

Tidal Circulation and Salinity Distribution in the Mandovi and Zuari Estuaries: A Case Study

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Abstract

The Mandovi and Zuari are two tropical estuaries along the west coast of India, characterized by mixed tides with semi-diurnal dominance and heavy fresh water influx during the southwest monsoon (June to September). Previous observations of tides in these estuaries show that the tidal effects in the upstream regions are subject to decay due to freshwater influx during the southwest monsoon. The longitudinal distribution of salinity in these estuaries undergoes large variations between the southwest monsoon and the dry season (February to May). The main objectives of the present study were to simulate the tidal circulation, the longitudinal distribution of salinity and the freshwater influence on tides and the salinity distribution. Another objective was to study the intra-seasonal variations of salinity during the breaks in the southwest monsoon. A hybrid network numerical model was used for the present study to simulate the tidal circulation and the salinity distribution in these estuaries. The model reproduced observed tides accurately during the dry and wet seasons. The model could reproduce the longitudinal distribution of salinity well during the dry season and the simulation of salinity distribution was reasonably well during the wet season. The simulated tidally-averaged salinities over the M_2 tidal period for varying river discharges show that even a small freshwater influx can affect the longitudinal distribution of salinity to a great extent in this type of estuaries.

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Introduction

The estuaries on the west coast of India are unique in their physical and bio-geochemical features and the Mandovi and Zuari are two of these estuaries (Fig.1a). These estuaries contribute tremendously to the regional economy. The Mandovi and Zuari are exclusively used for the transportation of iron and manganese ores from the mining places located along their banks to the nearest Mormugao Port (Fig. 1a). The lengths of the Mandovi and Zuari are about 50 km each and average depth of these estuaries are about 5 m. The upstream sources of the Mandovi and Zuari are in the Western Ghats (Mountain ranges along the west coast of India). A narrow canal, called the Cumbarjua canal, connects these estuaries. A number of tributaries also join the Mandovi and Zuari (see Fig. 1a). Tides in these estuaries are of the mixed semi-diurnal type and the tidal ranges are about 2.3 and 1.5 m during the spring and neap tides respectively.

The monsoon is a typical feature of this area. Southwesterly winds blowing from the Indian Ocean bring heavy rainfall into the Indian subcontinent during the southwest monsoon. The wind direction changes from southwesterly to northeasterly during the northeast monsoon (October to December) and this change in the wind direction also brings rainfall to the southern Indian peninsula, but the other parts of the Indian subcontinent become dry. In India, 80% of total rainfall in a year occurs during the southwest monsoon. The Mandovi and Zuari receive heavy freshwater discharge during the southwest monsoon, hence they are called “monsoonal” estuaries. During a tidal cycle, the salinity remains almost constant (35 psu) from February to May and varies from 8 to 22 psu from June to September (Cherian et al. 1975; Varma et al. 1975; De Sousa 1977; Qasim & Sen Gupta 1981; De Sousa et al. 1981; Shetye et al. 1995) at the mouth of these estuaries. 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 & Sen Gupta, 1981). By the end of September, the effect of freshwater influx is reduced and saline water intrudes further toward upstream regions. By February, these estuaries become an extension of the sea. The longitudinal distribution of salinity in the Mandovi and Zuari are subject to large variations during a year. The heavy rainfall and subsequent freshwater inflow into the catchment area during the southwest

monsoon hereafter referred to as 'wet season' stratifies the downstream regions consisting of 10 to 12 km from the mouth of these estuaries. In the region between 12 km and 35 km, from the mouth these estuaries, becomes completely freshwater-dominated. From February to May, hereafter referred to as 'dry season, these estuaries are vertically well-mixed throughout the regions (Cherian et al. 1975; Varma et al. 1975; De Sousa 1977; Qasim & Sen Gupta 1981; De Sousa et al. 1981). With the commencement of the wet season in June, freshwater influx due to heavy precipitation in this region decreases salinity sharply.

Relatively few models have exposed the hydrodynamics of these areas. Shetye and Murty (1987) used a one-dimensional numerical model to study the annual salt budget in the Zuari. Their model simulated the salinity fields fairly well during the dry season, though it could not reproduce the salinity distribution during the wet season. Shetye et al. (1995) found that the momentum balance in these estuaries is primarily between pressure gradient and friction. Unnikrishnan et al. (1997) developed a 1D network numerical model for the entire estuarine system including all the tributaries to study the decay of the tidal amplitude in the upstream regions of these estuaries, particularly during the wet season. They simulated the decay of tides in the upstream regions successfully during the wet season. They found that the mean downstream velocity associated with freshwater influx is sufficiently large to prevent upstream propagation of tides, thereby causing the decay. Sundar and Shetye (2005) calculated the amplitude and phase of major tidal constituents in the Mandovi and Zuari using a one-month sea level measured at different stations in these estuaries. They found that the amplitude and phase of five major constituents (M_2 , S_2 , N_2 , K_1 and O_1) increase from mouth to the upstream regions. Manoj et al. (2009) used a hybrid network numerical model to study the nonlinear response of the Mandovi and Zuari to the tidal forcing. In the present study, our main objectives were to simulate the tidal circulation and the longitudinal distribution of salinity in the Mandovi and Zuari during the dry and wet seasons. Our objective was also to study the freshwater influence on tides and the salinity distribution. Another objective was to study the intra-seasonal variations of salinity during the breaks in the southwest monsoon. A hybrid network model was used for the present study to simulate the tidal circulation and the salinity distribution in these estuaries.

Materials and Methods

Bathymetry data

The bathymetry data of the Mandovi, Zuari and Cumbarjua were obtained by digitizing the bathymetry maps (1968 – 1969) of the Minor Ports Survey Organization, Ministry of Shipping and Transport, Government of India. The 1D upstream regions of the Mandovi, Zuari and Cumbarjua were schematized into 75, 81 and 32 segments respectively (Fig. A1).

Sea surface elevation and salinity data

Shetye et al. (1995) made continuous observations of tides and salinity in the estuarine network. Tide pole measurements were carried out for different stations in the Mandovi, Zuari and Cumbarjua from 7 – 9 April and 19 – 21 August 1993. The salinity measurements were also carried out for the above period using portable CTD (Conductivity Temperature Depth) instrumentation. Tides and salinity were measured in April and August, since these are the two peak months of the dry and wet seasons respectively in these estuaries. The salinity in the estuaries undergoes maximum changes during these two months. In addition to the above data, we conducted some field measurements of salinity in August and September 2005 and March 2007 to study the longitudinal and the intra-seasonal variations of salinity. The salinity measurements during the above period was measured using portable CTD.

The sea level measurements carried out for the above period were not sufficient to force the model at open boundary for a longer period. To force the model at the open boundary for a longer period, the amplitude and phase of major tidal constituents were derived using TASK-2000 (Tidal Analysis Software Kit 2000) from one year of observed sea levels measured at Mormugao Port. These known tidal constituents were used in TASK-2000 to predict tides in April and August 1993. The sea level predictions for April and August 1993 at Mormugao after the application of the TASK-2000 software, were applied over the entire open boundary of the Mandovi and Zuari as the tidal ranges are nearly same from the southern boundary of the Zuari to the northern boundary of the Mandovi (short duration observations of the tides made near the

mouth of the Mandovi in 1993 do not show much variations in amplitudes and phases of the tides with those of Mormugao).

Freshwater influx data

The monthly mean averaged discharge data were obtained from the Central Water Commission, New Delhi, Government of India. The monthly mean averaged discharge data (1993) at Ganjem, an upstream station in the Mandovi (see Fig. 1a) were used for prescribing freshwater influx at the end points of the model domain of the Mandovi and Zuari. The data available at Ganjem were used for prescribing freshwater influx in the Zuari too as the discharge data for these upstream regions are available only at Ganjem (see Fig. 2).

Numerical model

We used a hybrid network consisting of a vertically-averaged 2D model coupled to 1D models (see Fig. 1b) for the estuarine network since these estuaries mainly exhibit 2D and 1D flow patterns at the mouth and upstream regions respectively. We used a Cartesian coordinate system where the x-axis is directed positive towards east and y-axis is directed positive towards north. The equations were solved using the finite-difference explicit method on an Arakawa C grid and the leapfrog technique to march in time. A brief description of the two models is given below.

