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EVALUATION OF STORM SURGE BEHAVIOR DUE TO DIFFERENT TYPHOON TRACKS AND WIND SPEEDS ALONG THE COAST OF DAGUPAN CITY, LINGAYEN GULF, PHILIPPINES

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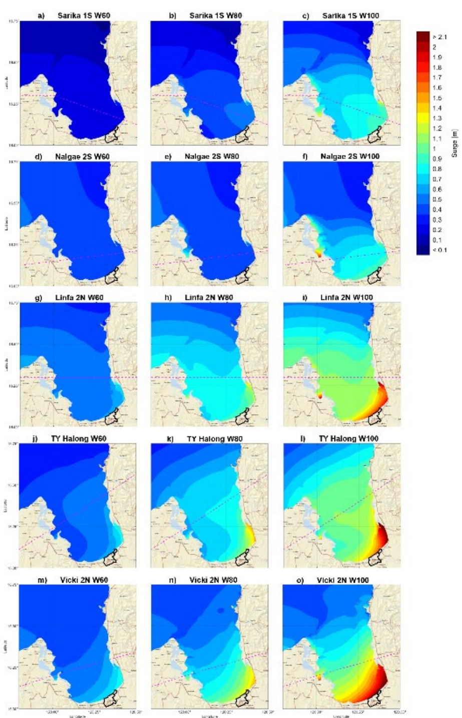
Graphical abstract



Abstract

Every year, an average of 19.4 typhoons traverse the Philippine Area of Responsibility and the country receives around nine landfalling typhoons. These typhoons can generate storm surges along the coasts and cause inundation of coastal communities. Dagupan City is a low-lying city located along the coast of Lingayen Gulf where 30% of its population live in the coastal barangays. As a coastal community located along the head of the Lingayen Gulf where the bathymetry is shallow, Dagupan city is susceptible to storm surges. This study aims to evaluate the storm surge behavior due to different typhoon tracks and windspeeds along the coast of Dagupan City. To achieve this objective, this study implements numerical simulation of storm surges using the Advanced Circulation (ADCIRC) model. A simple methodology is employed by selecting representative historical typhoons and creating synthetic typhoons by shifting the tracks along the latitude. Simulations of typhoons with different typhoon tracks reveal the critical tracks that give highest storm surges in Dagupan City. Finally, storm surges are simulated for windspeed intensities of 60, 80 and 100 knots which are applied to the identified critical tracks. The results of this study show that shifting the typhoon tracks affects the magnitude of storm surges in Dagupan City. Generally, the tracks that pass near the center of Lingayen Gulf generate the highest storm surge along the coast, however, eastward synthetic tracks near the mouth of the gulf can also potentially produce storm surges in Dagupan City. In addition, it is found that typhoon tracks coming from the West Philippine Sea can generate higher storm surges in Dagupan City compared to tracks from the Pacific Ocean. The highest storm surge generated by the representative historical typhoon is 1 m produced by Typhoon Vicki 1998 while a storm surge of 2 m could be potentially generated along Dagupan City by a typhoon with windspeed of 100 knots. The results of this study can be helpful in predicting storm surges for different typhoon tracks and windspeeds which can be used for coastal disaster preparedness in Dagupan City.

Keywords: storm surge, Dagupan City, Lingayen Gulf, ADCIRC, typhoon tracks

1.0 INTRODUCTION

The Philippines is an archipelagic country located in the Northwest Pacific Typhoon Basin, which is the most active typhoon generating basin. Every year, an average of 19.4 typhoons traverse the Philippine Area of Responsibility and around 9 of these typhoons make landfall in the country [1]. This makes the country exposed to coastal hazards such as storm surges, waves, and coastal erosion which may cause loss of lives and damages to coastal properties and infrastructure. There were many occurrences of storm surges that happened in the country, but the most devastating event was the storm surge generated by Typhoon Haiyan in San Pedro Bay in 2013. Typhoon Haiyan brought 7-8 m of storm surge in San Pedro Bay and killed 6,300 lives, most of which were due to drowning and trauma [2].

The magnitude of storm surge is influenced by the (1) typhoon-related parameters such as track, wind speed intensity, pressure drop, storm size and forward speed, and the (2) geographical area factors such as topography, bathymetry, reefs, and rivers [3]. The estimation of storm surge is thus very specific to the location of the study area. In the advancement of technology, numerical modelling is now an important tool in the investigation and prediction of storm surges for coastal hazard assessment [4,5]. Many studies have used numerical modelling for storm surge prediction and the output of these numerical studies gave acceptable results [6,7]. To carry-out numerical modelling of storm surges, the surface wind and pressure fields are needed and therefore the required input typhoon parameters, such as track, and intensity, critically influence the results of the storm surge models [8].

As the wind intensity of the typhoon increases, the generated storm surge also increases. This was presented in the study by Ma et al. (2022) where the increase in typhoon intensity also increases the storm surges [9]. In addition, the increase in intensity presents a noununiform and nonlinear patterns of storm surges around their study area [9]. Several studies determined the effects of typhoon paths on storm surge using numerical modelling. A study by Du et al. (2020) performed nine storm surge simulations based on three historical typhoons and found that the typhoon track significantly affects the storm surges in Pearl River Estuary [10]. Islam and Takagi (2020) considered the typhoon track in the sensitivity analysis of typhoon parameters on storm surges in Tokyo Bay and found that the critical track that produced the highest storm surges typically made landfall southwest of the central Tokyo Bay axis [11]. Yuxing et al. (2020) performed numerical modelling and evaluated the impacts of typhoon parameters on storm surge based on Hato storm over the Pearl River Mouth, China. They found that the sensitivity in typhoon landfall point changes the storm surge distribution [12]. Villalba et al. (2022) also determined the effects of varying typhoon tracks in Manila Bay and observed that the behavior of storm surge variation along the coast is mostly influenced by the bathymetry and shape of the bay [13].

Dagupan City is a low-lying coastal city in the Province of Pangasinan located along the inner coast of Lingayen Gulf. It is considered as the center of commercial and financial activities in the province and the next destination for Information Technology and Business Process Management (IT-BPM) industries in the country. Due to the high frequency of typhoons entering the country and the shallow bathymetry along the inner Lingayen Gulf coastline, Dagupan City is prone to storm surges. As of 2015 data of the Philippine Statistics Authority, around 30% of the city's population live along the coastal barangays of Bonuan Binloc, Bonuan Boquig, Bonuan Gueset and Pugaro [14]. Very few studies have been conducted in Lingayen Gulf where Dagupan City is located, specifically in understanding the storm surge response in the gulf. In addition, there are currently no tide gaging stations in the Lingayen Gulf that could be used for tides and storm surge studies [15].

This study aims to explore the storm surge behavior due to different typhoon tracks and windspeeds along the coast of Dagupan City in Lingayen Gulf. The results of this study will provide understanding to the storm surge hazard in Dagupan City which is important in disaster prevention and mitigation strategies such as in coastal hazard information and education campaigns, early warning systems, development of coastal zoning policies, identification of evacuation areas, and initial planning of coastal hazard protection structures. Essentially, with the prediction of typhoon wind strength and track by weather forecasting agencies, the possible storm surge height along Dagupan coastline could be estimated which is very much important in disaster preparedness and prevention.

