

Coupled Hydrologic-Hydraulic Modeling-Based Flood Inundation Mapping for a Segment of the Tullahan River in Valenzuela City, Philippines



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Abstract Anthropogenic activities brought about by accelerated urban expansion trigger changes in the hydrologic response of watersheds. The Philippines, being prone to the occurrence of extreme weather events and urban development, has experienced more frequent and more devastating floods that have caused damage to life and property throughout the years. Thus, the need for modern approaches to disaster risk and preparedness is essential to lessen the extent of damage that flood events bring to communities. This study was conducted to exhibit the capability of using a coupled hydrologic and hydraulic model to produce a flood inundation map for a segment of the Tullahan River in Valenzuela City, Philippines. A hydrology model was set up and calibrated using the Hydraulic Engineering Center Hydrologic Modeling System (HEC-HMS), and simulations show that the peak discharge for the 10-year and 100-year return periods ranges from 11.88 cubic meters per second (cms) up to 23.48 cms. Based on the produced flood inundation map using Hydrologic Engineering Center-River Analysis System (HEC-RAS), the maximum flood depths reach up to 2.91 m, and the inundated area covered 0.9419 km² for a storm with a 100-year return period which occurred close to the banks of the river at mid-stream. The findings of this study could help local planners in promoting the use of modern tools, such as computer models, in disaster-risk preparedness toward resilient communities.

Keywords Flood inundation mapping · Hydrologic modeling · Hydraulic modeling · Tullahan river

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1 Introduction

Global warming is the world's most dangerous environmental challenge [1]. Scientists and professionals are interested in extreme events, including heat waves, widespread flooding, and extremely violent storms, because of their potential to create significant harm and repercussions on people, infrastructure, and the environment [2]. As a result of global warming, extreme meteorological events occur more frequently [3]. Rainfall patterns have changed because of global warming, resulting in floods or drought that varies from place to place [4].

Floods are the most common and widespread catastrophic natural disaster, affecting many people worldwide [5]. Flooding is usually brought on by frequent typhoons and heavy rains [6] and it is also the world's most costly type of natural hazard in terms of economic losses and fatalities [7]. Moreover, flood-related damages can be severe and could impact human health, both infectious and noninfectious [8].

The Philippines is at risk of typhoons commonly occurring in the Northwest Pacific because of its geographic location and socio-economic conditions [9]. Each year, approximately 20 typhoons occur in the coastal area, equal to 25% of all identical events throughout the world. Additionally, 856 tropical cyclones entered Philippine waters from 1970 to 2013, and 322 were destructive [10]. Typhoon damage is defined through three interconnected factors including wind speed, floods, extreme rainfall, or storm surge [11]. With the country being more vulnerable to typhoons but also has limited capability for response due to lack of resources, proper planning toward disaster preparedness is essential.

One of the most common and hazardous natural disasters, inflicting significant damage to property and causing many fatalities, is floods. From a continental perspective, Asia experiences the most floods and has the largest flood-affected population [12]. Since the Philippines is in a part of the Pacific Ring of Fire, natural disasters and risks are common events where catastrophic typhoons originated, making them vulnerable to typhoons, floods, earthquakes, storm surges, and tsunamis [13]. Furthermore, it experiences an average of 20 typhoons yearly, with severity ranging from moderate to extreme events [14].

According to [15], the various disasters and extreme events pose different health hazards, such as waterborne and vector-borne disease. Waterborne diseases are typically spread by water ingestion and are closely related to drinking water quality. Diarrheal illnesses, cholera, shigella, typhoid, hepatitis A and E, and poliomyelitis are significant waterborne illnesses [16]. Leptospirosis, another waterborne disease, can be developed by contacting an open wound and contaminated water, such as rat urine [15]. The water caused by heavy rains and flooding is the breeding site of mosquitos carrying vector-borne diseases such as dengue, malaria, chikungunya, and Zika [17]. Moreover, severe flooding causes loss of livelihood, property damage, and fatalities [18]. Since floods pose a threat to public health, the use of tools for its prediction and mitigation is deemed necessary for flood-prone communities around the world.

Hydrological models are essential for studying water resource changes and simulating the water cycle. Real-world observations are used to choose model parameters as part of a calibration process to produce realistic model simulation results [19]. Different software was utilized to produce the best model near to reality, including the Geographic Information System (ArcGIS) and The Hydrologic Modeling System (HEC-HMS). ArcGIS is a software tool used for analyzing maps, geographic data, and spatial analysis [20]. After mapping the study area using the ArcGIS software, it is now possible to proceed with the hydrologic modeling using the HEC-HMS software to produce the discharge and precipitation-runoff processes [21].

