JOURNAL OF APPLIED GEOSPATIAL INFORMATION

Vol 4 No 1 2020

http://jurnal.polibatam.ac.id/index.php/JAGI
ISSN Online: 2579-3608

Flood Inundation Modeling Using Geomorphic Approaches, UAV, and GIS

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Received: May 10, 2020
Accepted: June 15, 2020
Published: June 18, 2020

Abstract

Flood is one of the most frequently occurring natural disasters in Indonesia. At the end of 2017, Tropical Cyclones Cempaka and Dahlia formed over the Indian Ocean, inducing extreme rains and floods in some parts of Java Island. The Special Region of Yogyakarta was among the most affected areas, especially along the Oyo River section in Imogiri District. This research was designed to identify and map the flood-prone areas in the district as part of flood mitigation measures. For this purpose, The Unmanned Aerial Vehicle (UAV) technology was used to not only provide a detailed and up-to-date description but also produce aerial photographs (orthoimages) and Digital Elevation Model (DEM). These two products were inputted to the inundation modeling developed with a geomorphic approach and simulated in a Geographic Information System (GIS). In terms of accuracy, the resulting models were quite reliable for mapping on a detailed scale and only slightly deviated from the traced inundation in the field. Also, five areas (sub-village) were found with the highest vulnerability to floods, namely, Trukan, Butuh, Dogongan, Siluk Satu, and Kedung Miri.

Keywords: flood, tropical cyclone, geomorphic, UAV, GIS

1. Introduction

In Indonesia, floods take the second-largest share in disaster events after tornadoes. From 2015 to 2019, the National Disaster Management Agency (BNPB) recorded 3,388 floods throughout the country or averagely 678 events per year. With a total of 978 flood events, 2017 is marked as the most intense year.

The high number of flood occurrences was attributable to Tropical Cyclones Cempaka and Dahlia at the end of 2017 that adversely impacted the southern part of Indonesia, especially the Java and Madura Islands (Fatkhuroyan, 2019). These tropical cyclones moved from the south to the east coast of Java then reached maturity in intensity in three days, i.e., on November 27, 2017 (Samrin et al., 2019). Furthermore, (Muhammad Najib Habibie, Sri Noviati, 2018) found that both events produced extremely heavy rainfall of up to 250-370 mm/day. During which, the rainfall in Gunungkidul, a regency in the Special Region of Yogyakarta (SRY), rose significantly by 750% to a maximum of 225 mm/day (Mulyana et al., 2018). This condition is categorically extreme because the average regional rainfall is only 10-30 mm/day.

Tropical Cyclones Cempaka and Dahlia devastated the entire Special Region, with the number of the affected population amounting to 5,046 people (BPBD DIY, in Tempo 2017). The Center for Disaster Management Operations Control (PUSDALOPS-PB) listed Bantul as the regency with the most damages, including 115 houses and 99 units of infrastructure in 35 villages/sub-districts. Seventy-six units or more than half of the damaged houses were in Imogiri District, especially Selopamioro and Sriharjo Villages.

Geomorphologically, both villages are situated in the flood plain of the Oyo River. Oyo is one of the major rivers in the SRY that has a cross-territorial watershed spanning three regencies, namely Wonogiri (Jawa Tengah Province) and Gunungkidul and Bantul (SRY). During Tropical Cyclones Cempaka and Dahlia, it overflowed its channel. Wicaksono and Khasanah (2019) state that the resulting inundation created a distribution pattern with the Oyo River at the center and areas at the radius of 200 m from it flooded by 0.9-2.25m water.

The mapping of flood-prone areas is the main instrument used in carrying out disaster mitigation measures. Among the most popular techniques are Remote Sensing (RS) technology and Geographic Information Systems (GIS). (Jung et al., 2014) and (Araújo et al., 2019) make use of Landsat imagery, Shuttle Radar Topography Mission (SRTM) images, Global Satellite Navigation System (GNSS) measurements, and discharge data to detect and create flood inundation simulations on a semi-detailed mapping scale. Meanwhile, for more detailed studies (e.g.,(Jaud et al., 2016), (Langhammer et al., 2017), (Mourato et al., 2017), and (Aji et al., 2018)), aircraft like Unmanned Aerial Vehicle (UAV) is used to obtain spatial data with high resolution in the form of aerial photographs (orthoimages) and Digital Elevation Model (DEM).

Based on the approach, flood modeling using RS and GIS can be differentiated into participatory, meteorological, hydraulic, and geomorphic. Participatory-based modeling utilizes knowledge provided by the communities in the affected areas and then spatially reconstructs it using GIS (Wicaksono and Khasanah, 2019), while the meteorological model emphasizes the influence of weather or climate variables on flooding (Aji et al., 2018). Hydraulic-based modeling is commonly used for engineering purposes that require high accuracy and at least four types of data, namely, cross-section profiles of waterways (rivers), discharge, daily rainfall, and land cover. As for modeling with the geomorphic approach, it relies on the environmental conditions of a landscape. (Manfreda et al., 2014) and (Samela et al., 2018) suggest that at least DEM and land cover data are needed to simulate flood-prone areas.

