# Impact assessment of tropical cyclone MORA along the coast of Bangladesh and recovery measures

Foyjonnesa, Irfan Raju, Farhana Zannat Eti, Md. Mahabub Alam, Gour Chandra Paul

**Abstract**— In this study, the cyclonic storm (CS) MORA, a category 1 tropical cyclone that hit the coast of Bangladesh in the morning of 30 May 2017 is simulated numerically as well the impacts of this storm are assessed and recovery measures are presented. It was seen that due to adopt some necessary measures taken by the Government of the People's Republic of Bangladesh depending upon the warning system produced by the storm warning centre of Bangladesh Metrological Department (BMD), the number of death was found to be decreased. But in spite of all the necessary measures, the economic loss and suffering were found to be great. A proper warning system can mitigate the sufferings. With a view to have an improved warning system, we have simulated the CS MORA numerically with a semi-implicit finite difference method. The results are found to agree well with some reported data. With the basis of the results and assessment of the impacts of the CS MORA, the study also discusses some necessary mitigative measures against storm surges, which may help to deal with upcoming cyclones and associated surges in reducing death tools and economic losses.

**Index Terms**— MORA, Storm surge, Bay of Bengal, Numerical simulation, Recovery measures.

## 1 Introduction

Bangladesh is one of the most disaster-affected countries in the world. The country is situated at the northern tip of the Bay of Bengal (BOB). It is noted here that the BOB and the North Indian Ocean are the sources of disasters like tropical cyclones [1]. The geographical location of the country makes it most vulnerable to these cyclones. The complex coastal geometry, numerous low lying small and big islands of different shapes, shallow bathymetry, long continental shelf, etc. increase the vulnerability [2]. Therefore, the cyclones occurred in the region of interest cause a considerable loss of lives and huge damages to the coastal infrastructure, wealth, livelihood, agriculture etc. Many tropical cyclones caused heavy devastation for the country of which the cyclones of November 1970, May 1985, November 1988, April 1991, Sidr 2007, Aila 2009 and MORA 2017 are worth mentioning [3]. To have a clear understanding of devastation made by the cyclones, a table (Table 1) is presented. The CS MORA is the most recent among the tropical cyclones, which struck the coast of Bangladesh. The awareness activities of the cyclone were quite developed, therefore, the number of death was reduced but the economic losses were huge. According to the Ministry of Disaster Management and Relief (MDMR), about 9 people were killed and the economic losses were reported as 1.7 billion US dollars. As in [4], about 81 fishermen were missing, the houses, roads, crops etc. were destroyed due to the storm and associated floods. According to the Bangladesh Red Crescent Society (BRCS), the two districts, namely Cox's Bazar and Chittagong were severely affected by MORA. About 132 Upazila, 52.532 families, 60,612 houses were directly affected and 468,000 people were evacuated during the course of the cyclone [5]. A heavy rainfall was occurred due to MORA in Bangladesh for two days. According to a report from the Indian Meteorological Department (IMD), the observed rainfall in Chittagong was 17.7 cm, whereas that in Sandwip and Kutubdia were recorded as 17.3 cm and 11.5 cm, respectively that made the situation a worse one. We cannot stop these natural disasters but we can better be prepared to reduce the damages resulting from them. To minimize the damages originated from a cyclone and its associated surge, an effective surge prediction model is highly desirable through which a proper warning system can be made [2]. A number of numerical studies have been developed for the prediction of storm surges occurring in the BOB region. The recent mentionable numerical studies are due to Rahman [3], Paul and Ismail [2, 6, 7], Paul et al. [8, 9, 10]. Among them, the investigations due to Rahman [3], and Paul and Ismail [6] were conducted to estimate water levels associated with a storm in non-appearance of the astronomical tide. But tide is a continuous process in the sea and it will interact with surge non-linearly. However, Paul and Ismail [7] improved the study due to Paul and Ismail [6] taking into account the nonlinear interaction of tide and surge. The aim of the study was to investigate the effect of entrained air bubbles during storm surges. They found water levels to be increased up to 10% due to air bubbles. But inverse barometer can be found to be more effective over air bubbles [8]. In actuality, bearing the facts in mind, Paul et al. [8] investigated storm surge problem with entrained air bubbles as well as inverse barometer. The study also incorporated wetting and drying effect, where the Meghna River fresh water discharge

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and coastal geometry were found to be incorporated with a considerable accuracy. Paul et al. [9, 10] in their studies investigated how the efficiency of a numerical model can be increased. But the both group of studies did not consider all surge influencing factors. In our numerical work, we have chosen recent tropical cyclone MORA to estimate water levels due to the tide, surge and the nonlinear interaction of tide and surge along the coast of Bangladesh with the codes used in [8]. It is of interest to mention here that the mentioned code was used as it incorporates almost all the surge affecting factors. The purpose of the proposed study is to give emphasis on numerical model based prediction and corresponding warning system so that the necessary steps can be taken into account to reduce the resulting losses emanated from cyclones and associated surges.

The rest of the paper is organized as follows. Section 2 presents the impacts of some notable cyclonic storms along the coast of Bangladesh. Synoptic history of our chosen storm and its aftermath impacts are presented in Sections 3 and 4, respectively. Section 5 deals with the socio-economic impact of the TC MORA. Relief and recovery process with reference to the storm MORA is discussed in Section 6. Cyclone preparedness activities during the course of the cyclone MORA is frame worked in Section 7. Numerical simulation of the storm MORA and discussion of results are kept in Sections 8 and 9, respectively. Storm surge mitigative measures and remarks are outlined in Section 10 and finally conclusion is placed in Section 11.