According to [22], it has become crucial to estimate the amounts of runoff by knowing the amounts of rainfall to determine the necessary water storage in reservoirs and to predict the possibility of floods. The topography and surface features of the modeled region were considered while using the HEC-HMS program to convert the rainfall data into the direct flow (e.g., length of the reach). The runoff computation in the software also considers routing, loss, and flow transformation. The data were verified, and the HEC-HMS model was constructed, producing files for the basin, the meteorological model, and several HEC-HMS parameters.

When predicting and issuing a flood warning, the river stage and discharge are considered variables. Among the many hydraulic factors, the roughness coefficient (also known as Manning's) is crucial, particularly in hydraulic modeling [23]. The Hydrologic Engineering Center-River Analysis System (HEC-RAS) model was created by the US Army Corps of Engineers and can be utilized to simulate flood development in either one or two dimensions. It offers four primary river study options: the steady flow rate in a river profile, simulation of an unsteady flow of water, calculations of the sediment transport and modifications of the riverbed and water quality analysis [24].

A study [25] used HEC-RAS and ArcGIS for floodplain mappings. This study has a flood model containing hydrologic, hydraulic, flood-plain mapping tools, and geospatial extraction. The digital elevation model (DEM) used data from Interferometric Synthetic Aperture Radar (ISFAR) helped create 2D models for processing the outcome of flood progression since it contains terrain elevation parameters, while the HEC-RAS modeling setup was generated to produce the floodwater level and simulate flood-inundated areas across different return times.

Having mentioned the risk of exposure of the Philippines to typhoon events, flooding as a result of urbanization, and the need for modern tools in the prediction and mitigation of flood events, this paper aimed to exhibit the use of a coupled hydrology and hydraulic model to capture the extent of flooding through inundation maps along a segment of the Tullahan River in Valenzuela Philippines, one of the flood prone areas in the country.

2 Materials and Methods

2.1 The Study Area

The City of Valenzuela, a part of the third district of Metro Manila (i.e. CAMANAVA), often known as the “Gateway to the North,” is one of the progressive places that transformed from being a bucolic town into a bustling city [26]. A highly urbanized, wealthy industrial and residential suburb in a low-lying location surrounded by the Tullahan, Polo, and Meycauyan rivers. Currently, it is known as the 13th most populous city among 144 cities in the Philippines, with an area of 47.02 square kilometers or 18.15 square miles [27]. As recorded by the Philippine Statistics Authority (PSA), the city has a population of 714,978, representing 5.30% total population of the National Capital Region as determined during the 2020 census. Shown in Fig. 1 is the administrative boundary of the Philippines highlighting Valenzuela City, the site of interest of this paper. According to [28], the City of Valenzuela seems to be at risk of natural calamities like flooding, earthquakes, liquefaction, and tsunamis. One of the most common problems the city experiences is flooding due to the average elevation of the city being just 2 m above sea level. Approximately 13.22% of the city is made up of tidal flats with unstable soil and low-lying topography. Moreover, the number of low-income families and informal settlers is still rapidly growing; thus, urban catastrophes like fires and flooding are typical.

