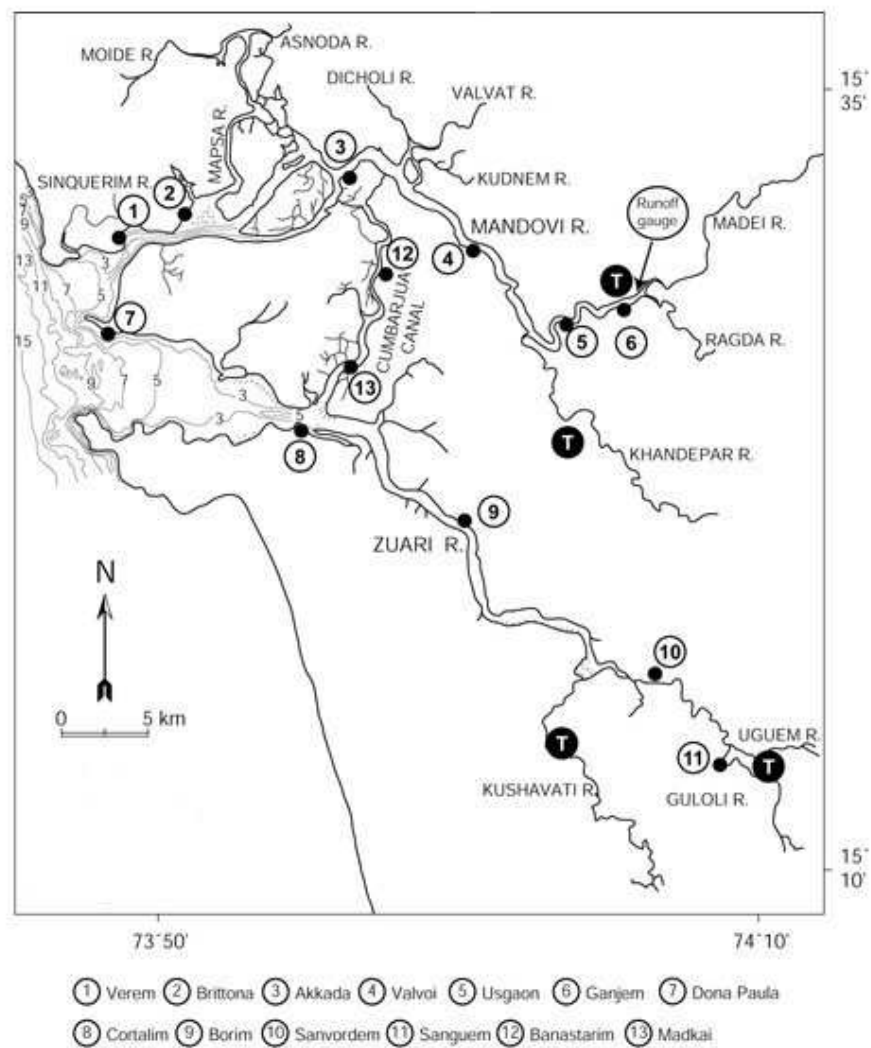
## 1.2 The study area

India has a vast coastline of over 7000 *km* and the major Indian cities, Mumbai, Kolkata and Chennai are situated along these coasts. There are more than 100 major and medium estuarine channels along the east and west coast of India. The estuaries along the east coast of India are long and wide whereas the estuaries along the west coast are smaller. Ganges-Brahmaputra Delta region along the east coast of India is the largest estuarine network in India. Since ancient times, estuaries in India have been a focal point of activities for human settlement, development of ports and harbours, transportation of men and material and for trade and commerce [Qasim, 2003].

The estuaries along the west coast of India are unique in their physical and biogeochemical features. Kochi Backwaters is one of the largest estuarine systems along this region and the other important estuarine systems along this coast are Ashtamudi estuary, Kali river, Mandovi and Zuari estuarine system, Mumbai Harbour and Thane Creek system and a number of small estuaries like Sabarmati, Tapti, Narmada etc. Monsoon is a typical feature of this region. The south-westerly winds blowing from the Indian

Figure 1.1 Map of the west coast of India



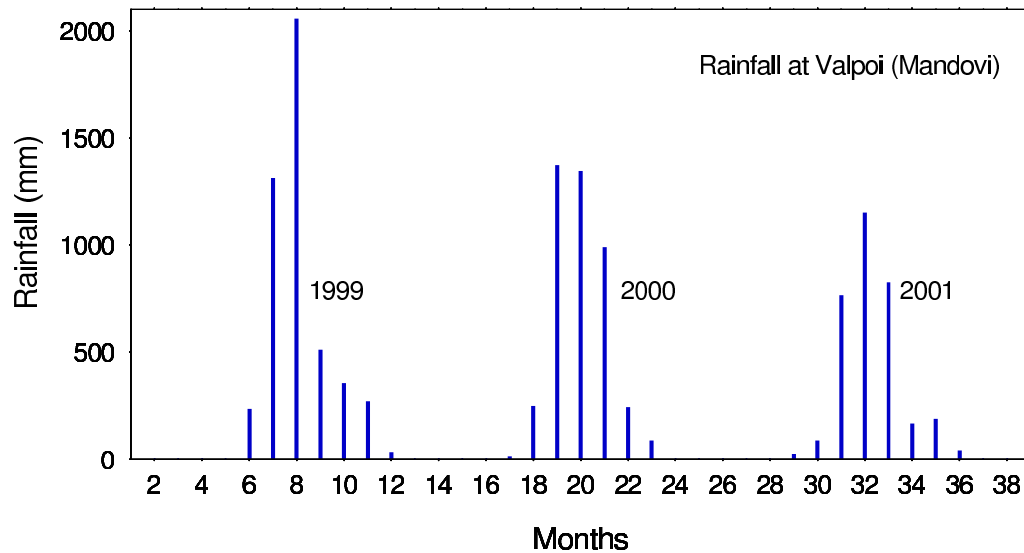
**Figure 1.2** Map of the Mandovi and Zuari estuaries

Ocean bring heavy rainfall into the Indian subcontinent during southwest monsoon (June to September) and these estuaries receive heavy river discharge during this period hence they are often called as “monsoonal estuaries”. Salinity distribution in these estuaries undergoes intraseasonal variations during southwest monsoon. Rainfall and subsequent river discharge during this period flushes out salinity very fast from these estuaries into the Arabian sea. Thermodynamics of the water column of these coastal regions of the Arabian sea is greatly affected by the rainfall and subsequent freshwater inflow [Shankar and Shetye, 1999, 2001; Shenoi et al., 2002; Shankar et al., 2004, 2005; Suprit and Shankar, 2008].

The understanding of estuarine dynamics is very important in many aspects because, apart from their role on influencing the physics and bio-geochemistry of the adjacent seas, their role in determining regional ecology and economy are also indispensable. Tidal dynamics, salinity distribution, flushing time etc. in an estuary are to be studied in detail for navigation, fishing, dredging and also, to determine oil spills, disposal of sewage and other potentially harmful wastes.

