

Spatial Modelling of Flood Inundation Case Study of Pesanggrahan Floodplain, Jakarta, Indonesia

Eko Kusratmoko¹, Kuswantoro Marko^{1*} and Amro M. M. Elfeki²

¹*Department of Geography, Faculty of Mathematics and Natural Science, University of Indonesia, Depok, Indonesia.*

²*Department of Hydrology and Water Resource Management, Faculty of Meteorology, Environment, and Arid Land Agriculture, King Abdulaziz University, Jeddah, Saudi Arabia.*

Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Background: Floods pose hazards to society, the environment, and the economy. For instance, the flood in Jakarta on 15–23 January 2013 blocked roads, forced businesses in the capital to close, and displaced at least 20,000 people.

Aims: This research is aimed at estimating the flood inundation in Jakarta City for different return periods of expected peak discharges.

Methodology: The hydraulics and floodplain delineation were conducted to identify the inundated areas using a coupled HEC-RAS and WMS approach for the January 2013 flood. Field survey to get flood depth and flood extent information from the local residents was also done.

Results: The results showed that the model estimates were close to the observed data and this approach can be applied to other flood vulnerable areas, particularly in floodplain areas. Finally, this study is useful for scientists and water engineers who are interested in the development of risk mapping of flood hazards.

*Corresponding author: E-mail: kusrif@yahoo.com;

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1. INTRODUCTION

Jakarta, the capital city of Indonesia is inseparable from the threat of flooding that can strike at any time. According to historical records, Jakarta has been flooded since 1621 when the Dutch colonized Indonesia. In the last decade, at least three major flood events happened in 2002, 2007, and 2013. The floods have produced extensive damage with economic impacts exceeding 500 million USD [1].

Geomorphology is an important aspect affecting floods in Jakarta. Jakarta is a lowland area with an elevation between 0 and 25 m.a.s.l. The area is relatively flat with topographical slopes between 0° and 2° in the northern and central parts of the city and between 0° and 5° in the southern part. There are about 13 natural and artificial rivers flowing through Jakarta, of which the largest are Ciliwung, Angke, Pesanggrahan, Grogol and Sunter. Approximately 40 percent of the total area of Jakarta is lowland which is highly susceptible to flooding.

Another aspect of the flooding issue is the high population growth that leads to development pressure on Jakarta and the surrounding areas. Population in Jakarta in 1930 was 533,000 people, in 1980 about 4.5 million people and in 2010 was about 9.5 million people [2]. Within an 80 year period population in Jakarta has increased by a factor of 18 times.

The Pesanggrahan River is one of the strategic rivers for Banten, West Jawa, with Jakarta being at the downstream area of the basin. Rapid population growth in the watershed has resulted in urbanized land representing 74% of the total area. Thus, every year when the rainy season comes the residents who are living in the downstream area of the Pesanggrahan Basin are prepared to face floods. There is no integrated management for the catchment area and consequently, flood control is more difficult and the flood problem in Jakarta becomes more complex.

Spatial modelling of floodplain inundation is an important aspect in disaster risk reduction for current and future events [3]. Various methods and approaches have been applied in many

studies [4] either via physical representation or mathematical computation. This study focuses on flood inundation mapping using a computational modelling approach. The linking between hydraulic modeling and floodplain delineation approaches was done using HEC-RAS and WMS software. Previous studies dealing with this approach have been conducted by Marko [5] for Jeddah City Saudi Arabia, and Sadrolashrafi et al. [6] in Iran. This study could be viewed as a preliminary disaster risk reduction approach that contributes to planning and solutions for disasters caused by floods in Jakarta.

2. MATERIALS AND METHODS

2.1 Study Area

The location of this research is a 2.6 km² of area in the downstream part of the Pesanggrahan Basin. The main river divides Cipulir Subdistrict into two areas and passes Ulujami, Sukabumi Selatan, and Srengseng Subdistricts in Jakarta Province, the capital city of Indonesia (Fig. 1). It is located at 106.74° – 106.79° East and 6.19° – 6.25° South. The surface elevation ranges from 9 to 23 m.a.s.l with slopes 0 – 2%, leaving the area susceptible to inundation during the rainy season from December to February.

