# CHARACTERIZING FLOOD HAZARDS IN AN ALLUVIAL FAN DURING EXTREME RAINFALL EVENTS USING LIDAR AND NUMERICAL MODELING

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**KEY WORDS:** Flood characteristics, alluvial fan, LiDAR, numerical modeling, rainfall return periods

**ABSTRACT:** In this paper, we characterize the flood hazards in an alluvial fan in Asiga Watershed in Agusan del Norte, Mindanao, Philippines through the use of high resolution topographic information derived from LiDAR and a suite of hydrologic and two-dimensional (2D) hydraulic models. The alluvial fan, with its active portion traversed by Asiga River, is of particular interest due to its recent flooding events that occurred in January and December 2014 caused by extreme rainfall brought by tropical storms Lingling ("Agaton") and Jangmi ("Seniang"), respectively. While it is known that flooding was caused by the overflowing of the Asiga River, the role and contribution of the alluvial fan to flooding was not yet fully understood. Using a calibrated hydrologic model based on the Hydrologic Engineering Center Hydrologic Modeling System (HEC HMS), we determined the inflows at the apex of the alluvial fan during rainfall events. Then, we used these inflows as inputs into a 2D hydraulic model based on the HEC River Analysis System (HEC RAS) to simulate the movement of water entering the alluvial fan. LiDAR-derived Digital Terrain Model was specifically used as input into the 2D model and made possible the generation of very detailed flood characteristics like flood extent, depth, velocity, and arrival time. The use of LiDAR data was very instrumental in mapping the distributary channels that contributed to the wide extent of flooding. Hydrologic and 2D hydraulic simulations were conducted to examine flood hazards in the alluvial fan under different scenarios of extreme rainfall events, e.g., rainfall events with return periods of 2, 5, 10, 25, 50 and 100 years. Spatial overlay analysis was also conducted to assess the exposure of infrastructures to the various levels of hazards within the alluvial fan under these extreme events which can become very important inputs in the development of flood adaptation and mitigation strategies of the concerned LGU and communities residing within the alluvial fan.

## 1. INTRODUCTION

### 1.1 Background

Every year, an average of nineteen (19) tropical storms coming from the Pacific region enters the Philippines area of responsibility, in which nine (9) are expected to make landfall (Virola, 2008). These storms usually brought heavy rains that causes flooding to several communities situated in low-lying areas. Because of climate change, rains from tropical storms are now becoming fiercer and more extreme (Kirby, 2016). It is into this case that the information in relation to flooding which can be generated through mathematical simulations is now very much in demand. This information will not only guide the disaster managers on where the hazardous areas are but will also help them in understanding how these disastrous events happen. Also, by simulating and knowing where the hazards are, we can also estimate and assess the possible impacts it could bring to the existing exposures in the floodplain area. These assessments are very important since these can help the communities and the Local Government Units (LGUs) on how they can strategize in minimizing or even avoiding the negative impacts of flooding.

### 1.2 Flood Hazards

In the Philippines, the flood hazard maps utilized in disaster planning and other related works only shows the maximum hazard levels based on the flood depth. These maps are categorized into three: low (flood depths of 0.5 m and below), medium (flood depths greater than 0.5 m to 1.5 m), and high (flood depths greater than 1.5 m). Although these maps already contain vital information, there are still other flood characteristics that are also important in flood disaster management such as: flood velocity and flood arrival times. Flood velocity hazard map can show information on where are the areas which might be impassable due to the fast moving water even if its flooding is not so deep. It also can show information of which among the flooded areas are not anymore safe for wading and for maneuvering of light vehicles. Velocity maps can also indicate areas which might have damaged their structures because of scouring caused by fast moving flood waters (NSW, 2005). Among all flood hazards, information on flood arrival times is very important for flood forecasting preparedness. It can be used to inform the community on how many hours it would take before they might get affected by a certain flooding and can also inform emergency response officials on where areas needs their resources immediately (Jones, et al., 2002).

