COMBINED EFFECT OF RIVER DISCHARGE AND STORM SURGE ON SAFE WATER LEVEL AROUND URBANIZED

Dong-Hwan Kim[1], Sung-Jin Hong[2], Hwa-Young Lee[3], Dong-Seag Kim[4],
Yong-Han Jung[5], Heon-Tae Kim[6], Chang-ill Yoo[7]

Suyeong Bay near Suyeong River, which is a well-known and highly populated area that offers attractions such as Haeundae and Gwangalli beaches, was extensively damaged by Typhoon Maemi in 2003. This region is exposed to the effects of global warming such as super typhoons, sea level rise, and heavy rain. Lowlands near river mouths are particularly vulnerable to the dual effects of flooding from heavy rain and storm surge. Therefore, accurate predictions of the interaction between river discharge and storm surge are crucial for the safety of residents. In this study, numerical simulations of storm surge and flooding were conducted using Advanced Circulation Model for Oceanic, Coastal, and Estuarine Water (ADCIRC) under Typhoon Maemi conditions. The model grid represented the characteristics of the bay and the domain of the Suyeong River basin accurately. In addition, an unstructured grid was used, which was driven by tidal forcing at the open boundary and river discharge at the upriver boundary. The results of this study indicate that the influence of storm surge and river discharge resulted in water levels of more than 0.381 m compared to estimates without river discharge. This study also examined the vulnerability of the river mouth using water elevation data combined with river discharge and storm surge. Interaction of river discharge and storm surge in coastal-inlet areas is essential for assessing water safety and developing a safety index for flood events.

Keywords: ADCIRC; river mouth; wind field; Typhoon Maemi

INTRODUCTION

In addition to increase in seawater temperature, the scale and intensity of typhoons are increasing on a global scale. In particular, a tropical cyclone known as Typhoon Maemi, which landed on the Korean Peninsula in September 2003, caused severe flooding around Busan and the coastal areas of Gyeongsangnam-do owing to the increased storm surge height, high tide, and ocean waves. High ocean waves and tidal waves triggered by typhoons often cause flooding in coastal lowlands and damage to various coastal structures (Yoon et al. 2012). Therefore, it is crucial to establish prevention plans in coastal areas with high population density. To prevent damage caused by typhoons in coastal areas, accurate predictions of storm surge are required. Thus, numerous studies on storm surge have been conducted worldwide.

Prandle and Wolf (1978) suggested that the mechanisms of tides and ocean waves should be considered because they can influence the generation and propagation of tidal waves. Oh and Kim (1990) determined tidal wave data using a storm surge model based on wind and pressure distribution of a typhoon. Their method is traditionally used for predicting the sea level during the passage of a typhoon. In their study, they combined calculated values with tidal level data obtained from a tide table to determine the total sea surface level. However, the aggregation of the linear sea surface generally overestimates the sea level because non-linear interaction between tide and surge is not considered, as suggested by Heaps (1983). In addition, Hur et al. (2006) conducted simulations to calculate the storm surge height under combined characteristic conditions of a typhoon, such as the central pressure and the typhoon's rate of movement and radius. The results were used to analyze the regional distribution characteristics of the storm surge height produced by a simulated typhoon that is likely to occur in the future. Similarly, many existing studies calculated the storm surge height by the summation of a linear sea surface level taking the rise in sea level due to tide, wind, and low pressure into consideration; river discharge was not considered. When a typhoon strikes, strong winds over the open sea induce storm surge, and rainfall and flooding also increase river flow. If the mouth of a bay is narrow, the average water level can also increase. Near the mouth of a bay, the flow can increase significantly, and fast waves from the open sea can influence the surge height. In a bay where a large amount of river discharge is expected, storm surge height prediction is crucial to minimize flood damage due to the storm surge.

