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Flooding and Flood Modeling in a Typhoon Belt Environment: The Case of the Philippines

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Abstract

Flooding is a perennial world-wide problem and is a serious hazard in areas where the amount of precipitable water has potential to dump excessive amount of water. The warming of the Earth's climate due to the increase in greenhouse gases (GHGs) increases the availability of water vapor and hence, of extreme precipitation as observed and forecasted by researchers. With rainfall intensity too high, the torrential rains coupled with weather systems that enhances its effects, flooding not only submerges anything low-lying, it also washes away living and non-living things along the course of the river and the floodplain. The flooding is even worsened by the increase in velocity of flow caused by unsustainable urbanization and denudation of the watershed at the headwaters. Nature's strength is an order of a magnitude that is way beyond that of the strength of men but human ingenuity enables us to transform our living environment into models that could help us better understand it. Flood modeling provides us decision support tools to deal better with nature. It also enables us to simulate the future especially nowadays that changes in our climate is imminent and even happening already in many parts of the world. Therefore, strategies on how to cope with our ever changing environment is very important particularly to countries that are at more risk to climate change such as the archipelagic Philippines.

Keywords: Flooding, flood modeling, climate change, hydrology, LiDAR

1. Introduction

An expression of nature when excess rainfall flows through the floodplain, flooding is a problem our ancestors, who started civilization had already dealt with. And now, even in our modern times, it is still a world-wide problem that seems to be a worsening problem due to increasing population, and hence, of urbanization that is usually leading to unsustainable development. Moreover, climate change makes the problem more intense as extreme precipitation, rainfall, in particular, near the equator is observed and projected to increase by researchers from the Intergovernmental Panel on Climate Change (IPCC) [1]. To be able to manage our watersheds, we have to understand it. Knowing how our rivers behave will give mankind a harmonious existence with the rest of the environment.

2. Rainfall potential

In the tropics, the amount of solar energy is the most radiated here since it is perpendicular, to near perpendicular to the sun's rays. This results to more energy converting the liquid water into water vapor, resulting to an increase in humidity in the area. The amount of precipitable water that could potentially become rainfall is a function of specific humidity which is proportional to the amount of vapor pressure which is a function of the temperature in the area [2]. This makes the wet tropics vulnerable to effects of climate change. Moreover, in this area in the tropics, since the sun's rays is concentrated, differential heating of the oceans and the lands will cause the air masses of different energy to move relative each other. Aside from the relative movement of the air masses, their differential densities will tend warm air mass to be lifted. Lifting of an air mass cools down the temperature adiabatically and results to condensation in the form of precipitation, or in the tropics, rainfall.

The effect of the changing sun's available energy which is caused by the varying tilt of the Earth's axis as it revolves around the sun results to the changes in seasons that the planet experiences yearly. Near the equator, it creates two distinct seasons while beyond the Tropic of Cancer in the northern hemisphere and Tropic of Capricorn in the southern hemisphere, it results to four different seasons in a year. In the Philippines, which is near the equator, the seasons is composed of the wet and the dry seasons that happen around May and November, respectively. The seasons is dictated by the presence of the monsoon winds – the Southwest Monsoon (SW Monsoon), locally known as Habagat season and the Northeast Monsoon (NE Monsoon), locally known as the Amihan season. During the SW Monsoon season, the wind comes from the southwest of the Philippines which is a moisture-laden air mass originating from the Indian Ocean which when it weakens, will be replaced by the NE Monsoon coming from the northwest in the cold northern regions such as Siberia.

