

# Chapter 4

## Salinity distribution in the Mandovi and Zuari estuaries

### 4.1 Introduction

This chapter describes salinity distribution in the Mandovi and Zuari estuaries. The longitudinal variations of salinity during dry and wet seasons, the intraseasonal variations of salinity during wet season, tidally averaged salinity and residual currents for varying river discharge and flushing time are discussed in this chapter.

As mentioned in the Chapter 1, salinity distribution in the Mandovi and Zuari estuaries shows large variations during a year. During wet season, heavy rainfall and subsequent river discharge into the catchment area stratifies of about 10 to 12 *km* from the mouth of these estuaries while the upstream regions of about 40 *km* become completely freshwater. During dry season, these estuaries are vertically well mixed throughout the length.

### 4.1.1 Numerical model

For the simulation of longitudinal distribution of salinity, 2D and 1D advection-diffusion equations of salinity were included in the tidal model. As mentioned earlier, unlike many other estuaries in the world, the Mandovi and Zuari estuaries are very unique in terms of salinity distribution associated with southwest monsoon. These estuaries are vertically well mixed most parts of the year. Only during June to September, the downstream regions of about 10 to 12 *km* from the mouth of these estuaries become partially mixed and the rest of these channels of about 40 *km* become fully freshwater. Hence, the density difference was taken as zero in the present model. The finite difference scheme for solving advection-diffusion equation of salinity and other details of model formulation for the simulation of salinity distribution are described in Chapter 2. The boundary conditions for the simulation of salinity during dry and wet seasons and the results are described in the following sections.

### 4.1.2 Initial and Boundary conditions

At the open boundary of the model, salinity was defined as a function of time, the model was initialized with constant salinity at different sections of the model domain based on the observations in 1993. The observations of salinity available for 3 days each in April and August 1993 were not sufficient to use as open boundary conditions, because the model could not reach the steady state during this time. Since the salinity remains about 35 *psu* throughout the tidal cycles during dry season at the mouth of these estuaries, salinity was defined as a constant value of 35.17 *psu* at the open boundary during dry season to force the model. Salinity varies from 7 to 22 *psu* in a tidal cycle at the mouth during wet season. So salinity was defined as a cosine function that can vary from 7 to 22 *psu* during a tidal cycle ( 12 *hours*). The cosine function used for prescribing the boundary condition in the model is given below.

$$S(t) = 15.0 + 7\cos(\omega t) \quad (4.1)$$

$$\omega = \frac{2\pi}{T} \quad (4.2)$$

Where  $T$  is the period

### 4.1.3 Diffusion coefficient

The diffusion coefficient for salinity is subjected to seasonal variations from the mouth to upstream regions in the Zuari estuary [Shetye and Murty, 1987]. The model was run for varying salinity diffusion coefficient values range from 10 to 250  $m^2s^{-1}$ . But we used 100 and 150  $m^2s^{-1}$  for the downstream and upstream regions respectively in the present model, because these values gave better match with that of observed.

## 4.2 Results

The model was run for two cases, simulating longitudinal distribution of salinity during dry and wet seasons in the Mandovi and Zuari estuaries and Cumbarjua canal. In the first case, the model was run for simulating salinity distribution during dry season and in the second case, the simulations were carried out for wet season. The model was run for two cases using different boundary conditions at the open boundary during dry and wet seasons.

### 4.2.1 Salinity distribution during dry season

During this season (April), the model was run for 10 days for the simulation of longitudinal distribution of salinity. The model reached steady state after 10 tidal cycles (5 days).

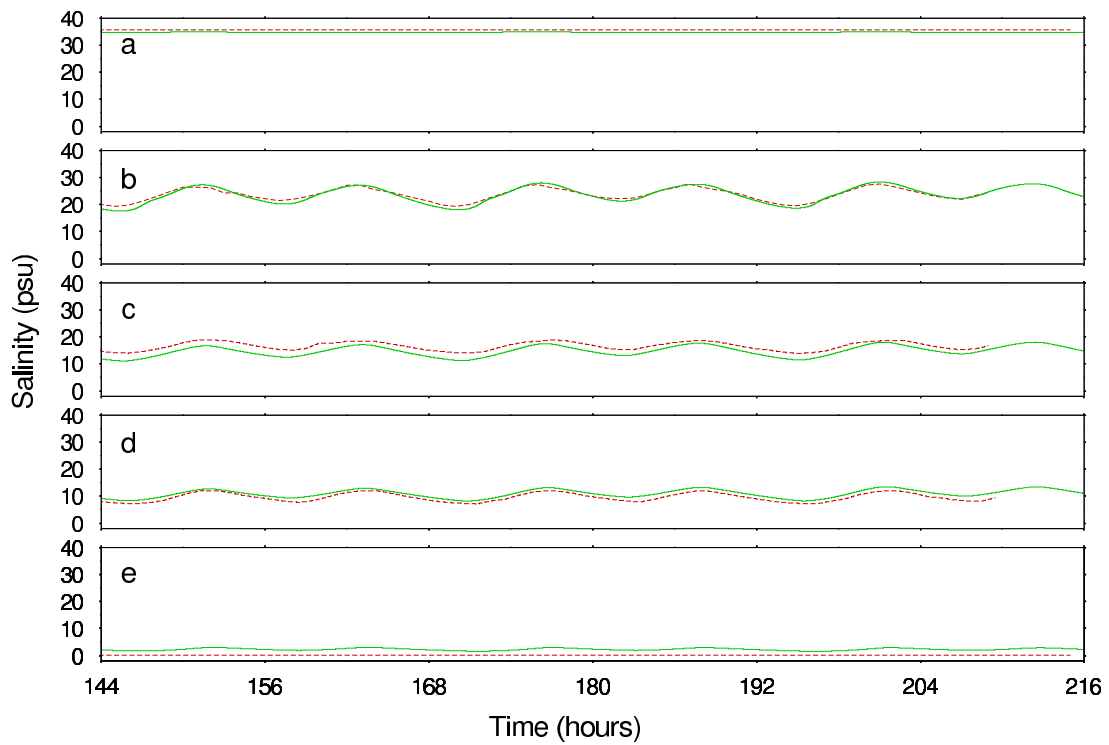
The 6<sup>th</sup> to 8<sup>th</sup> days simulations were used for the comparison. The computed salinity (Figures 4.1 and 4.3) matched well with those observed during dry season at different stations in the Mandovi and Zuari estuaries. Salinity values are more than 20, 10 and 8 *psu* at Sarmanas (20 *km*), Volvoi (33 *km*) and Sonamarg (45 *km*) respectively from mouth to the upstream regions in the Mandovi. But at Ganjem (50 *km*), an upstream end station in the Mandovi, salinity is nearly zero due to the small river discharge (  $10 \text{ m}^3 \text{ s}^{-1}$ ). At this end, the channel cross-sectional area is small and even a weak river discharge can influence salinity considerably [Shetye et al., 1995].

Figure 4.3 shows the salinity in the Zuari estuary and Cumbarjua canal. The simulation of salinity at Cortalim, Banastarim and Sanvordem are also reasonably well matched with that of observations. At Sanguem, both observation and model show that salinity is zero. Figure 4.3b shows salinity distribution in Banastarim, which is a middle station in the Cumbarjua canal where salinity is about 30 *psu*; it indicates that saline water is well transported from the Zuari to Cumbarjua canal by tides during flood.