### 1.3 Asiga Alluvial Fan

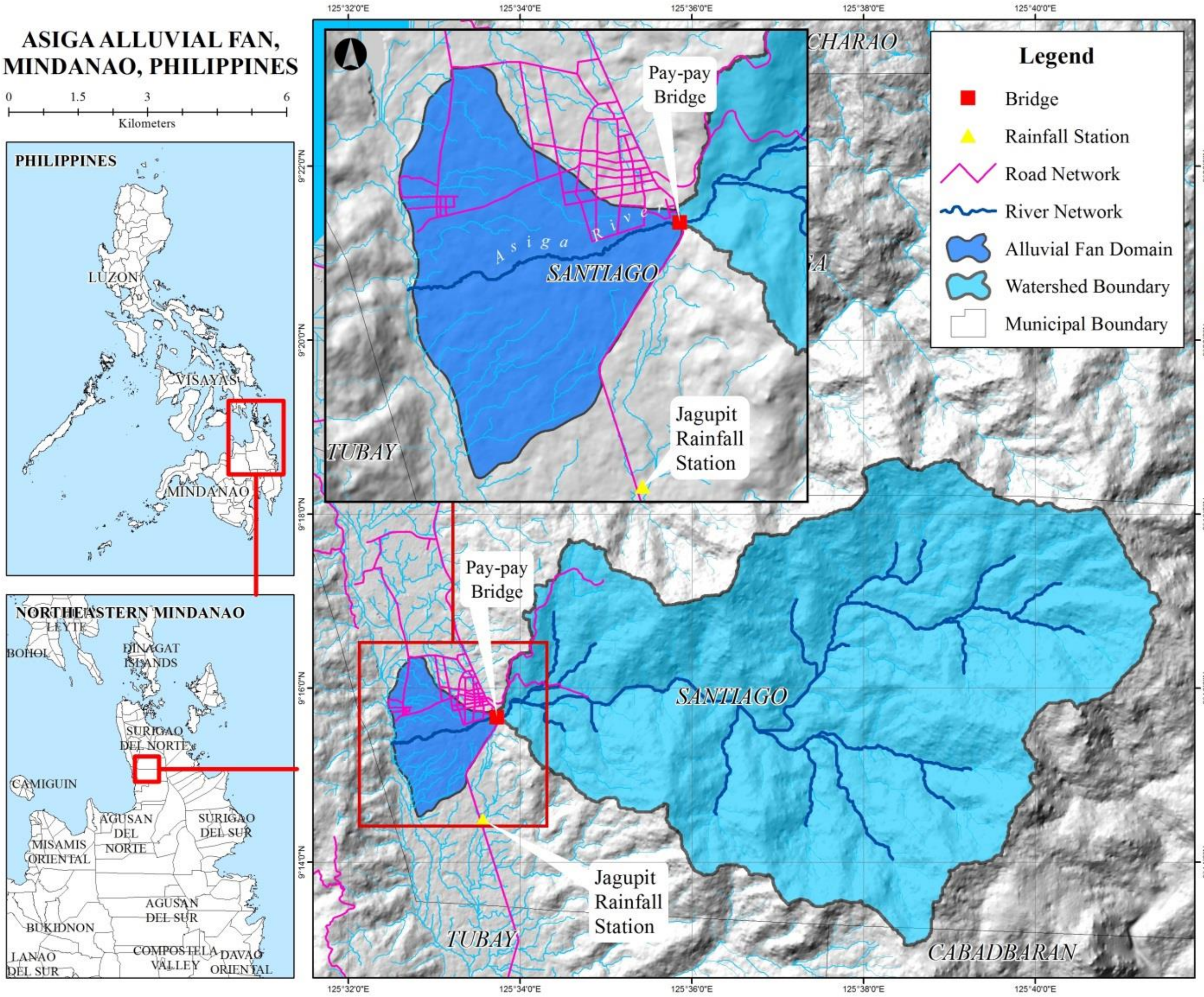


Figure 1. Map showing the location and coverage of Asiga Watershed and the alluvial fan.

Alluvial fans are a prominent landform type commonly present where a channel emerges from mountainous uplands to an adjoining valley. They are often characterized by a fan- or cone-shaped deposit of sediment crossed and built up by streams. Due to variations in climate, fan history, rates and styles of tectonism, source area lithology, vegetation, and land use, the hazards of flooding on alluvial fans are often difficult to understand (Blair and McPherson, 2009).

Asiga watershed is a sub-river basin of Mainit-Tubay river basin which has an alluvial fan floodplain area. It is located in the Municipality of Santiago, Province of Agusan del Norte in the island of Mindanao, Philippines. It has an approximate drainage area of 84.36 km$^2$. Its alluvial fan, having Asiga River as its active drainage, has an approximate area of 4.36 km$^2$ with its apex located in the upstream of Pay-pay Bridge (Figure 1). In 2014, the alluvial fan was one of the many areas affected by flooding due to heavy to torrential rains brought about by the passing of tropical storms Agaton and Seniang (NDRRMC, 2014; 2015). Although it was already known that the flooding was caused by the overflowing of the river, the contribution of the alluvial fan on the activity of flood water is not yet fully understood. An approach was introduced by Segura-Beltrán, et al. (2016) to understand the mechanisms of floods in an alluvial fan system which includes early warning plans and risk mitigation strategies.

### 1.4 Objectives of the Study

In this paper, we characterize the flood hazards in an alluvial fan in Asiga watershed through the use of high spatial resolution topographic information derived from LiDAR acquisitions and hydrologic and two-dimensional (2D) hydraulic models. Hypothetical flooding scenarios caused by extreme rainfall events with return periods of 2, 5, 10, 25, 50 and 100-years were simulated and characterized to understand how the alluvial fan contributes to the flooding in Asiga watershed. These flooding characteristics were also assessed on how their flooding extents, depths, velocities and arrival times impact the buildings within the alluvial fan floodplains.

## 2. MATERIALS AND METHODS

As summarized in Figure 2, high spatial resolution flood hazard maps needs to be produced and analyzed in order to better understand the flooding events that might happen in Asiga watershed, particularly in the alluvial fan. We utilized the 1-m spatial resolution LiDAR-derived Digital Terrain Model (DTM) as the major input data in numerical modeling. The numerical models (hydrologic and 2D hydraulic models) are parameterized using the information gathered from the land-cover map generated from satellite image analysis. Hydrologic model are inputted with hydrological data from the rainfall stations of the Advanced Science and Technology Institute of the Department of Science and Technology (ASTI-DOST) for the simulations and is calibrated using the hydrologic data (river discharge) acquired through field measurements. The discharge values computed by the hydrologic model are inputted to the 2D hydraulic model which generates the different flood hazards (extent, depth, velocity, and arrival time). Assessment of the possible impacts these hazards might bring, spatial overlay analysis is conducted to know the buildings which might be affected given a certain rainfall scenario.

