Proceedings of the 7[th] International Conference on Asian and Pacific Coasts (APAC 2013) Bali, Indonesia, September 24-26, 2013

STORM SURGE, WAVE, AND INUNDATION SIMULATION IN THE BAY 0F BENGAL

Hendri [1], H. S. Lee [2] and T. Yamashita [2]

ABSTRACT: Bangladesh's geographical and land characteristics along the coastal area has created the most disastrous country by tropical cyclones originating in the Bay of Bengal and associated with the storm surges. During the past 61 years (1950-2011), India Meteorology Department (IMD) was observed 902 events from deep depression (tropical storm) up to super cyclonic storm (tropical cyclone category 5) with average 5 storms per year. This condition is strengthening storm surge and increasing sea level to the sudden inundation and flooding along the Bangladesh coast. Consequently, the storm surge and sea level rise are the key factor of coastal damage. Therefore, it is critical to estimate the future storm surges in a changing climate for vulnerability study and adaptation strategy. In this study, numerical simulations are performed to validate the storm surge induced by the 1991 Bangladesh cyclone, one of the deadliest cyclone in the Bay of Bengal using an atmosphere-waves-ocean integrated modelling system. Then, further numerical experiments are performed to estimate the future storm surges in 2050 and 2080 and inundation map for Bangladesh's disaster management strategy.

Keywords: Tropical cyclone, storm surge, sea level rise, Bangladesh.

INTRODUCTION

Bangladesh's storm surges generated by tropical cyclone are the most hazard-prone country in the world along the coastal area in the Bay of Bengal which contributed 46% of the total Bangladesh natural disaster from the period 1980-2010. This disaster remains one of the worst sufferers of cyclonic causalities in the world. They reasoned that the area is vulnerable because of its (1) location in the paths of tropical cyclone, (2) the phenomenon of recurvature of tropical cyclone in the Bay of the Bengal, (3) wide and shallow continental shelf, especially in the eastern part of Bangladesh, (4) low-lying and poorly protected coastal areas, and (5) high density of population.

The deadliest storm surge event occurred on 29 April 1991with the maximum wind speed at Sandwip up to 235 km/h (65.3 m/s) and the central pressure of 938 hPa, as measured by the Chittagong Port Authority of Bangladesh. The estimated maximum pressure drop was about 60 hPa. The Storm surge (plus tide) was a range from 4 to 7 meter high inland over a wide area. The incident resulted to kill at least 140,000 people, leaving as many as 10 million homeless, and caused damage to agriculture area, animal husbandry, and freshwater fish. We use an atmosphere-ocean coupled process-based model to validate the disastrous cyclone surge of April 1991 in the Bay of Bengal.

Since storm surge is the key factor of coastal damage and disaster in the Bay of Bengal area, it is critical to accurately estimate and forecast these storm surges, taking into account the meteorological condition especially the atmospheric disturbance parameters such as sea surface pressure and wind data. Therefore, the objectives of this study are 1) to provide the atmospheric disturbance parameters field estimation using the Advance Research WRF (Weather Research and Forecasting) for precise meteorological condition, and 2) to estimate the future storm surges in 2050 and 2080, and 3) inundation map.

GEOMORPHOLOGICAL FEATURES AND TROPICAL CYCLONE HISTORIES

Geomorphological Features

The northwestern part of Bangladesh is bounded by the Indian border with the Ganges river in the southwestern, the Megna river on the southeastern, the Tista river in the northwestern, and the Brahmaputra-Jamuna river in the northeastern (Fig. 1). In the northern part, the Himalayan piedmont is the highland area with an elevation of more than 90 m, while the southern area is swamp and mangrove with elevation less than 10 m asl.

Based on geomorphologically, the area is divided into four regions; 1) Barind Tract, 2) Himalayan piedmont plains, 3) Alluvial lowland along the Brahmaputra-Jamuna river, and 4) Alluvial lowland along the Ganges river.

