

Circulation and salinity in Hooghly estuary: A numerical study

Y R Rao

National Institute of Ocean Technology, IC&SR Building, IIT Campus, Madras 600036, India

and

P C Sinha & S K Dube

Centre for Atmospheric Sciences, Indian Institute of Technology, Hauz Khas, New Delhi-110016, India

Received 23 May 1997, revised 20 November 1997

Numerical models are presented for tidal flow and salinity in the Hooghly estuary, along the east coast of India. A depth-averaged numerical model coupled with a one-dimensional model is discussed. The model has been validated with the available observations for the dry and wet seasons. The influence of storm surges on the circulation is also discussed in this section. A multi-level laterally averaged model for the estuary is also described. The vertical structure of the currents and salinity are validated with spring observations during both wet and dry seasons.

In India, a coastline of 7000 km and many estuaries are available for exploration. The management of these estuaries need knowledge of the flow dynamics. With the present day technology, it is possible to develop realistic models for the circulation and mixing in estuaries. This paper describes an attempt for understanding the circulation and salinity distribution in the Hooghly estuary.

Materials and Methods

The Hooghly estuary (Fig. 1) forms a part of the Ganges by the confluence of three rivers, the Bagirathi, the Jalangi and the Churni, and serves as the navigable waterway to Calcutta and Haldia ports. The Hooghly estuary communicates with the Bay of Bengal near Sagar island and it is tidal for nearly 250 km. Tidal waves approach the estuary from south-east and another from south-west and the wave crest is practically east-west at Sagar. The tide in the estuary is predominantly semi-diurnal. The vertical tide range at the mouth varies from 5.2 m during springs to 1.8 m at neap period¹. Due to funnel shape of the estuary, a near constancy of ranges is maintained over a long stretch of the estuary. The usual freshwater discharge into the estuary is of the order of $3000 \text{ m}^3 \text{ sec}^{-1}$ during monsoon period and $1000 \text{ m}^3 \text{ sec}^{-1}$ during the lean period. Gole and Vaidyaraman² have shown that due to shallow

depths and intense tidal mixing, the estuary is well-mixed for the major part of the year.

This paper describes briefly the depth-averaged model and the coupling of one-dimensional river model to study the circulation and salinity in Hooghly estuary. It also discusses the possible effect of storm surges on the circulation in Hooghly estuary. A multi-level laterally averaged model which uses a turbulence closure scheme for the parameterization of vertical exchange coefficients is also presented.

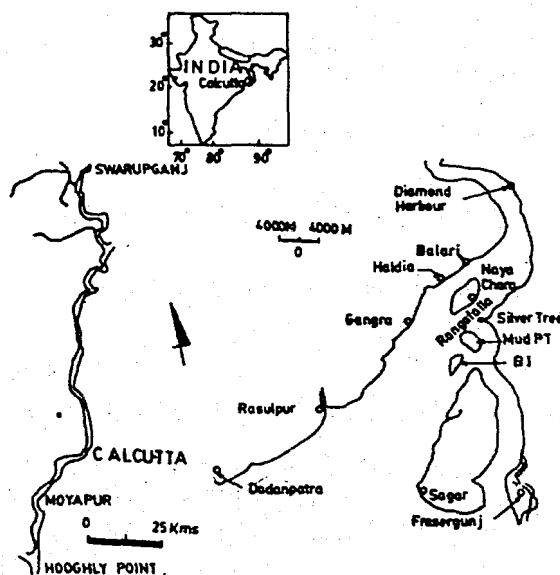


Fig. 1—The map of Hooghly estuary

Depth-averaged model for Hooghly estuary

In a well-mixed estuary the turbulent energy generated by bottom friction is sufficient to mix the mass and momentum efficiently throughout the water column, and there exists a reasonable uniformity of the horizontal currents. So by neglecting the vertical component of velocity, a three dimensional problem can be reduced to a two dimensional one by averaging the governing equations in the vertical. In the present study a vertically integrated numerical model has been developed to study the flow and salinity intrusion in the Hooghly estuary.

