

# Contribution of offshore islands in the prediction of water levels due to tide–surge interaction for the coastal region of Bangladesh

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Received: 6 May 2011 / Accepted: 1 August 2012 / Published online: 12 August 2012  
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**Abstract** In this study, a doubly nested tide–surge interaction model was established for the coastal region of Bangladesh. A fine grid model, capable of incorporating all major offshore islands, was nested into a coarse grid model extending up to 15°N latitude of the Bay of Bengal. To take into account the thickly populated small and big islands between Barisal and Chittagong and the extreme bending of the coastline accurately, a very fine grid model for this region was again nested into the fine grid model. Along the northeast corner of this very fine grid model, the Meghna River discharge was taken into account. The boundaries of the coast and islands were approximated through proper stair step, and the model equations were solved by semi-implicit finite difference technique using staggered grid. Appropriate tidal regime over the model domain was generated by forcing the sea level to be oscillatory with the constituent M2 along the southern open boundary of the coarse grid model omitting wind stress. This previously generated tidal regime was introduced as the initial state of the sea for nonlinear tide–surge interaction phenomenon. The model was applied to estimate water levels along the coastal region of Bangladesh due to the interaction of tide and surge associated with the storm April 1991, and the results were found to be in a reasonable agreement with those observed. The model was used to investigate the influence of offshore islands on water levels and water levels were found to be significantly influenced by offshore islands.

**Keywords** Nested grid · Islands · Storm surge · Tide · Discharge

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## 1 Introduction

The coastal region of Bangladesh is full of many small and big islands and the coast is very irregular in shape. The existence of the islands and irregularity of coastal shapes along with shallowness of water and huge discharge through the Meghna River are responsible for high surge even for a less intense storm along this region (Debsarma 2009). Moreover, the head of the Bay of Bengal is a large tidal range area. Thus, if a storm approaches the coast during high tide, water level due to tide–surge interaction becomes significantly high. Analysis and prediction on storm surge, tide as well as their interaction have been investigated by many authors for the Bay of Bengal region (see, e.g., Murty et al. 1986; Flather 1987; Johns and Ali 1980; Johns et al. 1985; Ali et al. 1997; Roy 1995, 1999a, b; Roy et al. 1999; Debsarma 2009). But investigations including offshore islands are limited. The first nonlinear tide–surge interaction model of Johns and Ali (1980) for the Bay of Bengal was conducted including the major rivers Ganga, Brahmaputra, and Meghna and offshore islands. The combined flow of the rivers discharges into the northeast corner of the Bay of Bengal under the name of Meghna and the discharges may modify the surge situation (Dube et al. 1986). However, the model of Johns and Ali (1980) was stair step. In a stair step model, the coastal and island boundaries are approximated along the nearest finite difference grid lines. Therefore, to represent the boundaries very accurately, the grid size should be very small. Since very fine resolution was not considered in the investigation of Johns and Ali (1980), the representation of coastal and island boundaries in their model could not be incorporated very accurately. To incorporate the facts accurately, Roy (1995) developed a model inserting a fine mesh model into a coarser parent model extending up to 15°N latitude in the Bay of Bengal. This study incorporated only major offshore islands of Meghna estuarine region accurately through proper stair step representation in the fine mesh model. Using boundary fitted grid technique, Roy (1999a) examined the effect of offshore islands on surge intensity along the coastal belt of Bangladesh without considering river discharge and showed that surge intensity could be reduced by offshore islands. But he pointed out that “before making any final comment, more investigation is required”. The study was also conducted incorporating only two major islands Sandwip and Hatiya and very high resolution was not considered. Roy and Kabir (2004), in their study, incorporated only major offshore islands along the whole coastal region of Bangladesh to estimate overall water levels due to the superposition of tide and surge. But this study was also conducted without considering very fine resolution, where the interaction of tide and surge was linear.

In the present study, the model of Roy (1995) is improved by nesting a very fine grid model into the fine grid model as well as extending the fine grid model for the whole coastal belt instead of Meghna estuarine region, where the very fine grid model is designed to incorporate river discharge, all offshore islands irrespective of small and big between Barisal and Chittagong as well as coastal bending very accurately.