Two dimensional model

Since the Mandovi (Zuari) estuarine mouth is about 3.5 (5.5) km wide, we used a 2D model in the downstream regions. The main purpose of using a 2D model in the downstream regions was to simulate tidal currents. The 2D model that we used for the present study was developed at National Institute of Oceanography, India (Unnikrishnan et al. 1999). During the present work, we also included the salinity gradient term in the momentum equation (Elliot and Reid 1976; Sinha et al. 1996). The differential equations governing tidal circulation and salinity distribution in the estuarine network are equations of momentum, continuity and salinity advection diffusion equation. The vertically averaged form of these equations are written as follows:

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}(uU) + \frac{\partial}{\partial y}(vU) = - \left(g(h + \eta) \frac{\partial \eta}{\partial x} + \frac{1}{2} g\beta(h + \eta)^2 \frac{\partial S}{\partial x} \right) + fV + A_H \nabla^2 U - C_D \frac{U \sqrt{U^2 + V^2}}{(h + \eta)^2} \quad (1a)$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}(vU) + \frac{\partial}{\partial y}(vV) = - \left(g(h + \eta) \frac{\partial \eta}{\partial y} + \frac{1}{2} g\beta(h + \eta)^2 \frac{\partial S}{\partial y} \right) - fU + A_H \nabla^2 V - C_D \frac{V \sqrt{U^2 + V^2}}{(h + \eta)^2} \quad (1b)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (2)$$

$$\frac{\partial S}{\partial t} + \frac{\partial}{\partial x}(uS) + \frac{\partial}{\partial y}(vS) = K_x \frac{\partial^2 S}{\partial x^2} + K_y \frac{\partial^2 S}{\partial y^2} \quad (3)$$

where u and v are vertically averaged velocities over the water column of height, $h + \eta$

$U = u(h + \eta)$ and $V = v(h + \eta)$ are transports along the x and y-axes

h = depth

η = free surface elevation

$\beta = 6.5 \times 10^{-4}$ the ratio of fractional change in density for unit change in salinity

t, g, f, A_H and C_D are time, acceleration due to gravity, Coriolis parameter, coefficient of horizontal diffusion of momentum and bottom drag coefficient respectively, S is salinity and K_x and K_y are the diffusion coefficients along the x and y-axis.

One dimensional model

For the upstream regions, where the channels are narrow, we developed a 1D model using the formulation given by Harleman and Lee (1969); Thatcher and Harleman (1972); Elliot and Reid (1976); and Sinha et al. (1996). The equations used in the one-dimensional model are the area averaged momentum and continuity equations, which are written as follows:

$$\frac{\partial Q}{\partial t} + \frac{2Q}{A}q - \frac{2bQ}{A} \frac{\partial \eta}{\partial t} = - \left(gA \frac{\partial}{\partial x} (z_0 + h + \eta) + g\beta A (z_0 + h + \eta) \frac{\partial S}{\partial x} \right) - g \frac{Q|Q|}{AC^2R} \quad (4)$$

$$b \frac{\partial \eta}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \quad (5)$$

where x , Q , q , b , A , R , z_0 are, respectively, the along channel coordinate, along-channel transport, fresh water influx per unit channel length, width of the channel, cross-sectional area of the channel, hydraulic radius and the distance between the bottom of the channel and an arbitrary level surface well below the bottom. The Chezy coefficient was determined using the formula given below:

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

where n is Manning coefficient

The Advection-diffusion equation for salinity is written as follows:

$$A \frac{\partial S}{\partial t} + \frac{\partial}{\partial x} (QS) = AK_x \frac{\partial^2 S}{\partial x^2} \quad (7)$$

The 2D model domain extends upto a distance of 15 km from the mouth of the estuarine network. For the upstream regions of the Mandovi and Zuari and Cumbarjua that connects them a 1D model was used. The formulation of the 2D and 1D coupling is described in the Appendix. Freshwater influx was included at the upstream end points of the model domain. Additional model grid details are provided on Fig. A1 (see Appendix). The stability of the present numerical scheme was determined by the standard Courant-Friedrichs-Lewy (CFL) stability criterion.

The time step Δt was chosen as 15 seconds in the model, and the space increments, Δx and Δy were chosen as 500 m. The bottom drag coefficient, C_D , was taken as 0.002. For 1D models, the

Manning coefficient, n was taken as 0.035. The coefficient of horizontal diffusion of momentum (A_H) for the present simulations was 500 m²/s. The salinity diffusion coefficient is subject to seasonal variations from the mouth to upstream regions in the Zuari (Shetye and Murty 1987). The model was run for varying salinity diffusion coefficient values range from 10 to 250 m²/s. But we used 75 and 150 m²/s for the 2D and 1D regions respectively in the present model since these values gave the best results.

Boundary conditions

At the western (open) boundary of the model, surface elevations and salinities were defined as functions of time, while zero flux conditions were applied along 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, the transport was calculated according to the discharge rate of freshwater influx (see Fig. 2). 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. Since the salinity remains about 35 psu throughout the tidal cycles during the dry season at the mouth of these estuaries, we defined a constant salinity of 35.17 psu at the mouth during the dry season to force the model. The salinity varies from 8 to 22 psu in a tidal cycle at the mouth of these estuaries during the wet season. So we defined the boundary condition with a cosine function that can vary from 8 to 22 psu during a tidal cycle (~12 hours):

$$S(t) = 15.0 + 7.0 \cos(\omega t) \quad (8)$$

where $\omega = 2\pi/T$

Results

Simulations of tidal currents, amplitudes and longitudinal distribution of salinity during the dry and wet seasons were obtained for three cases. These cases pertain to the different boundary conditions used. While simulating salinity fields, the model takes longer than the tidal

simulations to reach steady state. In addition, during the dry season, the model takes longer to reach steady state than during the wet season. A detailed account of the model simulations and results for the three cases are discussed below.

Simulation of surface elevation and tidal currents (Case 1)

In this case, the hybrid network model, with initial and boundary conditions was run for 6 days each for dry and wet seasons, while simulating surface elevations. The model was forced with sea surface elevation at the open boundary as described above. The model was run for 3 days (six tidal cycles) for spin-up and the remaining 3 days of modelled data were used for the study. Figs. 3 shows the observed and computed tides at different stations in the Mandovi whereas Fig. 4 shows those of the Zuari and Cumbarjua. The left and right panels of Figs. 3 and 4 are respectively for the wet (19 – 21 August 1993) and dry (7 – 9 April 1993) seasons. The forcing functions at Mormugao are shown in the top panels in Figs. 3 and 4 (Figs. 3a-3b and Figs.4a-4b). The tides simulated at Penha de Franca (Figs. 3c-3d) and Volvoi (Figs. 3e-3f) have good match with those observed. There is slight difference between the observation and simulation at Ganjem (Figs. 3g-3h) and the reasons are explained in the discussion section. The simulations at Cortalim (Figs. 4e-4d) and Sanguem (Figs. 4g-4h) in the Zuari and Banastarim (Figs. 4e-4f) in the Cumbarjua are also reasonably well with those observed.

The simulations of tidal currents for the spring and neap tides were performed for the month of April. They are shown in Figs. 5a and 5b respectively. During the spring tide, fairly strong tidal currents of about 0.8 m/s were found in the downstream regions of these estuaries. The magnitude of tidal currents are reduced to less than 0.4 m/s during the neap tide. It can be noticed from the Figs. 5a and 5b that both flood and ebb currents are stronger in the Zuari than in the Mandovi. This is because of the higher depth in the Zuari compared to the Mandovi. Tidal current observations (De Sousa, 1999; De Sousa, 2000) at Campal, near the mouth of the Mandovi (see Fig. 1a) were carried out on 15 – 16 April 1999. These measurements of tidal currents showed that the magnitude of tidal currents is of about 1.0 m/s during spring tide whereas the observations during neap tide (12 – 13 February 2000) showed that the magnitude of

these currents are of about 0.65 m/s. The simulated currents were slightly lower than that of those observed.