At the time that SW Monsoon is strong, the same solar energy received at the region in the Pacific Ocean brews low pressure area (LPA) that usually develop into tropical cyclones (TC) or typhoon as we call it in the Philippines and other countries in the Pacific. Forming over oceans where sea surface temperature as well as air temperatures are greater than 26°C, TC accumulates large amounts of sensible and latent heat as it spirals toward the center and further get strength [3]. The counter-clockwise rotation of the Earth that produces the trade winds or easterlies tends the low pressure area that forms at low latitudes but greater than 5degrees, to move westward toward the Philippines. Depending on the strength of the monsoons, the incoming TC moving as the trade winds will have its characteristic bend that determines if it will make landfall or not to the country. If the SW Monsoon is prevailing, it could interact with the TC and intensify the rainfall that the TC could bring to the area. **Figure 1** shows a record compiled by the Philippine Atmospheric, Geophysical, and Astronomical Services Administration or PAGASA showing the TC tracks per month from 1948 to 2016 that at times deflect away the country depending on the relative strength of the monsoons.

On average, 20 Tropical Cyclones enter the Philippine Area of Responsibility (PAR) every year, 8 to 9 of which make landfall, as tallied by PAGASA. Coupled with the SW Monsoon, the problem of flooding in the country is exacerbated by TCs which attracts the monsoon's moisture-laden airmass. Even during the cool months, some parts of the country experience excessive rainfall due to the tail-end of the cold front or TECF which happens when the cold air from the prevailing NE Monsoon meets with the warm Easterlies. The lifting of the warm air mass as it moves past the advancing cold air mass (a cold front) causes much rain that floods the eastern and south eastern sea board of the country.

