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Model simulation of tide-induced currents in Gauthami–Godavari estuary

Estuaries are often surrounded by protected ecosystems, and harbour significant human populations which exploit the area for leisure and tourism. Studies on Indian estuaries can be found in Qasim[1]. Several studies[2–11] reported various aspects of the estuaries, viz. Mandovi, Zuari, Cochin, Hooghly, Mahanadi and Godavari. Very few modelling studies[8,12–15] have been done for the Indian estuaries. Three-dimensional and two-dimensional models are commonly used to characterize hydrodynamic and transport processes in the estuarine, coastal and open ocean systems. Hydrodynamic models (3D) have the capability of simulating both spatial and vertical time-dependent frame, which is not possible with the 2D models. However, limited resources can make use of a 3D model infeasible for a particular study. In such cases, a 2D model, either a vertically or laterally averaged model must be used to understand the basic physical processes of a particular estuarine system. The application of 2D models with different types of closure schemes to determine the tidal circulation in the estuaries was reported from many parts of the world. A comparison of various closure schemes[16], and turbulence closure models[17] for stratified shallow water flows with application to the Rhine outflow region, have been reported. The laterally averaged flow and salinity structure in the Godavari estuary in July and only salinity structure in January were simulated[12]. In Mahanadi, laterally averaged velocity and salinity structures were simulated[8]. The model results could not be compared with the observations. A 2D numerical model to derive tides and residual currents was attempted in Thane Creek[13]. Sinha *et al.*[14] studied the laterally averaged currents and salinity distribution in the Hooghly estuary.

To our knowledge, no attempt has been made so far to study and validate the spatial currents pattern in the Godavari estuary, which is the third largest river in India. Here we have made an attempt to compare the model results with the systematic and accurate datasets collected in the estuary using sophisticated equipment. It may be mentioned that most of the earlier studies could not compare their model results in the estuaries, which could be due to lack of observations.

Godavari estuary is the third largest estuary in India and receives significant amount of freshwater from the upstream river. The discharge of freshwater from the upstream is mainly controlled by Low Dam at Dowleiswaram, where it bifurcates into two channels as Vasishta and Gauthami Godavari estuary (Figure 1)[18,19]. Discharge was maximal in August, and virtually no or negligible discharge between January and May[19]. Mixing in estuaries results from a combination of various effects such as tide, wind, the Earth's rotation and inflow from rivers. The interaction between dense saline waters entering from the sea and the freshwater derived from the upland discharge gives rise to a wide spectrum of circulation patterns and estuarine mixing. Virtually no discharge during the dry season made the estuary turn into well-mixed type and circulation is dominated by tides. Several investigators studied the seasonal variations in circulation and mixing characteristics of the Godavari estuary from the mouth to ~22 km upstream and observed that salinity in the estuary was mainly controlled by discharge during SW monsoon season with strong stratification, whereas well-mixed conditions were noticed in January[10]. This region experiences mixed tides with semi-diurnal as dominant and tidal range varying between 1.5 and 0.5 m from spring to neap tide. Hence, vertically integrated continuity and momentum equations were used in the present 2D numerical model for generating the tides and tide-induced circulation during different tidal phases.

To model the currents in Gauthami–Godavari estuary during dry season, TIDAL model is used. It is a well-known fact that bathymetry is one of the key input parameters for a model. As bathymetry in the estuary is highly variable with space and time, the model results greatly depend upon the bathymetry. Keeping these points in mind, the high-resolution bathymetry data had been collected in the estuary. Bathymetry of the Godavari estuary was collected in July 2008 for a stretch of ~ 32 km from mouth (Bhairavapalem) to upstream end (Kotipalli) with a grid spacing of 500 m × 50 m approximately and with reduced grid space at some areas where sills are present using a highly precise measuring instrument, differential global positioning system (DGPS). It measures from very shallow depth (30 cm) to 100 m depth with an update rate of 6 soundings sec^{-1}. The accuracy of the system is ± 1 m for geographical position and ± 1.0 cm of depth. The bathymetry was gridded to 50 m × 50 m space which has been used to get 100 m × 100 m grid space of 316 × 80 grid cells. During the dry season, discharge was negligible and hence boundaries upstream and small tributaries were closed. The model simulation starts from an initial state of rest (i.e. $u = v = t = 0$), and tidal elevation data for one month at the mouth (nearer to Bhairavapalem) of the estuary were given as input. Light to moderate wind conditions were noticed during the observation period. Hence the atmospheric forcing parameter was ignored. The coriolis parameter corresponding to this location was taken as 4.18×10^{-5} (lat. 16.7°). The bottom friction (C_f) was parameterized in terms of the coefficient of Chezy using the formula $C_f = (1/32) \times [\log_{10}(14.8\,H)/K]^{-2}$, where K is a roughness length and H the total depth. Horizontal diffusion terms in the momentum balance have been neglected since these are assumed to be small compared with the other terms present in the momentum equations. Stability of any numerical model depends on $\Delta t < \Delta x/(2gH_{max}^{-2})$, where Δx, g and H_{max} are grid size (in m), acceleration due to gravity and highest depth in the study region respectively. Hence in the present case 5 sec time-step is considered for solving the currents. The governing equations are solved with the initial and boundary conditions on a staggered grid system and run for two days[20,21]. Once it reaches a steady state, the results are compared with the observations. Nevertheless, the present model is a first step and it is useful for understanding the circulation pattern of the estuary under dry season.