2.0 METHODOLOGY

To be able to achieve the objective of this research, the Advanced Circulation (ADCIRC) model was implemented in the simulation of storm surges. First, a computational model domain was developed and calibrated using the observed tidal data in San Fernando, La Union. Next, historical typhoon data were collected using the best track data from the Joint Typhoon Warning Center and the Japan Meteorological Agency. From the historical data, representative historical typhoons were selected based on the track and intensity. The use of hypothetical typhoons for storm surge estimation have been useful for generating information that could be used for disaster risk management [3,11]. In addition to the historical typhoon tracks, this study also used synthetic typhoons derived from the selected historical typhoons. The synthetic typhoons were developed by shifting the selected historical typhoon track by 0.1° interval along the latitude covering the Lingayen Gulf area. Third, storm surge simulations were performed using the historical typhoons and synthetic typhoons. The results of the simulations were processed and analyzed to assess the effects of typhoon tracks on storm surges along Dagupan City coastline in Lingayen Gulf. In this study, we also evaluated the effects of windspeeds by simulating different windspeeds of 60, 80, and 100 knots using the identified critical tracks.

2.1 Model Description

In this study, the Advanced Circulation (ADCIRC) model, a finite-element based hydrodynamic circulation code developed by Leuttich and Westerink, was used to numerically simulate the storm surge [16]. The ADCIRC model was selected for this study because it is open-source and is widely used and verified in tidal simulations, storm surge studies, and coastal inundation modelling [17,18,19]. In addition, it uses an unstructured flexible mesh which has an advantage of modelling complex coastline of interest with high resolution mesh while keeping other areas with coarse resolution which makes it computationally efficient. The two-dimensional depth-integrated form (2DDI) of the ADCIRC model which solves the shallow water equations was implemented in this study. The governing equations in spherical coordinates are as follows:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{Rcos\varphi}\left[\frac{\partial UH}{\partial \lambda} + \frac{\partial (VHcos\,\varphi)}{\partial \varphi}\right] = 0, \quad (1)$$

$$\frac{\partial U}{\partial t} + \frac{1}{Rcos\varphi}U\frac{\partial U}{\partial \lambda} + \frac{1}{R}V\frac{\partial U}{\partial \varphi} - \left[\frac{\tan\varphi}{R}U + f\right]\mathrm{V} =$$

$$-\frac{1}{Rcos(\varphi)}\frac{\partial}{\partial \lambda}\left[\frac{p_s}{\rho_0} + g(\zeta - \alpha\eta)\right] + \frac{1}{H}M_\lambda + \frac{\tau_{s\lambda}}{\rho_0 H} - \frac{C_f(U^2+V^2)^{\frac{1}{2}}}{H}U, \quad (2)$$

$$\frac{\partial V}{\partial t} + \frac{1}{Rcos\varphi} U \frac{\partial V}{\partial \lambda} + \frac{1}{R} V \frac{\partial V}{\partial \varphi} - \left[\frac{\tan\varphi}{R} U + f\right] U =$$

$$-\frac{1}{R}\frac{\partial}{\partial \varphi}\left[\frac{p_s}{\rho_0} + g(\zeta - \alpha\eta)\right] + \frac{1}{H} M_\varphi + \frac{\tau_{s\varphi}}{\rho_0 H} - \frac{C_f (U^2+V^2)^{\frac{1}{2}}}{H} V, \tag{3}$$

where t is time; λ and φ are longitude and latitude, respectively; ζ is the free surface elevation relative to the geoid; H is the total water depth, $H = \zeta + h$, where h is the bathymetric depth relative to the geoid; U and V are depth-integrated west-east and south-north components of velocity, respectively; f is the Coriolis parameter, $f = 2\Omega sin\varphi$, where Ω is the angular speed of the Earth; p_s is the atmospheric pressure at free surface, α is the effective Earth elasticity factor, ρ_o is the reference density of water; g is the acceleration due to gravity; η is the Newtonian equilibrium tide potential; R is the mean radius of the Earth; $\tau_{s\lambda}$ and $\tau_{s\varphi}$ are longitudinal and latitudinal components of free surface shear stress; M_λ and M_φ are the momentum diffusion terms in the longitude and latitude, respectively; and C_f is the bottom friction coefficient.

For limited typhoon information, the study used the symmetric Holland 1980 Typhoon Model which is already integrated in the ADCIRC model. This parametric typhoon model is widely used and is capable of satisfactorily producing wind results especially at the inner part of the typhoon [13]. Using this typhoon model, the wind distribution and pressure field can be generated given the typhoon central pressure, maximum windspeed, and radius of maximum windspeed. The Holland 1980 model for wind and pressure fields are described as follows [20]:

$$p(r) = p_c + (p_n - p_c) e^{-\left(\frac{A}{r^B}\right)}, \tag{4}$$

$$V(r) = \left[\left(\frac{R_{mw}}{r}\right)^B e^{1-\left(\frac{R_{mw}}{r}\right)^B} V_{mw}^2 + \left(\frac{r^2 f^2}{4}\right)\right]^{0.5} - \frac{rf}{2}, \tag{5}$$

where r is the distance from the center of the typhoon; V is the gradient wind at radius r; p is the pressure at radius r; p_c is the central pressure; p_n is the ambient pressure; R_{mw} is the radius of maximum wind speed; V_{mw} is the maximum wind speed; f is the Coriolis parameter; and A and B are scaling parameters, given by

$$A = R_{mw}^B, \tag{6}$$

$$B = \rho e \frac{V_{mw}^2}{P_n - P_c}, 1 < B < 2.5, \tag{7}$$

here ρ is the density of air. While the Holland 1980 typhoon model is simple and can generate wind and pressure distributions from a few typhoon parameters, it assumes that the typhoon is axisymmetric.

2.2 Model configuration

The model domain used for the ADCIRC simulations is presented in Figure 1. This model mesh was developed with 200 m mesh size along the coast and 1 km mesh size in the open ocean boundary. The model mesh has a total of 22,285 nodes and 44,142 elements. The open ocean boundary of the model domain is driven by eight tidal constituents (K1, K2, M2, N2 O1, P1, Q1, and S2) which were generated from the Le Provost Tidal database. The bathymetric data that was used in the model mesh was obtained from digitizing the National Mapping and Resource Information Authority (NAMRIA) Bathymetric Chart 4209 [21] and from the General Bathymetric Chart of the Oceans (GEBCO) [22]. Figure 2 shows the bathymetry of Lingayen Gulf with depths of 0-100 m. The bathymetry of Lingayen Gulf shows a relatively shallow and mild sloping bathymetry at the head of the gulf where Dagupan City is located.