Formulation

In the formulation of the model, unsteady two-dimensional vertically integrated shallow water equations^{3,4} are used along with the depth-averaged salt conservation equation. Here the origin 'O' is in the equilibrium level of the sea surface. Ox points towards east, Oy points towards north and Oz is pointed vertically upwards. The displaced position of the free surface is given by $z = \zeta(x, y, t)$ and the position of the sea floor by $z = -h(x, y)$. To determine the density as a function of salinity, an equation of state is given by

$$\rho = \frac{\rho_0}{1 - \beta S} \quad \dots (1)$$

Assuming hydrostatic approximation and utilizing equation (1) the resulting equations of continuity, momentum and salt conservation are given by

$$\partial_t \zeta + \partial_x (Hu) + \partial_y (Hv) = 0 \quad \dots (2)$$

$$\begin{aligned} \partial_t u + u \partial_x u + v \partial_y u - fv = & -g \partial_x \zeta - \frac{1}{2} \beta g H \partial_x S \\ & - \frac{1}{H} \left(\frac{g}{C^2} u (u^2 + v^2)^{\frac{1}{2}} \right) + \frac{1}{H} \left[\frac{\rho_a}{\rho} C_D u_a (u_a^2 + v_a^2)^{\frac{1}{2}} \right] \end{aligned} \quad \dots (3)$$

$$\begin{aligned} \partial_t v + u \partial_x v + v \partial_y v + fu = & -g \partial_y \zeta - \frac{1}{2} \beta g H \partial_y S \\ & - \frac{1}{H} \left(\frac{g}{C^2} v (u^2 + v^2)^{\frac{1}{2}} \right) + \frac{1}{H} \left[\frac{\rho_a}{\rho} C_D v_a (u_a^2 + v_a^2)^{\frac{1}{2}} \right] \end{aligned} \quad \dots (4)$$

$$\begin{aligned} \partial_t (HS) + u \partial_x (HS) + v \partial_y (HS) \\ = \partial_x (KH H \partial_x S) + \partial_y (KH H \partial_y S) \end{aligned} \quad \dots (5)$$

where in Eqs. (1) to (5)

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

ρ = water density

ρ_0 = reference water density ($= 1000 \text{ kg/m}^3$)

ρ_a = air density

H = total depth $\zeta + h$

f = Coriolis parameter at 22°N

C_D = drag coefficient ($= 2.8 \times 10^{-3}$)

g = acceleration due to gravity

S = salinity in the estuary

K_H = horizontal diffusion coefficient for salinity

u, v = x and y components of depth-averaged velocity

u_a, v_a = x and y components of wind velocity

Here, horizontal diffusion terms in momentum equations are neglected as their effect is found to be very small in comparison with other terms. Both the bottom and wind stress terms are parameterized by conventional quadratic law, and Chezy coefficient, C , is evaluated by $C = n^{-1} h^{1/6}$ where $n = 0.025$ and h is the depth below the mean sea level. The constant horizontal diffusion coefficient for salinity has been taken as $600 \text{ m}^2 \text{ sec}^{-1}$ on the basis of observations⁵. In the upper estuary, where the flow is assumed to be unidirectional, a one-dimensional model has been used. Here, the baroclinic part of the pressure gradient term is not considered, as there is negligible salinity in this region. The complete details of the one dimensional model and its coupling with the depth-averaged model is discussed by Sinha *et al.*⁵

The analysis area has the following open boundaries at the seaward end (i) connecting Dadanpara and Sagar and (ii) at Frasergunj, and Hooghly point at the landward end. Along the seaward end, water levels are prescribed on the basis of observations discussed in Sinha *et al.*⁴ A constant fresh water discharge has been prescribed at Swarupgunj. At the lateral boundaries, the transport normal to the coastline has been taken as zero. The observed depth averaged salinity values have been prescribed as the boundary condition at

the seaward end and zero salinity at the landward end. At the lateral boundaries the normal salinity gradient vanishes.