[1] National Disaster Management Research Institute, Ulsan, 44538, Republic of Korea
[2] National Disaster Management Research Institute, Ulsan, 44538, Republic of Korea
[3] National Disaster Management Research Institute, Ulsan, 44538, Republic of Korea
[4] National Disaster Management Research Institute, Ulsan, 44538, Republic of Korea
[5] National Disaster Management Research Institute, Ulsan, 44538, Republic of Korea
[6] Department of Ocean Engineering, Pukyong National University, Busan 48513, Republic of Korea
[7] Disaster Management HPC Technology Research, Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea

Suyeong Bay in Busan, which is the study area of the present study, faces Gwangalli Beach to the west and Haeundae Beach to the east. The width and depth of Suyeong River, which empties into the bay, increase as the river flows downstream toward the mouth and into the open sea. The mouth is a coastal plain, and almost triangular shaped. In this area, the cross section in contact with the open sea is very large; therefore, water flowing inside the bay is directly influenced by fluctuations in the open sea water. Busan is a typical coastal city with a dense population distributed near the bay (Fig. 1). If a super typhoon hits a geographical area such as Suyeong Bay, where the hinterland is a densely populated urban area with high utility value, massive damage can be expected near the surrounding coastline. In this study, the risk of flooding at the mouth of Suyeong Bay was investigated by considering storm surge and river discharge due to localized torrential rainfall accompanying a typhoon.

The objective of this study is to investigate the interaction between typhoon storm surge and river discharge at the Suyeong River mouth. A numerical modeling framework was established, encompassing a broad range of hydrological conditions. To achieve this, the track of Typhoon Maemi and the wind fields were preserved, while shifting river discharge was considered on a case-by-case basis.

Figure 1. Location of the study area.

METHODS

This section introduces the storm surge model, model domain, as well as calculations and data used for the pressure forcing, surface wind, river discharge, and water level conditions.

Storm Surge Model

Advanced Circulation Model for Oceanic, Coastal, and Estuarine Water (ADCIRC) is a finite element model that can simulate seawater circulation over a wide area for a long period while performing precise boundary treatment (Luettich, Westerink, and Scheffner 1992). The model can predict fluctuations in sea surface in diverse locations such as along the coast, on a continental shelf, and in estuaries. Moreover, ADCIRC has been designated as the basic model of the National Hurricane Center in the United States, and has been employed to forecast the impacts of hurricanes in coastal regions such as Florida and southern Louisiana, including New Orleans. It has been reported that the model demonstrated superior reliability in several studies (Weaver and Slinn 2004; Westerink et al. 2004).

Model Domain

The model domain was designated as a wide region that includes the entire Korean Peninsula and the South Sea off the peninsula, as well as the narrow area of Suyeong Bay. Calculation results from this large region were used as boundary conditions for the narrow area calculations (Fig. 2). Data regarding each grid are presented in Table 1. In this study, we used an unstructured triangular grid in which the size gradually decreased upon reaching a narrow study sea area from a wide region; this approach was employed to precisely simulate the actual coastlines. The coastlines and depths of the study area were derived from the 2011 digital chart published by the Korea Hydrographic and Oceanographic Administration (KHOA).