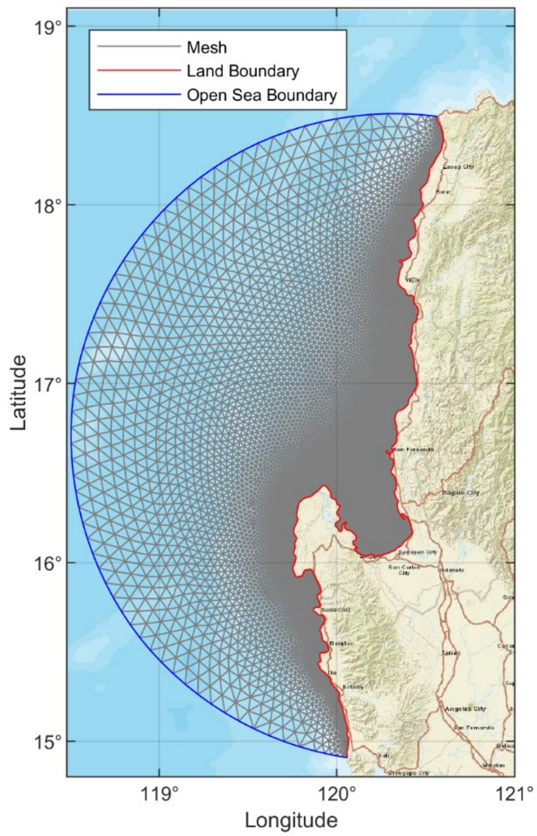


Figure 1 ADCIRC model domain and mesh of the study

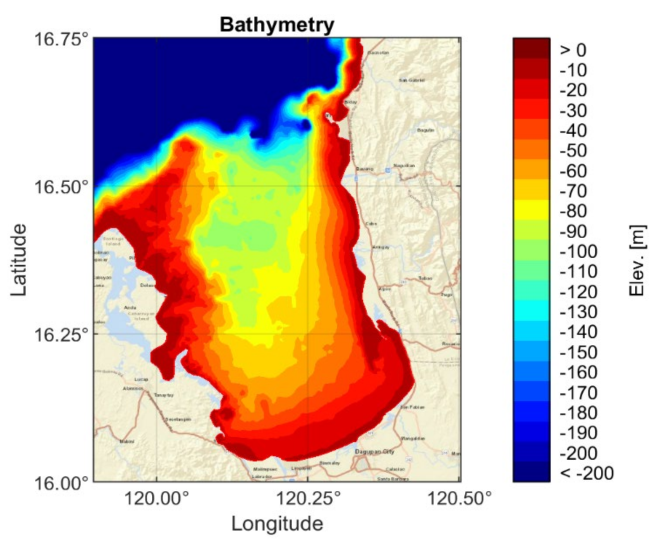


Figure 2 Bathymetry of Lingayen Gulf

2.3 Model Validation

The ADCIRC computational mesh was validated using the observed tide data from the nearest NAMRIA tide station in San Fernando, La Union. Figure 3 shows the comparison of the observed tide and simulated tide for the period September 1-30, 2016. The calculated root-mean-square error (RMSE) of the actual and simulated tides is 3.3 cm, which is considered acceptable [10]. There are no tide stations located inside of the Lingayen Gulf, and therefore there are no data that could be used for the validation of the simulated storm surges.

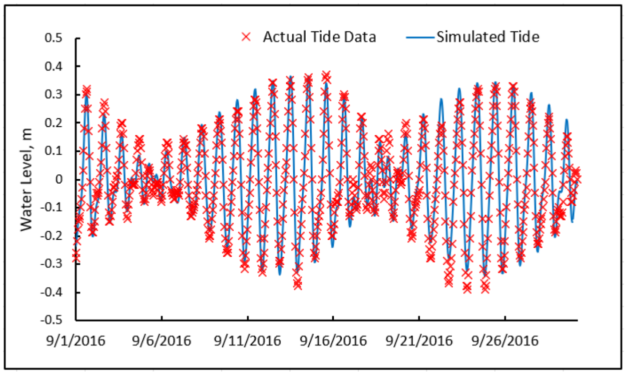


Figure 3 Time series of actual tide data and simulated tide at San Fernando, La Union from September 1-30, 2016

2.4 Selection of Historical Typhoons and Creation of Synthetic Typhoons

To determine the representative historical typhoons, the methodology in determining critical typhoons introduced by Camelo et al. (2017) was implemented in this study [23]. A search radius of 150-km centered from Dagupan City coastline was used to shortlist the historical typhoons using the best track data from the Joint Typhoon Warning Center (JTWC) and the Japan Meteorological Agency (JMA) within the period of 1977-2019 [24][25]. These typhoons were then ranked according to the maximum windspeed and distance from the study area. In addition, considering the counterclockwise direction of typhoon winds, only tacks traversing north of the study area and east of the study area were considered. Further analysis of historical typhoon parameters within the search radius showed that the minimum recorded historical central pressure is 940 hPa and the highest recorded 10-min maximum sustained windspeed is 45 m/s [15].

Table 1 presents the selected representative historical typhoons and Figure 4 shows the tracks of these typhoons. Typhoon Sarika, and Typhoon Nalgae originated from the Pacific Ocean while Typhoon Linfa, Typhoon Halong and Typhoon Vicki came from the West Philippine Sea. From these typhoons, synthetic typhoons were created by moving the tracks along the latitude with an interval of 0.1 degree north and south within the area of the Lingayen Gulf. Overall, there were 28 different typhoon tracks that were simulated.

Table 1 Selected representative historical typhoons

Year	Name	Central Pressure near Study Area (hPa)	Max 10-min sustained windspeed near study area (m/s)	Forward Speed (kph)
2016	Sarika	965	40	36
2011	Nalgae	965	40	29
2003	Linfa	985	25	25
2008	Halong	975	30	18
1998	Vicki	980	30	11

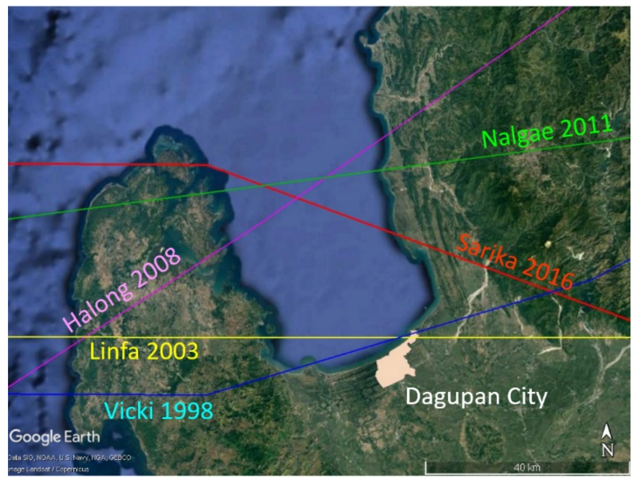


Figure 4 Tracks of selected representative historical typhoons

Analysis of the results of the simulations of different typhoon tracks determined the critical tracks that produced the highest storm surges among the representative historical tracks and shifted tracks. Using the critical tracks that were determined in the evaluation of different typhoon tracks on storm surges, additional synthetic typhoons were created by changing the intensity of the critical tracks. In order to determine the parameters that will be used in the development of synthetic typhoons with different windspeeds, analysis of the relationships of the central pressure to the maximum windspeed and radius of maximum windspeed was done using the JTWC typhoon data. The central pressure, maximum windspeed and radius of maximum windspeed were extracted from the typhoons that passed the 150-km search radius from 2001-2018.

Relationships between the central pressure and 1-minute sustained windspeed, and central pressure and radius of maximum windspeed were determined. Analysis showed that as central pressure decreases, the wind intensity increases (Figure 5). Meanwhile, the radius of maximum windspeed generally decreases as the central pressure decreases (Figure 6). However, the correlation is relatively low and the range of the radius of maximum wind is relatively wide for corresponding central pressures.

