Project NOAH
Open-File Reports

Vol. 3 (2014), pp. 37-44, ISSN 2362 7409

Development of Inundation Map for Bantayan Island, Cebu Using Delft3D-Flow Storm Surge Simulations of Typhoon Haiyan

Camille Cuadra, Nophi Ian Biton, Krichi May Cabacaba, Joy Santiago, John Kenneth Suarez, John Phillip Lapidez, Alfredo Mahar Francisco Lagmay, Vicente Malano

Abstract: On average, 20 typhoons enter the Philippine Area of Responsibility annually, making it vulnerable to different storm hazards. Apart from the frequency of tropical cyclones, the archipelagic nature of the country makes it particularly prone to storm surges. On 08 November 2013, Haiyan, a Category 5 Typhoon with maximum one-minute sustained wind speed of 315 kph, hit the central region of the Philippines. In its path, the howler devastated Bantayan Island, a popular tourist destination. The island is located north of Cebu City, the second largest metropolis of the Philippines in terms of populace. Having been directly hit by Typhoon Haiyan, Bantayan Island was severely damaged by strong winds and storm surges, with more than 11,000 houses totally destroyed while 5,000 more suffered minor damage. The adverse impacts of possible future storm surge events in the island can only be mitigated if hazard maps that depict inundation of the coastal areas of Bantayan are generated. To create such maps, Delft3D-Flow, a hydrodynamic modelling software was used to simulate storm surges. These simulations were made over a 10-m per pixel resolution IfSAR Digital Elevation Model (DEM) and the General Bathymetric Chart of the Oceans (GEBCO) bathymetry. The results of the coastal inundation model for Typhoon Haiyan's storm surges were validated using data collected from field work and local government reports. The hydrodynamic model of Bantayan was then calibrated using the field data and further simulations were made with varying typhoon tracks. This was done to generate scenarios on the farthest possible inland incursion of storm surges. The output of the study is a detailed storm surge inundation map that depicts safe zones for development of infrastructure near coastal areas and for construction of coastal protection structures. The storm surge inundation map can also be used as basis for disaster preparedness plans of coastal communities threatened by approaching typhoons.

1. INTRODUCTION

The Philippines is an archipelagic country with 17,461 kilometers of coastlines around its 7,107 islands. It is situated on the western part of the Pacific Ocean where 95 percent of the typhoons originate. Annually, an average of 20 typhoons enter the Philippine Area of Responsibility (PAR) of which 9 make landfall. The irregular coastlines and the frequency of typhoons make the country vulnerable to storm surges which cause more casualties rather than by winds (Brown et al, 1991).

Storm surges are induced by meteorological driving forces (e.g., wind stress, atmospheric pressure gradient, strong winds pushing on the ocean's floor). It is considered an important component of extreme sea levels during coastal flooding (Pugh, 1987). This abnormal rise of ocean waves can cause severe destruction and damage in its surrounding areas. Low-lying coastal areas are particularly more vulnerable to coastal inundation which can result in a substantial loss of life and property.

Storm surge events were recorded in the Philippines as early as 1589 in Manila Bay. Typhoon Kate (local name: Sening) hit the coastal areas of northern Mindanao and Luzon in 1970 and caused 583 deaths and destroyed 51,000 buildings. The province of Bataan was inundated by a 4-meter storm surge generated by Typhoon Vera (local name: Bebeng) on July 1983. During the onslaught of Typhoon Ike (local name: Nitang) in 1984, the southern and central islands of the country were affected with 5 meters of storm surge (Longshore, 2008).
Since the Philippines is geographically prone to disasters, the government established an institution for disaster response management in 1978 known as the National Disaster Coordinating Council (NDCC). However, failure in communication systems leading to poor public awareness is still one of the causes of large number of affected population and heavy losses from typhoons and storm surge (Henderson, 1988).

Bantayan Island, which is located in the west of the northern end of Cebu, is strategically a fishing island with a land area of 8,163 hectares (Philippine Statistics Authority, 2012). According to National Statistics Office (2010), Bantayan has a population of

136, 960. The island is a tourist destination known for its white sand beaches, old churches and poultry industry.

