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Devastating Storm Surges of Typhoon Yolanda

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Abstract— On 8 November 2013, Typhoon Yolanda, international code name Haiyan, made landfall in the central Philippine islands region. Considered one of the most powerful typhoons ever to make landfall in recorded history, the 600 km-diameter typhoon Yolanda crossed the Philippine archipelago, bringing widespread devastation in its path. Strong winds, heavy rainfall, and storm surges caused extreme loss of lives and widespread damage to property. Storm surges were primarily responsible for the 6,190 dead, 1,785 missing and 28,626 injured in Yolanda's aftermath. Here, we document the analysis made on storm surges spawned by typhoon Yolanda as basis for the warnings provided to the public 2 days prior to the howler's landfall. We then validate the accounts based on field data and accounts provided in the news. The devastating Yolanda storm surges are one of the biggest storm surge events in several decades, which exacted a high death toll despite its early prediction. There were many lessons learned from this calamity and information contained in this work may serve as useful reference to mitigate the heavy impact of future storm surge events in the Philippines and elsewhere.

Keyword: Storm Surge; Typhoon Haiyan; Typhoon Yolanda

1. Introduction

Typhoon Yolanda is one of the most powerful typhoons to have made landfall in recorded history, with maximum sustained winds reaching 315 kph (170 knots) with gusts up to 379 kph (205 knots) just before landfall (JTWC, 2013). This makes it equivalent to a Category 5 typhoon on the Saffir-Simpson hurricane scale (NOAA, 2013a), which has the capacity to cause catastrophic damage, high percentage of destruction of framed homes, total roof failure and wall collapse, isolation of residential areas due to fallen trees and power poles, and power outages that could last for weeks and possibly months (NOAA, 2013c).

It started as a region of low pressure in the West Pacific Ocean early on 02 November 2013 and was upgraded to a tropical storm (TS) with the name Yolanda after subsequent intensification (WMO, 2013). Upon entry of the typhoon into the Philippine Area of Responsibility (PAR), the Philippine Atmospheric Geophysical Astronomical Services Administration (PAGASA), gave it a local name of Yolanda (PAGASA, 2013). Regular 6 hourly bulletins on the severe weather disturbance were issued by the Philippine weather bureau with short updates given every hour. Typhoon Yolanda made landfall in Guian, Eastern Samar on 09 November 2013 at 0440H local time (Figure 1).

By 07 November, storm signal warnings had been raised by PAGASA, including storm surge warnings in many parts of the country. Typhoon Yolanda hit the eastern part of the Philippines on 08 November, following a track heading towards the West Philippine Sea (South China Sea), crossing the majority of the Visayas region at a speed of 40.7kph (22 knots) (NASA, 2013). Yolanda maintained its structure as it moved over the east central Philippines. JMA observed that the lowest value of central pressure was 895 hPa (very low central pressure means very high wind speed) and typhoon intensity increased from ``very strong'' to ``violent'' (JMA, 2013).

In terms of wind speed, JTWC touted Yolanda as the most intense tropical cyclone in the world for 2013. As Typhoon Yolanda traversed through the Visayas region (Figure 2), it caused damage to houses and infrastructure, flooding in low-lying areas, landslides and storm surges. Super Typhoon Yolanda is the deadliest typhoon ever to hit the Philippines in recent history leaving 6,201 dead, 1,785 missing and 28,626 injured (NDRRMC, 2014).

The storm surges of Yolanda were predicted two days in advance with a complete list that was broadcast over media the night before Yolanda made landfall. Unfortunately, despite the advanced warnings, these were not translated into appropriate action in every coastal village in the Central Philippines region. Here we elucidate the process behind the storm surge forecast for Yolanda, enumerate the lessons learned from the disaster and then recommend measures to prevent the same mistakes from happening again in the future.

