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The Impact of Dredging on Salinity in the Amba Estuary, West Coast of India

Jubin Thomas[1]*
Simhadri Naidu Velamala[2]

[1]CSIR-National Institute of Oceanography, Regional Centre, Lokhandwala Road, Andheri (W), Mumbai – 400053, India

[2]Environ Software Pvt Ltd, Electronic city, Banglore-560100

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***Corresponding author:**

Jubin Thomas

CSIR-National Institute of Oceanography
Regional Centre
Lokhandwala Road
Andheri (W), Mumbai-400053
India
Email: jubint90@gmail.com

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ABSTRACT

The effect of dredging carried out in the channel of the Amba estuary on the salinity variation was studied applying a 2D numerical model. The model hydrodynamics were calibrated and verified using observed tide data. Model results show good agreement with the observations. The model was also calibrated for salinity distribution in the estuary. Diffusion coefficients estimated are 20 m2/s and 0.15 m2/s in longitudinal and transverse directions respectively. The salinity distribution was simulated for different scenarios – zero discharge, medium discharge and high discharge, in high tide and low tide, for before and after dredging conditions. The results indicate that low salinity is noticed up to Patalaganga mouth during low tide in the monsoon, which is up to Dharamtar in the case of high tide. In the dry season, salinities vary between 36.7 and 36.6 ppt for both the tidal conditions. In the monsoon, sharp salinity gradient is found during high tide in the middle of the estuary due to convergence of freshwater flux and saline tidal waters. During this season, the higher gradients are found at the mouth in low tide. After dredging, a salinity ingress of 6.4 km is found at low tide at Mankhule during dry season. However, at high tide during wet season the ingress is reduced to 0.3 km. The simulation of residual velocities indicates the net higher residual flow which is directed upstream in the places where dredging was carried out. These resultant higher residual velocities are responsible for the salinity ingress in the region.

KEYWORDS

Amba Estuary, Salinity variations, Diffusion coefficients, Residual velocity, 2D Tidal Model, Hydrodynamic

INTRODUCTION

The behaviour of salt intrusion in the tidal estuary is mainly controlled by the upstream runoff and the downstream tidal current. When the high saline watermass flows into an estuary during flood, the saltwater adverts, diffuses and mixes with the freshwater entering from upstream, resulting in a salinity intrusion which makes the water in upstream river relatively salty (Chen and Zong, 1999; Zhiming Zhang, et al., 2010). Salt intrusion is an important phenomenon in an estuary and can constitute a serious problem to society due to the need for freshwater for industry, agriculture or households. The characteristics of an estuary are the mixing of saline and freshwater - a process which creates a salinity gradient that defines the physical, chemical and biological features and their interactions in these transitional ecosystems (Khelbovich, 1986, 1990; Wenping Gong, et al., 2011). Salinity gradients in an estuary affect the concentrations of phytoplankton biomass (Ahel, et al., 1996). It is a well-known fact that the mangrove formations adapt to the salinity gradients in the estuary.

Tidal propagation in an estuary is a function of its bathymetric configuration which in turn is influenced by natural processes and anthropogenic changes. Thus, siltation in the mouth segment which is common and sometimes seasonal, in many estuaries leads to tidal energy losses creating flood dominance. Anthropogenic interventions such as reclamation, construction of harbours, flood control measures etc, often result in changes in the bathymetry thereby affect the tidal propagation. Dredging, which is carried out in creeks or estuaries to maintain navigational channels to facilitate barges plying from the open sea to the ports that are constructed along the estuarine banks, also affects the tidal flow which ultimately changes the salinity pattern in the estuary. Generally in a monsoonal estuary, flow conditions due to upstream freshwater discharge vary seasonally.

Pritchard (1952) defined the basic dynamics of estuarine circulation. Hansen and Rattray (1965) followed with an analytical solution for the estuarine momentum and salt equations. Zhou Wei, et al. (2012) found that the net salt transport due to the estuarine circulation during neap tide was more than that during spring tide in the Zhujiang River Estuary, China. Wen-Cheng Liu, et al. (2007) studied the influence of freshwater discharge on residual current and salinity intrusion using a 3D model under different freshwater inflow conditions in the Danshuei River estuarine system. Comparing the estuarine circulation under low and mean flow conditions, they stated that the circulation is strengthened during low-flow period and its strength decreases at moderate river discharge. The river discharge is a dominating factor affecting the salinity intrusion in the estuarine system. Pinho and Vieira (2005) have shown that the extent of salinity intrusion depends on the balance between freshwater discharges and saltwater flow from the sea. Graas, et al. (2008) presented a salt intrusion model for the Pungue estuary with the aim to determine the minimum discharge required to prevent the salt intrusion from reaching the water intake situated 82 km from the estuary mouth. The salt intrusion model used in the paper was based on a fully analytical and predictive theory which was confronted with measurements of salt intrusion and estuary topography.

In the case of Indian coastal water bodies, a study by Binzy, et al. (2013) reveals that salt intrusion length in the Cochin estuary at high water varied from 10 km in monsoon to more than 40 km in premonsoon and it mostly depends on the freshwater discharge rather than spring-neap tidal oscillation. They also inferred that Cochin estuary experiences a transition from partially or well-mixed estuary during post and pre monsoon to a strongly stratified estuary during the monsoon season. The intrusion length is the least when river discharge during monsoon is maximum. Vijith, et al. (2009) pointed out that the estuaries that come under the influence of Indian Summer Monsoon (ISM) cannot be treated as being in a steady state at any time. These estuaries are located along the coastline of the Indian subcontinent, and their essential unsteadiness arises from the characteristics of runoff into them. Vijith and Shetye (2012) found that the estuarine geometry plays an important role in determining the relationship between the stratification, tide at the estuarine mouth and run off-forcing. They also concluded that it was not possible to separate the stratification regimes the way it was possible for estuaries with a prominent channel. Ghosh Bobba (2002) applied a model, SUTRA (Saturated-Unsaturated TRAnsport) to study the salt-water intrusion process in the Godavari Delta, India. The results indicated that a considerable advancement in seawater intrusion can be expected in the coastal aquifer if current rates of groundwater exploitation continue and an important part of the freshwater from the river is channelled from the reservoir for irrigation, industrial and domestic purposes. Naidu, et al. (2015) studied the effect of dredging on the residence time scales in the Amba estuary and found that the residence times have decreased marginally after dredging.