[1] The State University of Papua, Jl. Gunung Salju-Amban, Manokwari 98314, West Papua, INDONESIA
[2] Graduate School for International Development and Cooperation, Hiroshima University, 739-8529 Higashi-Hiroshima, JAPAN

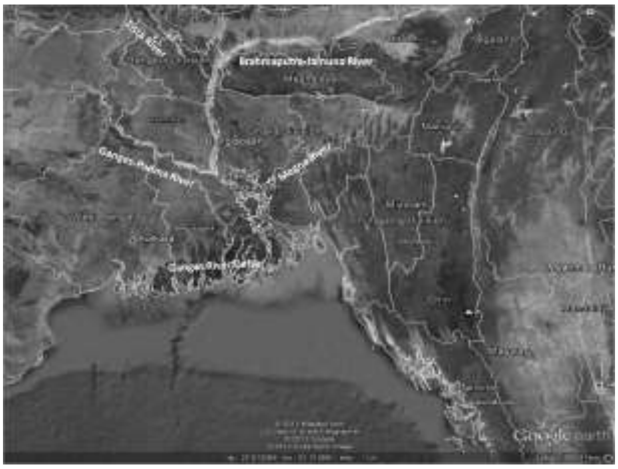


Fig. 1 Bangladesh's geographical location (courtesy from Google earth).

Barind Tract has a slightly highland than that of the alluvial lowlands with some differences between the west and the east Barind. The west Barind is higher with a dome shape, while the east Barind is a westerly-tilting terrace.

The Himalayan piedmont area is a complex of several fans formed by rivers flowing from the Himalayan Range. The eastern half is formed by floodplains of Tista river, while the western half is a relatively stable order fan of the former Tista. Flash floods are dominant accompanied with sand deposition from the catchment area of Tista.

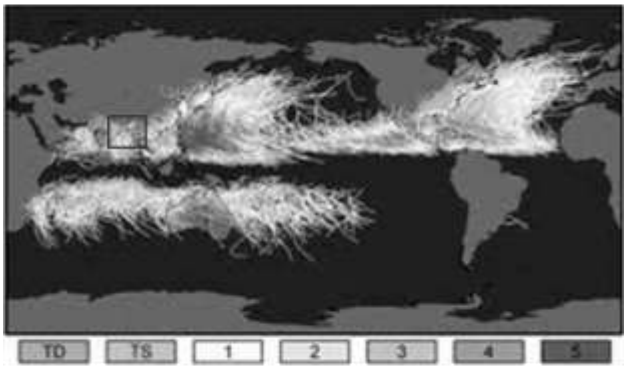
The Brahmaputra-Jamuna river changed its course from the Old Brahmaputra which now flows to the east of the Madhupur Terrace with poor growth of natural levees . Parallel to the Brahmaputra-Jamuna, the Ghagat, Bangali, Karatoya, and numerous other minor rivers flow with heavily meandering channels with large scars suffering from flood.

Large natural levees along the Ganges river and broad black-marsh areas occur along the lower Mahananda and the lower Atrai. The width of natural levees of the Ganges sometimes exceeds 10 km with the Rajshahi City as the center of natural levees. When the water level of the Ganges is high due to storm surges, flood water overtops the natural levees and flows into the back marsh.

Tropical Cyclone Histories

Based on IMD, tropical cyclones are presently classified according to the wind speed with the first stage detected as a depression, d (≤ 51 km/h). After that, it intensified into a deep depression, dd (52-61 km/h), cyclonic storm, cs (62-87 km/h), severe cyclonic storm, scs (88-117 km/h), very severe cyclonic storm, vscs (118-221 km/h), and the last developed into a super cyclonic storm, sucs (> 222 km/h). This classified is the same with the Saffir-Simpson hurricane scale which formed from tropical depression to cyclone category five.

Bay of Bengal is one of the areas in the world affected by tropical cyclones (see Fig. 2 in the red line). During the past 61 years (1950-2011), this area has been hit by 902 events with average 5 storms per year. From the historical cyclone, 38.5% (cyclonic storm of 24.0%, severe cyclonic storm of 14.0%, and very and super severe cyclonic storm of 0.5%) of the total were accompanied by a storm surge. Development a tropical cyclone in the Bay of Bengal has a lifetime of one week or longer.



Saffir-Simpson Hurricane Scale

Fig. 2 Map of the tracks and intensity of tropical cyclone during the period of 1851-2006.
(http://en.wikipedia.org/wiki/Tropical_cyclone)

The formation of cyclone in this area is strongly related to seasonal north south migration of the ITCZ (Inter Tropical Convergence Zone) around the pre (April, May) and post (October, November) monsoons. During this period, the ITCZ is generally located over a region of warm sea surface temperature about 29^{o}C with wind speed of 62-87 km/h and pressure drop up to several hPa.