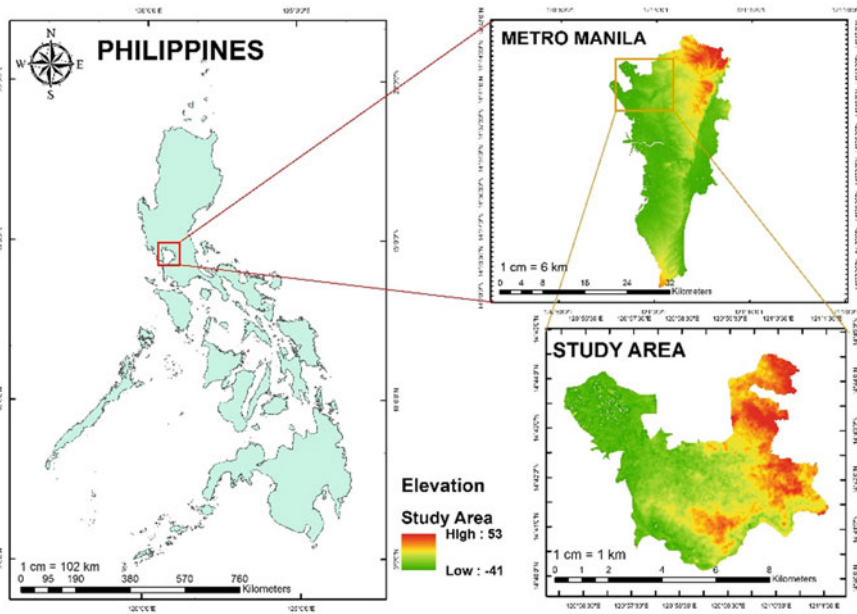


Fig. 1 Valenzuela City, Metro Manila

Table 1 Data sets used for the study

Type	Data	Purpose	Source
Spatial information	Digital topography (DEM)	Delineation of watershed	USGS
	Land use/land cover map	Curve number and manning's roughness determination	ESRI
Meteorologic data	Rainfall	Model input for rainfall-runoff simulation	PAGASA
River data	Discharge	Calibration and validation of hydrology model	DPWH

2.2 Data for Modeling

For this study, a coupled hydrology and hydraulic model were utilized to produce flood inundation maps and capture the flooding extent for a segment of the Tullahan River in Valenzuela City, Philippines. Enumerated in Table 1 are the data that were necessary to meet this objective.

Data gathering was done by requesting secondary data from government agencies and open-source websites while other model inputs were derived from these initial data sets. The digital topography of Valenzuela City was downloaded from EarthExplorer of the United States Geologic Survey (USGS) while the Land Use/Land Cover Map was downloaded from the website of ESRI. In setting up the hydrology model, the daily precipitation as well as the Rainfall Intensity Duration Frequency (RIDF) data was acquired from the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA). To ensure realistic model behavior [19], actual observed discharges that was used for calibration was acquired from the streamflow website of the Department of Public Works and Highways (DPWH).

2.3 Methodology

To achieve the objectives of this study, modeling and simulation was the general method utilized. Depicted in Fig. 2 is the general flow of the study.

The DEM was first delineated using ArcGIS to capture the watershed boundary and generate the watershed properties such as drainage area, curve number, and identify the watershed outlet. The delineated watershed was then used for hydrologic modeling in HEC-HMS to set-up the rainfall-runoff parameters to produce calibrated discharges which will then be used as an input for the hydraulic model. HEC-RAS was used to model the hydraulic behavior of the Tullahan River and produce flood inundation maps of the study area.

Watershed Delineation Using ArcGIS. The watershed containing the segment of the Tullahan river that runs from upstream Marulas up to the downstream in Malinta in Valenzuela City was delineated in ArcGIS. The digital terrain was processed to