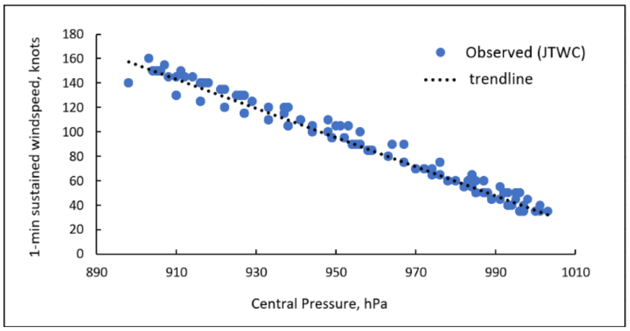


Figure 5 Relationship of Central Pressure to Maximum Wind

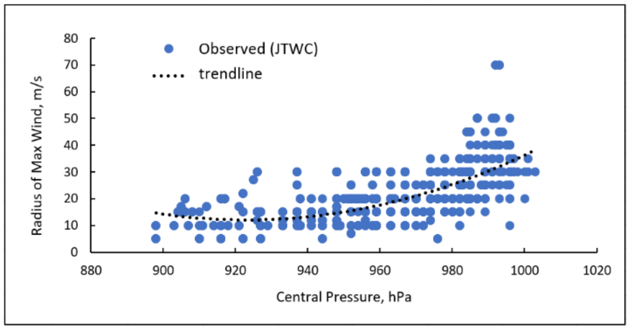


Figure 6 Relationship of Central Pressure to Radius of Maximum Wind

To vary the windspeed, we selected three windspeeds – 60, 80, 100 knots, which represent the Typhoon, Strong Typhoon, and Very Strong Typhoon categories in the World Meteorological Organization (WMO) typhoon classification, respectively [26]. Table 2 shows the parameters selected for the typhoon wind scenarios based on Figure 5 and Figure 6.

Table 2 Parameters of Typhoon Wind Scenarios

Wind Scenario	Vmax (knots) (1-min sustained)	Pc (hPa)	Rmax (nm)
W60	60	980	20
W80	80	963	20
W100	100	944	20

3.0 RESULTS AND DISCUSSION

This section presents the results and discussion of the simulations of storm surges using the Advanced Circulation model. Dagupan City is located at the inner part of the Lingayen Gulf along the mild sloping coast at the head of the gulf. We have selected five representative historical typhoons, namely, TY Sarika 2016, TY Nalgae 2011, TY Linfa 2003, TY Halong 2008 and TY Vicki 1998. These typhoons have different typhoon track approaches and directions with respect to the Lingayen Gulf. Based on the selected representative historical typhoon tracks, synthetic tracks were created by shifting the historical track by an interval of 0.1° latitude covering the area of the Leyte Gulf. By shifting the tracks, we aim to understand how the location of the tracks affects the storm surges along the coasts of Lingayen Gulf where Dagupan City is located. The historical typhoon data used in the simulations were obtained from the best track data of the Joint Typhoon Warning Center. Since the historical typhoon have different typhoon parameters, discussion of the results is referred to each selected representative historical typhoon. In the analysis of results, we present the surface plots of the simulated maximum water surface elevation (maximum storm tide) and the simulated maximum storm surge for the representative historical typhoon. The simulated maximum storm surge is calculated by subtracting the simulated astronomical tides to the simulated water surface elevations and getting the maximum values at all time steps. Then for the shifted tracks, we present the surge difference with respect to the base historical typhoon track. First, the results of the two typhoons originating from the Pacific Ocean are discussed followed by the three historical typhoons from the West Philippine Sea. From the analysis of storm surges generated from the different tracks, we then determined the critical track per historical typhoon group of synthetic tracks. The critical tracks were used to simulated the storm surges for different maximum windspeeds of 60, 80 and 100 knots.

3.1 TY Sarika 2016

Typhoon Sarika originated from the Pacific Ocean and traversed the Lingayen Gulf with a maximum 10-minute sustained windspeed of 40 m/s on October 16, 2016. The track of TY Sarika is towards the northwest direction. There are three synthetic typhoons created by shifting the base historical track of TY Sarika along the latitude. Figure 7 shows the results of the simulations. The simulated maximum water level along the coast of Dagupan City is 0.6 m and the maximum storm surge ranges at 0.4-0.5 m. Shifting the TY Sarika track northward decreases the storm surges while shifting it southward closer to Dagupan City increases the storm surges. The critical track that produces the highest storm surge along Dagupan City is the Sarika 1S track, which is the track shifted 0.1° latitude south of the base historical TY Sarika track.

3.2 TY Nalgae 2011

Similar to TY Sarika 2016, Typhoon Nalgae was formed in the Pacific Ocean and passed the Lingayen Gulf on October 1, 2011, with a maximum 10-minute sustained windspeed of 40 m/s. Both TY Nalgae and TY Sarika are stronger typhoons compared to the other selected representative historical typhoons. The track of TY Nalgae follows a westward direction and shifting the tracks along the latitude produced five synthetic typhoons that were simulated in this study. The results of the simulations are presented in Figure 8. The simulated maximum water level and maximum storm surge along the coast of Dagupan City produced by TY Nalgae is 0.7 m and 0.6 m, respectively. Shifting the track of TY Nalgae northward decreases the storm surge at the inner Lingayen Gulf and along the coast of Dagupan City. Meanwhile, shifting TY Nalgae track southward increases the storm surge but further moving it closer along the coast decreases the storm surge in Dagupan City. The critical track that would give the highest storm surge in Dagupan City based on the track of TY Nalgae is the Nalgae 2S track, which is the track shifted 0.2° latitude southward.

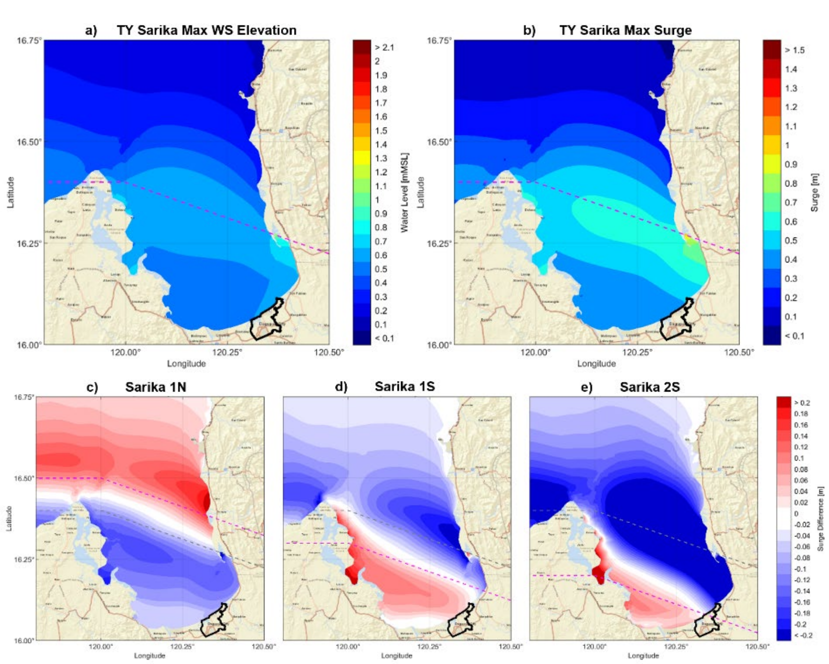


Figure 7 Surface plots of simulated (a) maximum water surface elevation (storm tide), (b) storm surge, and (c) – (e) surge difference of synthetic tracks with respect to the original historical typhoon track of TY Sarika 2016. The pink dashed line represents the tracks used in the simulation and the gray dashed line in (c) – (e) is the track of TY Sarika. Polygon with black solid line represents the boundary of Dagupan City.

