

# 3

## Numerical models

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### 3.1 INTRODUCTION

In a typical partially-mixed estuary, such as the Mandovi or Zuari, the tidally-averaged circulation consists of a downstream directed surface flow of fresher water and an upstream-directed flow of more saline water at the bottom. This circulation, however, is much weaker than the circulation observed during a tidal cycle, particularly when the tidal range is large (well over a metre). For practical applications such as determination of the fate of pollutants and other passive and active tracers, it is often important to simulate this more energetic circulation within a tidal cycle.

Variability in estuaries is a function of three-dimensional space and time ( $x, y, z$ , and  $t$ ). The partial differential equations that describe tidal circulation and salinity distribution in an estuary consist of the momentum equations, the equation of continuity, and the conservation equation for salt. A description of these equations is given in many text books on estuarine dynamics (Officer 1976). These differential equations cannot be solved analytically, except in very special situations. With the development of computers and advances in numerical methods, many numerical models have been developed for solving complex three-dimensional estuarine problems. Nevertheless, often, simpler models suffice.

The simplest type of these models is a one-dimensional model, often used for application to a narrow estuary. If wider sections are present in one such estuary, then such models can be supplemented by two-dimensional models. This chapter describes models of Mandovi and Zuari estuaries that follow both these approaches.

The next section describes a one-dimensional network model that was used to simulate water level heights in the estuary, and section 3.3 describes a model that uses the two-dimensional formulation in the wider sections of the estuaries and is one-dimensional in the narrower sections.

### 3.2 NETWORK MODEL OF MANDOVI–ZUARI ESTUARIES

In an early attempt at modelling of Mandovi–Zuari estuaries, Shetye and Murty (1987) used a one-dimensional model to simulate the annual cycle of salinity in the Zuari estuary. The model was successful in simulating the observed average salinity over a tidal cycle during different months of a year along the entire stretch of the Zuari. This model did not resolve the tides. It looked at the tides as merely a mechanism that permits diffusion of salinity in the channels.

Unnikrishnan *et al.* (1997) resolved the tides in a model constructed by connecting all the major tributaries of Mandovi and Zuari and the Cumbarjua Canal. In this network model, each estuary or river is represented by a one-dimensional channel. Since the channels are connected, we refer to the model as a ‘network model’. This model was used to simulate tides in the estuarine system, to study the dynamics of tidal propagation, and to identify the changes introduced in water-level variation by runoff during the wet season. The model used the following equations for conservation of momentum and mass in a one-dimensional channel.

$$\frac{\partial U}{\partial t} + \frac{2U}{A}q - \frac{2bU}{A} \frac{\partial \eta}{\partial t} = -gA \frac{\partial}{\partial x}(z_0 + h + \eta) - g \frac{U|U|}{AC^2R}, \quad (3.1)$$

$$b \frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} - q = 0, \quad (3.2)$$