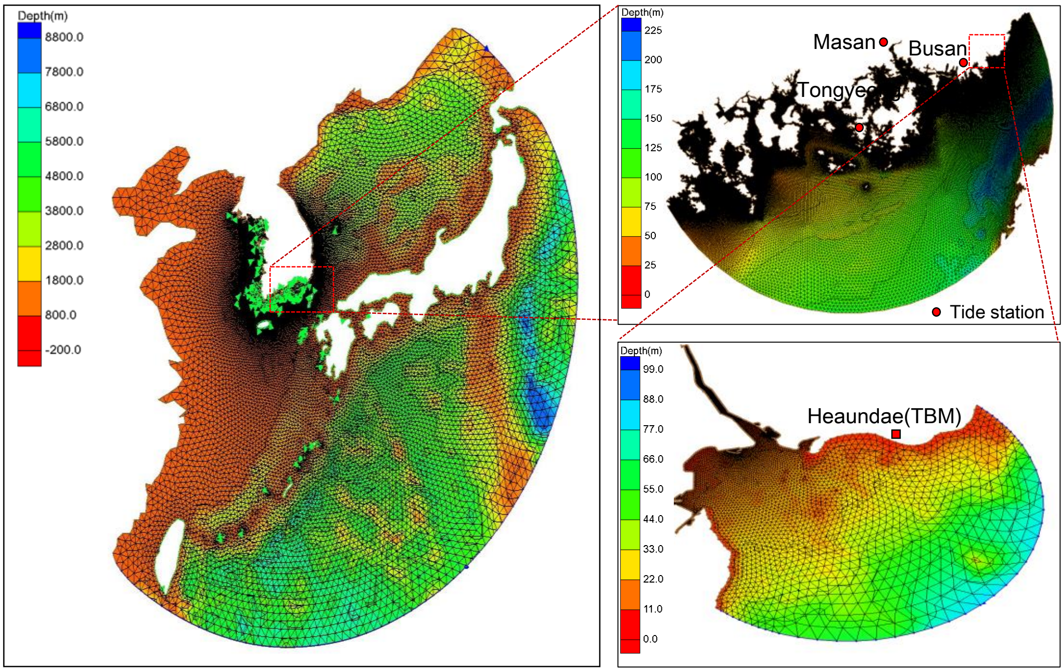

Figure 2. Domain of Advanced Circulation Model for Oceanic, Coastal, and Estuarine Water (ADCIRC) with bathymetry.

Table 1. Details of computation grids used in ADCRC.

Model Domain	Nodes	Elements
Korea	577,285	1,113,076
South Coast of Korea	161,539	309,430
Suyeong bay	2,927	5,393

Pressure Forcing and Surface Wind

The equation for calculating the pressure distribution is as follows (Holland 1980):

$$P(r) = P_c + (P_n - P_c)\exp -(R_{\max}/r)^B \qquad (1)$$

In the above equation, $P(r)$ refers to the pressure at a distance r from the center of the typhoon, P_c is the central pressure of the typhoon, P_n is the pressure outside the zone of the typhoon, B is the geometric parameter of the typhoon (range: 1–2.5), and $R_{\max}$ is the radius of the maximum wind. The wind velocity profile is often represented by the sum of the wind field of a symmetric circle calculated from the pressure distribution and the common wind field that follows the independent progress of the typhoon. When the progress direction is assumed as up, the asymmetric wind field inside a typhoon with strong winds can be expressed as the uppermost limit. The gradient wind can be calculated from the pressure distribution using the following equation (Holland 1980):

$$V(r) = -\frac{rf}{2} + \left[\left(\frac{rf}{2}\right)^2 + \frac{B}{\rho_a}\left(\frac{R_{\max}}{r}\right)^B (P_n - P_c)\exp -(R_{\max}/r)^B\right]^{1/2} \qquad (2)$$

In the above equation, $V(r)$ refers to the gradient at r, ρ_a is the air density, and f is the Coriolis coefficient. The weather data used in the numerical analysis were derived from the observed dataset of the Korea Meteorological Administration (KMA) collected during the progression of Typhoon Maemi. The weather data condition of ADCIRC was set as NWS 5. After obtaining weather data such as wind velocity, that is W(x), W(y), and atmospheric pressure for the nodal points of the entire study area, the input file (fort.22) was created. The track of Typhoon Maemi and the wind fields used are shown in Fig. 3.

