

Floodplain Modelling of Malaking-Ilog River in Southern Luzon, Philippines Using LiDAR Digital Elevation Model for the Design of Water-Related Structures

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Abstract. Hydrologic and hydraulic model applications for floodplain analysis are very limited in the Philippines due to the insufficiency of topographic, river geometric and hydrologic data. However, with Light Detection and Ranging (LiDAR) technology, the country is able to overcome this problem resulting to much more accurate mapping and modeling possibilities. With the use of a modern hydrologic modelling software, rainfall runoff model based on LiDAR data was created for Malaking-Ilog River in Batangas-Quezon with precipitation input of five, ten, twenty-five, fifty and a hundred-year return period. In this study, the significance of the hydrologic model and the selection of return period in the design of various water related structures were discussed. Moreover, river analysis software was utilized in a case study for design of a dike. The communities which are politically grouped as “barangays” surrounding the river that are directly affected when the river overflows were identified. With the help of the hydrographs generated from the rainfall runoff model in this study, the design parameters of various water related structures are easily determined leading to a more efficient design process.

1. Introduction

On average, there are about twenty (20) typhoons that hit the Philippines annually. These have consistently resulted in widespread flooding, casualties, and destruction of structures and properties on the typhoon’s path as it traverses the archipelago. In line with this, the Disaster Risk and Exposure Assessment for Mitigation (DREAM) Program was formed to help the country and its people prepare for such natural disaster. DREAM is part of the Nationwide Operational Assessment Hazards (NOAH)



project of the Department of Science and Technology (DOST). The said program involves different universities in the Philippines one of which is the Mapúa Institute of Technology (MIT) with its Mapua -Phil LiDAR 1 Project.

LiDAR uses light detection and ranging equipment to gather elevation data of an area. This remote sensing technology is done through an airborne mechanism which has the ability to gather geographic information of a terrestrial structure through recording of laser pulses which hit the land and reflected back to the sensors. Compared to the conventional photogrammetry and field surveying, gathering topographic information through LiDAR technology is not time consuming and it is accurate enough to provide the required elevation data [1]. The use of the LiDAR technology is now acknowledged by the government sectors in the Philippines. The project aims to produce an up-to-date 3-D flood and hazard maps as well as predict, in a more accurate manner, the extent of flooding in Southern part of Luzon using LiDAR DEM.

Malaking-Ilog River is located in the southern part of Luzon Island particularly in the boundaries of Batangas and Quezon provinces. The river is surrounded by developing municipalities with potentials for both social and economic growth. This development may include construction of water-related structures that can change the course of the river, which can affect an entire area or community. With this in mind, accurate urban planning for the future of the city is critical. Being one of the largest watersheds in southern Luzon, Malaking-Ilog drains an area of about seven hundred and thirty eight (738) square kilometers that includes most of Malepunyo Volcano, two-thirds of San Cristobal Volcano and the southwest quadrant of Banahaw Volcano. This extensive watershed causes flooding and flash floods in the lower reaches of the river. On October 12, 2012 the municipality was put under state of calamity due to flooding caused by overflowing of this river when typhoon Ofel (International name: Son-Tinh) hit the city. According to the mayor, 4,100 families or 20,000 individuals were affected while five died due to landslide and drowning. An estimated 125 million pesos worth of structures were damaged and 140 million pesos worth in agriculture. This problem, could have been prevented or at least controlled if only there were more accurate information regarding the geographical features of the river.

2. Floodplain Modelling

LiDAR-derived digital elevation models (DEMs) are important part of the floodplain modelling procedure. LiDAR data can provide a more accurate topographical information of rivers such as slopes, elevations, and cross-sections which are useful in the design aspect of water resources engineering. The process starts with the data acquisition through air-borne light detection and ranging. The gathered LiDAR data are pre-processed in a special computer software to generate the DEM. The data collected is then validated through conducting actual field surveys. Once validated, the data are processed using hydrologic and hydraulic modeling software of the namely: the Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) and the Hydrologic Engineering Center - River Analysis System (HEC-RAS). These are computer generated program developed by the US Army Corps of Engineers designed for runoff simulation and river analysis [2], [3]. The production of flood models and maps is done through incorporating generated digital elevation models with rainfall data. With the aid of these models, water resources engineers can provide information for

activities such as the development of new hydraulic structures and flood control measures, evaluation of the performance of existing water facilities, and preparation for disasters that may arise due to floods.