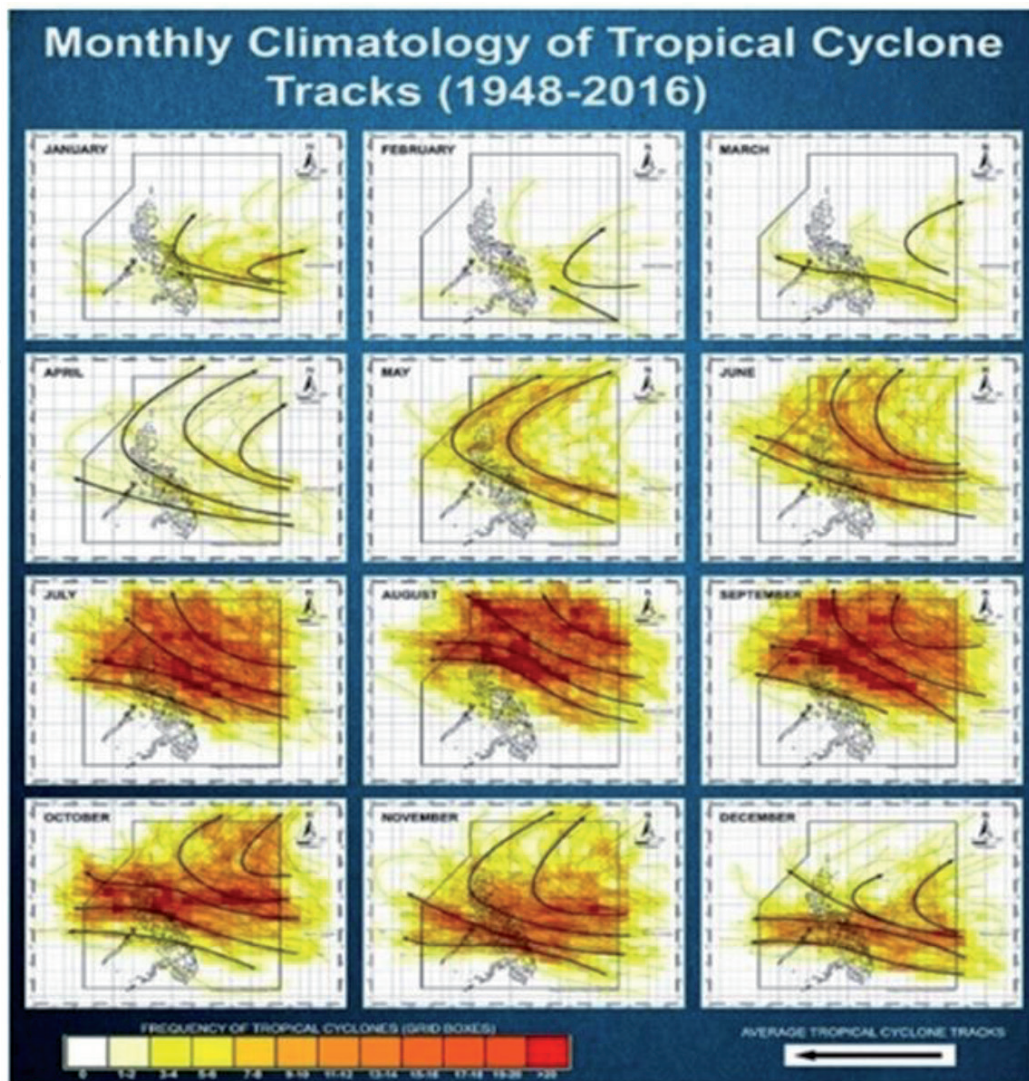


Figure 1.
Tropical cyclone tracks in the Philippines averaged from 1948 to 2016. Source: PAGASA, available at <http://bagong.pagasa.dost.gov.ph>

The same scenario happens in other countries in the tropics that are near a large body of water and are influenced by prevailing wind patterns that come together with different air mass of different thermal properties. Countries in the Indian Ocean experience cyclones while hurricanes are in the Atlantic, and typhoon in the Pacific – different naming that pertain to Tropical Cyclone that forms in the warm waters of the oceans and affects many countries in the tropics and dissipates as it reaches the colder latitudes.

3. Excess rainfall

Flooding is commonly brought about and intensified by tropical cyclones along with other weather systems that generate storms. The presence of abundant moisture in the air mass carried by the different weather systems, when precipitated, make our cities prone to excessive surface runoff from streams and through floodplains where most of these cities are located. Flooding is a natural reaction of a watershed when the excess rainfall which is the amount of rainfall that is not absorbed by infiltration to the ground, flows as surface runoff. However, urbanization tends to alter the permeability of the soil and reduces the infiltration rates of the surface by replacing the permeable ground with impermeable concrete

pavements and building structures. Natural waterways and floodplains that are the natural drainage systems and detention basins of floods are also blocked or replaced with built up environment. This makes flooding a major problem in areas where people and anthropogenic activities are thriving.

In many parts of the world, unprecedented experiences of flooding are documented. The distribution of rainfall is disrupted usually attributed to climate change. Climate change increases the frequency of heavy precipitation events (or the proportion of total rainfall from heavy falls), an observation reported in the IPCC Technical Paper VI on Climate Change and Water [1]. The increase will in turn increase the annual average runoff making previous efforts of flood control and drainage system insufficient to accommodate the runoff.

The amount of excess rainfall is also dictated by the residence time the rain water will remain on the surface such as by the interception of vegetation and the ponding on soil surfaces to be infiltrated. Since rainfall events are observed and even projected by the IPCC [1] to become more intense, i.e. higher rainfall depth on a shorter period of time due to climate change in the wet tropical regions, risk of flooding is projected to rise. Higher intensity rainfall results to lesser residence time for the rain water to be intercepted by the plant's foliage and to be infiltrated to the ground, thereby, causing the hydrograph to peak earlier resulting to flash floods.

4. Flooding consequences

In tropical watersheds, the natural environment is naturally designed to assimilate in its system the excess rainfall that flows as direct runoff through the hillslope, accumulating and flowing as channel flow in the river network. From the steep slopes of the headwater source, it reaches the flatter terrain of the floodplain that functions as natural detention basin before it finally exits to the sea or ocean.

The floodplain serves as a natural barrier to make the flow of water more efficient to in maintaining equilibrium in the watershed system. This equilibrium defines the natural environment of the watershed that hosts different flora and fauna unique to the environment.

Human intervention to promote development to support the demands of mankind and in modern civilization to support the requirements of the economy of a country has put the natural balance of the watershed environment in danger. The modification of our environment leads to the alteration of the hydrological processes. From the watersheds headwaters, the forests are cleared at a rate that leaves the mountains denuded reducing the capacity of the watershed to capture the rainfall for infiltration and recharge of the groundwater. The effect is an increase in surface runoff that endangers the downstream. Moreover, clearing of the forests also reduces the surface roughness of the terrain that tends to increase the velocity flow. Climate change, on the other hand, also modifies the hydrologic cycle and its effects is cascading. An increase in temperature will affect the atmospheric water and hence, the water balance. With increase flowrate and velocity due to anthropogenic alterations coupled with climate change, more floodwaters flow downstream.