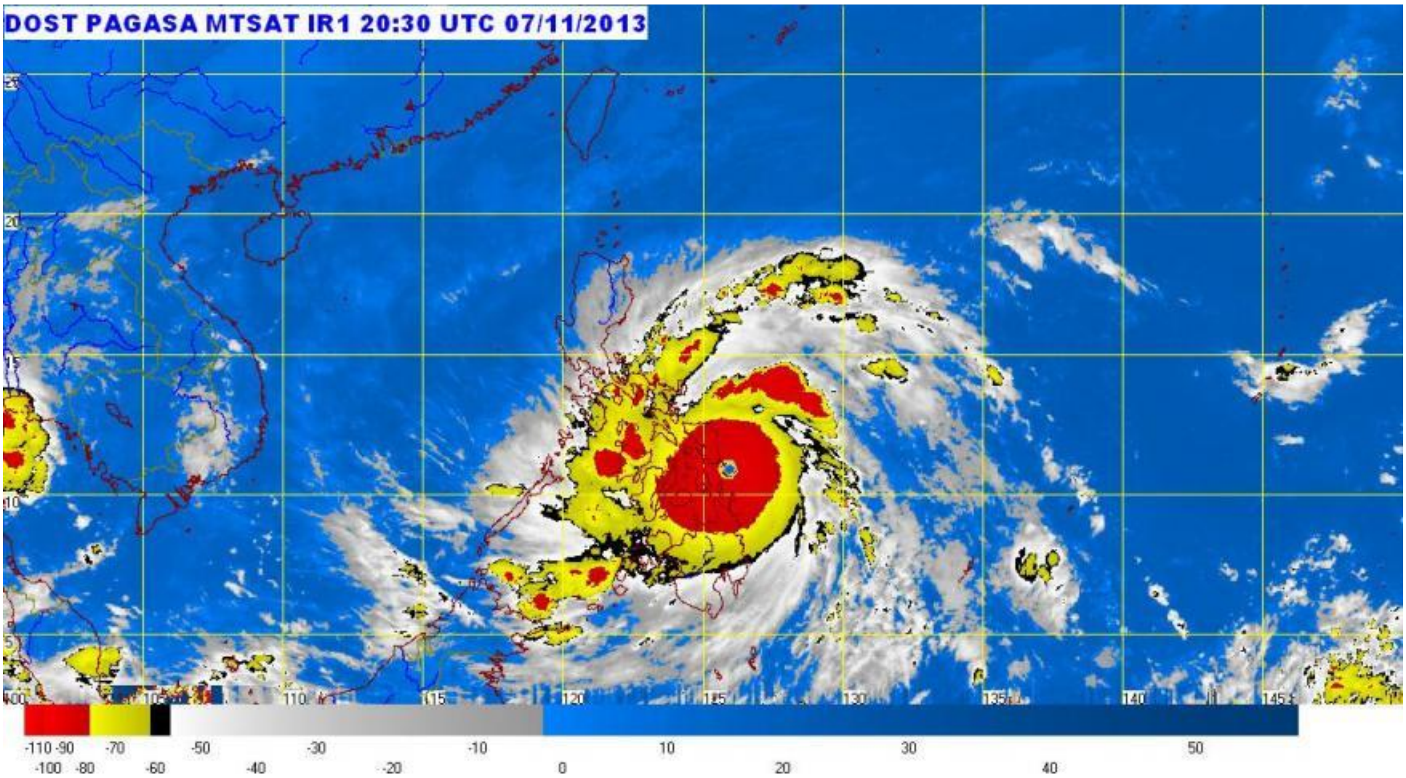

Figure 1. Image of Typhoon Yolanda at landfall. Source: PAGASA

2. METHODS

To model the hazards of Super Typhoon Yolanda, research scientists of the Nationwide Operational Assessment of Hazards (DOST-Project NOAH), the flagship disaster research program of the Department of Science and Technology, used the JMA Storm Surge Model. It is a numerical code developed by the Japan Meteorological Agency (JMA) to simulate and predict storm surges mainly caused by tropical cyclones.

Parameters used as input for the storm surge model include bathymetry, storm track, central atmospheric pressure, and maximum wind speed. These inputs determine the accuracy of simulation results.

Bathymetry used was the ETOPO2 with grid postings every 2 arc minutes. The bathymetry defines the sea floor bed or the depth of the ocean bottom relative to the sea level. Bathymetry was a necessary parameter input in the JMA model since the slope of the sea floor influences the height of the storm surge. Wide and gently-sloping sea floor produces higher storm surge heights, while narrow and steeply-sloping shelves produce lower storm surge heights (NOAA, 2013).

The predicted storm track used was the JMA model, freely available to the public and available for download at http://www.wis-jma.go.jp/. JMA releases tropical cyclone forecasts every 3 hours. Apart from the storm track, atmospheric pressure as well as the maximum wind speed were also derived from the JMA model. Storm surge simulated height values within the swath of the 600 km wide typhoon for selected coastal sites of the Philippines were then added to the tide data from WXTide - software that contains a catalogue of world-wide astronomical tides. Addition of the storm surge height to the WXTide tide height generates the storm tide values. These were used by DOST-Project NOAH to warn the public through PAGASA, of this type of hazard associated with Typhoon Yolanda.

After the Yolanda disaster, Flo2D simulations of storm surge inundation were generated to assess the extent of incursion of sea water inland. These were used to assess the possible damage of storm surges relative to the strong winds of Yolanda.

3. RESULTS

A 96-hour storm surge forecast was generated for Typhoon Yolanda for the period 0000 UTC 06 November to 0000 UTC 10 November 2013 (Figure 2). An unofficial list of the highest predicted storm surge and tide values within a 300-km radius along the track of Typhoon Yolanda was released on 6 November 2013 using the 1100H PST JMA track data. The storm surge simulations were updated every 6 hours and by 7 November, a list was provided to the Office of Civil Defense (OCD) and the NDRRMC. No less than the President of the Republic of the Philippines announced the severity of the impacts of the storm surges on primetime television. Included in his speech was reference to the DOST-Project NOAH website (http://www.noah.dost.gov.ph), where the list of storm surge heights can be found. The official list provided to the NDRRMC is shown in Table 1.