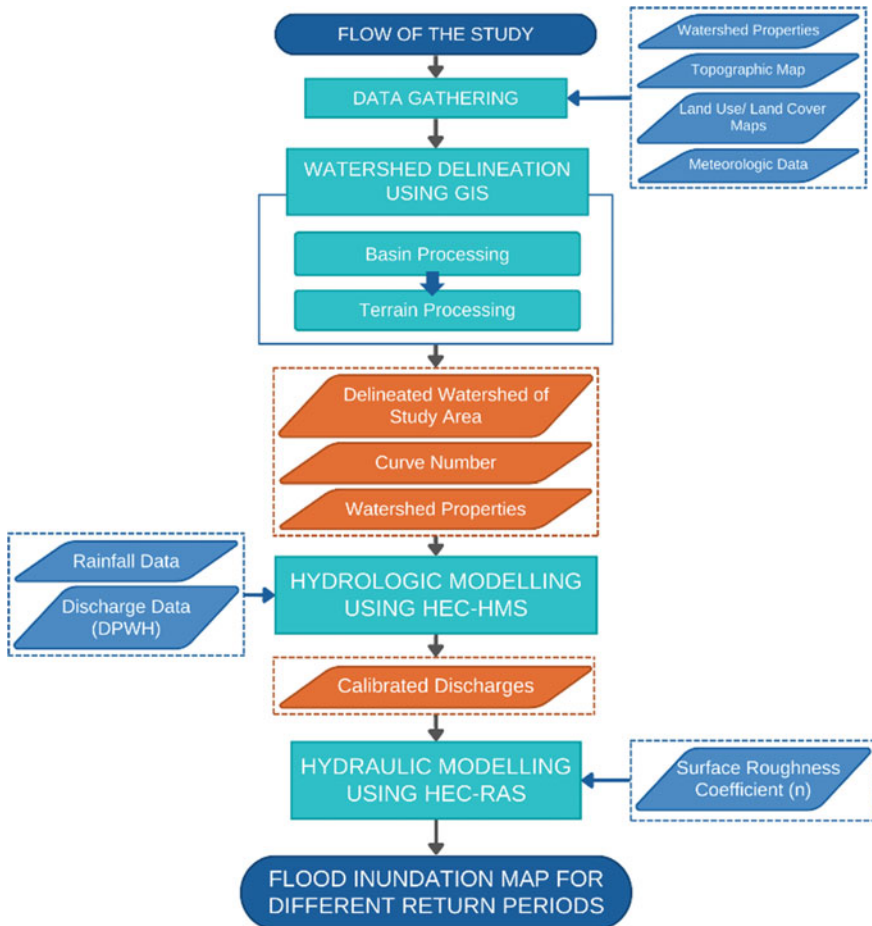


Fig. 2 Flow of study showing the data, models, and processes used

yield the hydrologic elements that will be necessary in representing the behavior of the study area [29].

Hydrology Modeling Using HEC-HMS. Hydraulic Engineering Center—Hydrologic Modeling System (HEC-HMS) is a software developed by the US Army Corps of Engineers for representing the rainfall-runoff process in a watershed [30]. The delineated watershed from ArcGIS was imported to HEC-HMS to assign parameters based on the different hydrologic processes.

Calibration of Hydrology Model. Calibration of the chosen was done to ensure a realistic model behavior [19]. The simulated discharges from the model were compared to observed data from DPWH for the period of October 26 to November 21, 2017. Model acceptability was based on statistical parameter of the Nash–Sutcliffe

Table 2 Model performance based on statistical rating [31]

Performance rating	NSE	PBIAS (%)
Very good	$0.75 < \text{NSE} \leq 1.0$	$\text{PBIAS} \leq \pm 15$
Good	$0.65 < \text{NSE} \leq 0.75$	$\pm 15 \leq \text{PBIAS} \leq \pm 30$
Satisfactory	$0.50 < \text{NSE} \leq 0.65$	$\pm 30 \leq \text{PBIAS} \leq \pm 55$
Unsatisfactory	$\text{NSE} \geq 1.0$	$\text{PBIAS} \geq \pm 30$

Efficiency (NSE) and Percent Bias (PBIAS). Shown in Table 2 is the general performance rating that was used in assessing model acceptability based on the study of [31].

After reaching a satisfactory model behavior, RIDF from PAGASA was used to simulate a frequency storm to produce discharges for a 10, 25, 50, and 100-year return period. These discharges were used as input in the hydraulic model to generate the flood inundation maps for the study area.

Hydraulic Modeling using HEC-RAS. Hydraulic Engineering Center—River Analysis System (HEC-RAS) is another software developed by the US Army Corps of Engineers. It is capable of performing one-dimensional steady flow hydraulics as well as one and two-dimensional unsteady river hydraulics [32]. Flow hydrograph boundary condition was utilized for the upstream, while a normal depth boundary condition was used for downstream. Surface roughness (n) was adjusted based on land cover to get a good representation of the river behavior through calibration of the unsteady flow model [32]. A twenty-four-hour frequency storm (10, 25, 50, and 100-year return periods) was simulated and the resulting inundation areas were plotted on map to see the extent of flooding for the study area as the general objective of this study.

3 Result and Discussion

3.1 Watershed Delineation and Hydrology Model Calibration

A total of 52 subbasins were generated with a total drainage area of 4.182 km². The largest subbasin was found with an area of 203,210 m² while the smallest subbasin was recorded at 2809.3 m². The hydrology model of the study area underwent calibration process to ensure realistic model behavior by fine-tuning watershed parameters that were selected to represent the different hydrologic processes. Simulated discharges from the period of October 26 to November 21, 2017, were compared with observed DPWH discharges and acceptability was based on statistical parameters of NSE and PBIAS. Calibration hydrograph was also produced by HEC-HMS to show the behavior of the simulated discharges as compared to the observed data on field.