For the present study, the Mandovi and Zuari estuaries (Figures 1.1 and 1.2) are chosen. These estuaries represent the other estuarine systems on the west coast of India in terms of tidal characteristics, channel convergence, heavy freshwater discharge etc. In addition, the Mandovi and Zuari estuaries play a vital role on regional economy as these channels are exclusively used for transportation of iron and manganese ores from their upstream regions to the nearest port, Mormugao which is one of the major Ports along the west coast of India. The length of the Mandovi and Zuari estuaries are about 50 *km* each and have their upstream regions in the Western Ghats (Mountain ranges along the west coast of India). The Mandovi and Zuari estuaries are shallow channels with average depth of about 5 *m*. The width at the mouth of Mandovi and Zuari estuarine system is about 9 *km* and the width narrow down to 200 *m* at their upstream regions. A narrow canal, Cumbarjua canal, connects these estuaries at a distance of 14 *km* from the mouth of the

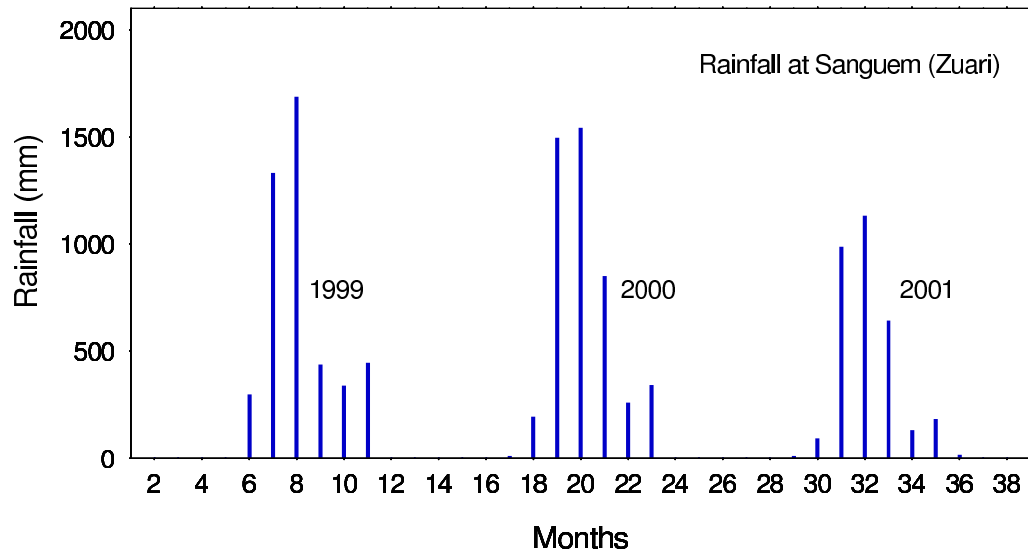
**Figure 1.3** Observations of rainfall during 1999–2001 at Valpoi in the Mandovi estuary. The months on the x-axis starts from January, 1999. The rainfall data were obtained from India Meteorological Department.



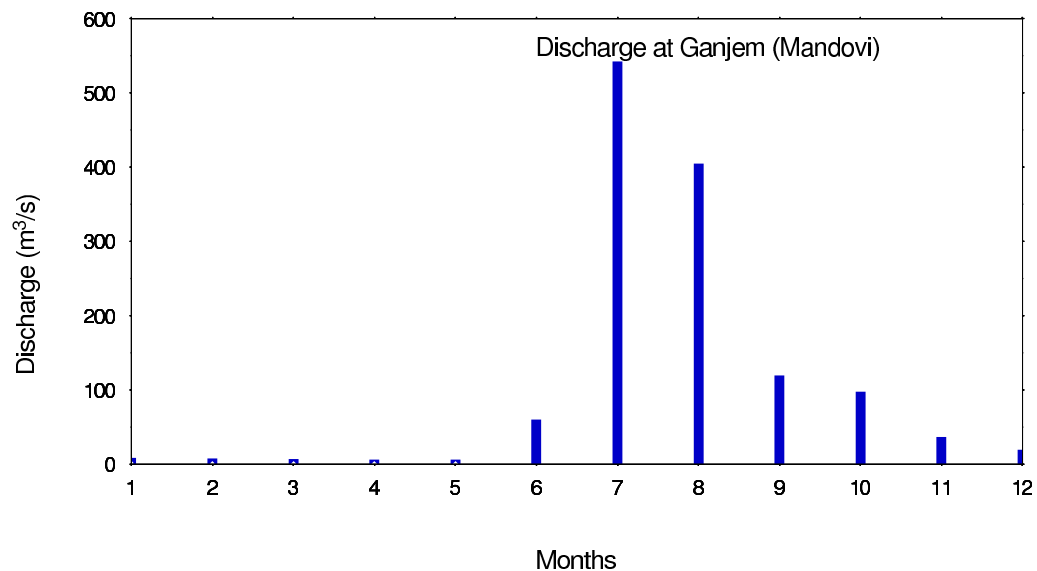
Mandovi and 11 *km* from the mouth of Zuari. The length of the Cumbarjua canal is about 17 *km* and has an average width of 0.5 *km*. A number of tributaries such as Sinkerim River, Mapusa River, Khandepar River join to the Mandovi estuary while Kushavati and Sanguem Rivers join to the Zuari estuary. As mentioned earlier, southwest monsoon is a unique feature of this region and the Mandovi and Zuari estuaries receive heavy river discharge during this period. The normal rainfall of this region is about 2500–3000 *mm* in a year and 80% of the total rainfall occurs during the southwest monsoon. Figures 1.3 and 1.4 show the observations of rainfall during 1999–2001 at Valpoi and Sanguem stations respectively in the Mandovi and Zuari estuaries. Rainfall reaches to its peak during July and August and river discharge from the upstream ends of these rivers is about 400  $m^3s^{-1}$  during this period (see Figure 1.5).

Based on tidal range, the Mandovi and Zuari are meso-tidal estuaries. Tides in these estuaries are semidiurnal mixed type and the tidal range is about 2 *m*. The studies on

**Figure 1.4** Observations of rainfall during 1999–2001 at Sanguem in the Zuari estuary. The months on the x-axis starts from January, 1999. The rainfall data were obtained from India Meteorological Department.



**Figure 1.5** River discharge for Ganjem in the Mandovi estuary. The months on the x-axis starts from January 1993. The river discharge data were obtained from Central Water Commission, Government of India.





hydrography of the Mandovi and Zuari estuaries started in early 1970s. The previous studies on tides and salinity in these estuaries were limited to observations. Dehadrai [1970]; Dehadrai and Bhargava [1972]; Das et al. [1972]; Murty and Das [1972]; Singbal [1973]; Thomas et al. [1975]; Varma et al. [1975]; DeSousa [1977]; DeSousa et al. [1981]; DeSousa [1999b] investigated some of the environmental features and the influence of tide in regulating the flow in these estuaries. Tidal amplitude in the Mandovi and Zuari remains unchanged upto about 40 *km* from the mouth, and then drops sharply over the next 10 *km* [Shetye et al., 1995]. Sundar and Shetye [2005] calculated amplitude and phase of the major tidal constituents in the Mandovi and Zuari estuaries using sea level measured during March–April 2003 at different stations in these estuaries. They found that the five major constituents  $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_1$  and  $O_1$  have amplitudes more than 10 *cm* at the mouth of these estuaries and the amplitude and phase of these major constituents increase from mouth to the upstream regions before topographic effect comes to play.