3. Methodology

The researchers gathered DEM files of Malaking-Ilog as shown in Fig. 1 which is processed through the aid of Geographical Information System (GIS) and the existing HEC-HMS parameters. The precipitation data for different return periods (5, 10, 25, 50, and 100-Year Return Period) were gathered from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). The researchers created a rainfall-runoff model based on the collected data and this were simulated using the HEC-HMS software. The outputs are graphs and time series which were analyzed to produce applications for water structures.



Figure 1. Digital Elevation Model of Malaking-Ilog.

3.1. Rainfall Data Acquisition

Precipitation data were gathered from PAGASA in the form of Rainfall Intensity Duration Frequency (RIDF) curve from Tayabas Synoptic rainfall station which is the closest station to Malaking-Ilog watershed.

In order to get the amount of rainfall from the given RIDF curve, interpolation and re-arrangement of values were done to produce a synthetic storm as seen in Fig. 2 where peak values are achieved at a particular time. The extreme values shown in Table I were computed based on a 41-year record.

TABLE I. RIDF VALUES FOR TAYABAS STATION GENERATED BY PAGASA

COMPUTED EXTREME VALUES (in mm) OF PRECIPITATION						
T (yrs)	1 hr	2 hrs	3 hrs	6 hrs	12 hrs	24 hrs
2	59.3	83	99.9	128.2	161.5	195.9
5	77.3	116.1	143	192.6	232.3	279.5
10	89.2	138	171.5	235.2	279.3	334.9
15	96	150.3	187.6	259.3	305.7	366.1
20	100.7	159	198.9	276.1	324.3	388
25	104.3	165.7	207.5	289.1	338.5	404.8
50	115.5	186.2	234.3	329.1	382.5	456.7
100	126.6	206.6	260.8	368.8	426.2	508.3

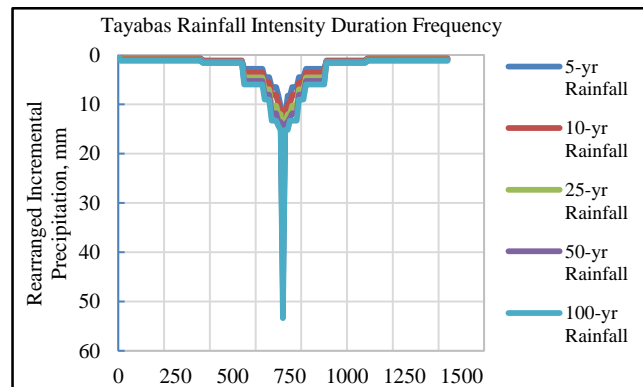


Figure 2. Synthetic storm for a 24-hr period generated at various return periods.

3.2. Data Processing

The researchers utilized HEC-HMS to compute for the discharge hydrograph of each return period. The incremental precipitation is processed in such way that the researchers would be able to identify the discharge hydrograph and the peak discharge on every return period [4].

The basin model shown in Fig. 3 for the Malaking-Ilog includes 68 subbasins, 34 River reach, and 34 junctions. Four important parameters were considered namely, SCS Loss method; Transform - Clark Unit Hydrograph; Baseflow – Recession; and Routing – Muskingum-Cunge. For each return period, there is a corresponding frequency storm. These are stored in the Meteorologic component of the HEC-HMS model with the computed extreme values shown in Table I as inputs After all the inputs were done, the model was simulated to obtain the discharge hydrograph and generate the rainfall-runoff model.

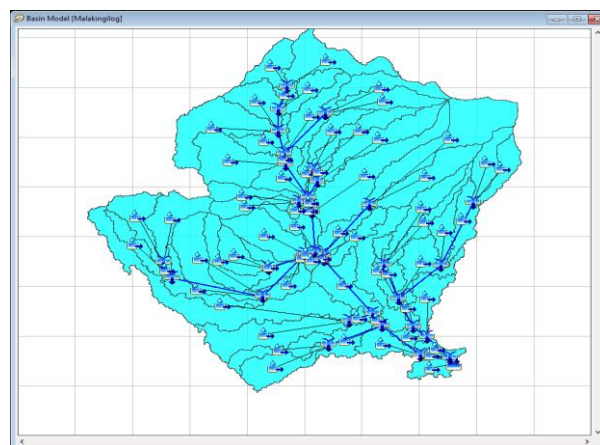


Figure 3. Malaking-Ilog Basin Model in HEC-HMS.