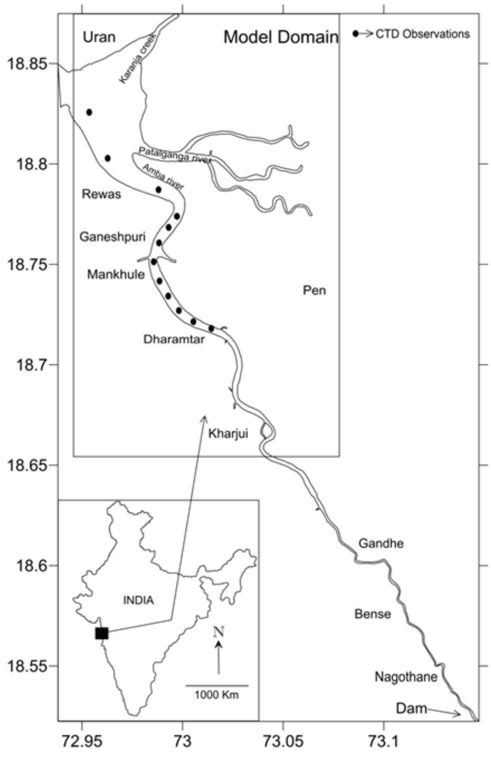

Figure 1: Area map with model domain and CTD observation locations

The objective of this paper was to study the effect of dredging on salinity distribution in the Amba estuary using a 2D model. The work involves calibration of the model to obtain dispersion coefficients and modelling the salinity distribution during high water and low water considering scenarios before and after dredging in dry and wet seasons. Residual circulation was calculated to ascertain the results of the salinity distribution.

Study Region

Amba estuary originates in the Western Ghats and follows a length of over 140 km before opening into the Mumbai harbor. Along the estuary several towns like Rewas, Dharamtar, Kharjui and Nagothane are situated. The Patalaganga estuary and the Karanja creek are the two tidal inlets that joins the Amba estuary from the east and north. A dam, constructed across the river at Nagothane (about 50 km upstream from the mouth), impounds the riverine flow, forming the source of supply of freshwater through the Maharashtra Industrial Development Corporation (MIDC) water supply scheme. The dam gates are generally kept open during the monsoon (June to September), allowing the riverine flow into the tidal waters. The freshwater discharge through the dam is restricted after September and is considered negligible during the non-monsoonal months. The lower reaches of the estuary is navigable up to the Dharamtar jetty. The spring tidal range of 4.8 m at Rewas decreases to 3.35 m at Nagothane, the neap tidal range is about 0.8 m throughout the estuary. Due to funnel effect, the tide increases into Dharamtar from where it gradually decreases. The estuarine salinity is generally comparable with that of the Mumbai Harbor at least upto Dharamtar during dry season. After the Jetty at Dharamtar was made operational in 1995, Maharashtra Maritime Board (MMB) has been maintaining a channel with depth of 3.5 m below spring low water and width of 135 m from mouth to Dharamtar for navigation of barges (Figure 1).

MATERIALS AND METHODS

The MMB has supplied 2 sets of bathymetry maps drawn out of the data collected in 1985 and 2000 which represent before dredging and after dredging scenarios respectively. The maps were digitized and are shown in Figure 2. The figure shows that mouth region of the Amba estuary is shallow with the depths of 6 m below low water. Tide data of Dharamtar was recorded in 1986 and 2007. The data shows that tide was mixed semi-diurnal with two unequal amplitudes. Maximum spring tide was 5.1 m and neap tide was 3.0 m. Tide data was collected at Dharamtar during the period 17th November 1986 to 02nd November 1986 and 26th May 2007 to 02nd June 2007. Salinity data was collected on 18/09/2014 in the Amba estuary, using a Valeport CTD. This data was used to derive dispersion coefficients.

Model Description

Amba estuary is a shallow unsteady system and in general has a vertically well mixed nature. Stoker (1957) explains the two-dimensional vertically integrated shallow-water equation for continuity and momentum balance. This equation has been used to obtain the tides and tide-induced circulation in the Amba estuary. In this study, a 2D model developed for simulating Thane creek tidal circulation has been applied to the estuary (Naidu and Sarma, 2001).

(a) Mass transport equation

$$\frac{\partial(HS)}{\partial t}+\frac{\partial(HUS)}{\partial x}+\frac{\partial(HVS)}{\partial y}-\frac{\partial(HD_x\frac{\partial S}{\partial x})}{\partial x}-\frac{\partial(HD_y\frac{\partial S}{\partial y})}{\partial y}-HSr \qquad \text{Eq....(1)}$$

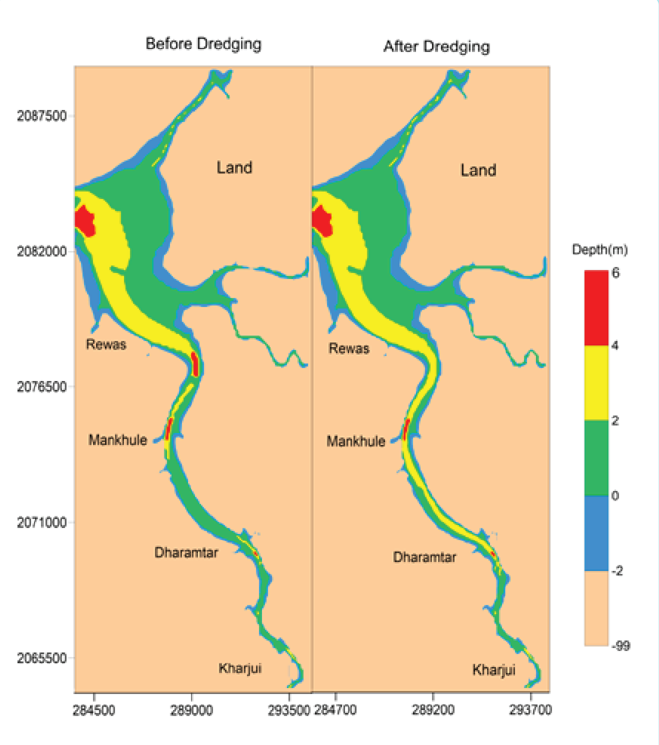

Figure 2: Bathymetry map (a) before dredging (b) after dredging.

