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Research paper

One-Dimensional (1D) River Analysis of a River Basin in Southern Luzon Island in the Philippines Using Lidar Digital Elevation Model

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Abstract

Flooding is a perennial problem in the Philippines during the monsoon season intensified by the effects of typhoon. On average, there are 20 typhoons that enter the Philippine Area of Responsibility (PAR), and many of these make landfall causing catastrophic aftermath. Extreme rainfall events could lead to flooding in the downstream floodplain and landslide in mountainous terrains. In this study, which is for the case of Calumpang River that drains to the populated and developing region of Batangas City, the focus is on flooding in the floodplain areas. The river was modelled using LiDAR digital elevation model (DEM) that has an accuracy of 20cm in the vertical and 50cm in the horizontal. The result of this is river hydraulic model that can be used to accurately generate flood inundation simulations and flood hazard maps.

Keywords: *watershed, hydrology, river hydraulics, flood map, LiDAR*

1. Introduction

Flooding is a major perennial problem in the Philippines during the monsoon season intensified by low-pressure areas (LPA) that develop to tropical storms and typhoons. The archipelago is considered to be in the "Typhoon Alley" of the western Pacific with an average of 20 tropical cyclones, mostly coming from the Pacific passing through the Philippine Area of Responsibility (PAR) each year. For instance, the strongest typhoon to ever made landfall, Typhoon Yolanda in 2013 in the Visayas Region with sustained wind speed of 315 kph and gusts as strong as 380 kph, left more than six (6) thousand people dead. In 2014, the country was hit by another strong typhoon - Typhoon Glenda (International name: Typhoon Rammasun) that directly hit the area of Batangas City. In the final report of the National Disaster Risk Reduction and Management Council, the typhoon attained 150 kph sustained winds and 185 kph gustiness within the PAR. The aftermath resulted to casualties numbering to 106 dead, 1250 injured, and 5 missing. On the other hand, damages in infrastructure and agriculture amount to PhP38.6 billion. The effects of flooding are mostly worse experienced in the low-lying downstream portion of the river where the flood waters occupy the floodplain mostly populated by communities and even with different sorts of developments in urbanizing areas. In the Philippines, there was no comprehensive study of watersheds that provides model of these to simulate river flow use in real-time flood warning and forecasting for all important river basins.

The national government of the Philippines through its Department of Science and Technology (DOST) has one of its responsibilities - disaster prevention and mitigation using science-based weather information and climate change scenarios with associated impact assessment that shall enable agencies to develop appropriate mitigation strategies for a disaster and climate resilient Philippines. This translates to the use of timely warnings and information on weather and climate change scenarios using state of the art technologies, best practices, and tools for the government agencies and the public. Nationwide LiDAR program was launch to cover all the floodplain areas in the country that is composed of 18 major and 247 principal river basins.

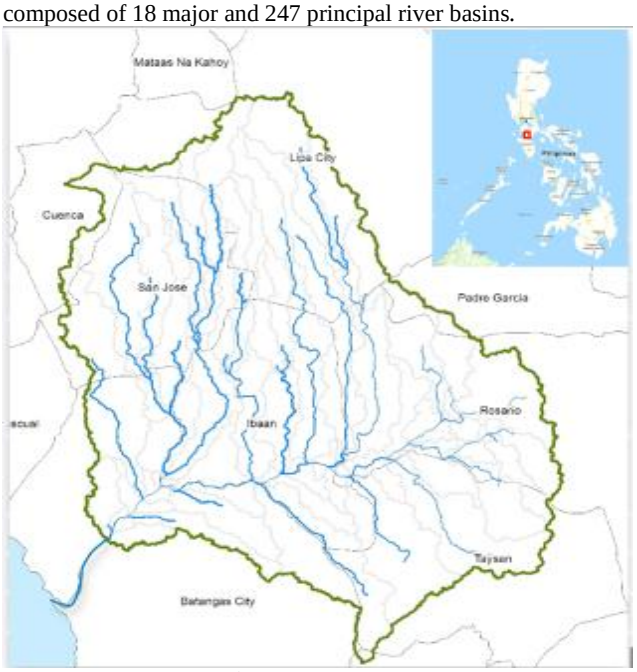

Figure 1. The study area of the Mapua-Phil LiDAR 1 DOST Project

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One of these river basins is the Calumpang River with catchment area of approximately 472 km^2 (182.2 mi^2) in the province of Batangas in the south of Luzon Island. It traverses the industrialized urban area of Batangas City. It also serves as the catchment basin for the municipalities of Ibaan, San Jose, Taysan, and Rosario and a portion of Lipa City. It drains into Batangas Bay, and its mouth is located in Batangas City as shown in Fig. 1.