The predictive equations are solved using a conditionally stable semi-explicit finite difference scheme on a staggered Arakawa-C grid. To study the circulation and salinity distribution in the lower estuary between Hooghly point and Bay of Bengal at Sagar including Frasergunj creek, we consider all major islands. The coastline is made up of stair steps consisting of orthogonal straight-line segments with a grid size of 750 m. The bathymetry used in this model was taken from Calcutta Port Trust. The breadth of the one-dimensional portion decreases from 1.5 km at the joining point (Hooghly point) to 500 m at the upstream point (Swarupganj). The depth varies smoothly from 6.5 m at the junction point to 4 m at the upstream end. The length of the one-dimensional stretch from Hooghly point to Swarupgunj was taken to be 160 km, and it was divided into 72 equal segments, making the grid distance to be 2.23 km.

Although the one-dimensional model can accommodate much larger time steps, to avoid any complication in the computations for both the models the same time step of 60s was utilized, which was found to be consistent with the computational stability.

A breadth averaged multi-level model for Hooghly estuary

Although the river Hooghly is well-mixed for the major part of the year, but during a brief period (monsoon season) due to large runoff, the salinities in the upper layer decreases slightly to make the estuary partially stratified in the upper part of the estuary. The length of the channel was chosen to be 45 km from the mouth at Sagar. The breadth decreases from 22 km at the mouth to 8 km at the upstream end. The mean centre line depth has been chosen as the representative bathymetry for the present study.

The origin 'O' of a system of a rectangular Cartesian co-ordinates has been taken at the equilibrium level of the free surface in the estuary. O_x points seaward and O_z is measured vertically upward from $z = 0$. The landward end has been taken at $x=0$ and the seaward end is denoted by

$x = L$. The elements of the free surface above its mean level is denoted by $z = \zeta(x,t)$ and the bottom topography by $z = -h(x)$. The breadth of the estuary at position x is denoted by $b(x)$. The Reynold's-averaged components of the fluid velocity and fluid density are denoted by (u,w) and ρ , respectively.

By invoking Boussinesq and hydrostatic approximations, the breadth-averaged momentum equation can be written as

$$\begin{aligned} \partial_t(bu) + \partial_x(bu^2) + \partial_z(buw) = & -gb\partial_x\zeta - \frac{b}{\rho_0} \int_z^\zeta \partial_x(g\rho) dz \\ & + \partial_z(K_M \partial_z(bu)) + \partial_x(bN \partial_x u) \end{aligned} \quad \dots (6)$$

The first term on the right hand side of Eq. (6) gives the barotropic contribution to the pressure gradient resulting from the slope of the free surface in the channel. The second term, in which ρ_0 is the density of the fresh water, gives the baroclinic contribution to the pressure gradient. The third term represents the vertical transfer of momentum by turbulent motions and is expressed in terms of conventional gradient law involving a vertical coefficient of viscosity, K_M . The final term simulates the effect of horizontal momentum exchange by turbulent scale motions.

The equation of continuity is expressed either as

$$\partial_x u + \partial_z w = 0 \quad \dots (7)$$

or

$$\partial_t \zeta + \partial_x (H \bar{u}) = 0 \quad \dots (8)$$

where H is the total depth, $(\zeta+h)$ and $\bar{u}$ is the depth-averaged velocity given by

$$\bar{u} = \frac{1}{H} \int_{-h}^{\zeta} u dz \quad \dots (9)$$

The density is related to the salinity, S , by an equation of state as

$$\rho = \rho_0 (1 + \Gamma S) \quad \dots (10)$$

where $G = 7.5 \times 10^{-4} / \text{ppt}$ and S is the salinity in the estuary.

The salinity is determined from a transport equation having the form

$$\partial_t(bS) + \partial_x(buS) + \partial_z(bwS) = \partial_z[K_s \partial_z(bS)] + \partial_x[bN \partial_x S] \dots (11)$$

On the right-hand-side of Eq. (11), the vertical transfer of salinity by turbulent process is represented in terms of gradient transfer law with an eddy coefficient, K_s . The second term simulates the effect of horizontal salinity flux by turbulent scale motions.

The turbulent energy density, E , is determined from the equation⁶

$$\partial_t(bE) + \partial_x(buE) + \partial_z(bwE) = bK_M(\partial_z u)^2 + bN(\partial_z u)^2 + \frac{g}{\rho_0} bK_S \partial_z \rho + \partial_x[K_E \partial_x(bE)] + \partial_x[bN \partial_x E] - b\varepsilon \dots (12)$$

where K_E , K_S are the exchange coefficients for turbulent energy density and salinity, respectively.