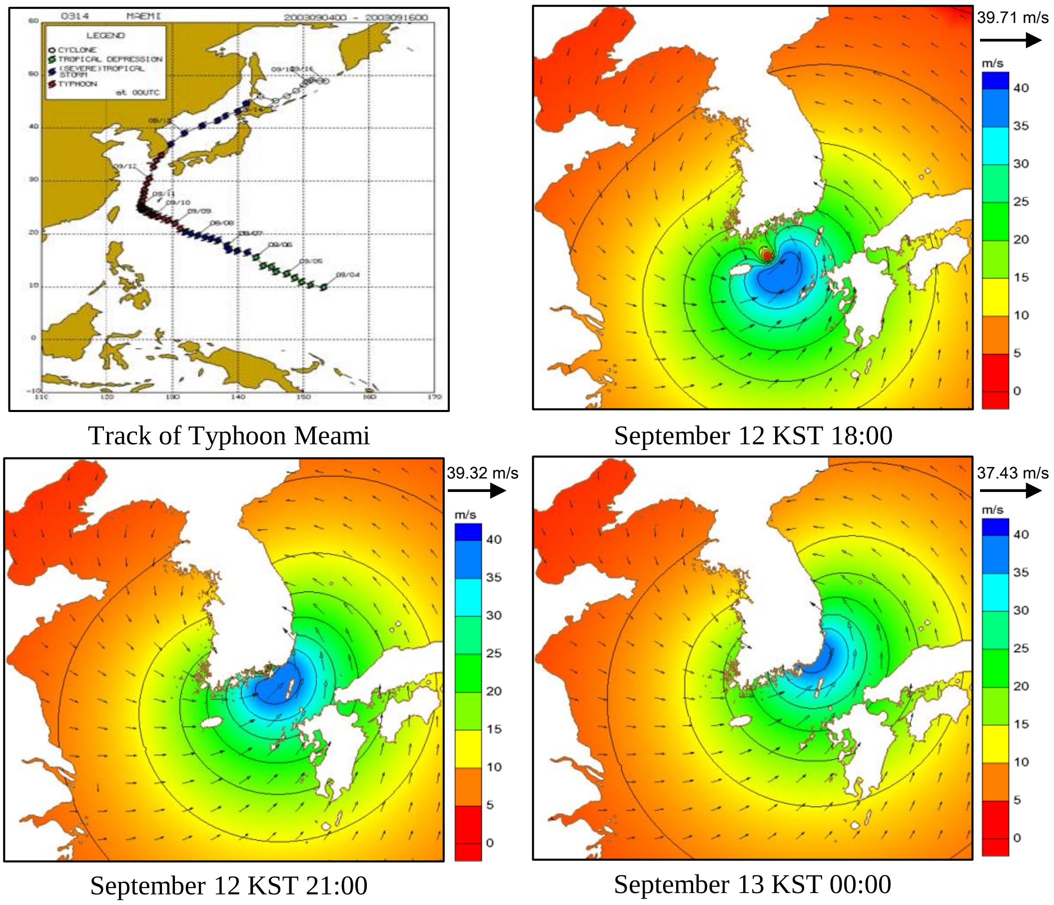

Figure 3. Track of Typhoon Maemi and wind fields used for numerical analysis.

River Discharge and Water Level Conditions

The estimated data for flooding of Suyeong River from May 1989 to April 1990 were compiled on monthly basis. Using the equation proposed by Officer (1976), the water storage and its flushing time were calculated. The results are summarized in Table 2.

The results indicate that the average water storage for February, May, and November is 4.0 m^3/s, which is moderate. However, the discharge in August when a typhoon hit the area or torrential rainfall occurred is approximately 1130 m^3/s, which is approximately 250 times the average value.

The experimental conditions were setup using typhoon pressure, wind, tide, and river discharge data as input data. Each condition is presented in Table 3.

Table 2. Calculated flushing time and total fresh water in suyeong Bay(Lee, Jo, and Kim, 1991).

Season	Total Fresh Water	River Discharge	Flushing Time
May	3,660,033	4	10.60
August	130,826,880	1,130	1.34
November	4,792,366	4	13.87
February	3,168,266	4	9.23

Table 3. Water level conditions in ADCIRC simulations.

Input	Case 1	Case 2	Case 3	Case 4
Tide (M_2, S_2, O_1, K_1)	○	○	○	○
River discharge(1130 m^3/s)		○		
Storm surge(Typhoon Maemi)			○	○

RESULTS

This section discusses the tide and surge validation data and simulation results.