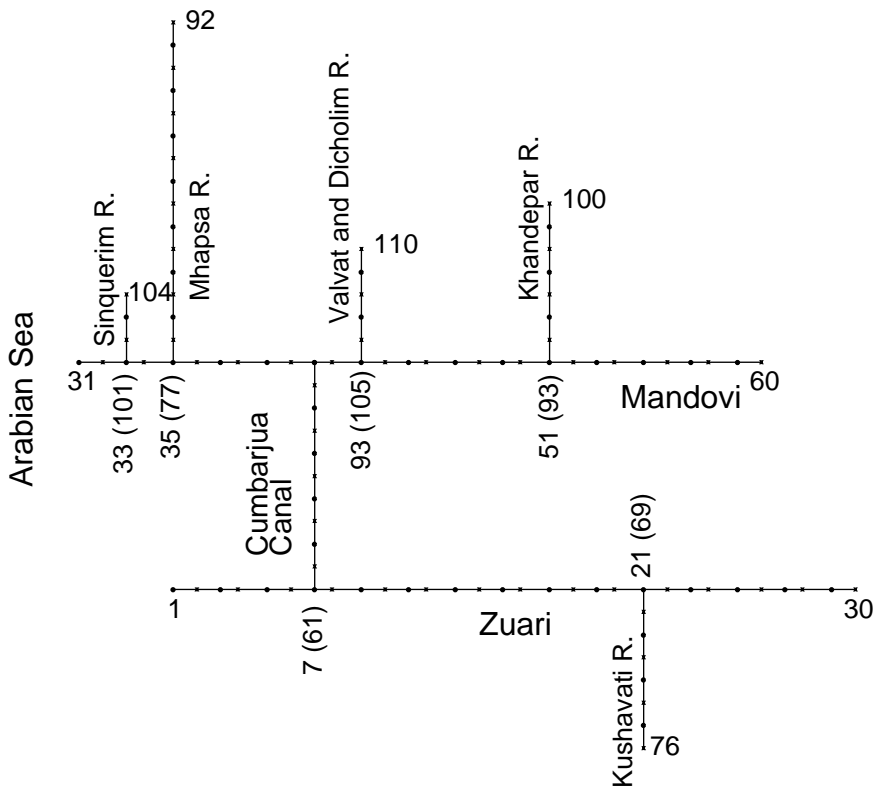
where  $t, x, U, \eta, q, g, h$  and  $R$  are, respectively, time, along-channel coordinate (increasing in upstream direction), along-channel transport, surface elevation with respect to mean water level, freshwater influx per unit channel length, acceleration due to gravity, depth, and hydraulic radius;  $z_0$  is the height between bottom of the channel and an arbitrary datum below the bottom;  $b_s$  is the width in which along-channel flow occurs, whereas width  $b$  includes mud flats, which act as storage.  $R = (A/P_r)$ ,  $P_r$  being the wetted perimeter and  $A$  the area of cross section (excluding mud flats);  $C = (1.49/n)R^{1/6}$ , where  $n$  is the Manning coefficient. The numerical scheme used by Harleman and Lee (1969) was used to solve the above equations. In this scheme, the continuity equation is solved at odd grid points to compute  $\eta$  at the next time step and the momentum equation is solved at even grid points to compute  $U$ . The original scheme of Harleman & Lee (1969) was developed for a single channel. For developing a model for the Mandovi–Zuari estuarine system, Unnikrishnan *et al.* (1997) modified the above scheme for application to a network

of channels. This was done by defining the equation of continuity at the junction of the network of more than two channels as follows:

$$\Delta x b_i \frac{\eta_{i,t+\Delta t} - \eta_{i,t}}{\Delta t} = U_{i-1,t} - U_{i+1,t} - U_{k,t}, \tag{3.3}$$

where  $k$  is the adjacent grid point located in a channel connected to the main channel defined by grid points  $(i - 1)$ ,  $i$ , and  $(i + 1)$ .

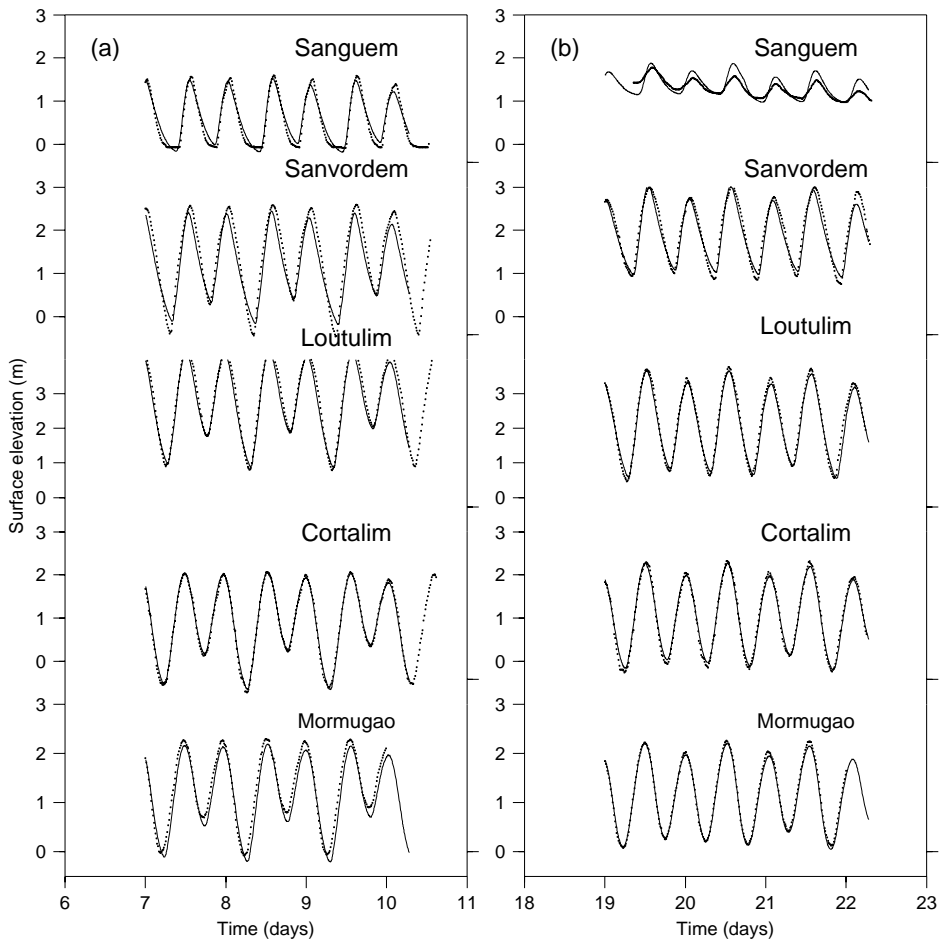
In the network model, as seen in figure 3.1, the Kushavati River is represented by a channel that is connected to the Zuari. The Mhapsa, Sinquerim, and Khandepar