The time series plots for the localities with the top three highest peak storm surge with astronomical tide heights show the predicted time of the peak surge and water level changes throughout the duration of the simulation (Figure 2). The plots show the trends of water level changes every ten minutes.

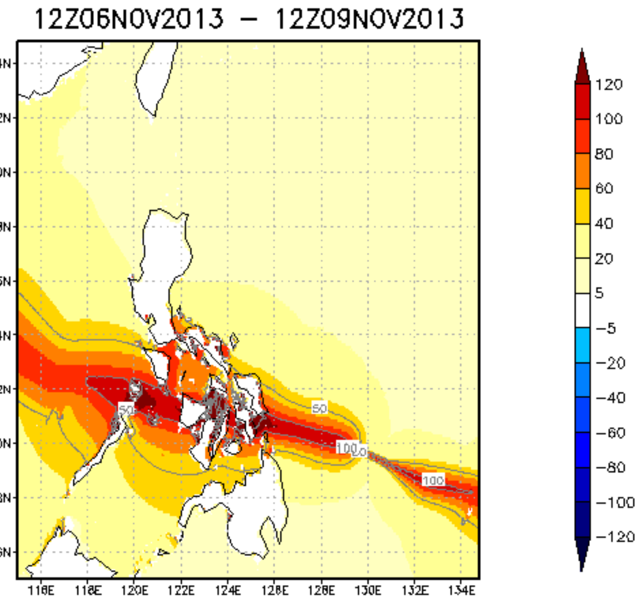

Figure 2. Plot of the predicted maximum storm surge heights (in cm) for Typhoon Yolanda

The highest predicted storm surge and tide height was 5.3 m for Matarinao Bay, Eastern Samar which covers the towns of Salcedo, Quinapondan, Gen. MacArthur, and Hernani. The second and third highest were 4.7 m in Poro Island, Biliran Straight, and 4.5 m in Tacloban straight, respectively. The predicted times of the peak surge were late by almost four hours depending on the location but the model was still able to capture the number of storm surges that hit Tacloban. The 4.5 m (14.7 feet) prediction for Tacloban was also consistent with some eyewitness accounts saying that the storm surge in several parts of Tacloban City reached 15 feet. Storm surge heights in other areas still need to be validated in the field. There is also video evidence of a surge estimated to be more than one-storey (3 m) high in Hernani, Eastern Samar at around 0600H local time on 8 November.