## 2 Basic equations

All conditions are referred to a set of rectangular Cartesian coordinates, where the curvature of the Earth is assumed to be zero. The origin,  $O$ , of the system is set at the undisturbed level of the sea surface,  $OX$  and  $OY$  are directed toward the south and the east, respectively, and  $OZ$  is directed vertically upward. The displaced level of the free surface of the sea is given by  $z = \zeta(x, y, t)$  and the position of the sea bed by  $z = -h(x, y)$  so that the total depth of the water column  $D = h + \zeta$ . Then, the vertically integrated shallow water equations in flux form can be given by (see, e.g., Debsarma 2009)

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{v}}{\partial y} = 0, \tag{1}$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial(u\tilde{u})}{\partial x} + \frac{\partial(v\tilde{u})}{\partial y} - f\tilde{v} = -gD \frac{\partial \zeta}{\partial x} + \frac{T_x}{\rho} - \frac{c_f \tilde{u}(u^2 + v^2)^{\frac{1}{2}}}{D}, \tag{2}$$

$$\frac{\partial \tilde{v}}{\partial t} + \frac{\partial(u\tilde{v})}{\partial x} + \frac{\partial(v\tilde{v})}{\partial y} + f\tilde{u} = -gD \frac{\partial \zeta}{\partial y} + \frac{T_y}{\rho} - \frac{c_f \tilde{v}(u^2 + v^2)^{\frac{1}{2}}}{D}, \tag{3}$$

where  $(\tilde{u}, \tilde{v}) = D(u, v)$ .

In the above equations,  $u$  and  $v$  represent Reynolds averaged components of velocity in the directions of  $x$  and  $y$ , respectively;  $f = 2\Omega \sin \varphi$  the Coriolis parameter, where  $\Omega$  is the angular speed of the earth rotation and  $\varphi$  is the latitude of the place of interest;  $g$  the acceleration due to gravity;  $\rho$  the density of the sea water, assumed to be homogeneous;  $C_f$  the friction coefficient;  $(T_x, T_y)$  represents the components of wind stress.

In this study, the wind stress components are derived using the conventional quadratic law (Johns and Ali 1980)

$$(T_x, T_y) = \rho_a C_D (u_a^2 + v_a^2)^{1/2} (u_a, v_a), \tag{4}$$

where  $C_D$  is the drag coefficient,  $\rho_a$  is the air density, and  $u_a$  and  $v_a$  are the  $x$  and  $y$  components of surface wind. The surface wind field over the model domain is derived from the empirical formula due to Jelesnianski (1965), which is given by

$$V_a = \begin{cases} V_0 \sqrt{(r_a/R)^3} & \text{for all } r_a \leq R \\ V_0 \sqrt{(R/r_a)} & \text{for all } r_a > R \end{cases} \tag{5}$$

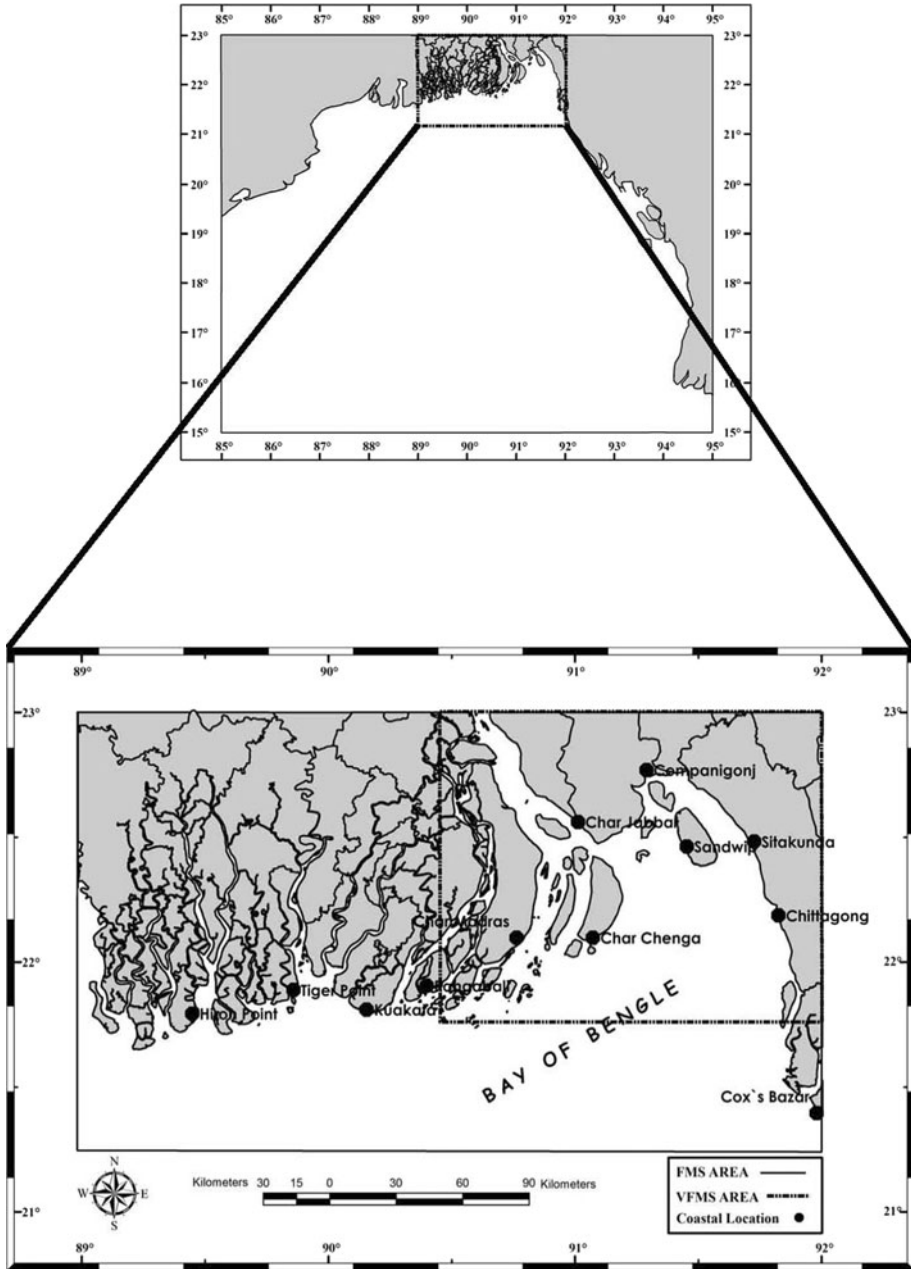
where  $V_0$  is the maximum sustained wind at the radial distance  $R$  from the eye of the cyclone and  $r_a$  is any radial distance from the eye at which the wind field is desired.