**Figure 3.1** Schematic representation of the one-dimensional network model. The two main estuaries, Mandovi and Zuari, the connecting channel, Cumbarjua Canal, and the major rivers that join the estuaries are represented by a one-dimensional model each. In the numerical staggered grid used, the stars (dots) indicate the computation points for velocity (surface elevation). The numbers shown indicate segment numbers. An intersection of two channels is assigned two grid-points: the first refers to the main channel (estuary) and the second, shown in brackets, to an intersecting channel (river). The grid spacing is 2 km. (After Unnikrishnan *et al.* 1997.)

rivers are represented by a channel each, while Dicholim and Valvat rivers are represented by a single channel and are connected to the Mandovi estuary. Each estuarine channel is divided into a number of segments. The parameters that describe a segment are the equivalent depth and equivalent breadth, which are the representative values for that particular segment. The distance between any two adjacent segments or the grid space used is 2 km and the time step used for numerical integration is 110. The values of Manning coefficient ( $n$ ) used varied from 0.025 to 0.030. When channel widths are less than 100 m,  $n$  was set at 0.03; elsewhere, it was 0.02.

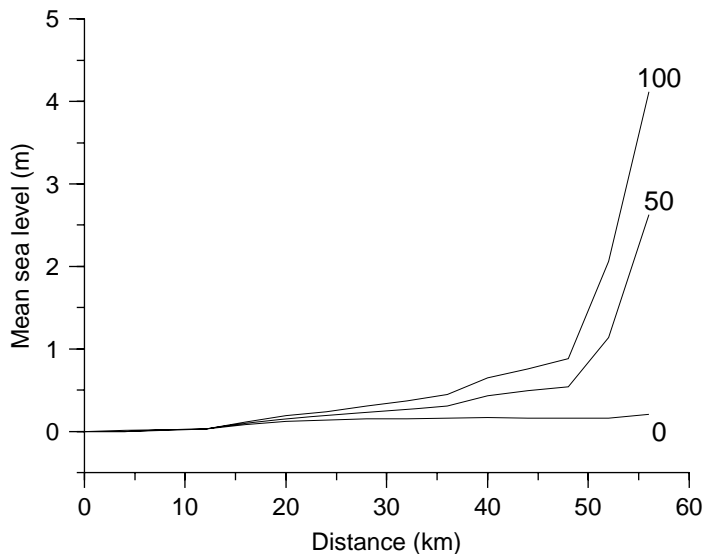
The tides simulated using the network model at various locations for the period, when observations were available in April (dry season) and August (wet season) in the Zuari estuary, are shown in figure 3.2. No significant change in tidal ranges is



**Figure 3.2** Simulated surface elevations (one-dimensional network model) plotted with observed surface elevations in the Zuari estuary during **(a)** 7–9 April 1993 (dry season) and **(b)** 19–21 August 1993 (wet season). Continuous (dotted) lines represent model (observed) values. (After Unnikrishnan *et al.* 1997.)

found at Cortalim and Loutulim when compared to that at Mormugao, suggesting that tides propagate upstream without undergoing any significant change for a distance of about 40km (up to Sanvordem) from the mouth. At Sanguem, however, observations show a rapid decay during the wet season, which is simulated well by the model. The characteristics of tidal propagation in the Mandovi estuary are similar to those in the Zuari, and are therefore not shown. Tides at Ganjem show a rapid decay during August 1993, just as is observed at Sanguem in the Zuari.