By following Johns and Oguz⁷ various eddy coefficients appearing in the formulation are expressed in terms of the turbulent energy density.

The above equations must be accompanied by appropriate dynamical boundary conditions through which the system is driven. At the floor of the estuary a no-slip condition has been applied. Further, no diffusive flux of salinity across the floor of the estuary is considered.

At the free surface, the applied wind stress and diffusive salinity flux are taken as zero. Boundary conditions to accompany Eq. (12) are that there is no vertical exchange of turbulence energy across the floor and surface of the channel.

Thus the fluid motion in the channel is driven solely by the boundary forcing to be applied at the extremities of the channel. In the present application tidal condition has been specified based on observations at the seaward end ($x = L$). At the landward end ($x = 0$), a radiation condition is applied, which takes care of outward transmission of the disturbance in the form of a progressive wave. To allow the formation of the salinity structure within the estuary, it is necessary that the boundary conditions to accompany Eq. (12) be correctly formulated. Essentially, the conditions to be applied at $x = 0$ and $x = L$ must be such that the salinity of inflowing water is prescribed and that of the out flowing water is determined by use of Eq. (11).

Results and Discussion

Depth-averaged model

The basic equations along with the boundary and initial conditions are integrated in time as described in the previous section. The model is run with north-easterly (NE) winds of 5 m sec^{-1} and a fresh water discharge of $1000 \text{ m}^3 \text{ sec}^{-1}$ for the dry season. The hydrodynamic model achieves steady state in eight tidal cycles. The results of the ninth tidal cycle are analyzed. The amplitude and phase are separated by Fourier decomposition. During 1992-93, hourly tide gauge data have been obtained at Gangra, Haldia, Balari and Diamond harbour. Account is taken for drying of the shallow zones during certain periods of a tidal cycle by carrying out tests before each u and v computation to determine whether the grid point is wet or dry. If the point is dry, then the current is set to zero. If the point is wet, the currents are updated by solving the momentum equations.

Figure 2 shows the computed and observed elevations in meters over a tidal cycle at Gangra, Haldia, Balari and Diamond harbour. The computed water levels are in good agreement with the observations. A comparison of the computed elevations and phases from the observed values is, on an average, within 3 cm and 0.5° , respectively. The sharpening of the flood and flattening of the ebb are reproduced well in the model.

From Fig. 3a it may be noticed that the tide in the Hooghly estuary exhibits a positive asymmetry which becomes stronger as it propagates along the channel. The ratio M_4/M_2 increases from 0.094 at Sagar to 0.28 at Diamond Harbour, as the first overtide amplifies through non-linear interactions for a spring tide. At the same time the phase difference varied between 100° to 120° which is depicted in Fig. 3b. The direct result of the above asymmetry is a shorter flood and longer ebb periods and may cause substantial sediment transport.

The computed and observed currents at Gangra, Haldia, Silvertree (in Rangafalla channel), and Moyapur over a tidal cycle are plotted in Fig. 4. Here a positive sign implies flood currents and a negative sign implies ebb currents. The surface current observations were taken during November 1992. The model predicted currents are in

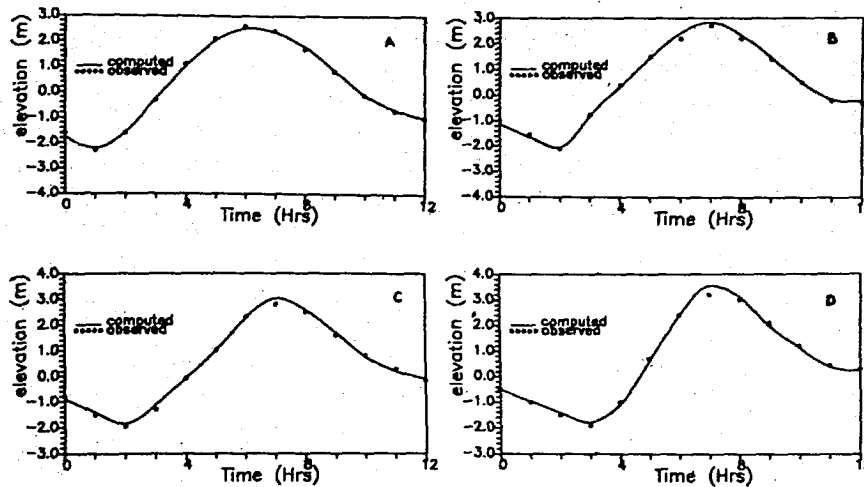


Fig. 2—Computed and Observed elevations in meters over a tidal cycle at (a) Gangra, (b) Haldia, (c) Balari and (d) Diamond harbour