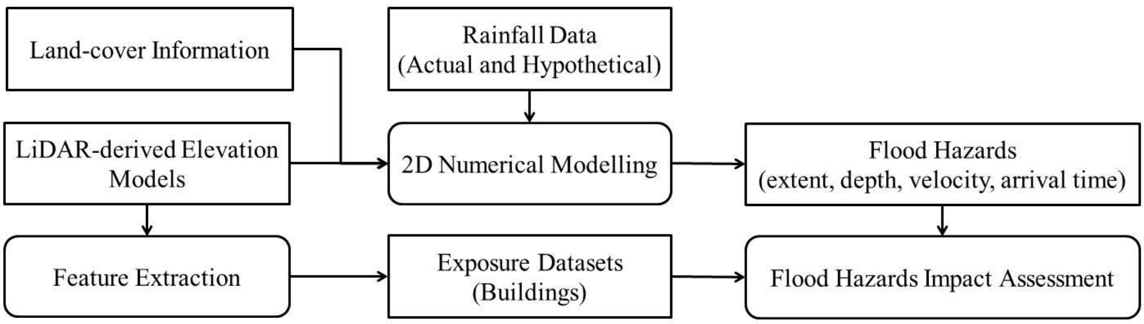


Figure 2. Flow chart showing how the different flood hazards are generated including the impact assessment.

### 2.1 Datasets Used

The development of the hydrologic model utilized the Synthetic Aperture Radar-Digital Elevation Model (SAR-DEM), and the rivers and stream networks of Asiga watershed in delineating the watershed boundary and the sub-basins with its corresponding rivers. These were parameterized using the land-cover information obtained through analysis of remotely sensed images acquired by the sensors of Landsat 7 Enhanced Thematic Mapper plus (ETM+) and Landsat 8 Operational Land Imager (OLI). Land-cover information is extracted from these images through the use of supervised classification algorithms. The main input of the hydrologic model in order to generate flow hydrographs, are the near-real time rainfall data recorded by the geographically positioned rainfall stations of ASTI-DOST; and is calibrated by utilizing the actual discharge values of the river computed through actual hydrological measurements. A detailed topographical data of the alluvial fan is the major input in generating detailed flood hazard maps. In this study, the major dataset used is the LiDAR-derived Digital Terrain Model (DTM). The buildings exposure datasets used in the flood impact assessment were extracted by utilizing the LiDAR-derived Digital Surface Model (DSM). Both LiDAR-derived DTM and DSM have 1-m horizontal and 20-cm vertical spatial resolutions.

### 2.2 Numerical Modeling and Flood Characterization

**2.2.1 Hydrologic Model Development and Calibration:** The hydrologic model of Asiga watershed is part of the already calibrated Mainit-Tubay river basin hydrologic model (Amora, et al., 2015). It is based on the Hydrologic Engineering Center Hydrologic Modeling System (HEC HMS) which is dependent on the three components: the basin model, meteorological model, and the set of control specification. The basin model, which is the physical representation of the watershed, was developed by utilizing the 10-m SAR DEM and the rivers networks in the delineation of watersheds; and is parameterized using the information from the land-cover maps that was generated through the analysis of Landsat 7 ETM+ and Landsat 8 OLI satellite images. To account the flow contributions from various locations in, a complete setup of the hydrologic model was made which includes the Asiga watershed and all adjacent and adjoining river systems. It was calibrated by relating the simulated flow hydrographs to the actual measured flow in the river. Hydrological data necessary for calibration was gathered from this station last 11/26/2014 to 12/05/2014 with the use of water level and velocity data logging sensors together with the river cross-sectional data. The model simulates flow hydrographs of the rivers for the control specification indicating the simulation period by inputting rainfall data from Jagupit rainfall station (Figure 3) to the meteorological model which uses inverse distance method for historical and present rainfall events and frequency storm method for the rainfall return periods.

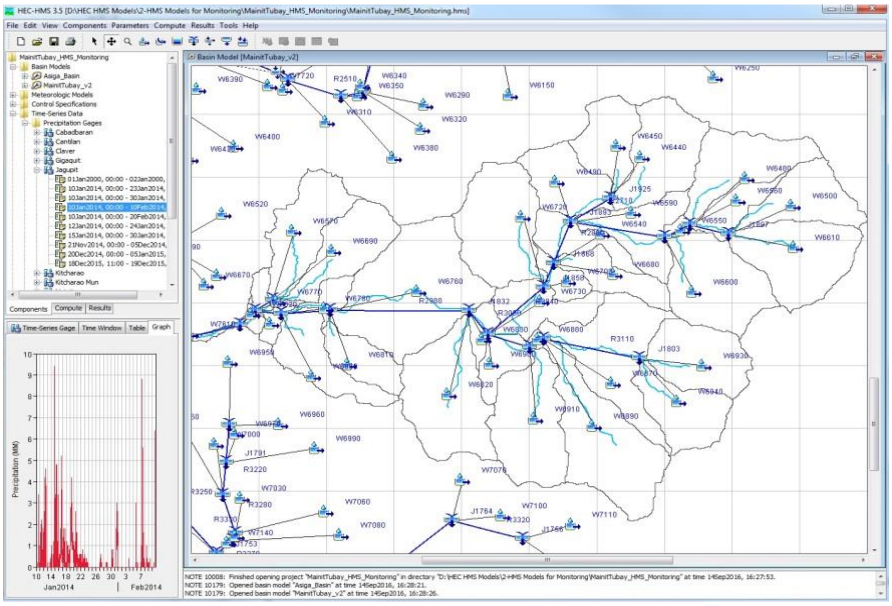

Figure 3. The setup of the hydrologic model of Asiga and adjacent watersheds.