3.3. Model Calibration

The four parameters used in the HEC-HMS model were calibrated by comparing actual discharge to simulated discharge produced by the model. In order to collect actual discharge, flow velocity from a rainfall event is needed. The discharge can be computed by multiplying the river cross sectional area to the accumulated velocity. Furthermore, precipitation data is also needed in the model calibration.

These were taken from the automatic rain gauges installed by DOST which is located on or near the watershed. These precipitation data were rainfall observations that are based on the actual rainfall event or typhoon which occurred during the accumulation of velocity.

With the observed discharge and precipitation already available, HEC-HMS can perform an automatic calibration by optimization trials which can estimate model parameters and other preliminary conditions. After every trial, the computed hydrograph is compared to the observed hydrograph to determine how well the model fits to the observed flow. Fig. 4 shows the observed and simulated discharge hydrographs in the Malaking-Ilog watershed.

The accuracy of the model was then measured in contrast to the actual values. Different methods of comparison were employed. The Root Mean Square Error (RMSE) method sums up the differences of the two values. It was identified at $4.4 \text{ m}^3/\text{s}$. The Pearson correlation coefficient (r^2) measures the linear relationship between the actual and computed value. A value close to 1 indicates that the two values have the best fit. It is identified to be 0.8708. The Nash-Sutcliffe (E) method was used to measure the certainty of the model with also an optimal value of 1. Here it is computed as 0.85. The Observation Standard Deviation Ratio, RSR, is an error index. A value of zero means the two values have a perfect match. The model has an RSR value of 0.39 [5].

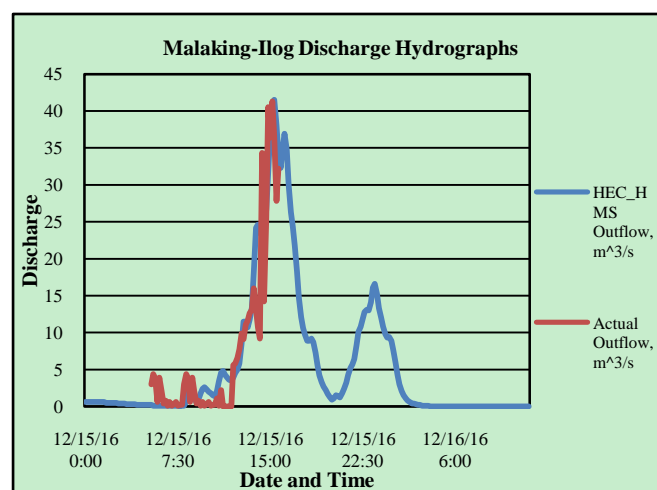


Figure 4. Malaking-Ilog HMS model outflow compared to actual outflow.

4. Results and Discussion

4.1. HEC-HMS Discharge Hydrograph

The HEC-HMS simulation for 5, 10, 25, 50, and 100-year return period reveals the time and value of peak discharge for each hydrologic element in a precipitation event. From this graph, it can be observed how discharge varies over time such that as the rain continues to fall the runoff discharge also continues to rise until it reaches its peak discharge in that case it gradually falls into recession.

During an intense rainfall event, the discharge of the river is high since there is an additional amount of water to the stream flow of the river. Precipitation has a great effect on the discharge of the river. More precipitation means more water will be flowing in the river. Precipitation highly depends on the recurrence interval (return period) of a particular rainfall event [6]. Observing the design hyetograph

in Fig. 5, precipitation increases depending on the return period being considered. The highest rainfall is 53.4 mm which occurred at 100-year return period. Based on the hydrograph, the highest discharge occurred also at 100-year return period with a flow of 11905.3 m³/s implying that return period, precipitation, and discharge has a direct relationship with each other.