Bantayan Island's location makes is vulnerable to hazards brought about by high winds and storm surges. The average landfall in that region is 1.9 typhoons every year (Brown et al, 1991). Typhoon Bopha (local name: Pablo) crossed south of the Philippines on December 2012 with a diameter of 600 kilometers that reached Bantayan Island placing it in public storm warning signal number 3. The eyewall of Typhoon Fengshen (local name: Frank) enveloped Bantayan Island with wind gusts of 150 kph to 170 kph on June 2008 (Alojado, 2010). The devastation in the island included poultry industry and coral reefs.

Bantayan Island is one of the worst hit areas in the Philippines when Typhoon Haiyan made its fourth landfall on 08 November 2013, causing communication and power breakdown in the municipalities of Sta Fe, Madridejos and Bantayan. The completely damaged houses reportedly reached over 11,000 while 5,000 more had minor damages leaving 26,796 families affected. The strong winds destroyed 90% of the infrastructure on the island including poultry farms. Even the meteorological buoy of the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) installed in Bantayan was not spared from damage.

Several modelling systems have been developed to simulate storm surge and coastal inundation at a range of scales. The numerical methods, model domains, forcing and boundary conditions are incorporated in the model to predict the impacts of tropical cyclones. Fountain et al. (2010) simulated possible storm surge events in Bunbury, Australia using Global Environmental Modelling Systems (GEMS) 2D Coastal Ocean Model (GCOM2D) and estimated its inundation with Australian National University and Geoscience Australia (ANUGA), a hydrodynamic modelling tool which is coupled with Shoreface Translation Model (STM) to include climate change scenarios. The National Weather Service (NWS) developed the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model to calculate flooding from the sea or inland water bodies triggered by storm surges (Jelesnianski et al. 1992). The HyFlux2 model by the Joint Research Centre (JRC) of the European Commission introduced atmospheric forcing in the shallow water equations in modeling storm surge and inundation (Probst and Franchello, 2012).

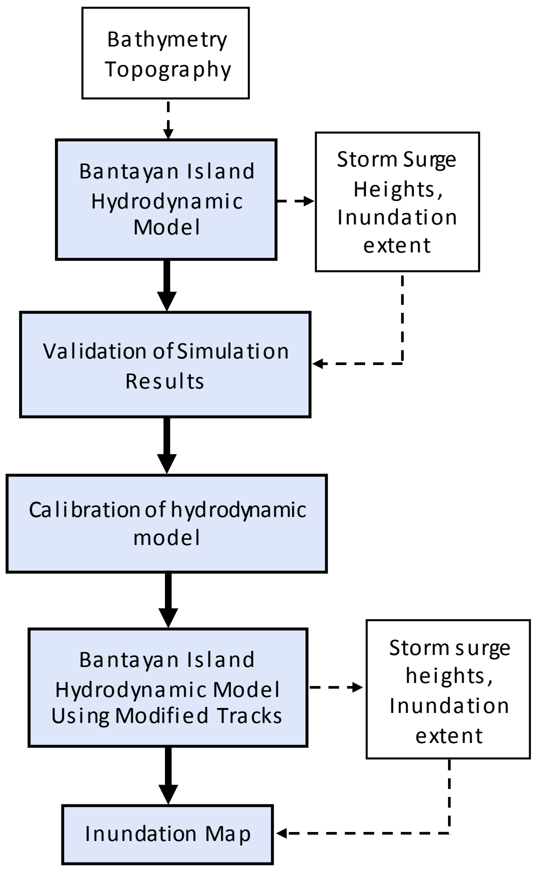
For this study, which is limited only to the storm surge event causes by Typhoon Haiyan in Bantayan Island, Delft3D-FLOW was used to create the hydrodynamic model for the island.

The study aims to validate the results of the simulation by comparing it to data collected during the fieldwork on the island.

From the results of the calibrated hydrodynamic models, an inundation map for the study area was produced. Storm surge flooding is visualized using an inundation map, a valuable tool in hazard mitigation and coastal zone management. The inundation map can be used in the determination of safe zones for development of infrastructure as well as in determining possible locations for protective coastal structures. Knowing the safe zones in an area is helpful in saving lives and minimizing the damage the typhoon can cause to properties.

