

A numerical model for residual circulation and pollutant transport in a tidal estuary (Hooghly) of NE coast of India

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To study pollutant dispersal in the estuary a non-linear vertically integrated numerical model has been applied to the Hooghly estuary along the east coast of India. The horizontal density gradient terms are included in a two-dimensional depth-averaged hydrodynamic model. Biochemical oxygen demand (BOD) was adopted as a tracer for water quality. The model uses a realistic tidal forcing, fresh water flow based on observations and climatic winds over the region of interest. The effects of wind and horizontal density gradients on the residual circulation are found to be significant. Pollutants discharged in the upper estuary do not affect the Haldia channel. The model predictions compare reasonably well with observed elevations and currents in the estuary. For verification of pollutant transport model, observational data is presently unavailable, however, the salinity distribution compares well with the observations.

Throughout the world, estuarine waters are frequently used to dispose treated or untreated municipal and industrial waste waters to the environment. A proper assessment of the dilution and dispersion of the discharged materials has to be done before setting a waste disposal system. Effluents entering the river may adversely affect the water quality by increasing turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), etc. For systematic and effective control of flow of effluent into the estuary a thorough investigation of various parameters is essential. It is often difficult to verify a contaminant model directly because of logistical considerations for sampling, the expense of analysis, and the episodic nature of the pollutant inputs. However, verifying a hydrodynamic and salinity transport model provides a start towards verifying a pollutant transport model.

The net transport of discharged pollutants is related to residual currents which may appreciably influence the residence time of nutrients and pollutants. The residual currents in an estuary are a function of freshwater discharge, density gradients, wind input and tidal forcing from the adjacent sea.

Two approaches have been used to simulate depth-averaged residual flow in a well-mixed bay or estuary. The first is based on averaging of tidal flow results, and was followed by Tee¹, Prandle², and many others. The second utilizes time averaged equations of motion as described by Nihoul & Ronday³. Residual circulation determined in the present paper is by time averaging the tidal flow. The tidal flow is determined using a coupled hydrodynamic/salt transport model. This model is different from many existing depth-averaged models as the horizontal density gradients are included in the formulation. The few modelling studies that have included baroclinic effects are primarily theoretical studies except for work reported for Suisun Bay⁴ and for Apalachicola Bay⁵.

Materials and Methods

The Hooghly estuary (Fig. 1) forms a part of the river Ganges and serves as a navigable waterway to Calcutta and Haldia ports. The estuary is funnel shaped meeting the Bay of Bengal near Sagar at a distance of 146 km below Calcutta. The port of Calcutta is located 66 km north of Hooghly point.

