

River discharge, storm surges and tidal interactions in the Meghna river mouth in Bangladesh

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सार — उत्तरी बंगाल की खाड़ी के एक द्वि-आयामी ऊर्ध्वाधर एकीकृत गणितीय निदर्श का प्रयोग करते हुए मेघना नदी के ज्वारनद मुहाने से विसर्जित जल, तूफानी तरंगों और ज्वार के बीच पारस्परिक क्रियाओं का अध्ययन किया गया है। नदी के मुहाने के समीप तीनों तरह के जलों की अलग-अलग क्रियाओं तथा इनके आपसी तालमेल से उत्पन्न पारस्परिक क्रियाओं पर इस अध्ययन में विचार किया गया है। नदी के मुहाने से विसर्जित जल ज्वार की तीव्रता को बढ़ाता भी है और कम भी करता है। यह ज्वार की अवस्था पर निर्भर करता है। उच्च ज्वार के समय तीव्रता को बढ़ाता है तथा निम्न ज्वार के समय ज्वार की तीव्रता को कम करता है। यह बात सभी तीनों क्रियाओं के आपसी तालमेल पर ही लागू होती है। दूसरी तरफ, अधिकांश मामलों में नदी से विसर्जित जल तूफानी तरंगों के विपरीत ही कार्य करता है। कुछ निश्चित परिस्थितियों और कुछ असामान्य अवसरों पर ही नदी का जल ज्वार की तीव्रता को बढ़ाने का कार्य करता है। तथापि नदी के जल का प्रवाह और तूफानी तरंगों के मध्य पारस्परिक क्रिया उनके प्रवाह की तीव्रता पर निर्भर करती है। जहाँ तक ज्वारनद मुहाने के क्षेत्र का कुल मिलाकर संबंध है, नदी से विसर्जित जल ज्वार की तरंगों की ऊँचाई में वृद्धि करता है। तथापि, ज्वारनद मुहाने से दूर, जल विसर्जन का कोई उल्लेखनीय प्रभाव नहीं है।

ABSTRACT. Interactions among river discharge, storm surges and tides in the Meghna river estuary in Bangladesh have been studied by using a two-dimensional vertically integrated numerical model of the northern Bay of Bengal. The study considers the interactions mostly in terms of flow across the river mouth under the three forcings, individually and in different combinations of them. River discharge and tidal flow across the river mouth act both positively and negatively depending on the tidal phase, positively during high tide and negatively during low tide. This is also true for the combination of all the three forces. On the other hand, in most of the cases, river discharge acts in opposition to the storm surges. Under certain conditions and on rare occasions they act positively. The interactions between river discharge and storm surges, however, depend on their relative magnitudes. In respect of total elevation in the estuarial region, river discharge tends to increase the surge height. However, away from the estuary, the effect of river discharge is hardly discernible.

Key words — Interaction, River discharge, Storm surges, Tides, Meghna river, Bangladesh.

1. Introduction

Tropical cyclones forming in the Bay of Bengal bring catastrophic ravages to the littoral countries, particularly to Bangladesh. In fact, Bangladesh is the worst sufferer of all cyclonic casualties in the world. Ali and Chowdhury (1997) have listed a total of 34 world cyclones due to each of which a minimum of 5000 human lives were lost. Out of these 34 cyclones, 15 struck Bangladesh and 11 struck India. Bangladesh had a share of about 53% deaths due to these cyclones. On the contrary, Ali and Chowdhury (1997) have shown that about 1% cyclones of the world total had hit Bangladesh. This shows the gravity of the situation as far as Bangladesh is concerned.

There are a number of reasons for the serious impacts of cyclones and the accompanying storm surges in Bangladesh. These have been discussed by different authors (Ali and Chowdhury 1997). The most disastrous effects of cyclones and storm surges in Bangladesh have been observed to occur in the Meghna river estuary that lies at the north-east corner of the Bay of Bengal. The reasons for this have also been discussed, for example, by Ali and Chowdhury (1997). Due to a favourable combination of different geomorphological and hydrological conditions and other dynamic forces, storm surges get here sufficiently amplified leading to catastrophic ravages.

Rivers play a dynamic and vital role in surge modification. As noted by Johns and Ali (1980), a river may principally have two-way effects. Firstly, river discharge might be expected to modify the sea surface elevation resulting from surge, tide and monsoonal wind. Secondly, its presence allows a potentially deep inland penetration of surge water originating in the Bay. A consequence of this is inland flooding.