Simulation of salinity distribution during dry season (Case II)

In this second case, for the simulation of salinity during dry season, two-dimensional and one-dimensional advection-diffusion equations of salinity were included in the model and the model was run for 40 days. The forcing functions for the salinity equations, as stated earlier, was a constant value of 35.17 psu at the mouth. The model reached steady state after 25 days. The 38th to 40th day's simulations were used for the study.

Simulation of salinity distribution during wet season (Case III)

In this third case, salinity was defined as a cosine function at the open boundary and the model was run for 40 days. The model reached steady state after 16 days. The 38th to 40th day's simulations were used for the study. Figs. 6 shows the observed and computed salinities at different stations in the Mandovi whereas Fig. 7 shows those of the Zuari and Cumbarjua. The forcing functions at Mormugao are shown in the top panels in Figs. 6 and 7 (Figs. 6a-6b and Figs.7a-7b).

The model could reproduce the longitudinal distribution of salinity well with those observed during the dry season and reasonably well during the wet season at different stations in the Mandovi, Zuari and Cumbarjua (The left and right panels of Figs. 6 and 7 are respectively for the wet (19 – 21 August 1993) and dry (7 – 9 April 1993) seasons). The salinity at Saramanas (Figs. 6c-6d), Volvoi (Figs. 6e-6f), Sonarbaag (Figs. 6g-6h) and Ganjem (Figs. 6i-6j) in the Mandovi were simulated well with those observed during the dry season. The simulations of salinity at Cortalim (Figs. 7c-7d), Banastarim (Fig.7e-7f) Sanvordem (Figs. 7g-7h) and Sanguem (Figs. 7i-7j) in the Zuari and Cumbarjua were also reasonably well though the model slightly overestimated the salinity at Cortalim (see Fig. 7d) during this season. The simulations of salinity in the above stations were reasonably well during the wet season.

Longitudinal distribution of salinity for varying river discharges

In order to understand the impact of freshwater influx on salinity, we performed 4 model simulations for one month with same boundary conditions used for the dry season. For each run, a freshwater influx of 0, 10, 25 and 50 m³/s was specified at the upstream end point of the Mandovi. The tidally averaged salinity over the M₂ tidal period was calculated and the results, shown in Fig. 8, indicate that the salinity is subject to large variations in the middle and upstream regions. The implications of these results are described in the discussion section.

Intra-seasonal variations of salinity in the Mandovi during wet season

Fig. 9 shows the vertical profiles of salinity in the longitudinal sections in the Mandovi during March 2007. It appears that the estuary is vertically well-mixed. Now if we look at the contour plots of salinity during August and September 2005, which are shown in Fig. 10 and 11 respectively, these data suggest that the salinity near the mouth was about 15 psu and about 3 psu at a distance of 11 km from the mouth in August (Fig. 10) whereas in September, the salinity was pushed more toward the mouth due to the inflow of freshwater. Figs. 10 and 11 also show that the water column was partially mixed in the downstream regions in August and September. The salinity remained nearly zero in the upstream regions.

Discussion

Tidal amplitudes are simulated well in both seasons in the Mandovi, Zuari and Cumbarjua. But their upstream stations (Ganjam and Sanguem), the simulations are not very accurate. Especially at Ganjam where the observations show that the tidal range is almost negligible during the wet season. During the dry season, the tidal amplification is visible only during the spring tide (the tides and salinity observations in 1993 were conducted during the spring tide). The model could not reproduce tidal amplitudes at this station accurately. This could be due to (i) freshwater inflow into the estuary from other small tributaries, we considered the freshwater input for the model only from the runoff gauge installed at Ganjam (ii) meandering effects of the channels were not considered in the present model. The meandering effects of channels can modify the

amplitude and phase of tides inside the estuaries. Tidal amplitudes at Banastarim (Fig4e-4f) in the Cumbarjua during the dry and wet seasons are almost similar to that of Cortalim (Figs. 4e-4d). This is likely to be the fact that the cross sectional area of the Cumbarjua at the junction with the Zuari is much larger than that of the Mandovi and thus the tide propagates into the Cumbarjua freely from the Zuari.

One of the main purposes of using a 2D model was to simulate tidal currents in the down stream regions. Fairly strong tidal currents of about 0.8 m/s were found in the estuarine network and the observed currents were about 1.0 m/s (De Sousa, 1999; De Sousa, 2000). The Mandovi and Zuari estuaries are meso-tidal estuaries where the vertical mixing of water column is mainly due to tidal activity. The magnitude of tidal currents found in the estuarine network are sufficient to keep the water column vertically well-mixed in the absence of freshwater influx.

In the 1D regions of these estuaries, the longitudinal distribution of salinity was found to be nearly the same (see Figs. 6 and 7) when the model was run without the salinity gradient term in Eq. 4. The model results plotted in Figs. 6 and 7 show that the longitudinal distribution of salinity in the Mandovi is better simulated than in the Zuari during the dry and the wet seasons. During the dry season, the simulations of salinity were carried out after prescribing the freshwater influx of $10 \text{ m}^3/\text{s}$. The simulations show that the freshwater influence does not reach in the mouth stations (see Figs. 6d and 7d) for the freshwater influx of $10 \text{ m}^3/\text{s}$. A numerical experiment was carried out for studying the freshwater influence on the longitudinal distribution of salinity for varying freshwater influxes. The experiment also shows the similar results as mentioned above. More discussion about this experiment is given in the following section.

The numerical experiment carried out for the simulation of the longitudinal distribution of salinity in the Mandovi shows that the salinity distribution undergoes large changes in the upstream regions for varying river discharges. In the downstream regions (0 to 12 km), the salinity is about 35 psu whereas the salinity dropped from 10 to 5 psu in the middle regions (20 to 35 km) and became zero further toward upstream regions when freshwater influx of $10 \text{ m}^3/\text{s}$

was specified (see Fig. 8). With a freshwater influx of $50 \text{ m}^3/\text{s}$, the salinity drops from 30 to 8 psu at about 20 km distance from the mouth. From 35 km to further toward upstream regions, salinity goes to nearly zero. The model results show that the salinity did not change in the downstream regions for varying river discharges. This numerical experiment was carried out for the month of April for dry season salinity boundary conditions. As mentioned earlier, the salinity was prescribed using 35.17 psu at the open boundary of the model during this period whereas during the wet season, the salinity was prescribed as a cosine function which was allowed to vary between 8 to 22 psu during a tidal cycle. The model could not flush out the salinity from the mouth due to the dry season boundary conditions prescribed at the mouth. But the model could simulate the freshwater influence in the upstream regions.

The freshwater influx in July and August is about $400 \text{ m}^3/\text{s}$, which can push the salinity completely from the upstream regions to the downstream regions. The upstream regions become freshwater dominated during the wet season. From the model results and field observations made, during the wet season, It is found that the Mandovi and Zuari are partially mixed in the downstream regions and the upstream regions of the channel are almost free from salinity.

The longitudinal variations of salinity (Fig. 10 and 11) during the selected days in August and September 2005 in the Mandovi, indicate that in a monsoonal estuary like the Mandovi, salinity is subject to intra-seasonal variations during the wet season. The high salinity found in the Mandovi in August 2008 could be due to the deficit of freshwater outflow associated with the low rainfall. In September 2008, the low salinity in the estuary indicates large quantity of fresh water influx into the estuary from the upstream regions due to the intensification of rainfall. An important characteristic of the southwest monsoon is variability on sub-seasonal timescales, with “active” periods of heavy rain interrupted by drier “break” periods (Vecchi and Harrison 2002). This breaks during the southwest monsoon reduces freshwater influx into the estuary and consequently, saline water intrudes into these estuary. When the monsoon becomes active once again, the saline water is pushed out of the estuary as shown in Fig. 11. The salinity data shown

Figs. 10 and 11 show that the salinity in the Mandovi is subject to intra-seasonal variations during the wet season.