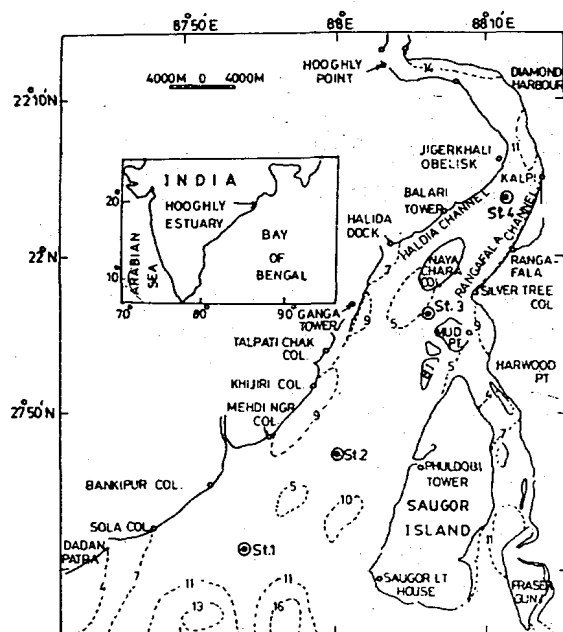


Fig. 1—Map of the Hooghly estuary and its bathymetry in meters

Normally, a freshwater flow of $1000 \text{ m}^3/\text{s}$ is discharged from Farakka barrage, situated 206 km north of Hooghly point to maintain navigational channel for Calcutta port during the dry season. The freshwater discharge in the river rises steeply to a magnitude of $3000 \text{ m}^3/\text{s}$ during monsoon season (June-September). The river is tidal for nearly 250 km and the vertical tide range at the mouth varies from 5.2 m during springs to 1.8 m at neaps. The tide is mainly semi-diurnal. The coastal geometry is quite irregular and the estuary contains a number of deep channels separated by shallow zones. Due to the presence of two major islands and a small island the flow field is quite complicated. Biswas⁶ and Gole & Vaidyaraman⁷ have established that due to shallow depths and intense tidal activity, the Hooghly estuary is well-mixed and vertically homogeneous during the dry season. From the measured salinity distribution pattern, it has been established that the variation of salinity from surface to bottom hardly exceeds 3 ppt. The maximum salinity during the dry season is found to be 28 ppt at Dadanpara and reduces to 13 ppt at Haldia. From there onwards it falls very rapidly. During the wet season the salinity will be as low as 13 ppt at Sagar and further decreases

northwards. The estuary is salt free after 50 km from the mouth of the estuary. A comparison of the observed currents and elevations at a few stations along the estuary show that maximum flood occurs about 1 hr before high water, and maximum ebb about 1 hr before low water. Since the estuary is very shallow (only 6 m on the average and nowhere deeper than 20 m), the tidal range constitutes a significant part of the total depth. As a result, tidal currents are uniform from surface to very close to the bottom. Tidal currents in the estuary are typically of the order of 1.0 to 1.5 m/s. The wind pattern in the estuary is more or less in line with the general wind system of the Indian sub-continent. SW winds prevail from May to October. Lighter North-East winds blow during the other months. Although major pollutant dumping takes place near Calcutta, the emergence of the port of Haldia and settlements around it may prove catastrophic for the local estuarine environment. In spite of self-purification in the upper estuary a significant amount of pollutants may enter into the lower estuary.

The model is fully non-linear and uses a semi-explicit finite difference scheme to solve the basic hydrodynamic equations on a staggered grid. This model has been modified by introducing BOD transport equation to study pollutant dispersal in the estuary. In order to include the dynamic affects of horizontal salinity gradients on the circulation in the estuary, the momentum and salt conservation equations are coupled with pressure gradient terms⁸. Basic data consisting of water levels, currents and salinity have been taken from an observational programme conducted during 1992-93. The bathymetry for the model was extracted from survey maps of Calcutta Port Trust. Since the aim of the study was to estimate the likely spread of an effluent in the estuary under various discharge conditions, we utilize BOD loading data as input into the estuary from a survey conducted by Central Pollution Control Board, India, during June 1980 to Dec 1981.

Formulation

In the formulation of the model, unsteady two-dimensional vertically integrated shallow water equations are used along with the depth-averaged

salt conservation equation. The complete details of the model are reported by Sinha *et al.*⁹. Solving the basic equations in time and averaging the results over a tidal period T , the residual flow

$$\langle U(x,y,t) \rangle = \frac{1}{T} \int_{t_0}^{t_0+T} U dt \quad \dots (1)$$

To determine the concentration field and movement of the pollutant, a depth averaged advection diffusion equation for BOD is used along with the hydromagnetic model as given by

$$\begin{aligned} \frac{\partial(HC)}{\partial t} + u \frac{\partial(HC)}{\partial x} + v \frac{\partial(HC)}{\partial y} \\ = \frac{\partial}{\partial x} \left(HD \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(HD \frac{\partial C}{\partial y} \right) \\ - (K_1 + K_2)HC + \langle S_c \rangle \quad \dots (2) \end{aligned}$$

where $K_1(=0.21/\text{day})$ is the decay rate for BOD by biochemical oxidation, $K_2(=0.13/\text{day})$ is the decay rate for BOD by sedimentation and adsorption of organic matter on the sediments at the sea bed¹⁰, C is the depth averaged concentration, S_c is the source of the pollutant and D is the dispersion coefficient ($750\text{m}^2/\text{s}$). In the absence of observational data, this value of D has been arrived at using theoretical arguments¹¹.