Modeling of the Calumpang River employed GIS to develop its watershed model using Interferometric Synthetic Aperture Radar (IFSAR) data with a vertical accuracy typically between 15 cm to 3 meters. The resolution used in this study is 5m by 5m which is enough for hydrological modelling. The watershed model developed in GIS was used in the development of the hydrological model which in turn is used as input to the river hydraulic model. The river hydraulic model was developed using Light Detection and Ranging or LiDAR DEM [1] that has accuracy of 20cm in the vertical and 50cm in the horizontal, making it the most detailed DEM currently available in the Philippines. Accurate DEM such as LiDAR is important for water depth mapping in the context of flood risk management [2].

Simulation in 1D of the river flow is done using a free software by the US Army Corps of Engineers' Hydrologic Engineering Center (HEC) river hydraulics called HEC-RAS (River Analysis System) and for hydrologic modelling, the HEC-HMS (Hydrologic Modeling System). Preparation of the DEMs and the watershed model development for use in HEC-HMS is performed in ArcGIS.

2. Watershed Model Development

The watershed model of Calumpang River was developed using GIS software. For this study, Arc-GIS version 10.1 of ESRI was used. This was also where the digital elevation model or DEM used was processed. Data needed in watershed development include: IFSAR DEM, river centreline, discharge point/s shapefiles, soil land use grid, CN grid. To process the watershed development for preparation for hydrological modelling in HEC-HMS, the HEC-GeoHMS Extension must be installed in ArcGIS. This extension is displayed in a toolbar that includes tools for Preprocessing, Project Setup, Basin Processing, Characteristics, Parameters, HMS, and other commands that will help develop the watershed model for hydrologic modelling in HEC-HMS.

The river centreline was digitized as seen on the DEM or from Google Earth starting from the project point going upstream. The project point is the location where simulated flow information is desired. The project point also called the discharge point that is set as point shapefiles is also where the actual observed flow for calibration are to be taken manually or with the aid of Automated Water Level Sensor (AWLS).

The processes in the tools are designed in an step-by-step manner. In the terrain Preprocessing, DEM reconditioning was performed using the data on river centreline to modify the terrain data by lowering the grid cells along the river line feature. To ensure that subbasin delineations from the terrain data are the same as the existing data sets, Build Walls option was performed. Depressions or pits in the DEM were eliminated using the Fill Sinks command to avoid possible clogging in the flow during simulation. The flow direction command, on the other hand, defined the direction of the steepest descent for each terrain cell to help determine flow direction while the Flow Accumulation command determined the number of upstream cells draining to a given cell. The output of Flow Accumulation was used in the Stream Definition command to define the stream network based on defined threshold. For Calumpang river basin, it was set as 5 sqkm. Stream Segmentation command divided the stream grid into segments from which the subbasins were delineated for each of the segments using the Catchment Grid Delineation command. After the subbasins were delineated, Catchment Polygon Processing command was performed to create a vector layer of the subbasins. Vector Stream Layer, on the other hand, was created using the Drainage Line Processing command and aggregated at every confluence in the Adjoint Catchment Processing command.

Project Setup for HMS started by defining a new project by a point and automatically created the HMS watershed boundary of interest by the Generate Project command. Subbasins are further divided into smaller subbasins in the Basin Processing tab. The Characteristics tab computed for the stream and subabasin river lengths, river slope of each reach, basin slope, longest flow paths, basin centroid, centroid elevation, and centroid flow path.