Based on IMD data, the pre and post monsoons contributed 50%-90% of the total events which included vscs and super cs (see Fig. 3).

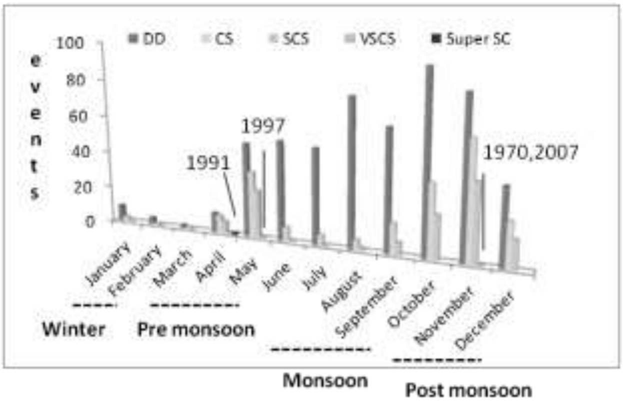


Fig. 3 Bangladesh's tropical cyclone from 1950-2011.

1991 BANGLADESH CYCLONE

Super Cyclonic Storm BOB 01 (IMD) / 02B (Joint Typhoon Warning Center, JTWC) Category 5 Tropical Cyclone (SSHS) is the deadliest cyclone formed in the morning of 25 April 1991 as a depression at 10.0ºN latitude and 89.0ºE longitude. After that, it intensified into a deep depression in the evening and then turned into a cyclonic storm at midnight time. The maximum sustained wind was 65-87 km/h with a central pressure of 996 hPa. On 27 April, it turned into a severe cyclonic storm with maximum wind speed of 90-115 km/h and central pressure of 990 hPa. At the midnight time on the same day (27 April), it gained into a very severe cyclonic storm with wind speed more than 130 km/h. Started on 28 April, the cyclone moved in a northeasterly direction. Finally, late on 29 April, cyclone made landfall near the coast north of Chittagong by category super cyclonic storm. The maximum wind speed observed at Sandwip was 235 km/h and the central pressure was 920 hPa with pressure drop of 80 hPa. The track of 1991 Bangladesh cyclone is shown in Fig. 4 together from simulated track using the atmosphere model.

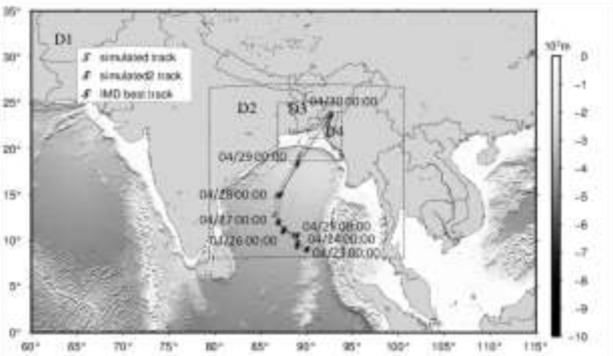


Fig. 4 Track and intensity of 1991 Bangladesh Cyclone. (http://en.wikipedia.org/wiki/1991_Bangladesh_cyclone)

This cyclone was conjunction with the full moon to bring enough power for raising tidal levels to the highest of the normal range. The storm surge plus tide was observed range from 4 to 7 m high in different areas along the east coast of Bangladesh (see Table 1 and Fig. 5).

Table 1 Water heights of 1991 Bangladesh Cyclone

Locations	Water Heights (m)
Noakhali	5.4
Sitakund	7.1
Chittagong	7.5
Anwara	7.15
Kutubdia	6.06
Moheskhali	5.06
Cox's Bazar	4.85
Teknaf	4.2

Source: Chittagong Port Authority of Bangladesh, 1991

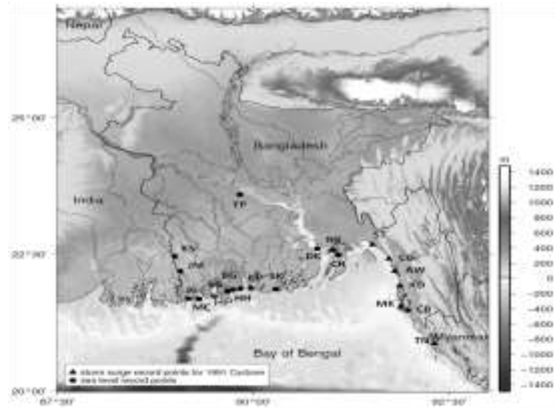


Fig. 5 Storm surge (black triangle) and sea level (black and red circles [long time period]) observations site along the coast of Bangladesh.