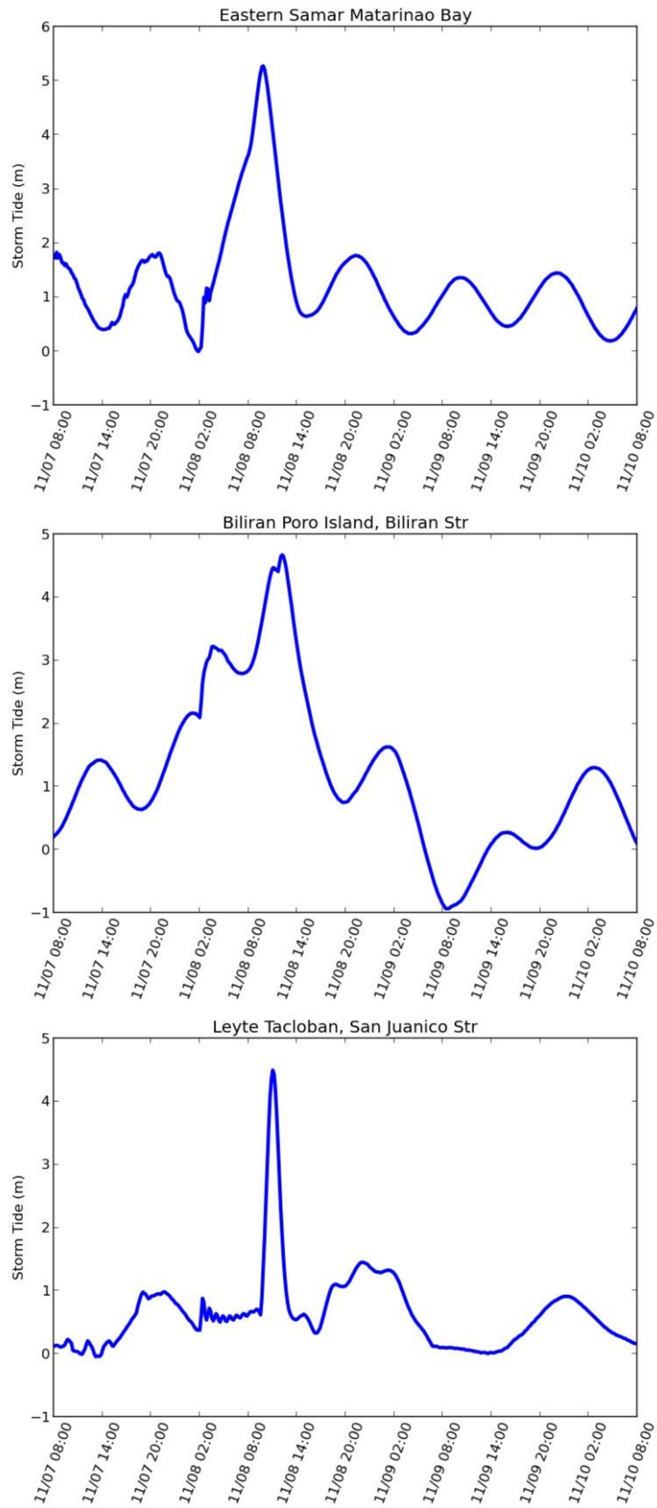

Figure 3. Time series plots of (a) Matarinao Bay, (b) Biliran Strait, and (c) Tacloban using 07 Nov 2013 1100h UTC JMA Best Track Data

Table 1. Predicted storm tide for Typhoon Yolanda, 2 meters and above.

Province	Location	Storm Tide(m)	Date	Time of Peak Height
Eastern Samar	Matarinao Bay	5.3	11/8/2013	09:50:00
Biliran	Poro Island, Biliran Strait	4.7	11/8/2013	12:10:00
Leyte	Tacloban, San Juanico Strait	4.5	11/8/2013	11:00:00
Quezon	Port Pusgo	4.4	11/9/2013	02:20:00
Eastern Samar	Andis Island, Port Borongan	4.3	11/8/2013	09:30:00
Quezon	Santa Cruz Harbor	4.2	11/9/2013	02:20:00
Palawan	Port Barton	3.9	11/9/2013	02:00:00
Iloilo	Banate	3.9	11/9/2013	02:10:00
Leyte	Palompon	3.9	11/8/2013	12:40:00
Leyte	Ormoc	3.8	11/8/2013	13:20:00
Northern Samar	Helm Harbor, Gamay Bay	3.7	11/8/2013	09:10:00
Cebu	Tuburan	3.2	11/8/2013	12:20:00
Negros Occidental	Himugaan River Entrance	3.1	11/8/2013	14:00:00
Negros Occidental	Cadiz	3.0	11/8/2013	03:10:00
Masbate	Bogo Bay	3.0	11/8/2013	12:50:00
Camarines Sur	Cabgan Island, San Miguel Bay	2.9	11/8/2013	08:10:00
Camarines Norte	Lamon Bay:Apat Bay	2.9	11/8/2013	09:00:00
Oriental Mindoro	Port Concepcion, Maestre de CampoI	2.8	11/9/2013	01:20:00
Palawan	Ulugan Bay	2.8	11/9/2013	01:30:00
Samar	Talalora	2.8	11/8/2013	12:00:00
Albay	Tabaco, Tabaco Bay	2.7	11/8/2013	09:20:00
Masbate	Masbate	2.7	11/8/2013	13:10:00
Oriental Mindoro	Calapan Bay	2.7	11/9/2013	01:30:00
Quezon	Torrijos	2.7	11/9/2013	02:00:00
Leyte	Canauay Island, Janabatas Ch	2.7	11/8/2013	12:00:00
Quezon	Aguasa Bay	2.6	11/9/2013	01:50:00
Negros Occidental	Danao River Entrance	2.6	11/8/2013	14:30:00
Camarines Sur	Tabgon Bay	2.5	11/8/2013	10:20:00
Negros Occidental	Carcar Bay	2.5	11/8/2013	14:40:00
Aklan	Aclan River Entrance	2.5	11/9/2013	01:40:00
Quezon	Atimonan	2.4	11/8/2013	08:50:00
Masbate	Port Barrera	2.4	11/9/2013	01:40:00
Capiz	Libas (Capiz Landing)	2.4	11/8/2013	15:30:00
Camarines Norte	Port Jose Panganiban	2.3	11/8/2013	08:50:00
Occidental Mindoro	Mangarin	2.3	11/9/2013	00:20:00
Camarines Norte	Lamon Bay:Capalonga	2.3	11/8/2013	08:40:00
Occidental Mindoro	Apo Island, Mindoro Strait	2.2	11/9/2013	01:10:00
Batangas	Anilao, Balayan Bay	2.2	11/9/2013	01:10:00
Occidental Mindoro	Sablayan	2.1	11/9/2013	01:10:00

EasternSamar	Hilaban Island	2.0	11/8/2013	08:50:00
Cebu	Carmen	2.0	11/7/2013	00:30:00
Samar	Uban Point, San Juanico Strait	2.0	11/8/2013	09:00:00
Iloilo	Miagao	2.0	11/9/2013	01:10:00
Camarines Norte	Guintinua Island, Calagua Islands	2.0	11/8/2013	09:20:00
Bohol	Maribojoc	2.0	11/8/2013	02:20:00