## 2 Impacts of some notable cyclonic storms in Bangladesh

The coastal belt of Bangladesh is a very cyclone prone region. Every year, on an average, 5-6 storms strike in this belt, which is developed over the BOB causing 80% of the global causalities [11]. Table 1 presents the losses caused by some notable previous cyclones and associated maximum water levels, wind speeds with date and affected areas to have a justification of the above description.

## 3 Synoptic history of the cyclonic storm MORA

Based on a report from the IMD, a low pressure area formed over southeast BOB and adjoining areas of central BOB at 0300 Universal Time Coordinated (UTC) of 25 May 2017. It kept it up its journey over the same region on May 26 and observed as a well-marked low pressure area at 0300 UTC of 27 May over east central and adjoining west central and southeast BOB. It moved northeastwards and strengthened into a depression over east central BOB at 0000 UTC of 28 May. Continuing its northeastwards journey, it further intensified into a deep depression (DD) at 0900 UTC and into a cyclonic storm (CS) MORA over east central BOB at 1800 UTC of 28 May. After that, it moved north-northeastwards and further intensified into a severe cyclonic storm (SCS) at 1200 UTC of 29 May. At 1500 UTC of the same day, the system moved northwards into central Bay and intensified further into a cyclonic storm MORA at 0000 UTC with maximum sustained wind speed 45 knots having a central pressure of 990 hPa. It continued to move nearly north-northeastwards and crossed Bangladesh coast close to the south Chittagong near Kutubdia coast at latitude $22^{\circ}$ N and longitude $91.90^{\circ}$ E during 0400-0500 UTC. After landfall, the system weakened into a CS at 0900 UTC of 30 May into a DD at 1200 UTC and depression at 1800 UTC. It further weakened into a well-marked low pressure area over Nagaland and neighbourhood at 0000 UTC of 31 May into a low pressure area at 0300 UTC and became less marked low at 0900 UTC on the same day. The time varying positions and characteristics of the cyclonic storm MORA is presented in Table 2 for better understanding. It is of interest to note here that the track of the storm is produced with the information from the BMD and IMD by a MATLAB routine and is depicted in Fig. 1, whereas Fig. 2 shows the severe cyclonic storm MORA at peak intensity for better perspective.

## 4 Impact of the tropical cyclone MORA

The life history of the tropical cyclone (TC) MORA, as discussed earlier in section 3, shows that it was a severe cyclonic storm and had a north-northeastwards moving track. Based on a report from the IMD, about 63% of the TC MORA moved north-northeastwards (from the area of Genesis) and crossed Bangladesh coast, 25% of it moved northeastwards and crossed Myanmar coast and 12% moved westwards towards Andhra Pradesh coast. TC MORA caused widespread devastation and severe flooding in Bangladesh, Sri Lanka, Andaman and Nicobar Islands, Myanmar and Northeast India. Damage due to the cyclone MORA over the said areas is discussed below through the following subsections.

### 4.1 Impacts of the TC MORA in Bangladesh

TC MORA made landfall at Kutubdia, an offshore island in Cox's Bazar district, with maximum wind speed 60 knots in the morning on 30 May 2017 and after several hours it passed through Chittagong district. The cyclone killed 7 people in Cox's Bazar, Rangamati and Bandarban after it made landfall [14]. In addition, 61 people got injured and 81 fishermen were reported to be missing after the storm. Due to the TC MORA, more than 52,000 houses were damaged in Chittagong and Cox's Bazar districts and about 3.3 million people were affected across four districts, namely Cox's Bazar, Chittagong, Bandarban, and Rangamati. Numerous trees were uprooted due to the cyclone. Besides, electricity was disrupted as well as roads and communication networks in remote parts of Bandarban district were interrupted. A brief statistics of infrastructure damaged over the said area is presented in Table 3.

The worst devastation took place in the Rohingya camps. The Rohingya are a Muslim minority shunned by Myanmar's Buddhist majority, who were displaced by conflict in neighboring Myanmar.

TABLE 1
APPROXIMATE LOSSES DUE TO PREVIOUS TROPICAL CYCLONES AND ASSOCIATED SURGES IN BANGLADESH (DATA SOURCES: KHALIL [12], DEBSARMA [13], NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA), AND WIKIPEDIA)