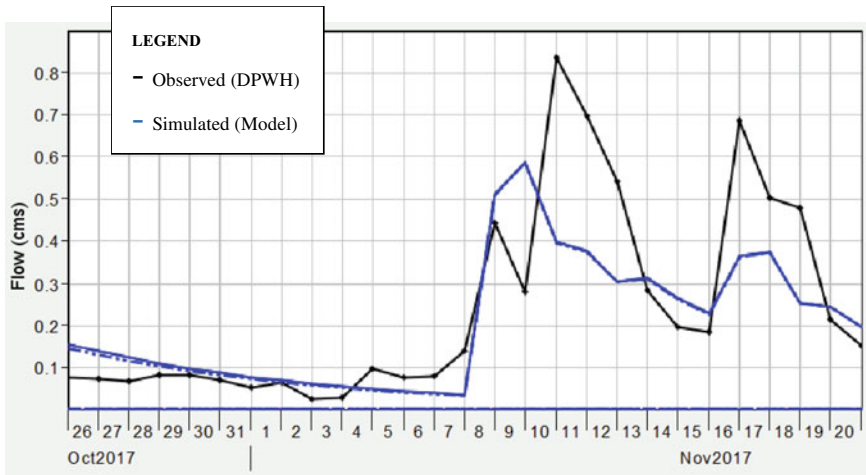


Fig. 3 Outlet hydrograph showing calibrated discharges imported from HEC-HMS

Shown in Fig. 3 is the outlet hydrograph from HEC-HMS for the watershed model after calibration process.

The Nash–Sutcliffe Efficiency is a statistical parameter that measures residual variance to the measured standard variance of data [33] while the goodness of the model that includes uncertainty measurement is described by the Percent Bias (PBIAS). The hydrology model showed an NSE of 0.536 and a PBIAS of -14.44% after the calibration of parameters. From the study of [31], the model exhibits a satisfactory performance based on the NSE and in terms of the PBIAS, it is rated as a good model.

The calibrated hydrology model was now used to simulate frequency storms corresponding to the 10, 25, 50, and 100-year return periods. Depicted in Fig. 4 are the outlet hydrographs for the different return periods that were simulated using a 24-h frequency storm in HEC-HMS. As shown by results of the simulation, peak discharge for the 10-year and 100-year return periods ranges from 11.88 cubic meters per second (cms) up to 23.48 cms. From these results, it is evident that the outlet discharge increases significantly as the rainfall intensity increases. The peak precipitation occurs at 12:10 p.m. and the peak discharge arrives about 4 h later (3:50 p.m. to 4:10 p.m.). The discharges from the frequency storm simulation were then used as boundary condition (input) for the hydraulic model in HEC-RAS.

3.2 Hydraulic Modeling Using HEC-RAS

The objective of this paper is to capture the extent of flooding through inundation maps along a segment of the Tullahan River in Valenzuela Philippines. A hydraulic

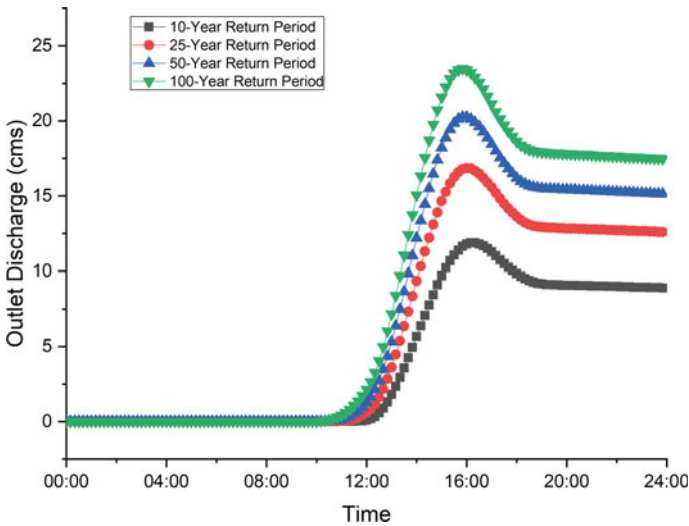


Fig. 4 Outlet hydrograph for watershed model after calibration

model was set-up using HEC-RAS and the calibrated discharge from the hydrology model were used as input for upstream boundary condition while the normal depth was used for downstream boundary condition. A twenty-four-hour frequency storm (10, 25, 50, and 100-year return period) was simulated to produce flood inundation maps. Shown in Fig. 5 are the generated flood inundation maps for the different return periods.