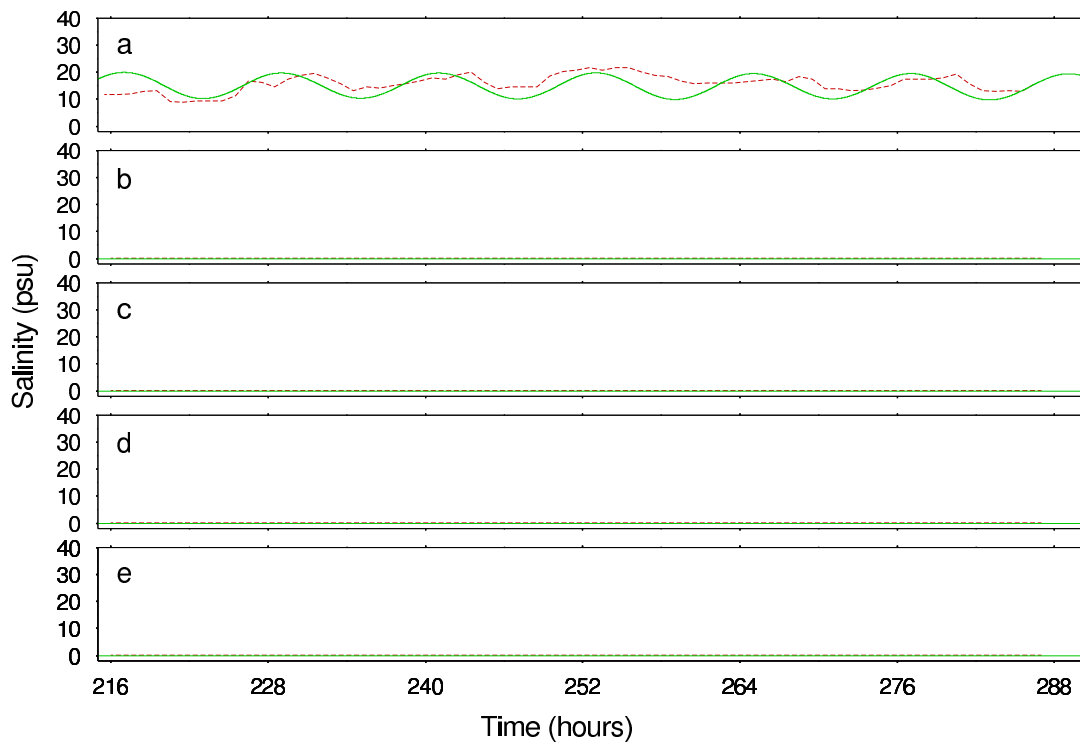
#### 4.2.2 Salinity distribution during wet season

For the simulations, during wet season (August), salinity was defined as a cosine function at the open boundary and the model was run for 12 days. At the upstream ends of these channels, river discharge of  $400 \text{ m}^3 \text{ s}^{-1}$  was introduced. The model reached steady state after 18 tidal cycles (9 days). The 10<sup>th</sup> to 12<sup>th</sup> days simulation of salinity were used for the comparison with the observation. Figures 4.2 and 4.4 show the observed and computed salinity at different stations in the estuarine network during wet season. These panels show that the observed and computed salinity is nearly zero in the upstream regions in the Mandovi and Zuari estuaries.

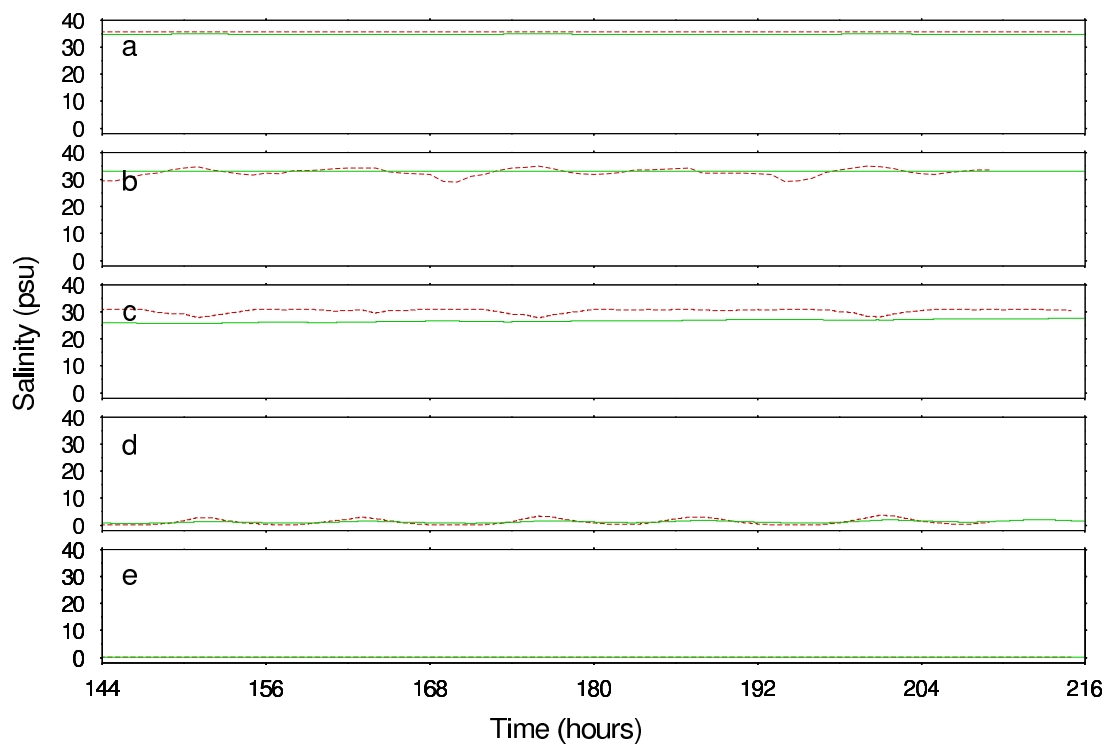
**Figure 4.1** The longitudinal distribution of salinity at different stations in the Mandovi estuary during dry (April 1993) season. The panels a, b, c, d and e represent Mormugao, Saramanas, Volvoi, Sonamarg and Ganjem respectively. The 144 *hours* on the x-axis correspond to 0.0 *hours* (IST) on 07/04/1993. Dotted and solid lines are observed and model respectively.