This research was conducted to create a simulation of large-scale (detailed) flood inundations using a geomorphic approach, UAV, and GIS as part of flood mitigation measures in Imogiri District, specifically Selopamioro and Sriharjo Villages.

2. Methods

Data Requirements

This research used five types of data acquired through field activities and sourced from Small-Format Aerial Photo (SFAP) data analysis. The required data are presented in detail in Table 2.1.

Table 2.1. Data Requirements

No.	Types of Data	Sources
1	Aerial Orthophoto	SFAP Processing*
2	Digital Elevation Model (DEM)	SFAP Processing*
3	GCP-ICP	Data acquisition with RTK geodetic GPS
4	Building Blocks Data	SFAP Analysis
5	Flood events data	Interviews with the community

Note : *) taken in August 2018 and July 2019

Research Area

The research was focused on some parts of Selopamioro and Sriharjo Villages in the Imogiri District, Bantul Regency. It covered the area lying in the flood plain (landform) and traversed by the Oyo River (Figure 2.1).

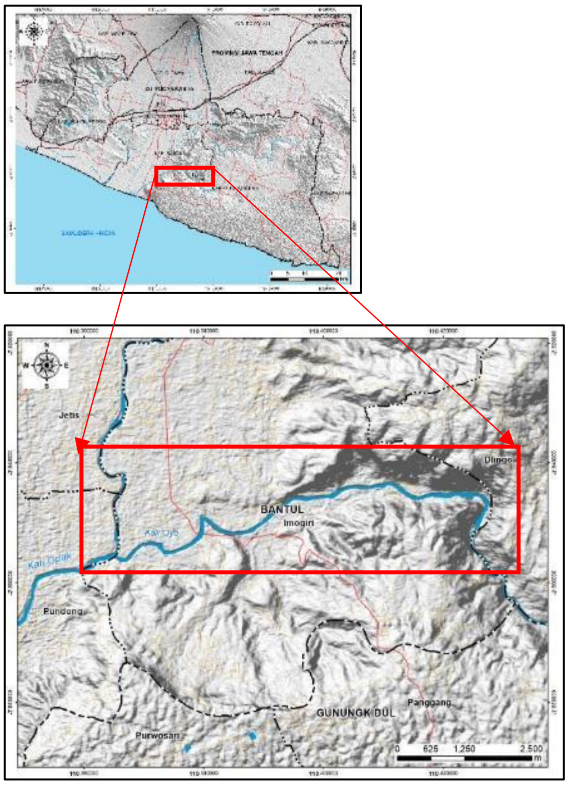

Figure 2.1 The Research Location

Small-Format Aerial Photo Acquisition

Small Format Aerial Photograph (SFAP) was acquired with a multi-rotor UAV, DJI Phantom 4 Standard, as the main instrument. Aerial orthophoto and DEM data were produced by a systematic acquisition and photogrammetric processing. The processes consisted of five stages, namely, the selection of Area of Interest (AOI), flight planning, the determination of Ground Control Points (GCP), and Independent Control Points (ICP), GCP-ICP measurements using Geodetic GPS, and SFAP processing. SFAP was processed in the Agysoft Metashape program to produce aerial photographs (ortho) and DEM.

SFAP data were acquired using a multi-rotor UAV with a 12MP camera and a 20mm focal length. The total area of the study was 726 ha, and the acquisition process required 12 flight missions with an altitude of 200-250m from ground level, sidelap-endlap set at 60% and 70%, and vehicle speed in standard mode (middle). These missions produced 1,470 photos.

Since the SFAP is used in the flood study, the time of its data acquisition is an essential factor to consider. The main object to analyze was the river channel, and, therefore, the data were acquired during the dry season when the river typically has the smallest discharge. This procedure can produce the maximum dimension of the river valley.

For high-accuracy data, the SFAP needs to be processed using a tie point or Ground Control Point (GCP). Geodetic GPS with Real-Time Kinematic (RTK) system was used to acquire GCP with high accuracy, i.e., below 1 cm. In the entire research area, there are 22 GCPs with a pre-mark system, in which measurements were carried out after the SFAP acquisition process by making use of objects that had clear and relatively permanent geometric shapes, distinct appearances both in the field and on aerial photographs, and adequate accessibility.

DEM filtering

In principle, the DEM generated from SFAP processing is still in the Digital Surface Model (DSM) format in which objects above the ground surface are recorded in the resulting elevation model. For this reason, additional analysis termed DEM filtering is needed to obtain the value of the Digital Terrain Model (DTM) by eliminating objects at ground level. With this fundamental step, the overflow in the flood inundation modeling is not obstructed by any objects that it can actually traverse, such as vegetation and gaps between buildings. The filtering of DSM to DTM was performed in PCI Geomatica software.