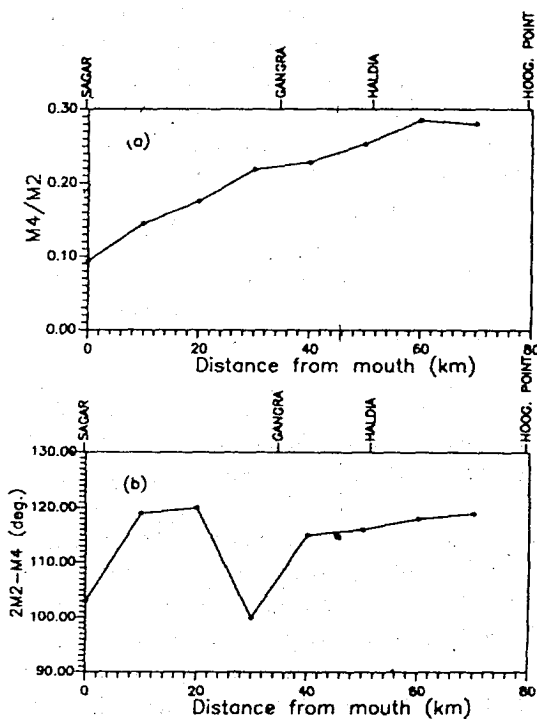


Fig. 3—Normalized elevations ($M4/M2$) and phase difference ($2M2-M4$) along the estuary.

reasonable agreement (within 15%) with the observed values. The simulations have shown flow bifurcation near Nayachara island. In the major portion of the estuary the flood currents varied from 0.5 m sec^{-1} to 2.0 m sec^{-1} . The flood currents

are found to be weak near Dadanpara and stronger to the left of Sagar island and Rangafalla channel where a deep channel is present. In Haldia channel flood currents varied from 0.8 m sec^{-1} to 1.4 m sec^{-1} . Strong ebb currents up to 1.75 m sec^{-1} are observed to the left of Sagar island. Also, strong ebb currents up to 1.6 m sec^{-1} are found in the Rangafalla channel supporting the observational study that the channel acts as an ebb channel.

Figure 5 depicts salinities along the estuary for dry and wet seasons, respectively. In Fig. 5a the maximum salinity is found to be 28.4 ppt at Sagar, which falls to 13.0 ppt in the first 10 km. This pattern of salinity distribution is maintained up to Haldia. The slightly higher salinities during the flood in the Frasergunj channel is attributed to the channel geometry and tidal phase difference. The computed results are in reasonable agreement, with a mean error of 0.8 ppt and a standard deviation of 1.5 ppt. By introducing a constant freshwater discharge of $3000 \text{ m}^3 \text{ sec}^{-1}$, the salinity conditions for the wet season are simulated. The computed salinity falls to as low as 13.0 ppt at Sagar (Fig. 5b) in comparison to 28.4 ppt for the dry season, and gradually decreases upward. The estuary is salt free after about 50 km from the mouth of the estuary. From both the figures it is found that model computed salinity intrusion lengths are in reasonable agreement with the observations.