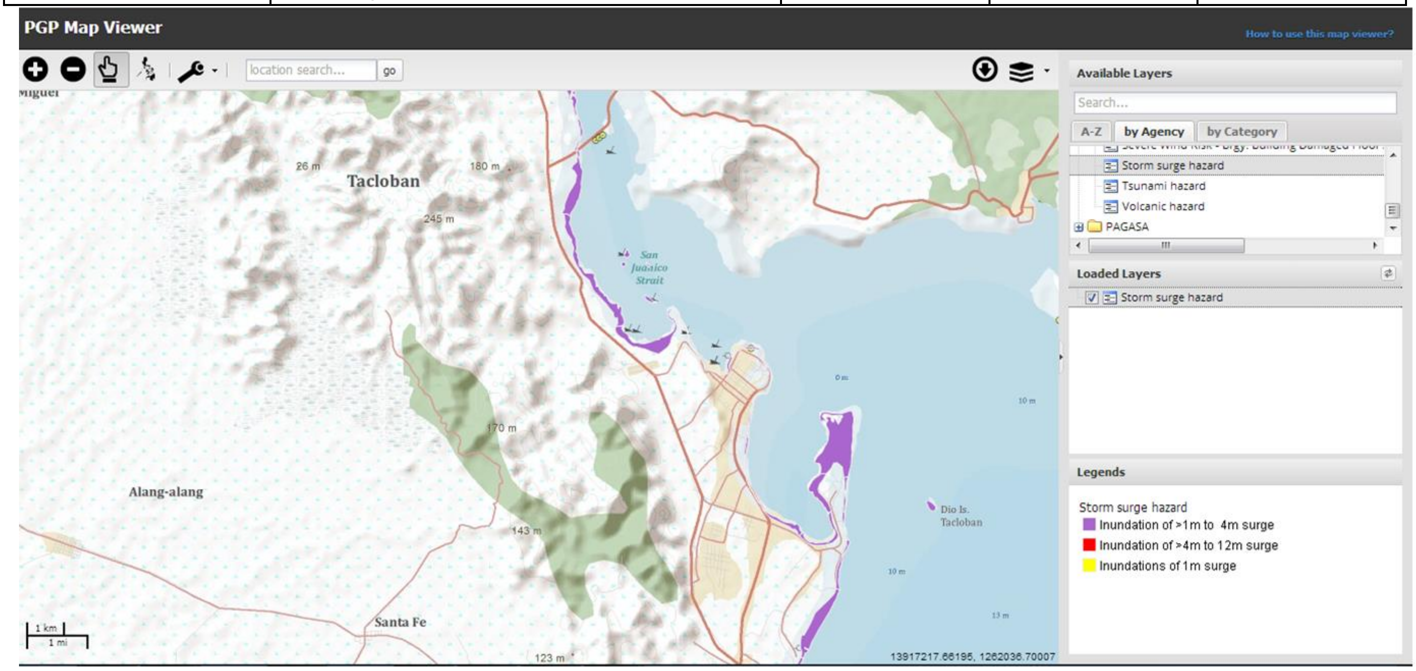

Figure 4. Storm surge inundation map prepared for the city of Tacloban by the READY project team. This map was accessed on 19 November 2013 from the NAMRIA geoportal.

4. DISCUSSION

4.1 Storm Surge Inundation Maps

The READY Project aims to reduce the problem of disaster risk management (DRR) at the local level by empowering the most vulnerable cities and municipalities in the country and enable them to prepare disaster risk management plans. The project hopes to develop a systematic approach to community disaster risk management. Supported by the United Nations Development Program (UNDP) and the Government of Australia Australian Aid (AusAID), storm surge hazards maps are among the outputs of the project, shared with the sub-national government units or communities and integrated into their local comprehensive development or land use plans. Ready hazard maps are made available to communities through the preparation of printed maps and also online through the NAMRIA Geoportal, among others. Figure 4 shows the READY map for Tacloban. The purple color refers to an inundation height of 1-4m. Based on reported storm tide heights and field data, this range is an underestimation of the actual water levels.

Whether or not reference to these maps was made in the pre-emptive evacuation action is unknown. However, since there was information, education campaigns (IECs) made in Leyte where disaster officials learn how to use these maps for preparedness and mitigation, it is assumed that they were at least aware of the hazard mapâ€™s existence. Under Republic Act 10121 or the Philippine Disaster Risk Reduction and Management Act of 2010", the local government should identify, assess and manage the hazards vulnerabilities and risks that may occur in their locality; and disseminate information and raise public awareness about those hazards, vulnerabilities and risks, their nature, effects, early warning signs and counter-measures (Philippine Congress, 2010).