Boundary and initial conditions

The analysis area has the following open boundaries at the seaward end (i) connecting Dadanpara and Sagar and (ii) at Frasersgunj, and Hooghly point at the landward end. During December, 1992 a simultaneous observational programme was conducted to collect half-hourly tide gauge data at various stations for a spring tide. A harmonic analysis of the data for this period resulted the following amplitudes and phases of M_2 astronomical tidal constituent and its overtides (M_4, M_6 and M_8 , respectively).

$$\begin{aligned} 2.40 \cos(\omega t - 196) + 0.225 \cos(2\omega t - 281) \\ + 0.102 \cos(3\omega t - 259) + 0.071 \cos(4\omega t - 287) \\ \text{at Dadanpara} \quad \dots (3a) \end{aligned}$$

$$\begin{aligned} 2.43 \cos(\omega t - 187) + 0.228 \cos(2\omega t - 269) \\ + 0.089 \cos(3\omega t - 267) + 0.065 \cos(4\omega t - 299) \\ \text{at Sagar} \quad \dots (3b) \end{aligned}$$

$$\begin{aligned} 2.20 \cos(\omega t - 170) + 0.195 \cos(2\omega t - 251) \\ + 0.089 \cos(3\omega t - 245) + 0.059 \cos(4\omega t - 278) \\ \text{at Frasersgunj} \quad \dots (3c) \end{aligned}$$

$$\begin{aligned} 2.30 \cos(\omega t - 245) + 0.75 \cos(2\omega t - 5) \\ + 0.389 \cos(3\omega t - 128) + 0.159 \cos(4\omega t - 208) \\ \text{at Hooghly Point} \quad \dots (3d) \end{aligned}$$

where the amplitude is in meters and $\omega = 2\pi/T$. Water surface elevation is prescribed at the open boundary connecting Dadanpara and Sagar by linearly interpolating the values obtained by Eq. (3a) and (3b). Similarly, the ζ (water surface elevation) value along the open boundary at Frasersgunj is prescribed by Eq. (3c). The constant fresh water discharge released into the estuary increases the mean water level at the upstream point. By adding a constant value in Eq. (3d), we produce the required discharge into the estuary. 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.

A motionless, unpolluted and salt free water was used as the initial condition.

Numerical procedure

The analysis region is represented using a mesh of 61×88 grid points, with a constant grid spacing of 750 m. The basic equations are solved using a finite difference scheme similar to that used by Sinha *et al.*¹² Here a conditionally stable semi-explicit finite difference scheme on an Arakawa-C type staggered grid is used. The space derivatives in momentum equations and continuity equations are discretized by central differences. The barotropic pressure gradient terms in the momentum equations are evaluated at advanced time level. The Coriolis term in x-momentum equation is evaluated explicitly at the previous time level whereas in y-momentum equation, it is evaluated at the advanced time level. Leendertse¹³ observed that the application of the above scheme for the Coriolis terms has given satisfactory results. In both the momentum equations baroclinic pressure gradient terms are calculated at the advanced time level. Finally in both the momentum equations, friction terms are evaluated

implicitly and forward differences are used for time stepping. A time step of 60 sec is found to be consistent with the computational stability. For the finite difference representation of the pollutant transport Eq.(2), a few techniques are tested based on central and upstream finite-difference forms. Since the central difference scheme which provides second order accuracy may lead to numerical instabilities if Peclet number exceeds 2, an upstream version is used¹⁴. The numerical diffusivity produced by upstream scheme was not considered important in the present study as its contribution is one order less than physical diffusion. It has been found that the upstream version is computationally more efficient, and hence the transport equation is solved explicitly with the advective terms represented by upstream difference method.

Drying of the shallow zones has been taken into account, 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 equations¹⁵.

BOD simulation

Here, two cases have been studied with different locations and discharge conditions. In the first experiment, an initial BOD level was specified at Diamond harbour and Jigerkhali Obelisk stations. In the second experiment, an outfall was chosen near Haldia. From June 1980 to December 1981, the BOD loading released at this location was reported as 3000 kg/day. Recently, several large industrial complexes have been developed in Haldia, and a much larger quantity of sewage now flows into the estuary. The model was used to simulate BOD distributions resulting from pollutant loading at several different locations in the estuary (Table 1).