In Bangladesh, there is a vast network of rivers numbering about 230. Most of these rivers are either the tributaries or the distributaries of the Ganga-Brahmaputra-Meghna river system of Bangladesh, which is one of the largest river systems in the world. There are about 26 rivers/inlets that cut across the coast of Bangladesh and they allow surge water to penetrate deep inside the country. About 96% of the flow discharge in Bangladesh occur through the Meghna estuary (Barua 1991).

There have been a number of studies on storm surges in the Bay of Bengal, a good review of which has been made, for example, by Dube (1995) and Dube *et al.* (1997). Some of these studies include tide-surge interaction (Johns and Ali 1980). The inclusion of river discharge has not drawn much attention, although this is an important factor. Johns and Ali (1980) while simulating storm-surges in the Bay of Bengal, studied the penetration of storm surge and tidal waters along the Ganga-Brahmaputra-Meghna river system in Bangladesh. But they did not consider the interaction among river discharge tides and storm surges. Sinha *et al.* (1985) and Dube *et al.* (1986) included the lower Meghna in storm surge modelling for the Bay of Bengal. They studied the impact of river discharge on storm surge by running the model with and without the river and found a negative impact of rivers on surge amplification. But the interaction again was not considered. Ali (1996) considered the intrusion distance of surge water inside Bangladesh under different climate change (sea level rise and atmospheric temperature increases) scenarios. This was again a one-way flow. Ali and Hoque (1994) using a vertically integrated two-dimensional limited area model of the Bay of Bengal investigated the back water effect (BWE) in the Meghna estuary due to SW monsoon wind only. Ali (1995) used a three-dimensional whole Bay area model to study the BWE in the Meghna estuary again with SW monsoon wind only. More detailed discussions on BWE in Bangladesh are available, for example, in Miah (1988), Ali and Hoque (1994), Ali (1995) and Ali *et al.* (1997). Ali *et al.* (1997) particularly considered the BWE of tides and storm surges on fresh water discharge through the Meghna estuary.

In the present study we investigate the interactions among river discharge, storm surges and tides in the Meghna estuary in Bangladesh by using the two-dimensional model of Ali and Hoque (1994).

2. Model outlines

The present analysis uses the model of Ali and Hoque (1994). For convenience, a brief outline of the model is given here.

The model area is shown in Fig. 1. The southern open boundary corresponds roughly to latitude 20°N. The other three boundaries are closed except at the north-east corner where an opening is kept to represent

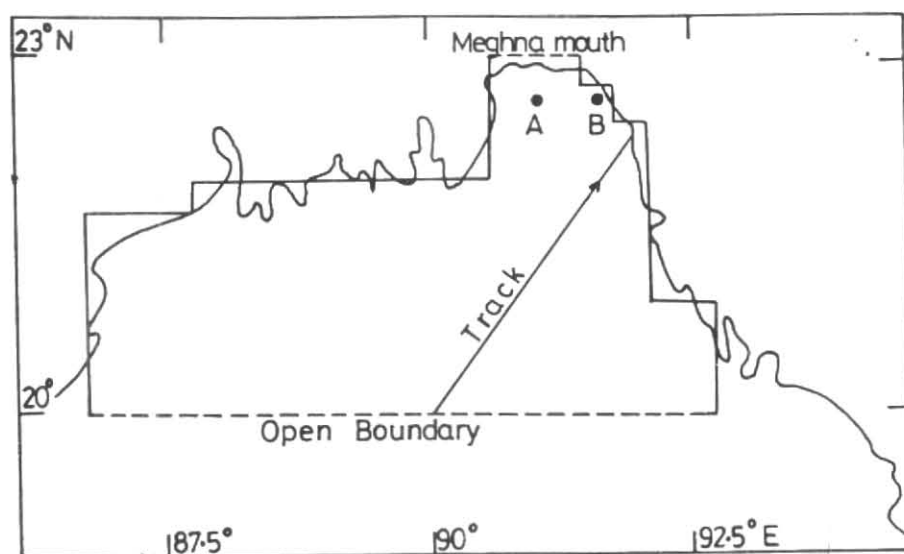


Fig. 1. The model area

the Meghna river mouth and to allow for river discharge as well as for penetration of water from the Bay into the river.

The model uses a system of cartesian coordinates with origin O , lying in the equilibrium level of the sea surface and in the extreme south-west point of the model area. The O_x and O_y are horizontal axes with O_x pointing towards the east (positive x -direction) and O_y pointing north (positive y -direction). The O_z is measured vertically upwards. The free sea surface corresponds to $z = \zeta(x, y, t)$ and non-moving impermeable sea bottom corresponds to $z = -h(x, y)$.