| Date, month and year | Affected area | Name of the phenomena | Maximum wind speed and surge height | Approximate losses/damages |
|---|---|---|---|---|
| -- May 1822 | Barishal | Most severe cyclone | - | 40,000 deaths, 100,00 cattle killed |
| 10-11th October 1960 | Meghna estuary | Severe cyclonic storm | 129 $km h^{-1}$ and 3 m | 6,000 deaths |
| 30-31th October 1960 | Chittagong coast | Severe cyclonic storm | 161 $km h^{-1}$ and 6 m | 70% of buildings in Hatia blown-off, 8,149 lives lost |
| 26-30th October 1962 | Feni-Chittagong coast | Cyclonic storm | - | 50,000 deaths |
| 10-12th May 1965 | Barishal-Chittagong coast | Severe cyclonic storm | 191 $km h^{-1}$ and 4 m | 19,270 deaths |
| 7-13th November 1970 | Khulna-Chittagong coast | Most severe cyclonic storm | 241 $km h^{-1}$ and 10 m | 300,000 deaths, innumerable animals killed, widespread damage to crops and properties |
| 24-25th May 1985 | Noakhali-Cox's Bazar coast | Severe cyclonic storm | 154 $km h^{-1}$ and 4 m | 11,069 deaths, 94,379 houses damaged, 64 km road and 390 km embankment damaged |
| 29th November 1988 | Sundarbans | Severe cyclonic storm | 160 $km h^{-1}$ and 5 m | 5,708 deaths, 6,000 people missing, 65,000 cattle killed |
| 29th April 1991 | Patuakhali-Cox's Bazar coast | Most severe cyclonic storm | 193 $km h^{-1}$ and 5 m | 138,882 deaths, 70,000 cattle killed, innumerable crops damaged |
| 15th November 2007 | Sundarbans, Patuakhali and Barguna | Cyclone Sidr | 260 $km h^{-1}$ and 5 m | 3,500 deaths, 8.9 million affecting people, 2,472,944 acres crops damaged |
| 27-29th May 2009 | Khulna and Satkhira | Severe cyclone Aila | 120 $km h^{-1}$ and 4 m | 179 deaths, three million people affected, 7,000 km road damaged, 500,000 houses damaged, more than 123,000 hectares' crops destroyed |
| 16-17th May 2013 | Patuakhali | Cyclonic storm Mahasen | 85 $km h^{-1}$ and 3 m | 17 deaths, 1.3 million people affected |
| 29th July 2015 | Chittagong | Cyclone Komen | 85 $km h^{-1}$ and 2 m | 132 deaths, 510,000 houses and 667,221 acres crops of fields destroyed |
| 21th May 2016 | Chittagong | Cyclone Roanu | 129 $km h^{-1}$ and 3 m | 26 deaths, 40,000 houses damaged |
| 29-31th May 2017 | Chittagong | Cyclone MORA | 110 $km h^{-1}$ and 2 m | 9 deaths, 52,000 houses damaged |

TABLE 2
TIME SERIES FOR THE POSITIONS AND THE NATURE OF THE CYCLONE MORA, 2017 (DATA SOURCES: BMD AND IMD)

| Date (2017) | Hour (UTC) | Latitude (° N) | Longitude (°E) | Central Pressure (hPa) | Maximum sustained surface wind (kt) | Nature of the storm |
|---|---|---|---|---|---|---|
| 28 | 0600 | 15.00 | 90.00 | 997 | 25 | Depression |
| 28 | 0900 | 15.40 | 90.50 | 996 | 30 | Deep Depression |
| 28 | 1200 | 15.70 | 90.70 | 995 | 30 | Deep Depression |
| 28 | 1500 | 16.00 | 91.00 | 994 | 35 | Deep Depression |
| 28 | 1800 | 16.30 | 91.20 | 994 | 35 | Cyclonic Storm |
| 28 | 2100 | 16.60 | 91.30 | 992 | 40 | Cyclonic Storm |
| 29 | 0000 | 17.00 | 91.30 | 990 | 45 | Cyclonic Storm |
| 29 | 0300 | 17.30 | 91.30 | 990 | 45 | Cyclonic Storm |
| 29 | 0600 | 17.80 | 91.40 | 988 | 45 | Cyclonic Storm |
| 29 | 0900 | 18.30 | 91.50 | 986 | 45 | Cyclonic Storm |
| 29 | 1200 | 18.60 | 91.50 | 984 | 50 | Severe Cyclonic Storm |
| 29 | 1500 | 18.80 | 91.50 | 980 | 55 | Severe Cyclonic Storm |
| 29 | 1800 | 20.00 | 91.60 | 980 | 55 | Severe Cyclonic Storm |
| 29 | 2100 | 20.30 | 91.60 | 978 | 60 | Severe Cyclonic Storm |
| 30 | 0000 | 21.10 | 91.80 | 978 | 60 | Severe Cyclonic Storm |
| 30 | 0300 | 21.80 | 91.90 | 978 | 60 | Severe Cyclonic Storm |
| 30 | 0600 | 22.80 | 91.90 | 982 | 55 | Severe Cyclonic Storm |



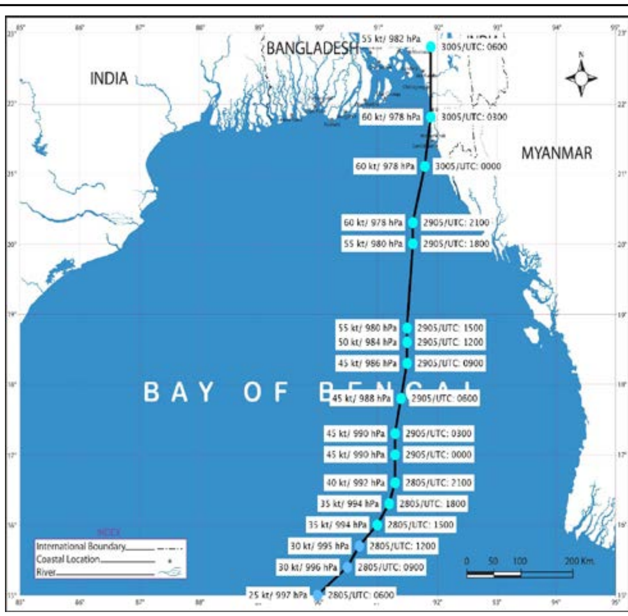


Fig. 1. The track, central pressure and intensity of the cyclone MORA according to the Saffir–Simpson scale (Data source: BMD and IMD).