The predicted water level elevations are illustrated in the map at increments for the river reach and corresponding land contour. Mapping the extent of inland flooding by a storm surge involves tropical cyclone forecast, oceanographic, estuarine, and riverine hydrodynamic model, watershed model of storm runoff and spatial inundation map (World Meteorological Agency, 2011).

2.2 Framework of the Study



2. METHODOLOGY

The focus of the study is to create inundation maps showing the greatest extent of inland inundation on the island using different scenarios of storm input.

The Haiyan storm surge event was simulated using Delft3D-FLOW with input wind data coming from the Joint Typhoon Warning Center (JTWC). The result of this simulation was validated using data gathered from the fieldwork conducted on the island and the model was calibrated based on information from the fieldwork.

To generate the different scenarios to determine the farthest extent of inland inundation on the island, the track of Haiyan was varied and used as the new wind input for the calibrated model. The results of the simulations were used to produce the inundation map of the island.

2.1 Data Gathering

Topographic and bathymetric characteristics of an area greatly affect storm surge height and extent of inundation. For the study, a 5-meter resolution digital terrain model from Interferometric Synthetic Aperture Radar (IfSAR) and 1-kilometer bathymetric data from General Bathymetric Chart of the Oceans (GEBCO), both based in Mean Sea Level (MSL), were used in generating the storm surge hydrodynamic model of the island.

2.2 Storm Surge Simulation using Delft3D-FLOW

Delft3D-FLOW can be used in predicting the flow of water in places such as shallow seas and coastal areas.

Delft3D-FLOW, with tide and wind-driven flows such as storm surges as one of its areas of applications, is part of the Delft3D suite developed by Deltares System for simulation of multi-dimensional (2D or 3D) non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear or rectilinear grid. Delft3D-FLOW is based on the full Navier-Stokes equations with the shallow water approximation applied.

For hydrodynamic models made using Delft3D-FLOW, flow is affected by tidal forcings applied at the open boundaries, wind stress at the free surface, and pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). Delft3D-FLOW model also takes into account the effects of the Earth's rotation, space and time varying atmospheric pressure on the water surface, drying and flooding of tidal flats, tide generating forces, and wind driven flows including tropical cyclone winds among others.

2.2.1 Model creation

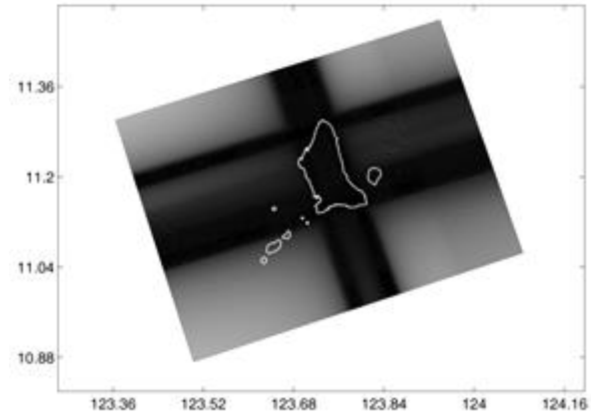


Figure 2. Computational grid of the Bantayan Island Hydrodynamic Model

For the study, a curvilinear grid with 25-meter resolution along the coastline of the island was used for the hydrodynamic model of Bantayan Island. The curvilinear grid was created by generating and refining the grid created from the splines in Delft-RGFGRID. This hydrodynamic model with fine resolution was nested on a 1-kilometer resolution hydrodynamic model of the Philippines with tidal forcing on the open boundaries.

For the large resolution model of the Philippines, the incorporated GEBCO and SRTM data in Delft Dashboard were used for the bathymetry and topography of the model while GEBCO and a 5-m resolution IfSAR data were interpolated on the computational grid.