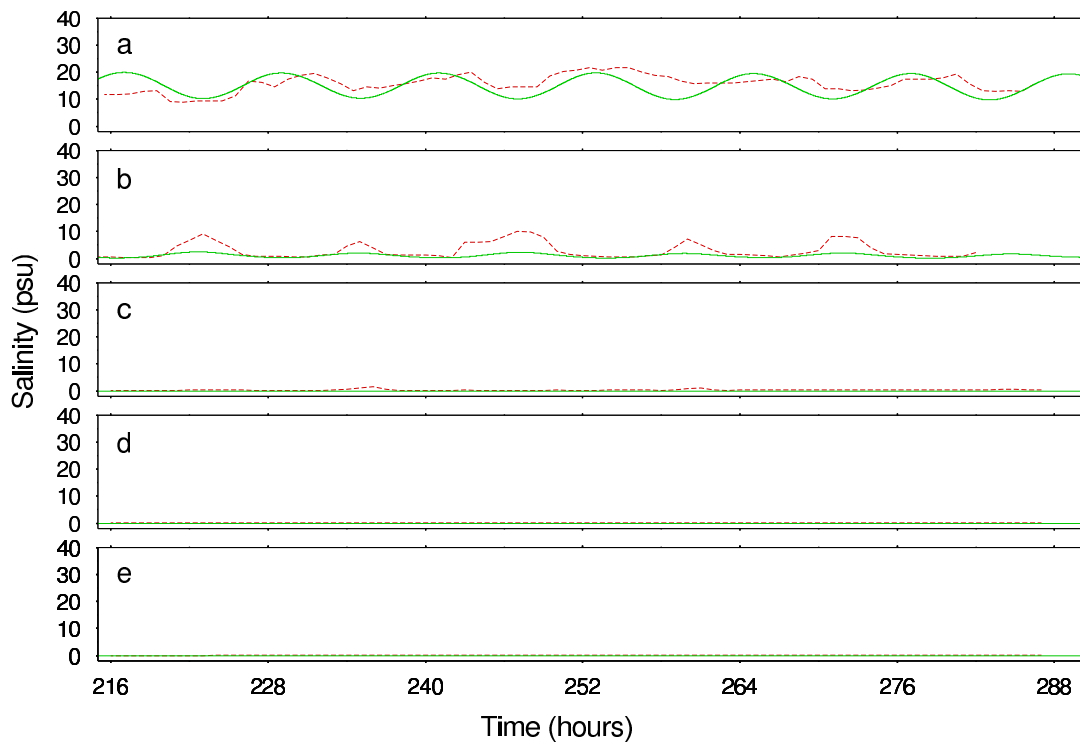
**Figure 4.2** The longitudinal distribution of salinity at different stations in the Mandovi estuary during wet (August 1993) season. The panels a, b, c, d and e represent Mormugao, Saramanas, Volvoi, Sonamarg and Ganjem respectively. The 216 *hours* on the x-axis correspond to 0.0 *hours* (IST) on 19/08/1993. Dotted and solid lines are observed and model respectively.



**Figure 4.3** The longitudinal distribution of salinity at different stations in the Zuari estuary and Cumbarjua canal during dry (April 1993) season. The panels a, b, c, d and e represent Mormugao, Cortalim, Banastarim, Sanvordem and Sanguem. The 144 *hours* on the x-axis correspond to 0.0 *hours* (IST) on 07/04/1993. Dotted and solid lines are observed and model respectively.



**Figure 4.4** The longitudinal distribution of salinity at different stations in the Zuari estuary and Cumbarjua canal during wet (August 1993) season. The panels a, b, c, d and e represent Mormugao, Cortalim, Banastarim, Sanvordem and Sanguem. The 216 *hours* on the x-axis correspond to 0.0 *hours* (IST) on 19/08/1993. Dotted and solid lines are observed and model respectively.





### 4.2.3 Simulation of longitudinal distribution of salinity for varying river discharges

A numerical experiment was carried out for simulating the longitudinal distribution of salinity for varying river discharges in the Mandovi estuary. For this purpose, the model was run for one month with same boundary conditions used for dry season and for each run, river discharges of 0, 10, 25 and 50  $m^3 s^{-1}$  were introduced at the upstream end of the model domain of the Mandovi.  $M_2$  tide is the major semidiurnal constituent, which constitutes 50% of the total tide in this region. Hence, the tidally averaged salinity was calculated over a  $M_2$  tidal period. The results of tidally averaged salinity have been shown in Figure 4.5 and the results show that salinity is subjected to large variations in the middle and upstream regions.

## 4.3 Residual currents

Residual currents of  $M_2$  tide in the Mandovi and Zuari estuaries were also calculated for varying river discharges using the numerical model. Residual currents are calculated using the following equation

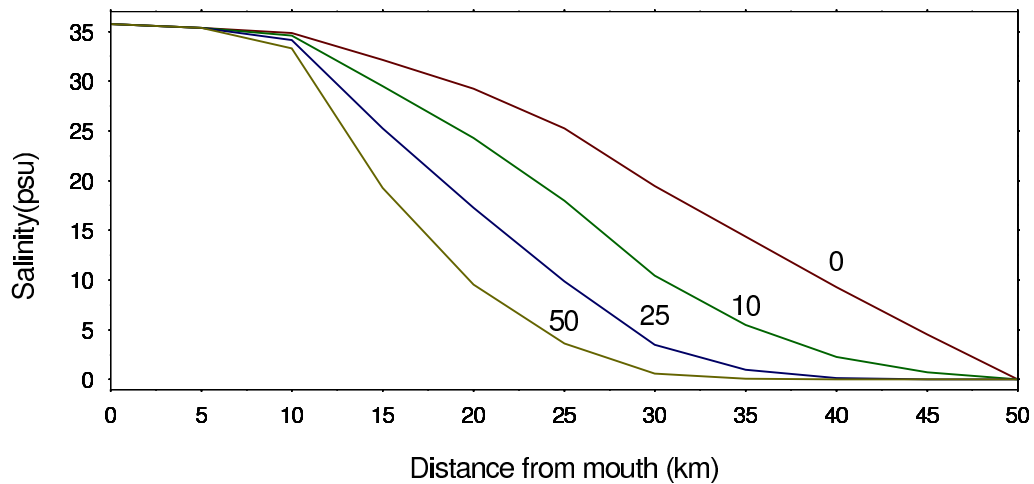
$$U_r = \frac{1}{T} \int u dt \quad (4.3)$$

$$V_r = \frac{1}{T} \int v dt \quad (4.4)$$

Where  $U_r$  and  $V_r$  are residual currents,  $u$  and  $v$  are velocities and  $T$  is the period of  $M_2$ , which is 12.42 *hours*.

For the simulation of residual currents, the model was run over a  $M_2$  tidal period and

**Figure 4.5** Simulations of tidally averaged salinity over  $M_2$  tidal period for varying river discharges in the Mandovi estuary.