Our model simulations demonstrate the fresh water influence on tides and longitudinal distribution of salinity. The model simulated the longitudinal distribution of salinity well during the dry season and reasonably well during the wet season. From the analysis of salinity measured during the wet seasons, a lot of measurements of salinity is required during the wet season to establish how the “breaks” in the southwest monsoon affect the longitudinal distribution of salinity. We think that further efforts are needed to study the above parameters in detail using 3D models.

Appendix

In the model, the finite difference explicit scheme was used for solving the equations. Arakawa C grid used for the computation of surface elevation, transport and salinity etc. is shown in Fig. A1. The finite difference form of continuity equation for coupling between 2D and 1D models and two 1D models are given below.

Coupling between 2D and 1D models

Surface elevation and salinity at the 1st grid points of the 1D domain of the Mandovi and Zuari were calculated using the following formulation:

$$\eta_{i,t+\Delta t} = \eta_{i,t-\Delta t} - \left(\frac{2\Delta t}{\Delta x b_i} \right) \left(Q_{i,t} - b_i (U_{i-1,t}) \right) \quad (9)$$

$$S_{i,t+\Delta t} = S_{i,t-\Delta t} - \left(\frac{\Delta t}{\Delta x A} \right) \left(Q_{i,t} (S_{i+1,t} - S_{i,t}) + A u_{i-1,j,t} (S_{i,t} - S_{i-1,j,t}) \right) + K_x \left(\frac{2\Delta t}{\Delta x^2} \right) \left(S_{i-1,j,t-\Delta t} S_{i+1,t-\Delta t} - 2S_{i,t-\Delta t} \right) \quad (10)$$

where $U_{i-1,j,t}$ and $S_{i-1,j,t}$ are respectively transport and salinity from 2D model ($i-1 = 24, j = 37$ in the Mandovi and $i-1 = 30, j = 14$ in Zuari, see Fig. A1) and $Q_{i,t}$ and $S_{i,t}$ are respectively transport and salinity from 1D models. Note that $Q_{i,t}$ and $S_{i,t}$ are general notations used for transport and salinity in 1D models in the above equations. But for the following calculations, $Q_{i,t}$ and $S_{i,t}$ are replaced by $Qm_{i,t}, Qz_{i,t}, Qc_{i,t}$ and $Sm_{i,t}, Sz_{i,t}, Sc_{i,t}$ respectively for the Mandovi, Zuari and Cumbarjua canal.

Coupling between two 1D models

Calculation of surface elevation and salinity at the 4th grid point in the Zuari and 1st grid point in the Cumbarjua (see the 4(1) grid point in Fig. A1) was made as follows:

$$\eta_{z_{i,t+\Delta t}} = \eta_{z_{i,t-\Delta t}} - \left(\frac{2\Delta t}{\Delta x b z_i} \right) (Qz_{i,t} + Qc_{i,t} - Qz_{i-1,t}) \quad (11)$$

$$\begin{aligned} Sz_{i,t+\Delta t} = Sz_{i,t-\Delta t} - \left(\frac{\Delta t}{2\Delta x A} \right) & \left(Qz_{i,t} (Sz_{i+1,t} - Sz_{i,t}) + Qz_{i-1,t} (Sz_{i,t} - Sz_{i-1,t}) + Qc_{i,t} (Sc_{i+1,t} - Sz_{i,t}) \right) \\ + K_x \left(\frac{2\Delta t}{\Delta x^2} \right) & \left((Sz_{i-1,t-\Delta t} + Sz_{i+1,t-\Delta t} - 2Sz_{i,t-\Delta t}) + (Sc_{i-1,t-\Delta t} + Sc_{i+1,t-\Delta t} - 2Sc_{i,t-\Delta t}) \right) \end{aligned} \quad (12)$$

As shown in the Fig. A1, the 4th grid point in the Zuari and 1st grid point in the Cumbarjua are same. Therefore,

$$\eta_{c_{i,t+\Delta t}} = \eta_{z_{i,t+\Delta t}} \quad (13)$$

$$Sc_{i,t+\Delta t} = Sz_{i,t+\Delta t} \quad (14)$$

Calculation of surface elevation and salinity at the 14th grid point in the Mandovi and 32nd grid point in the Cumbarjua (see the 14(32) grid point in Fig. A1) was calculated in a similar way.

$$\eta m_{i,t+\Delta t} = \eta m_{i,t-\Delta t} - 2 \left(\frac{\Delta t}{\Delta x b m_i} \right) (Q m_{i,t} - Q c_{i,t} - Q m_{i-1,t}) \quad (15)$$

$$\begin{aligned} S m_{i,t+\Delta t} = & S m_{i,t-\Delta t} - \left(\frac{\Delta t}{2 \Delta x A} \right) \left(Q m_{i,t} (S m_{i+1,t} - S m_{i,t}) + Q m_{i-1,t} (S m_{i,t} - S m_{i-1,t}) + Q c_{i,t} (S c_{i+1,t} - S m_{i,t}) \right) \\ & + K_x \left(\frac{2 \Delta t}{\Delta x^2} \right) \left((S m_{i-1,t-\Delta t} + S m_{i+1,t-\Delta t} - 2 S m_{i,t-\Delta t}) + (S c_{i-1,t-\Delta t} + S c_{i+1,t-\Delta t} - 2 S c_{i,t-\Delta t}) \right) \end{aligned} \quad (16)$$

The 14th grid point in the Mandovi and 32nd grid point in the Cumbarjua are the same (see Fig. A1). Therefore,

$$\eta c_{i,t+\Delta t} = \eta m_{i,t+\Delta t} \quad (17)$$

$$S c_{i,t+\Delta t} = S m_{i,t+\Delta t} \quad (18)$$

Note that (see Eq. 11) 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 Eq. 15), as per sign convention used, the flow in the Cumbarjua canal is taken as positive from the Zuari side to the Mandovi side.

Freshwater inclusion in the model

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

$$q_{n,t} = D/A \quad (19)$$

where D is the discharge in m³/s and A is the area of cross section in m²

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List of Figures

Fig. 1a. The Mandovi and Zuari estuarine network.

Fig. 1b. The schematic diagram shows the model domain of the estuarine network. The one dimensional model domains of the Mandovi and Zuari extend upto 73.17° E though it is not shown in the diagram since it distorts the Fig.'s view.

Fig. 2. The monthly mean averaged discharge at Ganjem in 1993.

Fig. 3. Observed (dotted line) and simulated (solid line) tides at different stations in the Mandovi during the wet and dry seasons are shown on the left and right panels respectively. 72 hours on the left panel correspond to 0.0 hours on 19/08/1993 and 72 hours on the right panel correspond to 0.0 hours 07/04/1993.

Fig. 4. Same as that of Fig. 3 but for the Zuari.

Fig. 5a. Modelled tidal currents during the spring tide in the Mandovi and Zuari. The high and low tides are shown with respect to Mormugao.

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Fig. 6. Same as that of Fig. 3 but for the salinity. 893.5 hours on the left panel correspond to 0.0 hours 19/08/1993 and 893.5 hours on the right panel correspond to 0.0 hours 07/04/1993.

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Fig. 8. Longitudinal distribution of salinity for varying discharges in the Mandovi. The simulations were carried out for 0, 10, 25 and 50 m³/s discharges.

Fig. 9. Observed Salinity for 30 March 2007 in the Mandovi. The time (hours) at which the observations were made are indicated in the bracket.

Fig. 10. Same as that of Fig. 9 but for 23 August 2005.

Fig. 11. Same as that of Fig. 9 but for 13 September 2005.

