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Discussions

Developing an early warning system for storm surge inundation in the Philippines

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Abstract

A storm surge is the sudden rise of sea water generated by an approaching storm, over and above the astronomical tides. This event imposes a major threat in the Philippine coastal areas, as manifested by Typhoon Haiyan on 8 November 2013 where more than 6000 people lost their lives. It has become evident that the need to develop an early warning system for storm surges is of utmost importance. To provide forecasts of the possible storm surge heights of an approaching typhoon, the Nationwide Operational Assessment of Hazards under the Department of Science and Technology (DOST-Project NOAH) simulated historical tropical cyclones that entered the Philippine Area of Responsibility. Bathymetric data, storm track, central atmospheric pressure, and maximum wind speed were used as parameters for the Japan Meteorological Agency Storm Surge Model. The researchers calculated the frequency distribution of maximum storm surge heights of all typhoons under a specific Public Storm Warning Signal (PSWS) that passed through a particular coastal area. This determines the storm surge height corresponding to a given probability of occurrence. The storm surge heights from the model were added to the maximum astronomical tide data from WXTide software. The team then created maps of probable area inundation and flood levels of storm surges along coastal areas for a specific PSWS using the results of the frequency distribution. These maps were developed from the time series data of the storm tide at 10 min intervals of all observation points in the Philippines. This information will be beneficial in developing early warnings systems, static maps, disaster mitigation and preparedness plans, vulnerability assessments, risk-sensitive land use plans, shoreline defense efforts, and coastal protection measures. Moreover, these will support the local government units' mandate to raise public awareness, disseminate information about storm surge hazards, and implement appropriate counter-measures for a given PSWS.

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1 Introduction

1.1 Background

The National Oceanic and Atmospheric Administration (NOAA) defines storm surge as a storm-generated abnormal rise of water – over and above the predicted astronomical tides. Storm surges are complex phenomena due to their dependence on the slightest changes on the tropical cyclones' parameters. These variables include central atmospheric pressure, wind intensity, storm size, storm forward speed, angle of approach to coast as well as the shape of the coastline, width and slope of the ocean bottom, and local features. Higher storm surges can be observed for an approaching tropical cyclone with lower central atmospheric pressure, stronger winds, larger storm size, perpendicular to the coastlines, faster translational speed on open coast, slower typhoon on enclosed bodies of water, gently sloping continental shelves, and the absence of natural or artificial coast barriers to impede the flow of sea water.

Storm surges result in more damaging flood conditions in coastal zones and adjoining low-lying areas (Dasgupta, 2009). According to the Coastal Services Centre of NOAA, flooding or inundation is among the more frequent, costly, and deadly hazards that can impact coastal communities. Storm surge imposes a major threat to the Philippine coastal areas, as manifested by Typhoon Haiyan (Fig. 1) on 8 November 2013 which claimed 6300 lives, left 1061 missing, and caused damages estimated at USD 2 billion (National Disaster Risk Reduction and Management Council, 2014).

Tropical cyclones are known to form in the tropical regions, such as Northern Australia, Southeast Asia, and other Pacific islands. The warm waters near the equator serve as the driving force to develop the tropical cyclones. Located in the south-western region of the Pacific Ocean, the Philippines is geographically prone to tropical cyclones (Fig. 2). According to the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA, 2014a), an average of 20 tropical cyclones enter the Philippine Area of Responsibility (PAR) per year and nine of which make landfall. In addition, the country's coastlines are low elevation coastal zones (LECZ) wherein 9.54 %

of the coastal municipalities and cities are 10 m or below based on GIS-derived SRTM data. McGranahan et al. (2007) define LECZ as the contiguous area along the coast that is less than 10 m a.s.l. Low elevation and the frequent onslaught of tropical cyclones are the major reasons that makes the country vulnerable to storm surge events.

1.2 Objective

In line of the recent disasters that the country experienced, the Department of Science and Technology (DOST) funded a project wherein a multidisciplinary approach in developing systems, tools, and other technologies helping to prevent and mitigate disasters was launched. This project herein is called the Nationwide Operational Assessment of Hazards (Project NOAH). Project NOAH together with PAGASA, the country's national meteorological institution, spearheaded a study to create early warning systems to mitigate impacts of storm surge events. The objective of the study is to develop storm surge inundation maps using simulations of historical tropical cyclones and their associated Public Storm Warning Signal (PSWS).

1.3 Public storm warning signal

The PSWS is issued by PAGASA to provide warning to the public of incoming weather disturbances. As shown in Table 1, these signals are raised when tropical cyclones are expected to enter the PAR and may also be upgraded or downgraded depending on the strength and proximity of the tropical cyclone. When PSWS is raised, the meteorological conditions are not yet prevailing over the area since its main purpose is to warn the public of the impending effects that the tropical cyclone would bring. The PSWS given to a certain region is based on the intensity, size of circulation, forecast direction, and speed of the tropical cyclone (PAGASA, 2014b).

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1.4 Limitations

It is important to note that this study is based on the PSWS issued by PAGASA; storm signals are forecasted wind speeds and may not be accurate. The study is also limited to the number of tropical cyclones that fall on every PSWS and the number of events with surge height associated with every PSWS.

1.5 Study area

Metro Manila including Meycauayan and Obando in Bulacan were used as a pilot site for the study. It was selected considering its high population density and its vulnerability to storm surges given that it is frequented by tropical cyclones and 27 % of Metro Manila is under the 10 m LECZ (Fig. 3).

2 Methodology

2.1 Storm surge modelling

The Japan Meteorological Agency (JMA) Storm Surge Model is a numerical code that is used to simulate and predict storm surges generated by tropical cyclones (Higaki, 2006). The numerical scheme of the model is based on two dimensional shallow water equations. Other governing equations include the equation of motion and the continuity equation with air pressure and wind fields used as external forcings.

The storm surge model uses storm track, bathymetric data, central atmospheric pressure, and maximum wind speed as input parameters for the model.