**2.2.2 2D Hydraulic Model Development:** The 2D hydraulic model was based on the Hydrologic Engineering Center River Analysis System (HEC RAS) version 5.0, which is designed to perform one-dimensional (1D), two-dimensional (2D), or combined 1D and 2D hydraulic calculations for a full network of natural and constructed channels (USACE, 2016). For Asiga alluvial fan and other contributing adjacent areas, 2D modeling was performed with no 1D element present. The 2D HEC RAS model was developed by creating a 2D flow area (i.e., the 2D model domain) representing the entire alluvial fan floodplain and other contributing areas. The created 2D flow area mesh has an approximate area of 29.30 km$^2$ and was computed using a 15-m by 15-m cell size. With the aid of break lines representing the roads, dikes, levees and river banks, the 2D flow area was finally computed to have a total of 130,978 cells. The 1-m spatial resolution LiDAR-derived DTM and the Manning's roughness coefficients extracted from the land-cover map were used as inputs in setting the model's geometric data. The model consisted of 5 boundary conditions in which 3 are inflows from upstream rivers, 1 as the normal depth boundary condition at the outlet, and 1 boundary condition for the precipitation that falls to the 2D area (Figure 4).

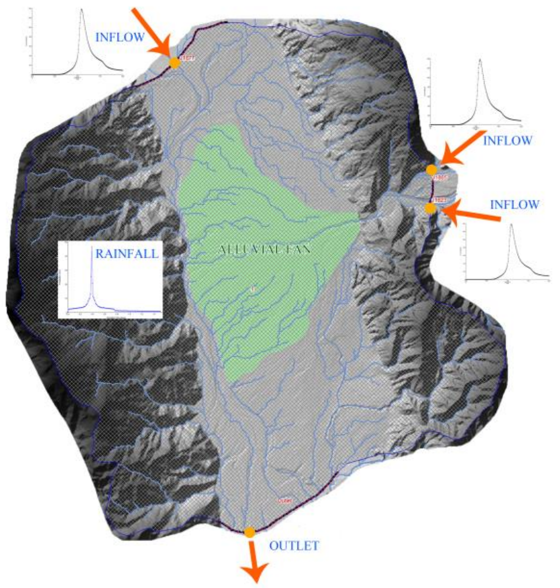


Figure 4. The boundary condition locations of the 2D hydraulic model of Asiga alluvial fan.

**2.2.3 Flood Characteristics Generation:** The flow hydrographs generated by the calibrated HEC HMS model were used as inputs into the HEC RAS 2D hydraulic model to predict or estimate the different flood characteristics. These flow hydrographs together with the time series of rainfall were utilized by the unsteady flow analysis module of HEC RAS to dynamically simulate the extent, depth, velocity and arrival time of flooding. For each extreme rainfall event flood simulation, a spatially-distributed grid of maximum flood extent, depth, and velocity, and arrival time from the start of the rain were generated.

**2.3 Flood Hazards Impact Assessment**

The impacts of flooding were assessed through spatial overlaying of the exposure datasets (buildings) with the generated flood hazard maps for the different rainfall events using ArcGIS software. The flooding impact to buildings were assessed by determining the possible maximum depth and velocity, and fastest arrival times of flooding that it may experience given a certain extreme rainfall event.

## 3. RESULTS AND DISCUSSION

### 3.1 Exposure Datasets

The digitized exposure datasets derived using the 1-m spatial resolution LiDAR-derived DSM of the alluvial fan in Asiga watershed floodplain areas totaled to 396 buildings. These features were checked and validated using the high-resolution satellite images from Google Earth.

### 3.2 Accuracy of the Hydrologic Model

Figure 5 shows the simulated flow hydrographs before and after the calibration of the HEC HMs model. In evaluating the model performance before and after calibration, three measures of accuracy were used. These are the Nash-Sutcliffe Coefficient of Model Efficiency (NSE), percentage bias (PBIAS), and the RMSE-observations standard deviation ratio (RSR). These measurements are computed by comparing the observed and the simulated hydrographs based on the evaluation guidelines (Moraisi et al., 2007). Based on the model performance evaluation, the overall performance of the hydrologic model before calibration is "unsatisfactory" which is very noticeable in the comparison between the observed and simulated hydrographs. After the calibration, the model performance statistics improved from -0.47 to a "good" 0.68 NSE, 1.21 to a "good" 0.56 RSR, and -56.53 to a "satisfactory" -22.54 PBIAS performances.

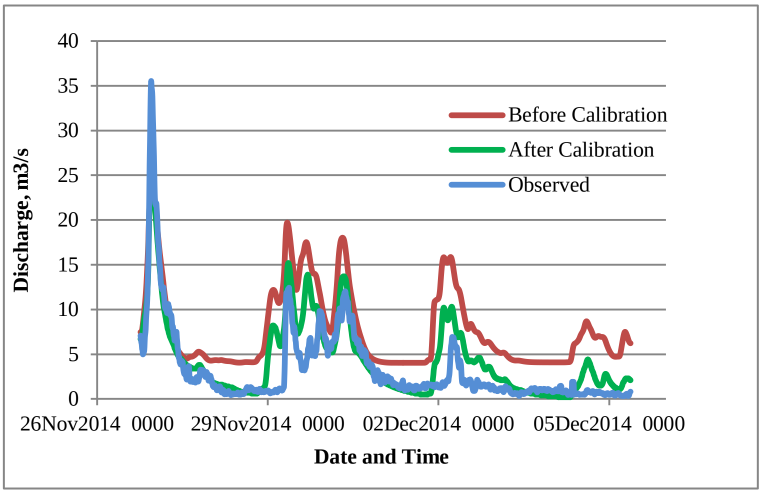

Figure 5. Comparison between the simulated discharge before and after calibration of the HEC HMS model.

### 3.3 Generated Flood Hazards

Example flow hydrographs simulated by the Asiga HEC HMS model at the apex of the alluvial fan for the different extreme rainfall events is shown in Figure 6. It can be observed that as the rainfall event becomes more extreme, the peak flow at the apex also increases. This is evident from a maximum discharge of approximately 250 $m^3$/s for a 2-year rainfall return period to almost 1,500 $m^3$/s for a 100-year rainfall return period.