Flood Modeling

Since the lack of availability data for hydraulic-based modeling, we develop much simpler methods that only using DEM and Orthophoto. The DEM has a role to develop an inundated area model, while the orthophoto was for identifying the water body. This method can be classified as a geomorphological approach because it is driven by the morphological condition of the river valley (Manfreda et al., 2014) and (Samela et al., 2018). The flood model developed with a scenario of water level rising and flowing over the river channels. The body of the river, defined as the appearance of water in a river channel, was extracted from orthophotos. Meanwhile, the elevation was obtained from the DEM of the aerial photograph. In the scenario, the depths of inundation were determined based on the characteristics of the river valley. This study used three flood inundation scenarios, namely, 5, 7, and 10 m.

Model Evaluation

The model was evaluated by comparing the simulation results with the information provided by the community in the affected locations. The variable tested was the depth of inundation. The model is declared successful if the resulting values are similar or close to the existing conditions at the time of flooding.

3. Results and Discussion

SFAP data processing result

The photogrammetric SFAP processing yielded two main products, namely, orthophotos and DEM. A total of 1,470 photos were overlaid and combined (mosaic) to produce orthophotos with a spatial resolution of 7.15 cm per pixel. Meanwhile, the DEM data had a spatial resolution of 28.6 cm per pixel. The orthophotos were then used to produce land cover maps of the affected locations to identify any potential damages associated with flood events. Meanwhile, the DEM was used as the main data in the flood inundation simulation.

In flood impact analysis, orthophotos from the SFAP processing are of vital importance. They can provide detailed information on land cover and has excellent data renewal. With a spatial resolution of up to 7.15 cm/pixel, the orthophotos are incredibly different when compared with high-resolution satellite imagery, with merely 40 cm/pixel. Moreover, their data renewal can be controlled more flexibly (updated only seven months after the event) at an operational cost that is much cheaper than purchasing high-resolution satellite images. The resulting orthophotos are presented in Figure 3.1.

The DEM treatment process began with filtering to eliminate objects above ground level or land covers. The main challenge of the filtering process at the study site was the extremely complex topographical conditions, i.e., hills, undulating regions, small hills, and flat-sloping areas. In practice, two types of filtering algorithms are used, namely flat terrain filter and hilly terrain filter, according to the topographical conditions observed.

Figure 3.2 shows the DEM data before and after the filtering process. Before the filtering, the DEM is referred to as DSM, whereas after the process, it is called DTM. The rough texture on the DSM shows the presence of land cover, especially vegetation, building blocks, and building-vegetation combinations. Vegetation and building-vegetation combinations were the most difficult objects to remove because they were located at widely varied elevations. With the combination of the two filtering algorithms, high-quality DTM can be produced. This conclusion is based on the visual condition of the two data (the DSM and DTM) in which the DTM has been changed from having coarse to more realistic texture representative of the ground surface (bare land). For flood modeling, the DEM data were resampled to modify the spatial resolution to 1 m.