The bathymetric data used was the ETOPO2 with 2 min gridded elevation data. Tropical Cyclone Best Track Data from the RSMC Tokyo-Typhoon Center were obtained from the JMA website. JMA releases tropical cyclone forecasts every 3 h and can be accessed for free on their site. The best track data text files contain the latitude and

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longitude of the center, central pressure (hPa), maximum sustained wind speed (knots), and the radius of 50 and 30 kn winds.

2.2 Tide data

The study used values for the astronomical tide derived from WXTide, a software containing archives/catalogues of world-wide astronomical tides (WXTide32, 2014). WXTide predicts tide levels from 1970 through 2037. It produces text outputs of the following: daily tide list, monthly calendar, and incremental tide. It also generates BMP graphics and text tide CSV spreadsheet files. WXTide has records of worldwide time zones and solar or lunar events. The software can save recent stations and real-time tide states.

2.3 Flood modelling

The proponents of the study used FLO-2D PRO, a Grid Developer System software that has maps with topographies and creates models based on the grid topographies, boundaries, and tides. This software is used in river studies and unconfined flood analyses, and is approved by the Federal Emergency Management Agency of the United States of America (FEMA). FLO-2D is a combined hydrologic and hydraulic model (FLO-2D Software, 2014). The software integrates river and floodplain flood routing. The following data are required for FLO-2D to simulate the flow of water: Digital Terrain Model (bare earth) data at 5 m resolution, hydrologic data (including rainfall and discharge hydrographs), and floodplain and channel detail. It also takes into account various parameters and detail features, such as surface roughness, street flow, presence of walls and levees, hydraulic structures, vegetation, and soil type.

2.4 Probability of exceedance

The storm surge numerical models greatly depend on the accuracy of the forecast of tropical cyclone's track, size, and intensity. Forecasting the storm surge height and

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time series with a hundred percent precision imposes great difficulty, since even the best tropical cyclone forecasts still have considerable uncertainty.

The exceedance probability curve gives the forecast probability that a particular parameter quantity will be exceeded at the location in question, for a given season for a given time (NOAA, 2012). This graphical representation describes the probability that some various levels of loss will be exceeded over a future time period or will be surpassed over a given time (Grossi and Kunreuther, 2005). Forecast curves also show the percentage anomaly of the most favored tercile of the climatological distribution: below normal, near normal, and above normal.

The storm surge time series generated by tropical cyclones were categorized according to the PSWS released when the tropical cyclone passed a certain area. Each PSWS is grouped in terms of the maximum sustained winds of the tropical cyclones. Of all the storm surge time series plotted by historical tropical cyclone's PSWS since 1971, it is difficult to select which actual typhoon-induced storm surge time series is likely to behave the same as the tropical cyclone to be forecasted.

To find the most accurate solution, the researchers used the probability of exceedance to evaluate the storm surge time series curves. For each region, the PSWS released for the tropical cyclones that affected the aforesaid region were categorized in order to determine the surge time series. The surge time series gives the change in surge height for each tropical cyclone. The tropical cyclones that produced the highest surge can be observed in this probability curves. The percentage of the exceedance curve determines the probability of a certain tropical cyclone-induced storm surge to behave within a certain exceedance range. A tropical cyclone with 1 % exceedance probability would produce storm surge of greatest intensity than those of the storm surges produced of the other historical tropical cyclones.

2.5 Nature of occupancy and probability of exceedance

The corresponding probabilities of exceedance were determined based on the classification of structures by nature of occupancy from the National Structural Code of the Philippines (Table 2).

To take into account the surge heights that will be used for the flood modelling, the researchers specified 1, 10, and 25 % probability of exceedance (Table 3). Each probability corresponds to a particular surge height for every province in the Philippines and for every PSWS. The given probabilities were specified with consideration to the surge height difference between the height values of 1, 10, and 25 %.

2.6 Process

The JMA Storm Surge Model was used to simulate 721 tropical cyclones that entered PAR and had made significant effect on the Philippine weather. Best track data of all the tropical cyclones in the Northwestern Pacific Basin from 1951 to 2013 were acquired from the JMA website.

A station file containing points specified by the user where surge will be computed is also needed. A total of 4996 observation points for the entire Philippines were identified. As shown in Table 4, ten of these points were in Metro Manila.

The input files for the 721 tropical cyclones were run using the JMA Storm Surge Model. These simulations produced time series plots of the storm surges produced by each tropical cyclone for all the observation points to determine the maximum surge height and time.

All PSWS raised for each province in the Philippines from 1971 to 2013 were grouped according to storm signals 1, 2, 3, and 4. These data were grouped based on the maximum PSWS that hit a specific province. For Metro Manila, there were 143 storms that reached PSWS No. 1, 46 for PSWS No. 2, 21 for PSWS No. 3, and 2 for PSWS No. 4 (Fig. 4).

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For each PSWS, the maximum surge heights per tropical cyclone per observation point were tallied to create a frequency distribution table to which the probability of exceedance was derived. The probability of exceedance was determined by solving for the cumulative probability of the maximum heights for each PSWS. This method allowed the study to determine the probability that a certain storm surge height will be exceeded. All of the storms time series that have the maximum surge height falling under the 1, 10, and 25 % probability of exceedance was grouped together to create an averaged time series that will be used as an input value for the FLO-2D software.

Each time series plot of all the tropical cyclones that fall for each storm signal was collected and was processed using the moving average smoothing method to produce HVT as input for FLO-2D. The moving average smoothing technique was used to create a single time series for each probability value under every PSWS category. Using this technique, each element of the time series is replaced by the simple average of *n* surrounding elements, where *n* is the width of the smoothing "window" (Box and Jenkins, 1976; Velleman and Hoaglin, 1981). The window width used was 20 time steps. The time series for each probability of exceedance was then converted to an HVT file which is the input file for the FLO-2D software. An HVT file contains the water level values to its corresponding time element. The study used a ten minute interval HVT file for its inundation simulation (Fig. 5).