The Pesanggrahan River passes through Bogor Regency, Depok City, and Tangerang City in West Jawa Province eventually reaching South, West, and North Jakarta. The whole Pesanggrahan Basin has a flat and elongated shape with some tributary channels entering the main river. The entire Pesanggrahan Basin is 112.06 km² with the main river length and the basin slope 73.68 km and 0.27%, respectively [7]. The Public Works Division [8] stated that the planned capacity of the Pesanggrahan River when built was 210 m³/s for a 25 year return period. Currently, the existing capacity condition of Pesanggrahan River is only 75 m³/s, while the planned discharge that must be accommodated is for a 25 year return period, hence flooding potential is high.

In 2005, landuse was dominated by built-up areas (60%) including settlements and roads, rice fields (20%), orchard land (13%) and forest (7%) [9]. Rapid population growth has increased

the urbanized areas in both the upper and lower parts of the basin which means the percentage of impervious areas also has increased. Consequently, the discharge of the surface runoff has increased. Table 1 shows that in 1900 only 12% of the watershed was urban area, then in

1990 increased to 45%, and in 2010 the urbanized area became 74% [10]. This condition must be a warning to people who live in the lower area of the basin due to the flood hazard threatening at any time when there is heavy precipitation.

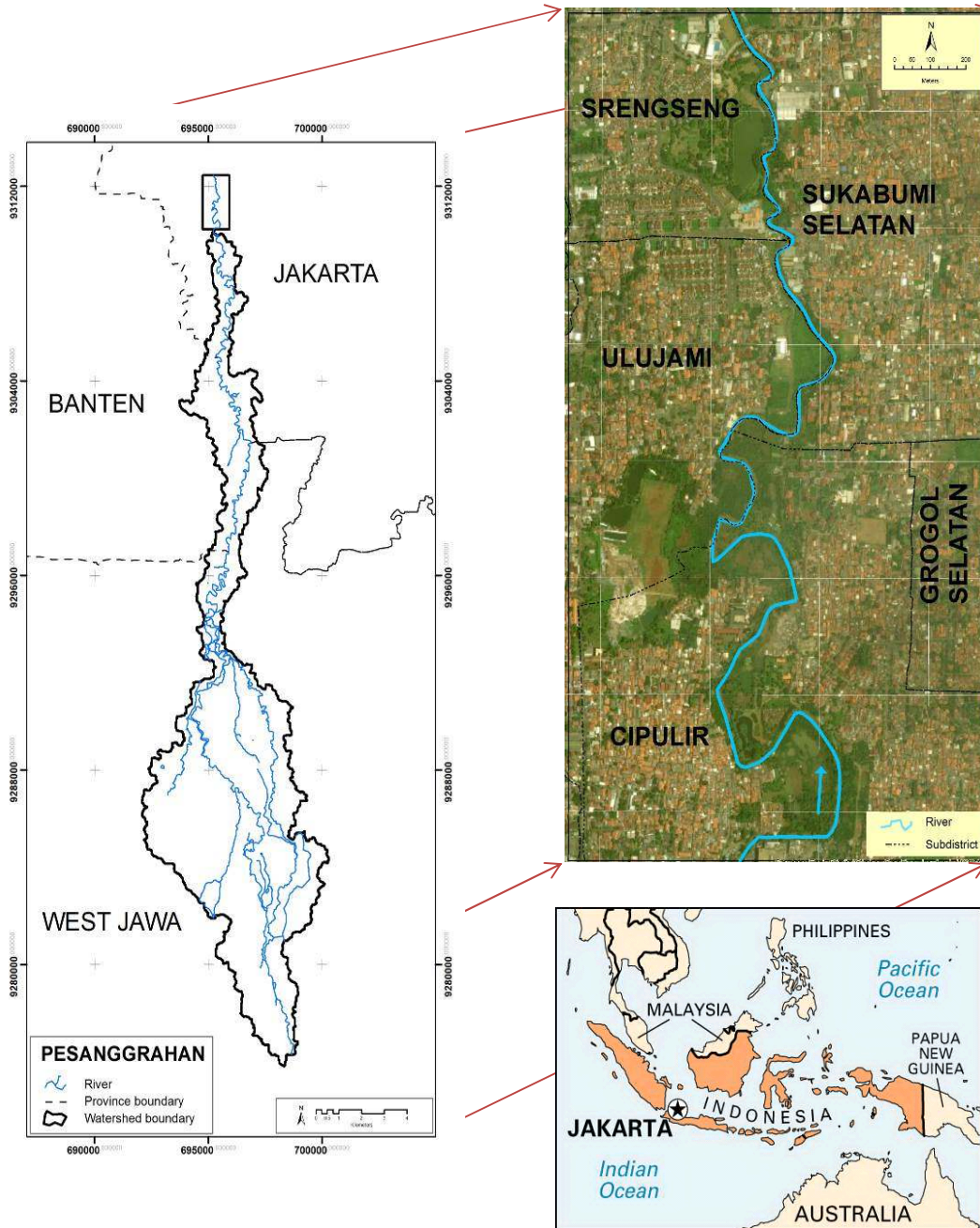


Fig. 1. Area of study for flood inundation modelling

2.2 Hydraulic and Floodplain Modelling

Hydraulic modelling is used to evaluate important elements of free surface fluid flow such as for flood forecasting and producing inundation maps [11]. The models are applied to the floodplain area that is usually inundated by the floods.

HEC-RAS is a windows-based hydraulic model developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. In this study, HEC-RAS is used for steady flow water surface profiles, using the energy equation with an iterative procedure called by a standard step method [12]. The energy equation is written as follows:

$$Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \dots (1)$$

where:

- Z_1, Z_2 = elevation of the main channel inverts,
- Y_1, Y_2 = depth of water at cross sections,
- V_1, V_2 = average velocities (total discharge/total flow area),
- α_1, α_2 = velocity weighting coefficients, that account for non-uniformity of the velocity distribution over the cross-section,
- g = gravitational acceleration, and
- h_e = energy head loss.

A steady flow is a condition in which depth and velocity at a given channel location do not change with time. Therefore, gradually varied flow is characterized by minor changes in water depth and velocity from one cross-section to another.

The cross section sub-division for the water conveyance is calculated within each reach using the following equations:

$$Q = K S_f^{1/2}, \text{ while } K = \frac{1.486}{n} A R^{2/3} \dots (2)$$

where:

- K = conveyance for subdivision,
- n = Manning roughness coefficient,
- A = flow area subdivision,
- R = hydraulic radius for subdivision (wetted area/wetted perimeter)
- S_f = friction slope

WMS is a comprehensive environment for hydrologic analysis. WMS 8.1 can perform operations such as automated basin delineation, geometric parameter calculations, GIS overlay computations, cross-section extraction from terrain data, floodplain delineation, mapping, and storm drain analysis. Flood inundation modelling was conducted using one of the tools within WMS, the WMS River tool to construct an HEC-RAS flow model. HEC-RAS also performs a step backwater curve analysis for either steady state or transient conditions to determine water surface elevations and velocities.

2.3 Methods for Flood Inundation Mapping

There were three basic steps to obtain the flood inundation map:

- a. Preparing a triangular irregular network (TIN) which represents the topography for the study area. The TIN is a type of DEM (digital elevation model) created from digital contour data sourced from the Spatial Planning Board of Jakarta Government. The contour data have a vertical accuracy of 1 m. In this study, TIN data were generated based on the DEM with a 10x10 m spatial resolution, after resampling from the digital contour of 1 m. This is to optimize time on the delineation process. This TIN resolution is suitable to be applied for a floodplain area to assess flood hazards [13].
- b. Preparing water surface elevation data as read in as a scatter point data set with stream stage values which are derived from HEC-RAS and subsequently read into WMS. Water elevation data consist of a series of surface water elevation points defined as x, y, z (where z is the elevation of the water surface). Some parameters required for the hydraulics model in HEC-RAS are stream centerline, main channel banks, cross-section lines, and material zones which are called channel geometry. The geometric data were derived based on the existing satellite imagery from Google Earth. A total of 26 cross sections were taken over the single reach modeled as seen in Fig. 2. Roughness coefficients (Manning's n) used in the study area were 0.013 for urbanized areas and 0.05 for bush-grass landuse.

A steady gradually varied flow analysis was used that considered peak discharge

(Q_p) data according to the flood discharge plan of the Pesanggrahan River for 5, 10, 25, 50, and 100 year return periods as seen in Table 2. The discharges were estimated by the Department of Forestry in a final report of A Detail Planning for Flood Management in Jakarta, Bogor, Depok, Tangerang, Bekasi, and Cianjur [14]. The normal depth upstream and downstream boundary conditions were set at a friction slope of about 0.024 and 0.012, respectively.

clicking at the expected location on the flooded areas.