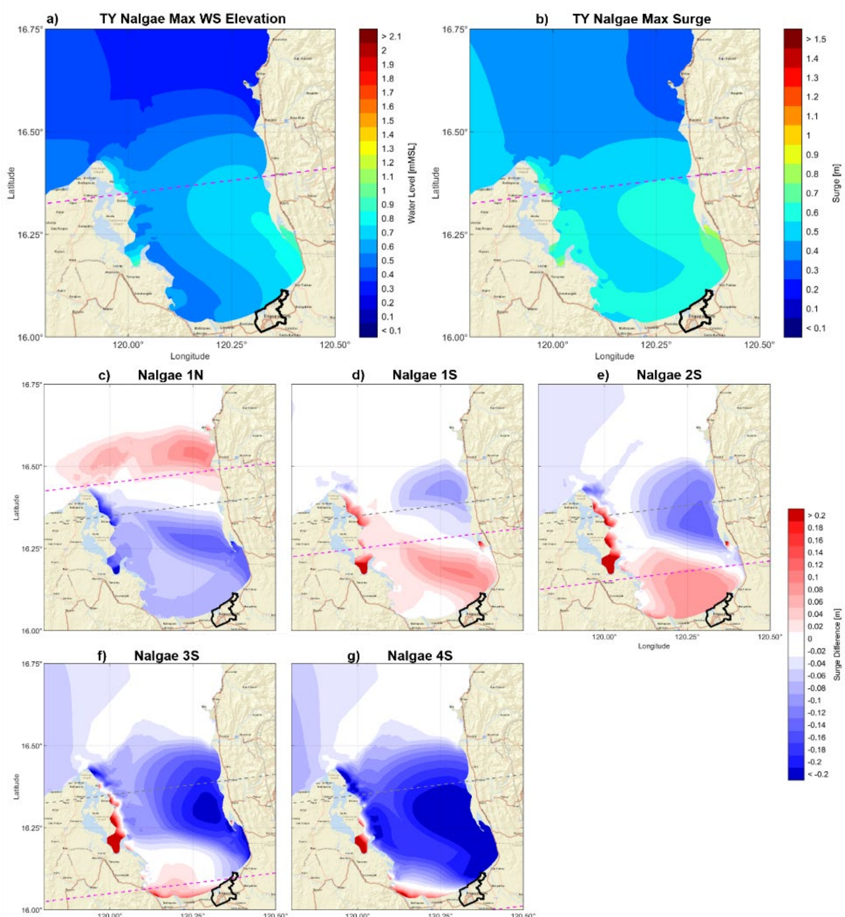


Figure 8 Surface plots of simulated (a) maximum water surface elevation (storm tide), (b) storm surge, and (c) – (g) surge difference of synthetic tracks with respect to the original historical typhoon track of TY Nalgae 2011

3.3 TY Linfa 2003

Typhoon Linfa crossed the Lingayen Gulf on May 27, 2003, with a relatively low maximum 10-minute sustained windspeed of 25 m/s. Even though it has a relatively low windspeed, TY Linfa was selected because it directly tracked Dagupan City. TY Linfa originated in the West Philippine Sea and its track follows a horizontal eastward track. Shifting the track of TY Linfa along the latitude created five synthetic typhoons that were simulated. The results of the simulations of TY Linfa and its synthetic tracks are presented in Figure 9. The simulated maximum water level generated by TY Linfa along the coast of Dagupan City is 0.3 m and the maximum storm surge is 0.4 m. Shifting the track of TY Linfa southward where the track already traverses land decreases the storm surge in Dagupan City. Shifting the track of TY Linfa northward increases the storm surge in Dagupan City, especially at the eastern section of the Lingayen Gulf. Synthetic tracks Linfa 2N, Linfa 3N and Linfa 4N produced similar storm surge response in Dagupan City and are considered critical to the study area.

3.4 TY Halong 2008

Typhoon Halong came from the West Philippine Sea and passed the Lingayen Gulf on May 17, 2008. Its track is directed northeast making it parallel to the mouth of Lingayen Gulf. Six synthetic typhoons were created by shifting the track of TY Halong along the latitude. Illustrated in Figure 10 are the results of the simulations for TY Halong and its synthetic tracks. The maximum water surface elevation and the calculated storm surge generated by historical TY Halong along the coast of Dagupan City are 0.7 m and 0.8 m, respectively. Comparison of the surge differences between synthetic tracks and the base TY Halong track showed that further shifting the track northward or southward decreases the storm surge along the coast of Dagupan City. Surprisingly, the historical TY Halong track is the critical track for the northeast directed track.

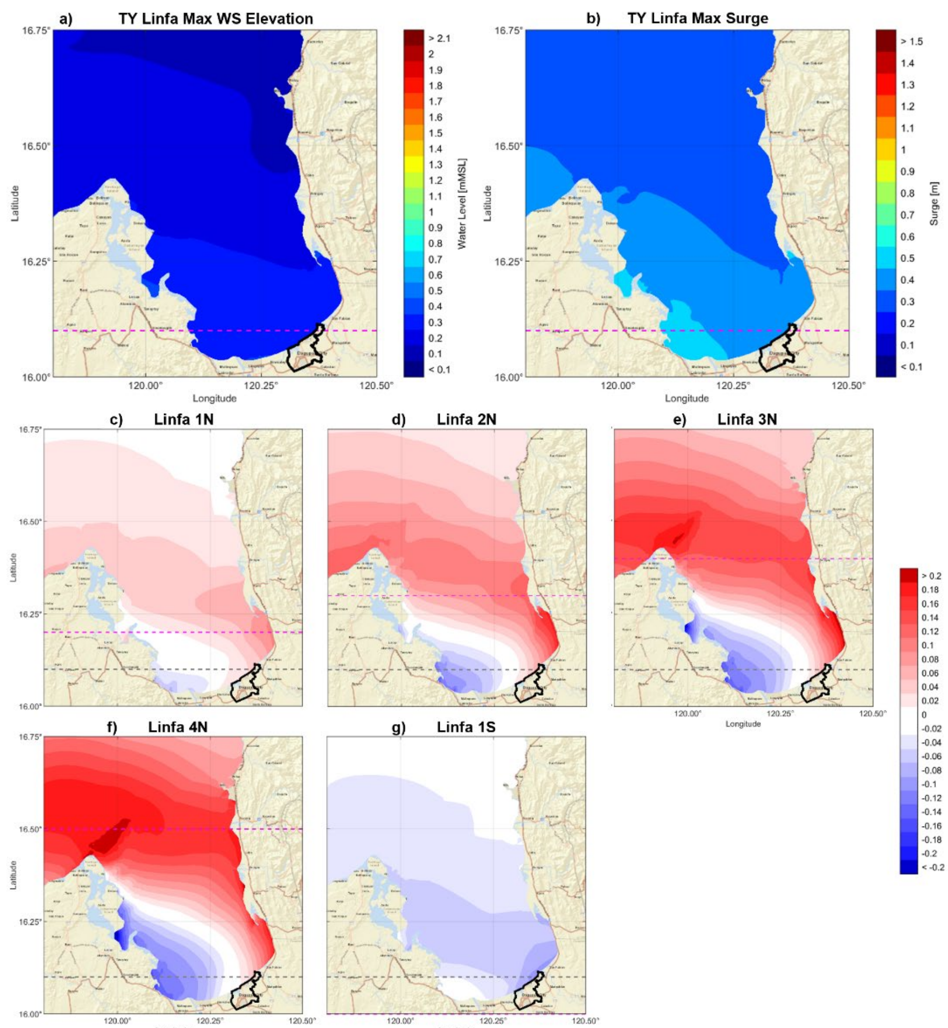


Figure 9 Surface plots of simulated (a) maximum water surface elevation (storm tide), (b) storm surge, and (c) – (g) surge difference of synthetic tracks with respect to the original historical typhoon track of TY Linfa 2003