Since the JMA Storm Surge Model only accounts for the height of the surge and does not include tidal parameters, the WXTide tide level data for the various observation points around the Philippines were added to the results of the JMA Storm Surge simulations.

The data generated by the JMA Storm Surge Model and by WXTide were run on FLO-2D to simulate the inundation level and extent from storm surge occurrences.

3 Results and discussion

To create a basis for drafting storm surge inundation maps in the Philippines, the researchers used frequency distribution method and exceedance probability curves of the sorted PSWS and the time series produced by the JMA Storm Surge Model.

The maximum surge height per tropical cyclone per observation point was tallied to create a frequency distribution table for PSWS number 1, 2, 3, and 4 of Metro Manila. This distribution of storm surge heights for each PSWS is illustrated in Fig. 6.

The exceedance probability distribution was derived from the frequency distribution. The graphical representation of the exceedance probability (Fig. 7) describes the probability that a particular storm surge height will be exceeded over a future time period or will be surpassed over a given time. The percentage of the exceedance curve determines the probability of a certain typhoon-induced storm surge to behave within a certain exceedance range. Each probability of exceedance has a corresponding storm surge height value.

Figures 8, 9, 10, and 11 illustrate the storm surge inundation maps per PSWS and per probability of exceedance. These maps show the varying extent of inundation depending on the probability of exceedance. As the percent of probability of exceedance increases, the extent of inundation decreases.

For PSWS 1 (Fig. 8) at 1 % probability of exceedance, Malabon, Manila, Navotas, Obando are largely inundated extending up to 6.5 km from the coast with flow depth reaching up to 3.01–4 m. Some parts of Caloocan, Makati, and Valenzuela are also inundated. For the 10 % probability of exceedance, it also extends up to 6.5 km and covering the same areas, but with shallower flow depth with mostly 1.01–2 m. At 25 % probability of exceedance, the maximum extent is up to 5.8 km covering the cities of Malabon, Navotas, and Obando with flow depths of mostly 1.01–2 m.

For PSWS 2 (Fig. 9), 1, 10, and 25 % probability of exceedance inundates up to 5.9 km from the coast, but with varying flow depths.

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For PSWS 3 (Fig. 10) at 1 % probability of exceedance, Malabon, Manila, Navotas, Obando are greatly inundated reaching up to 6 km from the coast with flow depth up to 3.01–4 m. For the 10 and 25 % probability of exceedance, inundation extends up to 5.9 and 5.7 km respectively and inundates the same areas with flow depths reaching to 2.01–3 m.

For PSWS 4 (Fig. 11) at 1 and 10 % probability of exceedance, the extent of inundation reaches 6 km and covers large areas of Malabon, Manila, Obando, and Navotas, but with different flow depths reaching 3.01–4 and 2.01–3 m, respectively.

There is no corresponding map for PSWS 4 at 25 % probability of exceedance. This can be attributed to the limited number of tropical cyclones that fall on PSWS 4. As mentioned in the introduction, the study is limited number of tropical cyclones that fall on every PSWS and the number of events with surge height associated with each PSWS.

It can be noticed that PSWS 1 at 1 % probability of exceedance has higher flow depths compared to that of PSWS 2. This is not to be expected, since higher PSWS should produce higher storm surges. This can be attributed to the accuracy of the forecasts and the release of PSWS by PAGASA. As mentioned in the limitations, it is important to note that PSWS are forecasted wind speeds and may entail errors. It is possible that a PSWS 2 was released for Metro Manila, but the actual maximum sustained winds did not reach 60–100 kph.

Based on the assigned probability of exceedance for every occupancy category, essential facilities and hazardous facilities must be located in areas beyond the 1 % probability of exceedance. On the other hand, special occupancy structures can be built beyond the 10 % probability of exceedance and standard occupancy structures and miscellaneous structures can be located beyond the 25 % probability of exceedance. It must be noted that the PSWS that recorded the highest surge heights must be used for the planning on where to build new structures.

The Philippine General Hospital is the largest hospital in the Philippines and is classified as an essential facility. As seen in Fig. 12, it is inundated with 1.07 m at PSWS 1 at

1 % probability of exceedance. However, since the structure is already built, appropriate engineering solutions must be done to ensure the safety of the people dependent on the structure.

Malacanang Palace is the official residence and principal workplace of the president of the Philippines. It is inundated with 1.06 m at PSWS 1 at 1 % probability of exceedance. Port of Manila and Navotas Fish Port Complex which are the major seaport and largest fish port in the country are largely inundated with surge heights reaching up to 3.52 and 3.21 m respectively. These structures support the major economic activities of the Philippines and must be protected.

Barangay Bangkal in Makati, Barangay Tonsuya and Longos in Malabon, and Barangay North Bay Blvd. South in Navotas are one of the largest residential areas in Metro Manila and are classified as standard occupancy structures. Tonsuya and Longos has surge heights of 2.94 and 2.08 m. Bangkal in Makati with 2.26 m and North Bay Blvd. South in Navotas with 2.54 m.

These structures are built inside the 1, 10, and 25 % probability of exceedance areas of inundation. Thus, these structures must be retrofitted in order to ensure the safety of the people if a surge height with the same intensity is to be expected.

4 Conclusions

The inundation maps show the areas in Metro Manila that are vulnerable to storm surges. These maps can help local government units (LGUs) to improve planning on building structures based on its nature of occupancy and assigned probability of exceedance. These maps can determine the areas where to build critical facilities such as evacuation centers, hospitals, fire stations, and police stations. These facilities must also be given consideration prior to its construction and should not be built in storm surge inundated areas. However, if it has to be built in the vulnerable areas, these facilities must be built with a higher level of protection. Additionally, these will help LGUs assess the structures already built if they need further retrofitting.

These maps will also help LGUs implement appropriate counter-measures when a tropical cyclone is expected and a PSWS is raised in their locality. This will give LGUs sufficient time to prepare for the incoming tropical cyclone and plan for the necessary measures to prevent loss of lives, injuries, and damages to properties.

