Development of Local Level Storm Surge Hazard Maps for Potential Use in Storm Surge Evacuation and Development Planning

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Development of Local Level Storm Surge Hazard Maps for Potential Use in Storm Surge Evacuation and Development Planning

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Abstract. The eastern seaboard of the Philippines is highly exposed to tropical cyclones. The hazards associated with typhoons consist of strong winds, storm surges and heavy rains-causing floods and/or landslides. In order to assess the disaster vulnerability of local communities to storm surge hazard, a case study was carried out on the generation of storm surge hazard maps for selected Typhoon Pablo (2012)–affected areas in Regions 10 and 11 in the eastern coastal plain of Mindanao. The methodology employed in this project involved: storm surge model simulation of Typhoon Pablo (*international name:* **Bopha**), field works, analysis and mapping. The work was carried out using the LiDAR-derived Digital Elevation Model (DEM) to identify inundation depths and extents then utilizing ArcGIS software for the analysis. The numerical simulations used to produce the storm surge hazard maps include the Japan Meteorological Agency (JMA) Storm Surge Model, Delft3D, XBeach and the SWAN Model for the offshore wave heights. Results from the models were then ground validated and pertinent data related to Typhoon Pablo were also gathered. Interviews with residents with personal accounts of the storm surge event and measurements of high water marks were conducted to determine the correctness of the initial storm surge hazard maps. Topographic survey using Real Time Kinematic Global Navigational Satellite System (RTK-GNSS) was also collected in the municipalities of Boston, Cateel, and Baganga in Davao Oriental to capture relevant natural and anthropogenic topographic features such as beach face, dunes and seawalls. The storm surge hazard maps produced in this project show the inundation depths and extents on a local/barangay level to raise the awareness and understanding of the general public on the storm hazard threat. It can also be an effective tool for local authorities for development planning and regulatory processes.

Keywords: Typhoon Bopha, Storm Surge Hazard Map, LiDAR, Field Validation, Development Planning

1 Introduction

Davao Oriental, the easternmost province of the great island of Mindanao in the Philippines, experienced only nine (9) tropical cyclone passages in sixty-five (65) years (i.e., 1948 to 2013) (Figure 1). It is for this reason that locals from the municipalities of Baganga, Cateel and Boston, all from Davao Oriental province did not believe that a strong typhoon will strike them on that fateful day of December 4, 2012. Typhoon Pablo (*international name: Bopha*) in 2012 made its first landfall over at Baganga, Davao Oriental.

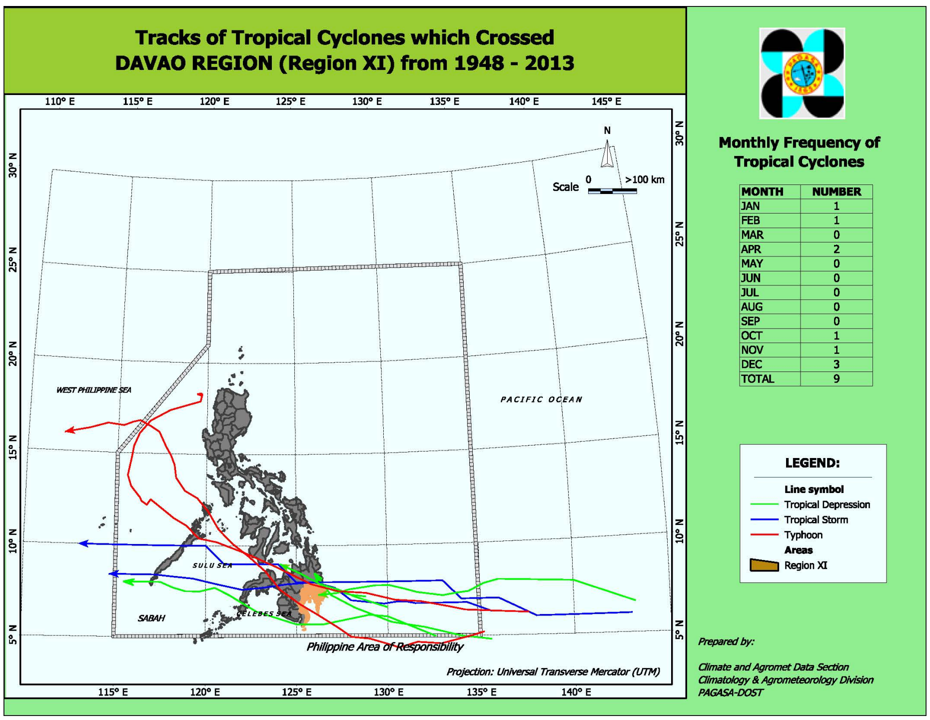

Fig. 1. Historical tropical cyclone tracks and intensities which crossed Davao Region from 1948–2013. Source: PAGASA-CADS.

One of the devastating impacts of the passage of a strong tropical cyclone on a coastline is due to the occurrence of storm surge. This phenomenon is characterized by an increase in the mean seawater level above normal, primarily due to the strong winds of the typhoon and ordinarily associated with tidal action. The morphology, topography and bathymetry of the seashore may also contribute to storm surge height characteristics.

Satellite observations from 1993 to 2015 show that the Tropical Western Pacific region, east of the Philippines, experienced sea level rise at a rate of 5–7

Table 1. List of tropical cyclones (TC) that crossed Davao Region from 1948–2013 (TD: Tropical Depression, TS: Tropical Storm, TY: Typhoon). Source: PAGASA-CADS.

Year	**M**onth	**T**ype	**T**C Name	**D**ate of Entry to PAR	**D**ate of Exit from PAR
1948	December	TD	TD4820	12/24/1948	12/25/1948
1955	January	TS	Violet	01/02/1955	01/06/1955
1970	October	TY	Titang	10/18/1970	10/22/1970
1993	April	TD	Bining	04/12/1993	04/13/1993
1993	April	TD	Daling	05/01/1993	05/04/1993
2011	December	TS	Sedong	12/15/2011	12/18/2011
2012	December	TY	Pablo	12/01/2012	12/09/2012
2013	February	TD	Crising	02/18/2013	02/21/2013
2013	November	TD	Zoraida	11/11/2013	11/12/2013

mm/year, which is more than twice the global average[1]. These indicate that there is a higher risk of sea level rise to coastal areas in the east of the islands of Samar and Mindanao and the south coasts of Zamboanga and Negros Islands.

The effects of climate change and the changing nature of cyclones, coupled with projected sea level rise may lead to an increased vulnerability to storm surge inundation in the province of Davao Oriental. With this, the generation of storm surge hazard maps for the municipalities of Boston, Cateel and Baganga in the province of Davao Oriental which were heavily affected by Typhoon Pablo is undertaken by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA).

The aim of this study is to assess the vulnerability of the municipalities of Baganga, Cateel and Boston, Davao Oriental to storm surge hazard. Specifically, it intends to:

- Assess the possible occurrence of storm surge during strong tropical cyclones such as Typhoon Pablo;
- Develop storm surge inundation maps due to Typhoon Pablo;
- Develop storm surge hazard maps arising from stronger tropical cyclones such as Super Typhoon Yolanda (worst-case scenario);
- Develop storm surge hazard map resulting from a worst-case scenario and a 0.7–meter sea level rise.

In doing this assessment, local governments will be informed of the greatest risks they face in relation to storm surges and the specific areas of vulnerability in the locality. Further, this can feed into the various local action and land-use plans developed by local governments and help focus attention and resources on disaster resilience efforts.

1.1 Study Area

The study area covers three municipalities of the province of Davao Oriental situated in the southeastern section of Mindanao namely: the municipalities of Boston, Cateel and Baganga (see Figure 2).

The municipality of Boston is situated in the northernmost part of the province and lies on the eastern part of Mindanao Island. It is characterized by rugged mountain terrain. Its great part is covered by forest while the eastern part along the coastal line is mostly plain and fertile land.

Cateel, Davao Oriental is bounded by the Pacific Ocean in the east, Municipality of Compostela, Davao del Norte in the west and by the municipalities of Boston and Baganga in the north and south, respectively. The northern and western parts of the municipality consist of hilly to mountainous forest land. The westernmost part, on the other hand, is alienable and disposable. The southern and middle parts are mostly plain with slight rolling and hilly areas.

Baganga is the largest municipality in the Province of Davao Oriental. It is bounded on the east by Pacific Ocean, on the north by the municipality of Cateel, on the west by the municipalities of New Bataan and Compostela–province of Compostela Valley, and on the south by the municipality of Caraga. The eastern part of the municipality has an uneven distribution of lowlands, upland, and swamps while the western part is generally hilly and mountainous.