Development often favors the flat terrain of the floodplain for accessibility and ease. It is also advantageous for growing crops as it is fertile enriched with nutrients coming from the mountains. Because of this, our floodplains became the usual sites of urbanization. The replacement of the natural environment with the built environment robbed the floodwaters of its own space. Every rainy season or typhoon season people's habitation are inundated with flood. It even encroaches now areas that we thought of not flood prone but are actually are. We just occupied the natural course and detention area of the floodwaters. During typhoons that amplify the



Figure 2.
Effects of flooding in Metro Manila, Philippines in 2012.

effects of the monsoon season, low-lying populated areas in the floodplains are a common scene in countries like the Philippines.

In 2009, the Tropical Cyclone Ketsana (Tropical Depression Ondoy which did not reach the typhoon category) wreak havoc to the capital and its suburbs that dumped a month's rainfall in just more than 3 hours. It was an unprecedented flooding event with the scale of its damage. Just three (3) years after in 2012, the same areas were affected even just by the Habagat or Southwest Monsoon rains enhanced by a tropical storm. **Figure 2** shows a swollen river and flooding in low-lying areas.

In countries frequented by tropical cyclones, riverine flooding is even exacerbated by sea level rise brought about by climate change and amplified by land subsidence, making worse the net sea level rise. Moreover, during typhoons, the effects of storm surge brought about by the gusts of winds, even worsens the flooding problem. In the Philippines, when the Tropical Cyclone Haiyan (Typhoon Yolanda) hit the central islands in 2013, it was estimated that more than 6000 people died and left the coastal towns and cities devastated.

5. Modeling flood inundation

The watershed is a very dynamic environment especially if it is being altered by anthropogenic activities. Human activities modify the hydrologic cycle to meet the demands of the population in order to survive. More often than not, the modifications we do to our watersheds lead to the deterioration and destruction of our natural environment impairing their natural purpose of efficiently conveying excess surface runoff downstream.

Because of the necessity to alter our watersheds to satisfy the needs of the society, it is imperative that we simulate the options that we want to do to minimize the problems that could be brought about by the modification that we will do. To alleviate the already existing flood problems we encounter in the floodplains we propose flood control measures that need to be simulated as well. The simulation of the flow of flood in a watershed or flood modeling is important as a decision support tool or system to achieve better options in solving our flooding problems given our limited resources.

In flood modeling, one of the most important inputs other than the rainfall, is the elevation. Water seeks its own level and therefore, elevation has to be accurately represented.

In the Philippines, extensive flood modeling of many of its riverbasin happened along with the introduction of LIDAR which stands for Light Detection and Ranging to create 3D digital elevation model (DEM). The LIDAR DEM generated has an accuracy of 20 cm in the vertical and 50 cm in the horizontal directions

generated from at least 2 data points averaged per square meter. A Digital Surface Model (DSM) kind of model is produced from this scan of the earth's surface. Sample DEM that shows purely terrain elevation called Digital Terrain Model or DTM is shown in **Figure 3**. It has a resolution of 1 m x 1 m as compared to Synthetic Aperture Radar (SAR) and Interferometric Synthetic Aperture Radar (IfSAR) DEMs which has a resolution of 30 m x 30 m and 10 m x 10 m or 5 m x 5 m, respectively.

Starting 2012, all of the 18 major river basins of the Philippines and its 247 principal river basins and other smaller river basins had their floodplains modeled using LiDAR DEM which was a priority project of the Department of Science and Technology (DOST) through its Nationwide Operational Assessment of Hazards or Project NOAH's Disaster Risk and Exposure Assessment for Mitigation or DREAM Component Project and the Phil LiDAR Program.