The dynamics in the model is described by the following depth-averaged equations of motion:

$$\frac{\delta u}{\delta t} - fv = g \frac{\delta \zeta}{\delta x} + \frac{1}{\rho(\zeta + h)} (F_{sx} - G_{bx}) \quad (1)$$

$$\frac{\delta v}{\delta t} + fu = g \frac{\delta \zeta}{\delta y} + \frac{1}{\rho(\zeta + h)} (F_{sy} - G_{by}) \quad (2)$$

where u and v are the depth-averaged components of velocity in the x and y directions respectively, t is time, g is the acceleration due to gravity ($= 9.81 \text{ m/s}^2$), ρ is the density of water ($= 1025 \text{ kg/m}^3$) and f is the Coriolis parameter taken constant and equal to $5 \times 10^{-5}/\text{s}$ for the model area F_{sx} and F_{sy} represent surface wind stresses in the x and y directions respectively. G_{bx} and G_{by} are bottom stresses in the

x and y directions respectively. It is to be noted that no density variation is considered.

The equation of continuity for incompressible fluid has the vertically-integrated form

$$\frac{\delta \zeta}{\delta t} + \frac{\delta}{\delta x} (u, h) + \frac{\delta}{\delta y} (v, h) = 0 \quad (3)$$

The surface and bottom terms in Eqns. (1) and (2) are parameterised by quadratic stress formula. The Eqns. (1) and (2) have thus been made partially non-linear through the introduction of quadratic bottom stress formulation. In determining the surface wind stresses, the wind speed in a cyclone is given by following Jelesnianski (1965):

$$V_r = V_{\max} \left(\frac{r}{r_0} \right)^{\frac{3}{2}} \quad 0 \leq r \leq r_0 \quad (4)$$

$$V_r = V_{\max} \left(\frac{r_0}{r} \right)^{\frac{1}{2}} \quad r > r_0 \quad (5)$$

where V_r is the wind speed in a cyclone at r and V_{\max} is the maximum sustained wind (MSW) speed (V_{\max}) in a cyclone at $r = r_0$; the radius of maximum sustained wind and r is the radius vector of the cyclone which is assumed symmetrical.

The boundary conditions at the closed boundaries are taken as zero normal flow. Two conditions are

used for the southern open boundary. In case of tidal forcing, tide is generated in the model by specifying tidal amplitudes at the southern open boundary by the relation :

$$\zeta = \zeta_0 \sin\left(\frac{2\pi T}{t}\right) \quad (6)$$

where $T = 12.4$ hrs is the semi-diurnal tidal period for M_2 tide and ζ_0 is the tidal amplitude. For wind forcing on the surface as well as for fresh water discharge at the Meghna mouth, the boundary conditions at the southern open boundary are applied according to the Johns *et al.* (1991). That is, we take

$$v + \sqrt{\frac{g}{h}} \zeta = 0 \quad \text{at } y = 0 \quad (7)$$

This permits free communication of water on both sides of the southern open boundary. At the northern boundary at the Meghna mouth, two open boundary conditions are used. In the absence of fresh water discharge (river discharge), we take

$$v - \sqrt{\frac{g}{h}} \zeta = 0 \quad \text{at } y = L \quad (8)$$

where L is the total north-south length of the model area. In the presence of fresh water discharge, we take,

$$v - \sqrt{\frac{g}{h}} \zeta = -2v_0 \quad \text{at } y = L \quad (9)$$

where v_0 is a velocity whose value is chosen to produce a southward flow of water across the Meghna mouth. Thus, the introduction of the fresh water discharge is made not by the dynamical representation of the Meghna river but through a radiation condition. This special feature has been incorporated into the model as in (Ali and Hoque 1994 and Ali 1995) and its application simulates a fresh water discharge with minimum computational efforts.

The initial condition is given by,

$$u = v = \zeta = 0 \quad \text{at } t = 0 \quad (10)$$

The Eqns. (1-3) are solved using the finite-difference method on a staggered grid distribution.

3. Numerical experiments

Numerical experiments are done using a grid spacing of 16 km in the x -direction and 15 km in the y -direction and a time increment of 155 sec. The whole model area is divided into 41×24 grid points (41 in the x -direction and 24 in the y -direction). A depth of 500 m is taken at the middle of the southern open boundary. The depth at the coastal boundary is taken to be 10 m and that at the Meghna mouth 5 m. The model is run with different forcings both individually and under various combinations, such as for (i) river discharge alone; (ii) tide alone; (iii) surge alone; (iv) river discharge and tide; (v) river discharge and surge; (vi) tide and surge and (vii) river discharge, tide and surge.