Parameters for each subbasin were estimated in the Parameters tab that gave us a selection of different methods for the different hydrological processes. For the loss method, SCS was chosen; for the transform method, Clark; for the baseflow method, recession; and for the route method,Muskingum-Cunge; Subbasin parameters such as the curve numbers were generated from raster of soil land use shapefiles and CN look up table. The Utility tab generated the CN raster grid which is added to the subbasin parameters in the Parameters tab's. Selecting the subbasin and opening its attribute table would reveal the filled up CN column. For the Muskingum-Cunge and kinematic wave parameters, the initial value of Manning's was 0.04. A separate toolbox was made available for the project to compute for the time of concentration (T_c) and the storage coefficient (S_c). The values generated were also shown in the attributes table columns.

In the HMS tab, the watershed model is converted to HMS ready files by selecting Maps to HMS units. Upon selecting the HMS Schematic of the area being studied, toggle Legend that includes HMS Legend, Regular Legend, Add Coordinates, Prepare Data for Model Export, Background Shape File, and Basin Model File. These sets of files would be readily available for use in HEC-HMS [3,4].

3. Hydrologic Model Development

After preparing the HMS input files such as the shapefiles in GIS, new HMS Project file was created in HEC-HMS. Files such as Basin Model was incorporated in the HMS environment. Meteorological model was created for the precipitation input. In this case, specified hyetograph was chosen. Control specification was created for the simulation and optimization runs. Time duration was at a considerable time before the flood discharge increases until enough time after the flood receded. It was set at 10-minute interval to match with the rainfall data and with the observed flow interval. Time-series data were created for the precipitation and discharge gauges.

Estimation of the Soil Conservation Services (SCS) Curve Number (CN) parameter were generated from the GIS procedure in the watershed model development based on the landcover and soil type shapefiles and the SCS CN Table. Dimensionless curve number ranges from 0 to 100. For impervious surface and water surfaces, CN = 100 and for natural surfaces CN is less than 100. Loss by initial abstraction (I_a) was estimated as [11]:

$$I_a = 0.2*S \quad (1)$$

where,

$$S = (25400/CN)-254 \quad (2)$$

Clark Unit Hydrograph's time of concentration was computed using Kirpich Method for grassy earth (mountain) in case not automatically computed in GIS:

$$T_c = 0.00032L^{0.77}/S^{0.385} \quad (3)$$

where,

L = the length of the river basin; S = slope of the basin computed with the Longest Flow Path Layer.

Baseflow recession used ratio to peak of 0.5, initial discharge computed as the ratio of thew product of area of the specific subbasin and outflow at the outlet to the total watershed area. Recession constant used was 1.0. For the routing, Muskingum-Cunge parameters used include 30m for the width, 45 degrees for the side-slope, and 004 for the Manning's.

Calibration was done by creating a simulation run, then an optimization trial was created. In the optimization trial, a parameter to be optimized added. Each sub basin was chosen together with the specific parameter to be optimized. The optimization search was by Univariate Gradient at tolerance of 0.01 with maximum iteration of 50.The resulting optimized run was plotted vis-à-vis the observed flow. The process was repeated for all the other parameters until both simulated and observed flow graphs match as shown in Fig. 2.

Performance rating of the calibrated model was computed using the Nash-Sutcliffe (E), Percent Bias (PBIAS), and RMSE-Observation Standard Deviation Ratio (RSR) methods and values should be at least good for the calibration to be acceptable [3,4],

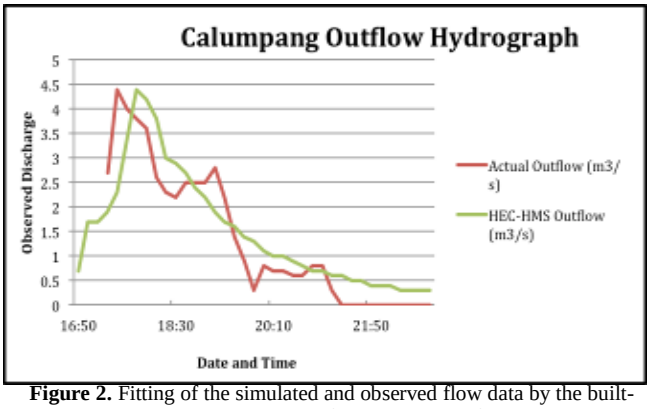

Figure 2. Fitting of the simulated and observed flow data by the built-in optimization tool in HEC-HMS for the creation of calibrated hydrological model of Calumpang River

4. River Flood Plain Model Development

The river flood plain was modelled using HEC-RAS with the aid of HEC-GeoRAS in GIS and Google Earth. Data needed were the LiDAR DEM of Calumpang River flood plain, discharge data at the project point, and shapefiles to define the river. In Google Earth, Calumpang River's centreline, left and right banks, and left and right flow paths were digitized and saved as KMZ file which were then converted to shape files with specified output coordinate system.