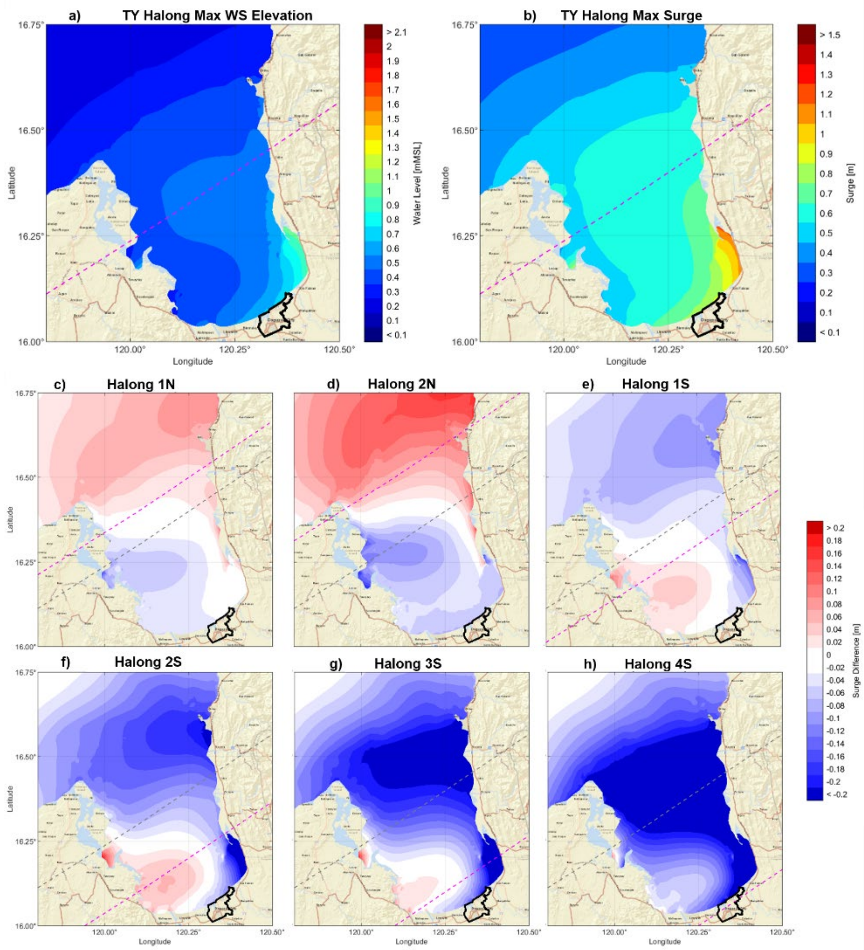


Figure 10 Surface plots of simulated (a) maximum water surface elevation (storm tide), (b) storm surge, and (c) – (h) surge difference of synthetic tracks with respect to the original historical typhoon track of TY Halong 2008

3.5 Typhoon Vicki 1998

Typhoon Vicki traversed the Lingayen Gulf on September 19, 1998, with a maximum 10-minute sustained windspeed of 30 m/s. The path of TY Vicki came from the West Philippine Sea and directed towards West-Northwest. There are four synthetic typhoons created from TY Vicki. Figure 11 presents the results of the simulations using TY Vicki and its synthetic typhoon tracks. Among the selected representative historical typhoons, TY Vicki produced the highest simulated water level and storm surge along Dagupan City with magnitudes of 1.1 m and 1 m, respectively. Shifting the track of TY Vicki northward increases the storm surge along Dagupan, however, further shifting it near the mouth of Lingayen Gulf decreases the storm surge along the inner gulf. The critical track that gives the highest storm surge in Dagupan City for this typhoon direction is synthetic track Vicki 2N.

3.6 Alongshore Distributions of Peak Storm Surges along the coasts of Lingayen Gulf for the Different Typhoon Tracks

While the focus of this study is the determination of the peak storm surges along Dagupan City, we also evaluated the alongshore distributions of peak storm surges along the coasts of Lingayen Gulf with regards to the sensitivity of shifting the typhoon tracks. Figure 12 presents the alongshore distributions of simulated peak storm surge levels along the coasts of Lingayen Gulf for all the tracks per typhoon group. Here, we can see that there is localized amplifications of peak storm surges along the coasts of the municipalities of Santo Tomas in the eastern side and Alaminos in the western part of the gulf. This is because Santo Tomas and Alaminos have concave coastlines. Large variation of storm surges is observed along the inner eastern and western side of the gulf as compared to the head of the gulf where Dagupan coast is located. This means that storm surges at the inner eastern and western side of the gulf are sensitive to typhoon tracks. In addition, we observe that there is relatively large variation of peak surges for TY Halong and TY Vicki group of tracks along the eastern side of the gulf compared to the western side of the gulf. Compared to the study of Villalba et al. (2022) in Manila Bay where the simulated peak surges are always found along the coast of Pampanga for different typhoon tracks, this study showed that the pattern of variations of peak surges along Lingayen Gulf is not the same for different typhoon tracks. For the case of Lingayen Gulf, the critical typhoon track for Dagupan City will not be the same for other coastal areas. Thus, it is important to evaluate the peak surges for different typhoon tracks for other coastal areas as well.