Where, Sr = Source term, S = Salinity (ppt), H = Instantaneous water depth, Dx & Dy = Diffusion coefficients in x and y directions

The model equations were solved in ADI scheme with finite difference grid system. Horizontal diffusion terms in the momentum balance have been neglected since these are small compared with the other terms.

Atmospheric forcing due to wind stress has also been ignored. Wetting and drying options have been considered in this model.

In this study, Coriolis para × 10^{-5} rad/s) and φ is the latitude of the study location in decimal degrees. The bottom friction (C_f) was parameterized in terms of 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 is the total depth. Stability of the numerical scheme is governed by $\Delta t < \Delta x / \sqrt{2gH_{max}}$ Where, Δx is grid size in meters and Δt is the time step in seconds and g is the acceleration due to gravity and H_{max} is the maximum depth in the model domain. As H_{max} is 6 m and Δx is 100 m, the Δt may be 9 s. It was assumed that initially the sea is at rest, i.e., at t=0, u=v=0. The Rewas tide data was specified as the boundary condition in the west. The southern boundary was closed during non-monsoon season and opened during the monsoon season.

Residual velocity

The residual velocity R_v was estimated using the following equation, (Tee, 1976).

$$R_v = \frac{1}{T}\int_0^t u\Delta t \qquad \text{Eq....(2)}$$

The model was run for one lunar tidal cycle (29.5 days) by storing U and V components of velocity of each grid at 20 min interval. The net velocity was calculated by integrating the velocity components respectively.

RESULTS AND DISCUSSION

Initial condition for hydrodynamics was assumed as specified in the earlier section. Tide data at Rewas was prescribed at the western boundary and the hydrodynamic model run was started from 16th November 1986 1400 h to 03rd December 1986 1853 h. First day output of the model was discarded as the instabilities are cropped up during the simulation due to cold-start initial condition. The model was run by varying bottom friction coefficient, K. The modelled tide of Dharamtar which was stored at 15 minute intervals was compared with observations (Figure 3a). Similarly tide data was collected at Dharamtar from 26th May 2007 to 03rd June 2007 and compared with model results (Figure 3b). The modelled tide is in fair agreement with the observations as correlation coefficient between these two data sets is 0.92. More calibration & verification details are presented in the earlier work (Naidu *et al.*, 2016). Hence, the value of K was fixed as 0.065.

Observed Salinity

In-situ salinity observations, collected on 18.09.2014 in the estuary clearly shows that there exist similar trends in the salinity variation from mouth to upstream for the surface, mid-depth as well as bottom (Figure 4). The surface salinity varied between 7.7 ppt and 22.9 ppt from upstream to mouth respectively. Variation in the observed salinity for the mid depth and bottom is negligibly small. Due to the fresh water influx during monsoon season, the surface salinity gets reduced to a minimum value of 7.4 ppt at station 13. The salinity observations at station 1 were 22.9 ppt, 28.8 ppt and 31.5 ppt for the surface, mid-depth and bottom respectively, which have similar decreasing pattern inside the estuarine channel. Thus it can be inferred that Amba estuary is not vertically stratified. Hence the use of a 2D numerical model is justified.

Calibration of the model using salinity observations

Salinity observations (Figure 1) made on 18th September 2014 in the Amba estuary, show 27.7 ppt was found at the mouth and 20 ppt at the upstream. The model simulation was started on 02nd September 2014. Salinity of 27.7 ppt was prescribed in the western boundary. As we do not have the actual discharge rate at upstream during observations, we assumed four discharge rates, 20 m^3/s, 15 m^3/s, 10 m^3/s, 5 m^3/s and compared the model results with the observed salinity. The model was run and modelled salinity data were stored at 20 minute intervals at the locations where CTD observations were made. The results are presented in Figure 5. Keeping D_y a constant at 0.15 m^2/s, D_x values were varied from 5.0 to 20.0 m^2/s. From Figure 5a, it is observed that the model simulations overestimated D_x by 20 m^2/s. No variation is found with upstream discharge and the same trend is noticed in Figure 5b and 5c. However, in Figure 5d it is clearly evident that the model simulations are in agreement with the observations at the discharge rate of 15 m^3/s. The results show that the best fit can be noticed in the Figure 5d and hence the values of D_x and D_y are fixed as 20.0 m^2/s and 0.15 m^2/s respectively with an RMS error of 1.03. Dispersion coefficients in Irish estuaries and coastal waters are presented in the work of Eliott, *et al.* (1997). Generally longitudinal dispersion coefficients are greater than the lateral counterparts. The values of D_x are in the range of 0.5 to 4.5 m^2/s while D_y varied between 0.02 and 0.4 m^2/s. In case of English waters, the values are in higher range. The D_x values ranged between 0.8 and 142 m^2/s and D_y varied between 0.02 and 0.7 m^2/s (Talbot and Talbot, 1974). In both the cases, the lateral diffusion is similar and small. In case of D_x, English estuaries and coasts have greater values, nearly 200 times, as compared to their Irish counterparts. The values derived in the present study are well within the range and are comparable with English waters.

Salinity variation due to dredging

The salinity distribution shows a prominent variation during the given two conditions, viz, high and low tide at three discharge conditions, viz high, medium and low for before and after dredging scenarios. At open boundary, we considered in-situ salinity observation of 27.7 ppt during monsoon (18/09/2014) and a pre-monsoonal observation of 36.5 ppt (Anonymous, NIO/SP-10/2013). Similarly in the upstream, the salinity of 0.04 ppt was assigned during monsoon and 32 ppt during dry season. In the upstream, we considered 3 scenarios of flow rates, 0 m^3/s (zero), 15 m^3/s (medium), 96 m^3/s (high).