Tide and Surge Validation

The tide data were applied with four major harmonic constituents (M_2, S_2, K_1, O_1) that were extracted using a harmonic analysis tool, T tide (Pawlowicz, Beardsley, and Lentz 2002); this analysis tool was used for the observed data during the arrival of Typhoon Maemi. Tide data of KHOA were also used. Busan and Heaundae harmonic constants are given in Table 4.

Table 4. Harmonic constant from KHOA.

	Busan		Heaundae	
WGS-84	35-05-41.2N 129-02-10.9E		35-13-08.2N 129-13-41.8E	
Tidal Constituents	Half Tidal Range	Phase	Half Tidal Range	Phase
M_2	40.0 cm	232.8°	29.1 cm	226.2°
S_2	18.9 cm	261.3°	14.1 cm	256.6°
O_1	4.4 cm	137.1°	3.1 cm	86.2°
K_1	1.6 cm	112.2°	14.1 cm	359.8°

Observed data and tidal simulation results were compared under the influence of Typhoon Maemi, as shown in Fig. 4. The simulation results were generally in agreement with the observed values at the Busan tidal station. Because there were no observed values during the influence of Typhoon Maemi in the Suyeong River area, these data were verified using the nonharmonic constant of the tidal bench mark (TBM) of Haeundae. The approximate higher high water (HHW) value at Haeundae TBM is 0.668 m, and that of the simulated ADCIRC tide is 0.631 m.

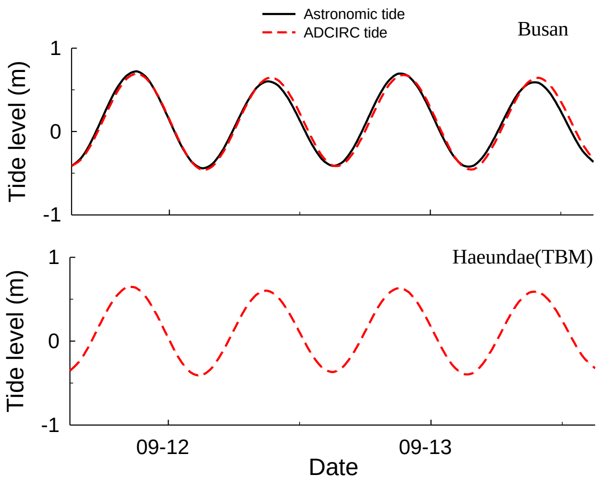

Figure 4. Comparison of simulated tide data and astronomic tide data during Typhoon Maemi in 2003.

During the arrival of Typhoon Maemi, pressure and wind fields were used as input values to simulate the storm surge. Fig. 5 shows a comparison of the simulated and observed values for the maximum surge levels. The predicted peak surge at Tongyeong closely matched the observed data. The predicted peak surge at the Masan tidal station is 0.2 m lower than the observed value, and the time of the peak surge also differed slightly. This is because the geographic features and the influence of river discharge were not considered. The predicted result at the Busan tidal station showed improved accuracy. During peak surge, it was not possible to compare the river data with observed values as there were no available data from nearby tidal stations or observation buoys; however, according to the impact analysis of tidal wave damage and the study by Hur et al. (2006), the calculated storm surge height of Suyeong River caused by Typhoon Maemi is 0.86 m. The results calculated using ADCIRC are 0.81 m in open sea area and 1.085 m inside the bay; a possible explanation for these results is that the water level increased when the storm surge infiltrated the narrow mouth of the bay.