The Mandovi and Zuari are partially mixed estuaries and the longitudinal distribution of salinity in these estuaries are subjected to large variations during a year. Near the mouth, during a tidal cycle, salinity remains almost constant (35 *psu*) between November and May. But salinity at the mouth varies from 7 to 22 *psu* during June to September. [Qasim and Sengupta, 1981; Shetye et al., 1995]. Heavy precipitation and land runoff from June to September bring about large changes in temperature, salinity, flow pattern, dissolved oxygen and nutrients when the estuary becomes freshwater dominated [Qasim and Sengupta, 1981]. Sandbars are formed at the mouth of the Mandovi estuary during this period and the formation of these sandbars halts the traffic in the Mandovi from June to September. But the navigation in the Zuari and Cumbarjua canal is uninterrupted during this period. By the end of September, the effect of river discharge is reduced and saline water intrudes towards upstream regions. By February, the downstream regions of these estuaries become an extension of the sea. The heavy rainfall and subsequent freshwater inflow into the catchment area during June to September hereafter referred to as 'wet

season' stratifies the downstream regions consisting of about 10–12 *km* from the mouth of the estuaries. From 12 *km*, to the upstream regions of about 35 *km* the estuaries become completely freshwater dominated. During the post monsoon (October to January), the saline water intrudes further into upstream regions. February to May, hereafter referred to as 'dry season', these estuaries are vertically well mixed throughout the regions. Shetye and Murty [1987] used a one dimensional numerical model for the simulation of salinity in the Zuari estuary. Unnikrishnan et al. [1997] used a one dimensional network model consisting of all the tributaries of the estuarine system for the simulation of tidal decay at the upstream regions during wet season in the Mandovi and Zuari estuaries. As mentioned previously, tide is a major driving force in an estuary and tidal asymmetry can change the duration of flood and ebb in an estuary. Though many studies [Unnikrishnan et al., 1999a; Shetye, 1999; Unnikrishnan and Luick, 2003; Sundar and Shetye, 2005] were conducted to understand the variation of major diurnal and semidiurnal constituents in the gulfs and estuaries on the west coast of India, no detailed study was undertaken to know the variations of overtides ( $M_4$ ,  $M_6$ ) and compound tides ( $MSf$ ,  $MK_3$ ,  $MN_4$ ,  $MS_4$ ) in these gulfs and estuaries. Overtides and compound tides have major role on tidal asymmetry inside the estuaries.

### 1.2.1 Objectives

The aim of the present thesis is to determine the characteristics of tidal propagation and salinity distribution in the Mandovi and Zuari estuaries using a hybrid network numerical model. The main objective are (i) to study the tidal characteristics such as the longitudinal variation of tidal amplitudes during dry and wet seasons, freshwater influence on tides and the tidal asymmetry caused by overtides and compound tides (ii) to study the longitudinal variation of salinity distribution and freshwater influence on salinity distribution and (iii) to study the intraseasonal variations of salinity in the Mandovi estuary during southwest monsoon with the help of salinity measurements made in the estuary.

In addition to this first chapter there are four more chapters in this thesis and the outline of these chapters is given below.

### 1.2.2 Chapter 2

Chapter 2 of the thesis deals with data and methodology. This chapter contains a detailed description of a numerical model developed for the present study. A hybrid network numerical model was developed to simulate tides, tidal currents and salinity distribution in the Mandovi and Zuari estuaries. A hybrid network model consisting of a vertically averaged 2D model and an area averaged 1D model was used. The vertically averaged 2D model was used for the downstream regions in the Mandovi and Zuari estuaries. An area averaged 1D model was used for the upstream regions in the Mandovi and Zuari estuaries and Cumbarjua canal. A finite difference numerical scheme was used for solving partial differential equations of motion, continuity and advection-diffusion equation of salinity. The bathymetry data of the Mandovi, Zuari and Cumbarjua channels were obtained by digitizing the bathymetry maps (1968–1969) of minor ports survey organization, Ministry of Shipping and Transport, Government of India. The monthly mean averaged discharge data (1993) of Ganjem, an upstream station in the Mandovi estuary were used for prescribing river discharge at the upstream boundaries in the Mandovi and Zuari estuaries. The continuous measurements of tides and salinity made in April and August 1993 were used for validation of the model and tidal measurements in March–April, 2003 were used to study the tidal asymmetry in these estuaries. In addition, we made salinity measurements along the longitudinal sections in the Mandovi estuary during the selected days of 2005–2007, which were used to study the intraseasonal variations of salinity during southwest monsoon.

### 1.2.3 Chapter 3

Chapter 3 describes the tidal characteristics in the Mandovi and Zuari estuaries. This chapter describes the results of simulation of tides, tidal currents and the influence of river discharge on tides. Also, the harmonic analysis of major diurnal and semidiurnal constituents, overtides, compound tides and the  $M_4/M_2$  amplitude ratio and relative surface phase ( $2M_2 - M_4$ ) are also discussed. The simulation of tides during dry and wet seasons in 1993, the study of freshwater effect on tides and the simulation of tidal currents were carried out using the hybrid network numerical model described in Chapter 2. To study tidal asymmetry in the Mandovi and Zuari estuaries, the 35-days observations of tide made in March–April, 2003 [Sundar and Shetye, 2005] were used for the harmonic analysis, and this 1-month duration of data was sufficient to resolve major diurnal and semidiurnal constituents, overtides and compound tides. The harmonic analysis of both observed and simulated tides was carried out using Tidal Analysis Software Kit-2000 [Bell et al., 2000]. To find the difference between observed and simulated tides, the complex difference module was calculated. The complex difference module gives synthetic information about the difference in both amplitude and phase between the observation and simulation. It is found that the model simulated tides successfully during dry and wet seasons in the Mandovi and Zuari estuaries. The results from the study show that fairly strong tidal currents in the absence of river discharge mix the water column vertically in the Mandovi and Zuari estuaries during dry season. During wet season, the velocity associated with river discharge prevents upstream propagation of tides. The rapid increase of the first and second harmonics of  $M_2$  and compound tides inside these estuaries show the nonlinear response of the Mandovi and Zuari estuarine systems to tidal forcing. The variation of  $M_4/M_2$  amplitude ratio from the mouth to head indicates that tide is subjected to more asymmetry in the Zuari than that in the Mandovi. The increase of the first harmonic of  $M_2$  and decrease of relative surface phase ( $2M_2 - M_4$ ) inside the Mandovi and Zuari estuaries show that these estuaries are flood dominant.

### 1.2.4 Chapter 4

Chapter 4 deals with the simulations of salinity distribution in the Mandovi and Zuari estuaries. The simulation of the longitudinal variation of salinity during dry and wet seasons, freshwater effect on salinity distribution and the intraseasonal variations of salinity during wet season are described in this chapter. The flushing time using freshwater fraction method in the Mandovi and Zuari was calculated using the hybrid numerical model. Tidally averaged salinity and residual currents over a period of  $M_2$  tide were also calculated to quantify the freshwater influence on salinity. The measurements of salinity in the Mandovi estuary during the selected days of 2005–2007 were used to study intraseasonal variations of salinity during wet season. The residual circulation in the Mandovi and Zuari estuaries was also determined.

### 1.2.5 Chapter 5

The results and significant findings from present study described in the previous chapters are summarized in this chapter. The limitations of the present approach and suggestions for further studies to improve the present understanding are also given in this chapter.

# Chapter 2

## Data and Methodology

### 2.1 Introduction

This chapter gives a detailed account of the development of a hybrid network numerical model, which was developed for simulations of tides and salinity distribution in the Mandovi and Zuari estuaries. The data sets used for prescribing boundary conditions, validation of the model etc. are also described in this chapter. A finite difference numerical scheme was used for solving partial differential equations of motion, continuity and advection diffusion equation of salinity. The details of the data sets used for the present study and the formulation of a hybrid network numerical model are given in the following sections.