The remainder of this paper is organized as follows: The typhoon that was studied, the sources of input data and the sea level change scenarios are described in Section 2. The adjustments to the DEM[3] data, model configurations and experimental design are described in Section 3. Experiment results and the effect of DEM adjustments to the hazard maps produced are discussed in Section 4, while conclusions are drawn in Section 5.

2 Description of Dataset

Input datasets utilized in the study such as TC case information, bathymetry and sea level rise are described in the following section.

2.1 Tropical Cyclone Data

Typhoon Pablo with international name Bopha (Figure 3), is the seventh tropical cyclone to affect Davao region from 1948 to 2013. Its maximum sustained winds as observed was 297 kilometers per hour (kph).

As early as November 29, 2012, Thursday, PAGASA projected that the system would head towards Mindanao or Visayas on December 2 or 3. The NDRRMC[4] alerted the public of the incoming storm, which could further intensify and bring more rains.

[3]Digital Elevation Model

[4]National Disaster Risk Reduction and Management Council

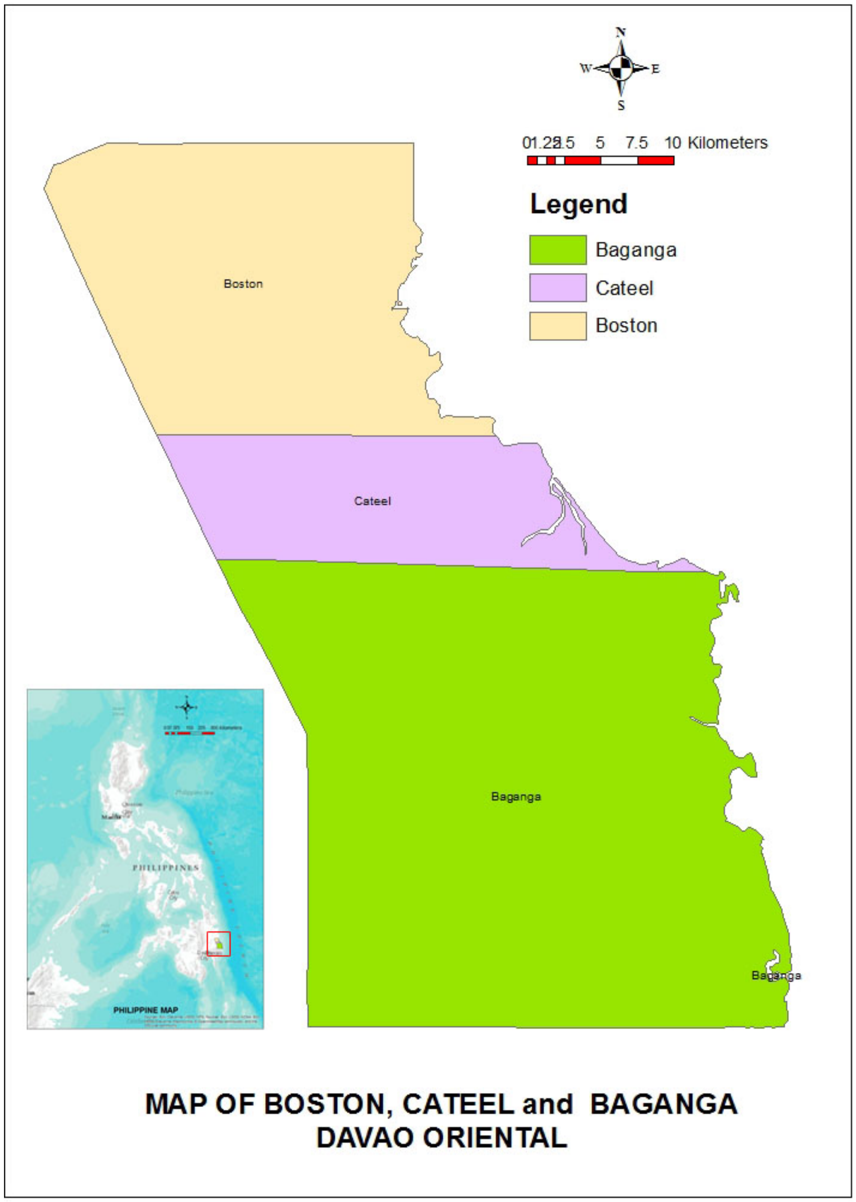

Fig. 2. Map of the Study Sites: Boston, Cateel and Baganga, Davao Oriental in reference to the Philippines.

On November 30, Friday, Typhoon Pablo continued to move west-northwest at 19 kph. The JTWC[5] warned residents of the Philippines of heavy rains and strong winds while PAGASA continued to monitor the storm.

[5] Joint Typhoon Warning Center

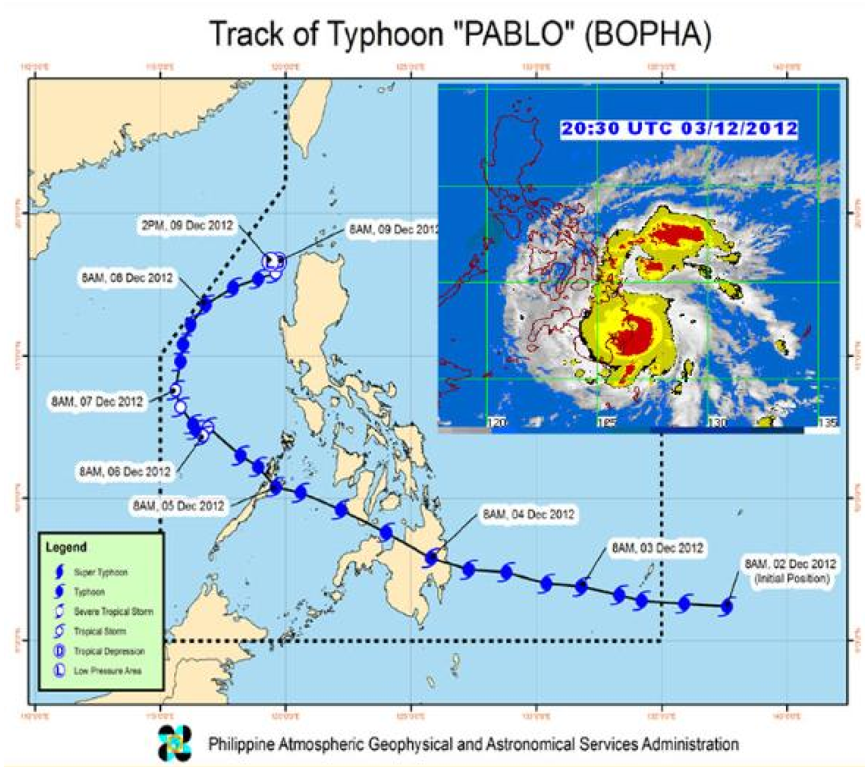

Fig. 3. Track of Typhoon Pablo from December 2 to 9, 2012. Inset is an enhanced MTSAT satellite image on December 4, 2012 at 4:30 AM, few minutes before landfall.

On December 1, Saturday, PAGASA warned the public that Typhoon Pablo could become a Super Typhoon and that it could be stronger and more destructive than Typhoon Sendong in 2011. It was forecast to make landfall either in northeastern Mindanao of Northern Samar in the evening of December 4 or early morning of December 5.

On December 2, Typhoon Pablo entered the Philippine Area of Responsibility (PAR) with typhoon category. Initially, it moved at 22 kph and increased to 26 kph in the evening.

On December 3, Monday, PAGASA, on its 11AM Weather Bulletin, placed various places in Visayas and Mindanao under Public Storm Warning Signal Number 3. Furthermore, PAGASA forecasted Typhoon Pablo to make landfall between Davao Oriental and Surigao del Sur between 4:00 to 6:00 the next morning, December 4, Tuesday.

On December 4, at around 4:45 AM, the eye of Typhoon Pablo made landfall over Baganga, Davao Oriental. This landfall shattered the residents' belief that Davao Oriental was a typhoon-free province.

2.2 Typhoon Pablo Return Period

An Automatic Weather Station (AWS) at Baganga municipal grounds, approximately 3 kilometres away from the coast, recorded the highest wind speed of 82.5 mps (297 kph) between 5:00 AM and 6:15 AM on December 4, 2012 (see Figure 4).