Dynamics in the model due to fresh water discharge are generated by specifying values of v_0 in Eqn. (9). Following the discussions by Ali and Hoque (1994) and Ali (1995), it was found by Ali *et al.* (1997) that a value of $v_0 = 0.25$ m/s gives the right order of magnitude of peak discharge rate through the Meghna mouth during the 1988 flood in Bangladesh when about two-thirds of the country went under water. Unless otherwise stated, this value of v_0 is used in all the numerical experiments. The results for the steady state condition are considered for presentation and discussions.

Tide is generated in the model by specifying the tidal amplitude (ζ_0) at the southern boundary by using Eqn. (6). Ali *et al.* (1997) found that a value of $\zeta_0 = 1.0$ m produces the right order of magnitude of M_2 tide at the Meghna mouth. This value of ζ_0 is used for all the tide-related experiments. The values under fully oscillatory solution are considered. For river discharge and tidal forcing combined, both v_0 and ζ_0 are applied simultaneously and the integration is continued until an oscillatory solution is reached. For surge alone, it is introduced, as usual, on the initial rest condition and the results are taken into account right from the beginning of the integration. In case of river discharge and surge, cyclone is introduced on the steady state solution.

Similarly, for river discharge, tide and surge, an oscillatory solution under the combined forcing of river discharge and tide is first obtained and then the cyclone is switched on.

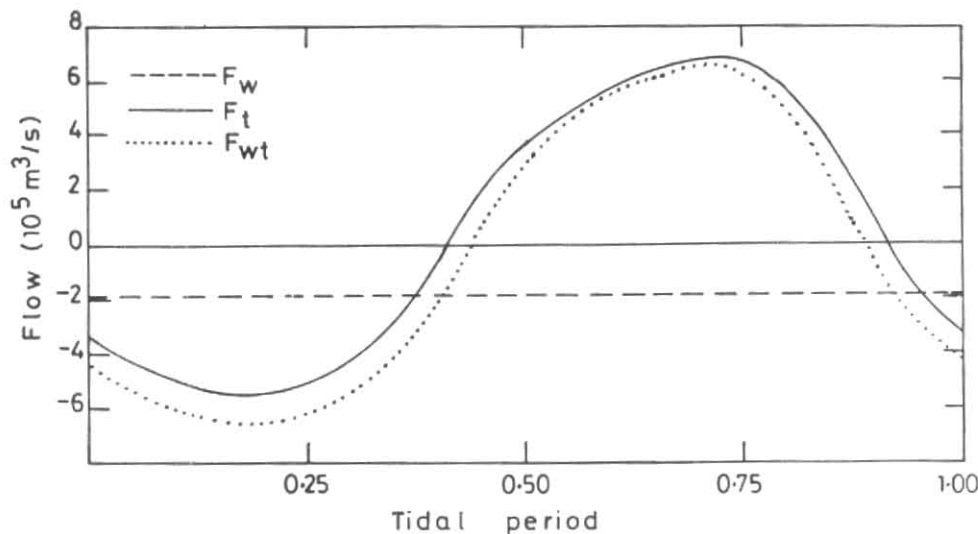


Fig. 2. Flow across the Meghna mouth due to (i) river discharge ($v_0 = 0.25$ m/s), (ii) tide ($\zeta_0 = 1.0$ m) and (iii) simultaneous introduction of (i) and (ii) (After Ali *et al.* 1997)

The results of different experiments are discussed below. Most of the discussions are related to flow across the Meghna mouth under different forcings. For convenience of discussions, we define a parameter F , the flow rate (m^3/s) across the Meghna mouth. Different subscripts to F are used to specify the forcing as follows :

F_w : Due to river discharge alone

F_t : Due to tide alone

F_s : Due to storm surge alone

F_{wt} : Due to river discharge and tide combined

F_{ws} : Due to river discharge and storm surge combined

F_{ts} : Due to tide and storm surge combined

F_{wts} : Due to river discharge, tide and storm surge combined.

F can be both positive and negative. According to the coordinate system used (y positive towards the north), a positive F means flow into the river from the Bay (inflow) and a negative F means outflow, *i.e.*, flow from the river into the Bay.

Ali *et al.* (1997) studied the interaction between tide and river discharge. For reference and convenience of discussions of the present results, the salient and relevant features of their findings are given in Fig. 2.