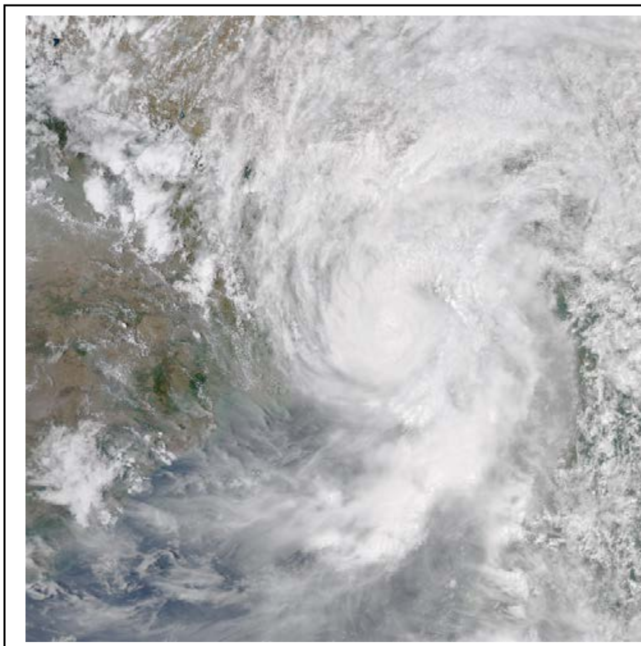

Fig. 2. Severe cyclonic storm MORA at peak intensity (Source: NASA Earth Observatory).

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The government of Bangladesh, recognize some 300,000 Rohingya as refugee and they are inhabiting in official camps made by Bangladesh government. But a huge toll of Rohingya people who had no recognition as refugee are inhabiting near the official camps as undocumented Rohingya. Almost 70% of undocumented Rohingya refugees live in three makeshift camps in Balukhali, Kutupalong and Leda. The damages in the said camps were severe with almost 10,000 thatched huts destroyed. But the damages in the official camps, situated in Nayapara and Kutupalong, were not severe. Most houses were partially damaged and almost 20% of them were severely affected. A few pictures are displayed in Fig. 3 for having a better understanding.

### 4.2 Damage due to MORA in other countries

TC MORA caused heavy rainfall in Sri Lanka and Northeast India along with Bangladesh and due to this heavy rainfall, there were devastating floods and landslides in Sri Lanka. According to Sri Lanka's Disaster Management Centre, more than 200 people were dead and 79 were missing. Besides this, 2,500 houses were destroyed and nearly 15,900 damaged in the affected areas. More than 683,000 people from 175,000 families were affected by MORA associated floods and landslides.

TC MORA reached the northeast part of India at late afternoon on 30 May 2017 after having landfall in Bangladesh. MORA brought heavy rain in several parts of Assam, Meghalaya, Arunachal Pradesh, Mizoram, Nagaland, Tripura and Manipur. According to a reported news of Hindustan Times, at least 110 buildings were damaged including a church and a hospital, many trees were uprooted and electricity and telecommunication links were broken in Mizoram.

TC MORA made landfall in Myanmar on the same day as that of Bangladesh and India. Severe destruction occurred in the Rakhine state due to the cyclone. Besides, Chin, Ayeyarwady, Magway, and Sagaing states also were affected more or less by this storm. About 11450 houses were partially damaged and 4968 were fully destroyed in the said areas [15]. In addition to some infrastructure damages were also reported. About 325 schools, 32 office buildings, 57 religious buildings, 23 hospitals and clinics, 23 government buildings, 3 bridges, 38 utility poles, 22 motorboats were damaged in Cyclone affected areas [16].

## 5 Socio-economic impact of the TC MORA

According to world population review, Bangladesh is one of the over populated countries in the world having a population of about 168.07 million [17]. This makes Bangladesh 9th in the world population ranking. Bangladesh is also regarded as one of the vulnerable countries of the world for natural disasters and manmade hazards. The vulnerable region of the country is her 47,201 $km^2$ long coastal belt which is about 32% of the total surface area of the country.



TABLE 3
Number of damaged houses (Source: EPOA, Bangladesh)

| District | Sub-district | Number of fully damaged house | Number of partially damaged house | Total number of damaged house |
|---|---|---|---|---|
| Cox's Bazar | Cohokoria | 1193 | 9035 | 10228 |
| Cox's Bazar | Teknaf | 4500 | 6000 | 10500 |
| Cox's Bazar | Moheshkhali | 5480 | 8700 | 14180 |
| Cox's Bazar | Kutubdia | 4270 | 6382 | 10652 |
| Chittagong | Swandip | 50 | 600 | 650 |
| Chittagong | Anwara | 215 | 819 | 1034 |
| Chittagong | Lohagara | 0 | 327 | 327 |
| Chittagong | Bashkhali | 2500 | 1000 | 3500 |
| Rangamati | All the Upazila | 150 | 1027 | 1177 |
| Bandarban | Nikonchori | 850 | 2000 | 2850 |
| Total | | 19208 | 35890 | 55098 |


Fig. 3. Some pictures related to the landfall, inundation, damaged houses, damages in Rohingya camps, strong winds due to the TC MORA in Bangladesh (Source: IMD and Google image); (a) land fall, (b) inundation, (c) damaged houses, (d)-(e) damages in Rohingya camps, (f) strong wind



Currently, about 35 million people are inhabiting in this coastal region which is about 29% of the total population of the country [18]. About 40 million people of the coastal areas of Bangladesh depend on agriculture directly or indirectly [19]. Fishing, poultry, and dry fish industry are also important income source for these coastal population. But this sector frequently is being affected by the natural calamities like tropical cyclones and associated surges, floods, salinity intrusion waterlogging etc. Almost every year the coastal people are facing a huge loss of their livelihood for the above mentioned calamities. As a result, they cannot hold a healthy economic condition. Most recently the coastal population faced the severe cyclonic storm, MORA that brought a huge loss to their livelihoods.