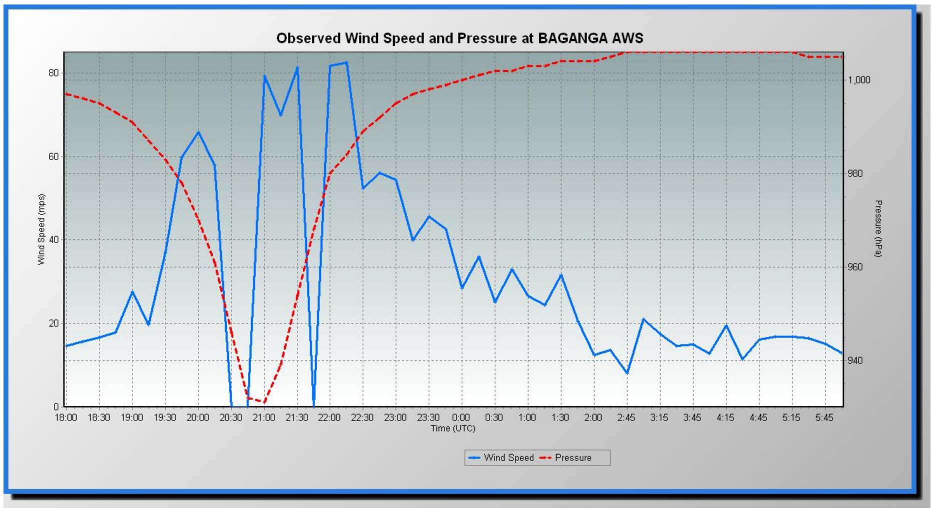

Fig. 4. Observed wind speed and mean sea level pressure from an automatic weather station in Banganga, Davao Oriental. Source: PAGASA.

Based on the study conducted by the severe wind component of the same project[6], the maximum wind speed of Typhoon Pablo simulated using the Tropical Cyclone Risk Model (TCRM) was 77.7 mps or 280 kph with a 100–year Return Period[2].

2.3 Digital Elevation Model

Digital Elevation Map used in the study was the LiDAR data acquired through the program Disaster Risk and Exposure Assessment for Mitigation (DREAM) (Figure 5). LiDAR data are obtained from aircraft-mounted laser sensors which emit pulses of light energy at the ground and measure the distance based on the time required for the pulses to reflect back to the sensor.

2.4 Bathymetry Data

Two types of bathymetry data were used in the study. First is the GEBCO-08 30 arcsecond data (900 x 900 m). This bathymetry data serves as input to the Japan

[6]"Tropical Cyclone Severe Wind Hazard Mapping for Compostela Valley and Davao Oriental Provinces"

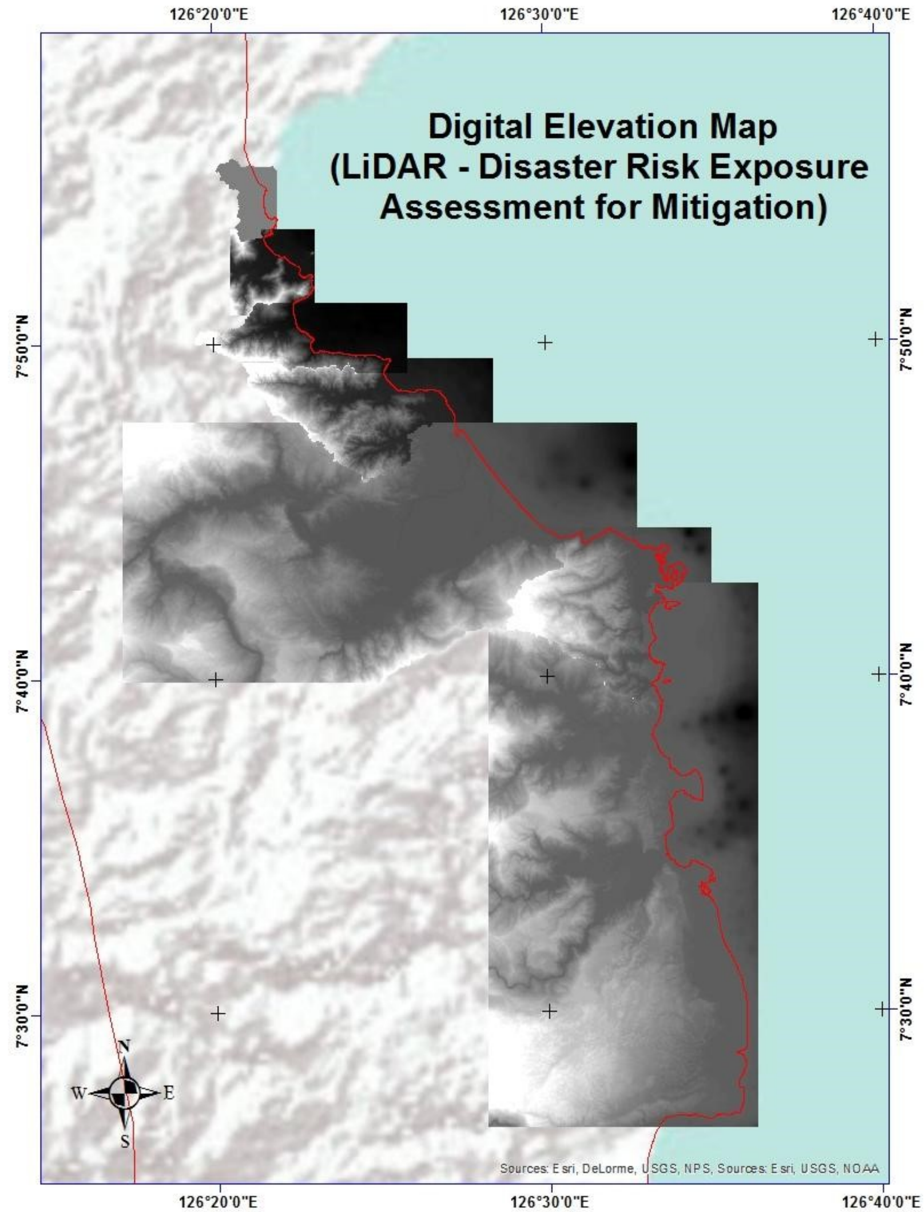

Fig. 5. LiDAR DEM over the study area used for storm surge inundation mapping. Source: DREAM Program.

Meteorological Agency (JMA) Storm Surge Model. The second one is the local bathymetry data over the study area acquired by the NAMRIA[7] Hydrography and Oceanography Branch which serves as input to the Delft3D model.

2.5 Tide Data

Tidal survey was conducted simultaneously with the local bathymetry data collection to collect local tide levels. A portable tide gauge was installed in Barangay Santa Filomena, Cateel, located between the municipalities of Boston and Baganga, Davao Oriental. Duration of the survey was from 15 May to 18 June 2016.

2.6 Sea Level Rise

Time series of the projected sea level change under RCP4.5[8] and RCP8.5[9] in Davao (Figure 6) shows that there is still a probability of about 30% that sea level will rise beyond the range presented, and the largest uncertainty lies in the future behavior of the Greenland and Antarctica ice sheets[3].

3 Methods

Adjustments to the DEM data, model configurations, experimental design and experiment results are discussed in the following section.

3.1 DEM Adjustment to Mean Sea Level

Digital elevation models are important to accurately map and assess the impacts of coastal inundations. The LiDAR data from the DREAM program provides the latest high resolution elevation information for the study area. The LiDAR system produces a series of point measurements with associated heights above the WGS84 ellipsoid[10] as the reference datum. For many coastal applications, including flood-risk mapping, lidar elevations are transformed from ellipsoid heights to orthometric heights. Orthometric heights are based on the geoid, an equipotential surface defined by the earth's gravity field, approximately equal to the mean sea level (MSL). To obtain orthometric heights, an adjustment must be made for the local vertical separation between the ellipsoid and the geoid[4].

The DEM used in the study had to be adjusted to have MSL as its reference datum. Field operations were conducted to determine the geoid height which is then used to transfer topographic data based on the ellipsoid to MSL. The equation used to calculate the geoid height between the local MSL and the WGS-84 ellipsoidal height is described in Figure 7.