### 2.2 Data sets

Numerical modelling of physical phenomena such as tidal circulation and salinity distribution in an estuary require a number of data sets, which include bathymetry data, surface elevation data, salinity data, river discharge data etc. for prescribing open boundary conditions, model validation etc.

### **2.2.1 Bathymetry data**

Bathymetry data of the Mandovi, Zuari and Cumbarjua canal were obtained by digitizing the bathymetry maps (1968–1969) of minor ports survey organization, Ministry of Shipping and Transport, Government of India. The one dimensional upstream regions in the Mandovi, Zuari and Cumbarjua canal were schematized into 75, 81 and 32 segments respectively based on the description given by [Harleman and Lee, 1969].

### **2.2.2 Tides and salinity measurements during April and August 1993**

Shetye et al. [1995] made continuous measurements of tides and salinity during 7–9 April and 19–21 August 1993 in the Mandovi, Zuari and Cumbarjua canal. Sea level obtained from the above observations were used for the model validation.

### **2.2.3 Measurements of tides during March–April 2003**

Sea level measurements were carried out at 13 locations in the Mandovi, Zuari and the Cumbarjua canal. These measurements were part of the ICMAM (Integrated Coastal and Marine Area Management) under the Ministry of Earth Sciences, Government of India. There are six stations in the Mandovi estuary; five stations in the Zuari estuary and two stations in the Cumbarjua Canal where continuous measurements of tides using tide poles were carried out during 10 March to 13 April 2003.

### **2.2.4 Salinity measurements in the Mandovi during 2005–2007**

An important characteristic of southwest monsoon is the breaks in rainfall during this period. The break during rainfall reduce river discharge, which in turn causes intrusion of salinity to further upstream regions in the Mandovi and Zuari estuaries. Saline water is pushed back into the sea when the rainfall once again becomes active. To study this intraseasonal variations of salinity during this period, we carried out salinity measurements

along the longitudinal sections in the Mandovi estuary during the selected days of 2005–2007. This data were analysed to study the intraseasonal variations of salinity during wet season.

### **2.2.5 River discharge data**

The monthly mean averaged discharge data in 1993 at Ganjem, an upstream station in Mandovi estuary were obtained from Central Water Commission, Government. of India.

### **2.2.6 Rainfall data**

Rainfall data during 1999–2001 at Valpoi and Sanguem stations respectively in the Mandovi and Zuari estuaries, and rainfall data at Panaji near the mouth of the Mandovi and Zuari estuaries, during the selected days of 2005–2007 were obtained from India Meteorological Department.

## **2.3 Numerical model**

Numerical models have a variety of applications in scientific and engineering fields. Numerical models are widely used for the simulations of physical processes in ocean and have many applications in the coastal regions and estuaries. To simulate tidal circulation, sedimentation, salinity distribution etc. in an estuary, various modelling techniques such as physical modelling, analytical modelling etc. are used. Though physical modelling techniques are useful for the predictions of the estuarine processes, this approach is expensive and have limitations in scaling some physical parameters. Analytical modelling is another tool to study the estuarine systems and many studies were carried out in estuaries using analytical models [Ketchum, 1950, 1951a,b, 1954, 1955; Ippen and Harleman, 1961; Hansen and Rattray, 1965].



Simulation of estuarine processes requires proper representation of bottom topography, irregular coastline etc. The limitations of analytical modelling is that it assumes a regular geometry of systems. The geometry of an estuarine system has an important role on circulation and phase speed of waves. An improper representation of geometry does not show the important characteristics of estuarine dynamics.

Advances in computer technology in 1950s made the solution of equations, which represent the systems easy and fast and many models were developed using one dimensional equations of motion, continuity and advection diffusion equation of salinity [Lamoen, 1949; Hansen, 1956; Harleman et al., 1968; Bella and Dobbins, 1968; Dronkers, 1969]. Some of the studies carried out using one dimensional modelling approach are described in the following sections.

Lamoen [1949] used a one dimensional numerical model to simulate tides and tidal currents in the Panama Canal and Hansen [1956] proposed a numerical model for the non-linear tidal propagation in Ems estuary, Germany. The finite difference explicit numerical scheme was used in the model. Later on, a one dimensional numerical approach was proposed by Harleman et al. [1968] to simulate dispersion coefficient in Potomac estuary. Posmentier and Raymond [1979] used a one dimensional model and the coefficient of longitudinal diffusion for salt was calculated from the distribution of salinity observed in the Hudson estuary. Their results suggested that the density induced, gravitational, vertical circulation does not dominate the longitudinal diffusion of salt in the Hudson estuary. A one dimensional hydrodynamical model was used by Uncles and Jordan [1980] to describe the crosssectionally averaged Stokes drift and Eulerian residual (tidally averaged) currents in a section of the Severn estuary between Porthcawl and Sharpness.

A time dependent, one dimensional, advection diffusion equation was used by Holloway [1981] to predict salinity distribution in the vertically well mixed upper regions of the Bay of Fundy. Tidal asymmetries at Nauset Inlet was studied using a one dimensional numerical model by Speer and Aubrey [1985]. Thatcher and Harleman [1981]

used another one dimensional model to study the salinity fields in Delaware estuary and Shetye and Murty [1987] used a one dimensional model to estimate the annual salt budget in the Zuari estuary on the west coast of India. Giese and Jay [1989] used a one dimensional harmonic transport model, which provides a qualitative explanation for and accurate quantitative predictions of along channel variations in tidal properties in terms of the momentum balance.

Savenije [1993] proposed a predictive steady state salt intrusion model in alluvial estuaries. Their method applies equally well to density or tide driven mixing and it can be used for estuaries with a wide range of shapes, as long as the estuary is alluvial and the longitudinal variation of the cross sectional area can be described by an exponential function. Li and Elliot [1993] used an array of one dimensional models to simulate the vertical structure of tidal currents and temperature of North sea. They used a turbulence closure scheme proposed by Mellor and Yamada [1974].

Unnikrishnan et al. [1997] used a network numerical model in the Mandovi and Zuari estuaries to simulate the tidal decay during wet season. Gillibrand and Balls [1998] formulated a one dimensional salt intrusion model to investigate the hydrography of the Ythan estuary, a small shallow macro-tidal estuary in the north east of Scotland. Their model successfully simulated salinity distributions for periods of high and low river flow, and was used to illustrate how total oxidized nitrogen concentrations fluctuated in response to variations in river flow. A box model was developed by Pritchard [1969] to simulate tides.

Most of these studies were carried out to understand the basic dynamical processes in the estuarine systems. Though one dimensional models are successful in simulating tidal hydrodynamics to a great extent, its inability to represent the changes of circulation and mixing in the lateral and vertical directions, which are significant in many of the estuarine systems, are the major limitations of this modelling approach.

The development of new generation computers since 1970s paved the way for devel-

opment of two dimensional simulations of estuarine systems fast and less costly. Two dimensional models can simulate circulation in wide bays and estuaries much better than one dimensional models. [Leendertse, 1967] developed a two dimensional model and he used a finite difference scheme to solve partial differential equations. Later, many two dimensional vertically and laterally averaged models were developed.

[Reid and Bodin, 1968] used a two dimensional numerical storm surge model in Galveston Bay. They simulated tide in the Bay without including the surface stress term in the equations. Heaps [1969] developed a numerical model for the North sea.