### 3 Numerical estimate

#### 3.1 Set up of nested models

In order to incorporate all offshore islands along the coastal region of Bangladesh very accurately in a numerical model, a very fine resolution is needed but it may involve numerical instability with more computing time. On the other hand, the analysis area should considerably be big so that a storm can move over it for 2–3 days before crossing the coast. Considering the facts, the study uses nested models. The features of these models are that they allow specification of high resolution in a desired region of interest only with lower resolution elsewhere. In our study, a high-resolution fine grid model (FGM), capable of incorporating all major islands, is nested into a coarse grid model (CGM). To take into account the thickly populated low lying small and big islands between Barisal and Chittagong and extreme bending of the coast line very accurately, a very fine grid model (VFGM) is again nested into the FGM. Figure 1 depicts the boundaries of the coarse grid, fine grid, and very fine grid model domains employed in the study. The grid sizes, number of computational points of the models used in the study are presented in Table 1.

The CGM is independent and the parameters  $\zeta$ ,  $u$ , and  $v$  calculated in the CGM are passed along the open boundaries of the FGM in each time step of the solution process. Similarly for the VFGM, the parameters  $\zeta$ ,  $u$ , and  $v$  are prescribed from those obtained in FGM in each time step of the solution process. Along the north east corner of the VFGM,



**Fig. 1** Domains of different models along with positions of some coastal locations at which water levels are presented

**Table 1** Domains, grid spacing, and number of computational points of different models

Model	Domain	Grid spacing along $x$ axis	Grid spacing along $y$ axis	Number of computational points
CGM	15°N to 23°N and 85°E to 95°E	15.08 km	17.52 km	60 × 61
FGM	21°15' N to 23°N and 89°E to 92°E	2.15 km	3.29 km	92 × 95
VFGM	21.77°N to 23°N and 90.40°E to 92°E	720.73 m	1,142.39 m	190 × 145

Meghna River is considered between 90.4°E and 90.6°E. Following Roy (1995), the discharge of the river is incorporated through

$$u_b = u + \frac{Q}{B(h + \zeta)}, \tag{6}$$

where  $Q$  and  $B$  are river discharge and breadth of the river, respectively.

### 3.2 Boundary conditions

The normal component of the depth averaged velocity at the closed boundary is set to zero, and for open boundaries, radiation type of boundary conditions is used to allow the disturbance, generated within the model area, to go out through the open boundary. Following Johns et al. (1985), the western (85°E), eastern (95°E), and southern (15°N) boundary conditions of the CGM are, respectively, given by

