

# Chapter 5

## Summary and Conclusions

The results obtained from this study are summarised in this chapter. The significant findings, the limitations of the present studies and the future studies to be undertaken etc. are discussed in this chapter. The objectives of the thesis were to determine the characteristics of tidal propagation and salinity distribution in the Mandovi and Zuari estuaries using a hybrid network numerical model. One of the main objective was to study the longitudinal variation of tides during dry and wet seasons and freshwater influence on tides. The study of tidal asymmetry was another objective. This is the first time an effort was made to study tidal asymmetry caused by overtides and compound tides in the estuaries on the west coast of India. Another important aim was to study the longitudinal variation of salinity distribution and freshwater influence on salinity. The study of intraseasonal variations of salinity during wet season was another important objective. The residual currents and flushing time were also computed using the model.

A hybrid network model, consisting of a vertically averaged 2D model and an area averaged 1D model was used to simulate tides and salinity distribution in the Mandovi and Zuari estuaries. The vertically averaged 2D model was used for the downstream regions of these channels. An area averaged 1D model was for the upstream regions in these estuaries and Cumbarjua canal. A finite difference numerical scheme was used for

solving partial differential equations of momentum, continuity and advection-diffusion equation of salinity.

## 5.1 Tidal propagation

Hybrid network model used for the present study was successful in simulating tidal circulation reasonably well in both dry and wet seasons in the Mandovi and Zuari estuaries. Both the observation and simulation of tide show that tidal amplitudes slightly increase toward the upstream regions. The Mandovi and Zuari estuaries are strongly converging channels and this leads to the amplification of tides in the upstream direction. The momentum balance in this type of estuary is primarily between pressure gradient and friction and the decay in amplitude due to friction gets cancelled by geometric amplification, which leaves the amplitude, unchanged over 40 *km* in these estuaries from the mouth. Tidal amplitude gets decayed in the remaining 10 *km* in these estuaries because of river discharge. The tidal oscillations are negligible at upstream stations in the Mandovi and Zuari estuaries due to small river discharge. The freshwater inflow through these narrow channel is sufficient to prevent tides entering at this stations. But the decay in tidal oscillation at the upstream station in the Zuari is less than that of the Mandovi. The channel's elevation from the sea level is also a factor preventing the tidal propagation further toward upstream regions. During wet season, the tidal oscillations are minimum at these two stations because of heavy river discharge.

Tidal currents in these estuaries are strong enough to mix the water column vertically during the dry season. The downstream velocities associated with river discharge prevent upstream propagation of tides during wet season.

Harmonic analysis of tides was carried out using observations and simulations at several station in these estuaries and the results show that the major tidal constituents increase toward the upstream regions in these estuaries. The Mandovi and Zuari estuaries are not

frictionally dominated estuaries. The amplitude and phase variations of the tidal constituents toward the upstream regions in the Mandovi and Zuari estuaries are not linear, which is a strong indication of the presence of a reflected wave in these estuaries.

Amplitude and phase of both overtides and compound tides increase toward the upstream regions in these estuaries. This rapid increase in amplitude and phase of the first and second harmonics of  $M_2$  and the nonlinear increase of compound tides show the nonlinear nature of the Mandovi and Zuari estuarine systems to the tidal forcing. The increase of  $M_4$  and decrease of relative surface phase in both the Mandovi and Zuari show that these estuaries are flood-dominated. But there are some mudflats in the Zuari estuary, that can increase the duration of ebb, which indicates that the Zuari estuary is less flood-dominant than the Mandovi estuary.

The complex difference of both observations and simulations of tidal constituents (major diurnal and semi-diurnal constituents, overtides and compound tides) increases slightly from the downstream regions to the upstream regions. One of the possible reasons for this increase is due to the use of a 2D square grid, which was not well adapted to the irregular configuration of coastline. The meandering effects of the channels influence the amplitude and phase of tide entering into the estuary.

## 5.2 Salinity distribution

The numerical model used for 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 was also reasonably good. Only at the down stream regions consisting of about 10–12 *km*, the simulated values of salinity were found to be underestimated.

The numerical experiment carried out for the simulation of longitudinal distribution of salinity for varying discharges in the Mandovi shows that salinity distribution undergoes

large changes with varying river discharge. River discharge in July and August in the Mandovi and Zuari estuaries is about  $400 \text{ m}^3 \text{ s}^{-1}$ , 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 computed residual currents found in the estuaries are strong enough to push saline water toward the mouth during wet season.

The longitudinal variations of salinity indicates that in a monsoonal estuary like the Mandovi estuary, salinity is subjected to intraseasonal variations during wet season. The present study in the Mandovi and Zuari estuaries show that these estuaries are partially mixed only in the downstream regions extending 10–12 *km* from the mouth during wet season. These channels become well mixed during other seasons. The estimated flushing time in the Mandovi is almost three times less than that of Zuari at any given river discharge. This is mainly because the total volume of the Zuari is much higher than that of the Mandovi.

### 5.3 Future studies

The present model could simulate tides both in the dry and wet seasons in the Mandovi and Zuari estuaries. The simulations of tidal constituents were also reasonably well both in these estuaries. However, more observations of currents are needed for better validation of computed tidal currents.

The results from Chapter 4 show that the simulations of salinity distribution is good during dry season in the Mandovi and Zuari estuaries. So this numerical model can be used in other estuaries in the tropical regions where the water column is vertically well mixed. Mandovi and Zuari estuaries are well mixed for almost 7 to 8 months in a year. The present approach is suitable for this kind of estuarine systems. From the analysis of salinity measured during wet seasons, we think that further efforts need to be brought to

study salinity distribution during wet season. Moreover, diffusion coefficient for salinity has to be estimated more accurately from field studies. The effect of wind stress on the tidal circulation, especially during southwest monsoon, needs to be examined. Using 3D models will be more appropriate for the simulation of salinity during wet season in this type of estuaries.

# Appendix A

## Notation

- $U = u(h + \eta)$  is the transport along the x-axis
- $V = v(h + \eta)$  is the transport along the y-axis
- $u$  and  $v$  are the vertically averaged velocity over the water column of height  $(h + \eta)$
- $h$ : depth
- $\eta$ : free surface
- $t$ : time
- $g$ : acceleration due to gravity
- $f$ : Coriolis parameter
- $A_H$ : coefficient of horizontal diffusion of momentum
- $C_D$ : bottom drag coefficient
- $S$ : water salinity

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- $K_x$ : diffusion coefficient along x-axis
  - $K_y$ : diffusion coefficient along y-axis
  - $b$ : width of the channel
  - $q$ : river discharge per unit channel length
  - $A = b(h + \eta)$  is the total cross-sectional area of the channel
  - $R = A/P_r$ : hydraulic radius, where  $P_r$  is the wetted perimeter
  - $C$ : Chezy coefficient
  - $n$ : Manning coefficient
  - $z_0$ : the distance between the bottom of the channel and an arbitrary level surface well below the bottom
  - $Q$ : along channel transport

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