[7] National Mapping and Resource Information Authority

[8] Medium to low stabilization scenario

[9] High end scenario where greenhouse gases concentrations continue to rise throughout the 21st century

[10] A smooth mathematical surface representing the earth

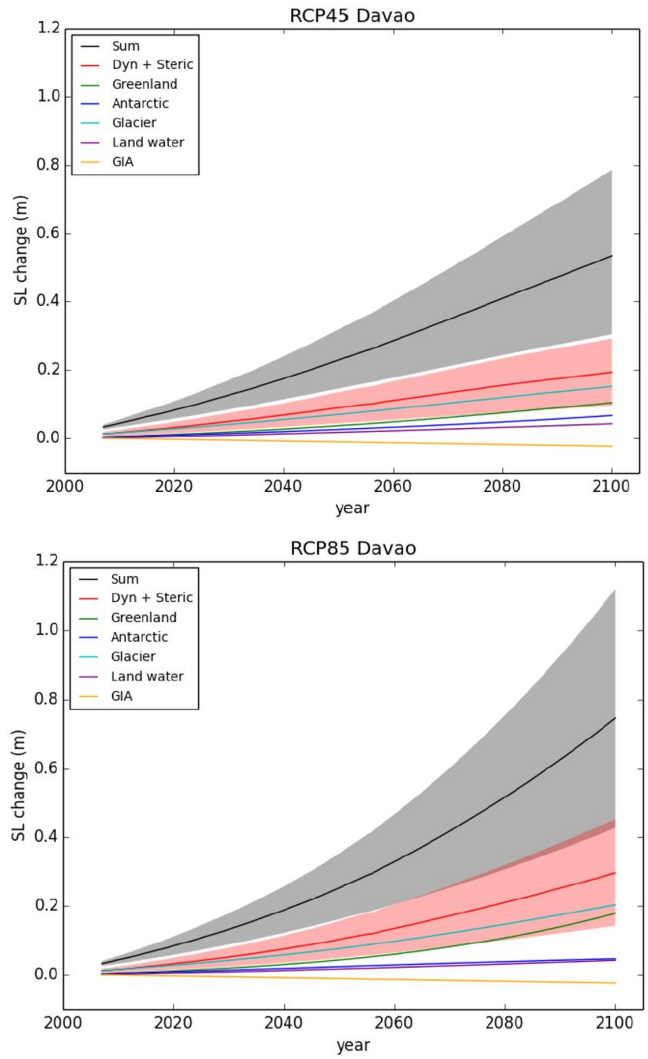

Fig. 6. Time series of the mean sea level change for Davao. The solid line represents the central estimate; shaded area represents the uncertainty of the likely range.

First, differential levelling was conducted to derive the MSL elevation from a known tidal benchmark. This was done using five identified benchmarks in the area (Figure 8) following the standard operating procedures on differential levelling. To reduce possible errors induced by Earth's curvature, the backsight and foresight distances for each level line were made to be most congruent. For some areas with inclined terrains, sharp-curved roads and somewhat crowded, it is inevitable to have unequal distances of the backsight and foresight. Never-

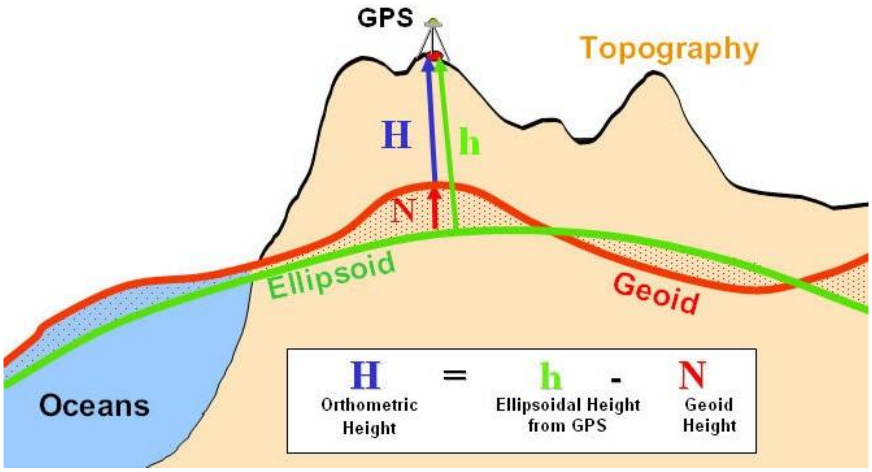

Fig. 7. Relationship between ellipsoidal height, geoid (MSL) and the undulation value (geoid height).

theless, the rodman and the observer tried to adjust the distances as the survey continued to compensate for the differences.

Fig. 8. Location of benchmarks used in the levelling. Yellow points are the benchmarks in reference to the location of the tide gauge (red point).

Next, topographic survey was conducted to obtain the coastal profiles in the study area. Previously identified benchmarks were employed to survey the coastal profiles using the Real-Time Kinematic functionality of the equipment[11] used. A base station is set up directly over a known benchmark and correction data is broadcast through radio to the rover. Survey measurements were collected to capture relevant natural and anthropogenic topographic features such as the beach face, dunes, and sea walls, especially areas that are at risk to storm surge.

Finally, hydrographic survey was conducted to get a seamless topographic–bathymetric dataset that will be used for the high-resolution modelling of storm surge. With the assistance from the Hydrography Branch of NAMRIA, a high-resolution single-beam bathymetric survey was conducted along the coast of the study area. The survey yielded approximately 682 kilometers of total survey lines.

In addition, tide level information was collected by installing a portable tide gauge in the study area[12]. Tidal measurements were logged every hour and downloaded at the end of the observation period. To assess the accuracy of the data collected, it was compared with the observations from the nearest primary tide station located at Surigao Port, Surigao del Norte.

3.2 Model Configurations

In this study, the JMA Storm Surge Model is used to simulate the increase in sea surface elevation due to wind and pressure set-up. However, initial results of the simulations reveal minimal storm surge heights contradictory to eyewitness accounts of 3- to 4-meter-high storm surges. This led to the use of other storm surge models that could reproduce the event as closely as possible. Models such as Delft3D and XBeach were used to simulate storm tide and wave-induced set-up, respectively, while the SWAN model was used to compute maximum offshore wave height. A combination of the outputs of these different models were employed to address the limitations of the other models and produce a more accurate representation of the storm surge heights.

JMA Storm Surge Model

Since 2011, JMA has operated storm surge model to support its provision of real-time storm surge prediction information to ESCAP/WMO Typhoon Committee Members. Outline of the specifications of the storm surge model is shown in Table 2.

Equations of the model are based on linearized two-dimensional shallow water formulae without advection terms. It includes wind setup due to strong winds

[11]Equipment used is the Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS). It consists of a base receiver and a rover receiver that communicates with GPS satellites and with each other. The RTK functionality increases accuracy in measurement of surveyed positions.

[12]Tide gauge was located in Barangay Santa Filomena, Cateel.

Table 2. JMA Storm Surge Model specifications for the regional storm surge watch scheme over Asia.

Parameter	**D**escription
Model	2-dimensional linear type
Grid	Lat-Lon
Region	0-42°N, 95-160°E
Resolution	2' x 2', 1951 x 1381 (∼3.7 km)
Time step	8 seconds
Forecast time	72 hours
Cycle	4 per day (every 6 hours)
Initial times (UTC)	00, 06, 12, 18
Members	No-typhoon situations: 1 (model GPV) Typhoon situations: 6 (model GPV + bogus)
Model GPV forcing	GSM (0.25° x 0.2°) GEPS (0.5625° x 0.5625°)
Typhoon forcing (bogus)	Pressure: Fujita formula Inflow angle: 30° Velocity for asymmetry

and inverse barometer effect associated with pressure drops, but does not incorporate schemes of wave setup, coastal inundation and sea level changes associated with other factors such as sea water temperature.

The necessary inputs for the JMA model are as follows: TC center location (in longitude and latitude), minimum pressure at the TC center, maximum sustained wind speed and radius of the 1000 hPa isobar.

To assess the occurrence of storm surge during the passage of Typhoon Pablo over Davao Oriental, the observed parameters for surface winds, atmospheric pressure and location of TC center were used. Parameters were obtained from PAGASA best track data archive. Figure 9 shows the simulation results of JMA Storm Surge Model for Typhoon Pablo.

For the worst-case scenario study, Super Typhoon Yolanda's (2013) minimum pressure was used as input in place of Typhoon Pablo's while other parameters were retained.