Due to TC MORA, standing crops of about 23,058 ha surface area had been affected along the coastal region, whereas Chittagong and Cox's Bazar were found to be mostly affected. In different places of Chittagong, about 10,000 ha Aush paddy was greatly threated due to a flood caused by the TC MORA. About 608 acres areas of crops, 250 acres salt fields were severely damaged in Cox's Bazar [20]. In most of the affected places loss of standings crops and paddy were more or less but the effect was severe in Teknaf and Maheskhali [21]. Besides agricultural area, poultry farm, dry fish farm, and other livelihood sectors were also damaged. As in [20] about 17290 acres shrimp hatchery, 33 fishing boats, 21 large fishing nets were damaged in Cox's Bazar. In order to reduce the losses in the coastal areas, an appropriate guideline is needed to make the coastal people aware.

## 6 Relief and Recovery

It is mentioned earlier that TC MORA made landfall close to the south Chittagong near Kutubdia coast on 30 May 2017 in Bangladesh. About 3.3 million people were affected by the cyclone [14]. But due to early preparedness, death toll was reduced significantly compared to the previous cyclones. A short description of the recovery and relief situation is documented below.

After the formation of depression on 28 May 2017 in the BOB region, the Government of Bangladesh (GOB) and the BDRCS, initiated their response to face an upcoming danger. As a part of it, about 55,260 CPP volunteers and staffs, disseminated early warning messages to the population living in the coastal districts. BDRCS distributed cash grants of 5000 Taka to more than 2,500 households to help them to prepare for or respond to the storm. Around 468,000 people were evacuated with the support of CPP and BDRCS volunteers. Following the landfall of MORA, BDRCS provided first aid services, dry food and clean water to the affected population. In response to the coastal people, the GOB allocated 150,00000 BDT and 1400 MT rice. Also, the World Food Programme allocated some 122 MT of biscuits to distribute among the TC MORA affected people. Besides this, The International Federation of the Red Cross and Red Crescent (IFRC) organized USD $107,000 from its Disaster Relief Emergency Fund (DREF) to provide emergency food, drinking water, storage and shelter materials. World Health Organization (WHO), provided emergency medical facilities to the cyclone affected people. To help the cyclone affected-pregnant woman, the United Nations Population Fund (UNFPA) distributed 300 safe delivery kits and also deployed more midwives for their support in an emergency. Besides, UNFPA distributed 3000 dignity kits, including soap, sanitary napkins, clothing, a towel, a torch, and a whistle to stay safe during emergencies. The International Organization for Migration and UNHCR distributed plastic sheets, rope and other items in camps housing refugees and other displaced persons.

## 7 Cyclone preparedness activities

A Cyclone is a worldwide familiar natural disaster. Bangladesh is known as the cyclone-prone country in the world. Almost every year Bangladesh is facing a huge loss of lives and properties due to storm surge associated with a cyclone. It is aforementioned that we cannot stop the occurrence of the cyclones but the losses due to a cyclone can be minimized by taking necessary preparation. In this regard, BMD plays a vital role. In fact, BMD is the only government agency for forecasting, preparing, issuing, and disseminating warnings for cyclones in Bangladesh [9]. BMD has two special branches, namely storm warning centre (SWC) and meteorological and geophysical centre. In order to make the coastal inhabitants' awareness, SWC issues special bulletins on a regular basis after forming a depression in the BOB. Based on the strength of a cyclone, the SWC issues different warnings in different stages. The following Table 4 covers the warning process discriminated by SWC.

TABLE 3
Cyclone warning stages (Based on the study of Paul et al. [9])

| Warning stages | Wind speeds ( $km h^{-1}$ ) |
|---|---|
| Cyclone alert stage | 50 |
| Cyclone warning stage | 51-61 |
| Cyclone disaster stage | Exceeds 61 |
| Cyclone great danger stage | Exceeds 89 |

Based on the warning stage, necessary messages are disseminated from the SWC. In the cyclone alert stage, an alert message is sent to the cyclone preparedness program (CPP), radio and television. Whenever cyclone reaches warning stage, then SWC informed the respective authorities with the information of the current and future states of the cyclone. A danger warning message is disseminated in every 30 minutes at cyclone danger stage. When a Cyclone turns into a great danger stage, a warning message, initiated before 10 hours of the predicted landfall, is usually disseminated every 15 minutes and the residents are urged to evacuate at this point. The National Disaster Management Council (NDMC), headed by the Honorable Prime Minister of the People's Republic of Bangladesh, then formulates and reviews disaster management policies and gives directives to all concerns for disaster risk reduction, mitigation, preparedness, evacuation, response, and recovery (see Paul et al. [9]). In this regard, CPP plays a vital role. The volunteers of CPP assist the coastal people in executing rescue operation, distributing relief goods, providing first aid under the supervision of the GOB local administration. Here an important point to be noted that at great danger stage, the SWC provides message before 10 h of the predicted landfall. Sometimes this 10 h may not be enough to evacuate the coastal people. So, it is required to take care of it so that a considerable time can be obtained for taking necessary measures. In this paper, an attention is taken care into account in this regard.