Results and Discussion

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 a north-easterly (NE) wind of 5 m/s and a fresh water discharge of 1000 m³/s representing the

dry season. The hydrodynamic model achieves a periodic steady state in eight tidal cycles. The model validation for circulation and salinity are discussed earlier by Sinha *et al.*^{9,12}. Table 2 gives the limited available data for residual currents at various stations along the estuary. The data presented here are not simultaneous observations but were collected during spring tide in December 1992 and January 1993 by Calcutta Port Trust. Essentially, the current data is collected every hour for a period of two tidal cycles during spring conditions at selected locations in the estuary. The residual currents are obtained by averaging the currents over a tidal cycle. However, this limited current data can give only broad picture of residual circulation in the estuary for peak spring period. Figure 2A depicts the computed residual currents without wind and density gradients on the basis of sixteenth tidal cycle. The net transport is towards south all along the estuary. The maximum strength of the residual current found inside the estuary during this period is 25 cm/s. Here, we notice the absence in Frasergunj channel. By including a NE wind of 5 m/s and horizontal density gradients, the computed residual currents are plotted in Fig. 2B. The maximum speed observed for this situation is 42 cm/s inside the estuary. It is generally found that the net transport is towards south. There is a

Table 1—List of numerical experiments

Experiment	Discharge type	Outfall locations	Quantity released
I	Instantaneous	Diamond harbour & Jigerkhali Obelisk	40 g/l
II	Continuous	Haldia	3,000 kg/day
III	Part Time (flood Period)	Haldia	10,000 kg/day
IV	Part Time (ebb Period)	Haldia	10,000 kg/day

Table 2—Observed residual current speeds and directions

Station name	Speed (cm/s)	Direction (deg)
Sagar	20.0	260
Black's point (Near strn.2)	5.0	210
Silver Tree	25.0	160
Gangra	9.0	260
Haldia	5.0	50
Balari	12.0	10
Rangafalla	16.0	220

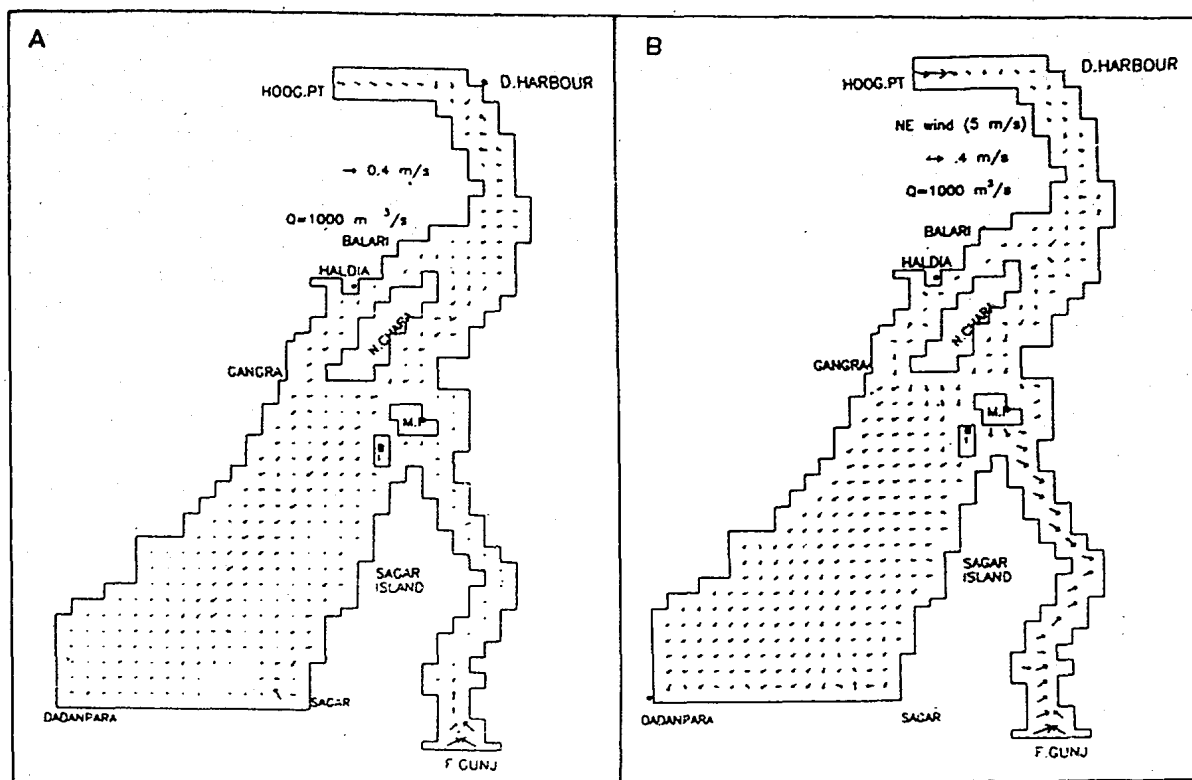


Fig. 2—Computed residual residual circulation—(A) without wind and density gradients, and (B) with NE winds of 5 m/s and density gradients.

weak northward flow of 5 to 10 cm/s in Haldia channel. The marginal strengthening of residual currents are attributed to wind and density gradients. These two features are in agreement with the observations (shown in Table 2). Due to the lack of current observations in Frasersgunj channel it is difficult to establish the inward flow in the southern part of the channel.