The model reproduces the observed increase of mean sea level towards upstream of the estuaries (Shetye *et al.* 1995) during wet seasons. When the river discharge is high, a pressure gradient force develops from the head towards downstream of the estuaries. In order to simulate this phenomenon, the model was run for different discharge rates, namely, 0, 50, and  $100\text{m}^3\text{s}^{-1}$ . The runs were made for a period of  $M_2$  tide (12 hours and 42 minutes), which is the principal lunar tidal constituent, and the values of surface elevation obtained during each time step were used to compute the average value over the tidal period (figure 3.3). When river discharge is zero, there is no variation of mean sea level from mouth to head. In the simulations with discharge rates of 50 and  $100\text{m}^3\text{s}^{-1}$ , an increase in mean sea level towards upstream is found. This increased mean sea level in the upstream direction generates a downstream directed current in wet seasons.



**Figure 3.3** Simulated mean sea level (one-dimensional network model) in the Zuari estuary for different river discharges (0, 50, and  $100\text{m}^3\text{s}^{-1}$ ) using the network model. The simulations were made for an  $M_2$  tide (period of 12 hours and 42 minutes) and sea surface elevations obtained at each time step were averaged over one tidal period to compute the mean sea level. (After Unnikrishnan *et al.* 1997.)

### 3.3 HYBRID NETWORK TWO-DIMENSIONAL MODEL

A feature of the Mandovi and Zuari estuaries is that the width of each of the two estuaries is large up to a distance of about 10km near the mouth, after which the channel narrows considerably. Manoj and Unnikrishnan (2007) have developed a hybrid model that uses a two-dimensional model for the wide portion near the mouths of the Mandovi and Zuari, and a one-dimensional network model for the rest of the system. They used the model to study the tidal circulation and salinity distribution.

To develop a two-dimensional vertically averaged model, the equations of momentum in  $x$  and  $y$  directions and the equation of continuity are integrated over the water column in the vertical direction (see Leendertse and Gritton 1971 for details). The vertically averaged equations can be written as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0; \quad (3.4)$$

$$\begin{aligned} \frac{\partial U}{\partial t} + \frac{\partial}{\partial x}(uU) + \frac{\partial}{\partial y}(vU) = & -g(h + \eta) \frac{\partial \eta}{\partial x} + fV \\ & + A_H \nabla^2 U - C_D \frac{U \sqrt{U^2 + V^2}}{(h + \eta)^2} \end{aligned} \quad (3.5)$$

$$\begin{aligned} \frac{\partial V}{\partial t} + \frac{\partial}{\partial x}(uV) + \frac{\partial}{\partial y}(vV) = & -g(h + \eta) \frac{\partial \eta}{\partial y} - fU \\ & + A_H \nabla^2 V - C_D \frac{V \sqrt{U^2 + V^2}}{(h + \eta)^2} \end{aligned} \quad (3.6)$$

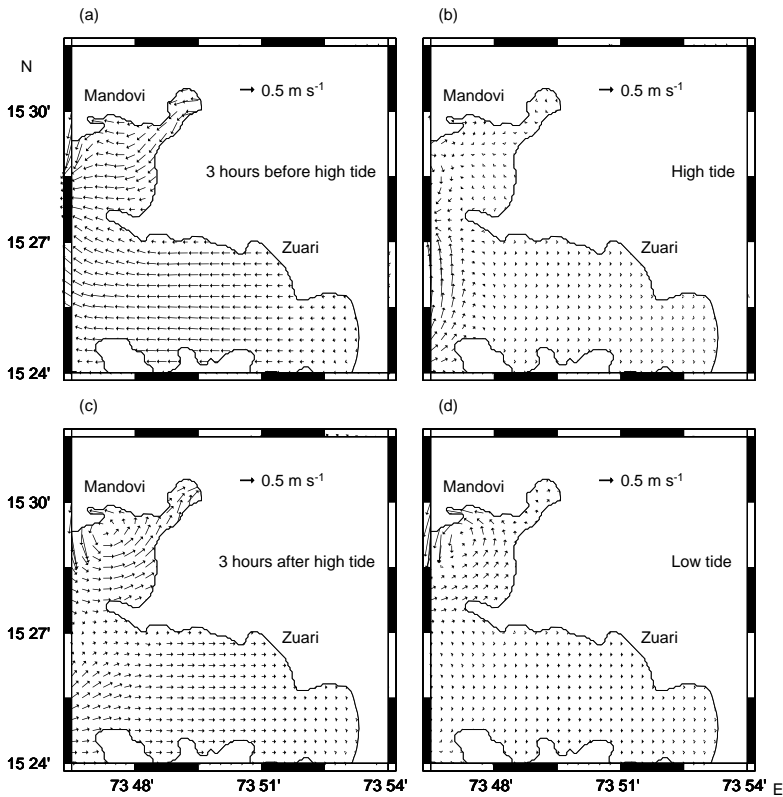
$$\frac{\partial S}{\partial t} + \frac{\partial}{\partial x}(uS) + \frac{\partial}{\partial y}(vS) = K_x \frac{\partial^2 S}{\partial x^2} + K_y \frac{\partial^2 S}{\partial y^2} \quad (3.7)$$