5.1 LiDAR data processing and validation

For the said projects, floodplains that did not have LiDAR data yet, manned airborne LiDAR data acquisition was conducted. LiDAR data collection and pre-processing is divided into three parts: 1) Data acquisition, 2) Point cloud generation, and 3) Data classification. Data acquisition included flight planning, system installation, data collection and data download. After data acquisition, pre-processing was done. Point cloud generation included the accuracy determination that will need the hardware and the software that came with the LiDAR system. For the data classification, Terrasolid was used for classifying infrastructures from the bare earth. The end-products of the preprocessing stage were unedited digital elevation models or DEMs.

Pre-processed LiDAR data were then subjected to processing. The processing of the LiDAR data began with manually editing some features of the unedited DEMs so that water will flow in a realistic manner. In the DEM, the bridges were removed, pits were filled and important features were removed in the last return digital

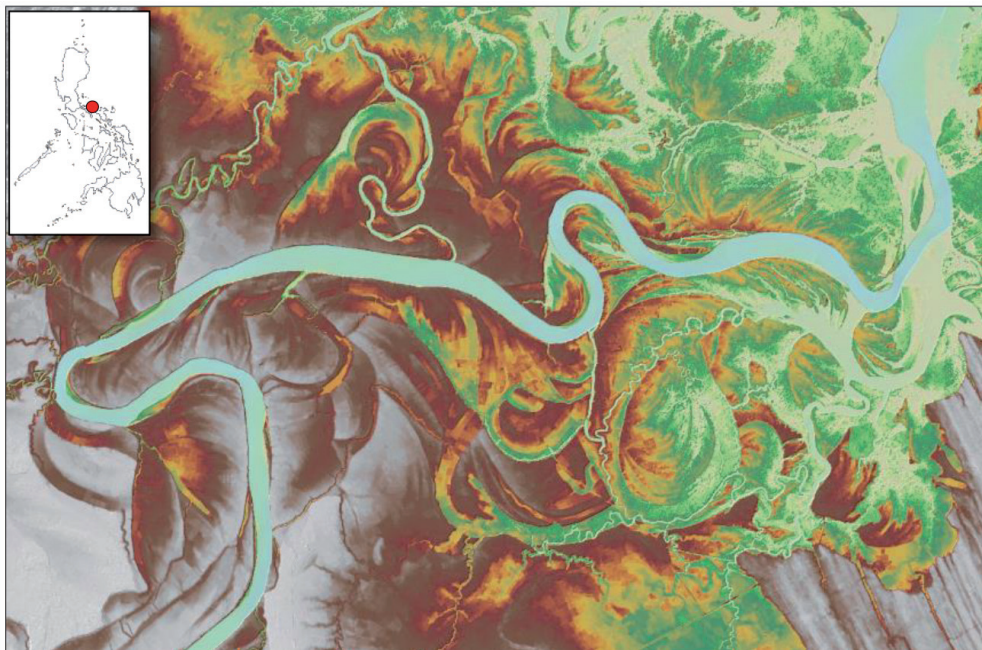


Figure 3. A LiDAR DEM processing output for Labo River basin in Camarines Norte Province, Philippines. It features a burned bathymetric data on LiDAR digital terrain model (DTM) processed by the Mapua-Phil LiDAR 1 Project of Mapua University through the Department of Science and Technology.

terrain model (DTM) retrieved from the secondary DTM. DTM, together with digital surface model (DSM) is a type of DEM. When DEMs were already edited, they were mosaicked into a bigger DEM and integrated with the bathymetric data gathered from the field. A minimum of ArcGIS 10.2 (or more recent version) was used in the project for the processing data since the scripts of Phil-LiDAR 1 Project was used. Simultaneously, feature extraction or digitizing features on LiDAR DEM were done. This also used ArcGIS for processing.