In ArcMap (ArcGIS), LiDAR DEM was loaded along with the shapefiles of the centreline, left and right banks, and left and right flow paths. In the RAS Geometry tab of the HEC-GeoRAS toolbar, RAS layers were created from the shapefiles. In GeoRAS, the cross-sections were constructed using the Construct XS Cut Lines button in which the interval used was 200m and the width was set to 2000m. In RAS Geometry, the above were exported as RAS data

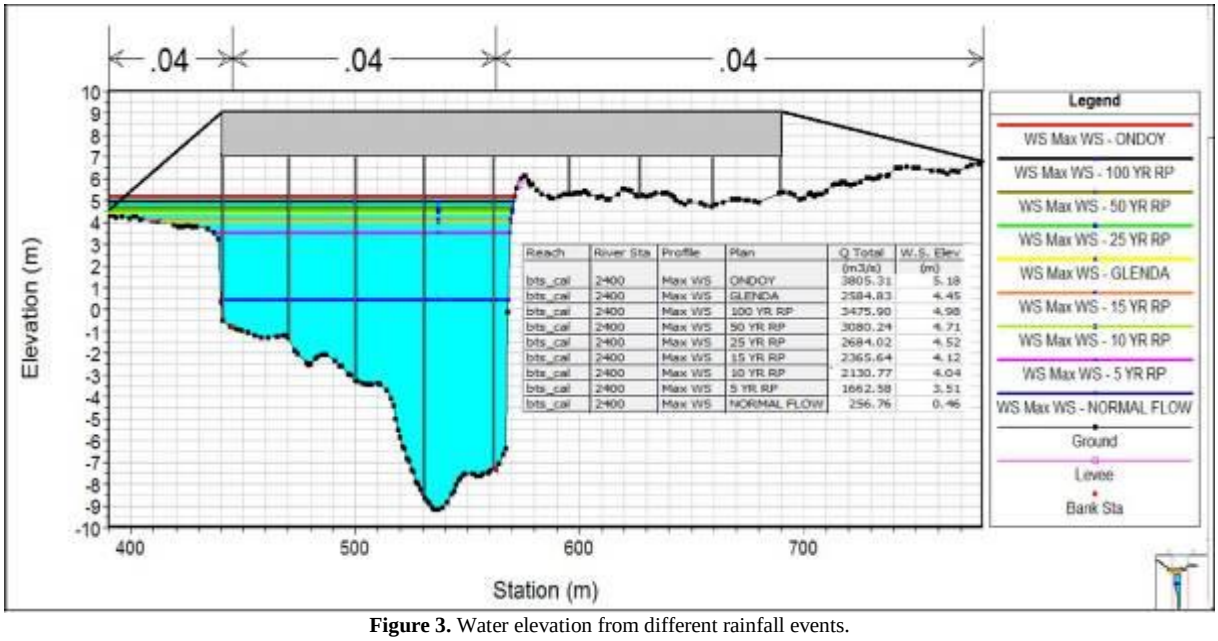

Figure 3. Water elevation from different rainfall events.

In the HEC-RAS environment, in the Geometric Data window, the data were imported in GIS Format creating the geometry schematic Calumpang River. Flow Data was inputted from the output of the calibrated HEC-HMS run at the project point. Unsteady flow analysis showed the result of flood elevation in each cross-section and the flood inundation plotted in 3D. Further visualization was aided by plotting the flood inundation in RAS Mapper [5,6].

Unsteady flow routing in HEC-RAS is based on the principle of conservation of mass and the principle of conservation of momentum. These are expressed as partial differential equations called the continuity equation and the momentum equations with the assumptions of uniform velocity, small channel bottom slope and hydrostatic pressure [10]. For practical purposes, the spatial variation in velocity across the channel with respect to the depth can be ignored, resulting to a one-dimensional unsteady open channel flow known as the Saint Venant Equations [11].