Two dimensional models were developed by [Leendertse, 1970; Leendertse and Gritton, 1971a,b] for the simulations of water levels and velocities in well mixed estuaries. Prandle and Crookshank [1974] used two dimensional and one dimensional models using a finite difference scheme to simulate tides in the St. Lawrence River. They used two dimensional model and one dimensional models for wider and narrow regions respectively.

A two dimensional numerical model in the longitudinal and vertical plane was developed by Hamilton [1975] to study the vertical structure of current and salinity in the Rotterdam Waterway. Laterally averaged equations were used in the model and the equations were approximated by a finite difference initial value method. Ross et al. [1977] developed a vertically integrated numerical model for water quality and sediment transport and this model was also used for hurricane surge computation. Blumberg [1977] developed a real time numerical model to simulate the dynamics of Potomac River estuary. The model output showed that simulations of surface elevation, velocity and salinity fields were in good agreement with that of observations.

Blumberg [1978] carried out numerical experiments to get the detailed features of tidal characteristics in an estuary. The simulations were carried out for two cases, one for varying density and another for constant density. In this study, it was found that the discharge through any section, the tidal range, and the tidal phases were independent of the density structure. However, the tidal amplitudes, the mean elevation and the vertical

structure of longitudinal velocity changed considerably in the various experiments.

[Johns, 1978] developed a parametrization scheme for modelling turbulence in marine systems and an application was made to the determination of tidal structure in an elongated channel. Prandle [1978] used a two dimensional vertically integrated numerical model to simulate the distribution of residual flow and the variation in mean sea level in the southern North Sea.

A nonlinear numerical tidal model by Bowman and Chiswell [1982] was used in Hauraki Gulf to determine the water levels, velocities, shallow water tides, residual circulation, energy dissipation rates and vorticity. Falconer et al. [1986] developed a depth averaged model for the simulation of tidal circulation in Rattray Island. Hamilton [1990] carried out simulations of time and depth dependent salinity and current fields of the Columbia River estuary using a multi channel, laterally averaged estuary model.

Lee et al. [1993] used a depth averaged model to study the pollutant dispersal in Masan bay Korea. The numerical model used for the simulation was a modified version of [Falconer et al., 1986]. Rady et al. [1994] used a model to examine the astronomical tides in the Gulf of Suez, Egypt. A vertically averaged two dimensional model was used for simulations of tides.

Unnikrishnan et al. [1999b] developed a two dimensional barotropic numerical model based on shallow water wave equations to simulate the sea level and tidal circulation in the shelf regions of the central west coast of India including Gulf of Khambhat, west coast of India. Their study showed that the circulation in the region is dominated by barotropic tides.

[Wang et al., 2004] calculated the residence time of the Danshuei River through a series of numerical experiments using a laterally integrated two dimensional hydrodynamic eutrophication model (HEM-2D). There are many other laterally averaged models for modelling transport processes in narrow rivers and estuaries [Chen, 1989, 1990, 2003, 2004a,b; Chen et al., 2000; Chen, 2007].

The high power computing availability nowadays facilitates the simulations of three dimensional nature of the estuarine systems. Some of these kind of models used for the simulations of tidal hydrodynamics, salt transports are those of Leendertse et al. [1973]; Oey et al. [1985] and Ji et al. [2007].

### **2.3.1 Numerical model for simulations of tides and salinity in the Mandovi and Zuari estuaries**

Three dimensional models are generally too complex for routine applications and their use is still confined to situations where the detailed spatial definition is essential [Lewis, 1997]. The Mandovi and Zuari estuaries are very shallow and narrow estuaries and the proper schematization is easier in a 1D formulation at the upstream regions and a 2D formulation for the wider regions near the mouth. If the significant variations of estuarine processes occur in horizontal plane, a vertically integrated modelling approach can be employed. In the present study, for the simulation of tides and salinity, a hybrid network numerical model consisting of 2D and 1D models was used. The 2D numerical model in the hybrid model is the modified form of a vertically averaged 2D numerical model described by Unnikrishnan et al. [1999b]. The 2D model was used for simulating tides and salinity in the downstream regions in the Mandovi and Zuari estuaries. The cross sectional area of the Mandovi and Zuari estuaries decrease rapidly toward the upstream directions. Hence for the simulation of tides and salinity at these narrow upstream regions, we developed an area averaged 1D model using the formulation given by [Harleman and Lee, 1969; Thatcher and Harleman, 1972]. The 2D and 1D models were coupled at a distance of about 15 and 12 *km* for the Mandovi and Zuari respectively from the mouth of these estuaries (Figure 2.1).

### 2.3.2 2D model equations

The vertically averaged equations of momentum, continuity and advection diffusion equation of salinity were used in the 2D model. A Cartesian coordinate system was used for the present model domain where x and y-axis are positive toward east and north respectively.

The momentum equation in the transport form can be written as follows

$$\frac{\partial U}{\partial t} + \frac{\partial(uU)}{\partial x} + \frac{\partial(vU)}{\partial y} = -g(h+\eta)\frac{\partial\eta}{\partial x} + fV + A_H\nabla^2U - C_DU\frac{\sqrt{U^2+V^2}}{(h+\eta)^2} \quad (2.1)$$

$$\frac{\partial V}{\partial t} + \frac{\partial(uV)}{\partial x} + \frac{\partial(vV)}{\partial y} = -g(h+\eta)\frac{\partial\eta}{\partial y} - fU + A_H\nabla^2V - C_DV\frac{\sqrt{U^2+V^2}}{(h+\eta)^2} \quad (2.2)$$

The continuity equation can be written as

$$\frac{\partial\eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (2.3)$$

Advection diffusion equation of salinity is written as follows

$$\frac{\partial S}{\partial t} + \frac{\partial(uS)}{\partial x} + \frac{\partial(vS)}{\partial y} = K_x\frac{\partial^2 S}{\partial x^2} + K_y\frac{\partial^2 S}{\partial y^2} \quad (2.4)$$

Where  $U = u(h+\eta)$  and  $V = v(h+\eta)$

### 2.3.3 Equations in 1D model

The equations used in the one dimensional model are area averaged momentum and continuity equations and advection diffusion equation of salinity [Harleman and Lee, 1969; Thatcher and Harleman, 1972].

The one dimensional momentum equation can be written as

$$\frac{\partial Q}{\partial t} + \frac{2Q}{A}q - \frac{2bQ}{A} \frac{\partial \eta}{\partial t} = -gA \frac{\partial(z_0 + h + \eta)}{\partial x} - g \frac{Q |Q|}{AC^2R} \quad (2.5)$$

The continuity equation is written as follows

$$b \frac{\partial \eta}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \quad (2.6)$$

Chezy coefficient is calculated using the formula given below.