2.2.2 Meteorological Forcing

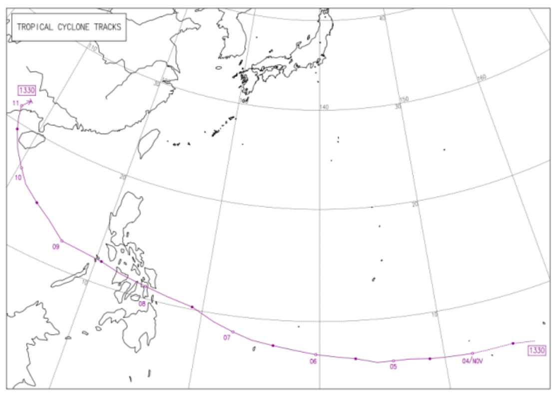


Figure 1. Typhoon Haiyan (local name: Yolanda) Storm Track (Source: Japan Meteorological Agency)

Typhoon Haiyan entered the PAR on 06 November 2013 wherein PAGASA assigned the local name "Yolanda." The typhoon intensified on 07 November as it moved to West Northwest towards Eastern Visayas.

Haiyan made multiple landfalls on 08 November in the Visayas regions of the country. The first landfall was in Guiuan, Eastern Samar at 4:40AM, the second landfall was in Tolosa, Leyte at 7:00AM, third landfall was in Daanbantayan, Cebu at 9:40AM, and the fourth landfall was in Bantayan Island, Cebu at 10:40AM. By 12:00NN, the typhoon made its fifth landfall in Concepcion, Iloilo and at 8:00PM, the last landfall was made over Busuanga, Palawan. Haiyan weakened as it moved over to the West Philippine Sea at 3:30PM on 09 November until it exited PAR.

Typhoon Haiyan was used as meteorological input for the model. The track data following the JTWC format was used as input in Delft Dashboard, a pre-processing tool for Delft-3D models, using the Tropical Cyclone Toolbox to create the wind field data for Delft3D-Flow. Tropical cyclone data is normally defined in a spiderweb grid and is internally interpolated into the computation grid during calculation. Delft Dashboard uses the Wind Enhancement Scheme (WES) following the Holland's Model.

Holland's model (Holland 1990) assumes that for a generic tropical cyclone, suface pressure field follows a modified rectangular hyperbola, as a function of radius and the tangential wind field is given by the pressure field via cyclostropic balance (Bao et al. 2006). WES was formulated to derive the wind field data given the different tropical cyclone parameters provided by different meteorological agencies.

2.2.3 Tidal Forcing

The open boundary of the overall model was forced with tides using the spatially varying phases and amplitudes acquired from the TPXO 7.2 Global Inverse Tide Model in Delft Dashboard. The extent of the study area is too large that gravitational forces on the motion of water cannot be neglected. The eight tidal constituents from semi-diurnal and diurnal tidal species were considered to give more effects on the simulation.

2.3 Fieldwork validation and calibration of model results

On the third week of February 2014, members of the Storm Surge Hazard Mapping component of the DOST – Project NOAH went to Bantayan Island to conduct a fieldwork whereon storm surge evidences were gathered and interviews to coastal residents were done.

The coastal communities that were included in the interviews were those within the 200 meters from the coast. Built-up areas for each municipality were selected and further divided into smaller areas. The number of respondents on each area was based on the density of houses that were identified from satellite images. Members of the fieldwork team interviewed residents who were in the vicinity during the typhoon.

The data from the interviews included information on the maximum reported flood depth. The interview respondents also reported storm surge evidences and structural damage caused by the storm surge due to the typhoon.

The interviews were from a sample of 194 residents from the entire Bantayan Island, 63 (32.5%) of which were from Santa Fe, 71 (36.6%) from Bantayan, and 60 (30.9%) from Madridejos. These respondents were residents of the coastal areas in the island and were in the vicinity when the typhoon struck. Most of the residents interviewed did not evacuate during Typhoon Yolanda; however, those who were able to evacuate were able to give their accounts based on the aftermath of the typhoon, such as the extent of flooding based on inundated household items and fallen coconut trees.

Damages and marks caused by the surge were documented as supporting evidence for the interviews conducted. When the respondents confirmed the presence of surge and the extent of flooding of their area, detailed observations were made to find any evidence that may have been left behind.

The flood depth accounts were compared to the simulation results to validate and calibrate the hydrodynamic model. This was done since there are no existing tide stations in the area.