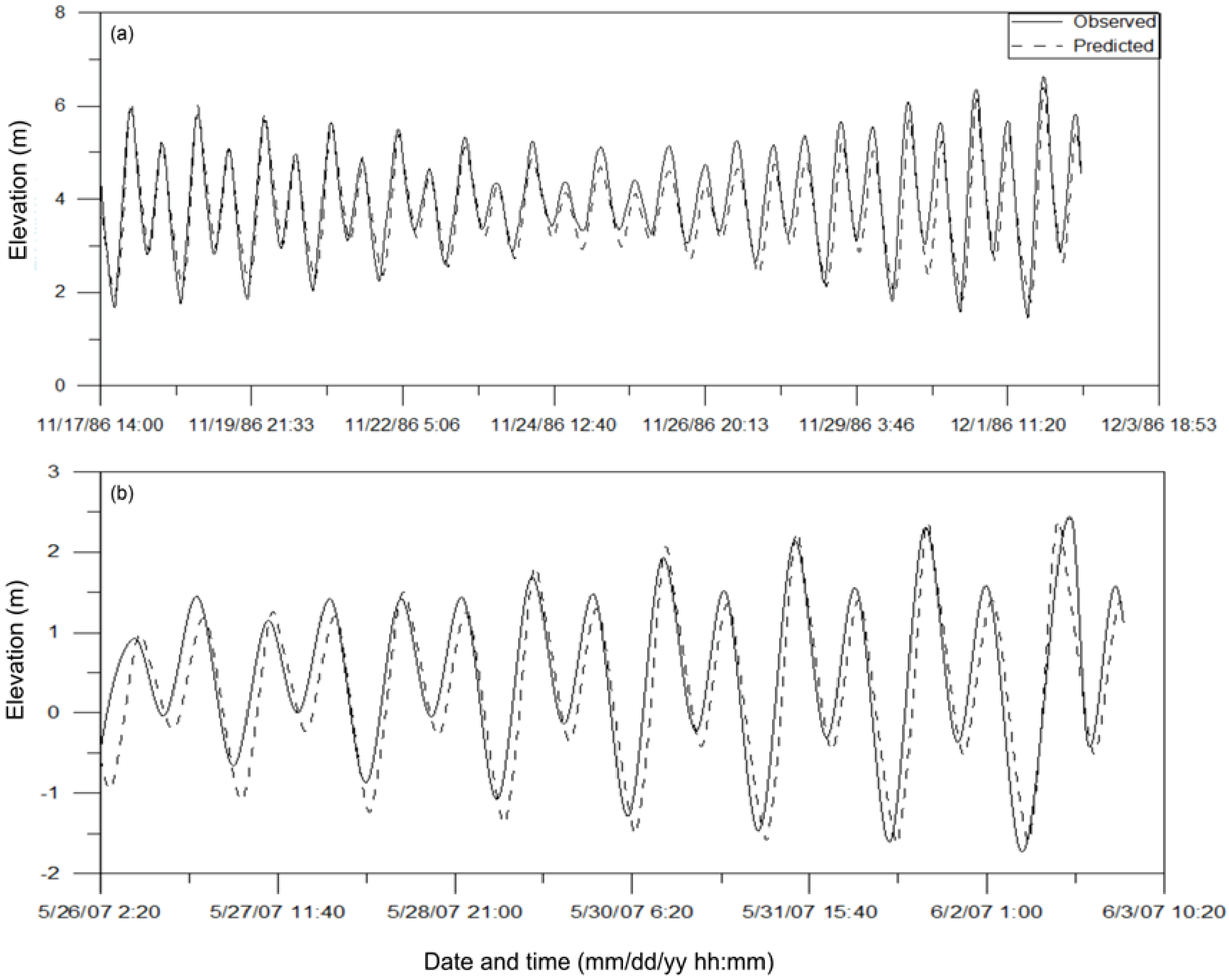

Figure 3: Comparison of observed and predicted tide at Dharamtar (a) before dredging (b) after dredging

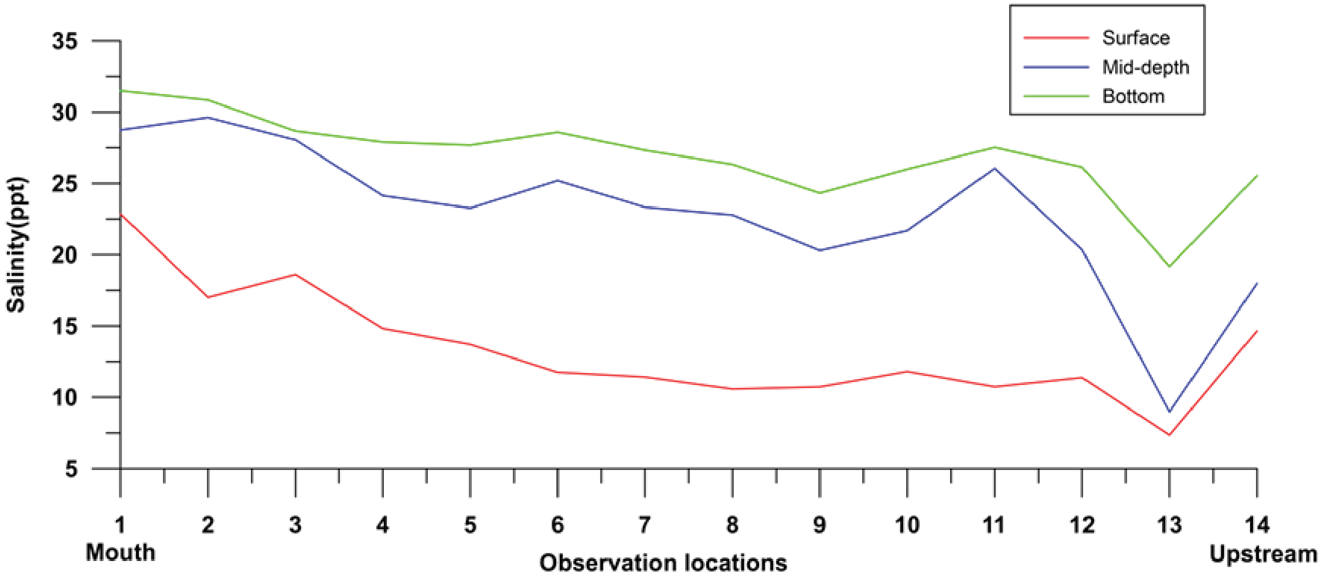

Figure 4: *In-situ* salinity observation in Amba estuary from mouth to upstream recorded on 18th September 2014