MODEL CONFIGURATION

The applied atmosphere-ocean coupled model consisted of the Advance Research Weather Research and Forecasting (WRF) model (v.3.2) (Skamarock *et al*., 2008) for atmosphere, the Simulating Waves Nearshore (SWAN) v.40.51 (Delft University of Technology, 2006) for wave, and the Primitive equation Ocean Model, POM (Mellor, 2004) for ocean.

This study referred to four domains with a (x, y, z) resolution of 27, 9, 3, and 1 km, respectively. The WRF computation was carried out on 23 April 1991 - 30 April 1991. The initial and lateral boundary conditions were imposed every six hours using JRA-25 with resolution surface data of 2.5º and pressure data of 1.25º. A Four-Dimensional Data Simulation (FDDA) technique applies to all domains in the wind, temperature, and mixing ratio fields. Table 2 displays the physical parameterizations used in the WRF simulations.

Table 2 Physics and parameterizations

Physics/ Parameterizations	Domain I	Domain II	Domain III	Domain IV
Cloud microphysics	New Thompson	New Thompson	New Thompson	New Thompson
Longwave radiation	RRTM	RRTM	RRTM	RRTM
Shortwave radiation	Goddard	Goddard	Goddard	Goddard
Boundary Layer	Yonsei University	Yonsei University	Yonsei University	Yonsei University
Cumulus	Kain-Fritsch	None	None	None

Surface-layer	Monin-Obukhov	Monin-Obukhov	Monin-Obukhov	Monin-Obukhov
Land-surface	5-layer thermal	5-layer thermal	5-layer thermal	5-layer thermal

The SWAN model is applied to the 1991 Bangladesh Cyclone-induced storm wave simulations for the same periods with the same configuration of four nesting domains as the WRF simulation to account for the accurate swell propagation. The external forcing of wind is used for the WRF model.

The POM simulation for sea level changes was also performed in the same period utilizing sea level pressure and wind data generated from the WRF model with bathymetry model domain taken from GEBCO 1-minute data.

RESULTS

Atmospheric Disturbances

The results of atmospheric disturbances are described in terms of the cyclone intensity and the track, pressure, and winds. Figure 4 demonstrates the comparisons between the best track from the IMD and the simulated results for the cyclone track using the WRF v.3.2 (simulated track) and the WRF v.3.4 (simulated2 track). Based on the result, the WRF v.3.2 was better fitting with the observed track. Then, this version will use for next simulation processes. The phenomenon of recurvature of tropical cyclone is also captured by this track on 28 April 1991.

Figure 5 shows the resultant fields of surface pressure and winds from the WRF simulation Domain I on 18.00 UTC, 29 April 1991 shortly before landfall. From this simulation, surface pressure can detect very well at the center about of 920 hPa. While, the wind speed is slightly underestimated of 50 m/s during the transition period from the very severe cyclonic storm to super cyclonic storm.

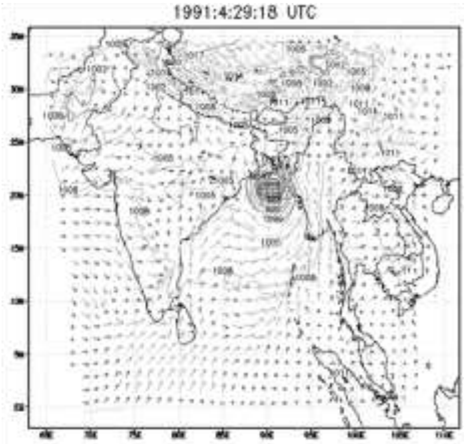


Fig. 5 The sea surface pressure and 10-m wind fields on 18.00 UTC 29 April 1991.