$$C = \frac{(1.49)}{n} R^{\frac{1}{6}} \quad (2.7)$$

Where  $n$  is the manning coefficient

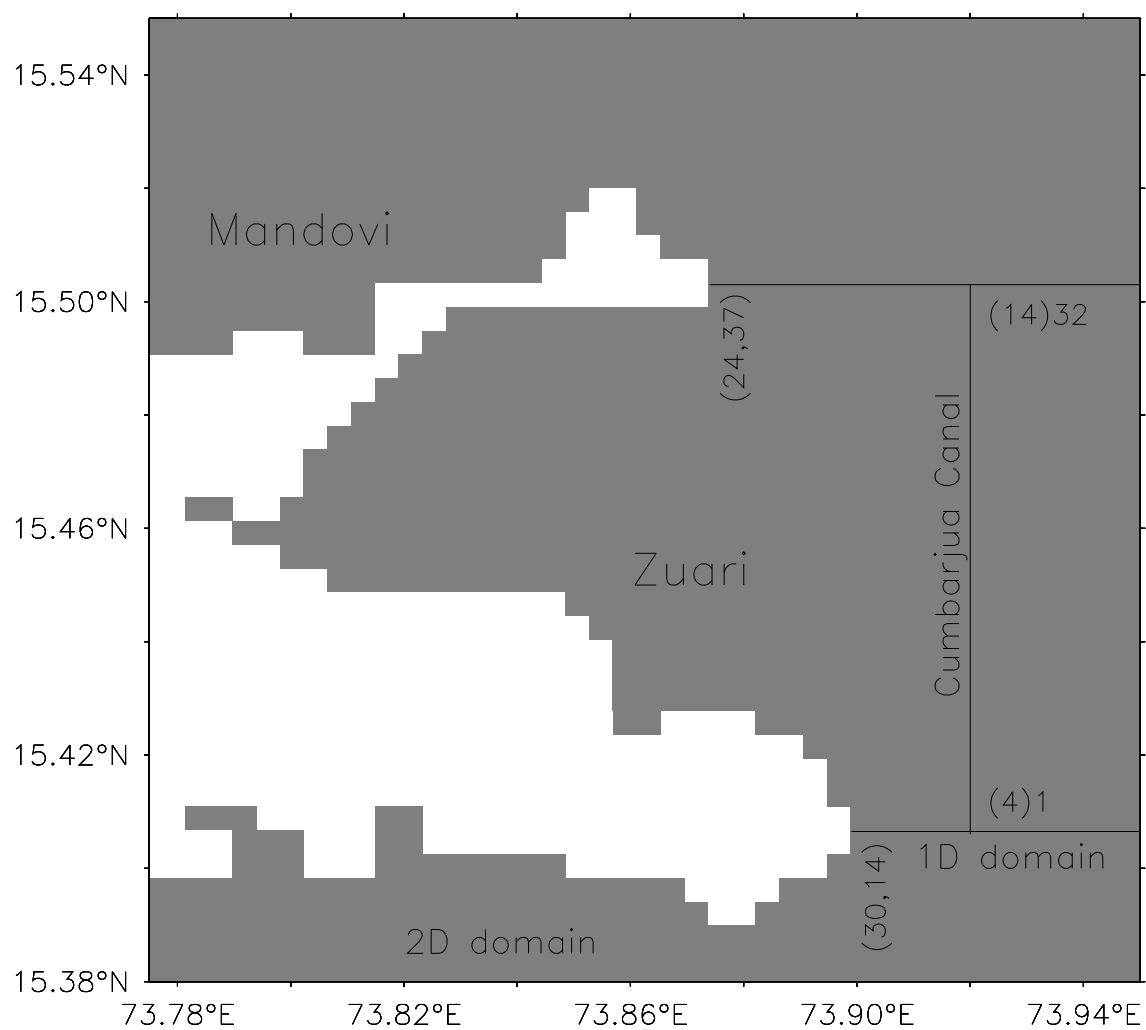
Area averaged advection diffusion equation of salinity can be written as

$$A \frac{\partial S}{\partial t} + \frac{\partial(QS)}{\partial x} = AK_x \frac{\partial^2 S}{\partial x^2} \quad (2.8)$$

### 2.3.4 Finite difference scheme

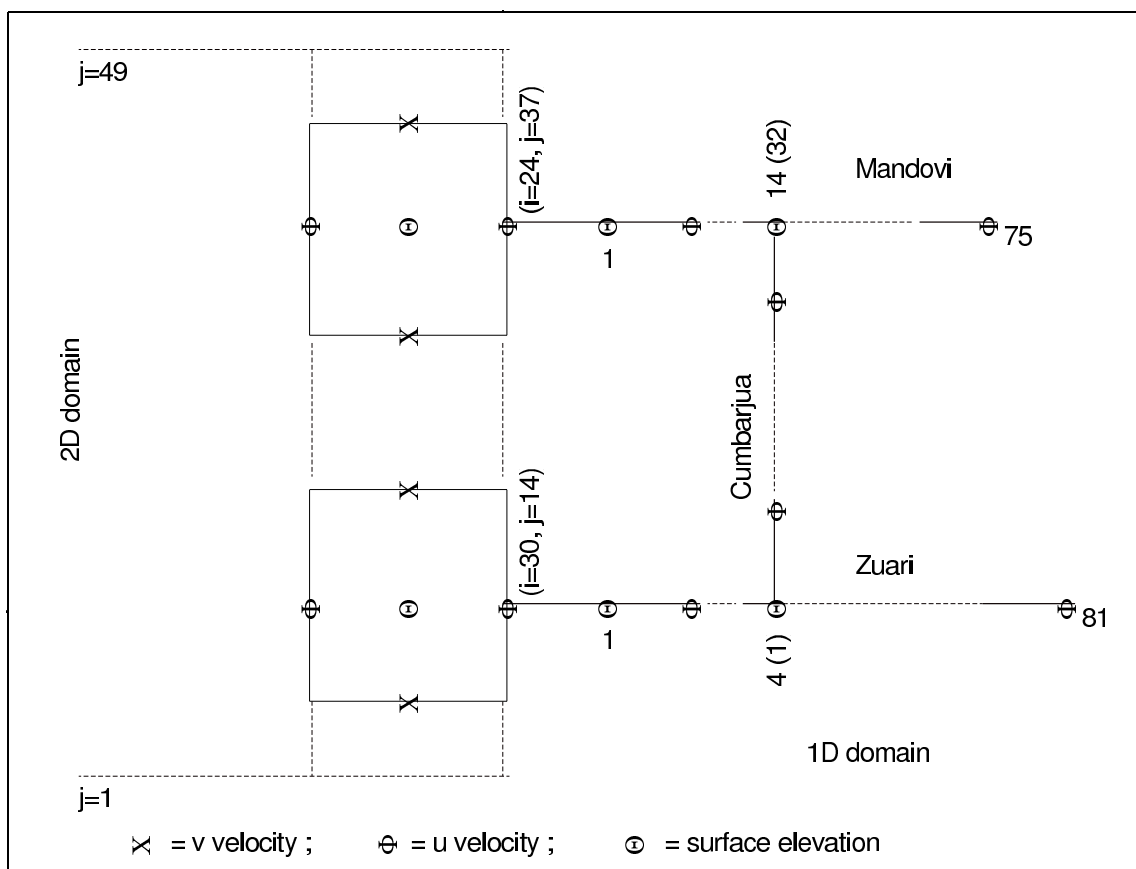
There are many numerical methods such as finite difference method, finite element method etc. for solving the partial differential equations. Finite difference schemes are widely

**Figure 2.1** Model domain of the Mandovi and Zuari estuaries.





**Figure 2.2** Schematic diagram showing the coupling between 2D and 1D models and two 1D models.



used numerical schemes because they give less complexity compared to other numerical schemes.