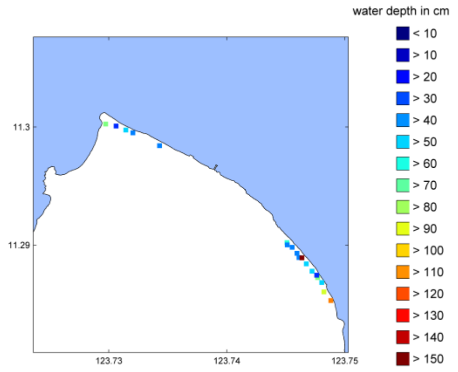


Figure 3. Flood depths in the municipality of Madridejos during Typhoon Haiyan according to respondents

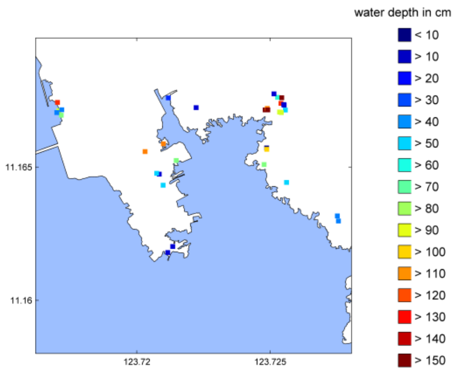


Figure 4. Flood depths in the municipality of Bantayan during Typhoon Haiyan according to respondents

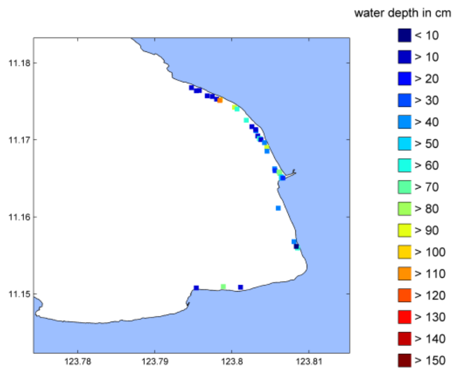


Figure 5. Flood depths in the municipality of Santa Fe during Typhoon Haiyan according to respondents

The Chezy roughness coefficient was adjusted until the model adequately simulated the observed water values during the fieldwork. A root mean square of 0.266 m was computed based on the observed and values. The root mean square error is a commonly used measurement of difference of the predicted values and observed values. The difference of the predicted and actual value is called the residual. The RMSE is calculated by getting the square root of the mean of the squares of the residuals. The smaller the value of the RMSE, the mode accurate the predicted values are.

Table 1. Inundation levels based on interviews and on results of Delft3D-FLOW simulation using the original Typhoon Haiyan track

Inundation based on interviews (m)	**Inundation based on Delft3D-FLOW (m)**
.3	0.13396
0.1	0.22859
0.6	0.72543
0.9	0.22216
0.52	0.24055
0.4	0.81404
0.4	0.17957
0.39	0.30578
0.5	0.80279
0.1	0.13620
0.8	0.88755
0.3	0.35624
0.1	0.07030
0.7	0.75643
0.1	0.00753
0.3	0.37274
0.3	0.38023
0.1	0.18349
0.1	0.04067
0.5	0.86906
0.65	0.06571

RMSE = 0.2658

2.4 Simulation of other scenarios

After the 25-meter resolution hydrodynamic model of Bantayan Island was calibrated based on the data collected from the fieldwork, several other typhoon scenarios were ran on the same 25-m resolution model.

The track of Haiyan was shifted 0.1 degree increments (approximately equal to 10 km) up and down from the original track. By running simulations using typhoons with parallel tracks, we get an idea of the maximum storm surge and inundation levels a typhoon may bring about to an area.

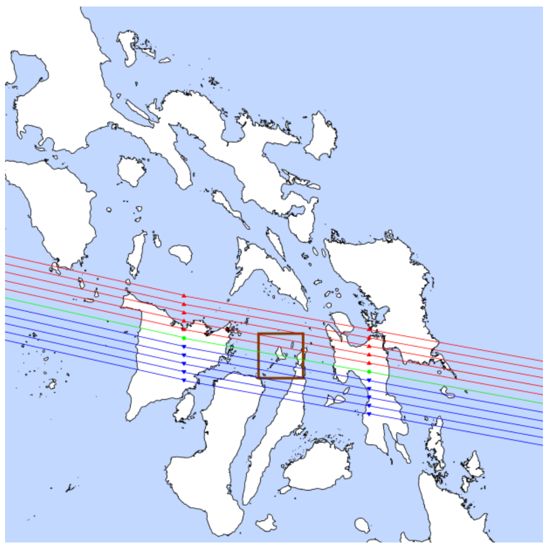


Figure 6. Shifted Typhoon Haiyan tracks used in the storm surge simulation of different scenarios

This process can be compared to the determination of the Maximum Envelope of Water (MEOW) for a particular basin using the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model.