## 8 Numerical estimation

In this part, the numerical estimation of the TC MORA is discussed and made a numerical simulation of this storm. It is to be noted here that the numerical simulation of a storm will help in developing a proper storm surge prediction model to provide an improved warning system, which in turn can be helpful in minimizing the damages resulting from these storms and associated surges. A considerable number of numerical models have been developed for the prediction of storm surges occurring in the BOB. The first pioneering work is due to Das [22]. After that many advances are made through the investigations of Das [23], Roy [24], Debsarma [13], Rahman [3], Paul and Ismail [2, 6, 7], and Paul et al. [8-11]. In the mentioned investigations, several cyclones were used. But the cyclone MORA has received a little attention. In [25], cyclonic storm MORA was used to estimate water levels due to the nonlinear interaction of tide and surge taking into account the influence of river on storm surges. But the study was conducted using only $M_2$ tidal constituent. In [26], cyclonic storm MORA was used to estimate the effect of cyclones during high tide and low tide on land. However, in both the studies, the inverse barometric effect was not taken into account.

In our numerical estimation, we have used the programming code that was ued in the study of Paul et al. [8]. The geometrical domain of our study region is taken from latitudes 15°-23° N and longitudes 85°-95° E. The input data of our study are meteorological, oceanographical, hydrological and geographical.

The meteorological input such as storm track, maximum sustained wind speed, the radius of maximum sustained winds, wind field, pressure drop are the major ones to produce and propagation of storm surge [27]. These data were obtained from BMD and IMD, which are discussed in section 3. The two geometrical factors, namely coastal and offshore islands' geometry are approximated with a proper stair step representation. The water depth data are collected from the British Admiralty Chart and water depth of the grid points are interpolated by using Shepard interpolation. Our interpolated bathymetry by Shepard interpolation with power parameter 2 is presented in Fig. 4. Hydrological input such as Meghna River discharge is taken into account. In order to generate a proper tidal condition over the study region four major tidal constituents namely $M_2$ (principal lunar), $S_2$ (principal solar), $O_1$ (principal lunar diurnal), and $K_1$ (luni-solar diurnal) are taken at the southern open boundary of the parent scheme in the absence of wind stress and pressure gradient force. The process of generation of each of the pressure and wind fields is similar to those of Paul et al. [8]. In our numerical experimentation, first the tide model is run from a cold start. After achieving a stable tidal condition, the surge model is run to estimate the water levels due to the nonlinear interaction of tide and surge at the model time $t = 0$. To attain pure surge (water levels obtained from meteorological forcing only), the model was also run from the cold start. The discussion of our estimated results, comparison and validation are described in the next section.

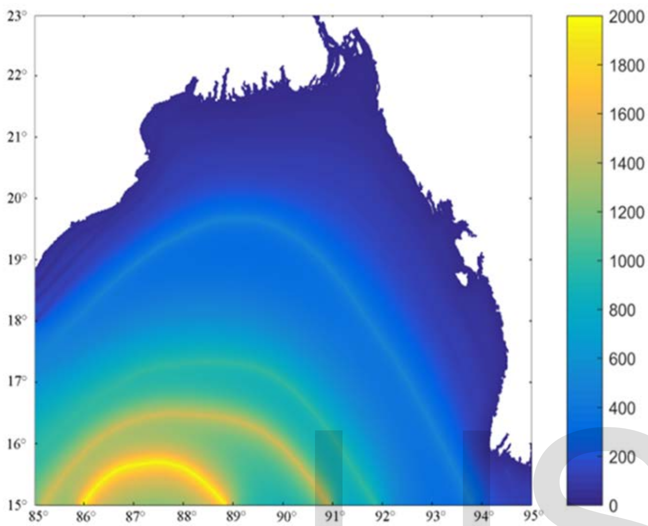


Fig. 4. A contour of interpolated bathymetry using Shepard interpolation from the British Admiralty Chart.

## 9 Results and Discussions

The results for the storm MORA are computed for 48 h (from 0600 UTC of 28 May to 0600 UTC of 30 May) but they are presented here for the last 24 h (from 0600 UTC of 29 May to 0600 UTC of 30 May) for better aspects at some coastal and islands locations along the Meghna estuarine region of Bangladesh (see Fig. 1). The representative locations are Char Madras, Char Jabbar, Char Chenga (Hatiya), Companiganj, Sandwip, Mirsharai, Sitakundu, Chittagong, Banshkhali, Cox's Bazar (see Fig. 4). The obtained results of our computations are presented in Figs. 5-7.