$$v + (g/h)^{1/2} \zeta = 0, \tag{7}$$

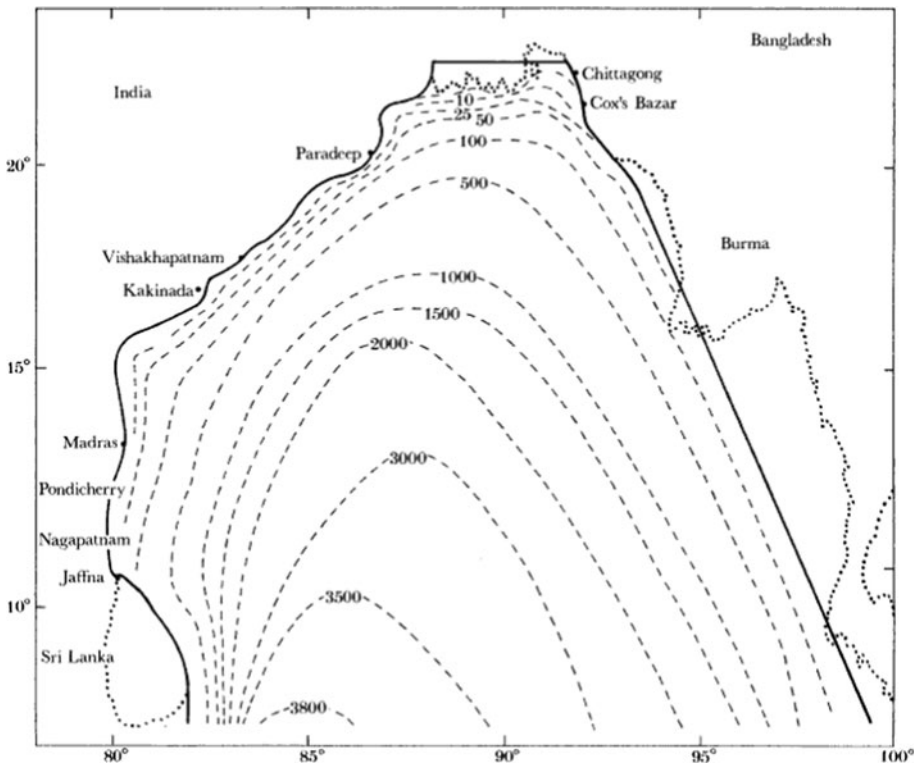
$$v - (g/h)^{1/2} \zeta = 0, \tag{8}$$

$$u - (g/h)^{1/2} \zeta = -2(g/h)^{1/2} a \sin\left(\frac{2\pi t}{T} + \phi\right), \tag{9}$$

where  $a$ ,  $\phi$ , and  $T$  are the amplitude, phase, and period, respectively, of the tidal constituent.

### 3.3 Numerical procedure

The governing Eqs. (1)–(3) as well as the boundary conditions given by Eqs. (7)–(9) are discretized by a forward-time, central-space finite difference scheme, and the equations are solved by a conditionally stable semi-implicit method using a staggered grid in which there are three distinct types of computational points. With  $i$  even and  $j$  odd, the point is a  $\zeta$ -point at which  $\zeta$  is computed. If  $i$  is odd and  $j$  is odd, the point is a  $u$ -point at which  $u$  is computed, and if  $i$  is even and  $j$  is even, the point is a  $u$ -point at which  $v$  is computed. The approximations of coastal and island boundaries are made according to Johns et al. (1985). Along the northern open boundary of VFGM,  $u_b$  is computed at points (1,  $j$ ) using Eq. (6) in which  $u$  on the RHS is replaced by  $u_{3,j}$ . The required meteorological inputs in our study are supplied from Bangladesh Meteorological Department (BMD). The water depth data are compiled from the figure quoted in Johns et al. (1985) (Fig. 2). In our numerical calculations, we have used  $C_f = 0.0026$ ,  $C_D = 0.0028$  (see, Roy et al. 1999),  $Q = 5,100.00 \text{ m}^3/\text{s}$  (Jain et al. 2007), and rest of the parameters involved in the problem have been assumed to



**Fig. 2** Bathymetric figure (After Johns et al. 1985) from which water depth data are compiled

have their standard values. The initial values of  $\zeta$ ,  $u$ , and  $v$  are taken as zero to represent a cold start. A stable tidal regime is then generated from this start by forcing the sea level to be oscillatory with the constituent  $M_2$  along the southern open boundary of the CGM omitting wind stress. The generation of stable tidal regime over the model domain is similar to that of Roy (1995). The initial values of  $a$  and  $\phi$  of the tidal constituent  $M_2$  are prescribed through Eq. (9) along the southern open boundary of the CGM following McCammon and Wunsch (1977). The period of the tidal oscillation  $T$  is taken as 12.4 h. It should be noted here that  $M_2$  and  $S_2$  constituents are predominant in the region of interest, and the period of the tidal oscillation is not completely periodic, but the mean period is always found to be approximately 12.4 h, which is of  $M_2$  constituent. Then with the values of the constants related to the tidal constituent  $M_2$  from initial state of rest in the absence of wind field, a stable tidal regime is achieved after 4 cycles of integration (see Roy 1995). But the problem to generate a pure oscillatory response in the region of interest corresponding to the tidal constituent with period  $T$  lies with the exact values of  $a$  and  $\phi$ . Thus, some techniques are needed for the precise specification of the values of the constants and in this regard we use the technique of Roy (1995) to adjust the values of  $a$  and  $\phi$ .

Since the astronomical tide is a continuous process in the sea, the surges due to tropical storms always interact with the astronomical tide. To take into account, the nonlinear interaction between the tide and surge, the generated pure tidal oscillations provide the initial condition at the model time  $t = 0$ . A time step of 60 s is used in order to meet Courant-Friedrichs-Levy (CFL) stability criterion.