Tides data near the mouth of the estuary were collected during February 2009 (Figure 2) with an interval of 5 min using a tide gauge installed by Marine Instrumentation Division, National Institute of Oceanography. For validating the model results, high-resolution currents (10 min interval) data were collected using RCM 9IW (Aandera Instruments, Norway; accuracy ± 0.15 cm s^{-1}) at three locations (Y1, Y2 and Y3) across the estuary (Figure 1, marked in a box) during 11–19 February 2009.

Model simulation was started with initial conditions and assumptions as men-

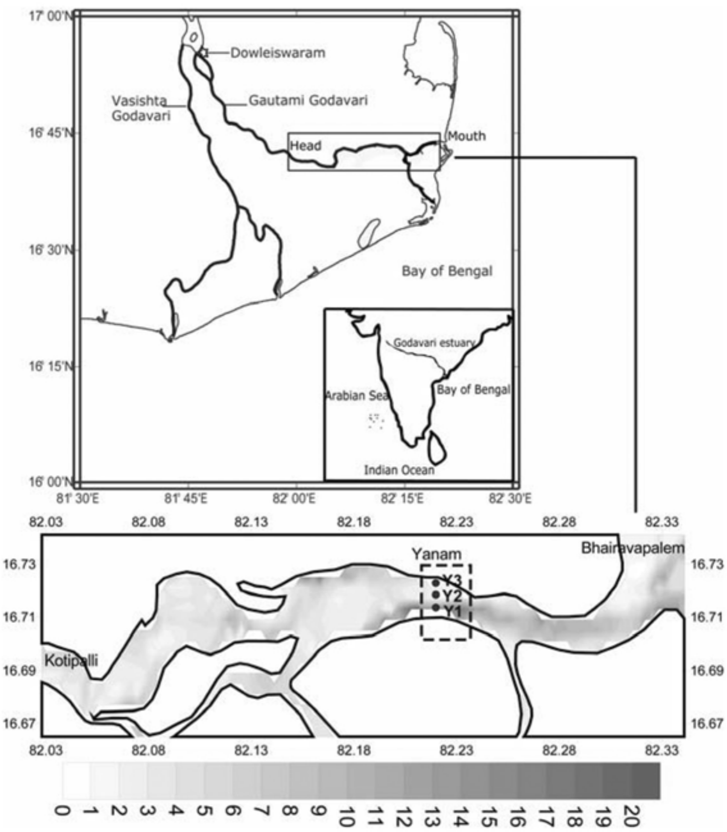

Figure 1. Locations (Y1, Y2, Y3 – shown in the box) for time-series data on currents at Yanam in the Gauthami–Godavari estuary.

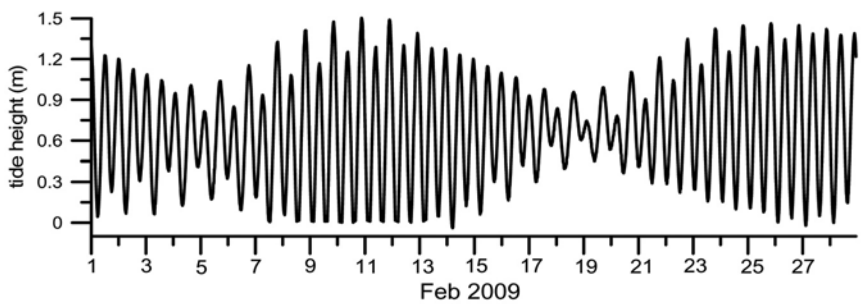

Figure 2. Observational tidal data at the mouth of the estuary during February 2009.