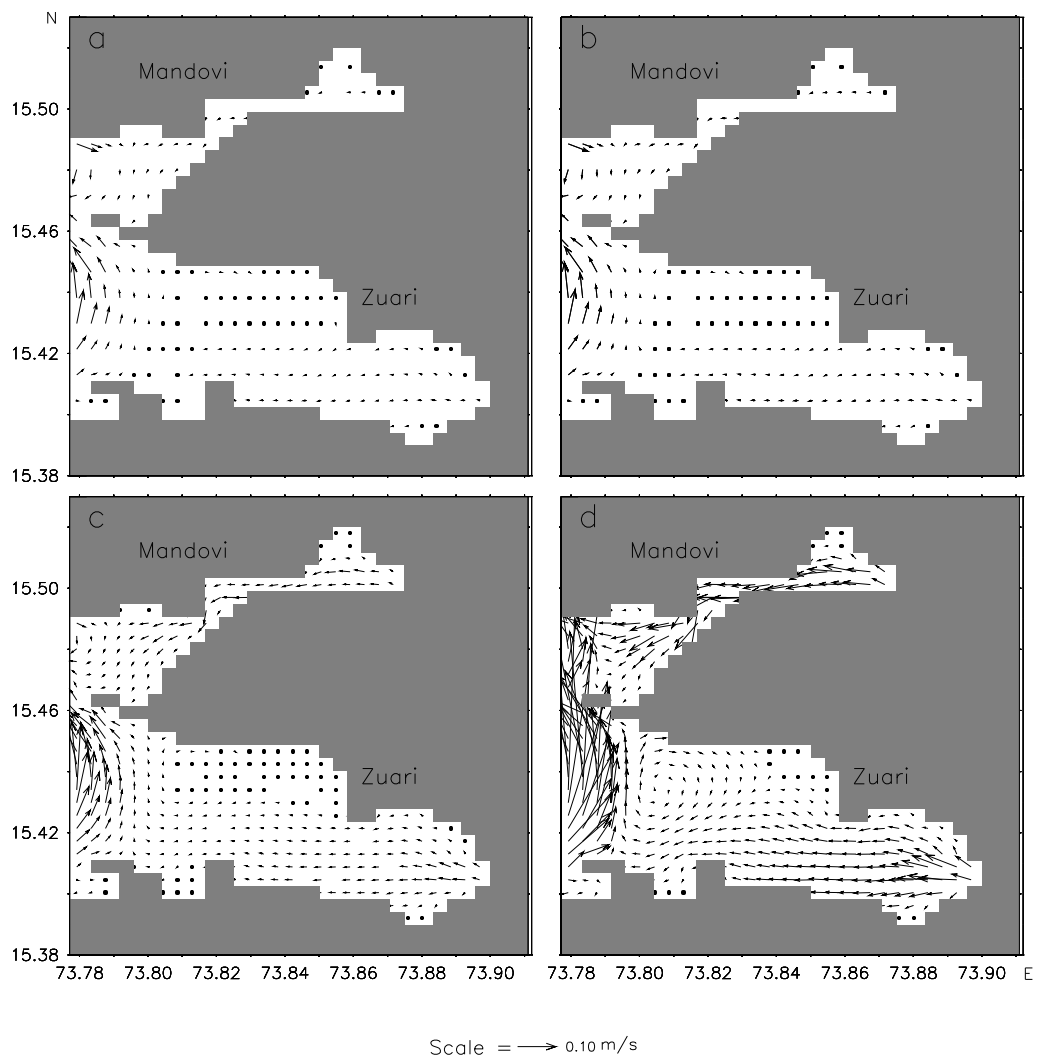


the model run was carried out for river discharges of 0, 10, 100 and 400  $m^3s^{-1}$ . The results of residual currents for varying freshwater discharges are given in the Figure 4.6. Strong residual currents of about 15–20  $cms^{-1}$  were found in the estuarine network when river discharge of 400  $m^3s^{-1}$  was introduced in the model.

#### 4.4 Intraseasonal variations of salinity

As mentioned above, salinity in the Mandovi and Zuari estuaries undergoes large changes during dry and wet seasons. So far, no study was conducted to study the changes on salinity during wet season or whether the breaks during the wet season affect the salinity in the estuary. To study the changes in salinity in detail during wet season, we made salinity measurements along the longitudinal sections in the Mandovi estuary during the selected days of 2005–2007. The measurements of salinity along the longitudinal sections were carried out to understand the salinity variations along the estuary, whereas on 19 September 2006, time series observations (10 hours) were conducted at Old Goa, located

**Figure 4.6** Simulations of residual currents over  $M_2$  tidal period in the Mandovi and Zuari estuaries. The panels a, b, c and d represent the model runs for varying river discharges of 0, 10, 100,  $400 \text{ m}^3 \text{ s}^{-1}$  respectively.

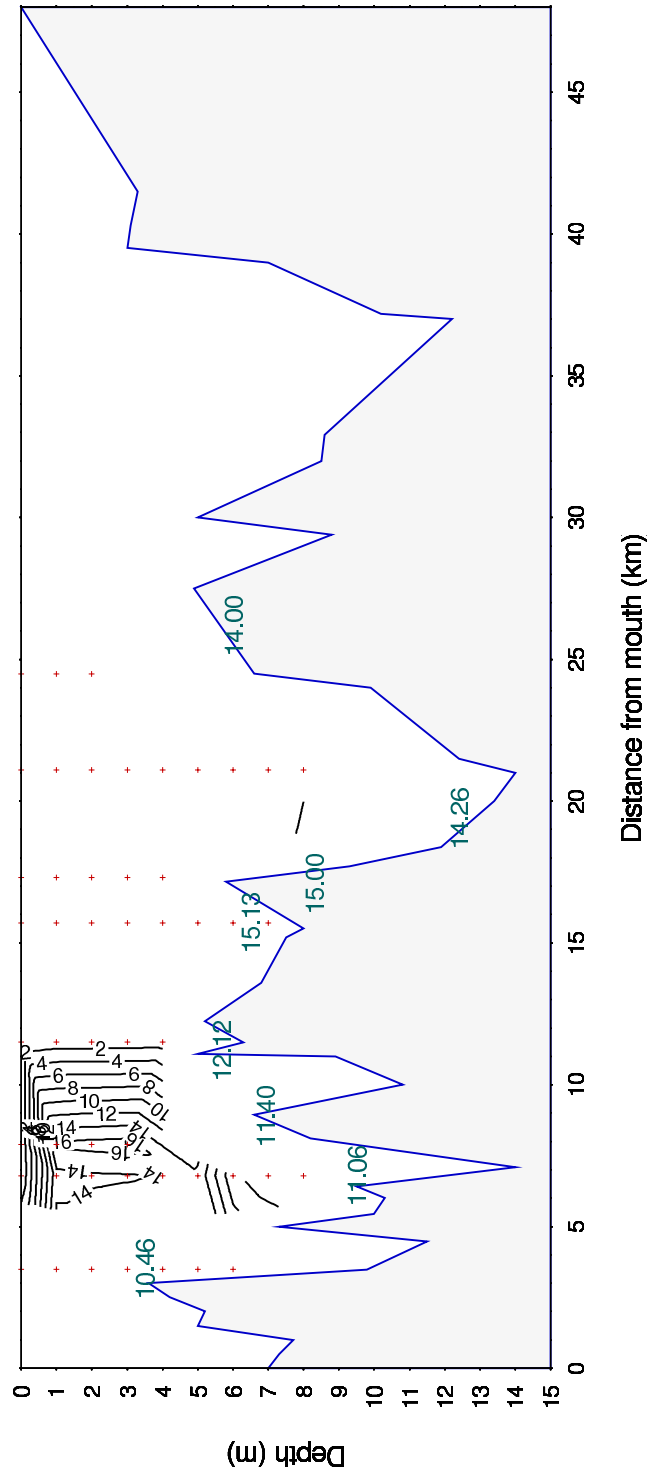


at distance of 15 *km* from the mouth of the Mandovi estuary to understand the salinity variations with time.

The vertical sections of salinity measured on 23 August 2005 is shown in Figure 4.7. The Figure 4.7 shows that salinity remains high (15 *psu*) at the surface in the downstream regions of about 8 *km* from the mouth, and from 12 *km* to further upstream regions, the channel is fully freshwater. Now if we look at the salinity measurements on 13 September 2005 (see Figure 4.8), saline water is further pushed toward the mouth. This was due to high rainfall in September compared to that of August 2005 (see Figure 4.15). During the time of heavy rainfall, salinity intrusion into upstream regions are minimised. This is evident from the continuous measurements of salinity (tidal cycles) made on 19 September 2006, which shows that salinity remains nearly zero from surface to bottom (see Figure 4.9) during two tidal cycles.