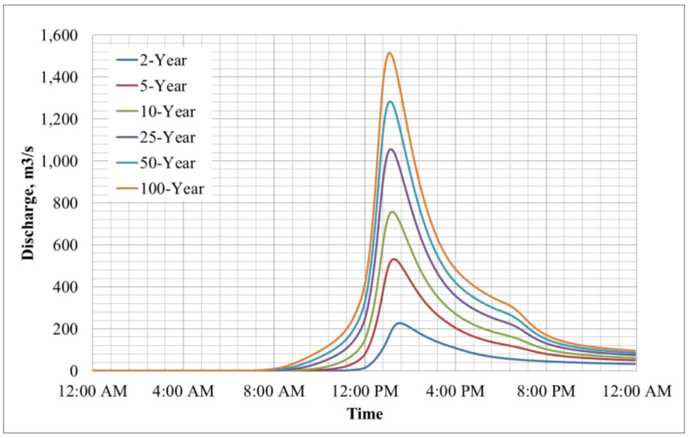

Figure 6. 24-hour outflow hydrographs generated at the apex of Asiga alluvial fan for the 6 rainfall return periods.

The generated flood depth, velocity and arrival time characteristics of Asiga alluvial fan floodplain are shown in Figure 8, Figure 9 and Figure 10, respectively. The categorization of the velocity hazard map was based on the Floodplain Development Manual of NSW Office of Environment and Heritage (2005). It can be observed from the generated maps that as the rainfall return period increases, the extent of flooding also increases (Figure 7). The maps also show that the flooding in the alluvial fan is mainly caused by the overflowing of Asiga River with a significant contribution from its geomorphological attributes.

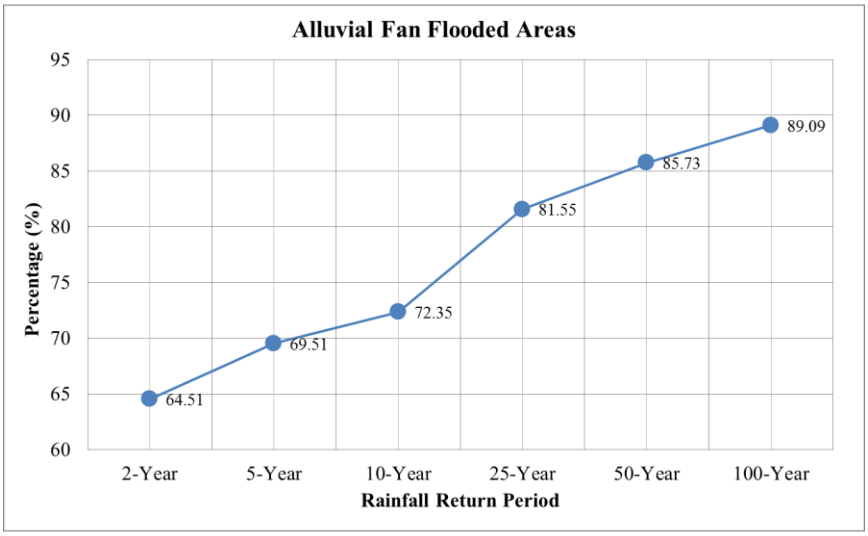


Figure 7. Percentage of the alluvial fan's total area (4.36 $km^2$) which are expected to be flooded during extreme rainfall scenario.