Delft3D Model

A separate model suite was used to have a more detailed perspective on the storm surge in the study area. The set consists of the following models: Delft3D

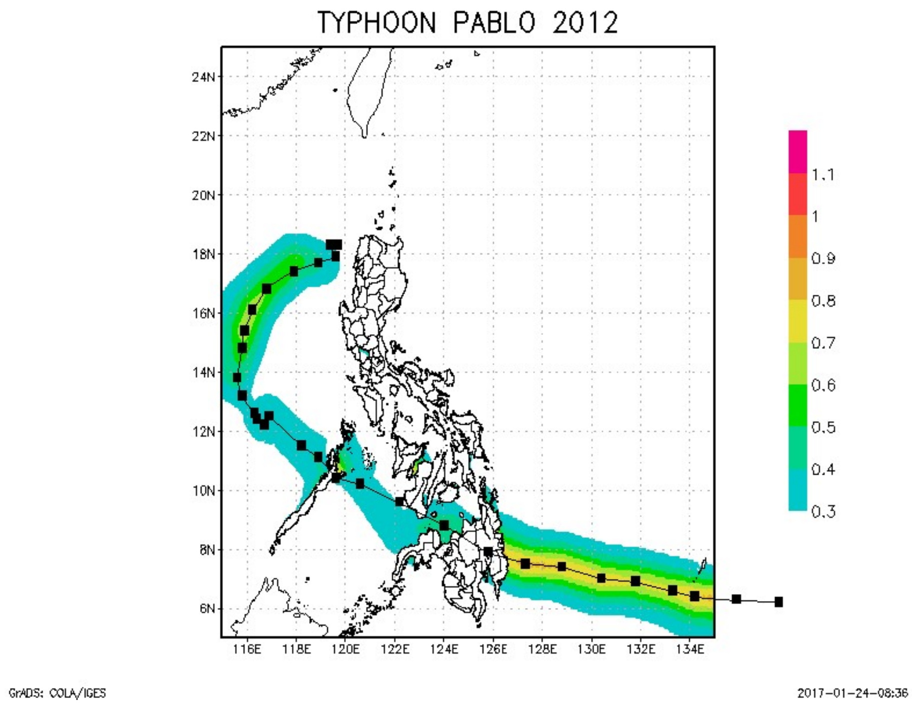

Fig. 9. JMA Storm Surge Model simulation results for Typhoon Pablo. Observed parameters were used as input.

to simulate storm surge due to pressure and wind disturbances; XBeach model to simulate wave set-up and run-up; and SWAN model to simulate offshore waves[13].

Delft3D is a model capable of 3D computations for coastal, river and estuarine areas. It can carry out simulations of flows, sediment transports, waves, water quality, morphological development, and ecology. One of its modules, Delft3D-FLOW, calculates non-steady flow and transport that result from tidal and meteorological forcing on a rectilinear or curvilinear, boundary fitted grid. It solves the unsteady shallow water equations in two (depth-averaged) or in three dimensions derived from the three-dimensional Navier Stokes equations for incompressible free surface flow on a Cartesian rectangular, orthogonal curvilinear or spherical grid.

Along with the flow computation performed by the Delft3D-Flow module, it is possible to combine the effect of waves using the wave module SWAN model. The wave characteristics are computed and interrelated with the flow module to account at each timestep for the interaction between the depth, the flow velocities, the water level, and the waves without including the bed update. The

[13]Simulations using the Delft3D model suite were performed with the assistance of Mr. Maarten Van Ormondt, the principal developer of the Delft Dashboard.

SWAN model solves the conservation of the action density, instead of the energy density, as the action density is conserved under the presence of currents, while the energy density is not.

XBeach Model

XBeach model[5] is an open-source numerical model originally developed to simulate hydrodynamic and morphodynamic processes and impacts on sandy coasts with a domain size of kilometers and on the time scale of storms. The model includes the hydrodynamic processes of short wave transformation (refraction, shoaling and breaking), long wave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation. The morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update and breaching.

3.3 Storm surge inundation mapping

To assess areas at risk of storm surge inundation, ground-validated results of the storm surge models and field surveys were used to develop storm surge hazard maps. Bathtub method was used to evaluate how far inland the seawater will flow as well as its height above ground. The method consists of comparing water levels with terrain elevations wherein areas with terrain elevation lower than or equal to the computed water level is considered as being flood prone.

3.4 Storm surge model and map validation

Model simulation results were validated by comparing it with visual observations or tide gauge recordings. For visual observations, field surveys were conducted (2014) in the target areas to look for evidence of high-water marks. People who personally witnessed the occurrence of storm surge in the area recounted their experiences before, during and after the passage of Typhoon Pablo. Information about the storm surge occurrence, flood heights, nature of the wind (direction and strength) as well as time of landfall were collected and referenced geospatially. Flood heights were measured against the sea level while total elevation and zip elevation altitude instruments were used to measure inundation depths and extents, respectively.

Initially-produced storm surge hazard maps were validated through peer review by local authorities and residents in the target areas (2016). Ground validation was conducted both in coastal areas and inland areas to verify inundation depths and extent. Hard copies of the storm surge hazard maps were presented to the residents to confirm the presence of water marks or if it matched actual flood heights.

4 Results and Discussion

This section discusses the results of the field surveys conducted and the storm surge model simulations.

4.1 Field surveys

From the geodetic levelling survey conducted, coordinates and elevation of newly established and recovered tidal benchmarks in Santa Filomena, Cateel, Davao Oriental is shown in Table 3.

Table 3. Coordinates and elevation above mean sea level (AMSL) of newly established and recovered tidal benchmarks in Santa Filomena, Cateel, Davao Oriental.

Name	Longitude	Latitude	Elevation (meters)
TGBMX 2016 NAMRIA	126°26'9.6"	7°48'36.5"	2.91617
TGBMCTL1	126°26'10.87"	7°48'34.27"	4.22494
TGBMCTL2	126°26'20.4"	7°48'31.72"	4.86533
BM1 1971	126°26'13.2"	7°48'36.5"	4.02179
DVE44 2007 NAMRIA	126°26'16.8"	7°48'33.01"	5.11057

The established coordinates for "TGBMX 2016 NAMRIA" is used to determine the undulation value. Through the levelling survey, it was found that the MSL height at this location is 2.91617 meters (from Table 3). In addition, the elevation for this location as derived from the LiDAR DEM was found to be 0.0350 meters. Using these values, the undulation value or geoid height was computed to be 2.8817 meters 2.9 meters. This undulation value is then applied to the ellipsoidal height (WGS84) to transform all elevation to the local MSL of the study area.

To confirm if the vertical adjustment of 2.9 meters to the LiDAR DEM was appropriate, the orthometric heights derived from the topographic survey were compared with LiDAR-derived DEM ground surface orthometric heights. Selected GPS points were overlaid to the DEM surface through GIS software and the orthometric height differences between the GPS and LiDAR DEM were calculated (see Table 4). The mean difference was 0.07 meters, confirming that the adjustment of 2.9 meters was appropriate. The LiDAR-derived DEM ground surface orthometric heights and GPS measurements were highly correlated, with a coefficient of determination $R^2 = 0.93$ (see Figure 10).

The hydrographic survey conducted resulted to about 620 kilometers of main sounding lines and 62 kilometers of cross line surveys using 100-meter spacing between sounding lines (Figure 11). To create the seamless topographic and bathymetric terrain data model, results of the hydrographic and topographic survey are combined, and an example for select areas is shown in Figure 12 with the respective profiles presented in Figure 13.

Table 4. GPS-derived orthometric heights compared with LiDAR-derived DEM ground surface orthometric heights

Station Name	GPS (m)	LiDAR DEM (m)	Difference (m)
DVE-3153	4.56	5.59	-1.02
DVE-44	6.04	5.68	0.36
TGBM-CTL1	5.22	5.19	0.03
TGBM-CTL2 2016	5.87	6.33	-0.46
TGBMX-2016	3.92	2.94	0.98
DVE-3126	3.50	4.35	-0.85
KINABLANGANPT1	2.61	2.90	-0.30
SAN VICTOR TP	5.57	2.90	2.67
DVE-3159	18.48	18.56	-0.07
KM POST 1562	7.52	6.40	1.11
LAMBAJON TP	5.23	5.56	-0.33
SAN ANTONIOPT1	4.77	6.00	-1.23
Mean			**0.07**
Standard Deviation			**1.09**

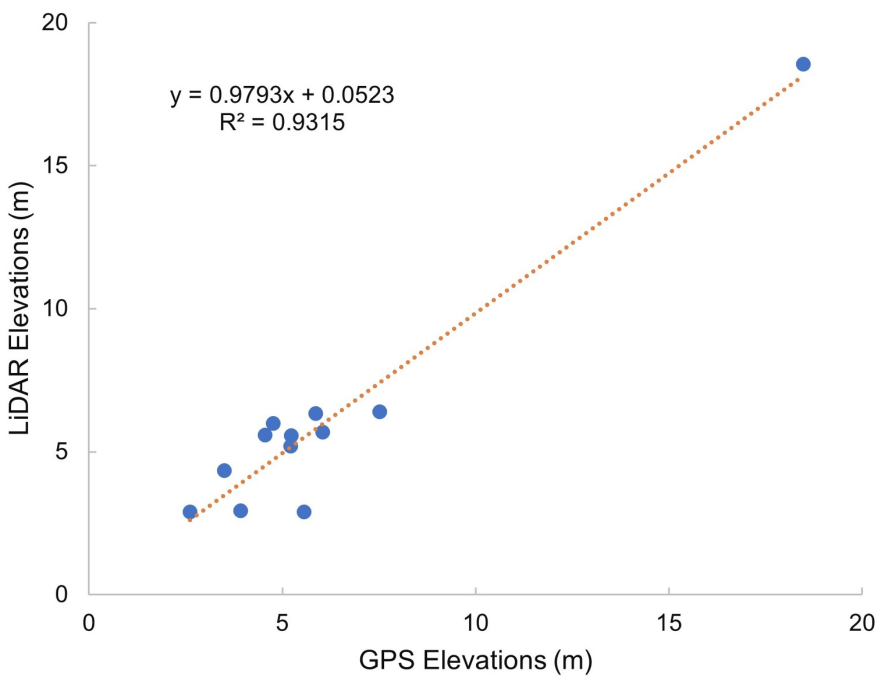

Fig. 10. Scatterplot of GPS and LiDAR-derived DEM ground surface orthometric heights.