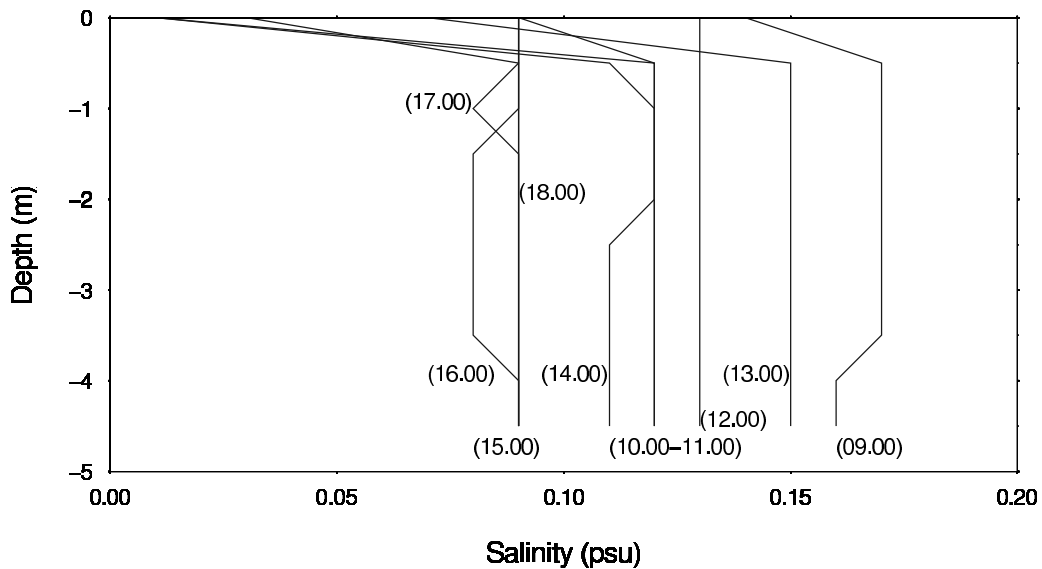
Salinity measurements during the dry season of 2007 show that these estuaries are vertically well mixed. Salinity measurements were carried out on 30 March, 25 May and 1 June 2007 in the Mandovi estuary. Figure 4.10 shows the vertical distribution of salinity along the estuary measured on 30 March 2007. From Figure 4.10, it can be noticed that the water column remains vertically well mixed from the mouth to upstream regions. But the measurements of salinity made on 25 May show that the water column is not fully well mixed (see Figure 4.11). This is not a sustained picture of salinity in May in this estuary, but because of a pre-monsoon shower occurred during the time of salinity measurements (see Figure 4.15e). The normal onset of southwest monsoon over Kerala (southern part of India) is on 1 June and it takes about 10 days to reach Goa. So the Mandovi and Zuari estuaries are well mixed till the 1<sup>st</sup> week of June and this is evident from Figure 4.12. Figure 4.12 also shows that saline water intrudes upto the upstream end of the estuary. Again salinity measurements made during wet season in 2007 show that salinity undergoes intraseasonal variations (Figures 4.13 and 4.14).

**Figure 4.7** Vertical distribution of salinity measured on 23 August 2005 in the Mandovi estuary. The time (*hours*) at which the observations were made are indicated in cyan colour.





**Figure 4.9** Time series measurements of salinity made at Old Goa, located at a distance of 15 km from the mouth in the Mandovi estuary on 19 September 2006. The time (*hours*) at which the observations were made are indicated in the bracket.



## 4.5 Flushing time in the Mandovi and Zuari estuaries

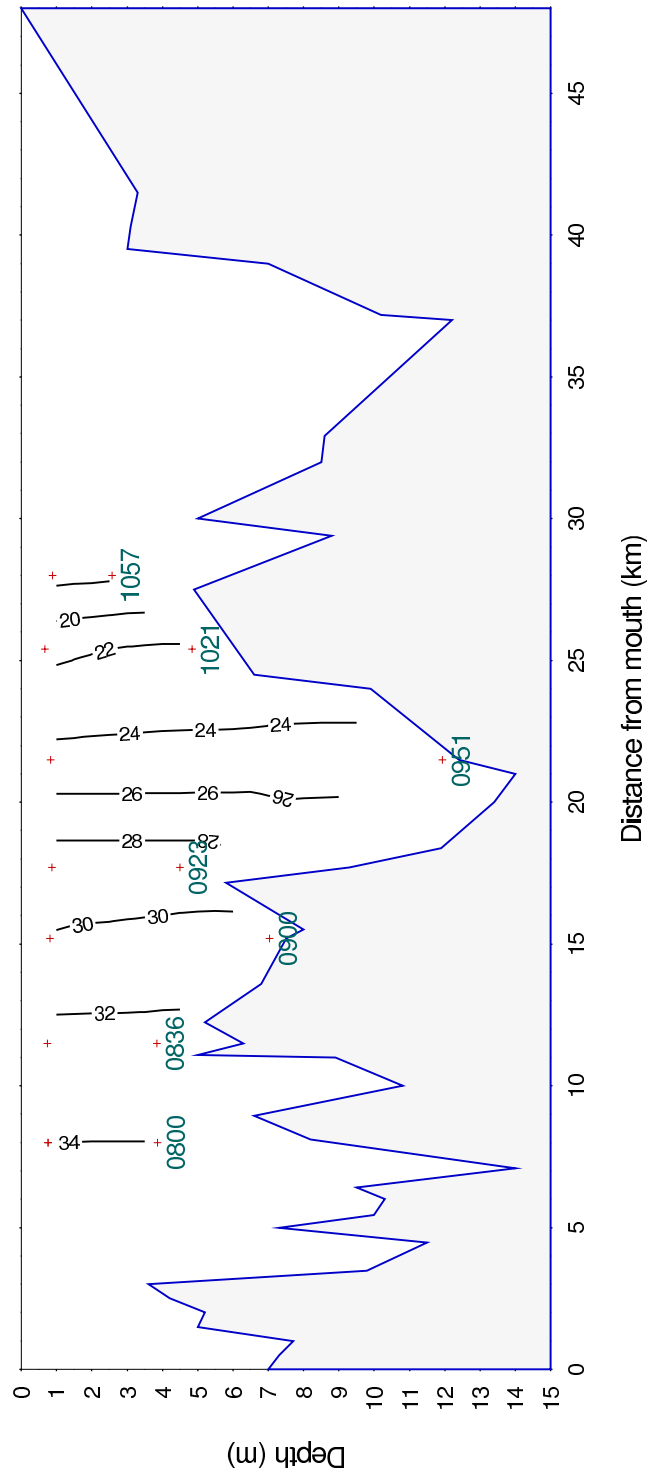
Flushing time is defined as the time required to replace the existing freshwater in an estuary at a rate equal to the river discharge [Officer, 1976]. This method can be used to estimate the estuarine tolerance to the potential harmful substances. The low flushing time keeps an ecosystem free from the adverse effects of pollutants to a great extent. This method also helps to handle oil spills or toxic material in an estuary.

### 4.5.1 Freshwater fraction method

Though there are many methods to calculate flushing time, for the present study, the flushing time was calculated using freshwater fraction method. In this method, the freshwater volume is estimated from the measurements of salinity at different sections in an estuary.