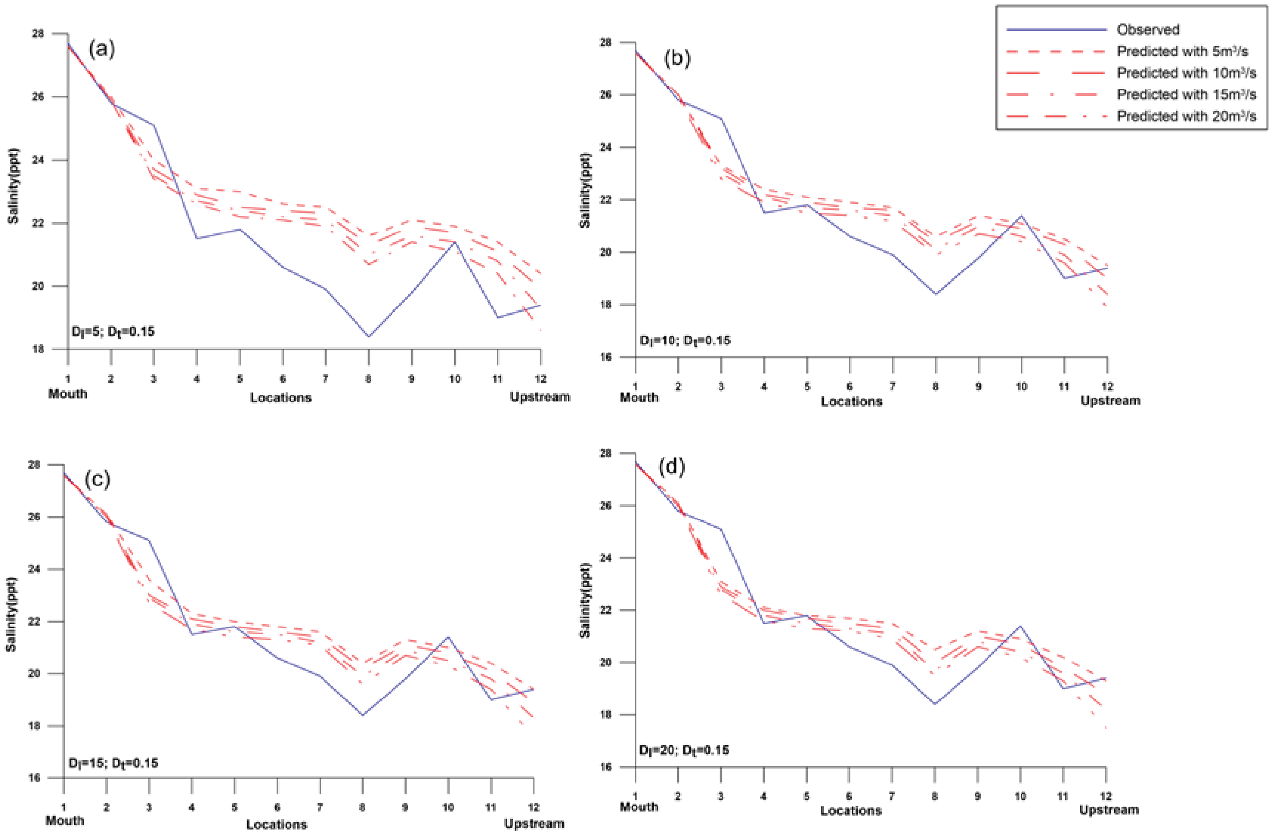

Figure 5: Comparison of modeled and observed salinity at 12 locations in the Amba estuary for different flow rates and diffusion coefficients

Variation of salinity in high tide

Salinity distribution in the high tide condition is shown in Figure 6. During dry season, salinity in the model domain varied narrowly between 36.6 and 36.7 ppt and this contour is extended to the mouth of the Patalaganga estuary. In this case a maximum shift of 3.09 km has been noticed for the 36.6 ppt contour. In medium discharge conditions, the salinity ranged from 27.7 to 20.0 ppt between the mouth and Dharamtar. Maximum egress is found south of Dharamtar with a shift of 687 m in 21 ppt contour. Minimum salinity variation is observed from mouth to a distance of 8.9 km (near to Mankhule) and a sharp gradient is found afterwards. However, during monsoon, salinity ranged between 26 and 0 ppt. A sharp salinity gradient is found upto 8.76 km from the Patalaganga mouth. These gradients are caused due to convergence of tidal waters that are reaching from the mouth and the monsoonal discharge from upstream. Salinity less than 2.0 ppt is found upto 9.8 km from the upstream. The effect of dredging is found in this season with maximum egress of 516 m at 15 ppt contour.

In the high tide condition during before dredging scenario, the current vector clearly shows that the surface current speed has maximum values of 1.1 m/s, 1.05 m/s and 0.9 m/s near to Dharamtar for zero, medium and high discharge rates respectively. Similarly after dredging, high current speed was noticed only at the dredged channel which has influenced the remarkable salinity ingress in the channel and got reduced after Dharamtar towards the upstream direction. In this case, maximum current speed is found at the mouth.

Variation of salinity in low tide

Salinity distribution in the low tide conditions is shown in Figure 7. During dry season, salinity varied from 36.7 ppt to 36.6 ppt. In this condition, maximum shift of contours is found due to dredging at Mankhule where salinity ingress of 6.36 km is noticed. A salinity egress of 2 km has been identified near to the mouth of the estuary for the 36.7 ppt contour. During medium discharge, nearly 1.7 km salinity ingress is found in 20 ppt contour near to Dharamtar. In the monsoon season, salinity of less than 2 ppt is found to the mouth of Patalaganga with reference to the upstream. In this case, the effect of dredging on salinity variations is relatively small. A steep gradient of 20 and 2 ppt is found within 6 km from the mouth. In the low tide condition, a prominent decrease in the surface current speed has been noticed after dredging, which resulted in the salinity egress of 2.06 km for the 36.7 ppt contour during dry season. In low tide, high magnitude (1.15 m/s) of surface current speed was found near to Mankhule during before dredging. After dredging, the surface current speed (0.85 m/s) was identified every discharge rates near Mankhule. The changes in current speed due to increase in depth are relatively lower when compared to differences in ebb current as the bottom frictional forces are low after dredging.