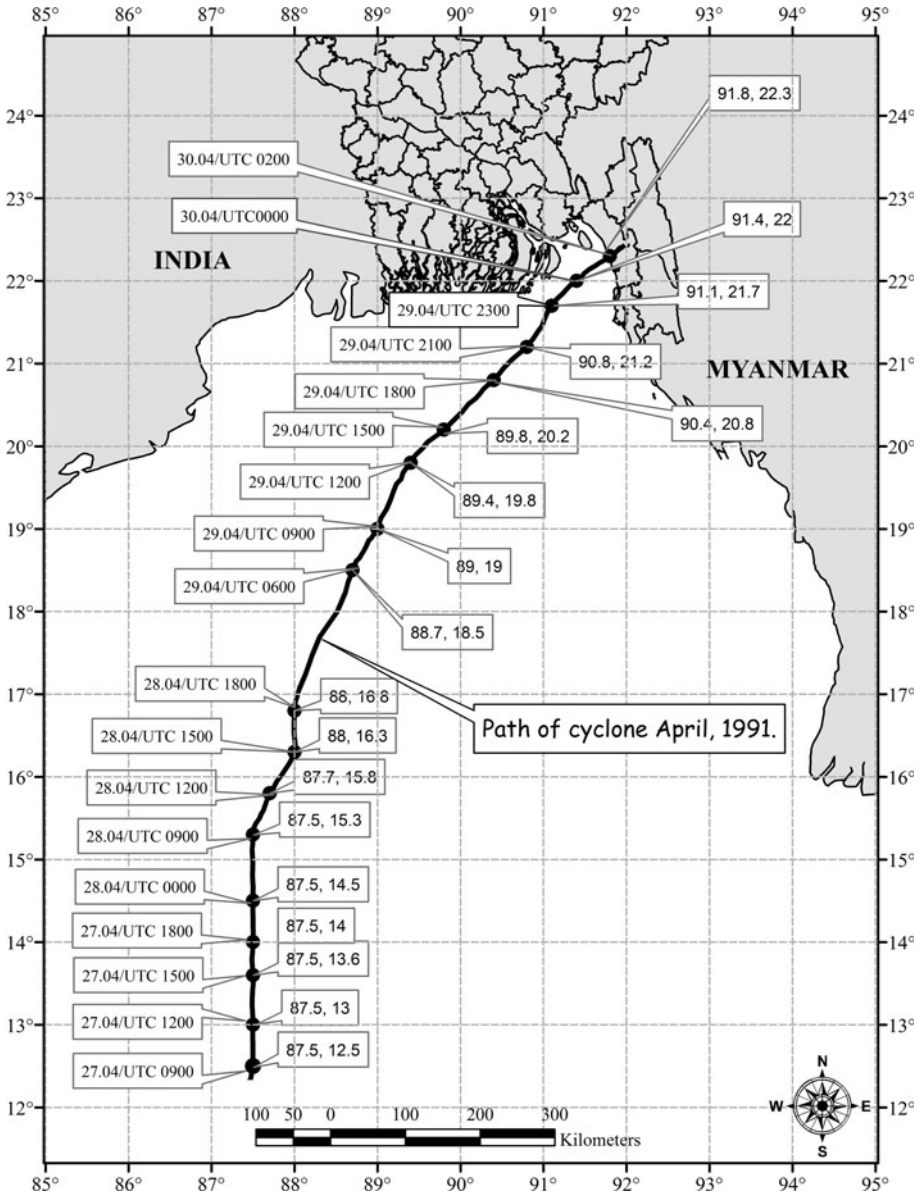
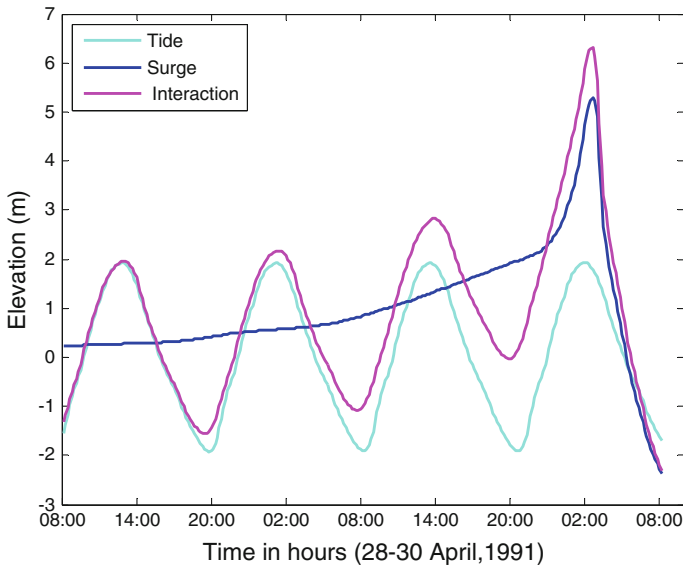