The graphs correspond to flow due to the three forcings, (i) river discharge alone ($v_0 = 0.25$ m/s), (ii) tide alone (range = 1.44 m at the Meghna mouth, which is produced through a forcing of $\zeta_0 = 1.0$ m at the open boundary) and (iii) river discharge and tide. The flow due to fresh water alone is represented by a straight line because it corresponds to a steady state and the negative sign indicates an outflow. Tidal flows, however, show both positive and negative values. During flood-tide period, taken here as that corresponding to positive F , water enters the river and flow due to tide is higher than that due to combined forcing. On the other hand, during ebb-tide period, corresponding to negative F , water leaves the river and absolute value of flow due to tide alone is less than that due to tide and river discharge. That is,

$$F_t > F_{wt} \quad \text{during flood tide} \quad (11)$$

$$|F_t| < |F_{wt}| \quad \text{during ebb tide} \quad (12)$$

The reasons, as explained by Ali *et al.* (1997) are: in the former case two opposing forces are present—tides want to enter the river and fresh water wants to oppose the entrance and hence the result is a lower value for the combination. In the later case, the two forces are in the same direction and hence a higher absolute value for combined flow.

Flood-tidal period with the combined forcing is shorter than that due to tide alone. On the other hand, ebb-tide period, due to combined forcing, is longer than that due to tide only.

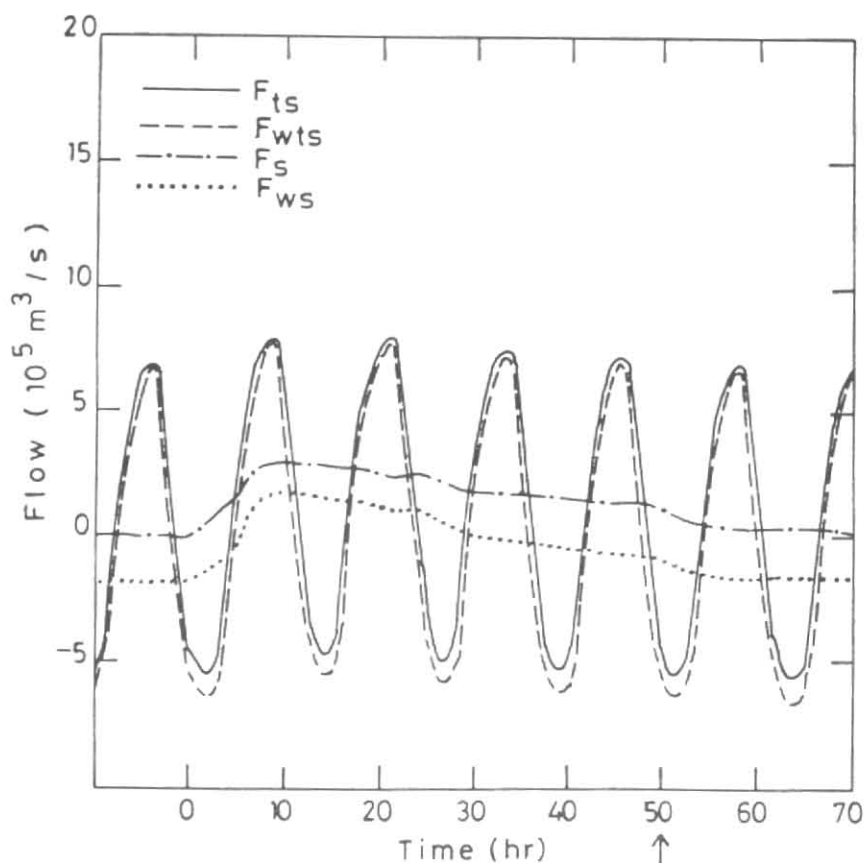


Fig. 3. Flow across the Meghna mouth due to (i) surge, (ii) river discharge and surge, (iii) tide and surge and (iv) river discharge, tide and surge ($v_0 = 0.25$ m/s, $\zeta_0 = 1.0$ m, $V_{\max} = 20$ m/s)

In Fig. 3 is given the time rate of change of flow across the mouth due to (i) surge alone (ii) river discharge and surge, (iii) tide and surge and (iv) river discharge, surge and tide. River discharge and tidal forcings are same as those used above for interaction between river discharge and tide (shown in Fig. 2), i.e., $v_0 = 0.25$ m/s and $\zeta_0 = 1.0$ m. V_{\max} is taken as 20 m/s and $r_0 = 50$ km. The track of the cyclone is shown in Fig. 1 and this roughly corresponds to the track of April 1991 cyclone. The cyclone moves with a translational speed of 5 m/s.

The time of introduction of the cyclone is shown in the figure as zero hour. The values before the introduction of the cyclone correspond, as the case may be, to steady state and/or oscillatory solution. Cyclone is withdrawn after about 50 hr since by this time the cyclone centre has crossed well inside the land. Integration is, however, continued for about

another 20 hr after the withdrawal of the cyclone to see how the flow behaves subsequently. In order to understand the flow behaviour after withdrawal, a run was also made without withdrawing the cyclone. Both the situations (with and without withdrawal) are depicted in Fig. 4. It is seen that if the cyclone is withdrawn, the flow values rapidly reduce to steady state condition initially started with before the introduction of cyclone. That means that the river discharge takes over the control on the flow dynamics near the mouth. On the other hand, if the cyclone is not withdrawn, the flow approaches almost asymptotically to the steady state condition.