The MEOW is generated by taking the maximum surge value from the entire family of cyclones at each grid cell regardless of which cyclone was responsible for generating the surge level. The surge levels were determined by running hydrodynamic models using hypothetical tropical cyclones with central pressures classified using the Saffir-Simpson Hurricane Wind Scale (National Hurricane Center, 2013).

3. RESULTS AND DISCUSSIONS

Figures 7 and 8 show the effect of shifting the typhoon track to the surge levels on the study area. A typhoon track shifted farther from the study area does not mean a surge level lower than those generated using the original typhoon track as shown in Figure 8. This means that the path of the storm affects the extent of inundation for a certain area. Two parallel storms of the same strength and path will produce different storm surge values and inundation for an area.

The maximum levels of inundation for points in the computational grid were computed after every storm surge simulation for the different scenarios has finished running. The maximum of the maximum levels of inundation for all the simulations performed were then obtained regardless which typhoon caused it and mapped.

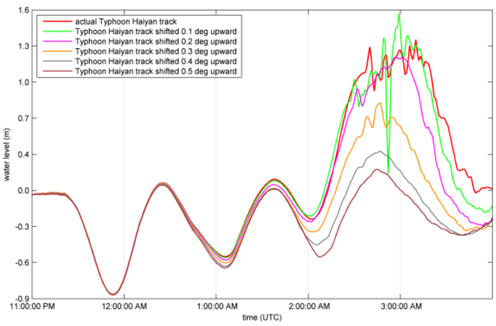


Figure 7. Time series plots of surge levels produced by Typhoon Haiyan track shifted upward

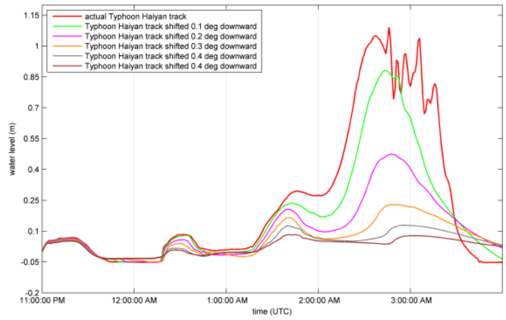


Figure 8. Time series plots of surge levels produced by Typhoon Haiyan track shifted downward

3.1 Inundation Map

Figure 9 shows the inundation map produced based on the maximum of the maximum storm surge values obtained from all the simulations performed using the parallel typhoon tracks.

Areas enclosed in rectangles are the ones which are more prone to high storm surges mainly because of the direction of approach of the typhoon as well as its counter-clockwise movement.

4. Conclusion and Recommendations

Two parallel storms of the same strength and path will produce different storm surge values and inundation for an area. By running simulations using typhoons with parallel tracks, the maximum storm surge and inundation levels a typhoon can cause can be determined.

Storm surge flooding is visualized using an inundation map which is a valuable tool in hazard mitigation and coastal zone management. The inundation map can be used in the determining safe zones for development of infrastructure.

To further improve this study, it is recommended that higher resolution bathymetric data derived from nautical charts be used as substitute for the GEBCO data used in the hydrodynamic model to get more accurate surge levels and inundation extent. It is also recommended that individual hydrodynamic models with finer resolution for those areas which are most prone to storm surges be made.