Validation was done by getting the difference in elevation of each check point and its corresponding LIDAR data point where the checkpoint locations were based on the guidelines provided by the American Society for Photogrammetry and Remote Sensing (ASPRS). Reference points and benchmarks established by National Mapping and Resource Information Authority (NAMRIA), Land Management Bureau (LMB) and other agencies were researched and checked on the field. The elevation of the geographic location labeled (X,Y) of these bench marks were determined through static observation using dual frequency GNSS (*Global Navigation Satellite System*) receivers. For water surfaces, detailed survey of the cross-sections and bathymetry were done.

5.2 Topographic and hydrographic surveys

Information on river topography and geometry and lake bathymetry is important in watershed and flood modeling. These features, nevertheless, are poorly represented in the LIDAR data due to low penetration of light signals in water. River profiling, cross-section and bathymetric surveying for lakes must be collected and integrated into the LIDAR data. GNSS kinematic surveys and topographic surveys using total station or digital level, and bathymetric mapping using an echo sounder equipped with GNSS positioning were done to obtain the above data needed. The collected data were analyzed and filtered to remove the outliers and then interpolated to come up with a continuous surface with the same spatial resolution as the LIDAR-derived elevation dataset. This surface data was subjected to accuracy assessment using an independent dataset and was ensured to have the same vertical accuracy as the validated LIDAR data or better. This was embedded into the LIDAR-data and used in modeling of the watershed and flood hazards.

Modeling and simulations were done using a combination of software that included GIS software, hydrologic modeling software and river and floodplain hydraulic software to generate flood hazard maps at different rainfall scenarios of 5, 10, 25, 50, and 100-year return periods. **Figure 4** shows sample two (2) dimensional flood hazard maps produced from flood hazard computer models simulated in 5, 25, and 100-yr return periods.

5.3 Hydrological assessment

In the development of the watershed, GIS proved to be useful in the derivation of the the catchment and subcatchment boundaries and properties. These are then used to create the hydrologic model with additional input of the rainfall data at different return periods. The hydrologic models were calibrated using actual or observed data taken during a rainfall event caused by storms or typhoons to capture the direct runoff that exhibits the response of the watershed to excess rainfall.

The hydrologic model simulations generate river flow or discharge that are input to the river hydraulics model which simulates the depth and velocity of flow in the river channel and the floodplain.

For the projects, hydrological measurements such as for rainfall, water level and discharge were done in the sub-basins for use in the flood model calibration and