Referring back to Fig. 3, it is seen that a rise in flow occurs when the cyclone is introduced. The flow due to surge and fresh water is always less than that due to surge alone, i.e.,

$$F_s > F_{ws} \quad (13)$$

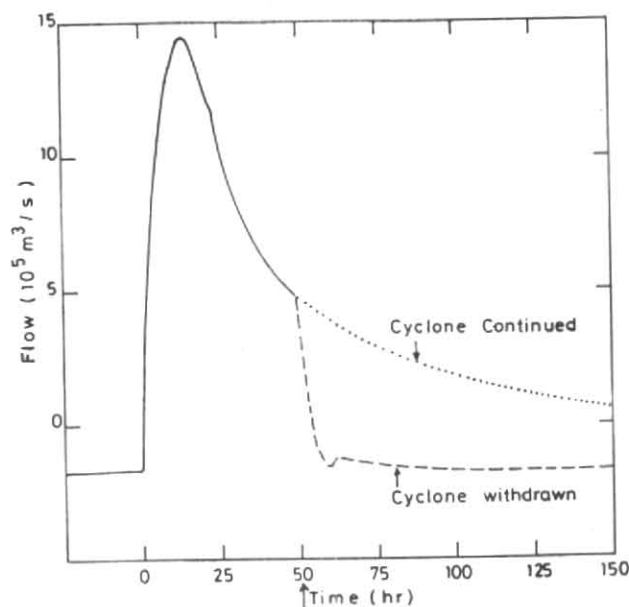


Fig. 4. Flow behaviour across the Meghna mouth with and without withdrawal of the cyclone after landfalling

In such a case, the impact of river discharge on surge is similar to that of river discharge on tide for a flood-tide (Eqn. 11) situation. The inflow period is shorter, lived if fresh water and surge are considered together in comparison to that due to surge alone. This is similar to the situation corresponding to river discharge and tide (flood-tide). Flow is tide-dominated if tidal component is also considered and F oscillates with the tidal cycle. Higher F occurs at high tide and lower F at low tide. Introduction of tidal component makes the results similar to those depicted by Eqns. (11) and (12), *i.e.*,

$$F_{ts} > F_{wts} \quad \text{during flood tide} \quad (14)$$

$$|F_{ts}| < |F_{wts}| \quad \text{during ebb tide} \quad (15)$$

Fig. 5 shows the situations under the same forcings as in Fig. 3 except that in this case MSW is taken as $V_{\max} = 62.5$ m/s, which represents the maximum sustained wind speed in April 1991 cyclone that took a death toll of about 138,000 people in Bangladesh.

The results here are not quite similar to those in Fig. 3. Some contrasting deviations are seen here particularly during the period approximately from 5 to 25 hr when flow is at its very high values, roughly

above about 10^6 m³/s. Calling this period as high F period (HFP), it is seen that before and after HFP, the flow obeys more or less the Eqns. (11) and (12) if tide is taken into account (compare the curves for F_{ts} and F_{wts} in Fig. 5) and the Eqn. (13) when tide is not considered (compare F_s and F_{ws} curves in Fig. 5). That is, the effect of river discharge is similar to those so far seen (in Figs. 2 and 3). However, during the HFP, the results are contrary to those given by the Eqns. (11), (12) and (13). Here

$$F_{ws} > F_s \quad (16)$$

$$F_{wts} > F_{ts} \quad (17)$$

That means river discharge has a positive contribution to the total value of F . This is something contradictory to the concept that two forces (river discharge versus surge and/or tide) act negatively. One possible explanation of this could be that the high surges due to high wind pushes back the water that is coming out or has already come out of the river, which is not possible in case of weaker wind. High wind may also force more water, than usual, to penetrate the river. It has, however, been found (not shown here) that if the value of v_0 is substantially increased (say $v_0 = 3.0$ m/s) keeping $V_{\max} = 62.5$ m/s fixed, this situation (positive interaction between fresh water and surges) does not occur.

It is interesting to note here the difference between F_s and F_{ts} and between F_{ws} and F_{wts} . The peak value of F_s (or F_{ws}) has degenerated due to tide into two peaks, one before and other after the respective peaks of F_s or F_{ws} . The results are similar to those of tide-surge interactions in terms of elevation as found by many authors (*e.g.*, Johns and Ali 1980).