The inundation map depicts the extent of flooding of the study area as well as the flood depths for the corresponding return periods. Maximum flood depth for the 100-year return period was calculated to reach as high as 2.91 m that occurs at the middle of the reach that can be attributed to its topography and the noticeable river bend on that segment of the river. Table 3 summarizes the outputs from HEC-RAS in terms of maximum flood depths and estimated inundated areas corresponding to the return periods used.

Based on the outputs of the hydraulic model, the depth of flood and inundated area increases as the intensity of rainfall increases. An increase of 27.25% in maximum flood depth and 34.56% increase in the total inundated area can be seen when comparing the results for a 50-year and a 100-year return period. Taking note from simulation results of the hydrology model that the time to peak is approximately four hours, these simulation results would be of aid to disaster management offices in their planning for instances of extreme weather events.

Results of this study could further be improved by using a better resolution of digital topography in modeling the hydrology of the area and as suggested by [34], to achieve high-accuracy models for flood hazard maps, it is recommended to use actual values of river discharge as input to the hydraulic model as compared to simulated discharges.

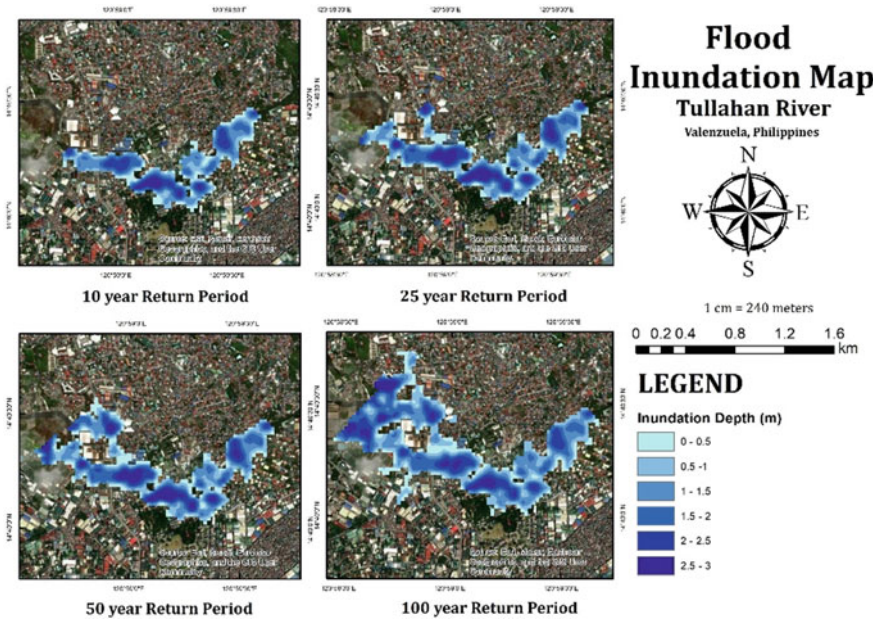


Fig. 5 Flood inundation map output from HEC-RAS

Table 3 Summary of calculated flood depths and flood inundated area

Return period	Max. Flood depth (m)	Estimated inundated area (km ²)
10-year	2.08	0.4492
25-year	2.19	0.5774
50-year	2.29	0.7002
100-year	2.91	0.9419

4 Conclusion

In this study, a coupled hydrologic and hydraulic model was used to produce flood inundation maps to assess the extent of flooding for a segment of the Tullahan River in Valenzuela City, Philippines.

Results from the calibrated hydrology model simulation indicate that the peak discharges range from 11.88 cms reaching up to 23.48 cms during a 100-year return period storm. The time of peak was also estimated to arrive 4 h after the maximum precipitation based from frequency storm generated discharges.

From the produced flood inundation map, it was found that areas close to the riverbanks were more prone to flooding having maximum flood depths of 2.08, 2.19, 2.29, and 2.91 m for the 10, 25, 50, and 100-year return periods, respectively. Flood levels are also found to be greater at the bend of the river midstream as compared to

upstream which can be attributed to the topography but in terms of flood inundated area, the flood water spreads after the bend thus causing a greater area affected downstream.

With flood events worsening over the years due to the changing climate, rapid urban development, and disruption of the natural hydrologic response of watersheds, modern tools such as computer models are now found to be useful in generating decision support information towards community resilience. Findings of this study could help planners and policy makers in disaster-risk response and management of areas that are prone to flooding. Moreover, results generated from this paper could still be improved by using a higher resolution digital topography and validating the hydraulic model by comparing it to observed data of water level from local agencies.

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