The simulated water levels due to pure surge associated with the storm in the absence of astronomical tide are depicted in Fig. 5. The maximum surge values from our estimation can be found to vary between 0.90-2.94 m. According to a report from the IMD, a storm surge of 1-1.5 m was realized above astronomical tide at the time of landfall along the coast of Bangladesh. Thus the results that came out through our model simulation are found to be in a reasonable agreement with the reported data by the IMD. Figure 6 shows our computed total water levels due to the nonlinear interaction of tide and surge at the stations mentioned above. The total water levels due to the dynamical interaction of tide and surge was found to range between 1.80-3.73 m with 2.61 m at Chittagong. Azad et al. [26] in their study obtained 3.34 m (approx.) water level due to the interaction of tide and surge. Thus our total peak water levels due to the interaction of tide and surge at Chitagong agree well with that of Azad et al. [26].

Thus our model simulated results agree reasonable well with some reported results. Based on a report from the IMD, the TC MORA made landfall between 0400 to 0500 UTC of 30 May along the Bangladesh (Chittagong) coast. In this regard, the model generated landfall time can be found to agree at Chittagong (see Fig. 6) with the reported data. Figure 7 depicts the interaction effect (true water level minus surge minus tide) of tide and surge at that of the stations mentioned in the case of Fig. 5. It can be inferred from Fig. 7 that the interaction effect of tide and surge for the region of interest as obtained can no longer be neglected.

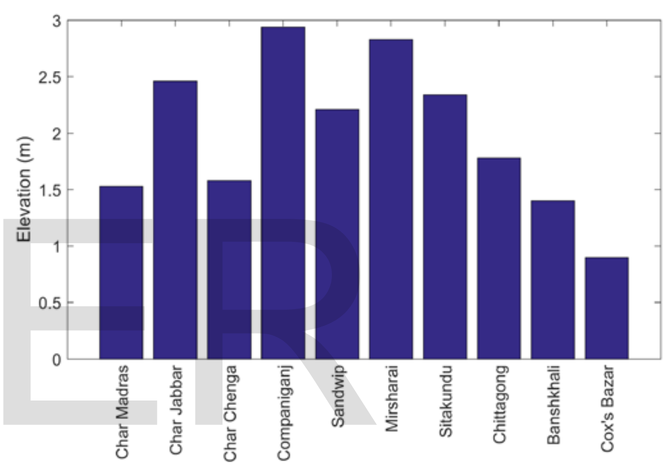


Fig. 5 Peak water levels with respect to the mean sea level (MSL) due to surge at some stations along the coast of Bangladesh during the storm MORA.

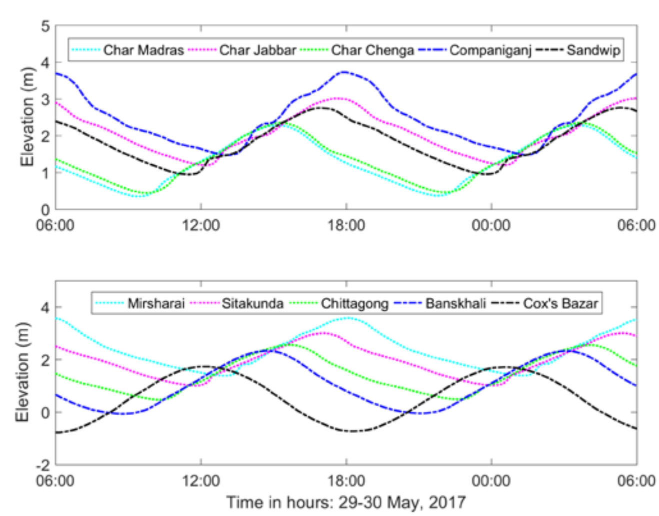


Fig. 6 Time varying water levels with respect to the MSL due to the dynamical interaction of tide and surge at some suitable stations along the coast of Bangladesh during the storm MORA.

The interaction effect of tide and surge may affect the timing and extreme water levels during cyclonic period. Thus, scientists need to apprehend the interaction of tide and surge associated with a storm along the coast of Bangladesh in order to better estimates of extreme sea level in coastal defense.

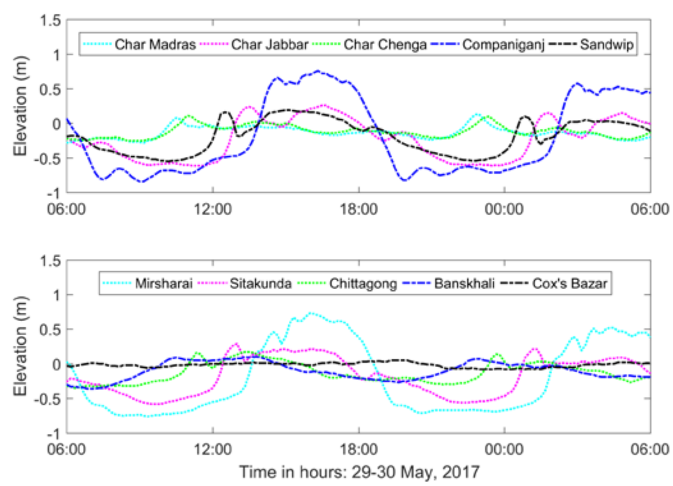


Fig. 7 Interaction effect (total water level due to the interaction of tide and surge – water level due to pure surge – water level due to tide) due to the nonlinear interaction of tide and surge at some stations along the Meghna estuarine area.