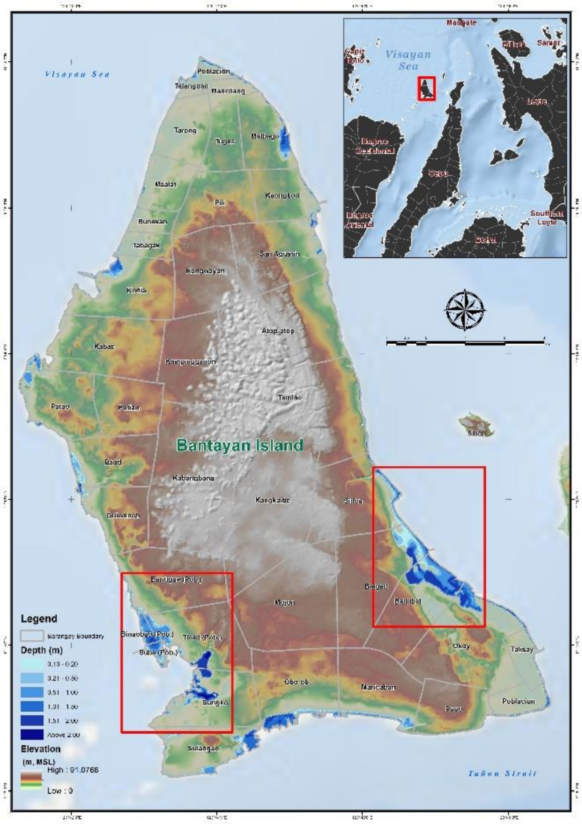


Figure 9. Inundation maps of Bantayan Island using the maximum of the maximum storm surge levels for computational grid cells located inside the island

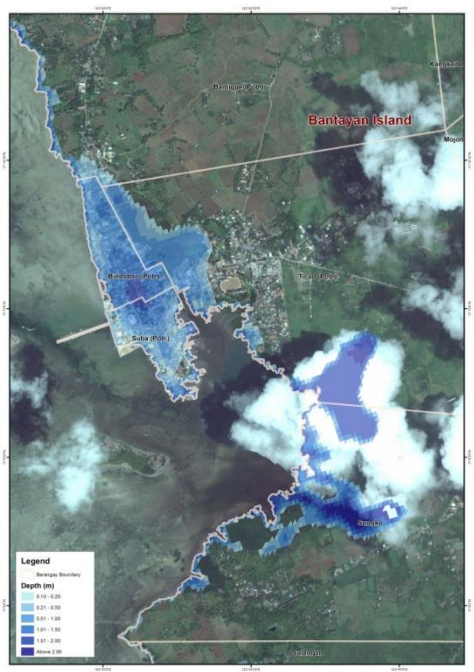


Figure 10. A more detailed inundation map for an area in the municipality of Bantayan which is one of the 2 areas determined to be more prone to high surge levels

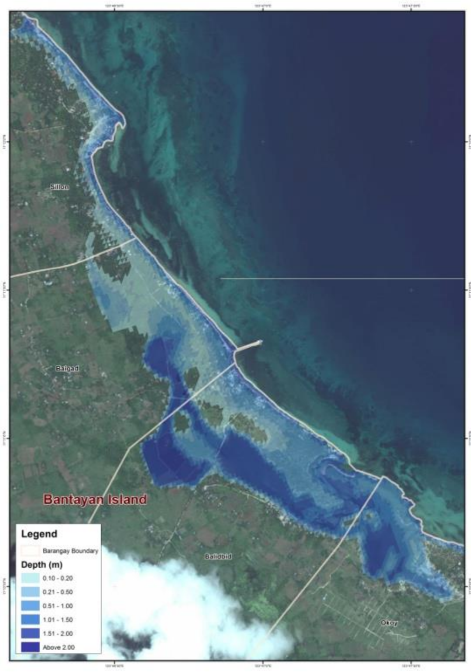


Figure 11. A more detailed inundation map for an area in the municipality of Sante Fe which is one of the 2 areas determined to be more prone to high surge levels