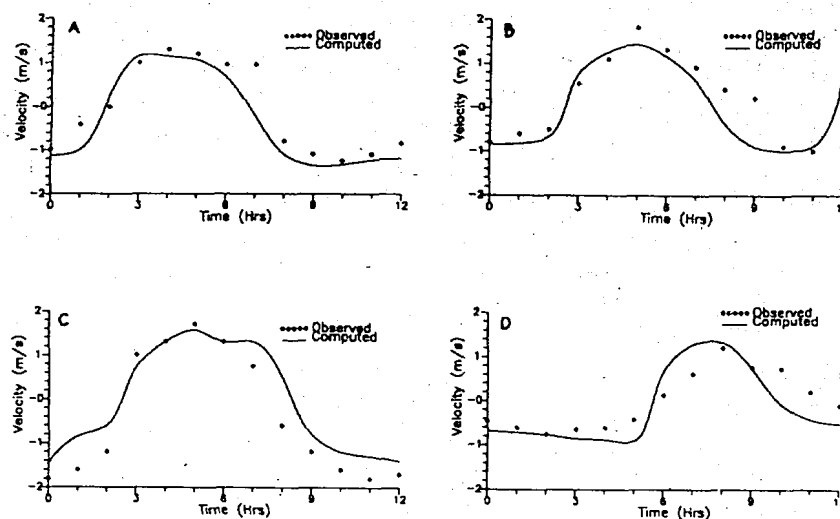


Fig. 4—Computed and observed currents at (a) Gangra, (b) Haldia, (c) SilverTree and (d) Moyapur

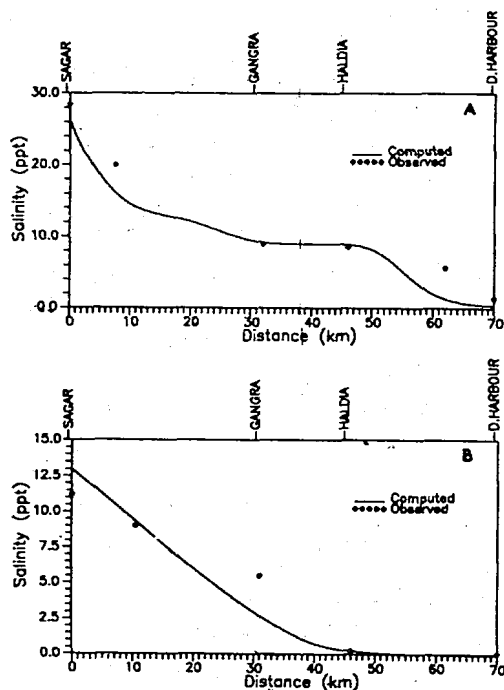


Fig. 5—Comparison of observed and computed salinities for (a) dry season and (b) wet season along the estuary.

Effect of storm surge on the tidal circulation

Sinha *et al.*⁸ investigated the tide-surge interaction in Hooghly estuary by coupling the model described earlier with a storm surge model developed for the Bay of Bengal. Essentially, the study consists of using the tidal solution to provide

the initial conditions for tide-surge interaction in the estuary. The storm-tide frequency calculation consists of generating surge by a given cyclone at the mouth of the estuary. The computed surge is then combined with the astronomical tide at the entrance of the estuary and the calculation continues within the estuary. Numerical experiments are performed with three cyclonic storms, having landfall points to the south of the estuary, at the mouth of the estuary and to the northeast of the estuary.

The Orissa coast of India was affected by the surge generated by a cyclonic storm on 3rd June 1992. The position of land fall is approximately 17km north of Paradeep port which is 220 km south of the estuary. It has produced a maximum positive surge of 1.4 m at the mouth of the estuary. The interaction between tide and surge at the mouth, Gangra, Haldia and Balari are shown in Fig. 6 a to d, respectively. Figure 6a depicts the sea surface elevations due to tide, surge and tide-surge interaction at the mouth of the estuary. The model is forced only with astronomical tide at the seaward end for first 12 hours before surge solution is combined at the open boundary. The peak tide surge response coincides with the time of low water conditions at the mouth, and increased total elevation to nearly 1 m. It is clearly evident from other figures that there is an increase in total elevations all along the estuary. Surge heights increase from 1.4 m to 1.51 m at Haldia. The effect

of surge on the tidal elevation is found to be negligible at the landward end.

Since the effect of negative surges in the estuary are particularly important due to the presence of two major ports, an experiment has been carried out with April 1991 Bangladesh cyclone, which produced a maximum negative surge of 2m near the mouth of the estuary. Figure 7 depicts the tidal elevations at four stations. It may be seen that the elevation due to surge and tide-surge interaction are predominantly negative in the lower part of the estuary. The surge induced a reduction in the high water levels all along the estuary.