Equation (3.4) is the continuity equation, equations (3.5) and (3.6) are the momentum equations in  $x$  and  $y$  directions respectively, and equation (3.7) is the conservation equation for salt;  $x$  and  $y$  are the horizontal directions in a Cartesian co-ordinate system,  $\eta$  is the surface elevation with respect to mean sea level,  $h$  the still water depth,  $u$  and  $v$  are the vertically integrated velocity components in  $x$  and  $y$  directions,  $g$  the acceleration due to gravity,  $f$  the Coriolis parameter,  $C_D$  the bottom friction coefficient, and  $A_H$  the horizontal diffusion coefficient.  $U = (h + \eta)u$  and  $V = (h + \eta)v$  are the transports in  $x$  and  $y$  directions.  $S$  is the salinity and  $K_x$  and  $K_y$  are the diffusion coefficients in  $x$  and  $y$  directions respectively. The grid resolution is 500m and the time step used is 15s. The value chosen for  $K_x$  and  $K_y$  are 100 and  $10\text{m}^2\text{s}^{-1}$  respectively. The value of  $C_D$  used is 0.002. Observed salinities at Mormugao during April 1993 and August 1993 are used for prescribing open boundary conditions along the open boundary at the mouth.

One-dimensional models are connected to the two-dimensional model domain where the estuaries become narrow. Besides, Cumberjua Canal and other tributaries are also represented by a one-dimensional model each. This entire network model is referred to as a hybrid model. The equation of momentum and continuity used for the one-dimensional models in this hybrid model are the same as those described in the previous section. Additionally, we used an equation for the conservation of salt in the one-dimensional form (Harleman and Lee 1969):

$$A \frac{\partial S}{\partial t} + \frac{\partial}{\partial x}(uS) = AK_x \frac{\partial^2 S}{\partial x^2}. \quad (3.8)$$