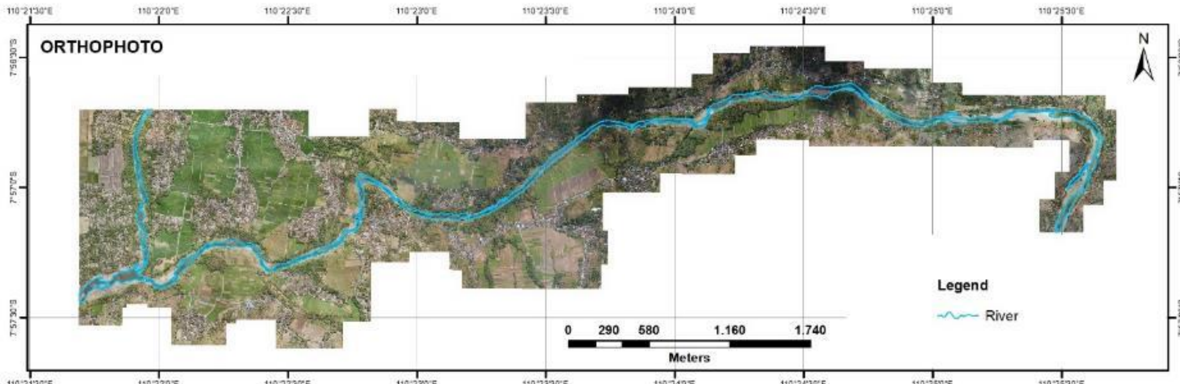

Figure 3.1 The Orthophoto of the Research Area

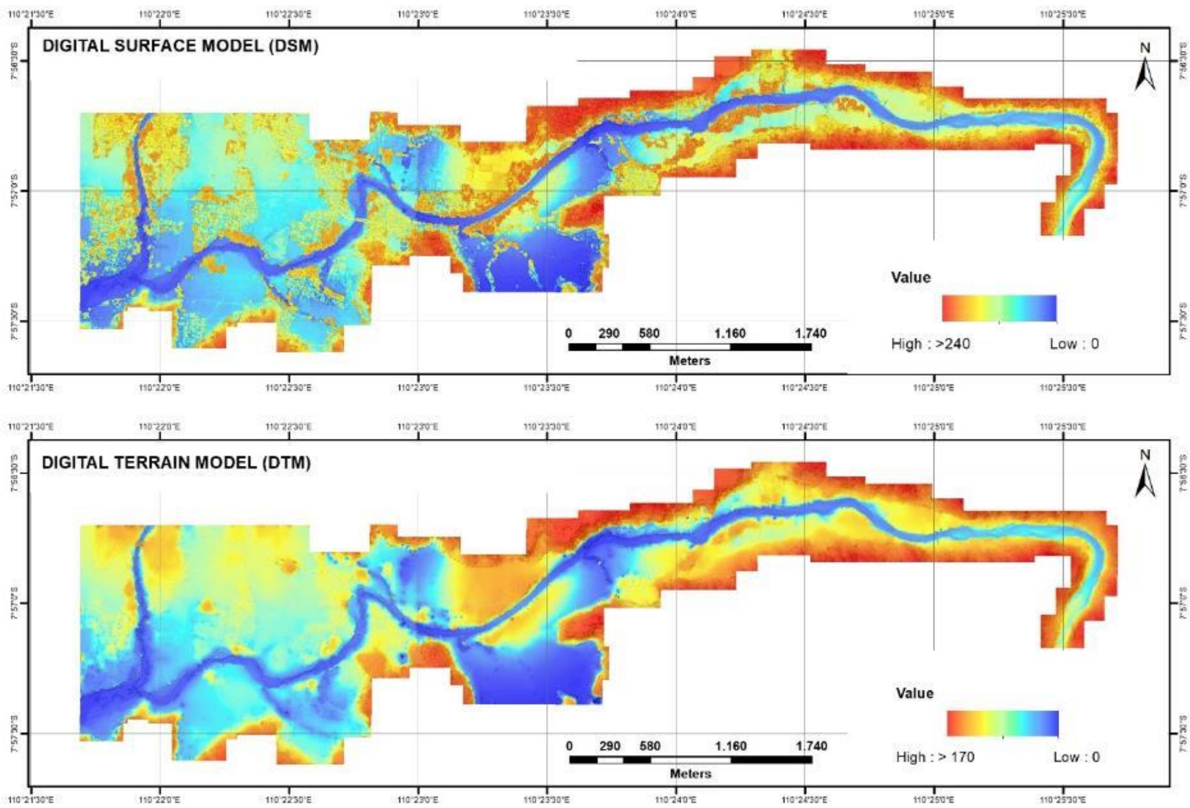

Figure 3.2 The Digital Surface Model (DSM) and Digital Terrain Model (DTM) of the Research Area

Analysis of River Morphometry

Flood modeling primarily takes into account the morphometric properties of the river observed. Morphometric analysis can give an idea about the morphological arrangements of existing fluvial landforms. Arrangement analysis attempts to understand the morphological order of these landforms, starting from the body of water to the surrounding riparian areas, i.e., valleys and terraces. The DEM data were processed to give a morphological description of the river valleys using ten cross-section lines (CS) along with the river flow (Figure 3.3).

Figure 3.4 shows the topographic profiles of the ten CS lines. The study identified river valleys with various conditions, i.e., from shallow to steep valleys and narrow to fairly broad valleys. The eastern section, represented by CS 1-3, shows an area with steep river valleys, varying depths between 4 and 5 meters, and narrow ramps on some parts of the terraces that directly border the foothills. The middle section (CS 4-7) has a sloping morphology with 7-15m deep river valleys and wide ramps on the terraces. Meanwhile, the western part (CS 8-10) has the most sloping morphology, and its valleys are 10-12m deep with broad ramps as the terraces. Under these conditions, the inundation scenario was set at a range of 5-10 meters from the river bed. This range is considered representative enough to create a flood inundation scenario with the assumption that water overflows the edge of the river valleys to the surrounding area.