It has been found that the salinity intrusion length for the positive surge did not increase significantly due to the constant freshwater discharge from the upstream point and negligible surge penetration beyond Diamond harbour. However, the intrusion length decreased due to the negative surge, as flood currents which normally carry the salt inside the estuary were seemingly absent.

Breadth-averaged model

By starting from an initial state of rest and constant salinity throughout the estuary, the

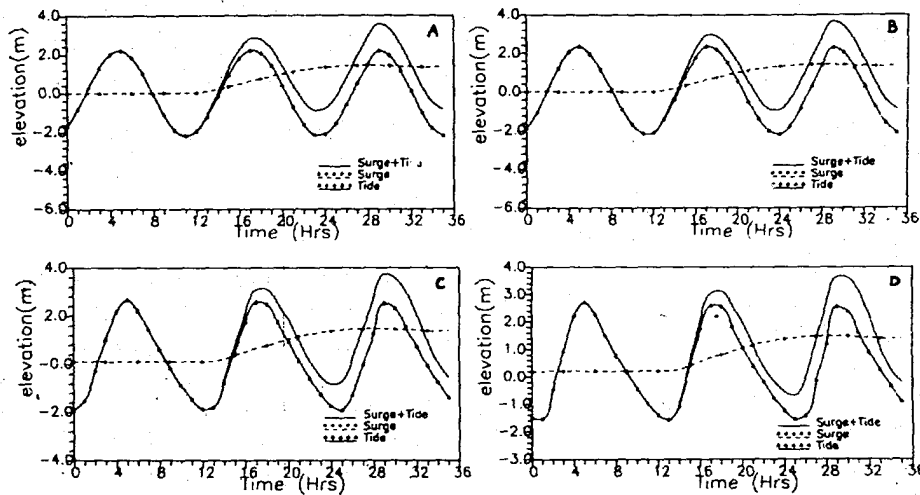


Fig. 6—Computed elevations in meters due to tide, surge and tide-surge interaction at (a) the mouth, (b) Gangra, (c) Haldia and (d) Balari, for 1982 Orissa cyclone

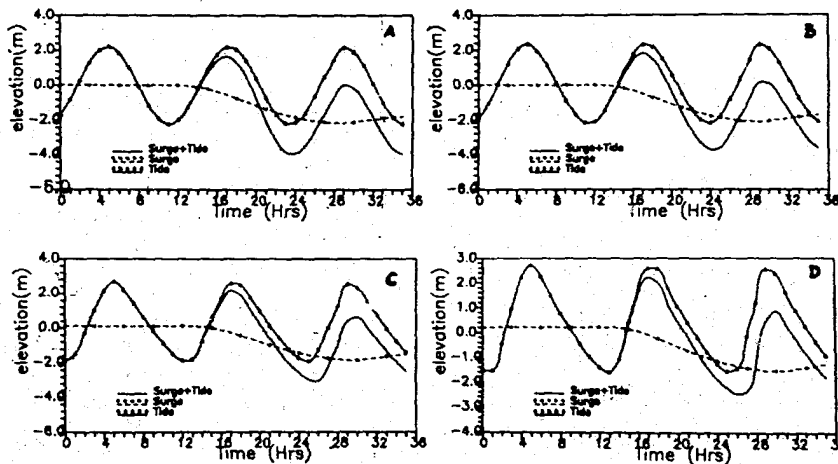


Fig. 7—Computed elevations in meters due to tide, surge and tide-surge interaction at (a) the mouth, (b) Gangra, (c) Haldia and (d) Balari for 1991 Bangladesh cyclone.

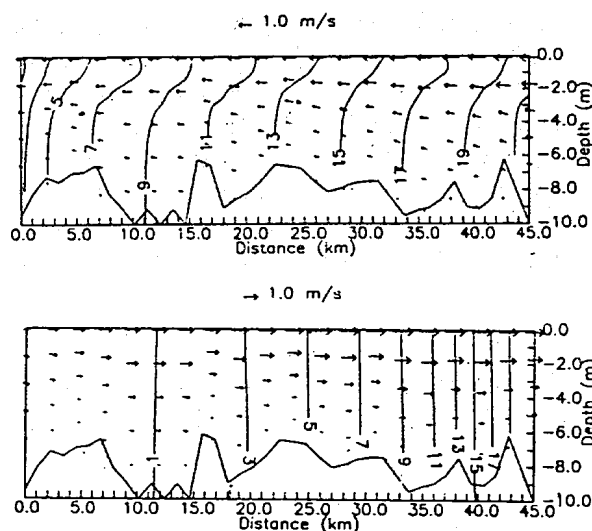


Fig. 8—Salinity and velocity fields during flood and ebb for low discharge conditions