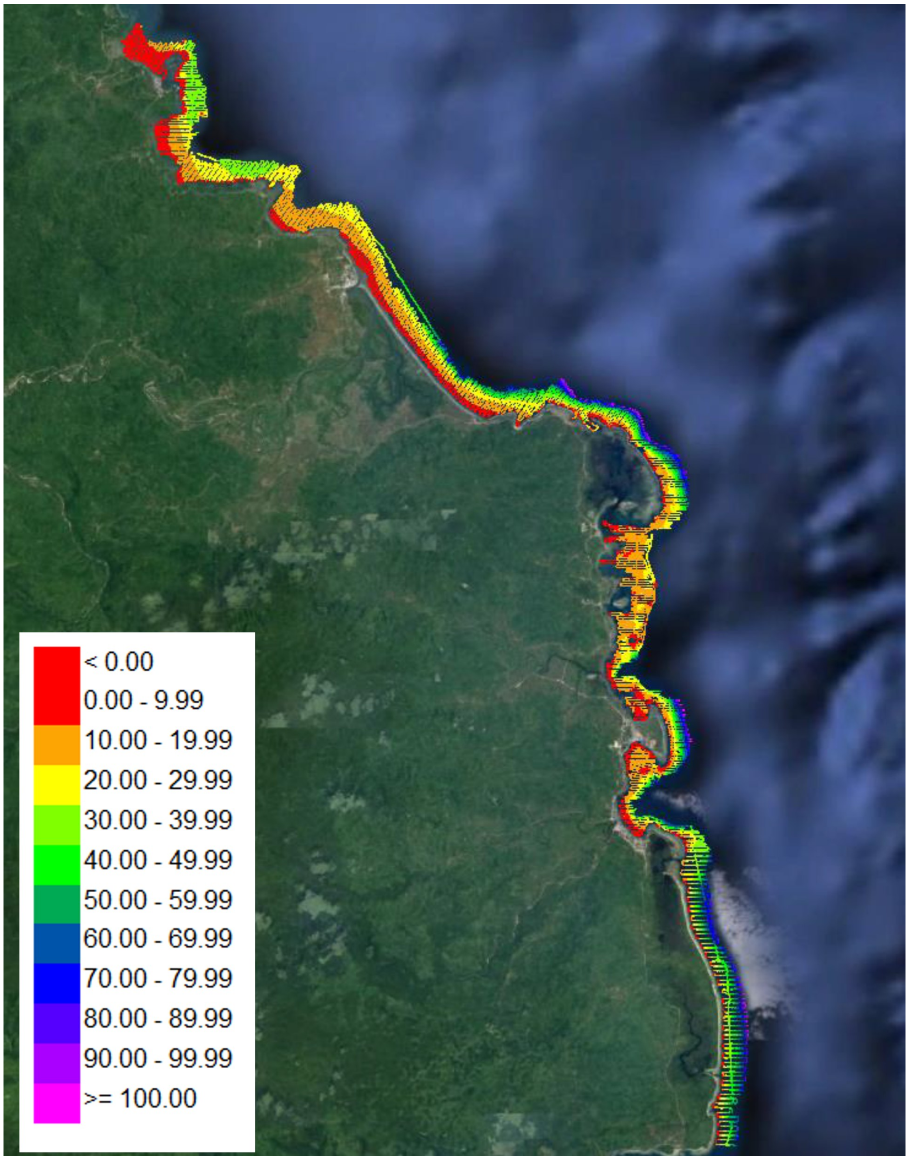

Fig. 11. Result of the hydrographic survey using the single beam echo sounder. Colors represent bathymetric information in meters.

Observations from the portable tide station installed were downloaded and processed by the Physical Oceanography Division of NAMRIA. The tide corrections were referred to MSL and were applied through HYPACK's Manual Tides program. Hourly records of tides showed daily variations in heights ranging from 100 cm to at most 300 cm.

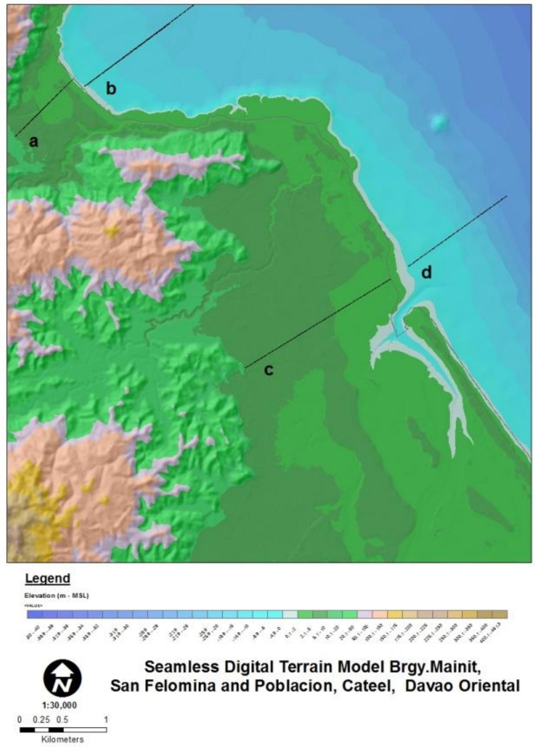

Fig. 12. Seamless Digital Terrain Model in the vicinity of Mainit, Santa Filomena and Poblacion, Cateel, Davao Oriental. The black lines represent the cross-section areas.

4.2 Experiment results

From the JMA Storm Surge model outputs, maximum storm surge heights for the study area reached around 0.5 to 0.9 meters. Time series plots for each of the target areas reveal the following maximum heights: 0.9 meters in Boston, 0.9 meters in Cateel and 0.8 meters in Baganga.

With the deep bathymetry offshore of the study areas and the coasts predominantly sheltered by fringing reefs, traditional numerical storm surge model alone cannot reproduce the destructive waves that caused the damages during Typhoon Pablo. To address this limitation, Delft 3D model suite were used to account for the wave set-up and run-ups.

From the simulations, water level of approximately 0.15 meters and 0.45 meters can be accounted due to wind stress and inverse barometer, respectively (Figure 14). Delft 3D XBeach model results for wave set-ups show higher water levels along the coast up to 2 meters above mean tide level while results for wave run-up show water levels of up to 3.5 meters above mean tide level (Figure

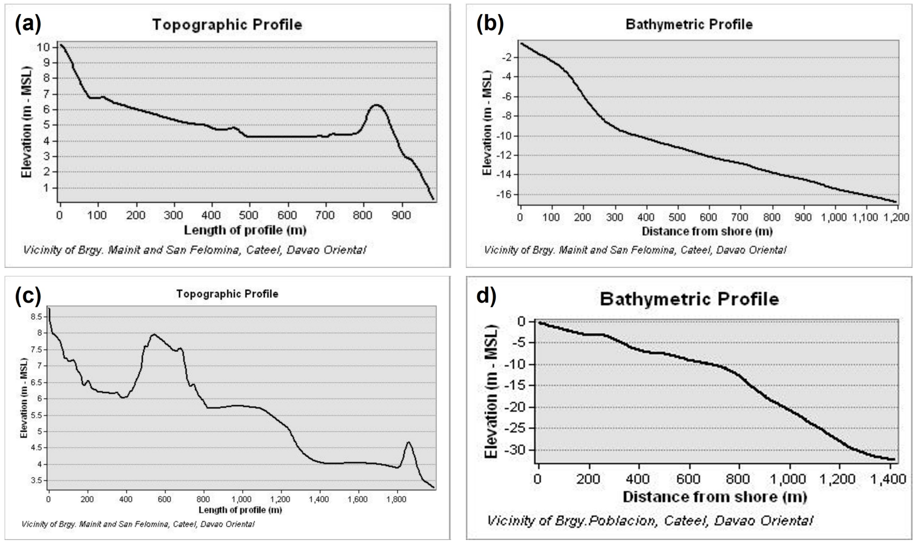

Fig. 13. Topographic and bathymetric profiles for cross-section areas in Figure 12. (a) and (b) are located in Mainit and Santa Filomena while (c) and (d) are in Poblacion.