From the above results, it was found that the Amba estuary becomes a river upto Patalaganga mouth in low tide during the monsoon. An earlier study (Anonymous, NIO/SP-10/2013), based on observations, also confirms that river conditions prevail upto downstream of Mankhule during low tide in the season. During high tide in the monsoon, low salinity waters are found downstream of Dharamtar. From high tide to low tide, the low salinity contour is shifted to 10.1 km from the upstream. The effect of dredging is prominent with 6.36 km shift of salinity contour of 36.6 ppt during dry season in low tide. In both the tidal conditions, salinity ingress is identified only up to the dredged channel (from mouth to Dharamtar) for each of the salinity contours. Salinity egress is observed after Dharamtar towards the upstream locations. An exception is found for the 36.7 ppt contour near to the mouth in the low tide condition which showed an egress of 2 km after dredging.

To understand the salinity variations, we calculated the residual velocity of the Amba estuary. The calculations were carried out as specified in the Eq. 2. The residual velocities were calculated separately for before and after dredging conditions during wet and dry seasons. The residual velocity of before dredging condition was subtracted from the after dredging scenario and presented in Figure 8. This

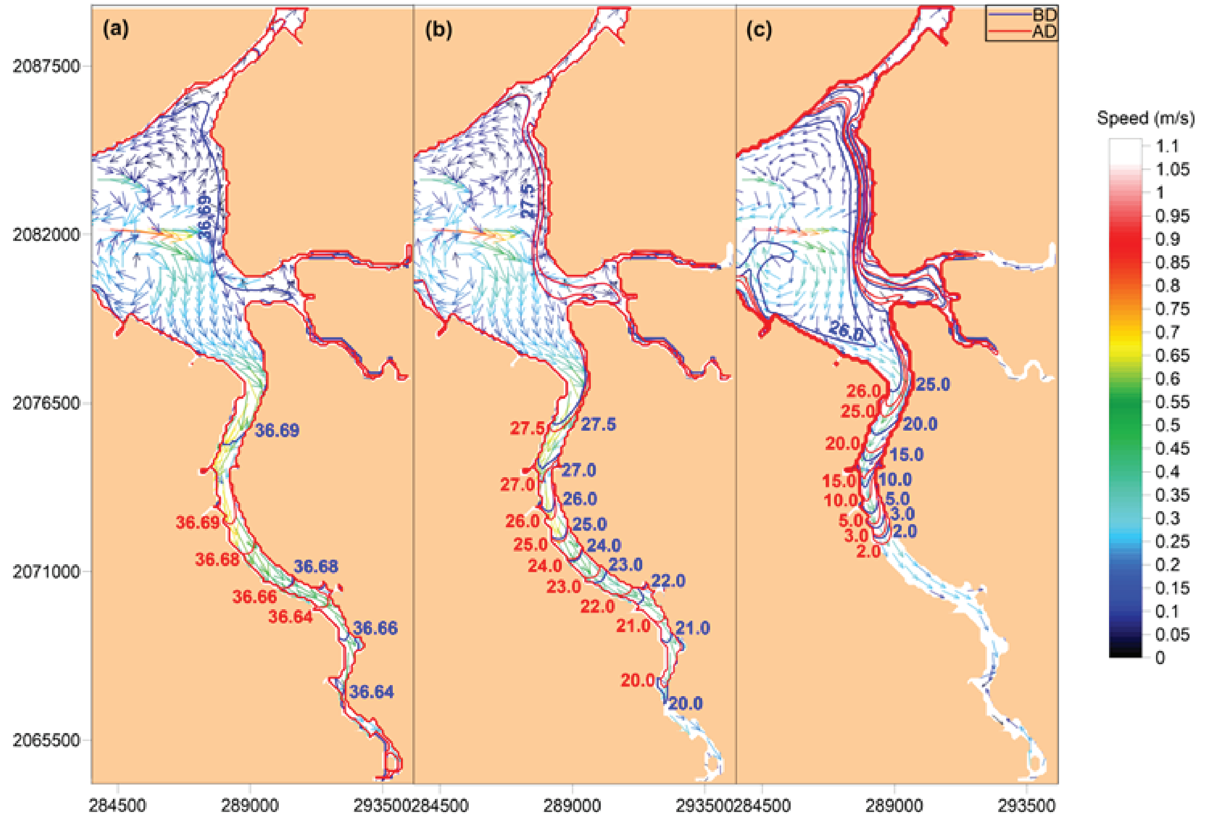

Figure 6: Variation of salinity at high tide condition before and after dredging (a) Zero discharge (b) Low discharge and(c) High discharge