Furthermore, these maps will help LGUs develop risk-sensitive land use plans, disaster mitigation and preparedness plans, and vulnerability assessments.

References

Association of Structural Engineers of the Philippines (ASEP): National Structural Code of the Philippines (NSCP) Volume I: Buildings, Towers and Other Vertical Structures, 6th Edn., Association of Structural Engineers of the Philippines, Inc. (ASEP), Quezon City, 2010.

Box, G. E. P. and Jenkins, G. M.: Time Series Analysis: Forecasting and Control, 2nd Edn., Holden-Day, San Francisco, CA, 1976.

Dasgupta, S., Laplante, B., Murray, S., and Wheeler, D.: Climate change and the future impacts of storm-surge disasters in developing countries, CGD Working Paper 182, Center for Global Development, Washington, D.C., http://www.cgdev.org/content/publications/detail/1422836 (last access: 3 February 2014), 2009.

FLO-2D Software: www.FLO-2D.com, last access: 3 February 2014.

Grossi, P. and Kunreuther, H. (Eds.): Catastrophe Modeling: A New Approach to Managing Risk, Springer, New York, NY, 2005.

Higaki, M.: A Guide to JMA Storm Surge Model, in: Fourth Regional Workshop on Storm Surge and Wave Forecasting, Office of Marine Prediction, Global Environment and Marine Department, Japan Meteorological Agency, Tokyo, 2006.

McGranahan, G., Balk, D., and Anderson, B.: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones, Environ. Urban., 19, 17–37, doi:10.1177/0956247807076960, 2007.

National Oceanic and Atmospheric Administration: Understanding the “Probability of Exceedance” Forecast Graphs for Temperature and Precipitation, available at: http://www.cpc.ncep.noaa.gov/ (last access: 26 March 2014), 2012.

NOAA, National Hurricane Center (Storm Surge Resources): http://www.nhc.noaa.gov (last access: 1 February 2014), 2013.

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PAGASA: Current Climate and Observed Trends, http://kidlat.pagasa.dost.gov.ph/cab/climate_change/CurrentClimateTrends.html (last access: 4 April 2014), 2014a.
PAGASA: The Philippine Public Storm Warning Signals, http://kidlat.pagasa.dost.gov.ph/genmet/psws.html (last access: 4 April 2014), 2014b.
Velleman, P. F. and Hoaglin, D. C.: Applications, basics, and computing of exploratory data analysis, Duxbury Press, Belmont, CA, 1981.
WXTide32: Tides and Currents for Win9x/NT, available at: www.wxtide32.com, last access: 9 February 2014.

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Table 1. Public storm warning signals from PAGASA.

PSWS # 1	Winds of 30–60 kph (16–32 kn) may be expected in at least 36 h
PSWS # 2	Winds of greater than 60 kph (32 kn) and up to 100 kph (54 kn) may be expected in at least 24 h
PSWS # 3	Winds of greater than 100 kph (54 kn) up to 185 kph (100 kn) may be expected in at least 18 h
PSWS # 4	Very strong winds of more than 185 kph (100 kn) may be expected in at least 12 h

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Table 2. Classification of structures – nature of occupancy (ASEP, 2010).

Occupancy category	Occupancy or function of structure
I – Essential Facilities	Occupancies having surgery and emergency treatment areas, fire and police stations, garages and shelters for emergency vehicles and emergency aircraft, structures and shelters in emergency preparedness centers, aviation control towers, structures and equipment in communication centers and other facilities required for emergency response, facilities for standby power-generating equipment for Category I structures, tanks or other structures containing housing or supporting water or other fire-suppression material or equipment required for the protection of Category I, II or III structures, public school buildings, hospitals, and designated evacuation centers.
II – Hazardous Facilities	Occupancies and structures housing or supporting toxic or explosive chemicals or substances, non-building structures storing, supporting or containing quantities of toxic or explosive substances.
III – Special Occupancy Structures	Single-story school buildings, buildings with an assembly room with an occupant capacity of 1000 or more, educational buildings such as museums, libraries, auditorium with a capacity of 300 or more students, buildings used for college or adult education with a capacity of 500 or more students, institutional buildings with 50 or more incapacitated patients, but not included in Category I, mental hospitals, sanatoriums, jails, prison and other buildings where personal liberties of inmates are similarly restrained, all structures with an occupancy of 5000 or more persons, structures and equipment in power-generating stations, and other public utility facilities not included in Category I or Category II, and required for continued operation.
IV – Standard Occupancy Structures	All structures housing occupancies or having functions not listed in Category I, II or III and Category V.
V – Miscellaneous Structures	Private garages, carports, sheds and fences over 1.5 m high.

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Table 3. Assigned probability of exceedance for every occupancy category.

Probabilty of exceedance	Occupancy category
1 %	Essential Facilities Hazardous Facilities
10 %	Special Occupancy Structures
25 %	Standard Occupancy Structures Miscellaneous Structures

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Table 4. Specified observation points of Metro Manila.