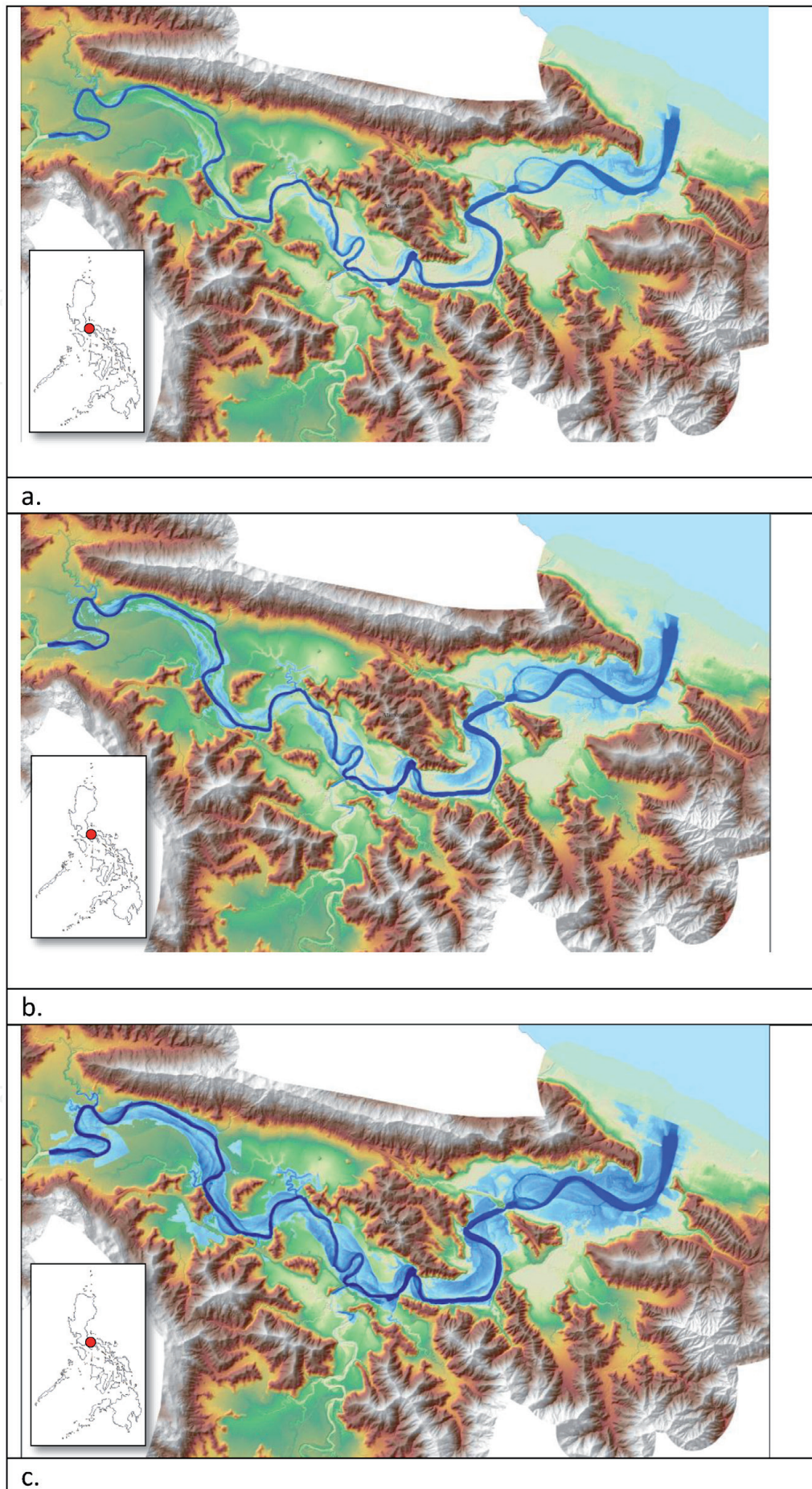


Figure 4. Flood hazard map generated using LiDAR digital elevation model in Maling River in Atimonan, Quezon Province, Philippines produced by the FRAMER Project of Mapua University and Department of Science and Technology (DOST).

validation. Existing data from different government agencies e.g. PAGASA were also collected and assessed. For ungauged watersheds, rain gauges, water level sensors, and velocity meters were used for at least a year to capture seasonal changes. At least one rain gauge was ensured to be present near the center of each river basin. On the other hand, water level and velocity sensors were used at a selected point in the river in the usually with the presence of a bridge for ease and safety in data gathering. At that location, called project point, cross-section measurements were done so that the rate of discharge can be computed. The water level and the computed discharge were needed in generating rating curves to be used in forecasting water stage.

5.4 Watershed and flood modeling and hazard mapping

It is in the hydraulic model that the LiDAR DEM plays an important part of giving accurate flood depths. The flood depths are represented geographically in a map to generate the flood hazard map of an area.

With the validated LiDAR-DTM, the sub-basins were delineated using watershed delineation algorithm in GIS. HEC-HMS (Hydrologic Modeling System) and HEC-RAS (River Analysis System) programs of the Hydrologic Engineering Center (HEC) of the US Corps of Engineers were utilized [4]. The hydrological model for the upstream watersheds were developed using HEC HMS where soil type and land-cover related parameters needed in program were derived through analysis satellite images, and from the Department of Agriculture's Bureau of Soil and Water Management (DA-BSWM) soil maps. Other parameters of the model were set to initial values and were adjusted during calibration. After calibration, the model were validated with an independent set of rainfall and discharge data [5].

The hydraulic model for the floodplain were developed using HEC-RAS. Cross-section data extracted from the validated LiDAR DTM was used in this program to create the geometry of the river system in each sub-basin. The land-cover related parameter which is the Manning's roughness coefficient were determined through analysis satellite images.