Surface Wave

Figure 6 exhibits the simulated significant wave heights from the SWAN simulation with focusing for three point locations in Chittagong, Anwara, and Kutubdia. There were no data available for continuous record data of wave and tide in Bangladesh. The observed data are just provided for one time of total surge (plus tide) after the disaster. It can be noticed that the peaks of surface wave in the simulation records occurred during and after the cyclone landfall along the east coast of Bangladesh.

In the simulated and observed results, the surface wave in the Kutudia was low more than 1 m differences from the Anwara and Chittagong which were near the central of the cyclone.

Storm Surge and Future Prediction

For the storm surge levels, the numerical simulations are performed by considering nao-tide, and pressure and wind from the WRF simulations. Overall, the peaks of simulated storm surges in the north southern area was low less than 0.2 m compared with the north eastern regions with the peaks of storm surges after the landfall (see Fig. 6).

The simulated total storm surge included wave, tide, pressure and wind in the northeastern regions agreed with the observed data. While, the north southern area simulation was slightly overestimated with the observed data due the effect of small island surround the point location.

After adjusting with the simulation, the peaks of total storm surge for each location can be written again in Table 3. The north eastern regions are slightly the same with the observed data, while the north southern is needed to add 1 m after the second peak of landfall. From the west coast, the observed of Hiron Point is a half value from the north southern regions caused by quite far from the central cyclone. Therefore, this point is only affected by the swelling and tide.

Table 3 Water heights of the total storm surges

Locations	Water Heights (m)
Noakhali	5.26
Sitakund	7.06
Chittagong	7.23
Anwara	7.13
Kutubdia	7.06
Moheskhali	6.06
Cox's Bazar	5.85
Teknaf	5.2
Hiron Point	1.74

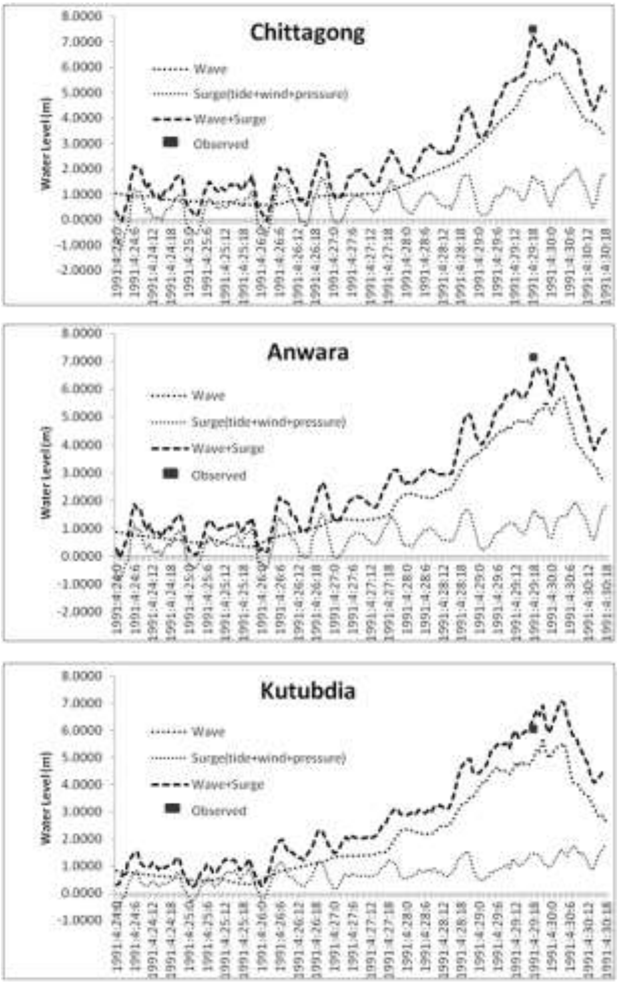


Fig. 6 The observed and simulated data of wave, surge, and total storm surge from the north eastern (Chittagong and Anwara) and the north southern coast (Kutubdia) of Bangladesh.

Sea Level Rise

Based on the peaks of total storm surge data, sea level rise (SLR) can be predicted along the coastal area of Bangladesh together consideration of non-linear of sea level rise conditions. The estimation of SLR for future predictions in 2050 and 2080 show in Table 4 which divide into two groups; 1) sea level record points and 2) storm surge record points. Since no observed long-term sea level records are available along the east coast of Bangladesh from Noakhali to Teknaf in the south, the observed maximum storm surge levels due to 1991 Cyclone is used for estimation of the SLR. Non-linear SLR due to global warming at the southern stations are assumed to be same with that of the observed Hiron Point (HP) on the east coast.