In order to have some more insight into the positive impact of river discharge, a series of runs are made using different values of v_0 and V_{\max} (no tide is considered). We define a parameter 'peak difference (PD)' by,

$$PD = (F_{ws})_{\text{peak}} - (F_s)_{\text{peak}} \quad (18)$$

PD can be both positive and negative, as discussed earlier with reference to Figs. (3) and (5). Fig. 6 shows the plots of PD against V_{\max} for different values of

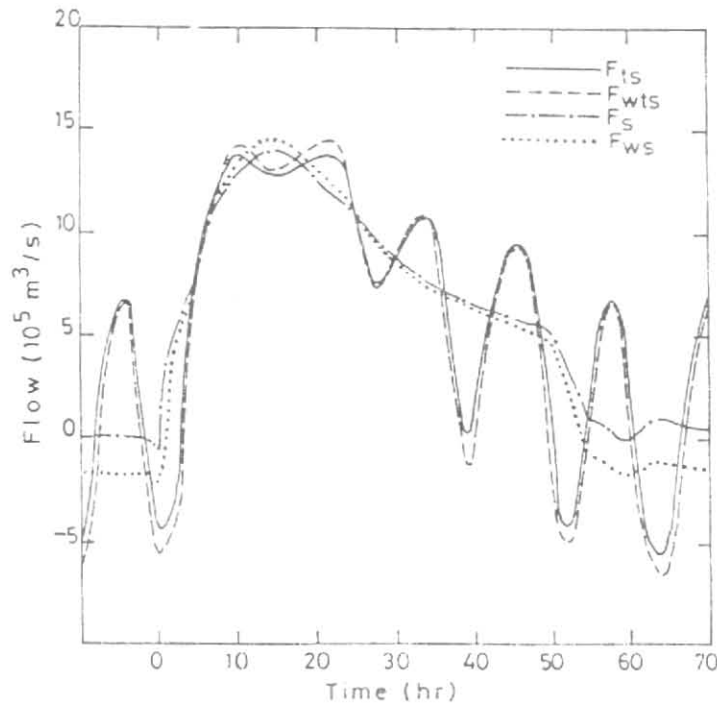


Fig. 5. Same as in Fig. 3 except that here $V_{max} = 62.5$ m/s

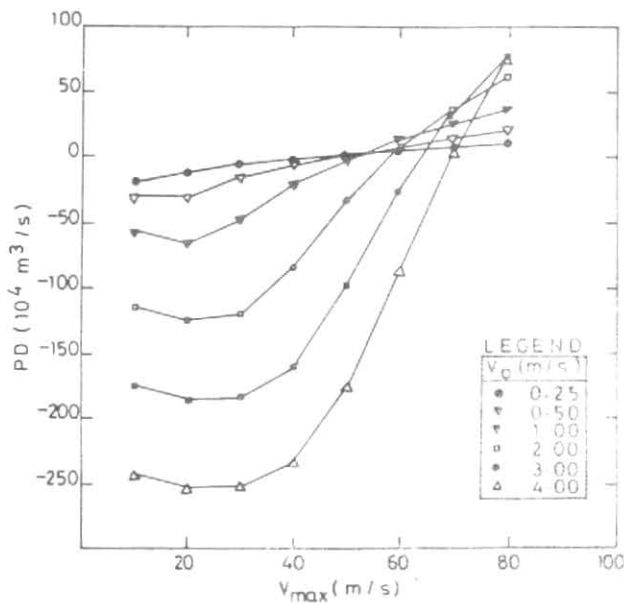


Fig. 6. Values of PD against V_{max} for different values of v_0

v_0). It will be seen that in most of the cases, PD is negative, meaning that peak flow due to cyclone is higher than that due to the combined forcing (as in Fig. 3) due to river discharge and surge. Only in a few cases, PD is positive. This may mean that the interaction (positive or negative) between fresh water

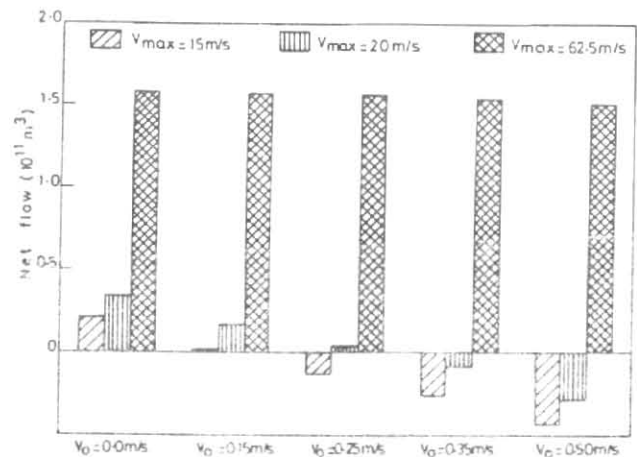


Fig. 7. Integrated values of flows during the cyclonic period (introduction to withdrawal) for different v_0 and V_{max}

and storm surges depends on the relative magnitude of each other. However, this needs further investigation.