15). While from SWAN model results, maximum wave heights were found to be approximately 14 meters at the 50-meter bathymetry contour (Figure 16).

All of the above-mentioned results were considered and consolidated as input for the storm surge inundation maps produced in the succeeding section.

4.3 Storm Surge Inundation Mapping

Results of the storm surge inundation mapping are presented to the residents of the study areas as a collection of maps. Three sets of hazard maps are developed based on these scenarios:

- Typhoon Pablo Surge Inundation Maps (baseline event)
- Storm Surge Hazard Maps (considering Typhoon Yolanda-intensity as worst-case scenario)
- Storm Surge Hazard Maps (considering worst-case scenario or Typhoon Yolanda-intensity with additional 0.7 meters due to Sea Level Rise)

The inundation maps show the inundation extents and depths above ground from the storm surge and wave simulations and mapped using the bathtub method. Each map is presented at the local or barangay level at a scale of 1:5,000 for the smaller barangays or 1:12,000 for the bigger barangays and has been designed to be printed onto an A3 paper size.

An example of the map sheet is shown in Figure 17. The map part shows the inundation depth and extent of storm surge flood within the barangay. The index

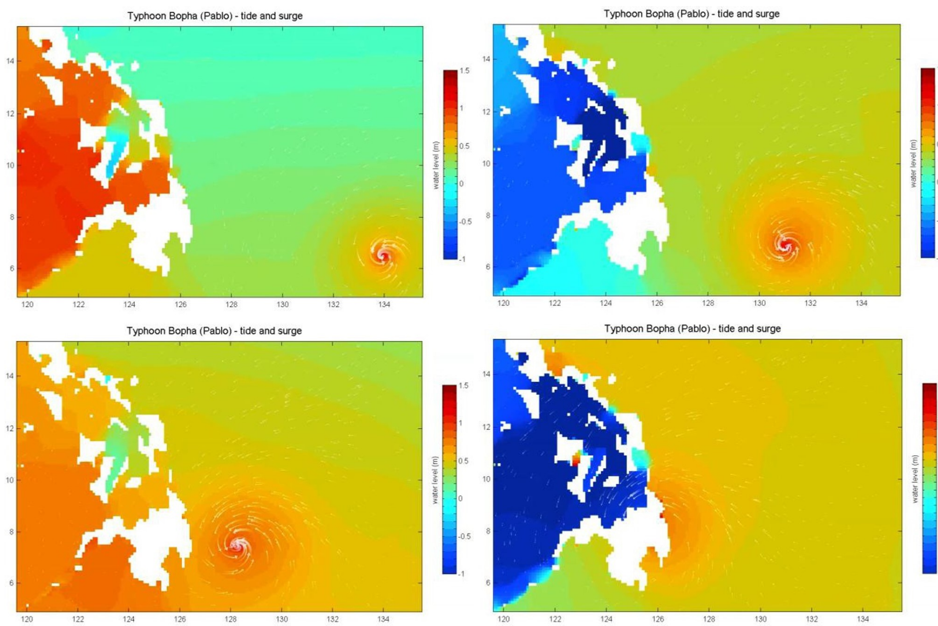

Fig. 14. Simulated tide and surge heights at different times using Delft 3D Flow module.

map is the map of the municipality which the barangay belongs to, with the red box indicating the location of the barangay with reference to the municipality. The legend shows the storm surge flood inundation classes divided into four levels: yellow representing less than 1-meter flood, orange representing flood height of more than 1 meter to 2 meters, red depicting more than 2 to 3 meters of flood height, while violet depicts extreme flooding of more than 3 meters.

Hazard maps produced for each scenario are presented in Figure 18 using Cawayanan, Boston as example. Figure 18a shows an example of the surge inundation map using the baseline event of Typhoon Pablo. Storm surge elevation of almost 4 meters relative to MSL was measured in this area from the surveys conducted. Figure 18b shows an example of the hazard map using the worst-case scenario Typhoon Yolanda-intensity. This increase in intensity has significantly increased the extent and depths of inundation. Figure 18c shows an example of the hazard map using the worst-case scenario with the addition of 0.7-meters attributed to sea level rise. The incorporation of sea level rise results in the most significant increase in inundation extent and depths. In most inundated areas, the difference is greater than 1 to 2 meters.

To consolidate the results of this study, a magazine-type resource material entitled ***Storm Surge Hazard Guide*** was produced containing the various hazard maps as well as information about Typhoon Pablo. Figure 19 shows the actual materials produced for and distributed to each of the municipalities in

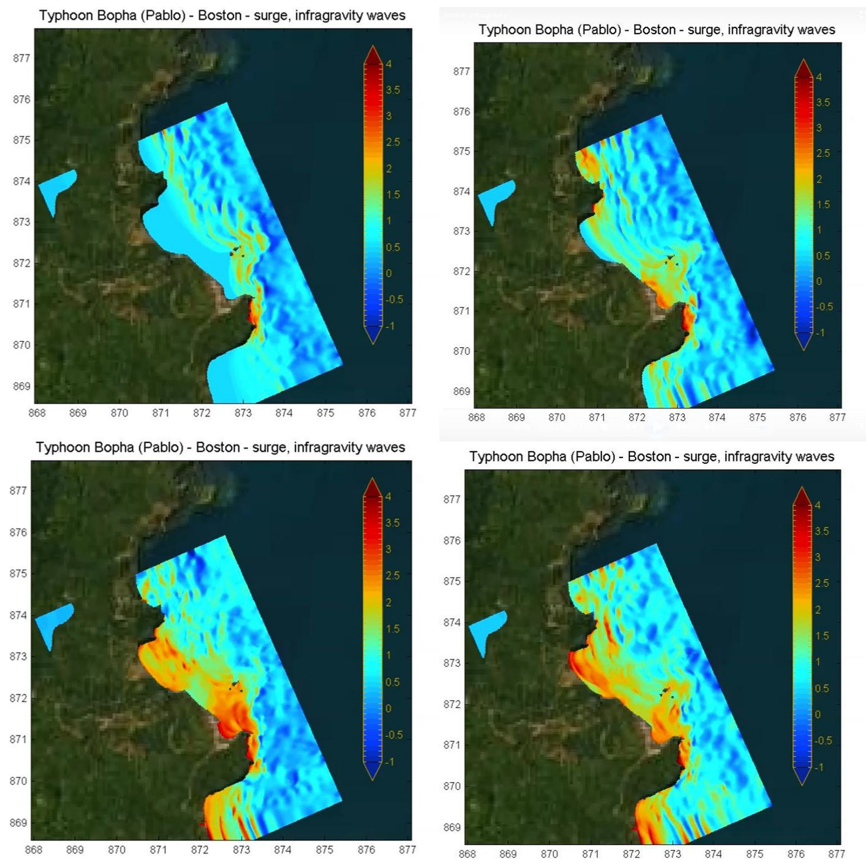

Fig. 15. Simulated surge and wave heights at different times using Delft 3D XBeach model.

the target area. Within the material, readers could get information about storm surges, its mechanisms, the warning information that they would receive relevant to it as well as a guide on how to use the maps. It also presents the inundation maps for the each of the respective Barangays within the Municipality. These materials could help guide the local governments in improving their evacuation plans and developing relevant land-use regulations. It could also aid in raising residents' awareness and understanding of storm surge hazards and its implications on their lives and livelihoods.

When local governments become informed and aware of their vulnerabilities, they become equipped to act appropriately, plan accordingly and boost their resiliency. Understanding where the areas of greatest risks are, local governments can subsequently focus their efforts and limited resources towards urgent mitigation plans and activities towards building more resilient communities.

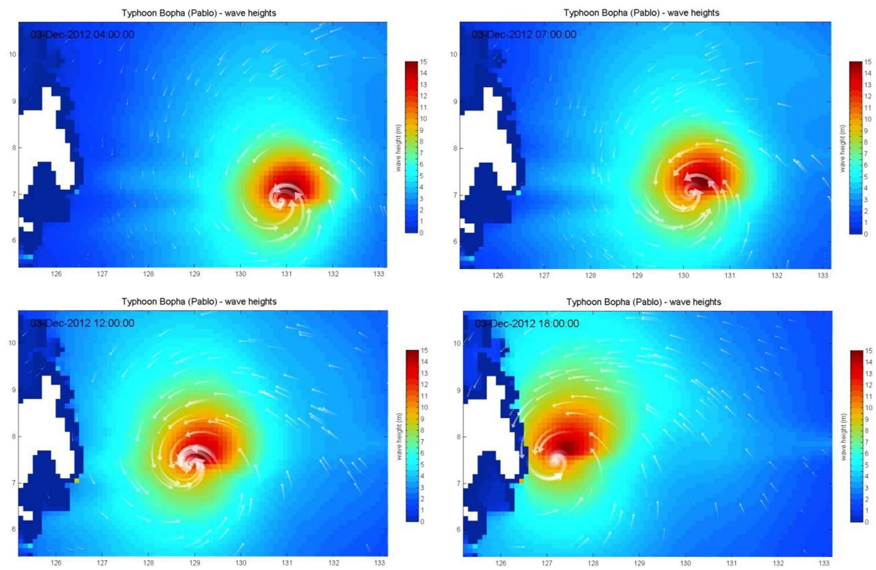

Fig. 16. Simulated offshore wave heights at different times using SWAN model.