Figure 3 shows the mean salinity distribution over a tidal cycle for a spring tide. Salinity decreased from 25 ppt at Frasersgunj to 0.1 ppt at Hooghly point. It may be noticed that the salinity gradients are large at the seaward end compared to the landward end. Here, the observations are shown in circles. The model simulated salinity values are in reasonable agreement with the observations.

In the first experiment, taking the outfall location at Diamond harbour (eastern bank), BOD equal to 40 g/l has been released instantaneously at one hour after low water time. The concentration (mg/l) after one day of integration has been plotted

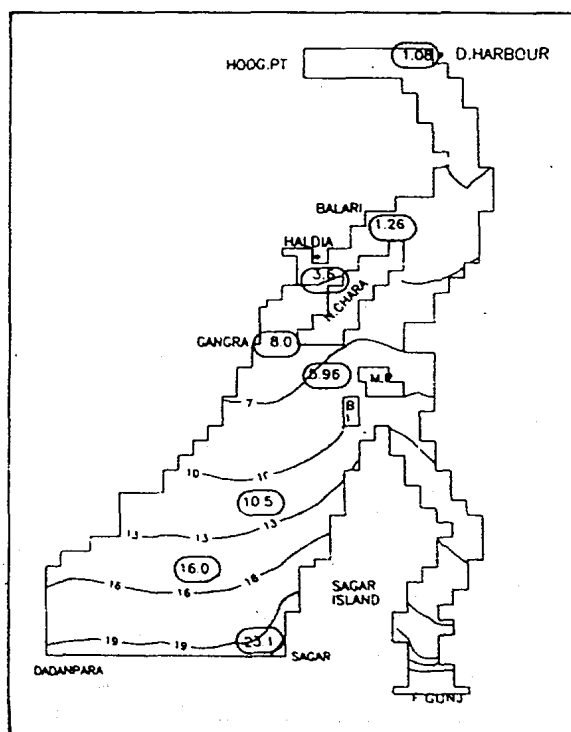


Fig. 3—Mean salinity distribution in Hooghly estuary (The numbers in circles shows the observations)

in Fig. 4A. In one day the pollutant patch has moved 20 km southward with a maximum concentration of 26 mg/l located in the north of Nayachara island. The contour of 1.0 mg/l extends all the way up to the sea at Sagar. Figure 4B shows the concentration distribution after one day of integration for the outfall location at Jigerkhali Obelisk (western bank) where the same amount was released instantaneously after one hour from the low water time. The maximum concentration observed is 18 mg/l to the east of Nayachara island. A slight build up of concentrations are noticed during this period to the west of Sagar island. It shows (Fig. 4A,B) that the Haldia channel is less affected due to the release of pollutants in the up-estuary. After integrating further for two days, very little concentrations are left in the estuary which confirms the high flushing action of the estuary.

To study the likely spread of the effluent under the existing discharge conditions, an amount of BOD equal to 3000 kg/day has been released at Haldia continuously. Figure 5A shows the

concentration field after 24 hours of integration. Here the maximum concentration of BOD is 1.1 mg/l which is found in the vicinity of the outfall location. The area affected by the effluent is only confined to the region near Haldia. The places near Gangra and Balari are not affected by any contamination. By integrating a further 6 hours, we depict the concentration field during flood situation in Fig. 5B. Here, the maximum concentration of BOD is 0.91 mg/l near the outfall. The reduction in concentration is due to the availability of more water due to flood and the consequent dilution of the pollutant. The affected area has slightly increased than the ebb situation. Figure 6 shows the concentration of BOD at two points, each being 4 km south and north of Haldia, respectively. Due to the continuous discharge the concentrations have increased with time. It has been found that the concentrations are more in southward direction than the northward direction which is consistent with residual currents.