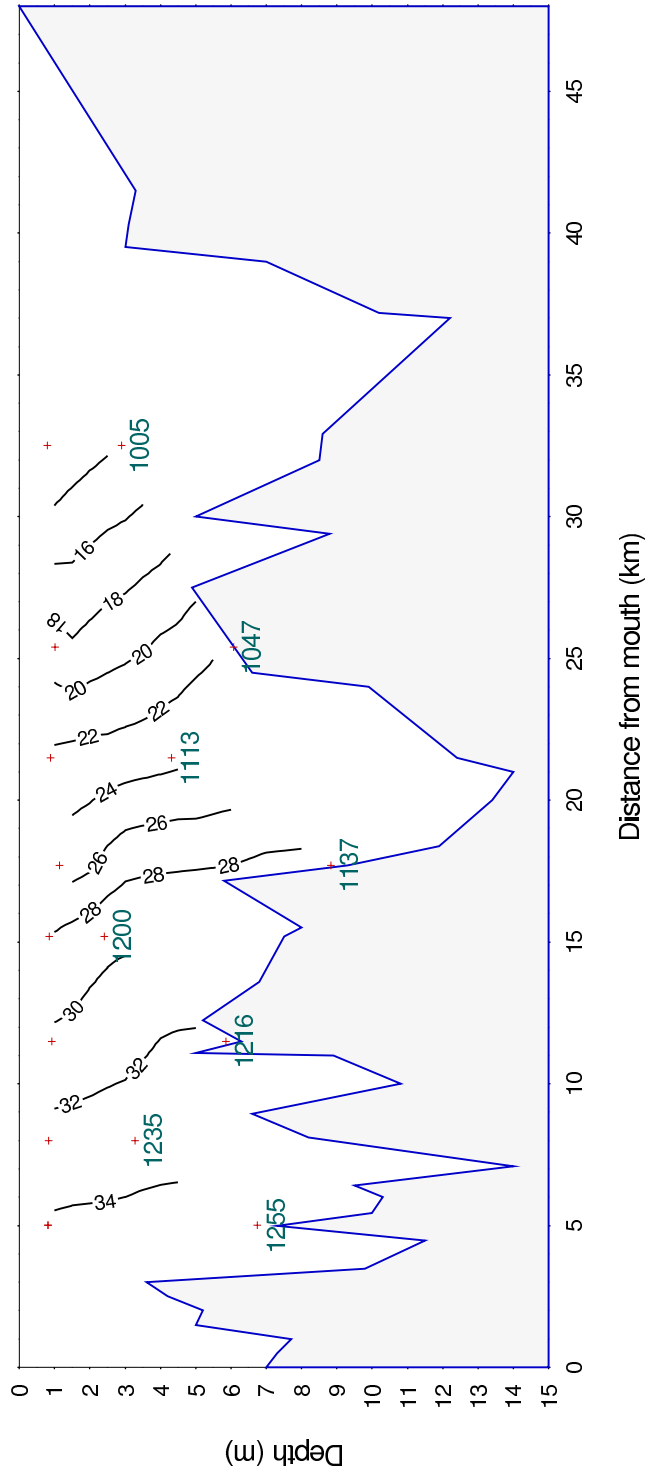
If we assume a linear mixing process, the freshwater fraction  $f$  can be written as

**Figure 4.10** Vertical distribution of salinity measured on 30 March 2007 in the Mandovi estuary. The time (*hours*) at which the observations were made are indicated in cyan colour.