Total flow across the river mouth during the wind forcing period has been calculated under different combinations of v_0 and V_{max} . The wind forcing period is counted from the time of introduction to the

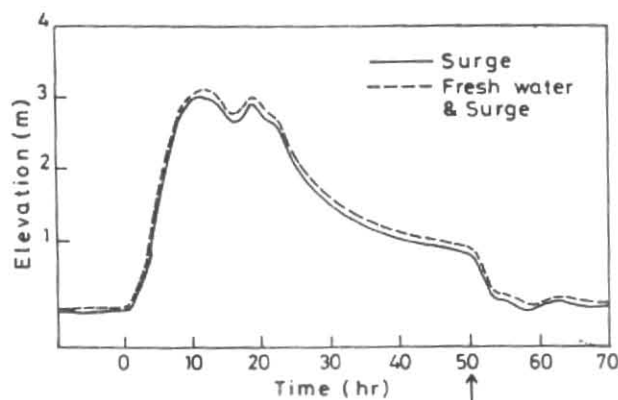


Fig. 8. Time rate of change of elevation at point A (Fig. 1).

withdrawal of the cyclone. The results are shown in Fig. 7. Three wind forcings are taken : 15 m/s, 20 m/s and 62.5 m/s. The first one represents depressions, the second cyclonic storms and the third cyclonic storms with a core of hurricane winds, the typical nomenclature used in the Bay of Bengal region. The values of v_0 used are 0.0 m/s, 0.15 m/s, 0.25 m/s, 0.35 m/s and 0.50 m/s.

It is found that for smaller winds, the total flow gradually goes from positive values to negative values with an increase in v_0 . But it remains almost unaffected with a very strong wind (e.g., 62.5 m/s), the flow remains all through positive meaning that fresh water discharge has little effect on flow across the mouth of the river under a very strong wind.

Figs. 8 and 9 give the time graph of elevation at grid points A and B respectively (shown in Fig. 1) for cyclone alone and for cyclone and fresh water ($v_0 = 0.25$ m/s and $V_{max} = 62.5$ m/s). Both the points are 45 km south of the Meghna mouth but points A and B are 464 km and 528 km respectively east of the western-most north-south boundary. A is directly under the influence of river discharge and B is little away (east) from the river influence. Fig. 8 shows that total elevation due to fresh water and surge is higher (though nominal) than that due to surge alone. But this difference is hardly distinguishable in Fig. 9 for the point B. Thus it is found that the influence of river discharge on total elevation is a localised phenomenon and does not noticeably affect other regions.

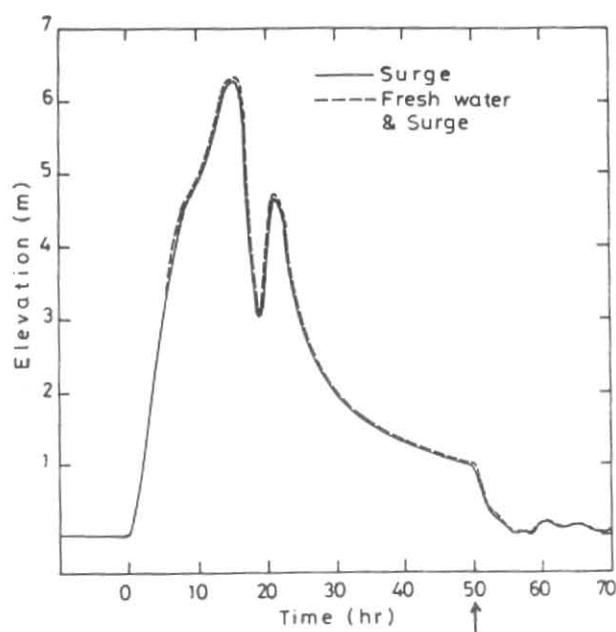


Fig. 9. Same as in Fig. 8 but for point B (Fig. 1).

4. Conclusion

A two-dimensional vertically integrated numerical model of the northern Bay of Bengal has been used to investigate the interactions among river discharge through the Meghna river in Bangladesh, astronomical tides and storm surges. The model has been able to produce some interesting results. However, these findings need to be substantiated with further studies using reliable and extensive coverage of data which are lacking. The results however may be treated as indicative instead of substantive.

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