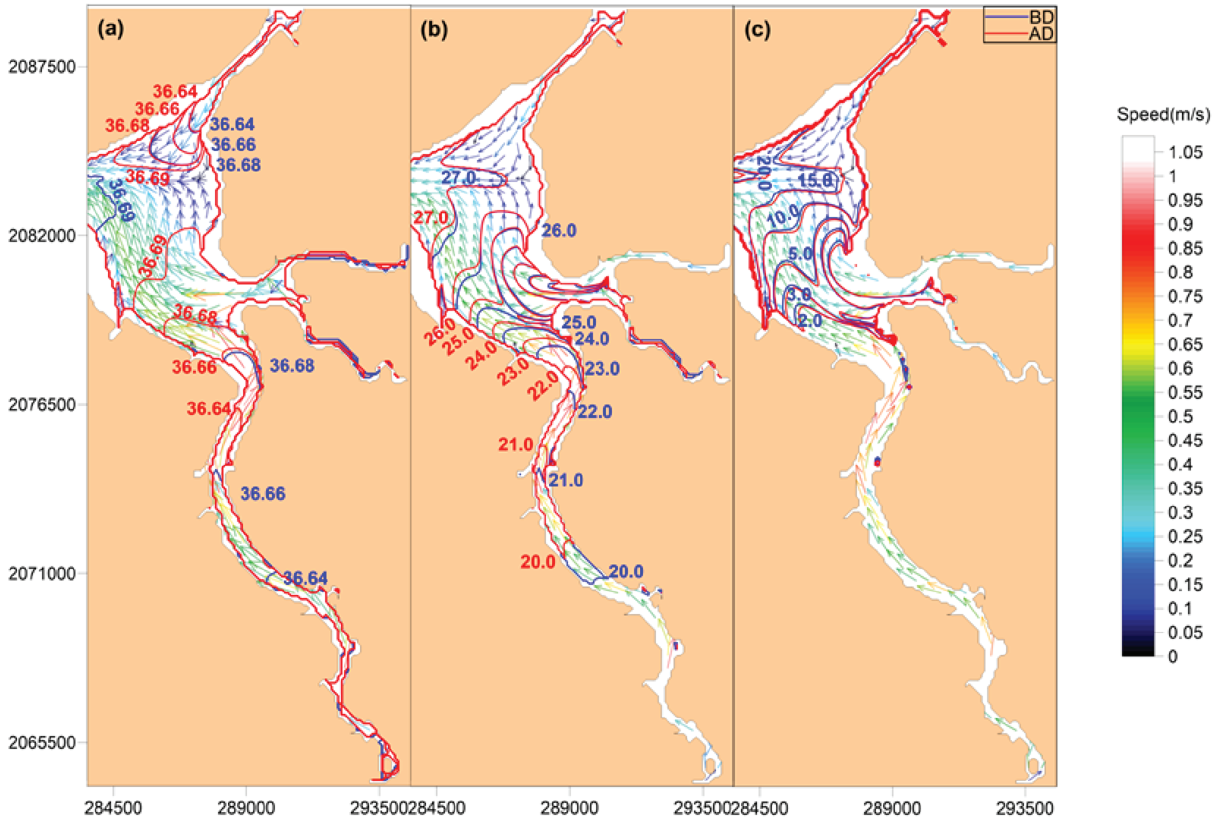

Figure 7: Variation of salinity at low tide condition before and after dredging (a) Zero discharge (b) Low discharge and (c) High discharge

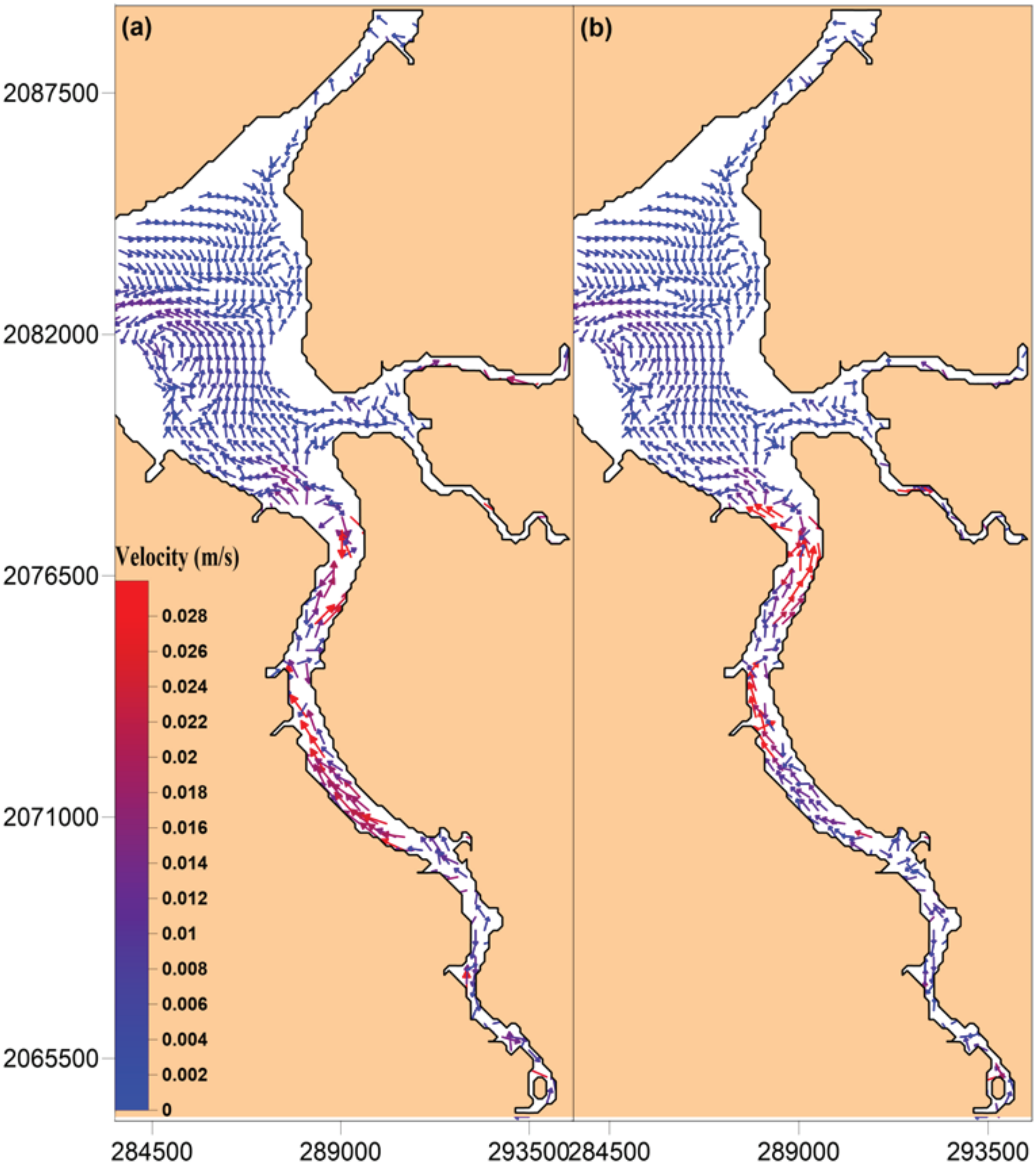

Figure 8: Difference of residual velocity (BD-AD) for (a) with flow (b) without flow

indicates that net flow during both wet and dry seasons is directed towards upstream. High values (0.028 m/s) are found in the places where dredging was carried out. A larger area is covered with higher values during monsoon as compared to dry season. As a result of net upstream flow, the salinity ingress is noticed in the estuary. Anti-cyclonic eddy is present at the mouth region in both the cases. The earlier work (Naidu, *et al*., 2015), which studied the tidal propagation to understand the effect of dredging in the channel on residence time of the Amba estuary, concluded that the dredging has a minor impact on the residence time. But in the present study, substantial salinity ingress of 6.4 km is noticed.