Fig. A1. Schematic diagram showing the coupling between 2D and 1D models and 1D and 1D models. 1st grid point of 1D model in the Mandovi is coupled to the grid points ($i = 24, j = 37$) of 2D and 1st grid point D model in the Zuari is coupled to the grid points ($i = 30, j = 14$). In the 1D model domains, 4th grid point in the Zuari and 1st grid point in the Cumbarjua are same. Similarly, 14th grid point in the Mandovi and 32nd grid point in the Cumbarjua are same. The total number of grid points in the Mandovi, Zuari and Cumbarjua are 75, 81 and 32 respectively

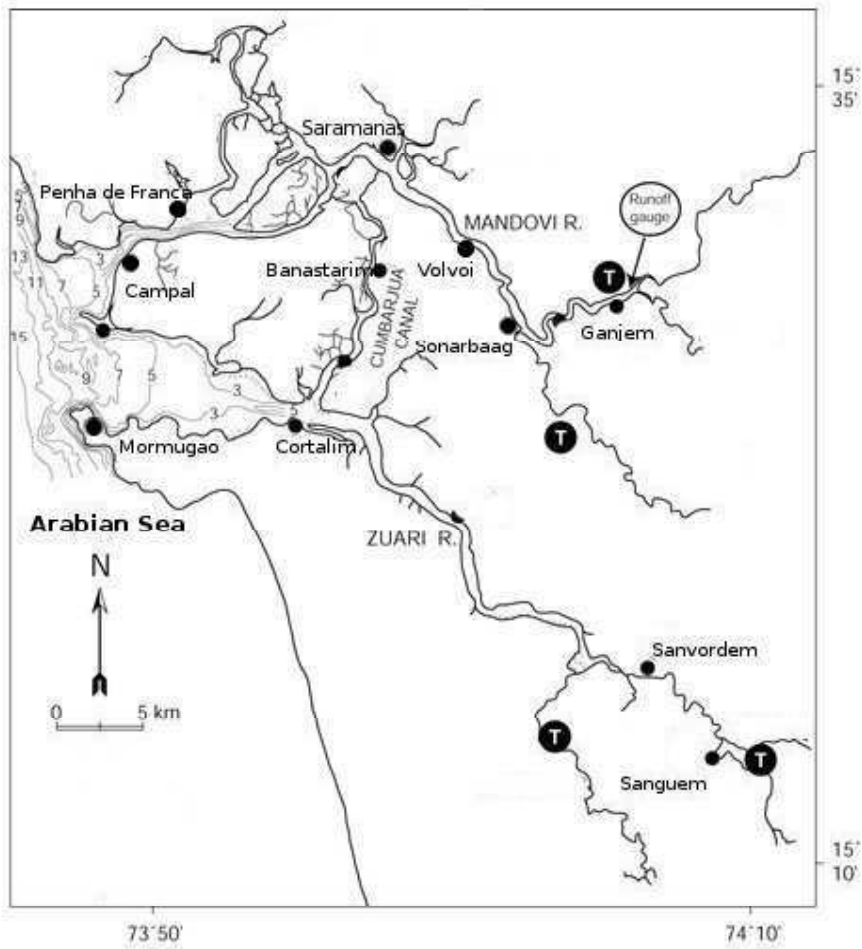


Figure 1a

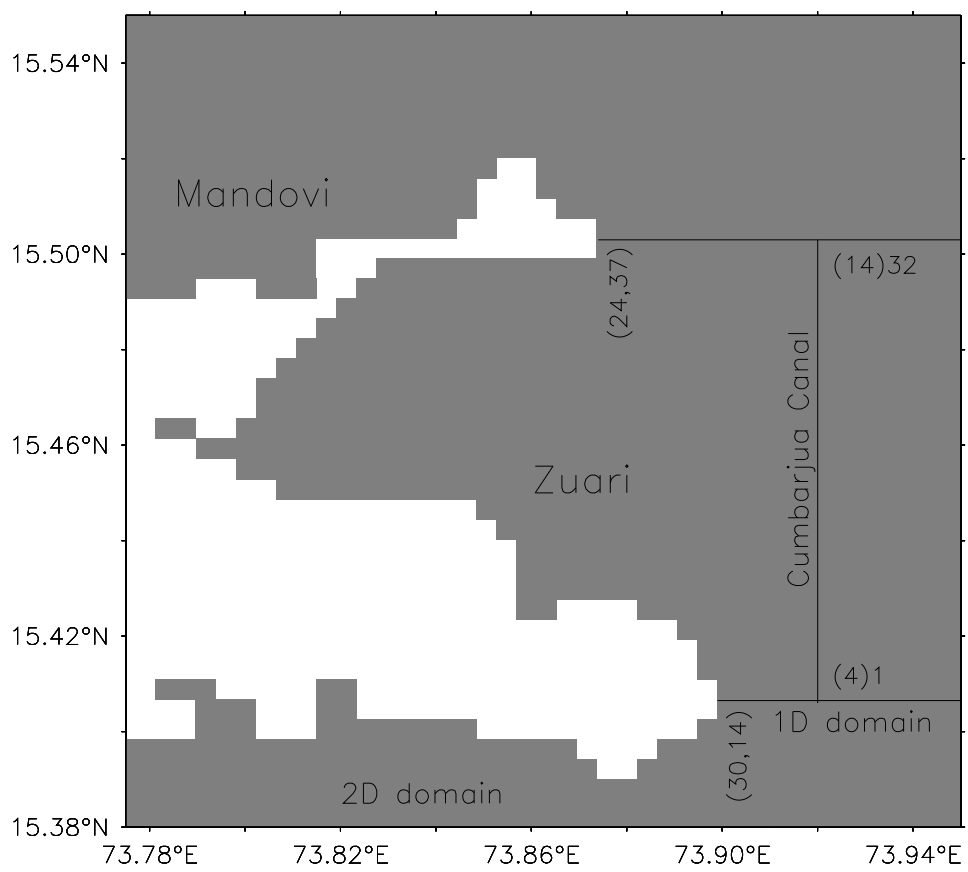


Figure 1b

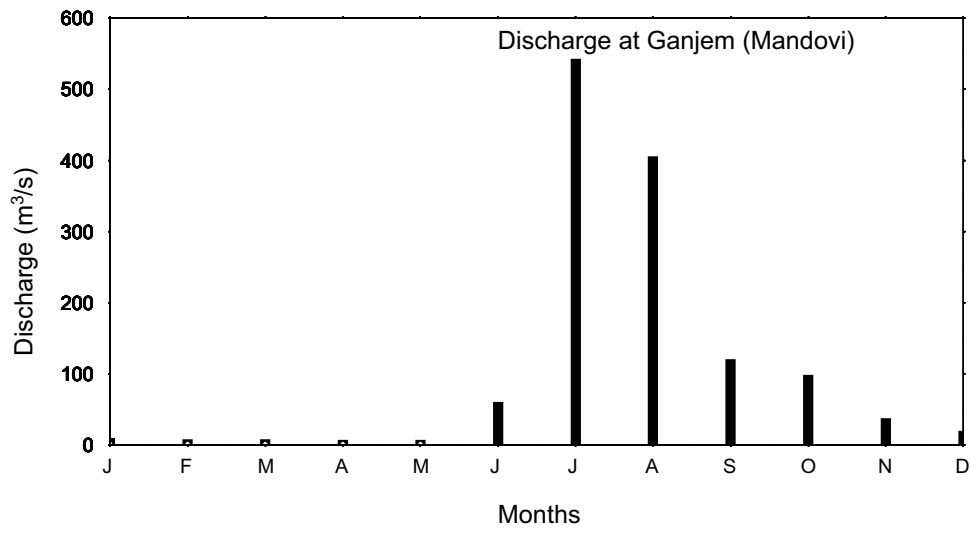


Figure 2

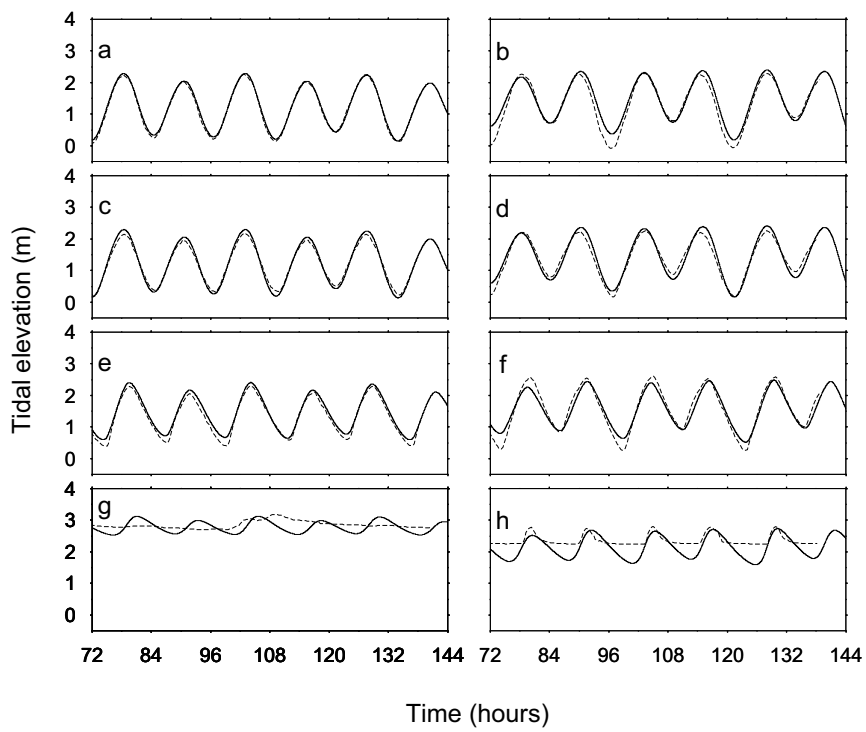


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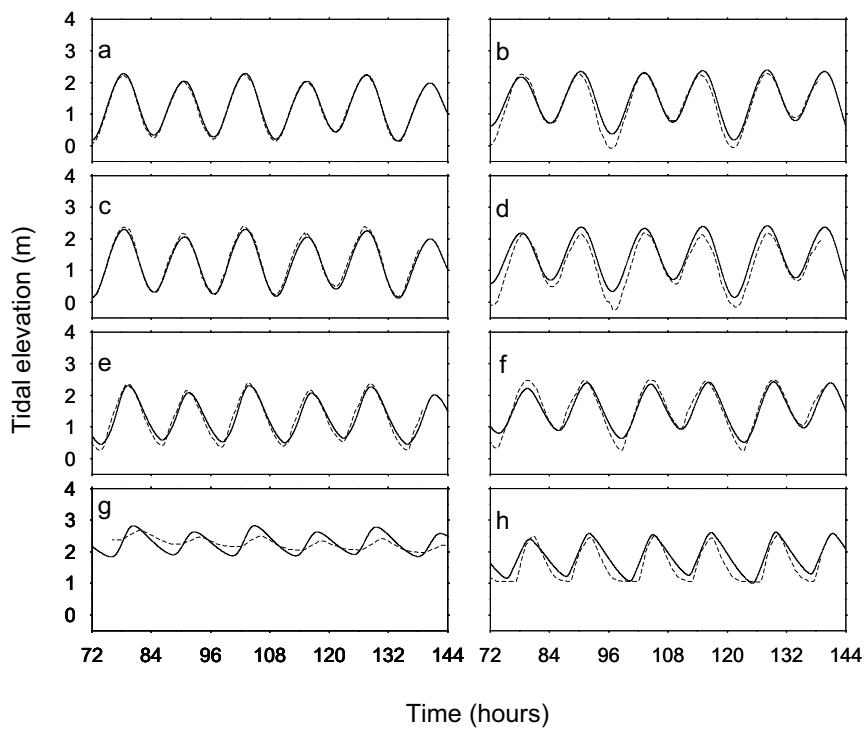
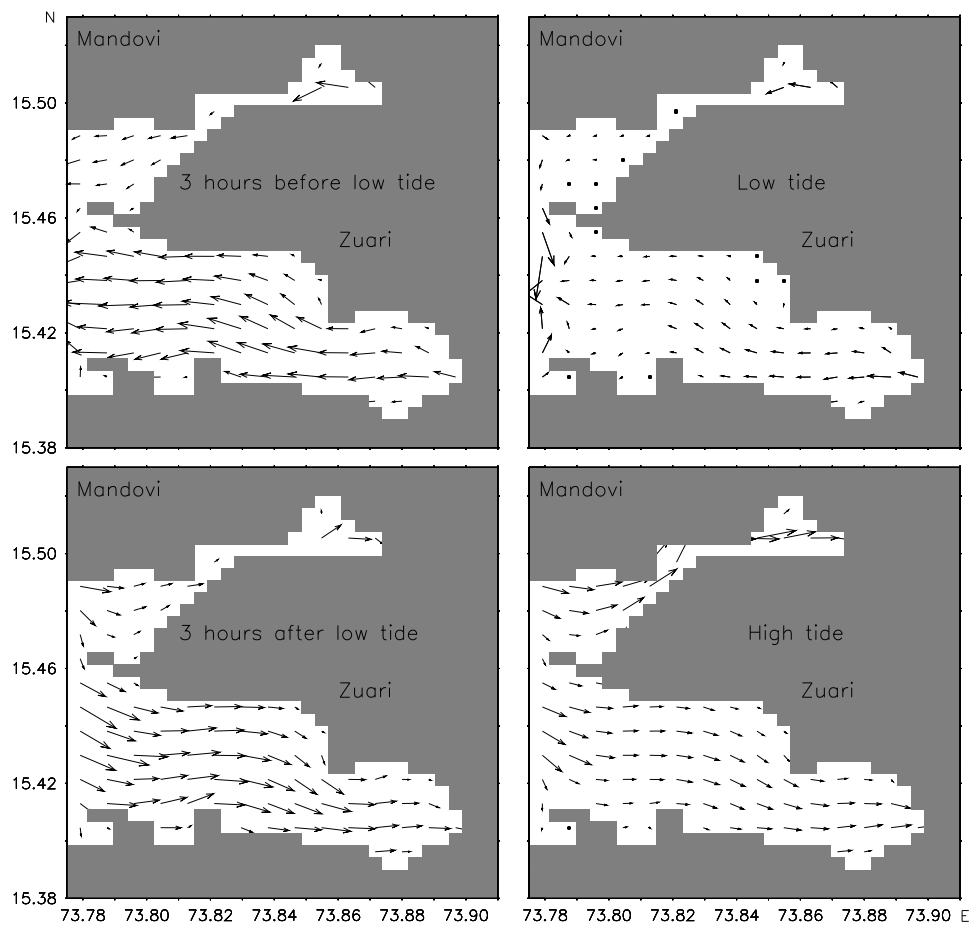