The model was run with part-time (flood or ebb) discharge at Haldia, to simulate the

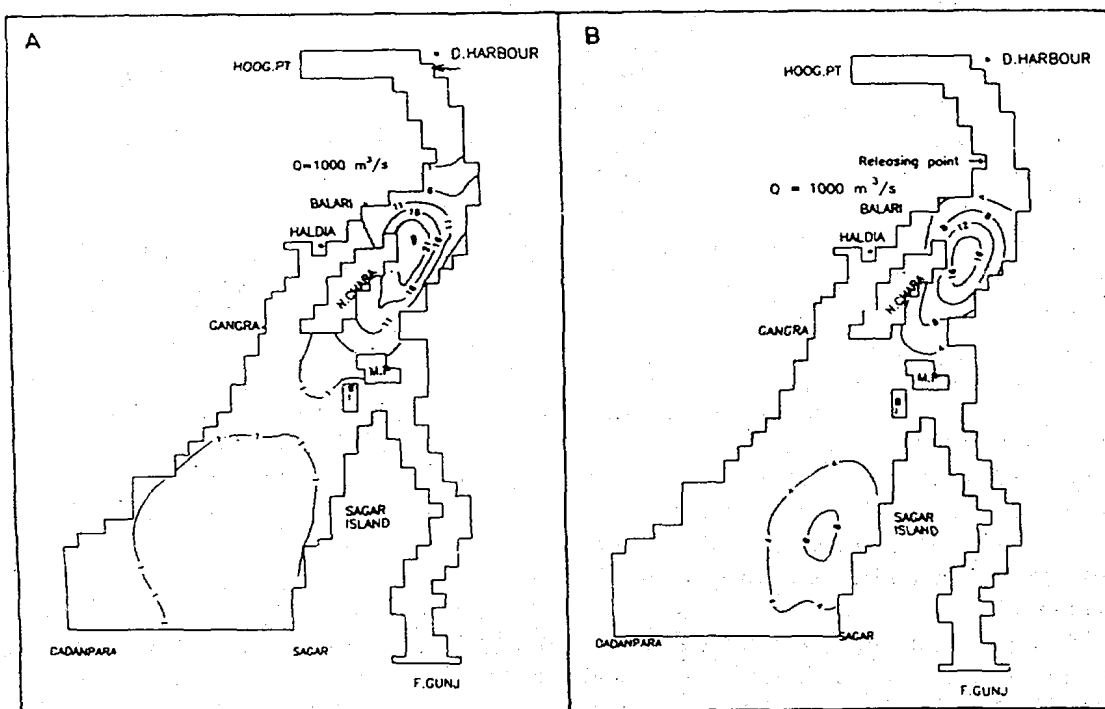


Fig. 4—Concentration distribution in mg/l —(A) after 24 hrs for the outfall location at Diamond harbour, and (B) for outfall location at Jigerkhali Obelisk.

concentration profiles in the estuary. In the first experiment an amount of BOD loading equal to 10,000 kg has been discharged for 5 hours (hour 1 to hour 6 in the model) during the flood period.

The model is integrated for one day. Figure 7A shows the concentration field after 30 hours of integration. By this time Haldia channel is free from pollutants. The pollutants moved towards the