CONCLUSIONS

A 2D model was applied to calculate the salinity distribution in the Amba estuary for different flow and tidal conditions. The model was not only calibrated with hydrodynamic data collected but also with salinity observations made in the estuary. The calibration for salinity results in diffusion coefficients $D_x = 20\ m^2/s$ and $D_y = 0.15\ m^2/s$. The study indicates that the dredging in the channel has caused salinity egress of 0.4 km at Dharamtar during high tide in the Amba estuary, for medium and high freshwater discharges. However, its impact in the low tide is substantial with maximum salinity ingress of 6.36 km at 36.6 ppt in dry season. The ingress of 1.7 km is found for 20 ppt contour during medium discharge condition. The results of residual velocity show that the net flow towards upstream is increased after dredging in the channel which leads to higher salinity ingress during medium discharges and dry seasons. During monsoon, the effect of dredging on salinity ingress is negligibly small as the strong currents generated by low tide and river run off dominate the bottom frictional forces.

The work shows the importance of geometry to the processes inside an estuary as noted by Prandle (2009). The impact of salinity ingress on the other water quality parameters, viz. DO, BOD, nutrients, biological characteristics (Chlorophyll, phytoplankton and zooplankton) in the Amba estuary should be studied using a numerical water quality model.

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BIBLIOGRAPHY

1. Ahel M, Barlow RG, Mantoura RFC. Effect of salinity gradients on the distribution of phytoplankton pigments in a stratified estuary. Marine Ecology Progress Series. 1996;143:289-295. http://www.int-res.com/articles/meps/143/m143p289.pdf.
2. Anonymous. Periodic monitoring of Amba estuary. NIO/SP-10/2013.
3. Binzy J, Revichandran C, Naveen KKR. Salt intrusion in Cochin estuary-using empirical models. Indian Journal of Geo-Marine Sciences.2013;42(3):304-313.http://nopr.niscair.res.in/bitstream/123456789/19659/1/IJMS%2042%283%29%20304-313.pdf.
4. Chen X, Zong Y. Impacts of sea level rise on agriculture in the Shanghai area, China. Applied Geography. 1999;19:69-84.
5. Elliot AJ, Barr AG, Kennan D. Diffusion in Irish coastal waters. Estuarine, Coastal and Shelf Science. 1997;44:15-23. http://ac.els-cdn.com/S0272771497800030/1-s2.0-S0272771497800030-main.pdf?_tid=82fa69d2-c8b4-11e5-b911-00000aab0f27&acdnat=1454311512_76525456617dfb03c7a5534d09244615.
6. Ghosh Bobba A. Numerical modelling of salt-water intrusion due to human activities and sea-level change in the Godavari Delta, India. Hydrological Sciences-Journal-des Sciences. 2002;47(S):67-80. http://dx.doi.org/10.1080/02626660209493023.
7. Graas S, Savenije HHG. Salt intrusion in the Pungue estuary, Mozambique: effect of sand banks as a natural temporary salt intrusion barrier. Hydrology and Earth System Sciences Discussions. 2008;5;2523-2542. http://www.hydrol-earth-syst-sci-discuss.net/5/2523/2008/hessd-5-2523-2008.pdf .
8. Hansen DV, Rattray M. Gravitational circulation in straits and estuaries. J Marine Res. 1965;23:104-122.
9. Khlebovich VV. On biological typology of the estuaries of the USSR. Proceedings of the Zoological Institute Academy of Sciences. 1986;141:5-16.
10. Khlebovich VV. Some physico-chemical and biological phenomena in the salinity gradient. Limnologia (Berlin). 1990;20(1):5-8.
11. Liu WC, Chen WB, Cheng RT, Hsu MH, Kuo AY. Modeling the influence of river discharge on salt intrusion and residual circulation in Danshuei River estuary, Taiwan. Continental shelf research. 2007;27;900-921. http://dx.doi.org/10.1016/j.csr.2006.12.005.
12. Naidu VS, Jubin Thomas, Sanjay Bari, Shubhangi Kachave. The Impact of Dredging on residence time in the Amba estuary, West coast of India. Environmental Earth Sciences. 2016;75(2):1-14. http://link.springer.com/article/10.1007/s12665-015-4851-3.
13. Prandle D, 2009. Estuaries: Dynamics, Mixing, Sedimentation and Morphology. Cambridge University Press, Cambridge. 236.
14. Pinho JLS, Vieira JMP. Mathematical modelling of salt water intrusion in a Northern Portuguese estuary. The fourth inter-celtic colloquium on hydrology and management of water resources. IAHS Publ. 2007;310.
15. Pritchard DW. Estuarine hydrography. Advances in Geophysics. 1952;1:243-280.
16. Stoker JJ. Water waves, Interscience Publishers. New York. 1957.
17. Talbot JW, Talbot GA. Diffusion in shallow sea and in English coastal and estuarine waters. Rapp. P-V Reun Cons Ins Explor Mer. 1974;167:93-110.
18. Tee KT. Tide induced residual current, a 2D nonlinear numerical tidal model. J Marine Res. 1976:34;603-628.
19. Vijith V, Shetye SR. A stratification prediction diagram from charactertics of geometry, tides and runoff for estuaries with a prominent channel. Estuar Coast Shelf Sci. 2012;98:101-107. http://dx.doi.org/10.1016/j.ecss.2011.12.006.
20. Vijith V, Sundar D, Shetye SR. Time-dependence of salinity in monsoonal estuaries. Estuar Coast Shelf Sci. 2009;85(4):601-608. http://dx.doi.org/10.1016/j.ecss.2009.10.003.
21. Wenping Gong, Jian Shen. The response of salt intrusion to changes in river discharge and tidal mixing during the dry season in the Modaomen Estuary, China. Continental Shelf Research. 2011;31:769-788. http://dx.doi.org/10.1016/j.csr.2011.01.011.
22. Zhiming Zhang, Baoshan Cui, Hui Zhao, Xiaoyun Fan, Honggang Zhang. Discharge-salinity relationships in Maodomen waterway, Pearl river estuary. Procedia Environmental Sciences. 2010;2:1235-1245. http://dx.doi.org/10.1016/j.proenv.2010.10.134.
23. Zhou W, Wang D, Luo L. Investigation of saltwater intrusion and salinity stratification in winter of 2007/2008 in the Zhujiang River Estuary in China. Acta Oceanol Sin. 2012;31(3):31-46. http://dx.doi.org/10.1007/s13131-012-0204-1.