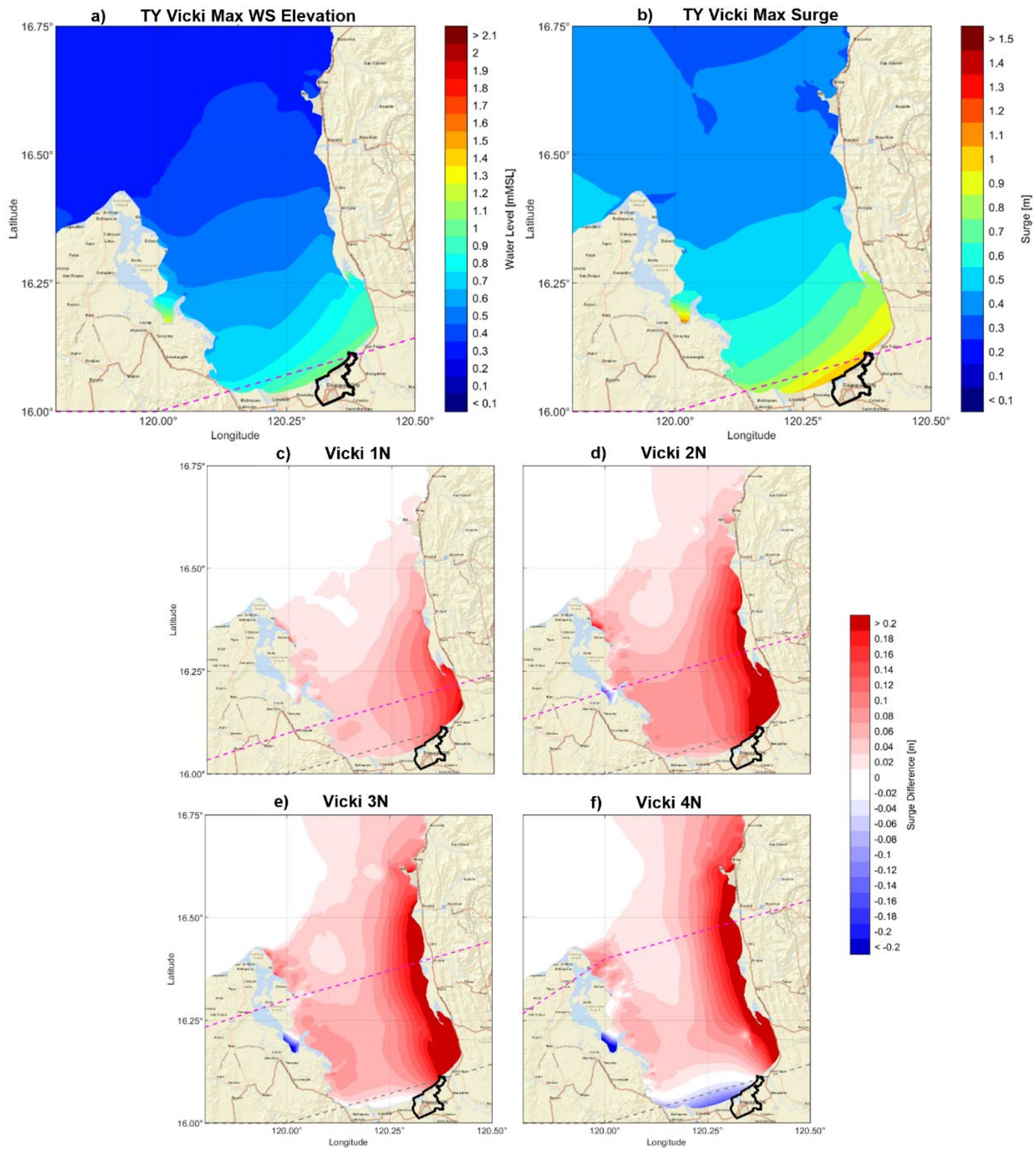


Figure 11 Surface plots of simulated (a) maximum water surface elevation (storm tide), (b) storm surge, and (c) – (f) surge difference of synthetic tracks with respect to the original historical typhoon track of TY Vicki 1998

3.7 Evaluation of Different Windspeeds on Storm Surges

To be able to help in the coastal disaster preparedness of Dagupan City, we also simulated the storm surges for different windspeeds. The effect of increasing the maximum windspeeds on storm surges increases the magnitude of storm surges along the coast [13]. Determining the possible magnitude of storm surges for different windspeeds will be useful for forecasting the magnitude of the storm surge given the intensity of the typhoon. This will also help in coastal disaster preparation especially in early warning systems.

Figure 13 shows the surface plots of the storm surges for different wind intensities of 60, 80 and 100 knots for the identified critical tracks. This figure can be used for predicting the possible storm surges in Dagupan City for similar typhoon tracks and intensity. As expected, increasing the wind intensity results to increased storm surge levels. The synthetic tracks Sarika 1S and Nalgae 2S which originate from the Pacific Ocean produced less simulated storm surges compared to tracks Linfa 2N, TY Halong, and Vicki 2N which all come from the West Philippine Sea. We find that the maximum simulated storm surge reached up to 2.2 m produced by the synthetic typhoon Vicki 2N. However, it should be noted that historically there are no strong typhoons with wind intensity of 100 knots that passed the study area.

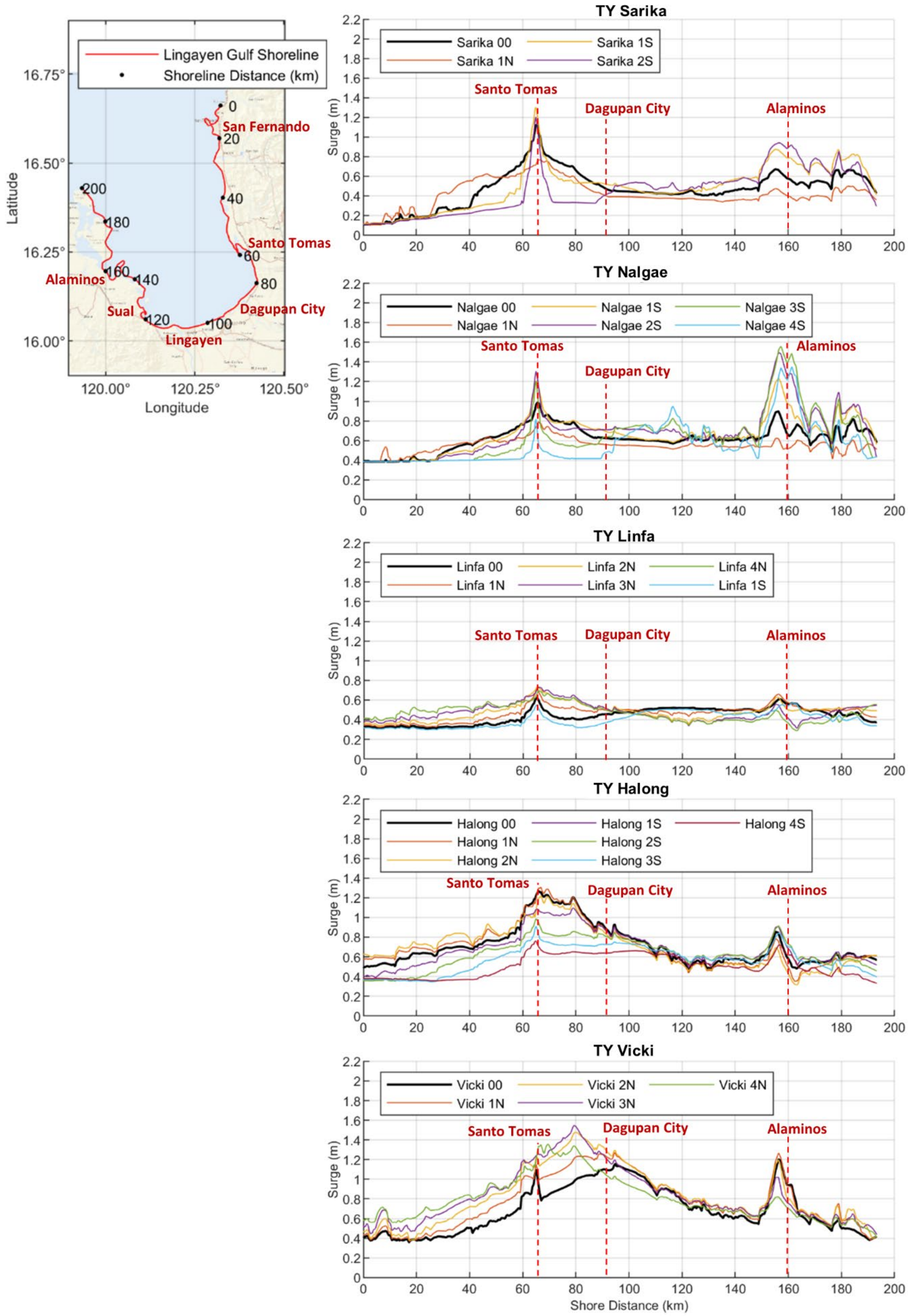


Figure 12. Alongshore distributions of simulated peak storm surge levels along the coasts of Lingayen Gulf for all the tracks per typhoon group.