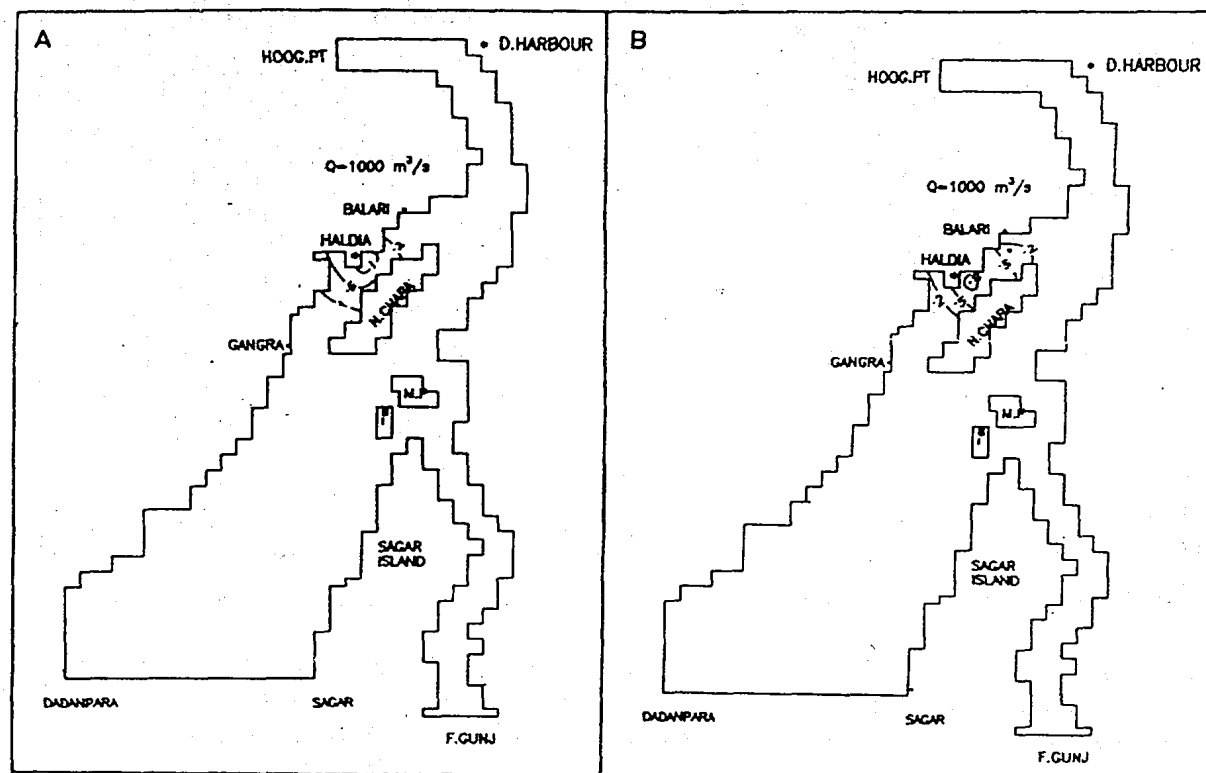


Fig. 5—Concentration distribution in mg/l—(A) after 24 hrs for the outfall location at Haldia. (B) for 30 hrs.