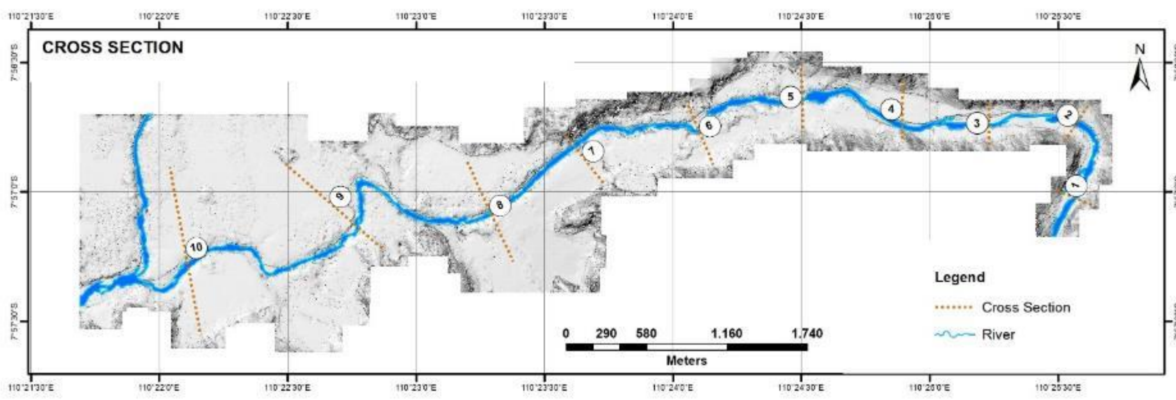

Figure 3.3 The Cross-section Lines of the Oyo River

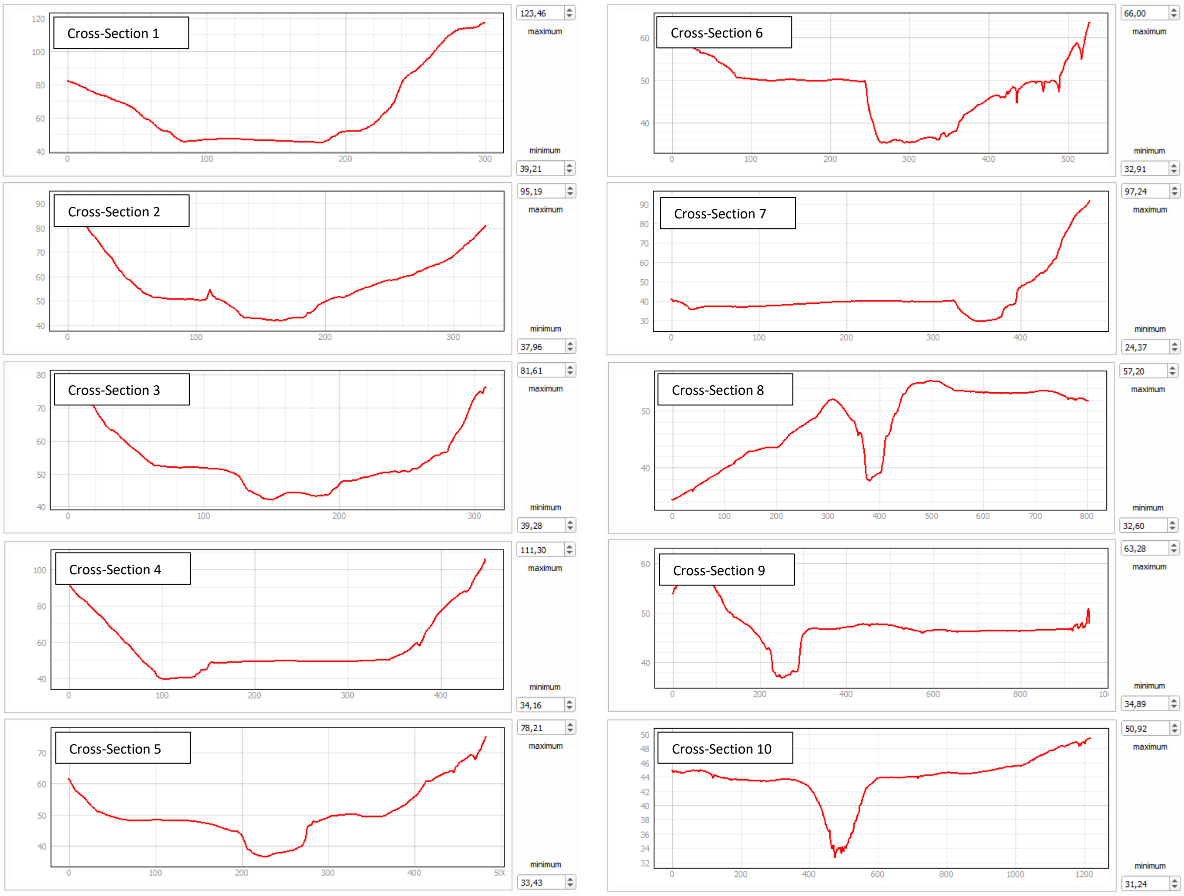

Figure 3.4 The Cross-sectional Profiles of the Oyo River

Flood Modeling

The study mainly applied the geomorphic approach to flood modeling. In this approach, the characteristics of river valleys are analyzed from the DEM data to determine the heights of the simulated overflow/flood. Also, as proven by the resulting spatial resolution, data renewal, and realistic visual appearance, the quality of the DEM data has an essential role in the modeling process.