## 10 Storm Surge Mitigative Measures and Remarks

The main objective of this present study is to produce a proper warning system based on numerical storm surge model, where the CS MORA is taken care into account for assessing impacts and experimenting numerically, which may help for practical forecasting along the coast of Bangladesh. The cyclones and associated surges are not fully controlled but the destruction resulting from it can be reduced by using a proper forecasting technique. According to the study of Murty and El-Sabh [28], the storm surge mitigating problems can be divided into three classes, (1) control the strength of the cyclone that moves over the BOB, (2) control the intensity of the tropical cyclone (where it is borne) that gives rise to the surge and (3) coastal defenses against storm surges. Classes 1 and 2 are not possible to measure technically or scientifically in practice. Therefore, until now, all mitigative measures are mainly addressed by item 3. Many national and international agencies are connected in order to take mitigative measures against storm surge in Bangladesh since 1950 [9]. Effective mitigation measures against the cyclones and associated surges are appended below. Though some of the mitigative measures can be found in [9, 12, 29, 30], our remarks in coordination with the gist of them are presented below.

i. Embankments construction is the major mitigation measures. During the 1960s and 1970s, a major number of embankments was built along the coast of Bangladesh in order to save the southern coastal area of Bangladesh from storm surges and associated floods and obstruct entry of saline water from the sea [12]. Coastal embankments have been helped to protect life and properties from severe types of natural disasters and to raise agricultural production. The government of Bangladesh constructed many embankments. The conditions of some of the embankments are now very poor. So, these embankments should be repaired and also the required new embankments, roads and bridge along the coastal area should be reconstructed to reduce the economic losses during the cyclones. In order to remove the coastal erosion, many types of fruit trees should be planted with specific plan along the embankments and roads.

ii. The Sundarbans is the world's largest single mangrove forest which represents the 25% total forest areas of Bangladesh. It acts as a buffer against cyclones and associated surges. As for example, Sundarbans served as a buffer against cyclone Sidr, consequently the effects of the cyclone were reduced significantly [29]. Sundarbans also protects the country from the greenhouse effect and also helps to dissipate storm surge energy. It also provides effective protection to save lives and property against the cyclones and storm surges along the coastal region of the country. The Sundarbans is estuarine and swampy, it receives fresh water from the river and saline water from the sea and helped to balance the ecosystem. So, it is important to save Sunderbans from destructive effects of the TC.

iii. The CPP is a disaster management program which helps to reduce the destruction before and after the cyclone. In order to take better preparation against storm surges, it can be of help to decrease human and cattle death, and destruction of property. The CPP of BDRCS started their program in 1972. The Bangladesh government approved this CPP program in 1973 and undertook economic responsibility. They created two programs such as policy committee and implementation board. The other non-governmental organizations also take different activities for pre-disaster, during-disaster and post-disaster, which includes disaster preparation guidelines. The coastal people are directly dependent on the activities of CPP because they are the main beneficiaries of the Programme of CPP during cyclones. The volunteers of CPP are devoted and committed and they are always ready to face any disaster for protecting lives and properties. But the number of volunteers are not enough for helping the coastal people before and after the cyclone. The number of volunteers should be increased and also the extraordinary volunteers' team should be needed for supporting the coastal people of Bangladesh during disaster.

iv. Cyclone warning systems are more effective among all the mitigative steps to reduce the damage of property and loss of lives. It is highly dependent on the prediction of numerical models which can estimate water levels, landfall time with the location, wind speed, central pressure, resurgent etc. with a considerable accuracy. The warning system of Bangladesh starts to publish bulletins based on the warning produced by BMD. But the maximum rural people of the coastal area of this country are not literate. Therefore, it should be important to reach a comprehensible cyclone warning in every corner of the affected areas.

v. Public awareness plays a vital role in disaster managements. It should be increased through volunteers, radio, television, publicity campaign, posters, leaflet and booklet, staging of drama, folk songs to aware the coastal people what should be done during the disaster.

vi. Forecasting of future cyclones is also included with mitigative measures against storm surges. But this part is totally dependent on the numerical modeling, which can be able to predict water levels, land fall position, inundation area, etc. with a considerable accuracy during the TC. An accurate prediction of storm surge is obviously important to forecast future cyclones taking into account the factors influencing surge levels, namely the complex coastal geometry, offshore islands, wind stress effect, bottom friction effect, inverse barometric effect, tidal effect, gravitational effect, Coriolis effect, sea bed roughness, river discharge, etc.

vii. In future, sea surface level can be increased due to greenhouse warming from the present time [9]. So, the frequency of cyclones with higher surge levels can be observed by the coastal community. A considerable number of well positioned cyclone shelters with suitable height can be a solution in this regard. But the number of cyclone shelters is very few in comparison with increased population. So, the number of tenable cyclone shelters should be constructed in right places in order to save lives with the accurate estimation of maximum water levels due to a storm.

## 11 Conclusion

In this study, the CS MORA is simulated numerically as well the impacts of this storm are assessed and recovery measures are presented. Bangladesh has made significant efforts to reduce the loss resulting from TCs and associated surges. But in spite of all the necessary measures, the less intense CS MORA caused heavy damage to the infrastructure and economic assets and leave a negative impact on the livelihood of people. Therefore, the study suggests an improved warning system via an optimal storm surge prediction model through which a significant reduction of losses resulting from these CS can be made. So, the development of a precise cyclone warning system through an accurate storm surge prediction model is highly recommended. This study also suggests to make tenable embankment, afforestation on right places, development of disaster shelters and maintenance, construction of more suitable disaster shelters on suitable positions as well as suitable public awareness system to minimize the losses. Also, climate change may amplify the frequency of the disasters, which is a big challenge to economic growth for the developing country like Bangladesh.

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