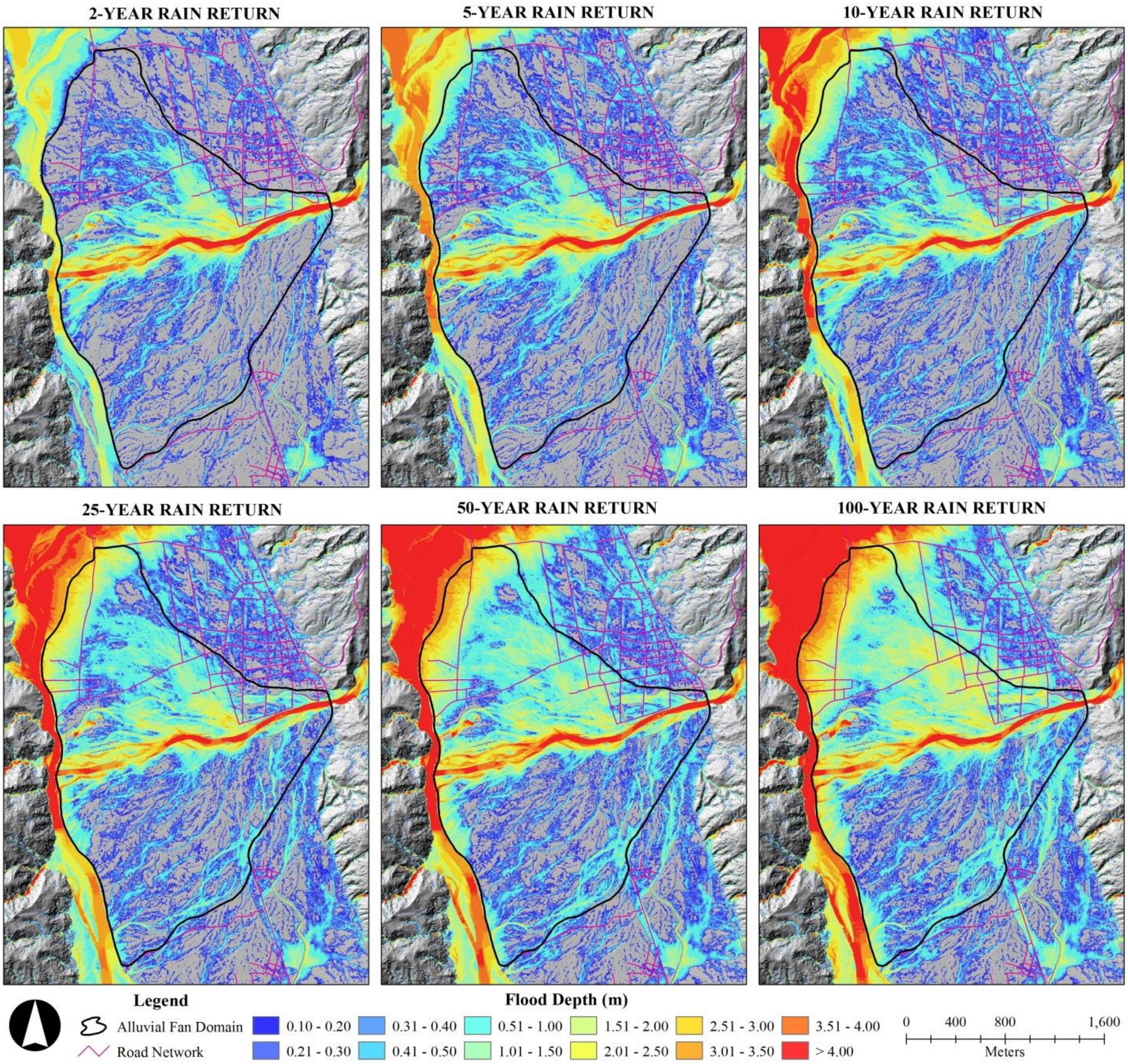


Figure 8. The generated flood depth hazard maps of Asiga alluvial fan and nearby areas for the 6 rainfall return periods.

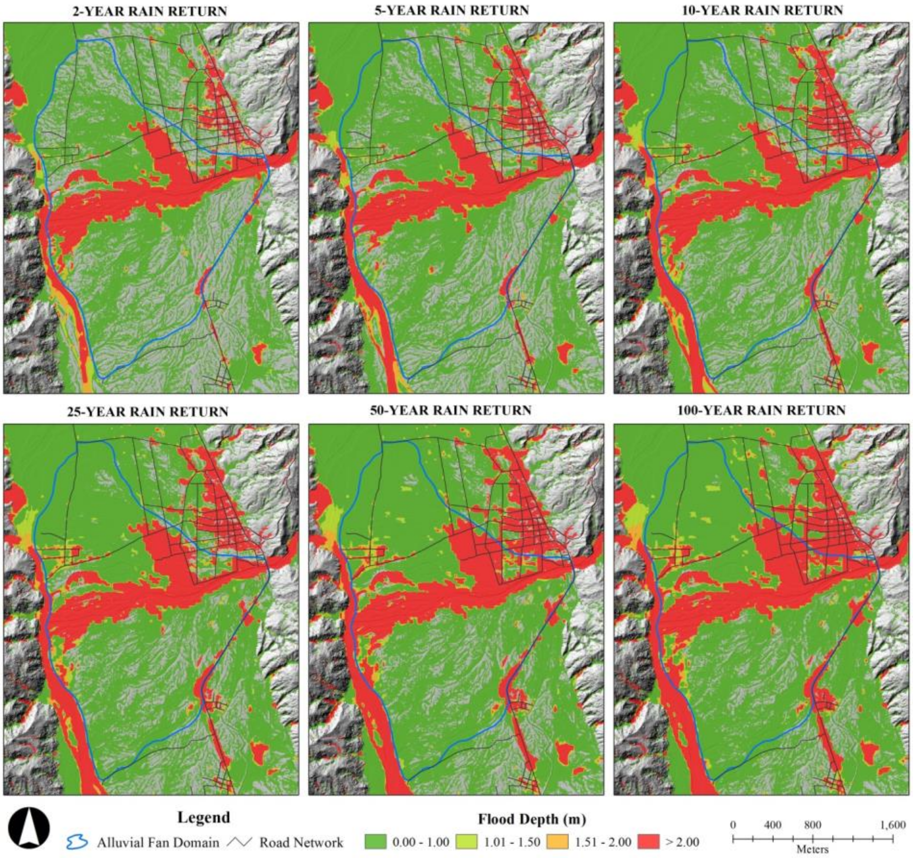


Figure 9. The generated flood velocity hazard maps of Asiga alluvial fan and nearby areas for the 6 rainfall return periods.