Flood occurrence is simply defined as the overflow of water volume due to exceeded drainage (river) capacity. With this concept, the scenario calculated the height of the overflow from the lowest water level extracted from the analysis of SFAP captured in the dry season. Then, according to the morphological conditions of the river valley, the height scenarios were set at 5, 7, and 10 m. The 10m scenario was assumed to represent maximum floods, as in the case of Tropical Cyclones Cempaka and Dahlia. Global Mapper was used for simulating the rise in water level using two inputs: DEM and data on river channels. The modeling results can be seen in Figures 3.5 and 3.6.

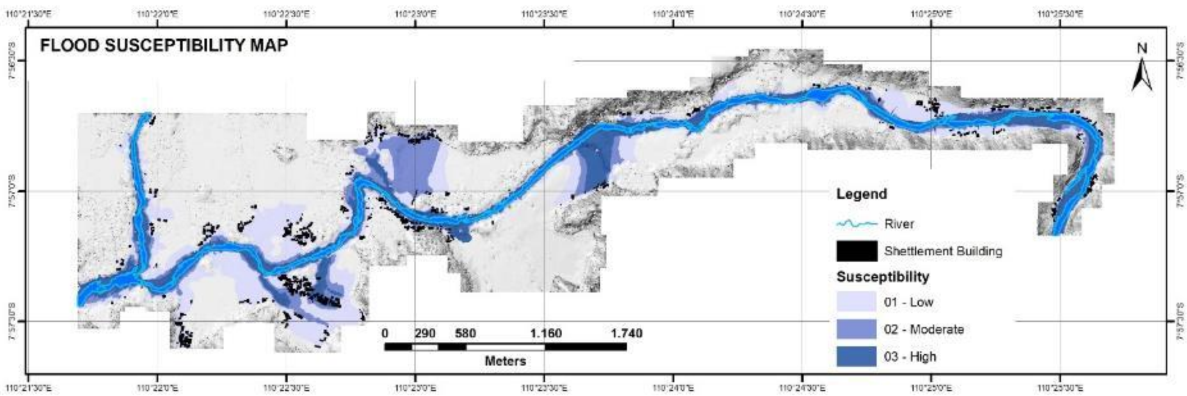

Figure 3.5 Flood Susceptibility

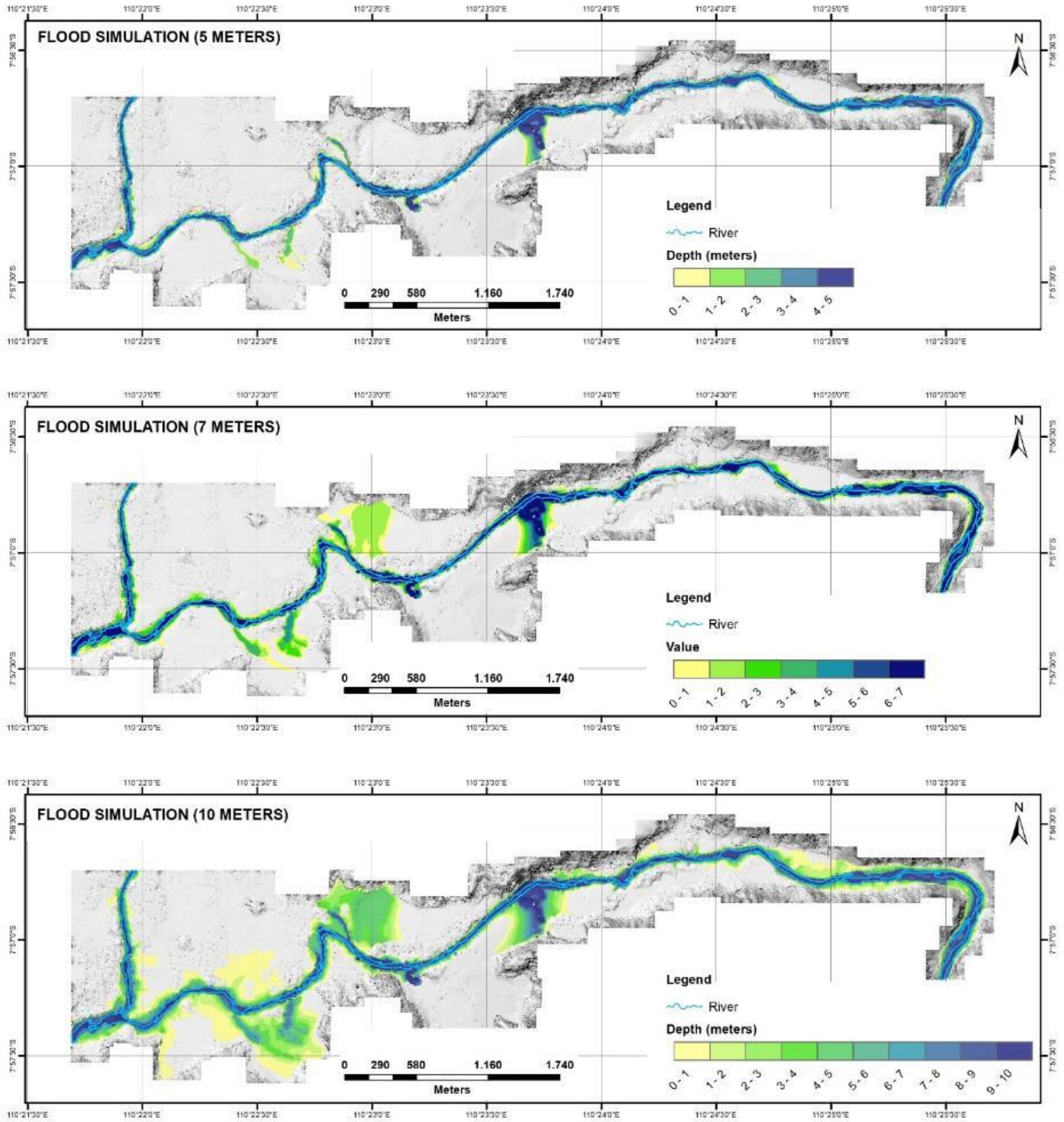

Figure 3.6 Flood Inundation Modeling with 5m, 7m, and 10m Scenarios

Different scenarios produced different areas of inundation. In the 5m scenario, the affected area was 91.6 ha. This figure multiplied to 133 ha and 234.1 ha each in the 7m and 10 m scenarios. These three modeled inundations affected 92, 281, and 1,329 units of buildings, respectively (Figure 3.7-A).

Model Evaluation

Figure 3.7-B compares the results of the 10m inundation scenario with the participatory mapping during Tropical Cyclones Cempaka and Dahlia, while Figure 3.8 compares the two data spatially. From both figures, the