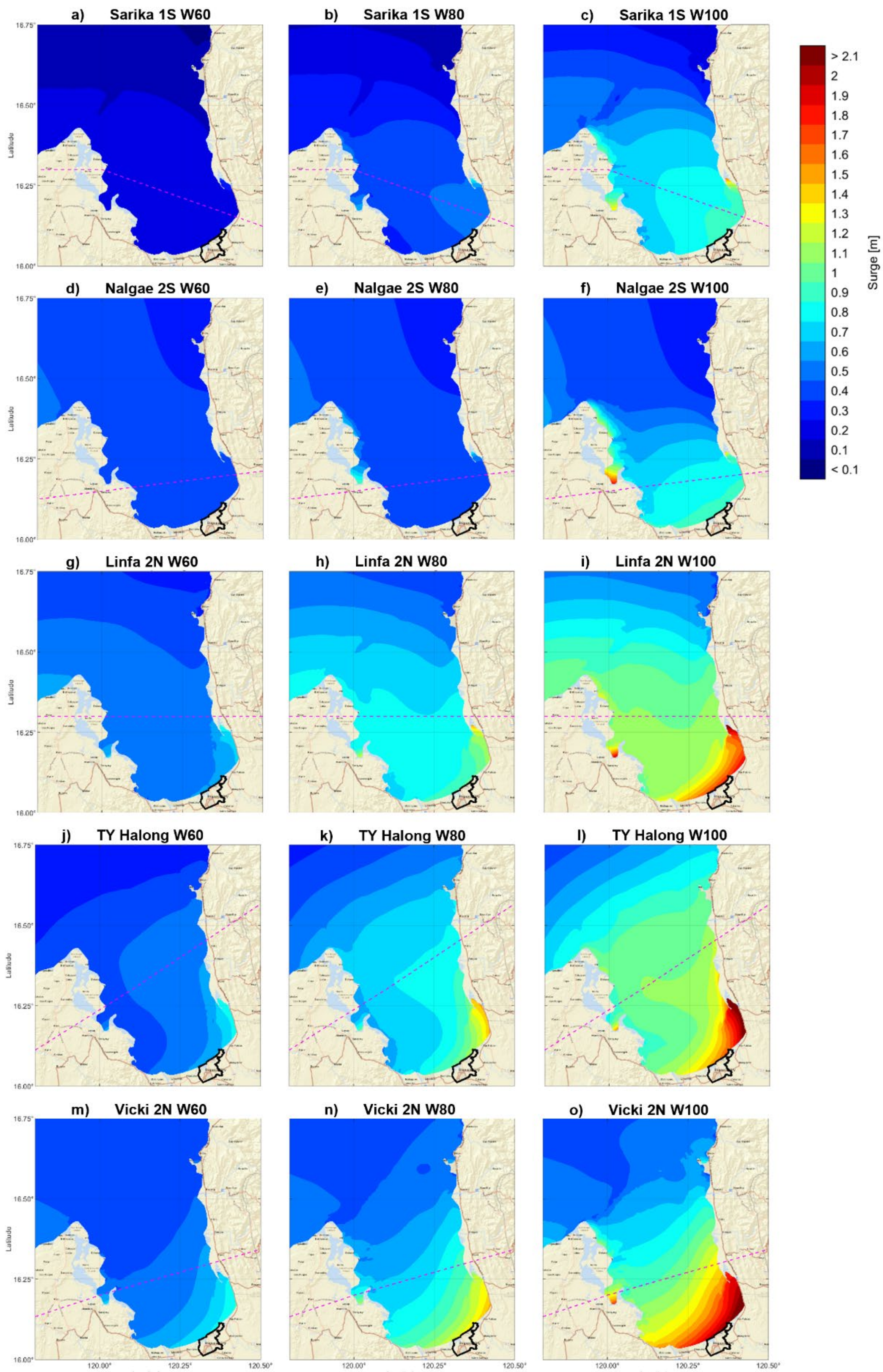


Figure 13 Surface plots of maximum storm surges for the critical tracks with windspeeds of 60, 80, and 100 knots (a) to (o). Plots in rows are the identified critical tracks for the five historical typhoon groups. W60, W80 and W100 notations refer to windspeeds of 60, 80, 100 knots, respectively.

4.0 CONCLUSION

Dagupan City is a coastal city in Pangasinan located along the inner coast of Lingayen Gulf. It is a low-lying coastal city where 30% of its population live in the coastal barangays. Exposed to typhoons annually, Dagupan City is regarded as vulnerable to coastal hazards such as storm surges. The objective of this research is to evaluate the storm surge behavior due to different typhoon tracks and windspeeds along the coast of Dagupan City in Lingayen Gulf through numerical modelling. For a coastal city with no tide gaging stations and limited coastal hazard studies, results from numerical modelling benefits Dagupan City in understanding the storm surges brought by different typhoon tracks. A simple methodology was implemented for the determination of different typhoon tracks that will be simulated. First, representative historical typhoons were selected based on distance, maximum windspeed and track orientation. Next, synthetic typhoons were created by shifting the representative historical track along the latitude. The storm surges generated by the historical and synthetic typhoons were simulated using the ADCIRC model. The Holland 1980 typhoon model was used to generate the wind and pressure fields of the typhoons. Analysis of the simulated storm surges was done to determine the critical track that produced the highest storm surges among the historical and shifted typhoon tracks. Using these critical tracks, additional synthetic typhoons were simulated using wind intensities of 60, 80 and 100 knots.

Generally, storm surges are observed to occur at the head and at the eastern side of Lingayen Gulf. Among the representative historical typhoons that were selected, TY Vicki 1998 produced the highest maximum simulated storm surge reaching 1 m along the coast of Dagupan City. This study showed that shifting the historical typhoon tracks along the latitude northward or southward affected the magnitude of storm surges along the coast of Dagupan City as well as the characteristics of distribution of storm surges in Lingayen Gulf. Identified critical tracks that produce highest storm surges along the coast of Dagupan City were found to be passing near the center of Lingayen Gulf, except for the synthetic tracks Linfa 3N and Linfa 4N that are located near the mouth of the gulf and can still produce high storm surges along Dagupan City. While the focus of this study is on the evaluation of storm surges along Dagupan City, we also recognize that the orientation of the typhoon track affected the variation of storm surges along the coasts of Lingayen Gulf. This means that critical tracks for Dagupan City may not be applicable for other coastal areas in Lingayen Gulf. Thus, is it important to evaluate different typhoon tracks for other coastal areas through numerical simulation.

Simulation of storm surges for increasing wind intensities produce higher storm surges in Lingayen Gulf. This study provides estimated storm surges for different wind intensities of 60, 80 and 100 knots which can be used in predicting storm surges in Dagupan City for similar typhoon tracks. The maximum simulated storm surge for this study is found to be produced by synthetic typhoon Vicki 2N with corresponding simulated maximum storm surge of more than 2 meters generated by a wind intensity of 100 knots. It should be noted however that there were no records of typhoons with intensity of 100 knots passing the Lingayen Gulf. This study also reveals that typhoons coming from the West Philippine Sea (going towards east or northeast) can generate higher storm surges compared to typhoons coming from the Pacific Ocean. However, typhoons coming from the West Philippine Sea are generally relatively weaker than typhoons forming in the Pacific Ocean. With regards to timing of peak storm surges, due to the nature of the typhoons in the northern hemisphere where typhoon winds are circulating counterclockwise and the orientation and shape of Lingayen Gulf, typhoons coming from the Pacific Ocean will generate peak storm surges as it approaches the Lingayen Gulf while typhoons from the West Philippine Sea will produce peak storm surges after it has passed the Lingayen Gulf. This study only explores the effect of typhoon tracks and windspeeds on storm surges in Dagupan City. Other typhoon parameters, such as forward speed and size, can be investigated in the future as well. Because of the lack of data to validate the simulated storm surge, the results of this study are purely based on numerical investigation. It is recommended that tide gaging stations and meteorological stations be installed in Lingayen Gulf to improve the understanding of coastal hazards in the area.

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