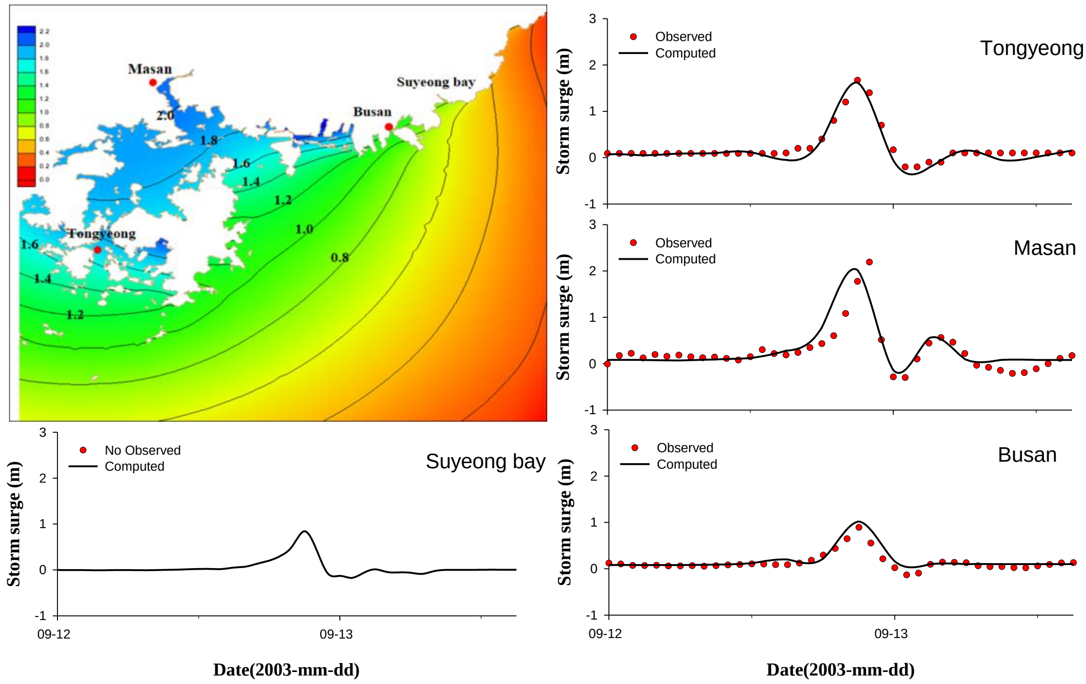

Figure 5. Time series of maximum surge levels.

Simulation Results

The water level fluctuations near Suyeong River at 21:00 on September 21, 2003 were analyzed using tide, storm surge, and river discharge data. Fig. 6 shows simulation results for each case at five stations near the river mouth and three offshore stations. When the river discharge, tide from the open sea, and storm surge (Case 4) were taken into consideration, the water level rose to 3.2 m.

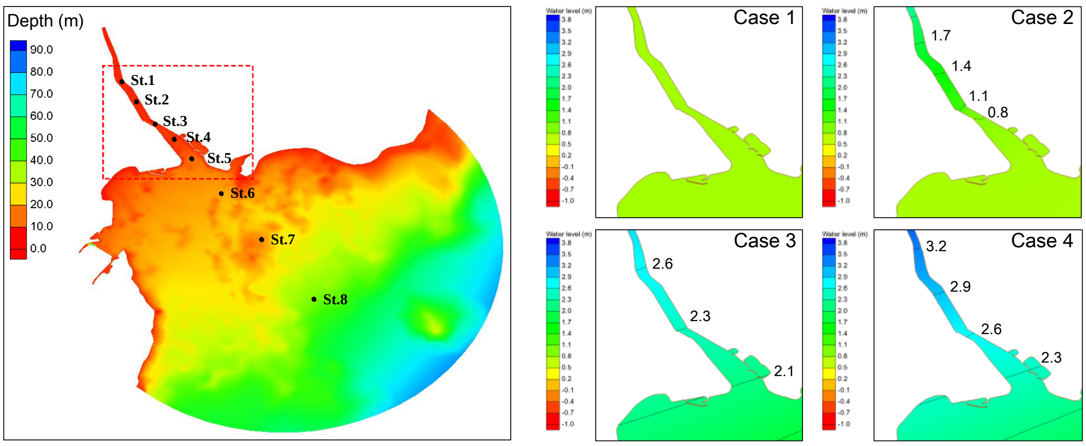

Figure 6. Images of water levels at 21:00 KST on September 12, 2003.