Fig. 3 Track of the April 1991 cyclone

#### 4 Discussion of results and model verification

Cyclone April 1991 is taken to analyze and compare model results with observation. According to Bangladesh Meteorological Department, the cyclone was first detected as a low-pressure area over the southeast Bay and adjoining Andaman Sea in the morning of April 23. It developed into a depression near 10.0°N and 89.0°E at 0003 UTC of April 25 and intensified into a deep depression at 1200 UTC and very quickly turned into a cyclonic

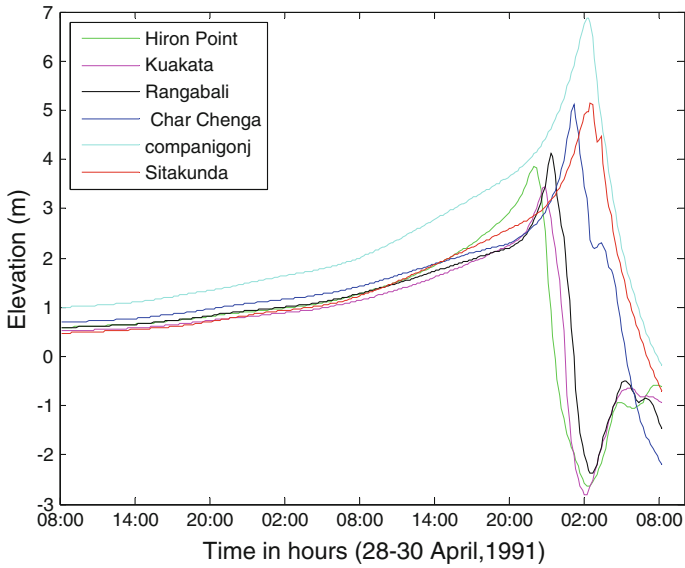


**Fig. 4** Computed water levels with respect to the mean sea level due to tide, surge, and their interaction at Chittagong

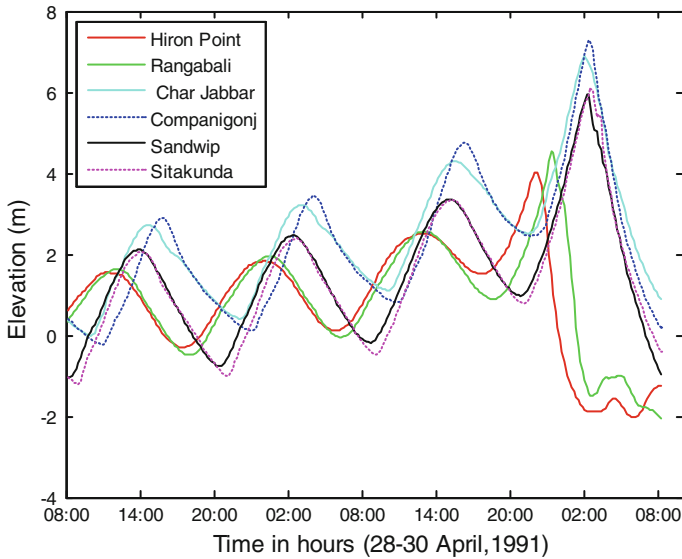
storm near  $11.8^{\circ}\text{N}$  and  $88.5^{\circ}\text{E}$  at 1800 UTC of April 25 with maximum sustained wind speed 65–87 km/h. Figure 3 shows the track of the cyclone April, 1991, where the data were obtained from Bangladesh Meteorological Department. The results are computed along the coastal region of Bangladesh for 72 h and are presented for the last 48 h at some locations as shown in Fig. 1. Thorough comparison of our computed time series elevation data to the observed one in each case is restricted because of lack of authentic observed data.

Figure 4 shows our computed water levels due to tide, surge, and their interaction at Chittagong. The maximum water levels as calculated by the model due to tide, surge, and their superposition at Chittagong were found to be 1.93, 5.29, and 6.31 m (see Fig. 4), respectively. Our computed water levels for Chittagong agreed fairly well with the results obtained by Flather (1994), As-Salek (1997), and Roy et al. (1999). Figure 5 shows our computed water levels due to surge. It can be seen from the figure that the maximum surge level varies between 3.44–6.88 m. According to Bangladesh Meteorological Department, the maximum surge level at Chittagong was 5.5 m, and there was 3.5–6.1 m surge along the coastal region of Bangladesh. Khalil (1993) reported 4–9 m high storm surge in different coastal areas of Bangladesh, whereas the model of Dube et al. (2004) predicted a maximum surge of about 7 m along these areas. Thus, our computed water levels due to surge at Chittagong and at other coastal locations compare well with observed results and with the results obtained by different investigations. The maximum overall water levels, as simulated by the model, came out to be 3.82–7.29 m (Fig. 6). Our simulated overall water levels at Hiron Point, Char Chenga (Hatiya), and Chittagong (Fig. 7) can be found to be in good agreement with observed data. Due to unavailability of observed data at other locations, we could not compare our simulated overall sea surface elevation with observed data but can be found to be in good agreement with the results obtained with simulations of Flather (1994) and As-Salek (1997). It can be observed from our simulated results that tide dominates water level when the storm is far from the coast but water level can be found to