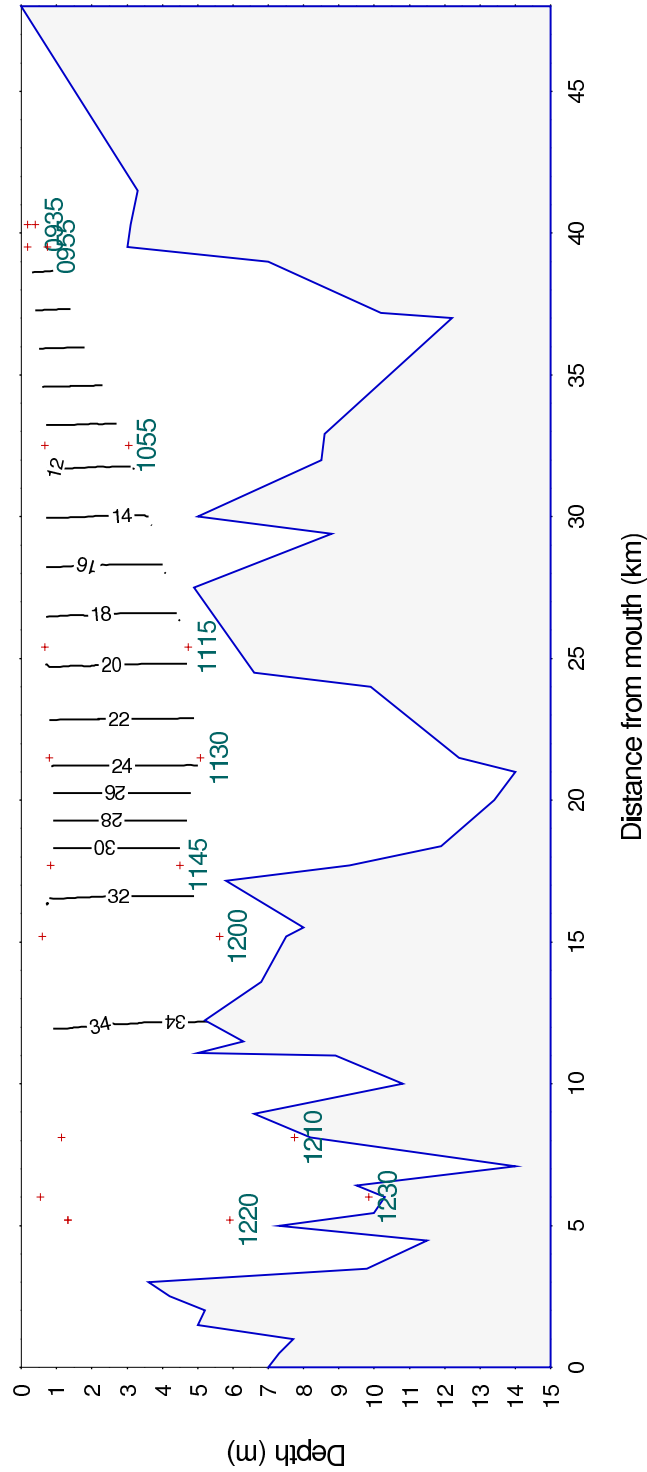




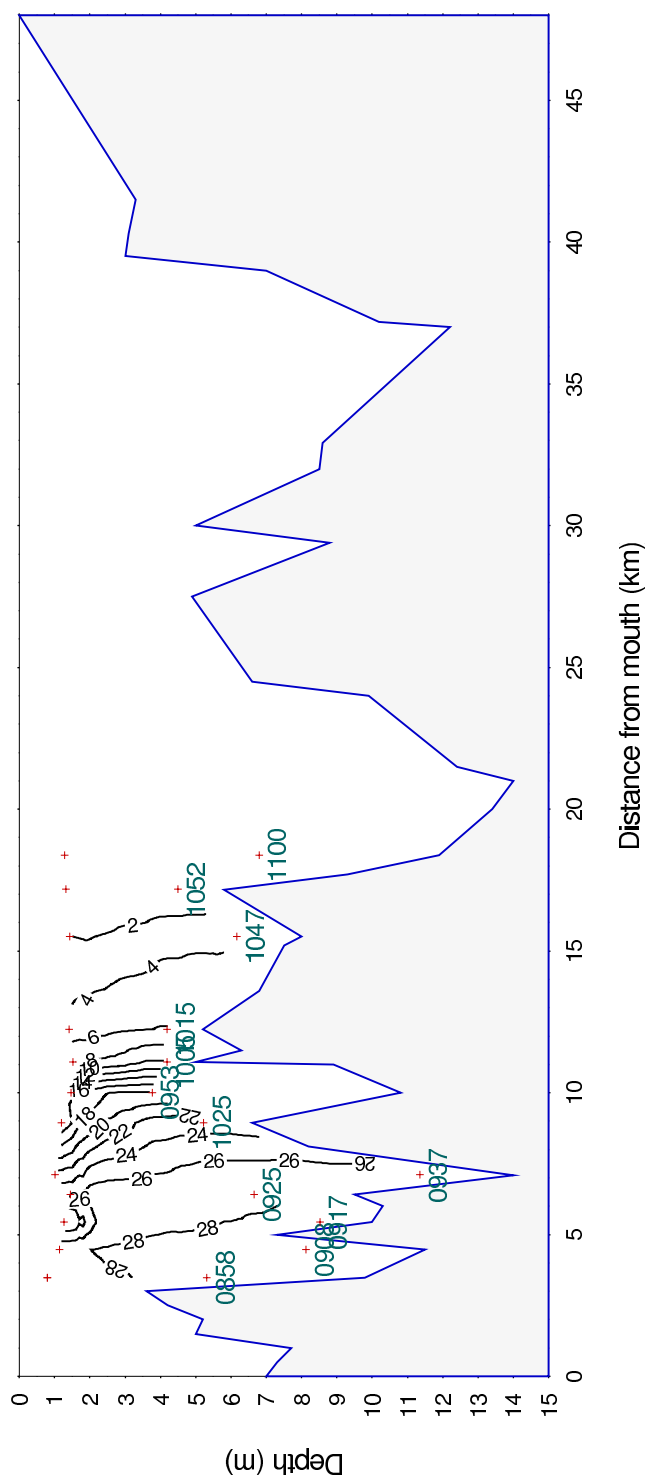
**Figure 4.11** Vertical distribution of salinity measured on 25 May 2007 in the Mandovi estuary. The time (*hours*) at which the observations were made are indicated in cyan colour.



**Figure 4.12** Vertical distribution of salinity measured on 1 June 2007 in the Mandovi estuary. The time (*hours*) at which the observations were made are indicated in cyan colour.

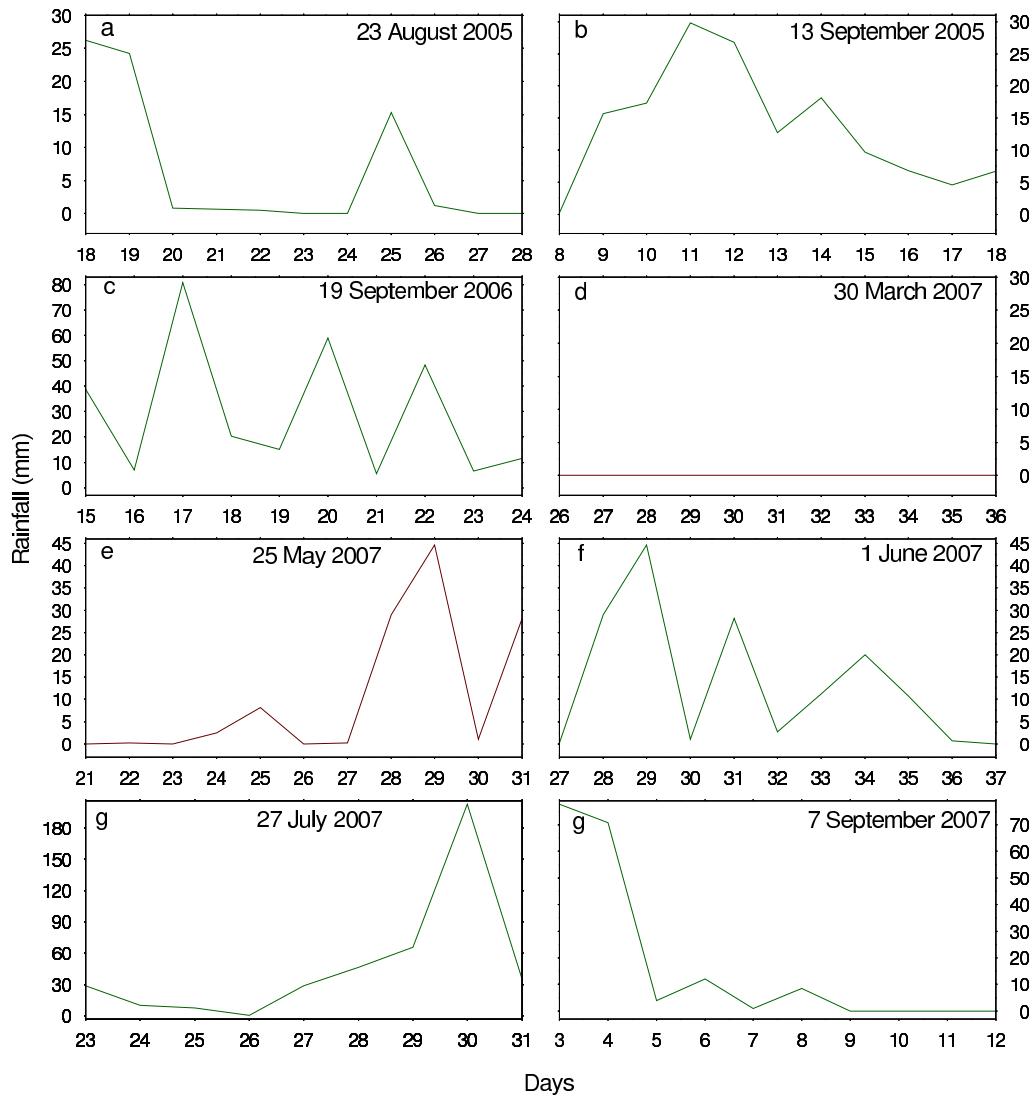


**Figure 4.13** Vertical distribution of salinity measured on 27 July 2007 in the Mandovi estuary. The time (*hours*) at which the observations were made are indicated in cyan colour.





**Figure 4.15** Figure shows rainfall at Panaji (near the mouth of Mandovi) during the time of salinity measurements in the Mandovi estuary. Rainfall is plotted for about 5 days before and after the date (shown in each panel) of salinity measurements. The green and red curves indicate rainfall during wet and dry seasons respectively. The 32<sup>nd</sup> day on the panels d and f are for 1<sup>st</sup> April and June respectively.



follows

$$f = \frac{S_0 - S}{S_0} \quad (4.5)$$

Where  $S_0$  is the normal ocean salinity and  $S$  is the salinity at given location inside the estuary. So the freshwater volume of particular section or an entire estuary is the volume integral of  $f$  and which can written as

$$f^* = \int f dv \quad (4.6)$$

Where  $f^*$  is the average freshwater fraction integrated over  $f$ . So, the flushing time can be written as

$$T = \frac{f^*V}{q} \quad (4.7)$$

Where  $q$  is the freshwater input for the study period and  $V$  is the volume of a section or an entire estuary.