4.2 Pre-emptive Action

Because of the weather bulletins issued by PAGASA, work and classes were suspended on 7-8 November in several provinces in the path of the typhoon. Each city and municipality has the authority to declare suspensions and base their decisions mainly on bulletins provided by the Philippine weather bureau, supplemented by information from other international and local sources, including those posted by DOST-Project NOAH on its website and mobile applications.

Regional offices of the Department of Public Works and Highways (DPWH) conducted assessments of structural integrity of schools, cleaning of waterways and drainages, clearing of roads and pruning of trees.

Response teams and heavy equipment were put on standby. The Department of Health (DOH) prepositioned medicine, and first aid kits and placed hospitals on alert (NDRRMC, 2013). The Armed Forces of the Philippines had the Naval Forces Southern Luzon (NAVFORSOL) dispatch trucks, relief goods, diving gear, rubber boats, portable generators and squad tents in Albay. The Philippine Navy was placed on alert and directed all its floating assets to prepare and take necessary precautionary measures for the typhoon (Official Gazette, 2013).

The Tacloban local government unit also evacuated people near the coast and had food packs ready (Dalangin-Fernandez, 2013). The DOH in Tacloban also augmented their stock of medicine and body bags. In Eastern Samar, Governor Conrado Nicart Jr., said they had rescuers and rescue boats on standby before

Typhoon Yolanda hit the province (Rappler.com, 2013).

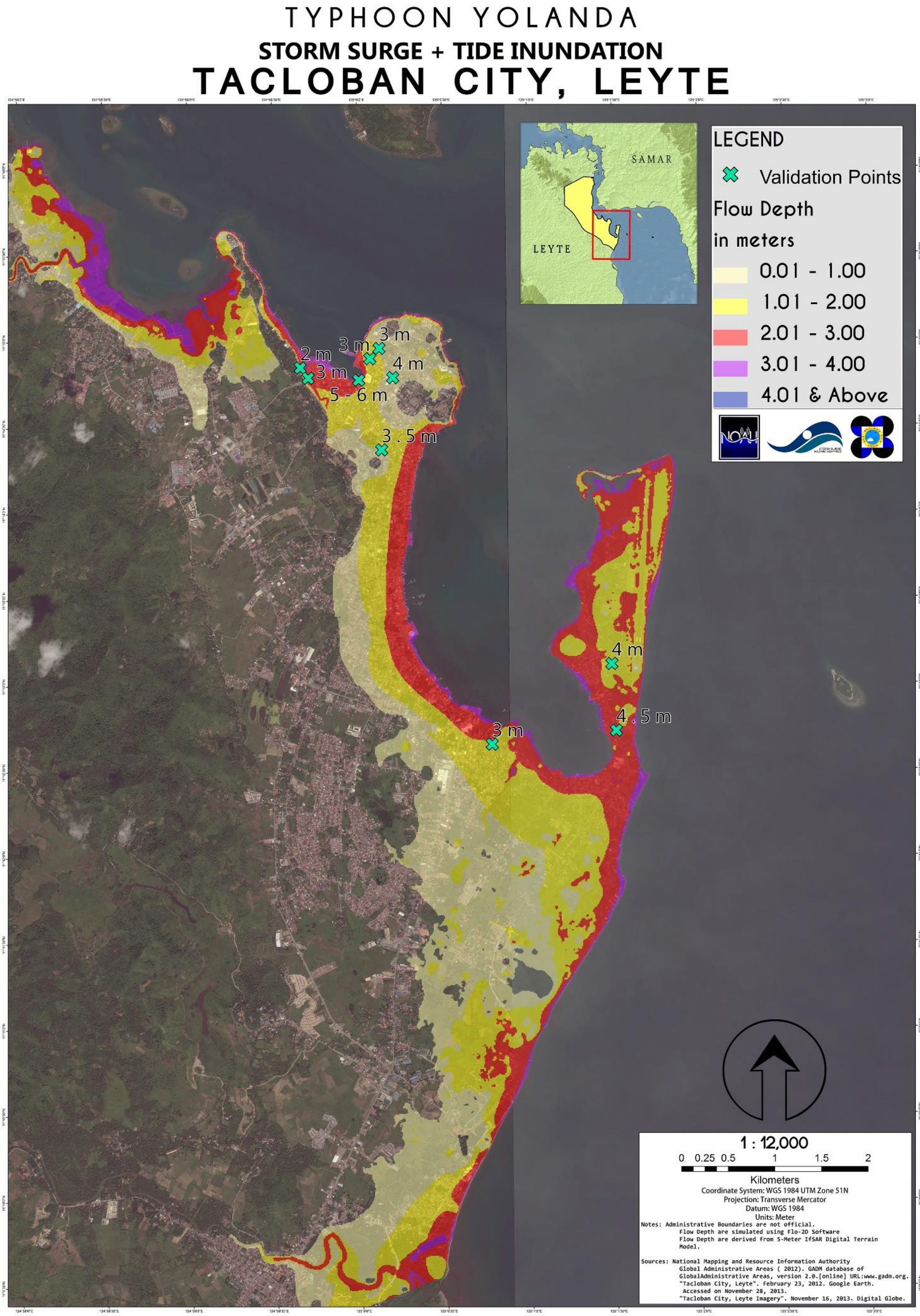

Figure 5. Storm surge and tide inundation map for Tacloban City generated over a high-resolution digital terrain model (DTM) with observed values.}

The newly installed Doppler radar station in Guiuan, 52

where the typhoon first made landfall, provided images of the oncoming typhoon
and was used as part-basis for the issuance of warnings which depicted the severity of the cyclone. The mayor of Guiuan informed all barangay officials to evacuate. Some residents evacuated, some did not (Ranada, 2013).