The continuity equations [5] for the channel and the floodplain are written as:

$$\delta Qc/\delta xc + \delta Ac/\delta t = qf \quad (4)$$

$$\delta Qf/\delta xf + \delta Af/\delta t + \delta S/\delta t = qc + ql \quad (5)$$

where the subscript c and f refer to the channel and floodplain, respectively. S refers to the storage at non-conveying portions of the cross-section, q_l is the lateral inflow per unit distance, A is the cross-section area, Q is the flow, t is time, and x is the distance along the channel. This is approximated by implicit finite differences.

The momentum equations [5] for the channel and the floodplain are written as:

$$\delta Qc/\delta t + \delta(Vc\ Qc)/\delta xc + gAc(\delta z/\delta xc + Sfc) = Mf \quad (6)$$

$$\delta Qf/\delta t + \delta(Vf\ Qf)/\delta xf + gAf(\delta z/\delta xf + Sff) = Mc \quad (7)$$

where M_c and M_f are momentum fluxes per unit distance exchange between the channel and floodplain, respectively.

5. Results and Discussions

Results of the river hydraulic run demonstrated how the effect of different rainfall input data were clearly represented as water elevation at a given cross-section as shown in Fig. 3.

A cross-section of interest is at the Calumpang Bridge where the depth of the flow is very significant for the stability of the structure. It showed the normal flow, which is basically contributed by base flow. The model showed that at different river discharges, at a certain location, the model could show relative incremental change in water elevation shown in Fig. 3. The model displays simultaneously the water levels at normal condition (baseflow), at 5, 10, 15, 25, 50, and 100-year return period, during the Tropical Storm Ondoy that dumped a month's equivalent of rainfall, and at a certain extreme destructive rainfall event that occurred during the Typhoon Glenda (International name: Rammasun) that made the bridge collapse. The water level did not reach the deck of the bridge but it collapsed potentially initiated by scouring at the bottom of the piers [12].

With this model, if precipitation data could be made available in real-time, flood inundation extent could be determined, and if forecast would be available, a forecast of the flooding extent could also be predicted. This 1D simulation is advantageous if computational speed is required at a timely fashion [8] such as for flood warnings generated as shown in Fig. 4.

Figure 4. Flood inundation map at flowrate equivalent to100- year return period.

In [13], they showed that 1D provides quite low computational cost and 2D is time consuming especially when dealing with fine grid size resulting to high number of cells. However, 1D will be very difficult when flow exchange between the channel and the floodplain cannot be neglected.

For mapping purposes, two-dimensional (2D) models for the Phil LiDAR 1 research project were also developed. These models are able to capture the flooding in the entire floodpalin without difficulty, nevertheless, at a greater amount of time especially when using LiDAR data.

6. Conclusions and Recommendations

This paper discussed about the use of available software such as ArcGIS, HEC-HMS, and HEC-RAS that were used to come up with flood models of Calumpang River for real-time and forecasted flood information that benefits flood prone areas commonly experiencing extreme flooding during the monsoon season amplified by the presence of typhoons. The process was utilized nationwide in almost 300 river basins using LiDAR data to accurately map the flood hazard extent.

The 1D model easily provides real-time flood levels given the availability of $_{\text{Automated}}$ Water level Sensor (AWLS) and automated or telemetered Rain Gauges; and forecasted flood levels when adequate rainfall forecast information are available. The 2D model, on the other hand, provides comprehensive flood hazard maps. These models and the maps produced help the local government units and even the public themselves, to be able to do the necessary actions for disaster risk reduction and management to protect their properties and help save lives.

Continuous updating of the models – the river hydraulic model as well as the LiDAR digital elevation model – is necessary in the future to update the changes brought about by development especially for developing regions such as Batangas City where the Calumpang Watershed traverses. Highly dynamic rivers such as this must also have their bathymetry updated regularly for a more accurate model representation. Two-dimensional flood model should be explored for real-time and forecasted flood levels as this

better predicts out-of-bank flow patterns and overbank depositional patterns [9].

Acknowledgments

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