The model generated from the combined HEC-HMS and HEC-RAS programs were used to run the actual flood events for each sub-basin using historical flood data. Flooding due to hypothetical extreme rainfall events of various return periods obtained from PAGASA were simulated to see the effects of such events in the watershed. The flood simulations were then used to generate water surface elevation grids which were overlain into the high resolution LiDAR-DTM to generate flood hazard maps. To enhance the flood hazard maps, a 2D hydrodynamic model was utilized as well [6]. This 2D model in HEC-RAS utilized the discharge hydrographs generated by HEC HMS.

6. Flood modeling results

The use of a more sophisticated equipment to measure elevation at higher resolution is necessary when it comes to modeling flood inundation. Elevation is one of the most important inputs as this will tells us the depth of water which is a serious concern to people and for properties.

In **Figure 4**, sample flood hazard maps for one of our study areas in Quezon Province show the different flood inundation levels at different rainfall return periods, i.e. 5, 25, and 100 years. The flood hazard maps serve as an important tool for use by the Local Government Units (LGUs) planners and responders, and by the public in general. The maps produced show the flood inundation that can be related to the forecast of rainfall event the weather agency releases. Across the Philippines,

PAGASA has synoptic weather stations, each has corresponding rainfall intensity, duration, frequency curves (RIDF). A station nearest to the area of study adopts this specific RIDF.

During a storm or a typhoon, forecast of rainfall depth in time or intensity in an area i.e. with respect to a watershed, is checked with this curves for equivalent return period. The determined return period will tell us which flood hazard map should be used. From the specific inundation map, we can clearly see the extent of the flooding as well as the relative depth of flood. The geographic location of flooding can be easily visualized when it is overlain on the elevation DEM. When data of exposure is included, the number of households and establishments affected can be determined.

As shown in **Figure 4**, flood hazard maps are an important tools that can be used to see spatially the occurrence of flood and the potential impact it may cause to the area. Moreover, a risk assessment of the flood hazard that incorporates the aspects of exposure and vulnerability of elements such as the population and economic activities in the area has to be done in order to identify flood prioritization response for cost efficiency on responses [7]. Flood hazard and flood risk assessments are two different but related procedures whose outputs are an important decision-making tools for identifying flood prone areas needed for the design of flood control and drainage projects, and for the prioritization of responses for saving lives and properties, respectively.

Rainfall data such as in the RIDF should be continuously updated to account for new entries that reflect the effects of extreme climate variabilities such as climate change. Although there are still uncertainties in the projections of climate scenario due to limited knowledge, it has been observed that there are widespread increases in heavy precipitation events which are associated with the increase in water vapor in the atmosphere consistent with the observed warming [1]. Aside from rainfall, behavior of storms and tropical cyclones that brings with them rain are becoming stronger as manifested in the introduction of a higher category of Tropical Cyclones in the Philippines by its weather agency, PAGASA. In May 1, 2015, a new category Super Typhoon with speeds more than 220kph is added in the Tropical Cyclone Classification as a consequence of the strongest typhoon TC Haiyan (Typhoon Yolanda as it is locally known). Changing precipitation volumes and intensities increase the risk of flash flooding and urban flooding in many areas in the region and even the world.

7. Conclusions

Flooding, especially in tropical countries that has the hydrometeorological factors that generate huge quantities of precipitable water, is a yearly event that disrupts people's lives. Flood control structures and proper drainage design can help mitigate this but quantification of the surface runoff should be accounted for correctly. Present technologies such as computer models aid us in doing this. Along with the better input data we have nowadays, these models can give us flood hazard information that enable us to quantify the amount of flood water our mitigating measures should accommodate to reduce or even eradicate flooding problems in certain areas. Continuous update of data parameters, nevertheless, should be done to account for rapid changes happening in the environment including climate change. Specifically, affected by climate change is the rainfall variable that designers of flood control and drainage structures should consider. This is to ensure that our mitigating solutions are not just satisfying future capacity requirements but are also climate-proof for better life and continuous progress.

Acknowledgements

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