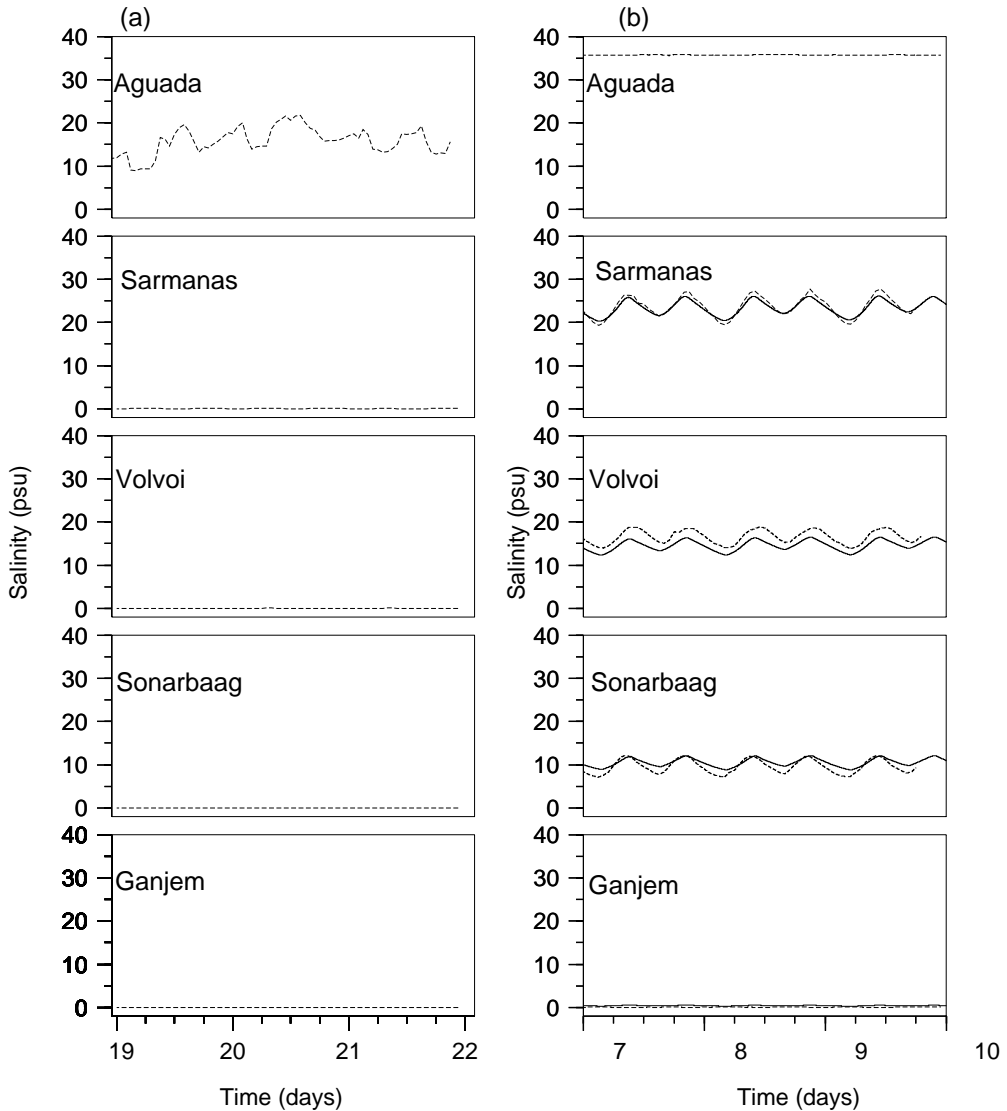
In the one-dimensional models also, the grid resolution is 500m, and the value of the diffusion coefficient is  $100 \text{ m}^2 \text{ s}^{-1}$ . The tidal currents simulated using the hybrid model during a spring tide are shown in figure 3.4. The model runs made for a few



**Figure 3.4** Simulated tidal circulation in a two-dimensional model of the bays of the Mandovi and Zuari estuaries during a spring tide. The timings of the occurrence of low tide and high tide are with respect to Mormugao: (a) three hours before the occurrence of low tide, (b) at low tide, (c) three hours after low tide, and (d) at high tide. (After Manoj and Unnikrishnan 2007.)

months, consisting of many spring and neap cycles, have shown that the magnitudes of currents in the downstream regions vary between  $0.4$  and  $0.8 \text{ ms}^{-1}$ .

The simulations (figure 3.5) using the hybrid model were made to study the longitudinal salinity distribution during dry and wet seasons. The results indicate that the model reproduces the longitudinal variation of salinity very well during the dry season and reasonably well during the wet season. During the dry season,



**Figure 3.5** Simulated (two-dimensional model) and observed distribution of salinity at various locations in the Mandovi estuary: (a) 7–9 April 1993 (dry season) and (b) 19–21 August 1993 (wet season). The continuous (dotted) lines represent model (observed) salinities. (After Manoj and Unnikrishnan 2007.)



the estuaries are well mixed, and during wet season, they are partially stratified in the downstream regions and nearly free from salt in the upstream regions. The present study illustrates that the model is capable of reproducing the observed salinity distribution fairly well and is useful for determining the longitudinal salinity distribution in the Mandovi and Zuari estuaries. The main inputs required for the model runs are accurate boundary conditions: tides and salinity distribution along the open boundary at the mouth and freshwater influx at the head of the estuaries.

### 3.4 CONCLUSIONS

All the efforts made so far at simulating the Mandovi–Zuari estuarine system treat the estuary as a well-mixed estuary. While this is a good approximation to simulate the horizontal distribution of active and passive variables of the estuaries, the next challenge lies in developing the capability to simulate distribution in the vertical. It is hoped that this summary of work in mathematical modelling on the Mandovi and Zuari estuaries carried out so far will induce researchers to take up this challenge.

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