Baclaran, Paranaque
Barangay 275
Barangay 649
Las Pinas
Pasay
North Bay Blvd. South, Navotas
San Jose, Navotas
Tambo, Paranaque
Tangos, Navotas
Tanza, Navotas

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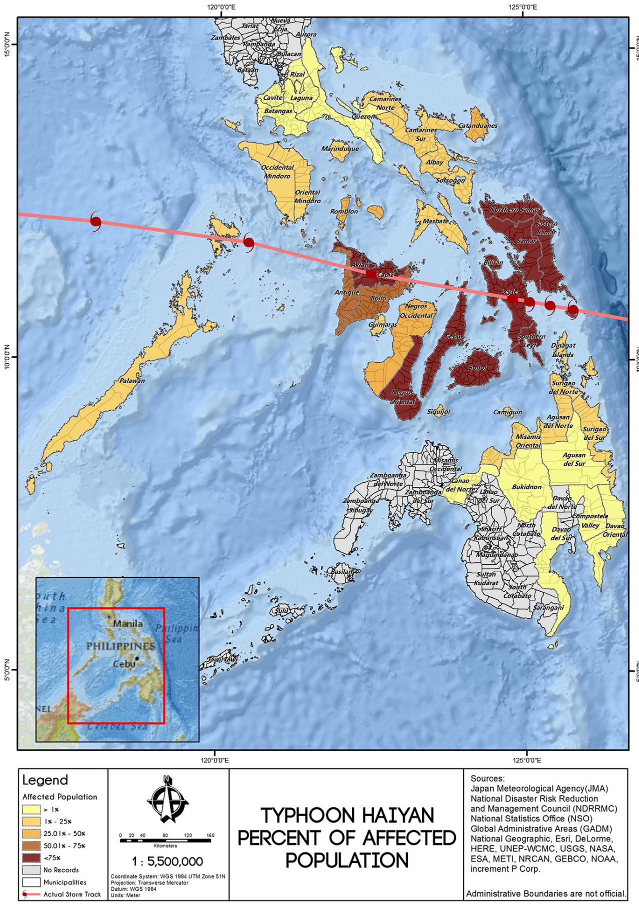

Figure 1. Typhoon haiyan percent of affected population (Project NOAH).

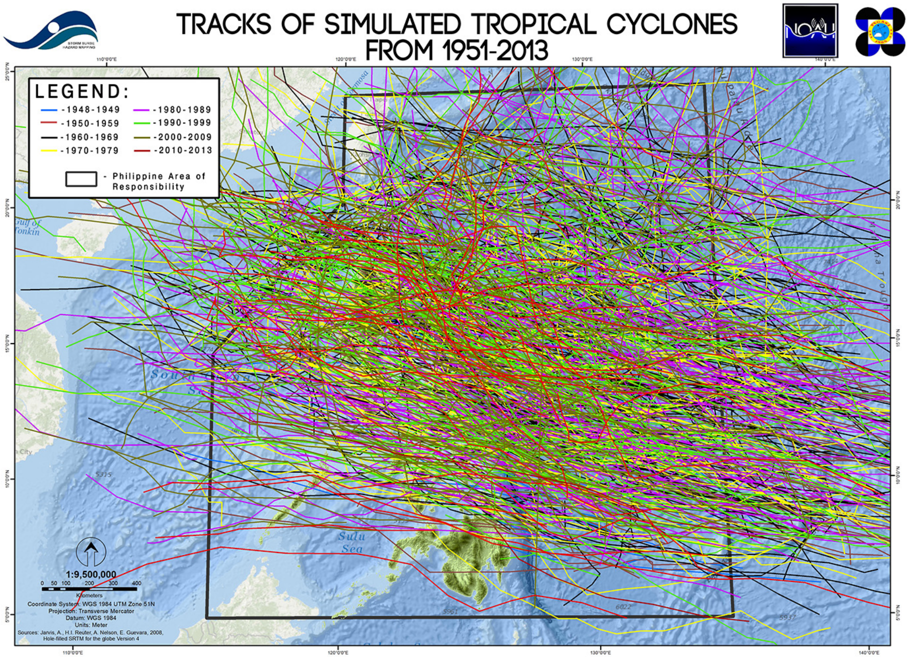

Figure 2. Tracks of tropical cyclones that entered the Philippine Area of Responsibility from 1951–2013 (Project NOAH).

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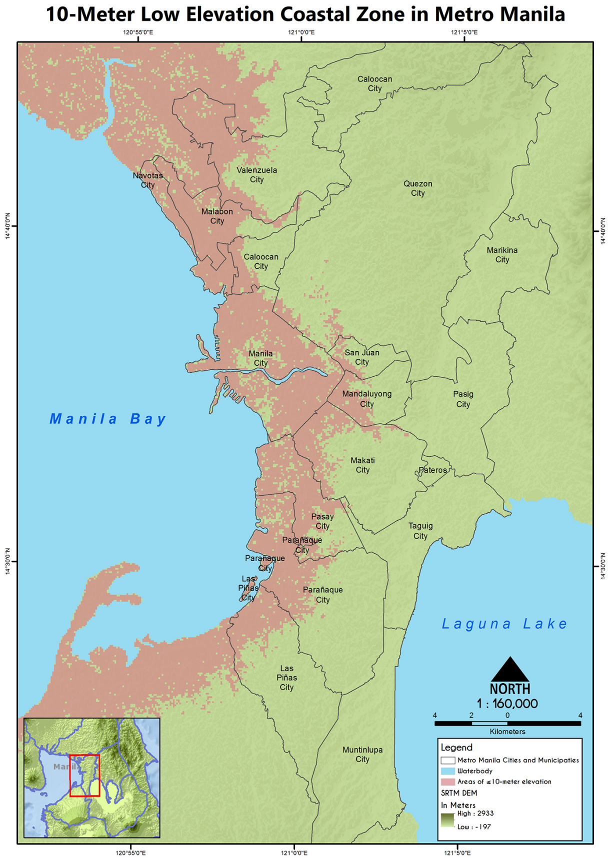

Figure 3. 10 m low elevation coastal zone in Metro Manila.

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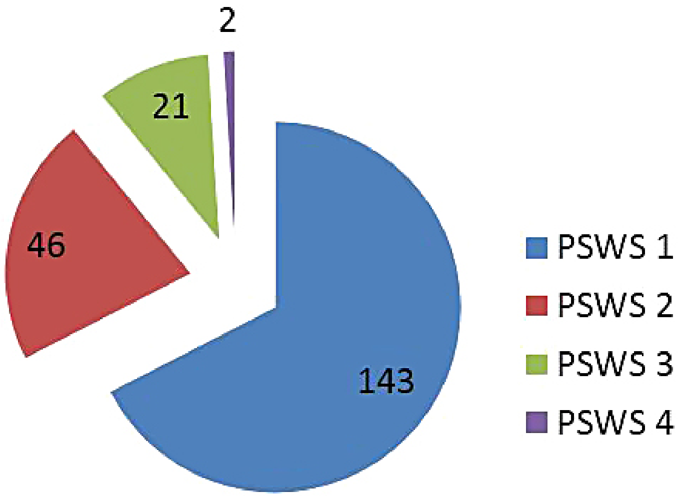

Figure 4. PSWS frequency distribution for Metro Manila.