Hydrodynamic modelling of estuaries normally requires the physical dimensions to be approximated by a computational grid [Martin and McCutcheon, 1999]. There are various types of model grids and a grid is selected for approximating the solutions of differential equations based on what kind of numerical scheme is used. In the present model, an Arakawa C grid [Arakawa and Lamb, 1977; Thubum, 2007] was used (see Figure 2.2). Arakawa C grid is a staggered grid and u and v velocities are computed at the grid boundaries and free surface elevation and salinity are computed at the centre of the grid. The advantage of using this grid is that it enables the user to include barriers, across which no flow is allowed. Also, a zero velocity boundary condition can be applied at the closed boundaries [Grzechnik, 2000].

The leapfrog scheme was used to march in time. The leapfrog scheme is a three time level scheme having second order accuracy. Despite its three time level structure, the leapfrog scheme is efficient because it requires derivative computations only once at each time step. It is neutrally stable, with no dissipation error [Zhou, 2002].

The continuity equation in finite difference form can be written as

$$\frac{\eta_{i,j}^{n+2} - \eta_{i,j}^n}{2\Delta t} = - \left( \frac{U_{i,j}^{n+1} - U_{i-1,j}^{n+1}}{\Delta x} \right) - \left( \frac{V_{i,j}^{n+1} - V_{i,j-1}^{n+1}}{\Delta y} \right) \quad (2.9)$$

Advection diffusion equation of salinity in finite difference form can be written as

$$\begin{aligned} \frac{S_{i,j}^{n+2} - S_{i,j}^n}{2\Delta t} = & -\frac{1}{\Delta x} \left\{ \left( u_{i,j}^{n+1} \right) \left( \frac{S_{i+1,j}^{n+1} - S_{i,j}^{n+1}}{2} \right) + \left( u_{(i-1),j}^{n+1} \right) \left( \frac{S_{i,j}^{n+1} - S_{i-1,j}^{n+1}}{2} \right) \right\} \\ & -\frac{1}{\Delta y} \left\{ \left( v_{i,j}^{n+1} \right) \left( \frac{S_{i,j+1}^{n+1} - S_{i,j}^{n+1}}{2} \right) + \left( v_{i,j-1}^{n+1} \right) \left( \frac{S_{i,j}^{n+1} - S_{i,j-1}^{n+1}}{2} \right) \right\} \\ & + K_x \left( \frac{S_{i+1,j}^n + S_{i-1,j}^n - 2S_{i,j}^n}{\Delta x^2} \right) + K_y \left( \frac{S_{i,j+1}^n + S_{i,j-1}^n - 2S_{i,j}^n}{\Delta y^2} \right) \end{aligned} \quad (2.10)$$

The momentum equation along the x-axis in finite difference form can be written as

$$\begin{aligned} \frac{U_{i,j}^{n+2} - U_{i,j}^n}{2\Delta t} = & -\frac{1}{\Delta x} \left\{ \left( \frac{u_{i,j}^{n+1} + u_{i+1,j}^{n+1}}{2} \right) \left( \frac{U_{i,j}^{n+1} + U_{i+1,j}^{n+1}}{2} \right) - \left( \frac{u_{i-1,j}^{n+1} + u_{i,j}^{n+1}}{2} \right) \left( \frac{U_{i-1,j}^{n+1} + U_{i,j}^{n+1}}{2} \right) \right\} \\ & -\frac{1}{\Delta y} \left\{ \left( \frac{v_{i+1,j}^{n+1} + v_{i,j}^{n+1}}{2} \right) \left( \frac{U_{i,j}^{n+1} + U_{i,j+1}^{n+1}}{2} \right) - \left( \frac{v_{i+1,j-1}^{n+1} + v_{i,j-1}^{n+1}}{2} \right) \left( \frac{U_{i,j}^{n+1} + U_{i,j-1}^{n+1}}{2} \right) \right\} \\ & -\frac{g}{\Delta x} \left\{ \left( \frac{h_{i,j} + h_{i+1,j}}{2} + \frac{\eta_{i,j}^{n+1} + \eta_{i+1,j}^{n+1}}{2} \right) \left( \eta_{i+1,j}^{n+1} - \eta_{i,j}^{n+1} \right) \right\} \\ & + f \left\{ \left( \frac{V_{i,j}^{n+1} + V_{i+1,j}^{n+1} + V_{i,j-1}^{n+1} + V_{i+1,j-1}^{n+1}}{4} \right) \right\} \\ & + A_H \left\{ \left( \frac{U_{i+1,j}^n - 2U_{i,j}^n + U_{i-1,j}^n}{\Delta x^2} \right) + \left( \frac{U_{i,j+1}^n - 2U_{i,j}^n + U_{i,j-1}^n}{\Delta y^2} \right) \right\} \\ & - C_D (U_{i,j}^n) \left\{ \sqrt{\left( \frac{(U_{i,j}^n)^2 + (V_{i,j}^n)^2}{(h_{i,j} + \eta_{i,j}^n)^2} \right)} \right\} \end{aligned} \quad (2.11)$$

Momentum equation along the y-axis in finite difference form is written as

$$\begin{aligned}
\frac{V_{i,j}^{n+2} - V_{i,j}^n}{2\Delta t} = & -\frac{1}{\Delta x} \left\{ \left( \frac{u_{i,j}^{n+1} + u_{i,j+1}^{n+1}}{2} \right) \left( \frac{V_{i,j}^{n+1} + V_{i+1,j}^{n+1}}{2} \right) - \left( \frac{u_{i-1,j}^{n+1} + u_{i-1,j+1}^{n+1}}{2} \right) \left( \frac{V_{i-1,j}^{n+1} + V_{i,j}^{n+1}}{2} \right) \right\} \\
& -\frac{1}{\Delta y} \left\{ \left( \frac{v_{i,j}^{n+1} + v_{i,j+1}^{n+1}}{2} \right) \left( \frac{V_{i,j}^{n+1} + V_{i,j+1}^{n+1}}{2} \right) - \left( \frac{v_{i,j}^{n+1} + v_{i,j-1}^{n+1}}{2} \right) \left( \frac{V_{i,j}^{n+1} + V_{i,j-1}^{n+1}}{2} \right) \right\} \\
& -\frac{g}{\Delta y} \left\{ \left( \frac{h_{i,j} + h_{i,j+1}}{2} + \frac{\eta_{i,j}^{n+1} + \eta_{i,j+1}^{n+1}}{2} \right) (\eta_{i,j+1}^{n+1} - \eta_{i,j}^{n+1}) \right\} \\
& -f \left\{ \left( \frac{U_{i,j}^{n+1} + U_{i,j+1}^{n+1} + U_{i-1,j}^{n+1} + U_{i-1,j+1}^{n+1}}{4} \right) \right\} \\
& + A_H \left\{ \left( \frac{V_{i+1,j}^n - 2V_{i,j}^n + V_{i-1,j}^n}{\Delta x^2} \right) + \left( \frac{V_{i,j+1}^n - 2V_{i,j}^n + V_{i,j-1}^n}{\Delta y^2} \right) \right\} \\
& - C_D (V_{i,j}^n) \left\{ \sqrt{\frac{\left( (U_{i,j}^n)^2 + (V_{i,j}^n)^2 \right)}{\left( h_{i,j} + \eta_{i,j}^n \right)^2}} \right\}
\end{aligned} \tag{2.12}$$

One dimensional equations of momentum, continuity and salt equation were also solved in a similar fashion.

### 2.3.5 Coupling of numerical models

The 2D model domain extends to 15 and 12 *km* in the Mandovi and Zuari estuaries respectively from the mouth (see Figure 2.1). A 1D model was used for the upstream regions of the Mandovi and Zuari estuaries and for the Cumbarjua canal.