The first group is a representative area of the west coast with the SLR estimation until 2080 about of 2 m. And, the second group is a representative area of the east coast with the range prediction of sea level rise until 2080 from 5 to 7 m.

Twice time differences from the west and east coast of Bangladesh are caused by the phenomenon of recurvature of tropical cyclone in the Bay of Bengal. This condition is presented in Fig. 7 that the track was almost going to the east coast during the period of 1960-2009.

Table 4 Sea Level Rise Estimation in 2050 and 2080

Station Name	**Storm Surge 2050 (m)**	**1)Total SLR 2050 (m)**	**2)Total SLR 2080 (m)**
Betmar_Gang (BG)	1.74399	1.80384	2.00185
Chitalkhali (CH)	1.74399	1.80384	2.00185
Daulatkhan (DK)	1.74399	1.80384	2.00185
Faridpur (FP)	1.74399	1.80384	2.00185
Haringhata (HH)	1.74399	1.80384	2.00185
Hiron Point (HP)	1.74399	1.80384	2.00185
Jamuna (JM)	1.74399	1.80384	2.00185
Jamuna_617400 (J6)	1.74399	1.80384	2.00185
Kanksiali (KS)	1.74399	1.80384	2.00185
Khepupara (KP)	1.74399	1.80384	2.00185
Malancha (MC)	1.74399	1.80384	2.00185
Sela_Gang (SG)	1.74399	1.80384	2.00185
Supoti_Khal (SK)	1.74399	1.80384	2.00185
Noakhali (NK)	5.26	5.31985	5.51786
Sitakund (ST)	7.06	7.11985	7.31786
Chittagong (CG)	7.23	7.28985	7.48786
Anwara (AW)	7.13	7.18985	7.38786
Kutubdia (KD)	7.06	7.11985	7.31786
Moheskhali (MK)	6.06	6.11985	6.31786
Cox's Bazar (CB)	5.85	5.90985	6.10786
Teknaf (TN)	5.2	5.25985	5.45786

1) non-linear 2050 = 0.05985

2) non-linear 2080 = 0.1071

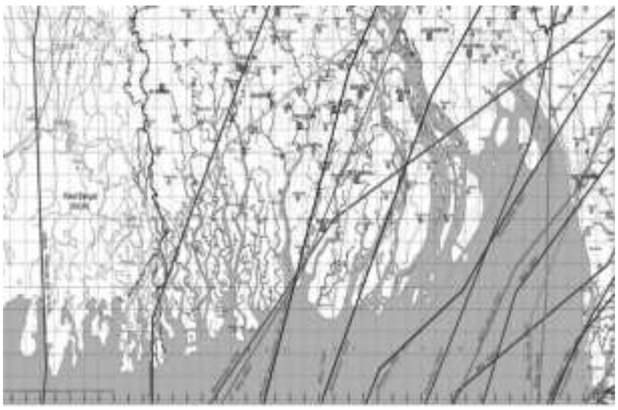


Fig. 7 Track of tropical cyclone in the Bay of Bengal during period 1960-2009.
Source: Bangladesh Meteorological Department (BMD)

Inundation Map

Referred of the SLR estimation and Bangladesh's DEM, the inundation map was created by Arch GIS v.9.3 along the east and west coast of Bangladesh in 2050 (see Fig. 8) and 2080 (Fig. 9). From the both figures, the west coast is a more surfer from inundation than the eastern regions caused by the lowland area along the Ganges river until 2080.

If the inundation map applied to road network (Source: Urban System Design Group, GEL's Program, IDEC, HU), the affected road length is almost 60% of the total network. And the affected national road length estimates about of 23%. Up to 2080, the increasing affected road is range from 1%-2% (see Table 5).

Table 5 The SLR impacts on road infrastructure

Year	Affected Length (km)	Total Length (km)	Percentage (%)
Road Length			
2050	4745.02	7828.47	60.61
2080	4920.97	7828.47	62.86
National Length			
2050	4745.20	20205.96	23.48
2080	4920.97	20205.96	24.35

Considering the impacts disaster of climate, atmosphere, and ocean interaction for the other sectors, Bangladesh's Government should create the new plan for disaster management strategy until the community level.