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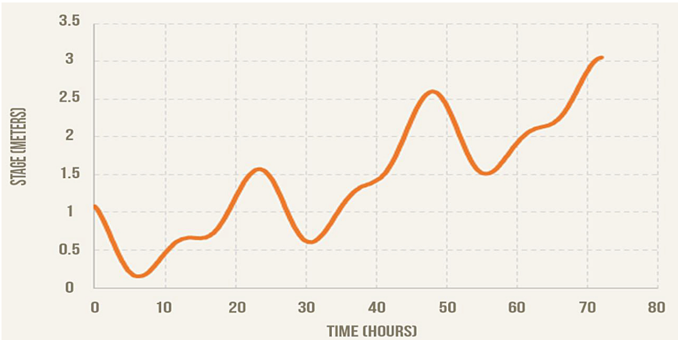

Figure 5. Example storm tide of Metro Manila.

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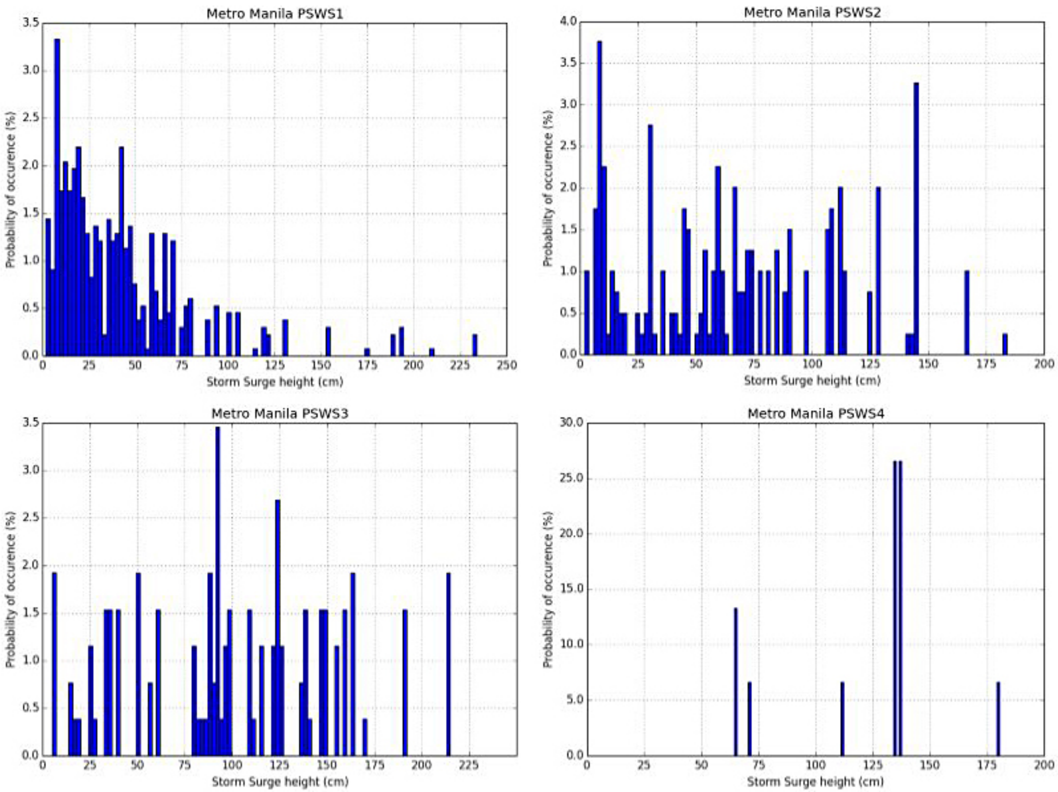

Figure 6. Frequency distribution table for PSWS numbers 1, 2, 3, and 4 of Metro Manila.

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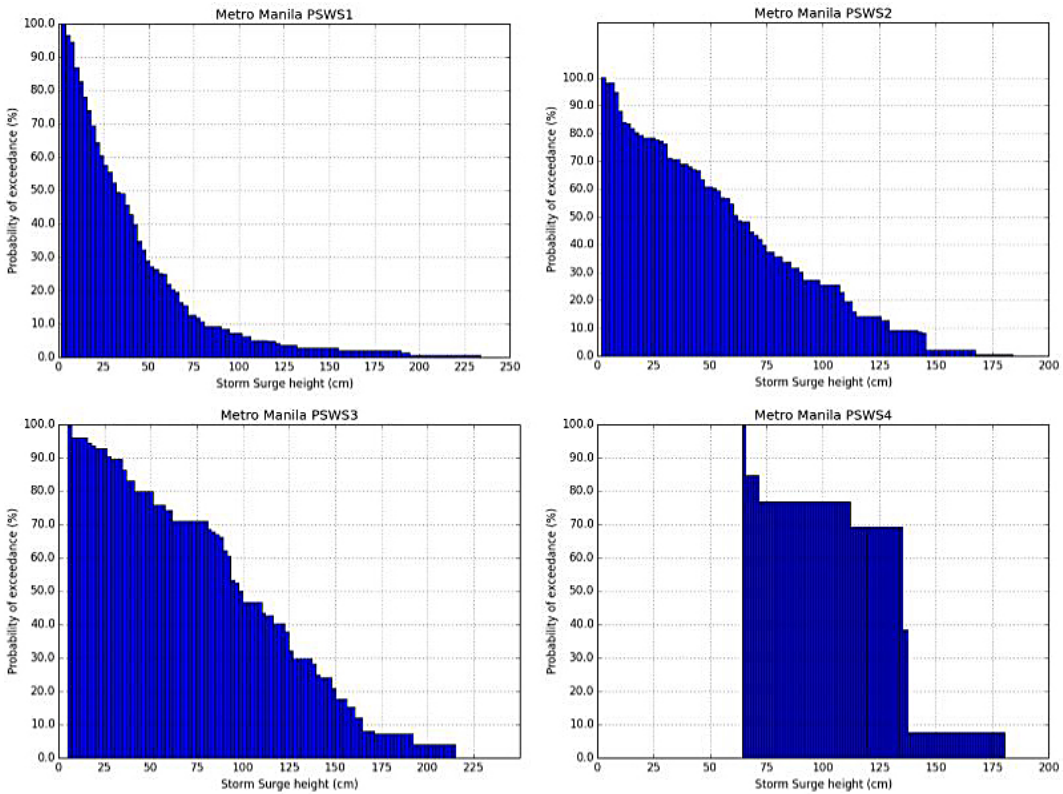