REFERENCES

1. Alcala, A. C. 09 December 2012. Typhoons Sendong and Pablo: Reef Destroyers. Dumaguete MetroPost. http://dumaguetemetropost.com/typhoons-sendong-and-pablo-reef-destroyers-p3336-98.htm
2. Algarme, C. 24 November 2013. Homeless at Bantayan Island in Yolanda's aftermath. GMA News Online.
3. Alojado, D. 2010. The twelve worst typhoons of the Philippines (1947-2009). Typhoon 2000. http://www.typhoon2000.ph/stormstats/12WorstPhilippineTyphoons.htm
4. Bao, S., Xie, L. and Pietrafesa, L. J. 2006. An asymmetric hurricane wind model for storm surge and wave forecasting.
5. Bongcac, D.C. and Napallacan, J. 24 June 2008. 6. 'Help us,' governor asks contractors. Cebu Daily News. http://globalnation.inquirer.net/cebudailynews/news/view/20080624-144464/Help-us-governor-asks-contractors?ModPagespeed=noscript
6. Brown, N., Amadore, L. and Torrente, E. April 1991. Philippines Country Study, a paper presented at the Regional Round Table on "Disaster Mitigation Policies and Management". Asian Development Bank, Philippines.
7. Deltares Systems, Delft3D-FLOW User Manual, 2013.
8. Flores, H. 26 December 2013. Yearender: 2013 a year of major natural disasters. The Philippine Star. http://www.philstar.com/headlines/2013/12/26/1272092/yearender-2013-year-major-natural-disasters
9. Fountain, L., Sexton, J., Habili, N., Hazelwood, M. and Anderson, H. 2010. Storm surge modelling for Bunbury, Western Australia, Professional Opinion. No.2010/04.
10. García-Herrera, R. , Ribera, P., Hernández, E. and Gimeno, L. Typhoons in the Philippine Islands 1566-190. Submitted to JGR - Atmospheres.

http://pendientedemigracion.ucm.es/info/tropical/philippine.html

11. Henderson, F. 1988. Philippines: a country profile. Technical report, Office of U.S Foreign Disaster Assistance. http://www.gmanetwork.com/news/story/336716/opinion/homeless-at-bantayan-island-in-yolanda-s-aftermath
12. Hill, D. F. June 2007 Tidal Modelling of Glacier Bay, Alaska – Methodology, Results, and Applications
13. Inquirer Visayas. 15 November 2013. Bantayan Island execs say devastation just temporary setback. Inquirer News. http://newsinfo.inquirer.net/527987/bantayan-island-execs-say-devastation-just-temporary-setback
14. Jelesnianski, C. P., Chen, J. and Shaffer, W. A. 1992. SLOSH: Sea, lake, and overland surges from hurricanes. NOAA Tech. Report NWS 48, 71 pp.
15. Longshore, D. 2008. Encyclopedia of Hurricanes, Typhoons and Cyclones, New ed.. Facts on File, Inc., New York.
16. National Disaster Risk Reduction and Management Council. 2014. Situational Report re Effects of Typhoon Yolanda (Haiyan). http://www.ndrrmc.gov.ph/index.php?option=com_content&view=article&id=1125%3Asituational-report-re-preparations-for-typhoon-qyolandaq&catid=1%3Andrrmc-update&Itemid=1
17. National Hurricane Center. 2013. Sea, Lake, and Overland Surges from Hurricanes (SLOSH). http://www.nhc.noaa.gov/surge/slosh.php
18. National Statistics Office. 2010. Census of Population and Housing – Central Visayas. http://www.census.gov.ph/
19. Pedalino, M. 04 December 2012. "Pablo" skirts Southern Leyte, hits landfall off Davao Oriental. Philippine Information Agency. http://news.pia.gov.ph/index.php?article=1301354591319#sthash.9mPTZJs8.dpuf
20. Philippine Statistics Authority. 2012. Municipality Statistics. http://www.nscb.gov.ph/activestats/psgc/listmun.asp?whichpage=8
21. Philippines country report on disaster response management. 3rd ASEAN Inter-Parliamentary Assembly (AIPA) Caucus. 31 May - 3 June 2011. Manila, Philippines.
22. Probst, P. and Franchello, G. 2012. Global storm surge forecast and inundation modeling. JRC Scientific and Technical Reports. Joint Research Centre, European Commission, EUR 25233 EN – 2012.
23. Pugh, D., 1987. Tides, Surges and Mean Sea Level, John Wiley and Sons
24. Ranada, P. and Cupin, B. 09 November 2013. Bantayan Island, 3 Cebu towns completely isolated. Rappler. http://www.rappler.com/nation/43319-cebu-municipalities-isolated
25. World Meteorological Agency. 2011. Guide to storm surge forecasting. WMO-No. 1076