Figure 4



Tidal currents \rightarrow 0.25 m/s

Figure 5a

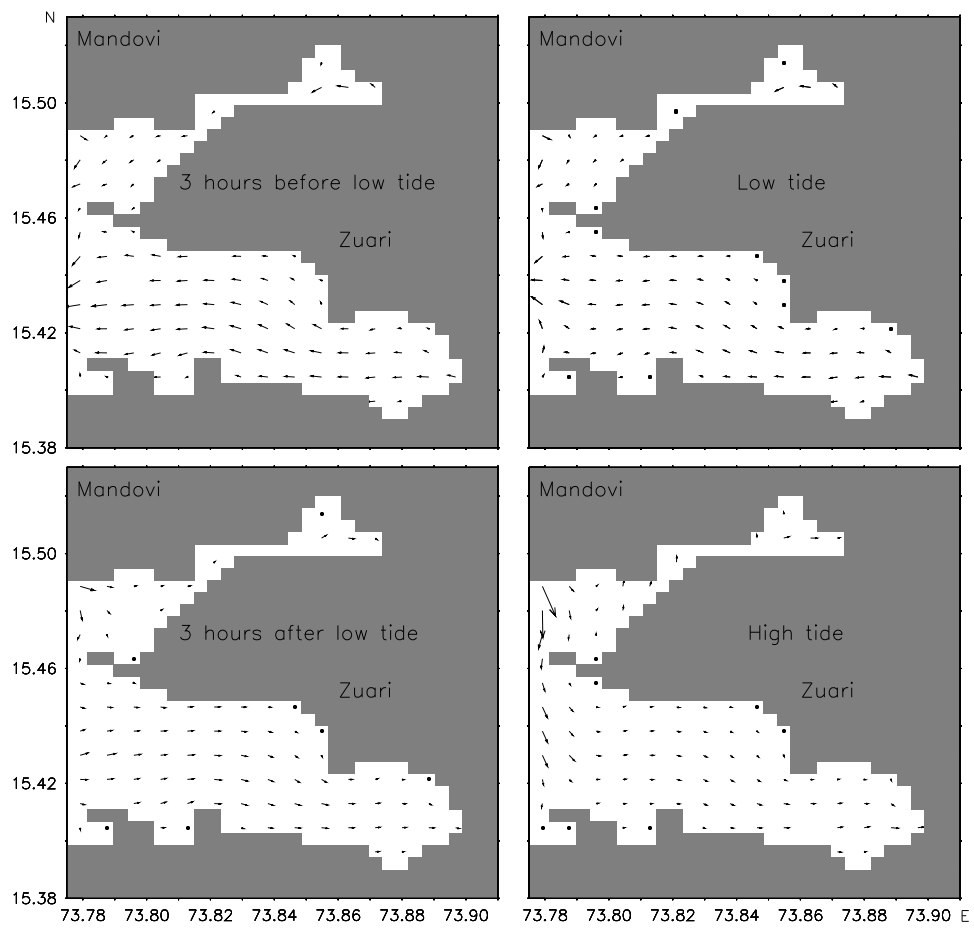


Figure 5b

Tidal currents \rightarrow 0.25 m/s

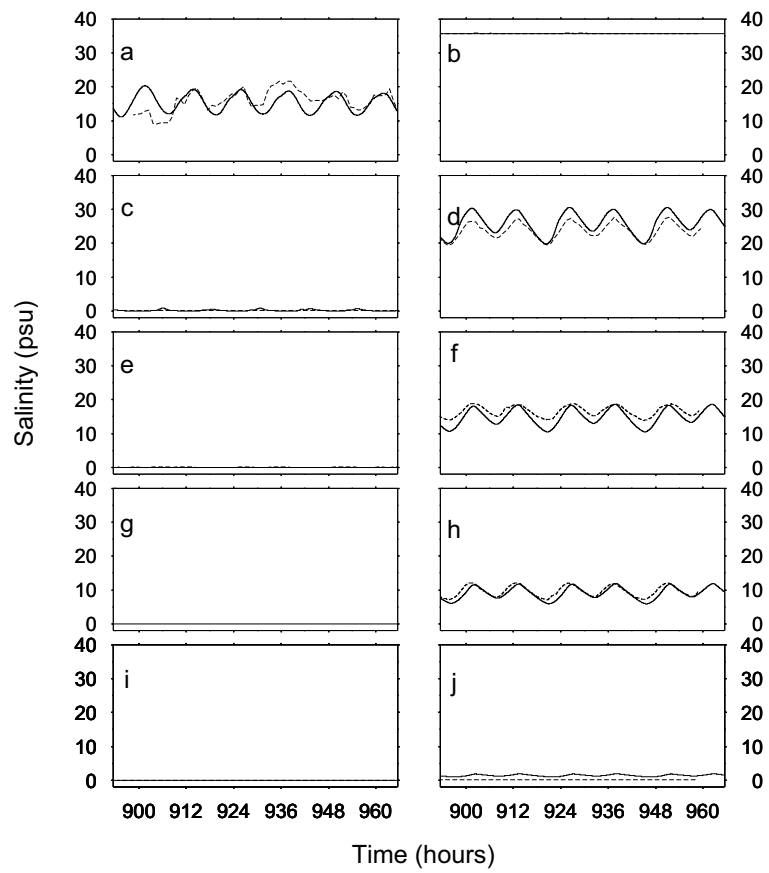


Figure 6

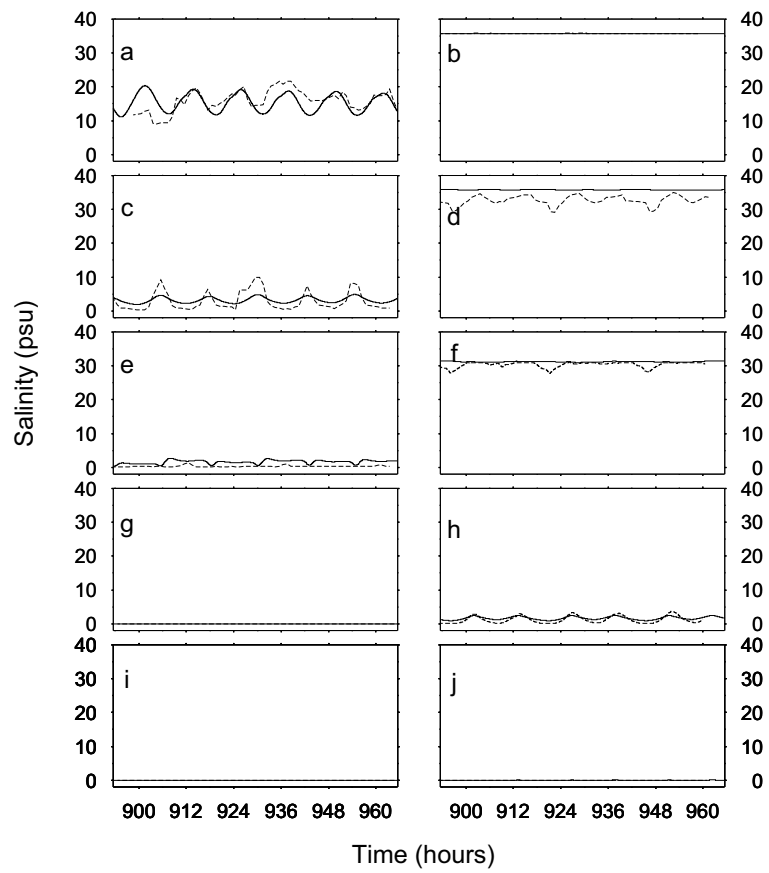


Figure 7