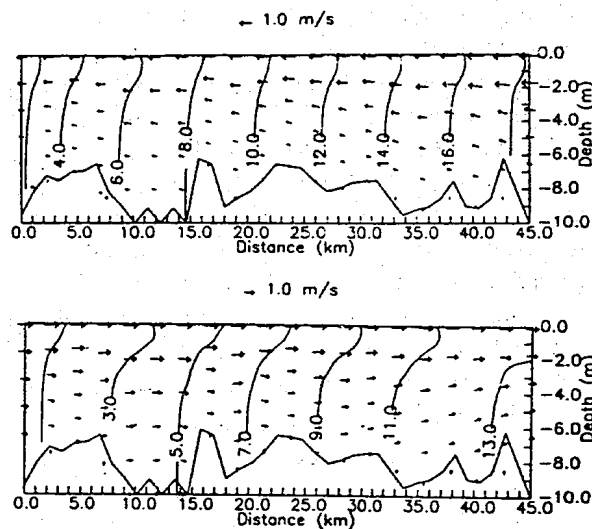


Fig. 9—Salinity and velocity fields during flood and ebb for high discharge conditions.

governing equations are integrated forward in time till a steady state is achieved.

Figure 8 shows the tidal currents and salinity along the channel for flood and ebb periods, respectively. The vertical component of the velocity was scaled by increasing two orders of magnitude. The magnitude of the bottom currents are underestimated in comparison with the observations. The maximum current speed of 2.0 m sec^{-1} is found just below the surface, which is in good agreement with the available observations. The results have clearly shown that the currents are either flood directed or ebb directed for the respective tidal phase. The effect of fresh water seems to increase the surface flow during the ebb period. Slight stratification is evident during the flood period with a maximum salinity of 21.0 ppt at the mouth and gradually decreased to 3 ppt at the landward end. Well-mixed profiles are noticed during ebb period with salt intrusion being limited to 35 km from the mouth. This is due to intense mixing during ebb in shallower zones.

By introducing a fresh water flow of $3000 \text{ m}^3 \text{ sec}^{-1}$, the salinity and velocity distribution for the monsoon season has been depicted in Fig. 9

for the flood and ebb periods. No significant changes in current patterns are noticed. The salinity in the flood period varied from 17.5 ppt at the seaward end to 0.0 ppt at landward end. The estuary is more stratified during this period. During the ebb, the estuary lost more salt and the maximum is 14.0 ppt at the seaward end. The top to bottom salinity varied by 1.5 ppt in some portions of the estuary. The results are in good agreement with the observations, and the intrusion length is confined to 40 km from the mouth of the estuary.

References

- 1 Biswas, A N, *J Inst. Engr (India)*, 66 (1985), 61.
- 2 Gole G V & Vaidyaraman P P, *Proc Tenth Congress of Coastal Engg, (IAHR) Tokyo*, 2(1966), 1412.
- 3 Sinha P C & Mitra A K., *Computer mathematics and applications*, 16 (1988), 153
- 4 Sinha P C, Dube S K, Rao Y R & Chatterjee A K, *Non-linear World*, 2 (1995), 257.
- 5 Sinha P C, Rao Y R, Dube S K, Rao A D & Chatterjee A K, *Mar Geod*, 19 (1996a), 197.
- 6 Rao Y R, Sinha P C, Rao A D & Dube S K, *Proc of TROPMET, (NRSA, Hyderabad, 1995)* (in press).
- 7 Johns B & Oguz T, *Dyn Atmos & Oceans*, 14 (1990), 229
- 8 Sinha P C, Rao Y R, Dube S K, Rao A D & Chatterjee A K, *Mar-Geod*, 19 (1996b), 257.