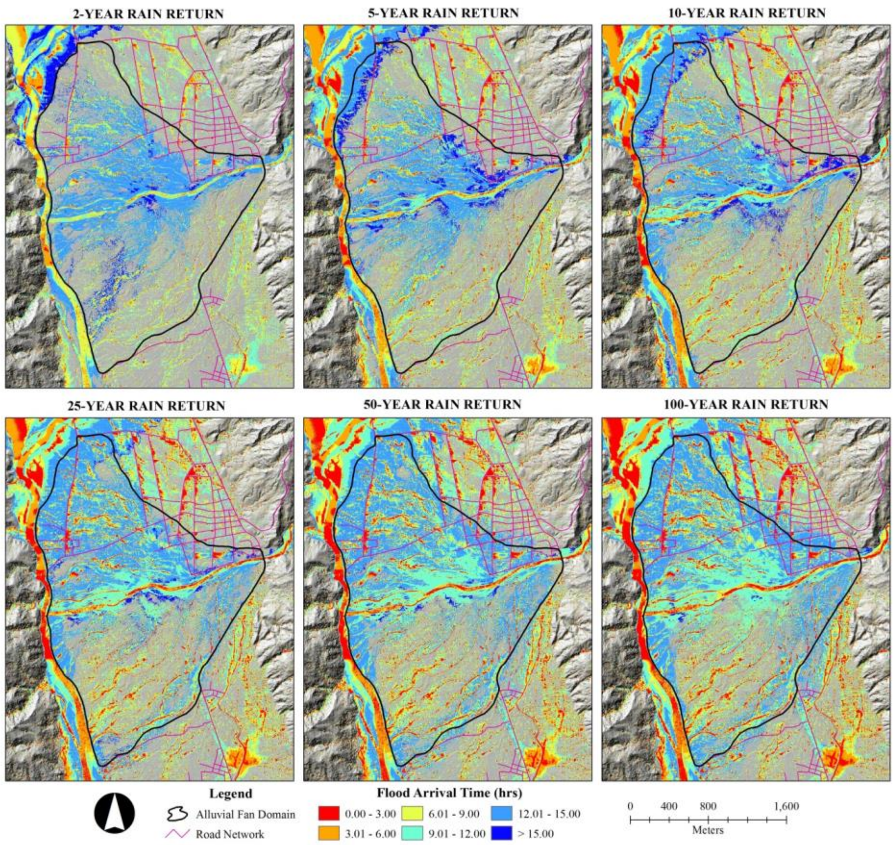


Figure 10. The generated flood arrival time maps of Asiga alluvial fan and nearby areas for the 6 rainfall return periods.

### 3.4 Flood Hazards Impact Assessment

The results of assessing the impacts of the depth, velocity and arrival time flooding characteristics to the buildings within the alluvial fan floodplain are shown in Figure 11, Figure 12, and Figure 13, respectively.

It can be observed that relatively inconsistent statistics were computed to the flooding impacts in Asiga floodplain as the rainfall scenario becomes more extreme. Usually, as the rainfall event becomes more extreme, it can be expected that worse condition would be experienced by the exposed elements present in the floodplains. Although this situation is true if we look at the number of affected buildings (i.e. more flooded building as rainfall event becomes more extreme), the depth, velocity and arrival time values vary and does not show any direct relationship with the rainfall return period. For example, there were more buildings that experienced more than 1.5 m flood depth during a 2-year rainfall return flooding compared during the 5, 10, 25 and 50-year rainfall returns. All these varying frequency can be observed in all the flood characteristics. One of the possible reasons for these inconsistent statistics maybe the ranges used in classifying hazard, velocity, and flood arrival time.

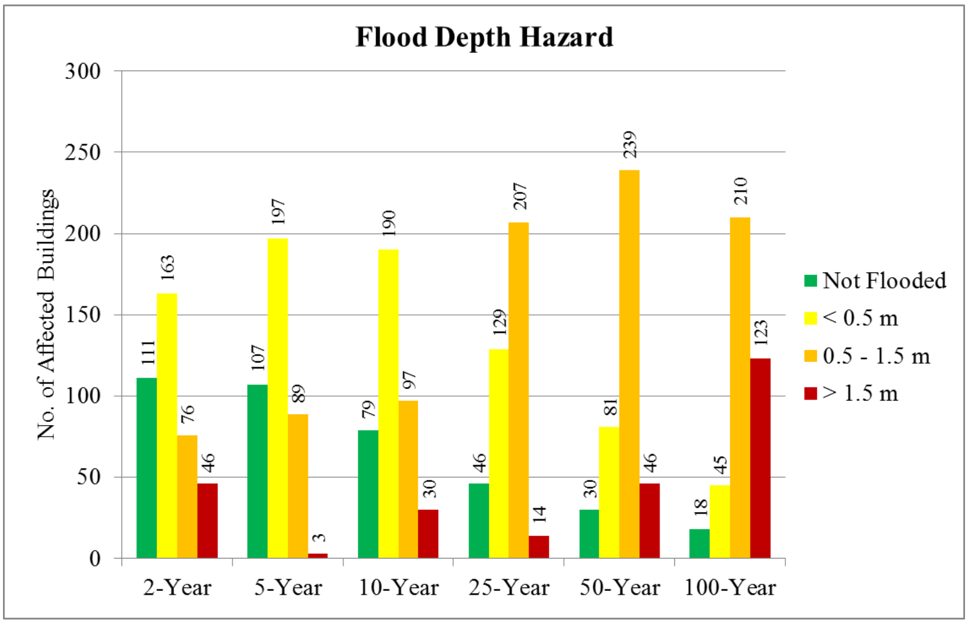


Figure 11. Flood depth affected building within Asiga alluvial fan for the 6 rainfall return periods.