### 2.3.6 Coupling between 2D and 1D models

Surface elevation and salinity at the 1<sup>st</sup> grid point of the 1D domain of the Mandovi and Zuari were calculated using the following formulation

$$\eta_i^{n+2} = \eta_i^n - \left( \frac{2\Delta t}{\Delta x b_i} \right) \left( Q_i^{n+1} - b_i \left( U_{i-1,j}^{n+1} \right) \right) \quad (2.13)$$

$$\begin{aligned} S_i^{n+2} = S_i^n - \left( \frac{\Delta t}{\Delta x A_i} \right) \left\{ Q_i^{n+1} (S_{i+1}^{n+1} - S_i^{n+1}) + A_i u_{i-1,j}^{n+1} (S_i^{n+1} - S_{i-1,j}^{n+1}) \right\} \\ + K_x \left( \frac{2\Delta t}{\Delta x^2} \right) (S_{i-1,j}^n + S_{i+1}^n - 2S_{i,j}^n) \end{aligned} \quad (2.14)$$

Where  $U_{i-1,j}^{n+1}$  and  $S_{i-1,j}^{n+1}$  are respectively transport and salinity from 2D model. In the above equation, (i-1) corresponds to 24 and j corresponds to 37 in the Mandovi. In the Zuari, (i-1) corresponds to 30 and j corresponds to 14.  $Q_i^{n+1}$  and  $S_i^{n+1}$  are respectively transport and salinity from 1D models. Note that  $Q_i^{n+1}$  and  $S_i^{n+1}$  are general notations used for transport and salinity in 1D models in the above equations. But for the following calculations,  $Q_i^{n+1}$  and  $S_i^{n+1}$  are replaced by  $Qm_i^{n+1}$ ,  $Qz_i^{n+1}$ ,  $Qc_i^{n+1}$  and  $Sm_i^{n+1}$ ,  $Sz_i^{n+1}$ ,  $Sc_i^{n+1}$  respectively for the Mandovi, Zuari and Cumbarjua canal.

### 2.3.7 Coupling between two 1D models

Calculation of surface elevation and salinity at the 4<sup>th</sup> grid point in the Zuari and 1<sup>st</sup> grid point in the Cumbarjua (see the 4(1) grid point in Figure 2.2) were made as follows

$$\eta z_i^{n+2} = \eta z_i^n - \left( \frac{2\Delta t}{\Delta x b z_i} \right) (Q z_i^{n+1} + Q c_i^{n+1} - Q z_{i-1}^{n+1}) \quad (2.15)$$

$$\begin{aligned} S z_i^{n+2} = & S z_i^n - \left( \frac{\Delta t}{2\Delta x A_i} \right) \\ & \{ Q z_i^{n+1} (S z_{i+1}^{n+1} - S z_i^{n+1}) + Q z_{i-1}^{n+1} (S z_i^{n+1} - S z_{i-1}^{n+1}) + Q c_i^{n+1} (S c_{i+1}^{n+1} - S z_i^{n+1}) \} \\ & + K_x \left( \frac{2\Delta t}{\Delta x^2} \right) \{ (S z_{i-1}^n + S z_{i+1}^n - 2S z_i^n) + (S c_{i+1}^n + S c_i^n - 2S c_i^n) \} \end{aligned} \quad (2.16)$$

As shown in the Figure 2.2, the 4<sup>th</sup> grid point in the Zuari and 1<sup>st</sup> grid point in the Cumbarjua are same. Therefore,

$$\eta c_i^{n+2} = \eta z_i^{n+2} \quad (2.17)$$

$$S c_i^{n+2} = S z_i^{n+2} \quad (2.18)$$

Calculation of surface elevation and salinity at the 14<sup>th</sup> grid point in the Mandovi and 32<sup>nd</sup> grid point in the Cumbarjua (see the 14(32) grid point in Figure 2.2) were calculated in a similar fashion.

$$\eta m_i^{n+2} = \eta m_i^n - \left( \frac{2\Delta t}{\Delta x b m_i} \right) (Q m_i^{n+1} - Q c_i^{n+1} - Q m_{i-1}^{n+1}) \quad (2.19)$$

$$\begin{aligned}
Sm_i^{n+2} = & Sm_i^n - \left( \frac{\Delta t}{2\Delta x A_i} \right) \\
& \{ Qm_i^{n+1} (Sm_{i+1}^{n+1} - Sm_i^{n+1}) + Qm_{i-1}^{n+1} (Sm_i^{n+1} - Sm_{i-1}^{n+1}) + Qc_i^{n+1} (Sc_{i+1}^{n+1} - Sm_i^{n+1}) \} \\
& + K_x \left( \frac{2\Delta t}{\Delta x^2} \right) \{ (Sm_{i-1}^n + Sm_{i+1}^n - 2Sm_i^n) + (Sc_{i-1}^n + Sc_i^n - 2Sc_i^n) \}
\end{aligned} \tag{2.20}$$

The 14<sup>th</sup> grid point in the Mandovi and 32<sup>nd</sup> grid point in the Cumbarjua are same (see Figure 2.2). Therefore,

$$\eta c_i^{n+2} = \eta m_i^{n+2} \tag{2.21}$$

$$Sc_i^{n+2} = Sm_i^{n+2} \tag{2.22}$$

Note that (see Equation 2.15) for calculation of surface elevation at the junction of the Zuari and Cumbarjua, the transport at first grid point of the Cumbarjua was added but that of Mandovi, the transport at the last grid point of the Cumbarjua was subtracted (see Equation 2.19), as per sign convention used, the flow in the Cumbarjua canal is taken as positive from the Zuari side to the Mandovi side.

### 2.3.8 Freshwater influx inclusion in the model

Freshwater influx was included in the model by calculating transport from the river discharge data at the upstream end of the model domain. Transport at the upstream end of the model domain was calculated as follows.

$$q_n^{n+1} = \frac{D}{\Delta x} \quad (2.23)$$

Where  $q$  is freshwater influx per unit channel length ( $m^2s^{-1}$ )

### 2.3.9 Stability criterion of the numerical scheme

The stability of the scheme was determined by Courant-Friedrichs-Lewy (CFL) stability criterion, which can be written as follows

$$\Delta t \leq \frac{(\Delta x, \Delta y)}{\sqrt{2g(h + \eta)}} \quad (2.24)$$

Where  $\Delta t$  is the time step, which was chosen as 15 seconds in the present model.  $\Delta x$  and  $\Delta y$  are space increments in x and y-directions, which were chosen as 500 m. The grid spacing between x and y-directions should be minimised so that it can resolve the effect of irregular coastlines of the estuaries and bays better, but the reduction in grid spacing leads to small time step and this in turn consumes more computational time. In the present model, the  $\Delta x$  and  $\Delta y$  were chosen as 500 m to represent islands and embayments of the Mandovi and Zuari estuaries more accurately.



### **2.3.10 Initial and Boundary conditions**

At the western boundary (open boundary) of the model, surface elevation and salinity were defined as a function of time, while zero flux conditions were applied in the eastern, southern and northern boundaries. For the simulation of surface elevation and tidal currents, the model was initialized with zero surface elevation and velocity throughout the network. At upstream end points of the model domain, transport was calculated according to the river discharge rate. For the simulation of longitudinal distribution of salinity, the model was initialized with constant salinity at different sections of the model domain based on the observations available in 1993.