Figure 7. Exceedance probability curve for PSWS numbers 1, 2, 3, and 4 of Metro Manila.

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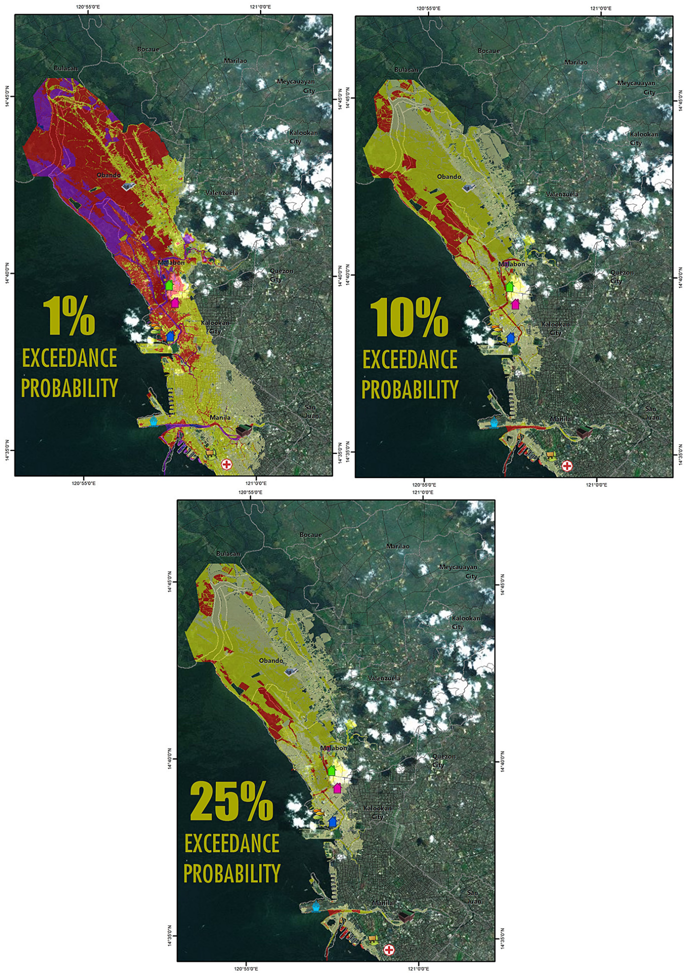

Figure 8. Storm surge inundation maps for PSWS 1 (please refer to Fig. 11 for the legend).

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Developing an early warning system for storm surge inundation in the Philippines

J. Tablazon et al.

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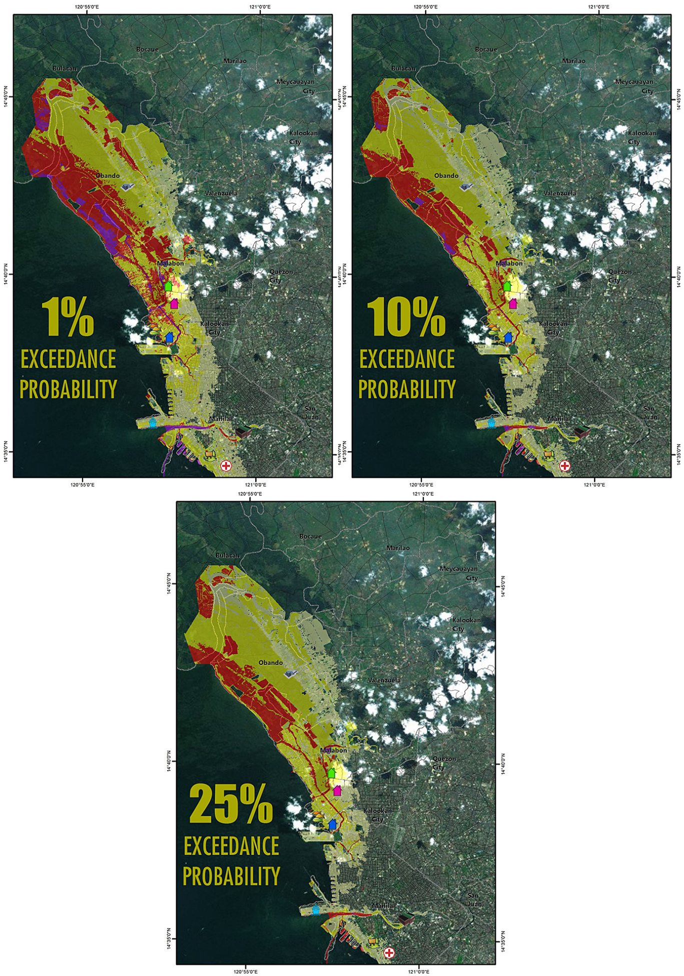

Figure 9. Storm surge inundation maps for PSWS 2 (please refer to Fig. 11 for the legend).