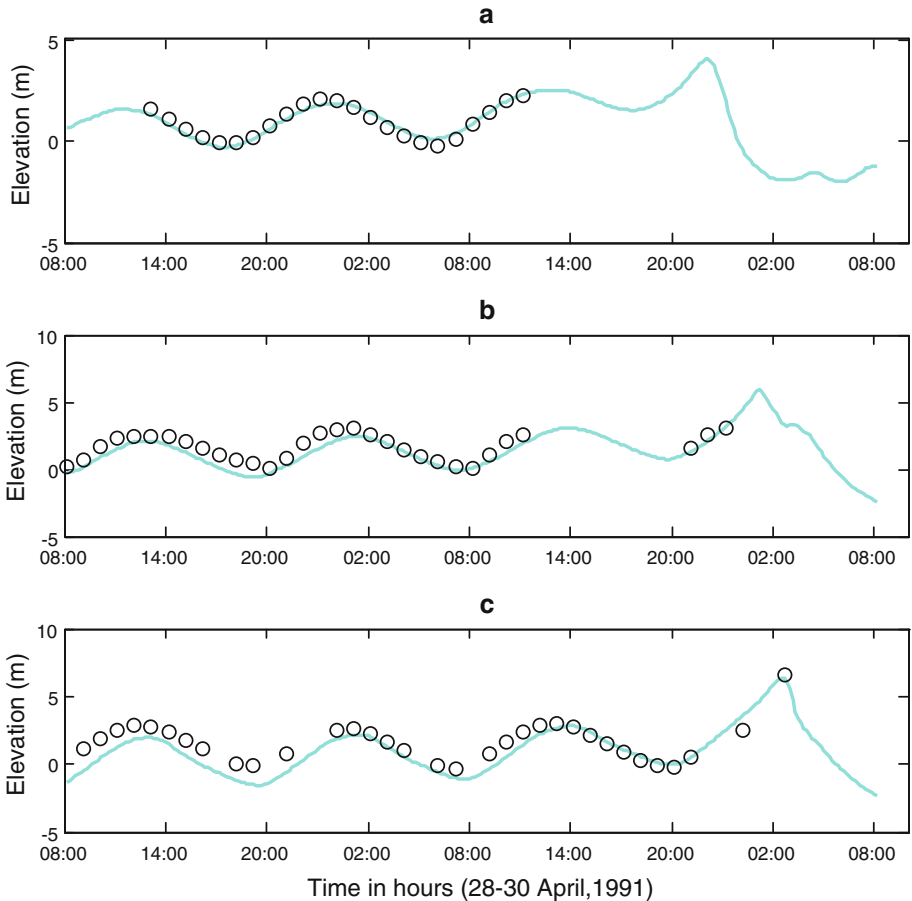


**Fig. 5** Computed water levels with respect to the mean sea level due to surge at some positions along the coastal region of Bangladesh associated with April 1991 storm



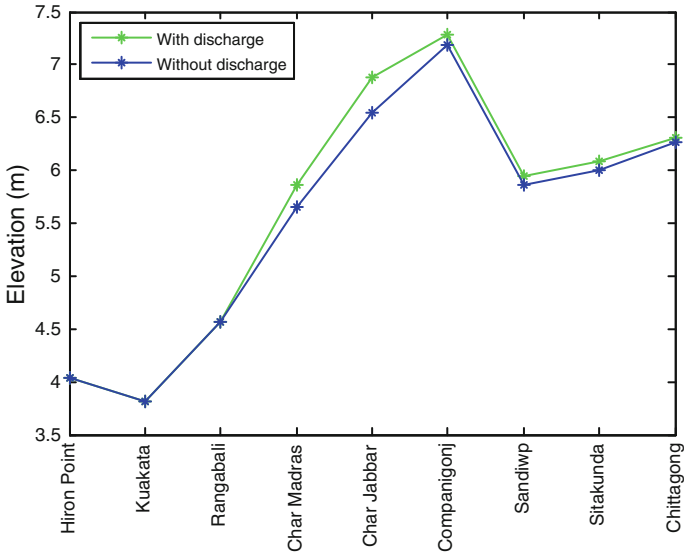
**Fig. 6** Computed water levels with respect to the mean sea level due to the interaction of tide and surge at some locations along the coastal region of Bangladesh associated with April 1991 storm

be dominated by the surge when the storm is near the coast (Fig. 4). This nature can also be found to be true for the water levels at all positions. Since to show all such graphs would be space consuming and not physically instructive, they have not been included. Figure 5 shows that surge level at each location increases with time as the storm approaches the