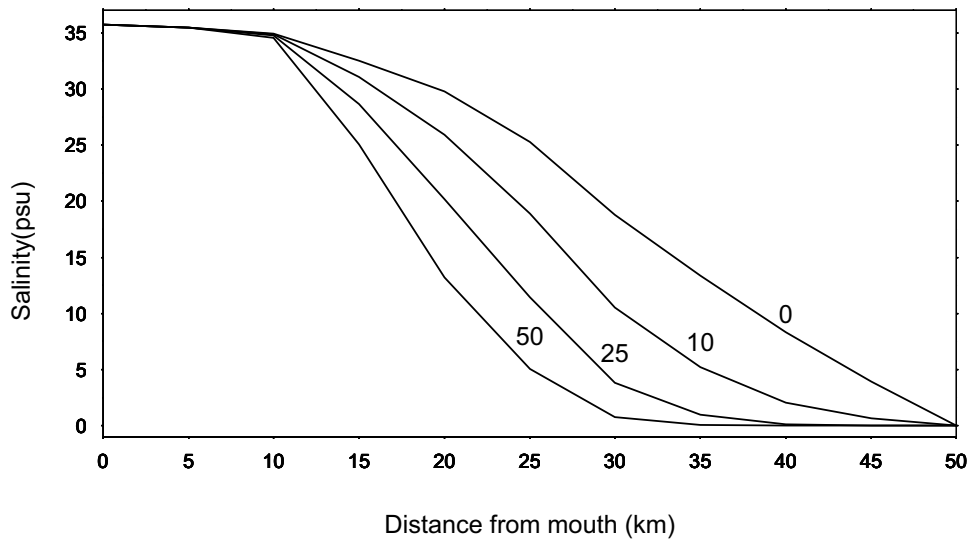


Figure 8

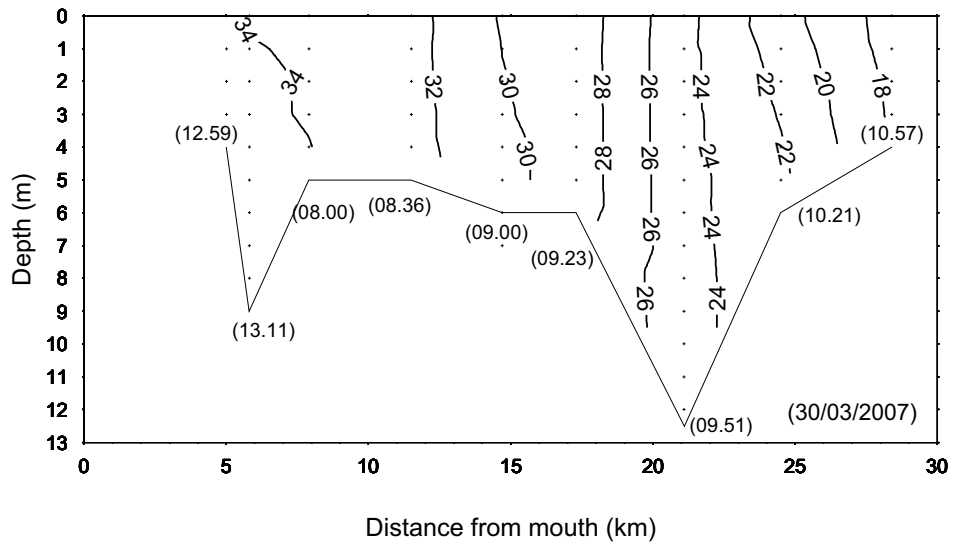


Figure 9

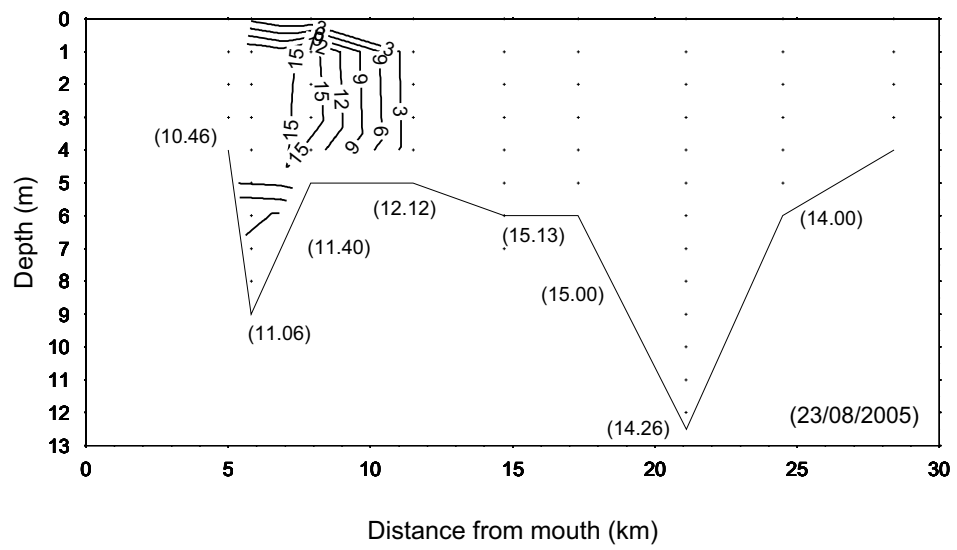


Figure 10

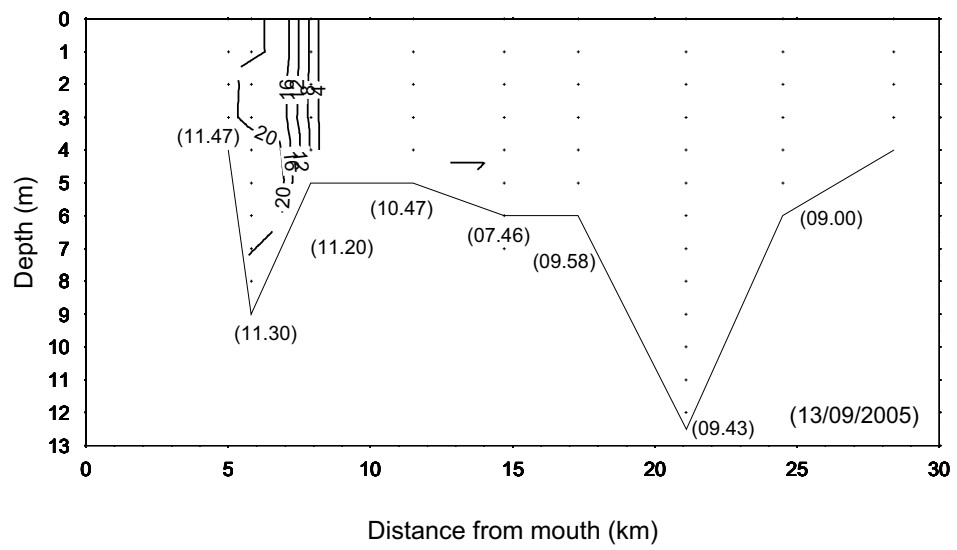


Figure 11

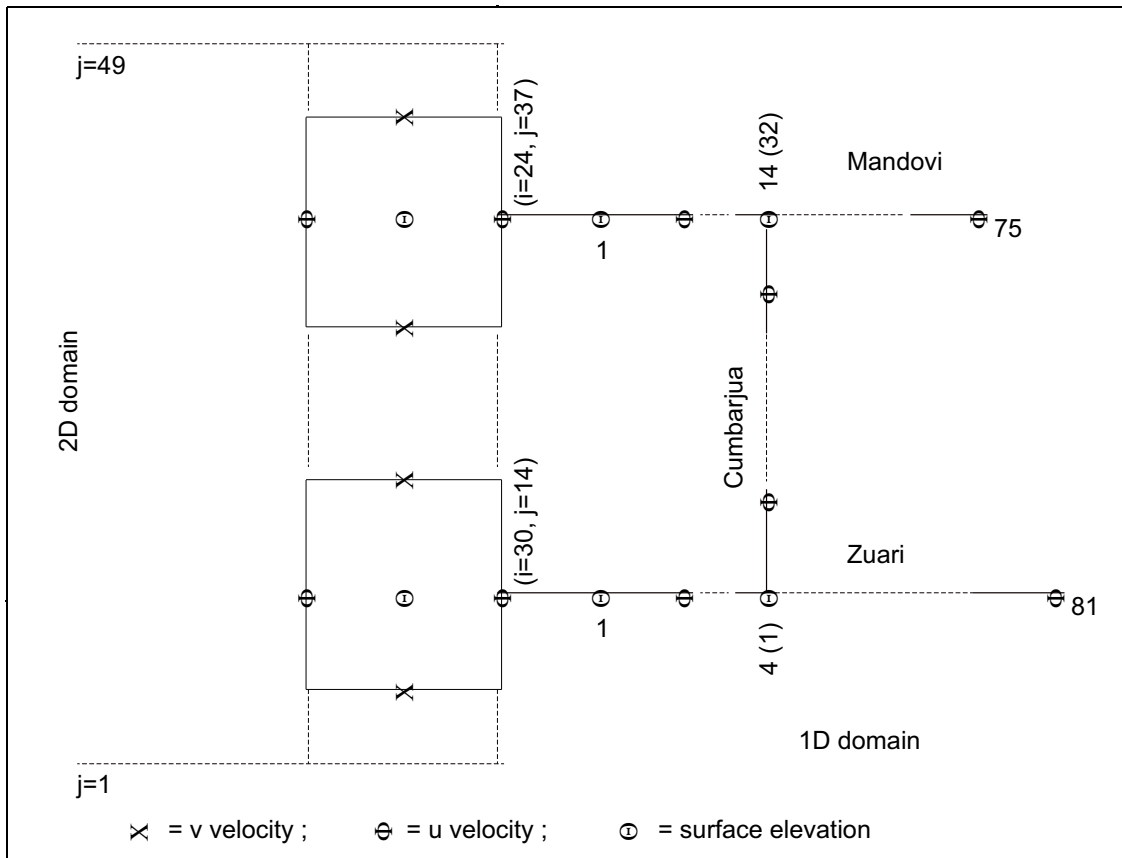


Figure A1