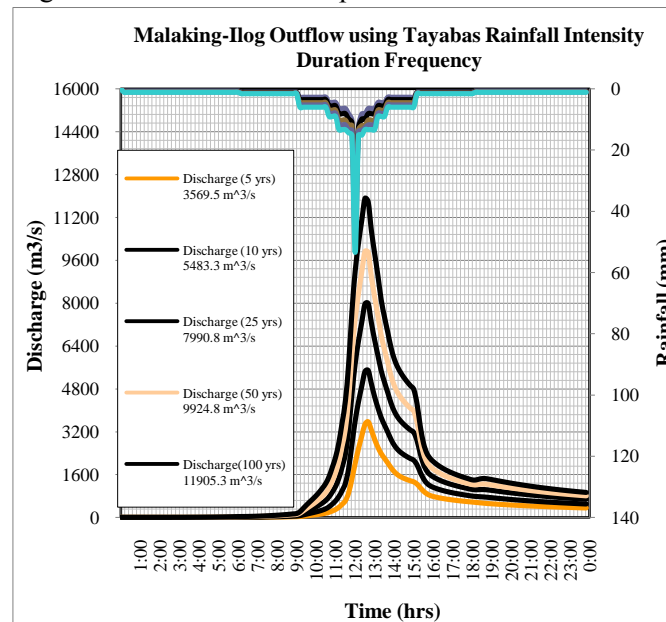


Figure 5. Simulated Discharge Hydrograph with Corresponding Rainfall

4.2. Application of Design Discharge

Considering the following structures, the role of a rainfall runoff model, return period, and accurate LiDAR DEM in the design of water related structures are discussed. Ponce [7] provided some guidelines for the selection of return period. For drainage systems, 25 to 50-year return period is needed wherein peak discharge from hydrograph determines the design capacity and the cross-section of the pipe needed. For dams, 25 to 100-year return period is required. Considering its complex routing process, frequency analysis of variables such as flood peak and volume (discharge) are necessary. As for bridges, necessary data is based on the maximum design discharge corresponding to 100 to 500-year return period. With these data, the substructures of the bridge such as abutment and pier could be designed. Fishways are hydraulic structures usually built on disrupted path of flow of fishes caused by construction other hydraulic structures such as dam or dikes.

Other water related structures, like revetment and bulkhead, also requires the discharge value in order to be designed. Revetments and bulkheads are structures capable of protecting riverbanks from eroding and sliding. It can be constructed in areas where some parts of the riverbank can be drag away due to high discharge rate. Although, revetment and bulkheads are not mainly designed to prevent flooding but rather control the discharge and prevent it from breaking the banks. As for design, hydraulic parameters like local-depth average velocity, velocity near the bed, waves, level of turbulence in the flow, and various water levels, are necessary to determine the stable sizes of both structures. The values that will be adopted for each of the hydraulic parameters mentioned above will depend on the return period for which the structures will be designed [8].

In the design of a dike, one has to consider the maximum water surface level in critical cross-sections of the river. If the maximum water surface level (design flood level) surpasses the elevation of the riverbanks, the river overflows and construction of dike must be initiated. The height of the dike is based on the design flood level which can be calculated using available flow hydrographs. In determining the design hydrographs on medium risk dikes, 50 to 100-year return period can be considered. In line with the main objective of this paper, the researchers present an application of the rainfall runoff model by designing a dike which can be constructed along the banks of a river for the purpose of protecting the landslide from overflowing floodwater by confining the stream flow in the regular channel.

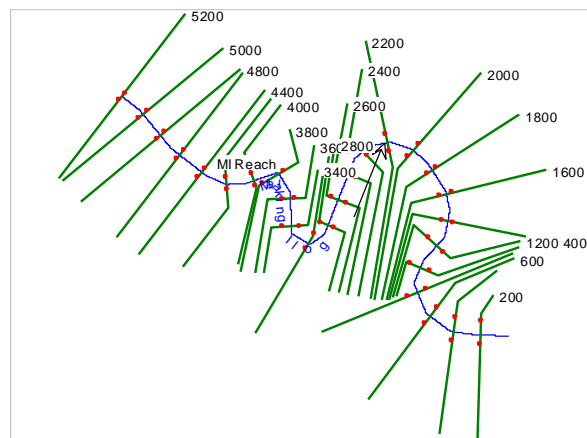


Figure 6. Stationing of Malaking Ilog

In HEC-RAS, cross-sections for 26 river stations were created as shown in Fig. 6. Unsteady flow simulation was performed. Boundary conditions for the upstream were selected as the flow hydrograph of Station 5+200. For the downstream, normal depth as boundary condition was chosen which was measured to be 0.0003. The flow hydrograph considered for a medium risk dike is of 100-year return period. Taking that as an input to HEC-RAS, the design discharge for every station and the elevation of the maximum water surface that the river can reach are determined. Whereas, the design flood level is calculated by subtracting the elevation of the edge of the river from the water surface elevation. Consequently, it is identified that 25 out of 26 stations are susceptible to overflow.