Table 5 and Figure 7 illustrate the water levels of Station 1 to Station 8 and the influence of river discharge. To illustrate the influence of river discharge on changes in the water level, the differences between Cases 2 and 1 and Cases 4 and 3 (see Table 3 for the case definitions) at Station 3 are computed as 0.297 m and 0.381 m, respectively. Thus, taking the river discharge into consideration resulted in higher water levels. The latter comparison showed a higher difference than the former due to interaction between the storm surge and flow. Even without considering the density current, the influence of river discharge was significant from a hydrodynamic perspective. Damage caused by typhoons can be severe near coastal areas and rivers. The findings from this study suggest that river flow should be considered when calculating storm surge in the future.

Table 5. Calculated Water Level.

Case	Water Level (EL.m)							
	St.1	St.2	St.3	St.4	St.5	St.6	St.7	St.8
Case 1 (Tide)	0.633	0.633	0.634	0.634	0.634	0.631	0.631	0.631
Case 2 (Tide+River discharge)	1.696	1.366	0.931	0.741	0.683	0.643	0.633	0.633
Case 3 (Tide+Storm surge)	2.32	2.309	2.278	2.126	1.984	1.502	1.181	0.903
Case 4 (Tide+Storm surge+River discharge)	3.267	2.926	2.659	2.397	2.219	1.651	1.276	0.951
Case 2 – Case 1 (River effect)	1.063	0.733	0.297	0.107	0.049	0.012	0.002	0.002
Case 4 – Case 3 (River effect)	0.947	0.617	0.381	0.271	0.235	0.149	0.095	0048

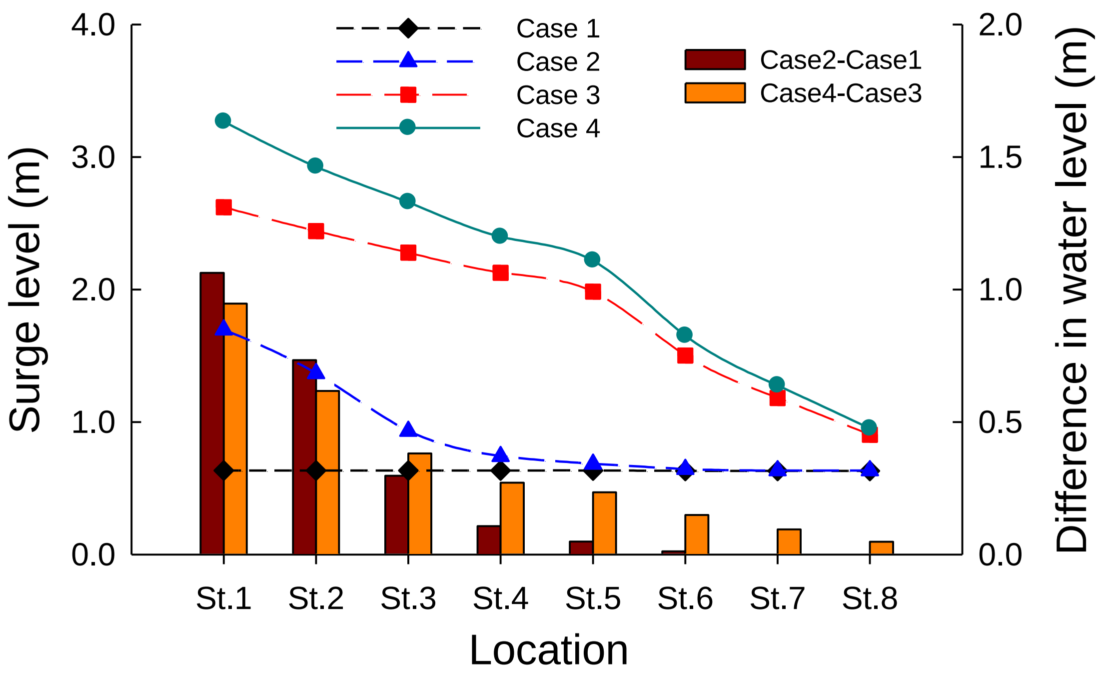

Figure 7. Water level fluctuations for the four Advanced Circulation Model for Oceanic, Coastal, and Estuarine Water (ADCIRC) cases.