4.3 News Accounts

Coverage of Yolanda's aftermath was in both local and international news. Although the devastation was widespread in the central Philippines region, attention was focussed in Tacloban City, where national government officials and many of the weather news crews tasked to cover the Supertyphoon positioned themselves. According to journalist James Reynolds, Typhoon Yolanda was the most terrifying event he has witnessed. Reynolds, who has spent the past eight years filming Asia's deadliest natural disasters said, ``Yolanda was the most calamitous event he has ever witnessed'' (Ford, 2013).

Local Philippine news reporter Jiggy Manicad, described the event was like they were ``inside a washing machine'', as intense winds blew for hours spawning deadly surges (Archangel, 2013). According to the provincial government of Leyte, the storm surge was estimated to reach as high as the equivalent of three floors of a building (Valderama, 2013). Others estimated the waves that flattened Tacloban, destroyed most of the houses, upturned vehicles on the road, and took the life of thousands to be 20 feet high (Lopez, 2013). In Samar, where the typhoon made its first landfall, reports of a storm surge as high as five meters filled the roads with debris (Liljas, 2013). In the coastal towns of Basey, Samar the local government was paralyzed after it was hit by a 15-feet storm surge (Cuevas-Miel, 2013). Anecdotal accounts by eyewitnesses reported varying heights of the waves and must be validated to establish accuracy and reliability of data.

4.4 Field Validation

On November 30, 2013, researchers of DOST-Project NOAH conducted field validation and interviews in Tacloban regarding the storm surge brought by Typhoon Yolanda. Interviewees were present during the storm surge event; their firsthand accounts of the event were recorded to help validate the result of the simulation.

In other areas with no witness of the storm surge event, the team searched for water marks to determine the highest level water reached. The heights pointed by the interviewees and high water mark were measured vertically relative to the ground using meter tape. Based on the interviews, water levels reached 4 to 5 meters in Brgy. San Jose and the surrounding areas of the airport. The downtown area of Tacloban experienced 5 to 6 meters of flooding due to the storm surge. The areas validated are shown in Figure 5.

4.5 Interviews with Tacloban City Residents

Interviews with Typhoon Yolanda survivors were conducted to find out how they prepared for the Supertyphoon, what happened when the storm surge hit, and how people were able to survive.

According to eyewitnesses, the water level rose to 15 feet in 20 minutes. The storm surge did not just come from the direction of the sea but also from the airport and had moved like a whirlpool. People survived by climbing up trees or roofs. They said that the local government did not lack in warning them but it was the people who refused to heed them. Some people did not evacuate because they either wanted to protect their property or they thought their concrete-built houses were safe. Tacloban is often hit by typhoons but based on their experience, typhoons only bring wind and rain and it was the first time a storm surge happened there.

Several evacuation sites proved disastrous because they were overwhelmed by storm surges. However, one evacuation site, a coliseum called the Astrodome, despite being beside the coastline of Tacloban, saved 4000 people. Refugees inside the Astrodome were able to climb up the gallery (personal communication, Mayor Alfred Romualdez of Tacloban City and Ted Failon, TV anchor).

A university administrative staff said that those areas damaged by storm surges should be made into permanent danger zones, and that a hazard map of the area is necessary. The same person said that if a tsunami alert had been given, residents might have listened to the evacuation orders. Some of the informal settlers who were interviewed said that a barangay captain warned them of a tsunami, the night before the storm. One resident narrated that several hours after the deluge in Tacloban, someone shouted ``Tsunami'' and caused panic among some residents. The mad rush towards higher ground resulted in injuries. Another interview said that around 100 people went up the hills beside the coast and survived while those who did not believe the warning and stayed in their houses did not make it.