In the present study, for calculating flushing time, the numerical model was run for 41 days each for varying freshwater inputs of 10, 25, 50 and 100  $m^3 s^{-1}$ . After the spin-up of 11 days, the remaining 30 day of salinity was used for computing freshwater fraction at each grid point of the model domain of the Mandovi and Zuari estuaries. The freshwater fraction obtained thus, was averaged over 30 days and the flushing time was calculated using the Equation 4.5. The model results are given the table 4.1 and as well as in Figure 4.16.

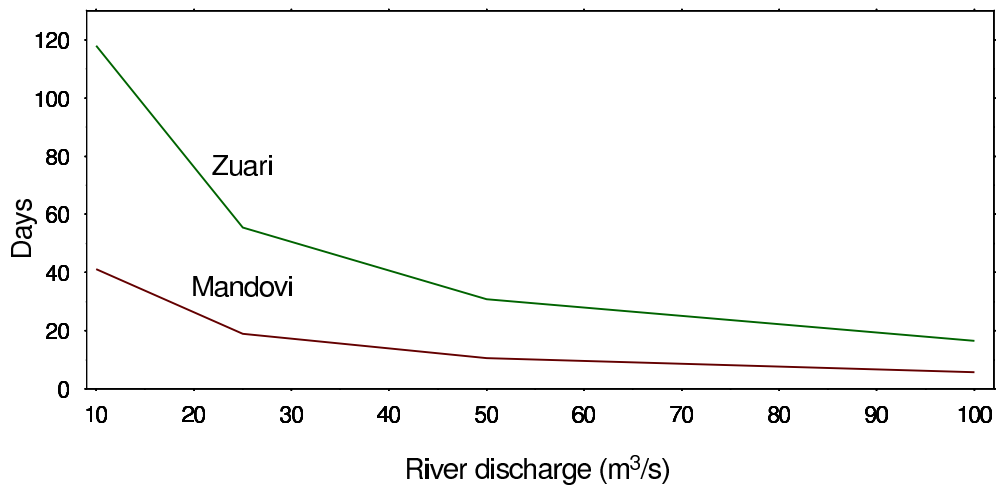
## 4.6 Discussion

The hybrid network model used in the present study could simulate salinity distribution well in the Mandovi and Zuari estuaries during dry season and the simulation of salinity during wet season at upstream regions were also reasonably good. Only at the down

**Table 4.1** Table shows the computed flushing time for varying river discharges in the Mandovi and Zuari estuaries

River discharge $m^3s^{-1}$	Mandovi <i>Days</i>	Zuari <i>Days</i>
<b>10.0</b>	<b>41.22</b>	<b>117.95</b>
<b>25.0</b>	<b>18.93</b>	<b>055.43</b>
<b>50.0</b>	<b>10.54</b>	<b>030.87</b>
<b>100.0</b>	<b>05.68</b>	<b>016.49</b>

**Figure 4.16** The computed flushing time for varying river discharges in the Mandovi and Zuari estuaries.



stream regions, consisting of about 10 to 12 *km*, the simulated salinity was underestimated. During wet season, the upstream regions are fully freshwater and hence no stratification and both observation and simulation show that salinity is nearly zero at these regions. The downstream regions consisting of about 10 to 12 *km* are partially mixed due to heavy river discharge from the upstream regions and incoming saline water driven by tides.

Salinity diffusion coefficient was chosen as 100 and 150  $m^2s^{-1}$  for downstream and upstream regions respectively in the present model. But it was found that the difference between the simulations of salinity for 100 and 150  $m^2s^{-1}$  was minimum.

The continuous measurements of salinity in April and August 1993 were used for the validation of the model. After the validation, this model was used to simulate salinity distribution for varying river discharges. A numerical experiment was carried out for this purpose. The results shows that the salinity distribution undergoes large changes for varying river discharges. Even with river discharge of 50  $m^3s^{-1}$ , salinity distribution remained almost steady upto 5 *km* from the mouth of the Mandovi estuary. Salinity dropped from 10 to 5 *psu* in the middle regions (20 to 35 *km*) and became zero further toward upstream regions when river discharge of 10  $m^3s^{-1}$  was introduced. For river discharges of 50  $m^3s^{-1}$ , salinity drops from 30 to 8 *psu* at about 20 *km* distance from the mouth. From 35 *km* to upstream regions, salinity goes to nearly zero. River discharge in July and August in the Mandovi and Zuari estuaries is about 400  $m^3s^{-1}$ , which can push saline water completely from the upstream regions to the downstream regions. The upstream regions of about 35 *km* become freshwater dominated during wet season.

The simulation of salinity for varying discharge show that the advective transport of salinity toward downstream regions are very strong even for a river discharge of 25  $m^3s^{-1}$ . The longitudinal distribution of salinity both in the Mandovi and Zuari estuaries are almost same. The Mandovi estuary has a lower average salinity than that of Zuari because the Mandovi estuary receives considerable amount of runoff through a large tributary sys-



tem [Qasim and Sengupta, 1981].

The residual currents computed for varying river discharge also show freshwater influence on tides. The residual currents found in these estuaries are strong enough to push salinity toward the mouth.

The longitudinal variations of salinity (Figures 4.7 and 4.8) during the selected days during 2005–2007 indicate that in a monsoonal estuary like the Mandovi estuary, salinity is subjected to intraseasonal variations during wet season. High salinity found in the surface on 23 August 2005 was due to deficit river discharge associated with the low rainfall (see Figure 4.15). The low salinity in the surface on 13 September 2005 indicates large quantity of river discharge into estuary due to heavy rainfall. An important characteristic of the southwest monsoon is variability on sub-seasonal time-scales, with active periods of heavy rain interrupted by drier break periods [Vecchi and Harrison, 2002]. These breaks during southwest monsoon reduces river discharge into the estuaries and consequently, saline water intrudes into the estuaries. When the monsoon becomes active once again, the saline water is pushed out of the estuary as shown in Figure 4.8. Similarly in 2007 also, salinity intruded into further upstream regions in July, again in September, salinity pushed towards mouth (Figure 4.13 and 4.14). This analysis of the salinity measurements made during the selected days of 2005–2007 indicate that salinity undergoes changes due to the breaks in the southwest monsoon. The analysis of the continuous measurements of salinity on 19 September 2006 shows that salinity remains zero from surface to bottom even during a tidal cycle if there is heavy freshwater flow. Present study in the Mandovi and Zuari estuaries show that these estuaries partially mixed only in the downstream regions consisting of 10 to 12 *km* during wet season and well mixed all other seasons (see Figures 4.10 and 4.12). The measurements of salinity in the Mandovi estuary show that salinity undergoes intraseasonal variations during wet season.

Flushing time in the Mandovi is almost three times less than that of Zuari for any given river discharge. This is because of the total volume of Zuari is about 291  $Mm^3$  and

that of Mandovi is about  $102 \text{ Mm}^3$ . The high volume of Zuari retain the freshwater for long time in the channel than that of Mandovi.

## **4.7 Conclusions**

The model simulated the longitudinal distribution of salinity well during dry season though the simulation of salinity at the downstream regions were not reproduced well during wet season. But the simulation of salinity distribution at upstream regions were reasonably good during this season. From the analysis of salinity measured during wet seasons, further efforts need to be brought to study variations of salinity in the downstream regions of these estuaries in detail using the 3D models in order to improve the simulation of salinity during wet season.