depths of inundation deviated by up to 4.8 m, with an average of 1.2 m. This condition is attributable to four issues, namely, the poor quality of the DEM data, technical errors during the interviews with the local community, significant errors or bias values in DEM and data collected during the interview, and other external factors (outside the parameters used in the modeling). However, the simulation model is deemed reliable because the average deviation is close to 1 m or equivalent to the resolution of the DEM data used.

The modeled inundations were used to analyze the regional vulnerability to flooding. The vulnerability assessment was focused on the residential buildings constructed in areas affected in the 10m scenario. It used one-hectare grids as the sampling unit, and the size of the residential buildings was divided by 1 ha to produce a vulnerability index. A higher vulnerability index means that there are a more significant number of at-risk elements (houses) requiring special attention in flood mitigation measures in the study area. High vulnerability index was found at several sub-villages, namely Trukan, Butuh, Dogongan, Siluk Satu, and Kedung Miri Sub-villages (Figure 3.9)

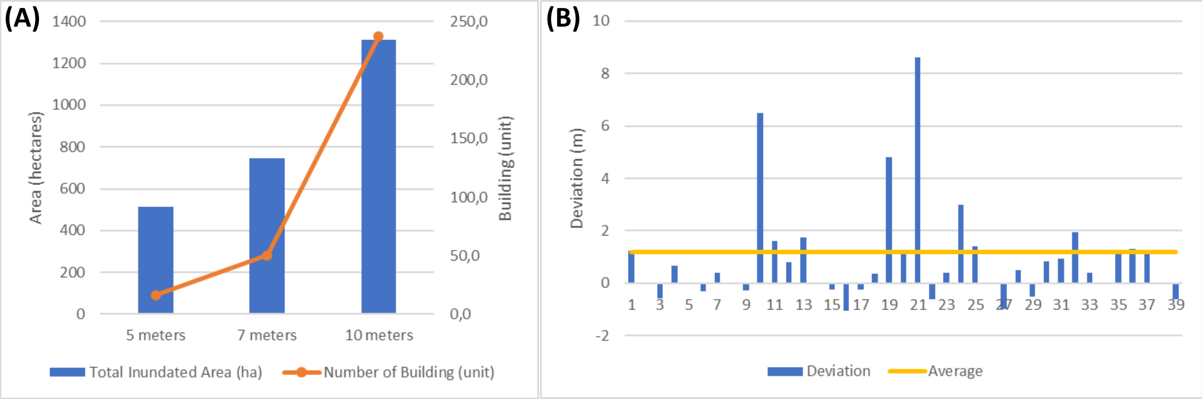

Figure 3.7 (A) The Impact of Each Inundation Scenario and (B) The Simulation Outputs Compared with the Participatory Mapping Results