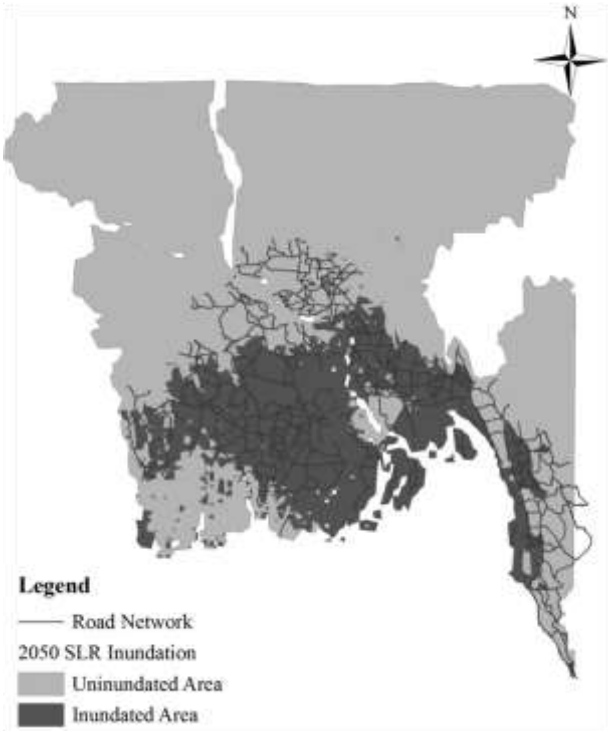


Fig. 8 Bangladesh's inundated areas with the impacts of roads in 2050.

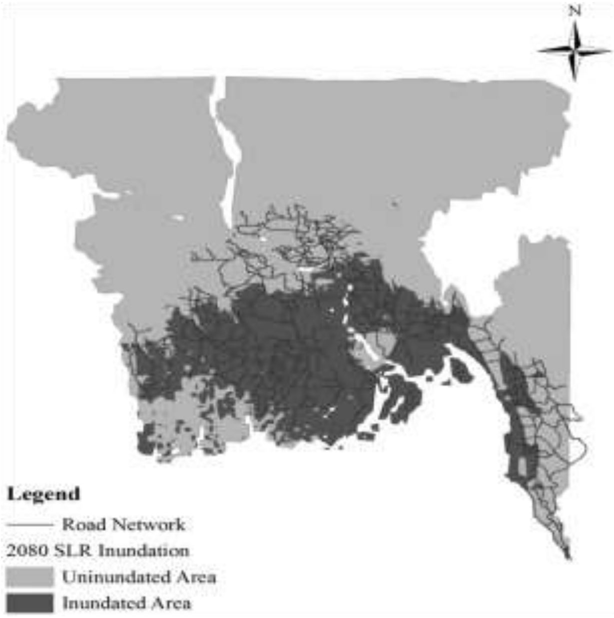


Fig. 9 Bangladesh's inundated areas with the impacts of roads in 2080.

CONCLUSION

WRF, SWAN and POM simulations were conducted to simulate an SLR along the coast of Bangladesh. Simulation results showed that the lower atmospheric pressure disturbance with a 920 hPa moving slowly northeasterly was reproduced. The surface wave height of the south and northeastern coast computed by SWAN was range 5-6 meter. The observed storm surge (plus tide, wind, pressure, and wave) was 6-7 m.

Considering the storm surge data and non-linear of SLR condition, the SLR estimation in 2050 and 2080 was created with the west coast about of 2 m and the east coast up to 7 m. These conditions were affected the road infrastructure with estimation about 60% of the total network and 23% of the national road.

REFERENCES

Chittagong Port Authority. (1991). Background information on the Storm Surge Modelling. Report, Appendix 17 pp.

Delft University of Technology. (2006). SWAN User Manual, 137 pp.

Mellor, G.L. (2004). User guide for a three-dimensional, primitive equation, numerical ocean model, Prog.in Atmos. And Ocean. Sci.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.Y., Wang, W. and Powers, J.G. (2008). A Description of the Advanced Research WRF Version 3. NCAR/ TN-475 + STR NCAR TECHNICAL NOTE: 113.