Municipality/ City	Number of deaths	Actual population (NSO, 2010)	Percentage of death relative to total population	Province
Tacloban City	2542	221,174	1.20%	Leyte
Tanauan	1252	50,119	2.50%	Leyte
Palo	1088	62,727	1.70%	Leyte
Basey	195	50,423	0.40%	Samar
Guiuan	101	47,037	0.02%	Eastern Samar
Hernani	72	8,070	1.00%	Eastern Samar
Estancia	52	42,666	0.10%	Ilo-ilo
Dagami	43	31,490	0.10%	Leyte
Ormoc City	37	191,200	0.00%	Leyte
Tolosa	32	17,921	0.20%	Leyte

Table 2. Top ten cities/municipalities with fatalities caused by Typhoon Yolanda

A storm surge is a rise in the water level over and above the predicted astronomical tide due to the presence of the storm (NOAA, 2013). It is produced when ocean water is pushed toward the shore by strong winds associated with cyclonic storms and influenced further by other factors such as underwater topography and water depth (Botts, 2013). Meteorological factors affecting storm surge include storm data such as wind speed, pressure, and storm track. Physical factors include near-shore bathymetry, coastal shape, and topography. The height of the surge highly depends on the strength of the winds carrying it. However, physical factors must also be considered. For example, a storm surge is more dangerous in areas with a gently-sloping seafloor, as there is no barrier for the waves to stop the surge from going further inland (NOAA, 2013c). Predicting storm surges requires taking all of these factors into consideration and inputting them into the storm surge models to be able to create accurate simulations and hazard maps.

Compared to the killer storm surge events on 12 November 1970 and 29 April 1991 in Bangladesh, which caused 300,000 and 138,882 deaths, respectively \citep{Bangladesh07}, the toll of Yolanda is less than 10,000 fatalities. Many of the casualties of typhoon Yolanda are from Tacloban City and its adjacent southern municipalities of Palo and Tanauan (Table 2). These areas rank among the top 3 highest percentage number of fatalities relative to the population. Based on these metrics, it is clear that the number of deaths is not only related to the landscape of the affected areas and proximity to where the eye of the typhoon made its initial impact but also with the population.

5. CONCLUSION AND RECOMMENDATIONS

The storm surges of Typhoon Yolanda were predicted two days in advance with a complete list that was broadcast over tri-media and social media. DOST-Project NOAH hosted the list of areas that were to be affected by storm surges, which identified specific places and heights. That warning was echoed by no less than the President of the Philippines over primetime television on the eve of Yolanda's landfall. Unfortunately, despite the advanced warnings, these were not translated into appropriate action in every coastal village in the Central Philippines region. Not everyone knew what a storm surge was and could do. Although disaster responders encouraged people to leave the coastal villages of Tacloban, there was still difficulty in getting all the people out of harm's way. Based on the interviews made in Tacloban and reactions of people in general, the reasons for the disaster appears to have been complicated, a product of a multiplicity of factors, which include the following: 1) extremely powerful typhoon that was 600 km in diameter; 2) maps from the READY project did not reflect the actual storm surge flooding extent; 3) men stayed behind to protect their houses 4) inability to understand a 5 meter storm surge; 5) local belief that they know their sea better than anyone else; 6) residents of the disaster area did not learn from history - 2 devastating storm surge events happened in 1897 which killed up to 1,500 (Bankoff, 2007) and in 1912 killed 15,000 people (The Washington Herald, 1912); 7) people were more familiar with the term tsunami and storm surge was new to them; 8) common folk are generally disinterested in learning about hazards because daily concerns are more important ; 9) the stars were out the previous night and did not appear that a catastrophe was imminent; 10) pressing political issues diverted media attention; 11) there were large communities of informal settlers along the coastal towns vulnerable to the storm surge hazards; 12) inadequate information dissemination 13) evacuees took refuge in places overwhelmed by storm surges.

To prevent an impending disaster, there are two important points to consider: 1) Warning and 2) Action (Response). The warning must be accompanied by knowledge by the people on what to do in case the alarm is raised. For Yolanda affected areas, the storm surge warning was raised days in advance but incomplete action was made to prevent the loss of lives by the thousands. This was complicated by a variety of reasons as mentioned above. However, it is important to note that there must have been preparedness action made by the communities since the extremely devastated places are coastal areas which had on average about 99\% of their population survive.

To achieve a much lower fatality count, there is a need to strengthen hazards education at the barangay (village) level and develop a culture of preparedness. Although this is already embodied in section 12 articles 9 and 10 of Republic Act No. 10121, its actual implementation leaves much to be desired (Philippine Congress, 2010).

Moreover, reference to more detailed maps that depict the scenario of inundation for any given storm surge warning is imperative (Figure \ref{survey}). Maps that are low resolution and developed through field interviews are insufficient or even dangerous because anecdotal accounts can be incomplete. Detailed maps can only be created through highly accurate digital terrain models (DTMs), surveyed through Light Detection and Ranging (LIDAR) or equivalent survey instruments. Computer models of storm surge inundation are made on these high-resolution DTMs, printed out for display for each barangay or shown through the internet for reference by the public to know the action to take when there is a warning. The public will want to move from an unsafe place to another which is safe based on the detailed storm surge hazard maps.

The Philippines is visited by 20 cyclones each year and storm surges are common. The one that happened in the central Philippine region during Yolanda is the most powerful in recent history and it will not be the last. The sooner the detailed and high-resolution storm surge hazard maps are created, the better the people can respond to any warning of an impending storm surge hazard.

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