tioned above. At each 5 sec interval tidal elevation, zonal and meriodonal currents were generated in the entire domain for calibration. Results were stored at three observation locations (Figure 1, marked in a box) at each time-step of 10 min interval. After four tidal cycles, transients generated by the cold-start initial conditions were suppressed by the bottom friction factor and the model was stabilized. Model was run from $k = 0.025$ to 0.1 with an interval of 0.005. The standard deviation between observed and model data was minimum at $k = 0.085$ m (Figure 3). Earlier studies[12,22] used 1 cm as bottom roughness length without any calibration for Godavari and Mahanadi estuaries, which was about eight times higher in the present case. Model results were compared with the observations collected during 11–19 February 2009 (Figure 4). Speeds were calculated from model velocities and then compared with the observations at three locations. The results show that the predicted current speeds are in reasonable agreement with those observed, both temporally and spatially. It is interesting to note that the model could reasonably capture the variability of the currents, except under peak flood/ebb tide conditions, particularly during spring and neap tides. Current comparisons had been made with caution, since the point observations were compared with the depth and grid-averaged current speeds, particularly when the bed gradients within the grid limit are more. The results were well comparable during and after the spring tide, but not at neap tide. Stations Y2 and Y3 are shallower and ± 1 cm s^{-1} of error was noticed between the model and observed currents, but this error was increased to ± 4 cm s^{-1} at Y1 station. Error of ± 2 cm s^{-1} was noticed between the model and observed speeds of three stations together. Data are not available for validation of the model after the neap tide. Similar results are found for Thane Creek[13].

After calibration, currents were generated spatially during flood and ebb tides on 11 February 2009 at 10 : 10 h and 15 : 40 h respectively. The distribution of currents clearly explains the variability of the flow from mouth to head (Figure 5). Model results reveal that majority of the flow was found to be along the channel axis with minor cross-sectional flow. Direction of currents changes from southwest to northeast when tides change from flood to ebb and these velocities

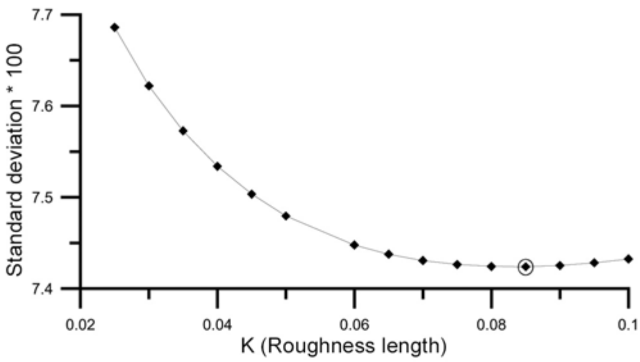

Figure 3. Calibration of bottom roughness length (k) with standard deviation.

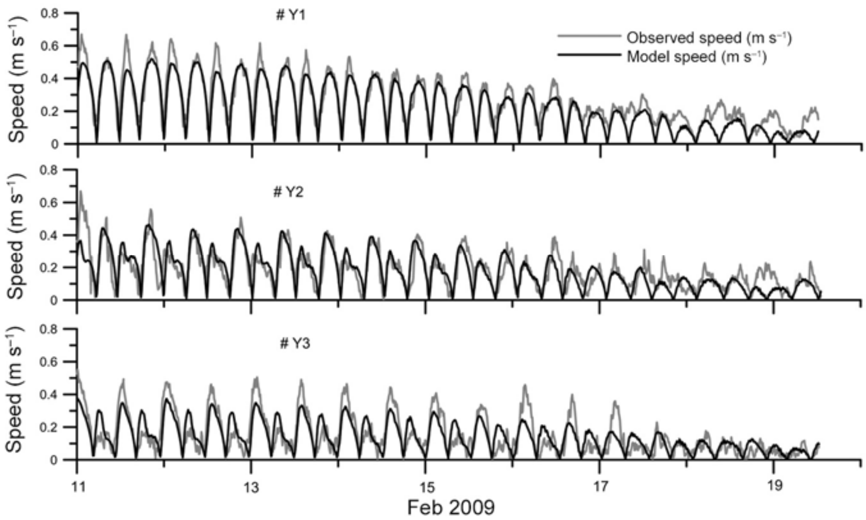

Figure 4. Validation of model and observed currents at three locations (locations marked in Figure 1).