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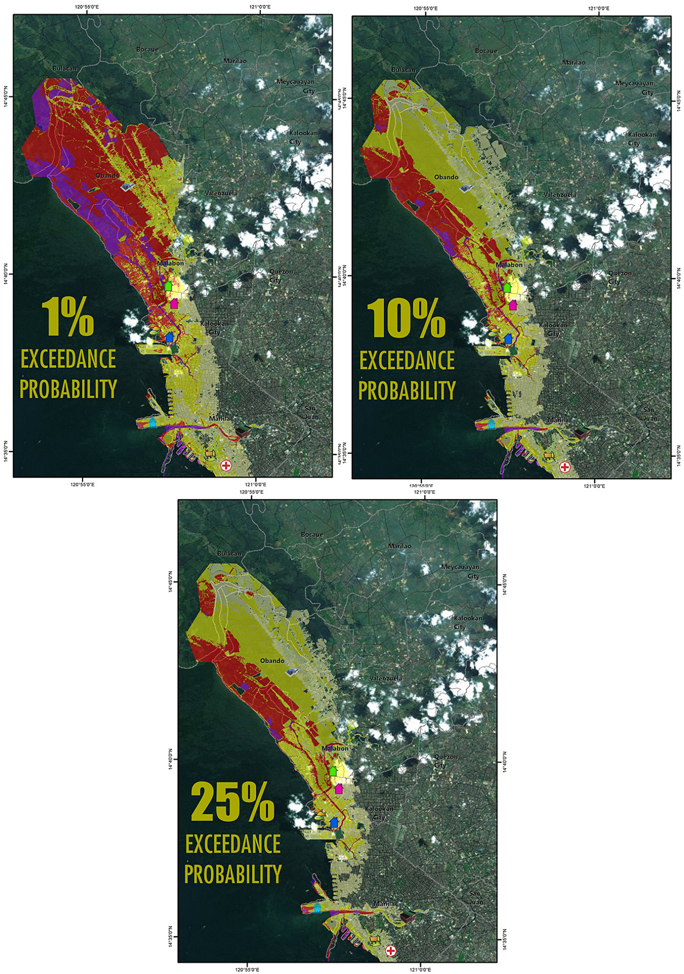

Figure 10. Storm surge inundation maps for PSWS 3 (please refer to Fig. 11 for the legend).

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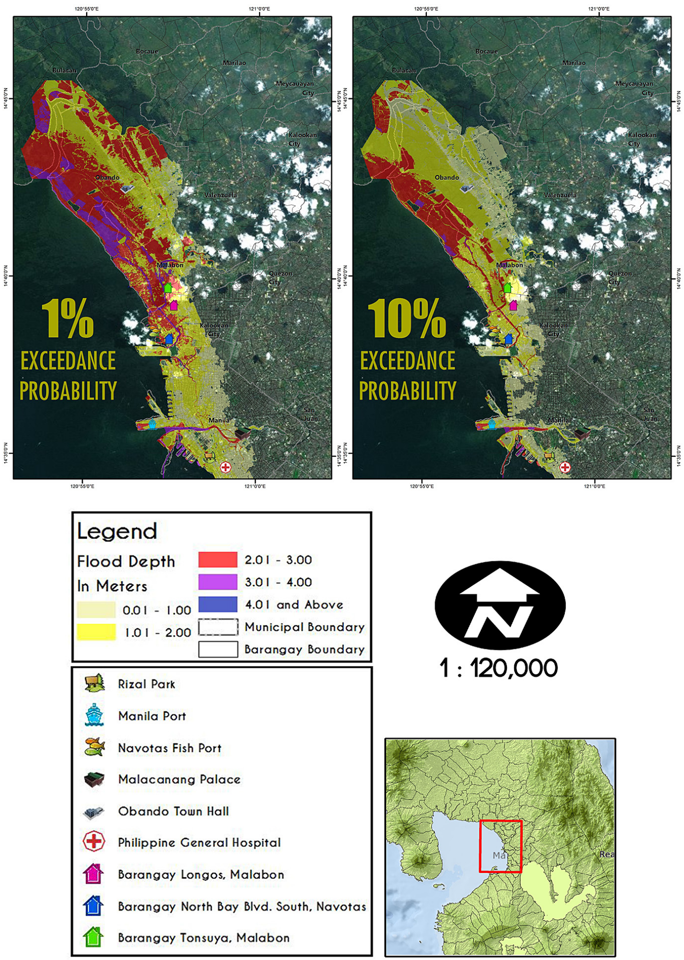

Figure 11. Storm surge inundation maps for PSWS 4 (with legend).

Location	PSWS1			PSWS2			PSWS3			PSWS4	
	1	10	25	1	10	25	1	10	25	1	10
Philippine General Hospital	1.07	0	0	0.18	0	0	0.35	0.27	0	0.78	0
Malacanang Palace	1.06	0	0	0	0	0	0	0	0	0.65	0
Navotas Fishport Complex	2.90	1.82	1.51	2.68	2.39	2.17	3.21	2.63	2.41	2.90	2.34
Port of Manila	2.24	0.81	0.47	1.46	1.43	1.23	3.52	3.38	3.32	3.31	3.26
Barangay North Bay Blvd. South, Navotas	2.43	1.35	1.09	2.21	1.84	1.60	2.52	2.08	1.77	2.54	1.82
Barangay Tonsuya, Malabon	2.94	1.58	1.30	2.19	1.81	1.70	2.14	1.90	1.73	2.47	1.73
Barangay Longos, Malabon	1.97	1.07	0.80	1.25	0.93	0.81	1.25	1.02	0.86	2.08	1.16
Barangay San Isidro, Makati	0.68	0.60	0	0	0	0	0	0	0	0	0
Barangay Bangkal, Makati	2.26	1.35	0	0	0	0	0	0	0	0	0

Note: Colors are based on the flow depth range from the inundation maps and height values are in meters.

Figure 12. Surge height values for the selected points of interest.

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