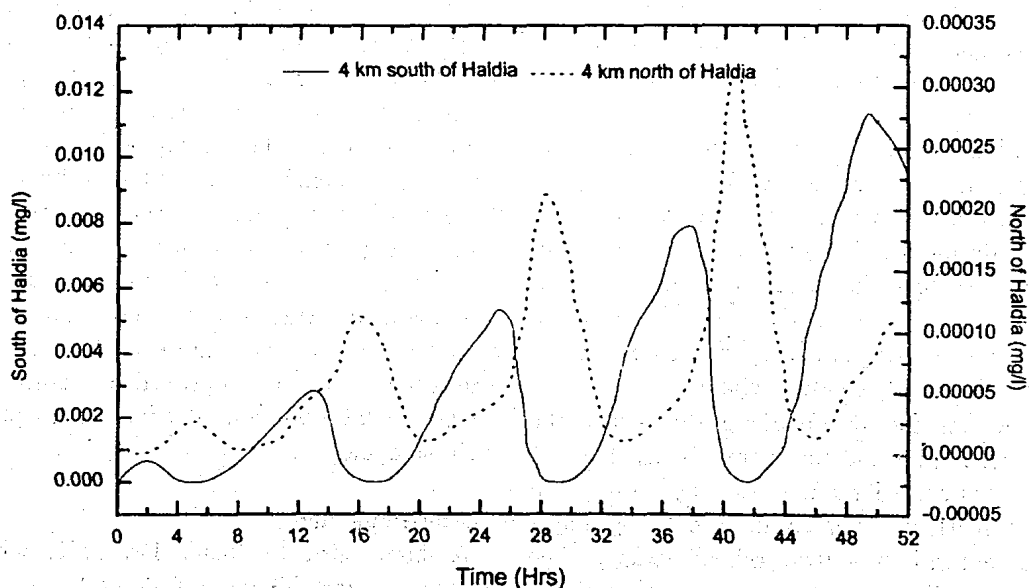


Fig. 6—Time history of pollutant at 4 km south and north of Haldia

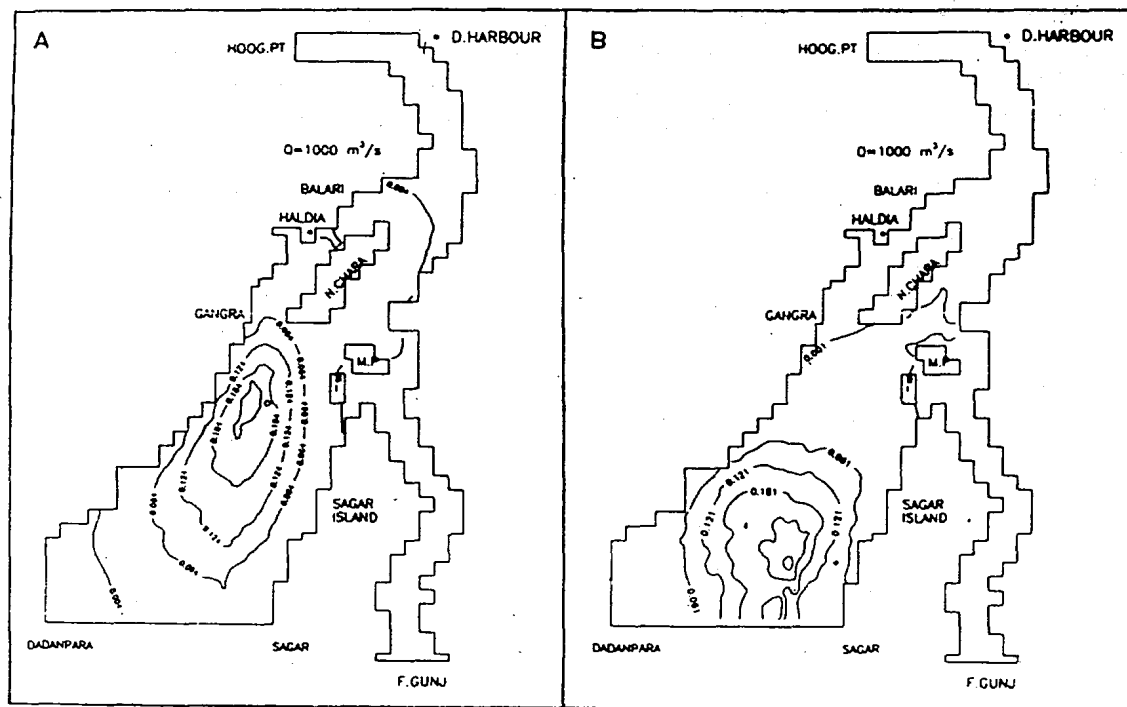


Fig. 7—Concentration distribution after 24 hrs for the release during (A) flood and (B) for ebb discharge only.

sea with a maximum concentration of 0.245 mg/l near Black's point (St. 2 in Fig. 1). A further integration of 6 hours shows only a trace amount of concentration in the estuary. To simulate the effect of discharge during ebb, an experiment was conducted by releasing the same amount for 6 hours (hour 7 to hour 13 in the model). Figure 7B shows the concentration field after 36 hours of integration. A small amount of the pollutant is still present in the Haldia channel. The maximum concentration of 0.3 mg/l was found during this time in the south of Gangra. But further integration of 8 hours shows very little concentrations in the estuary. With the relatively weak ebb currents and low water depths, the channel seem to retain concentrations for a long time. In both cases a major amount of the pollutants are flushed out of the estuary through Rangafalla channel.

A numerical model developed to study the residual circulation and pollutant dispersal in the Hooghly estuary demonstrates the utility of simpler numerical schemes in simulating many observed features in a well-mixed estuary. The model described here can be used to make realistic estimate of residual circulation and pollutant

transport and is a useful step towards construction a three-dimensional model. In this non-linear vertically integrated model the effect of wind and the horizontal salinity gradients on the residual circulation are found to be very significant. The computed magnitude and direction of the residual velocities are in reasonable agreement with the available observations for the dry season. The model's results clearly show that the pollutants discharged from the up-estuary do not affect the Haldia channel. The strong ebb flow in the Rangafalla channel flushes of the pollutants out of the estuary. The pollutants released near Haldia have the tendency to remain for a longer time due to weak ebb flow. Due to the limited water depths and weak currents the concentration near the outfall increases during the low water conditions. This situation can be improved by controlling the release of the pollutants during certain phases of the tidal cycle.

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