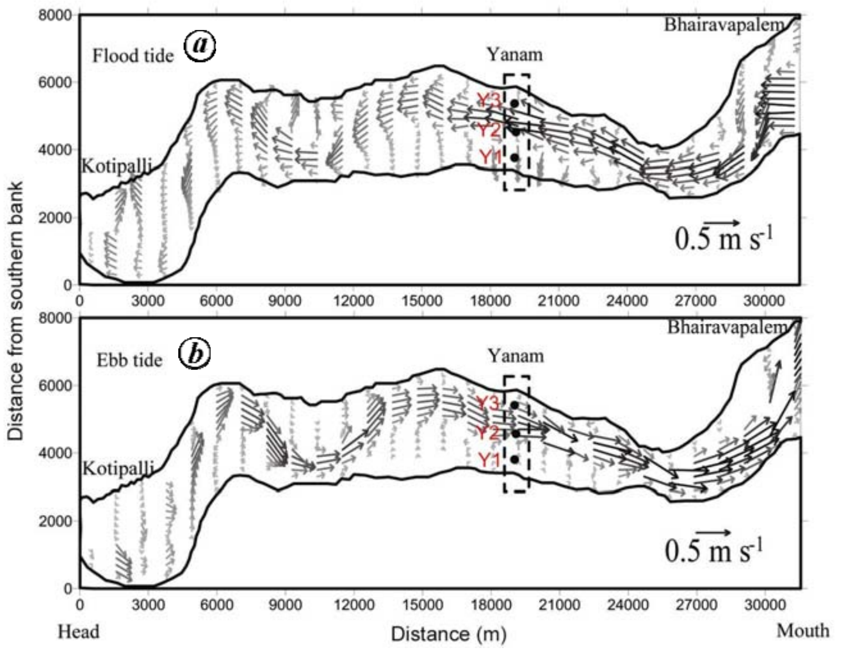

Figure 5. Model generated spatial currents during (***a***) flood and (***b***) ebb tide on 11 February 2009.

change with distance from the mouth. During dry season, velocities at the head of the estuary were negligible compared to those at the mouth of the estuary. Thus average current speeds during flood and ebb tides are similar and vary from 0.02 to 0.6 m s^{-1}. Across Yanam (marked in box in Figure 1), the model-generated average flood and ebb currents were 0.18 and 0.22 m s^{-1} respectively, which are close to observations (0.16 and 0.20 m s^{-1}).

The estuary was vertically well mixed in terms of density stratification during the dry season due to less run-off compared to tidal prism. It is therefore sufficient to use the TIDAL model for the present case, since the vertical approximations associated with averaging are likely to be small. Model results reveal that majority of the flow was found to be along the channel axis (i.e. high iso-bath contour). During floods, flow is the southwest direction and it changes to northeast direction during ebb period, which indicates that the model results resemble flow in the real estuarine system. However, secondary baroclinic flows, which are often generated in estuaries (although shallow depths ensure a vertically mixed water column for the present case studies), will not be simulated in a depth-averaged model and, therefore, 3D modelling will be required. Further, the model was run for a grid size of 100 m. Increasing the grid resolution and data from small tributaries further improve the accuracy of the simulations. The value of roughness length (K) is suggested as 0.085 m, which is about eight times higher than that used earlier by the modellers[12,22]. Using the above value, incorporating the freshwater discharge from the small tributaries and increasing the grid resolution (50 m × 50 m) may further improve the model results.

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Occurrence of rare titanium–niobium-rich astrophyllite in the Podili alkali granite pluton, Prakasam district, Andhra Pradesh, India

Close to the eastern margin of the Proterozoic Cuddapah basin[1,2] and to the south of Podili, a crudely foliated alkali granite pluton occupying an area of 10 sq. km is emplaced within the metavolcano–metasedimentary sequence of the Archaean Nellore schist belt (NSB). In its western part, the 'Podili alkali granite pluton' exhibits sharp contact with N–S to NNE–SSW-trending quartz–chlorite schist and quartzite of NSB (Figure 1). Enclaves of NSB lithounits are noticed in the pluton. The Podili pluton is traversed by a semi-elliptical syenite, dykes of alkali feldspar granite and tourmaline-bearing quartz veins. Astrophyllite–arfvedsonite-bearing alkali granite is localized along the western part of the Podili pluton[3]. It is coarse-grained, leucocratic in appearance and shows N–S banding.