CONCLUSIONS

This study investigated the interactions of storm surge and river discharge as Typhoon Maemi tracked across Suyeong Bay, Busan, South Korea. A storm surge model (ADCIRC) was implemented to calculate the storm surge height taking river discharge in a narrow bay area into consideration; the model preserved the spatial and temporal characteristics of the typhoon wind fields. The simulated tidal levels and surge levels from the model were generally in good agreement with observed data.

The case where river discharge was considered in the model along with tide and storm surge showed that the predicted water levels were higher than those obtained when river discharge was not considered. Thus, the findings highlight the need to consider river discharge when assessing the potential risk of flooding at the mouth of the bay, especially during typhoon conditions. Typically, only the tide and storm surge are considered during storm safety assessments, as the latter tends to dominate the flooding process. However, this can lead to underestimation of the risk, which can result in serious problems in urbanized coastal areas.

This research investigated a simple case study of the interaction between river discharge and storm surge in a narrow bay, and future work should focus on more complex conditions (i.e., variations in topography and bathymetry with high resolution). Following such research and further validation work, the proposed integrated model, which combines ocean waves, storm surge, and river discharge could find widespread use in risk assessment application in coastal zones.

REFERENCES

Heaps, N.S. 1983. Storm surges, 1967–1982, *Geophysical Journal International*, 74, 331–376.

Holland, G.J. 1980. An analytic model of the wind and pressure profiles in hurricanes, *Monthly Weather Review*, 108, 1212–1218.

Hur, D.S., G.S. Yeom, J.M. Kim, and K.S. Bae. 2006. Estimation of storm surges on the coast of Busan, *Journal of Ocean Engineering and Technology*, 20(3), 37–45.

Korea Hydrographic and Oceanographic Administration. http://www.khoa.go.kr.

Korea Meteorological Administration. http://www.kma.go.kr.

Lee, B.G., G.D. Jo, and D.S. Kim. 1991. A study on the seasonal variations of fresh water distribution and flushing time in Suyong Bay, *Journal of the Korean Society of Fisheries Technology*, 27(3), 170–177.

Luettich, R.A. Jr., J.J. Westerink, and N.W. Scheffner. 1992. *ADCIRC: An Advanced Three-dimensional Circulation Model for Shelves, Coasts and Estuaries. Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL*, U.S. Army Corps of Engineers, Dredging Research Program Technical Report DRP-92-6, Vicksburg, Mississippi, 137 p.

Officer, C.B. 1976. *Physical Oceanography of Estuaries and Associated Coastal Waters*, John Wiley and Sons, New York, 480 p.

Oh, I.S. and S.I. Kim. 1990. Numerical simulation of the storm surges in the seas around Korea, *Ocean Science Journal*, 25(4), 161–181.

Pawlowicz, R., B. Beardsley, and S. Lentz. 2002. Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE, *Computers and Geosciences*, 28(8), 929–937.

Prandle, D., and J. Wolf. 1978. The interaction of surge and tide in the North Sea and River Thames, *Geophysical Journal International*, 55(1), 203–216.

Weaver, R.J., and D.N. Slinn. 2004. *Effect of Wave Forces on Storm Surge*, Master's thesis, University of Florida, Gainesville, Florida, 68 p.

Westerink, J.J., J.C. Feyen, J.H. Atkinson, R.A. Luettich, C.N. Dawson, M.P. Powel, J.P. Dunion, H.J. Roberts, E.J. Kubatko, and H. Pourtaberi. 2004. A new generation hurricane storm surge model for southern Louisiana, *Bulletin of the American Meteorological Society, in review*.

Yoon, J.J., K.C. Jun, J.S. Shim, and K.S. Park. 2012. Estimation of maximum typhoon intensity considering climate change scenarios and simulation of corresponding storm surge, *Journal of the Korean Society for Marine Environment & Energy*, 15(4), 292–301.