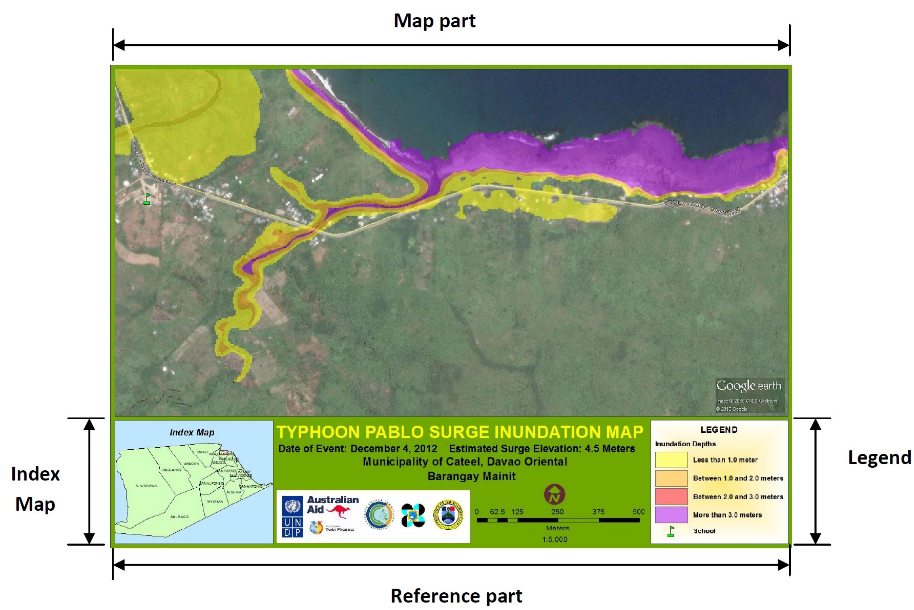

Fig. 17. Sample Storm Surge Hazard Map.

5 Conclusion

This study assessed the storm surge inundation risk of coastal barangays in three municipalities of Davao Oriental namely Boston, Cateel and Baganga. Initially,

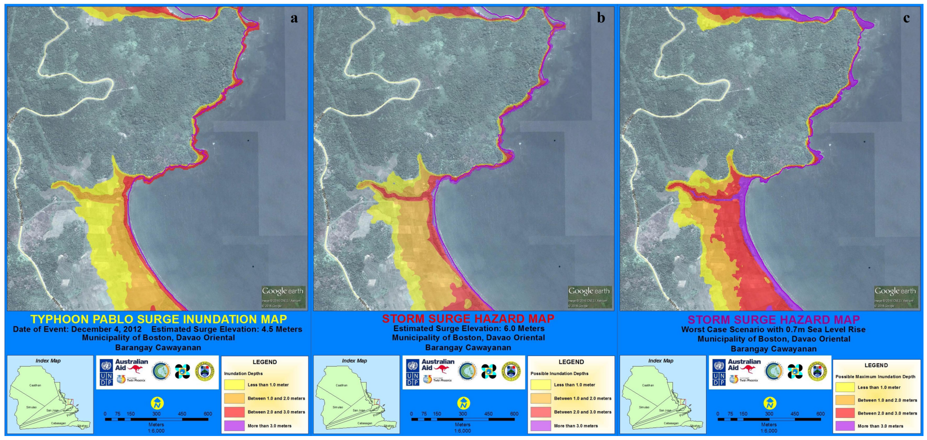

Fig. 18. Sample of hazard maps produced for Barangay Cawayanan, Boston, Davao Oriental for each scenario: a) Typhoon Pable Surge Inundation Map, b) Storm surge hazard map using worst-case scenario, and c) Storm surge hazard map using worst-case scenario with sea level rise.

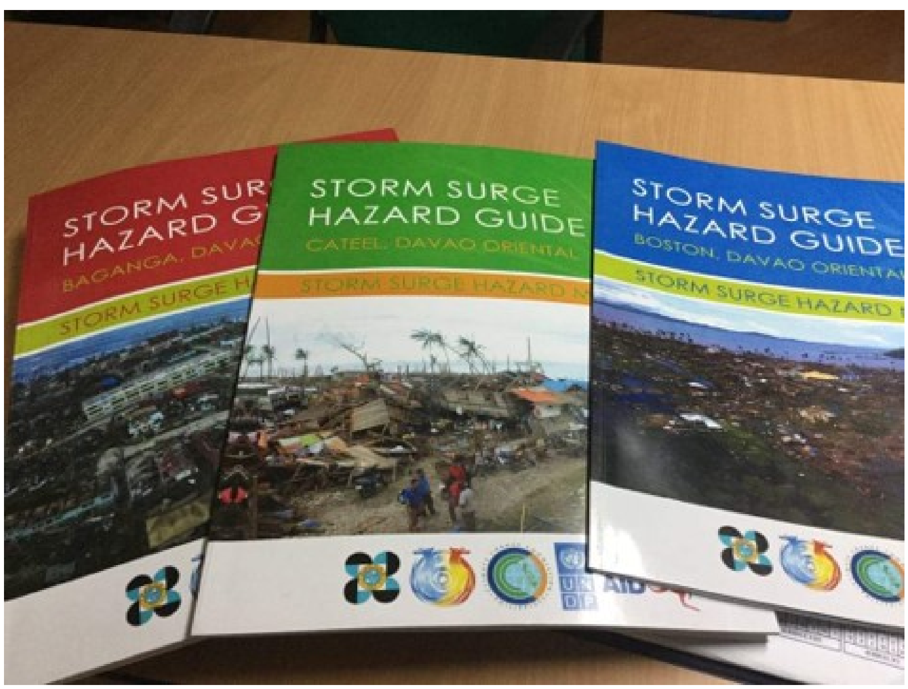

Fig. 19. Storm Surge Hazard Guide for Baganga, Cateel and Boston, Davao Oriental.

DEMs were validated through the conduct of field surveys such as differential levelling and topographic survey using the RTK-GNSS.

Model simulation for storm surge used the JMA Storm Surge model but results showed very limited surge in contrast to the residents' descriptions during the high-water mapping survey. With deep bathymetry offshore and coast predominantly sheltered by fringing reefs, traditional numerical storm surge model alone could not reproduce the destructive waves that caused the damages during Typhoon Pablo. To address this limitation, Delft 3D model suite were used to account for the wave set-up and run-ups. For each of the inundation maps produced, a combination of the outputs from the JMA Storm Surge model, Delft3D and XBeach models were used to accurately represent the storm surge inundation that occurred during Typhoon Pablo.

For the inundation mapping, a common methodology called bathtub method was used. It is a relatively straightforward technique, but the resulting inundation surface can sometimes be inaccurate. Results of the inundation mapping are presented as a magazine-type material which contains the collection of inundation and hazard maps for three scenarios: Typhoon Pablo as baseline event; Worst-case scenario using Typhoon Yolanda-intensity; and Worst-case scenario with additional sea level rise.

From the combined effects of climate change and changing nature of cyclones, coupled with projected rise in sea levels, we have seen an increased vulnerability to storm surge inundation in the study area. This research builds on the past works on storm surges in the area but also adds value to the existing storm surge knowledge in the Philippines. With previous hazard mapping initiatives in the study area, traditional methods were employed to generate hazard maps based only on storm surge heights derived from models. Through this research, a comprehensive methodology to storm surge hazard mapping is presented which accounts not only the storm surge heights produced by models but also incorporates natural and anthropogenic topographic and bathymetric features. It also produced easy-to-understand guidelines for storm surge designed to be used by local communities. It gives local governments confidence to utilize the hazard maps as there is an increased appreciation and awareness of the storm surge hazards in their areas. Disaster managers can further establish relevant mitigation and resilience efforts following the increased awareness and understanding of the vulnerability to storm surges. Likewise, researchers can employ the methodology used in this work to other areas to increase the state of knowledge on storm surge hazards in the Philippines.

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