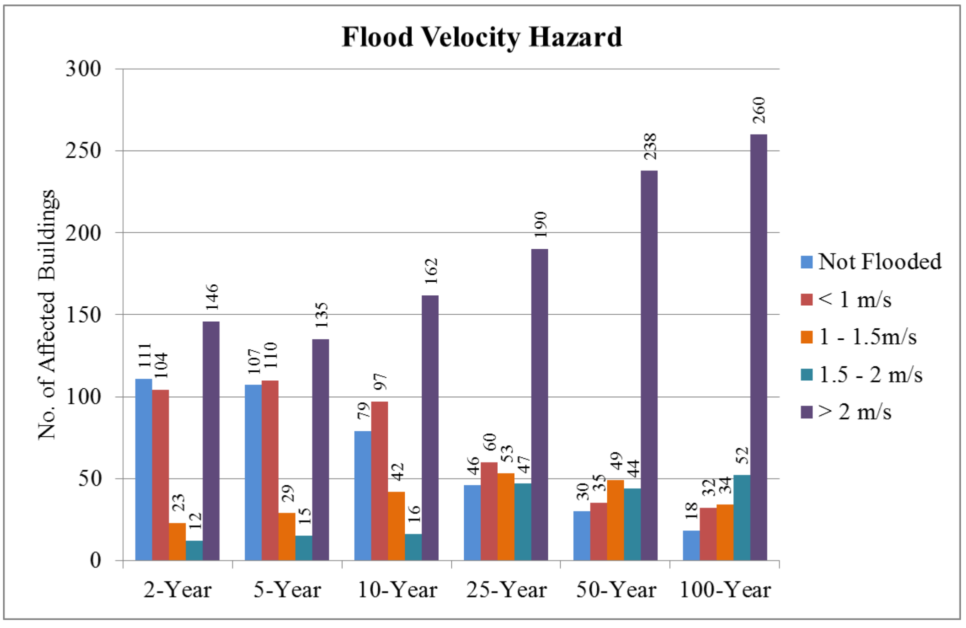


Figure 12. Flood velocity affected building within Asiga alluvial fan for the 6 rainfall return periods.

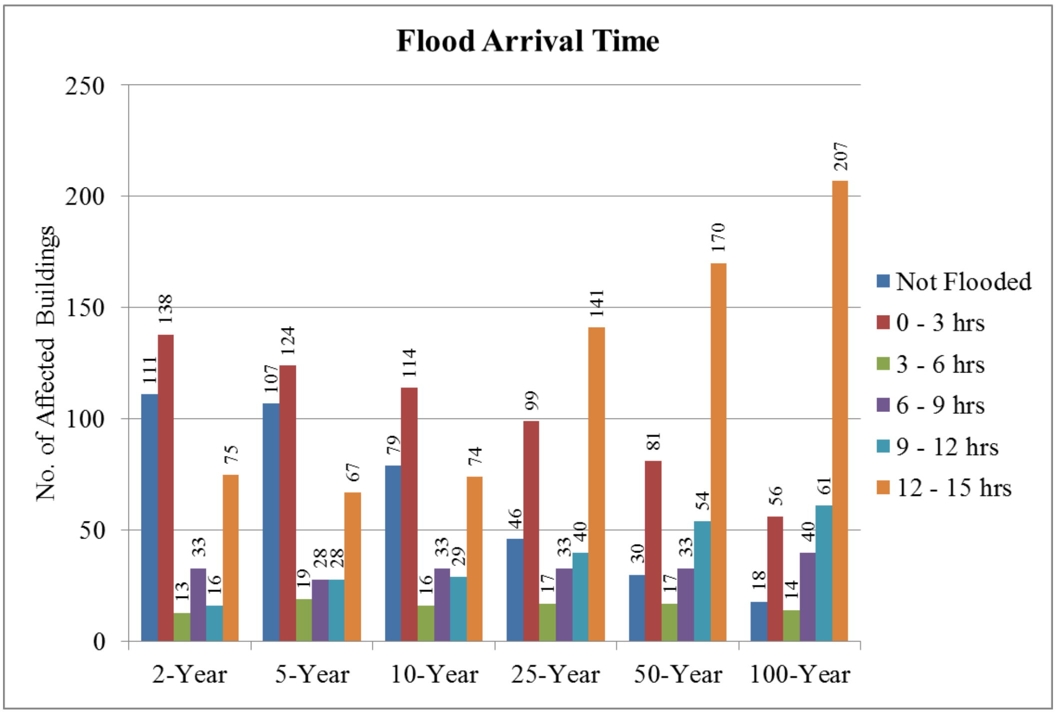


Figure 13. Flood arrival time to affected buildings within Asiga alluvial fan for the 6 rainfall return periods.

## 4. CONCLUSION

By utilizing the high spatial resolution elevation models extracted from LiDAR and 2D numerical models, we were able to characterize the different flood hazards in an alluvial fan floodplain. These characteristics were the flood extent, depth, velocity and arrival time. We were able to show the distributary channels of Asiga River which contributed in widening the extent of flooding in the alluvial fan. Flood characteristic maps were generated for the 2, 5, 10, 25, 50 and 100-year rainfall return periods. These maps were utilized in assessing the possible impacts that a certain rainfall scenario could bring to the community within the alluvial fan floodplain.

The information extracted from the impact assessment can be very useful to the Local Government Unit and communities within Asiga floodplain as an aid in determining buildings at risk to the different characteristics of flooding. From the flood arrival time maps, information on how many hours from the start of the rainfall before flooding would occur can be extracted. This will warn and help the citizens and the disaster managers to allocate enough time in preparing for the necessary measures to lessen or possibly avoid a flooding disaster.

## 5. RECOMMENDATIONS

Several things can still be done to improve and maximize the outputs of this study. Some of these are: (i) by re-calibrating the Asiga sub-basin parameters that utilizes actual flows gathered at Asiga River; (ii) the accuracy of the generated flood grids also needs to be determined by conducting actual field surveys in the floodplain area and extract information of the recent flooding occurrences which will be utilized in comparing the actual and the model simulated flooding scenarios; (iii) by conducting flood impact assessment to the other exposure datasets (roads, bridges, land-cover); and (iv) by mapping, determining and assessing the combined effect of flood depth and velocity to the exposures in the alluvial fan floodplain.

## ACKNOWLEDGEMENTS

This work is an output of the Caraga State University (CSU) Phil-LiDAR 1 project under the Phil-LiDAR 1. Hazard Mapping of the Philippines using LiDAR program funded by the Department of Science and Technology (DOST). The SAR DEM and the LiDAR DTM and DSM used in this work were provided by the University of the Philippines Disaster Risk and Exposure for Mitigation (UP DREAM)/Phil-LIDAR 1 Program. We thank all CSU-Phil-LIDAR 1 technical staff and assistants, as well as the Local Government Units in the watershed for their assistance during the conduct of hydrological measurements and flood map validation surveys.

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