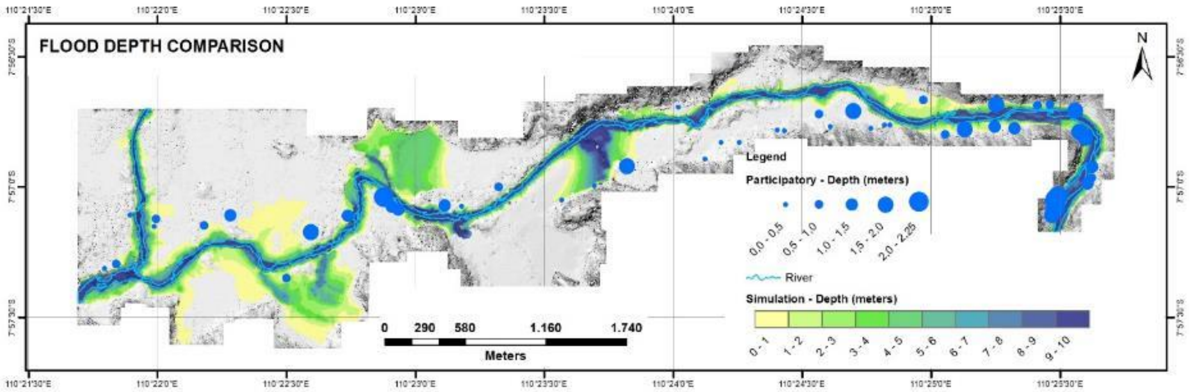

Figure 3.8 The Modeled Inundation and the Results of the Participatory Mapping

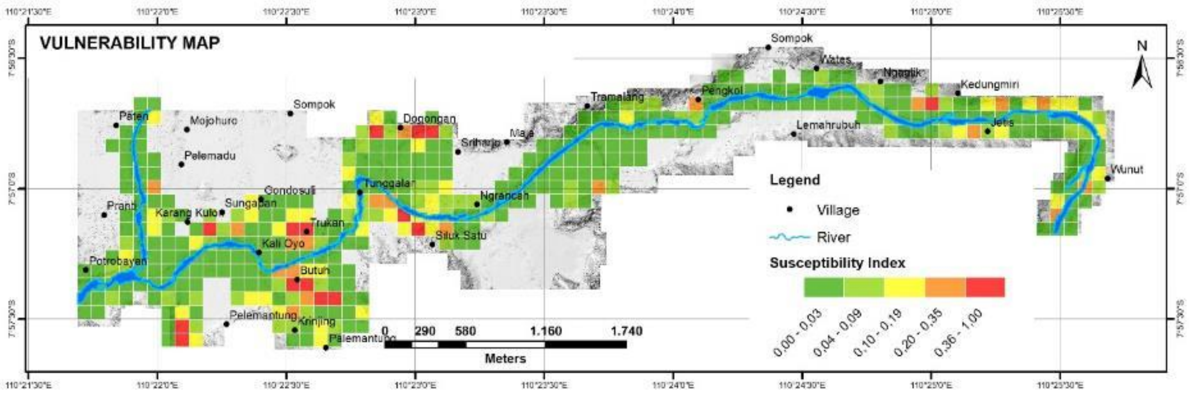

Figure 3.9 Regional Vulnerability Index. Sub-Village Name are Shown by Black-Dots Feature in The Map.

4. Conclusion

The use of UAV and GIS to simulate flood inundation on a detail scale yields fairly reliable accuracy. UAV can produce SFAP data with a high resolution in the form of aerial photographs (ortho) and DEM, as the input of the flood modeling. With the geometric approach, the main obstacle of flood modeling is the high sensitivity of the results to the quality of the DEM data generated, especially during the filtering process of DSM to DTM. For this reason, using more accurate sensors, such as Light Detection and Ranging (LiDAR), is highly recommended to obtain optimal DTM.

Based on the vulnerability analysis, there are five sub-villages highly vulnerable to inundation, namely Trukan, Butuh, Dogongan, Siluk Satu, and Kedung Miri. These five sub-villages can, thereby, be prioritized in any flood mitigation programs prepared for Bantul Regency.

Acknowledgments

The authors would like to thank the Vocational School of Universitas Gadjah Mada as the main sponsor of the research and the Geographic Information Systems (GIS) and Remote Sensing (RS) Laboratories of the Department of Earth Technology for facilitating the laboratory analysis.

Profound appreciation is extended to the students of the Remote Sensing and Geographic Information System (RS-GIS) Program in the Vocational School, including Amri Rosyadi, Hildawati Nugraheni Putri, Khoiriyah Ambarwati, Shahita Ardiya Kurniady, Ramdhina Finita, and Sasvita Gevi Meliyasari, for their assistance in data collection in the field. Lastly, the authors would like to acknowledge the Governments of Selopamioro and Sriharjo for granting the permit to research both villages and the local communities for their active roles in the participatory mapping.

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