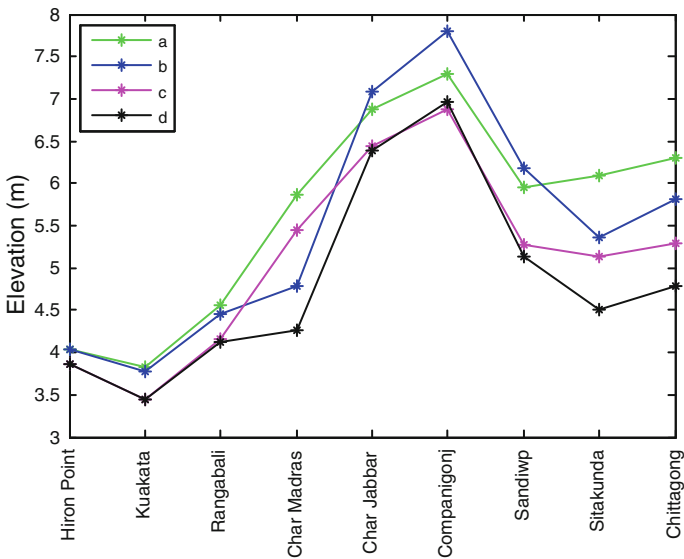


**Fig. 7** Comparison of computed water levels with observed data (Source Bangladesh Inland Water Transport Authority). In each case, a *solid curve* represents our computed time series data, and a *circle* represents an observed data (whenever available): **a** at Hiron Point, **b** at Char Chenga (Hatiya), and **c** at Chittagong

coast and finally there is a recession. The beginning of recession at places of coastal region delays with the increase in their east longitudes (Figs. 5, 6). Water levels (maximum) at the locations around Chittagong (Figs. 5, 6) were found to be higher than the water levels along western coastal locations. This is expected as the track of 1991 storm was almost over Chittagong and the peak surge coincided closely with high tide (Fig. 4). Maximum water levels due to both surge and superposition of tide and surge were found at Comanigonj (Figs. 5, 6), which is situated at Noakhali coast and north of Sandwip (Fig. 1). This may be due to the fact that the storm crossed the coast just north of Chittagong keeping Sandwip to its left (Fig. 3). Flather (1994), in his simulation, also found highest overall water level (7.21 m) on the Noakhali coast. Thus, our simulated overall water level at Noakhali coast (7.29 m) fairly agrees with the simulated results by Flather (1994). Figure 8 depicts the peak water levels (overall) with and without inclusion of discharge of Meghna River. It is clear from the figure that the model simulates higher water levels along the Meghna estuarine area when discharge is taken into account. Figure 9 shows the effect



**Fig. 8** Peak water levels along some coastal locations of Bangladesh associated with the April 1991 storm



**Fig. 9** Water levels along some coastal locations of Bangladesh associated with the April 1991 storm, where *a* and *b* represent overall peak water levels (i.e., tide–surge interaction including river discharge) with and without inclusion of offshore islands, whereas *c* and *d* represent peak water levels due to surge only with and without inclusion of offshore islands

of offshore islands on water levels. It can be shown from the figure that the peak overall water levels at all locations except at Char Jabbar, Companigonj, and Sandiwp decrease in the absence of offshore islands. Again, in the absence of offshore islands, water levels due to surge at each location except at Companigonj can be shown to be reduced. Therefore,

high tidal range and river discharge can account for high water levels (overall) at Char Jabbar and Sandwip in the absence of offshore islands. On the other hand, complex coastal geometry and route of the cyclone as mentioned before may account for the exception in water level at Companigonj. Thus, only with a single exception, surge levels can be found to be increased in the presence of offshore islands. It is noted that our calculations were also carried out with the bathymetric data used in the study of Roy (1999a). The results in this case also generally agreed the figures used in our study. It is to be noted here that the study of Roy (1999a) estimated lower surge levels in the presence of offshore islands. This may be due to the fact that the study was carried out including only two major offshore islands Sandwip and Hatiya without consideration of fine resolution, where the coastal region of Bangladesh is thickly populated with so many small and big islands.

## 5 Conclusion

In this study, doubly nested numerical model was used, and the models incorporated islands and coastal bending properly to simulate water levels along the coastal region of Bangladesh due to the interaction of tide and surge associated with the tropical storm April 1991. The model simulation results were found to be reasonable. The water levels were found to be influenced by both offshore islands and river discharge. Thus, in order to predict water level very accurately along the region, along with river discharge, all offshore islands should be properly taken into account.

**Acknowledgments** This research is supported by the research grant by the Government of Malaysia and the authors acknowledge the support. The authors are grateful to Md. Mizanur Rahman, Department of Mathematics, Shahjalal University of Science & Technology, Sylhet-3114, Bangladesh, for providing necessary data and helpful suggestions. We would like to thank both anonymous referees for comments and suggestions that helped improve the manuscript.

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