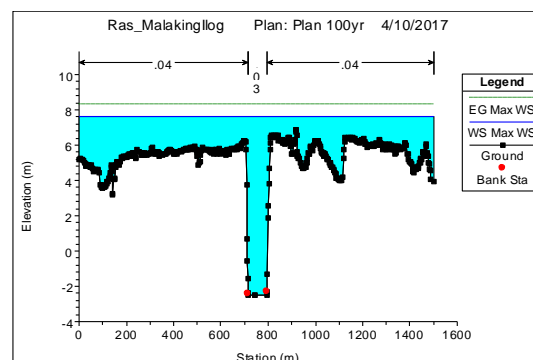


Figure 7. Cross-sectional area of Station 5+000 based on 100-Year Return Period.

The cross-section of each station within the river can also be viewed upon simulation of HEC-RAS. The stations where water overflows start from Station 5+000 to the downstream which is at Station 0+200. Fig. 7 shows the water surface level at Station 5+000 based on 100-year return period.

The general dike design considerations are specified in Table II. The freeboard and crest width are computed based on the acquired value of discharge, Q . For discharge $2,000 \text{ m}^3/\text{s}$ up to $5,000 \text{ m}^3/\text{s}$, the freeboard height is 1.2 meters while crest width is 5 meters. For $5,000 \text{ m}^3/\text{s}$ up to $10,000 \text{ m}^3/\text{s}$, the freeboard height is 1.5 meters while crest width is 6 meters. For $10,000 \text{ m}^3/\text{s}$ and over the freeboard height is 2 meters while crest width is 7 meters. As for the slope, since the distance from the crest to the river bed is more than 6 meters, the slope is 3:1 [9].

TABLE II. DIKE DESIGN CONSIDERATIONS OF CRITICAL AREAS

River Sta	Discharge Total (m^3/s)	Design Flood Level (m)	Free-board (m)	Dike Design Height (m)	Crest Width (m)	Slope (H: V)
5+000	8066.85	1.41	1.5	2.91	6	3:1
4+800	11746.97	2.02	2	4.02	7	3:1
4+600	11692.55	2.47	2	4.47	7	3:1
4+400	11630.32	2.29	2	4.29	7	3:1
4+200	11563.59	2.41	2	4.41	7	3:1
4+000	11499.72	2.91	2	4.91	7	3:1
3+800	11447.66	3.04	2	5.04	7	3:1
3+600	10778.64	2.62	2	4.62	7	3:1

5. Conclusion

The latest technology from Mapúa-DOST-Phil LiDAR1 allowed the researchers to define highly accurate topographical parameters of Malaking-Ilog for a rainfall runoff model considering 5, 10, 25, 50, and 100 year return period. This model easily computes discharge for various return periods and may be utilized to develop a floodplain analysis to design flood control structures such as dikes, embankments, dikes, drainage systems etc. The results can also provide information for the design of other hydraulic structures such as weirs and dams.

Based on the results, the researchers came up with the following findings: Malaking Ilog experiences an overflow when strong typhoons hit the province of Batangas. In an ocular visit to the study area, the researchers confirmed these theoretical outputs by conducting an interview with the residents living beside the river. According to them, due to strong typhoons in the past the river tends to overflow resulting to floods in the area.

So far, with the coupled simulation of the hydrologic and hydraulic modeling programs, the water level in Malaking-Ilog overflows especially to the areas where people reside. Residences were observed just beside the river and when the river overflows, the lives of the residents are in danger. From this the researchers conclude that flood control facilities/measures must be instigated in order to reduce the risks. With the help of the hydrographs from the rainfall runoff model in this study, the design parameters of various water related structures could easily be determined.

This study can serve as a reference for water resources engineers and designers who decide to pursue construction of flood control facilities. With the knowledge on return periods considered for individual water structures, engineers could utilize the rainfall-runoff model developed by the researchers to determine the design discharge. Furthermore, the use of river analysis software, HEC-RAS, is recommended in this study for identifying the areas that needs flood control measures and facilities.

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