The methodology using the coupled WMS and HEC-RAS is illustrated in Fig. 3.

c. Mapping of flood inundation areas

After computing water surface elevation along the channel geometry of the Pesanggrahan River, mapping of flood inundation areas was carried out using the flood analysis function of the WMS package. It involves interpolation of water surface elevation on the cross-sectional area along a 100 m radius. The flood depth information for each location within the inundated areas can be identified by

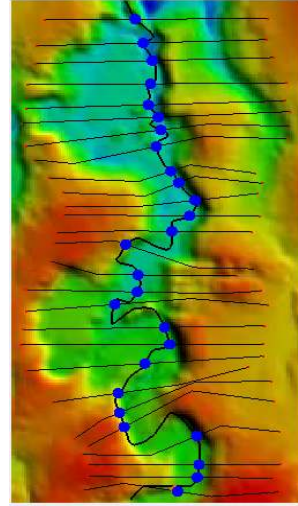


Fig. 2. Cross-section lines used for modeling with DEM as a background image

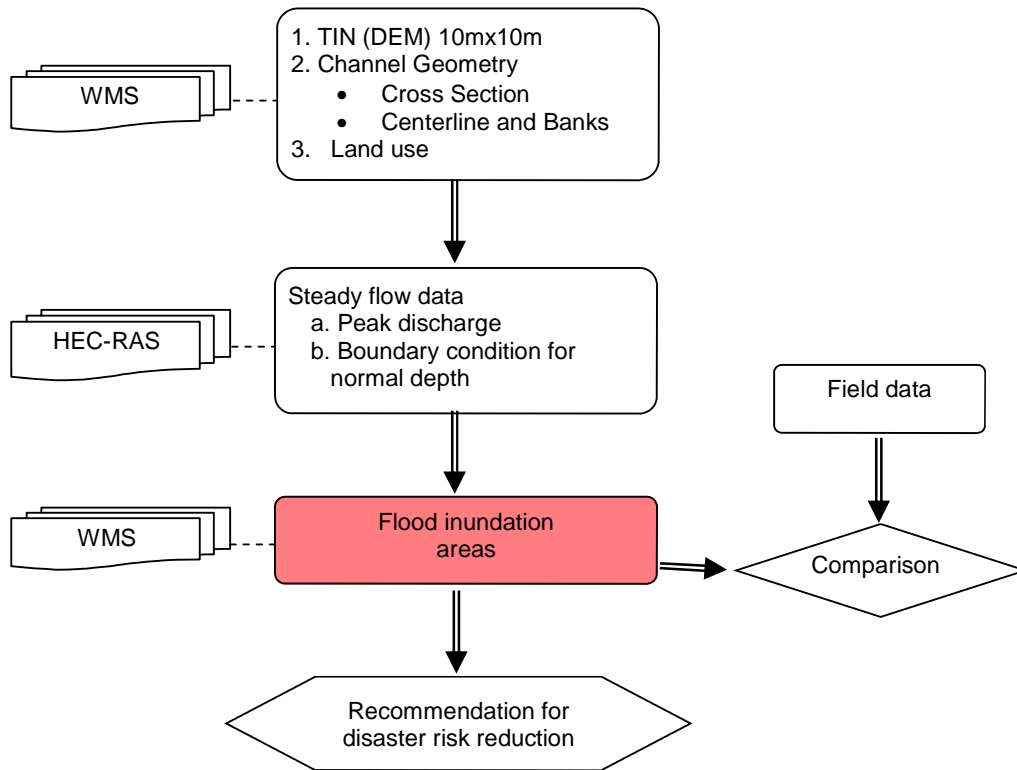


Fig. 3. Scheme of methodology

Table 1. The changing of urbanized areas percentage in Pesanggrahan Basin in the periods 1900-2010

Basin	Area (sq. km)	% urban areas to the basin					
		1900	1940	1980	1990	2000	2010
Pesanggrahan	121.8	12	17	24	45	62	74

Table 2. Flood discharge plan (m³/s) of the Pesanggrahan River

Return period	5 yr	10 yr	25 yr	50 yr	100 yr
Q (m ³ /s)	151.3	177.7	215.5	228.9	242.4

3. RESULTS AND DISCUSSION

The floodplain delineation process was completely executed for the five scenarios based on the return period of peak discharges (Table 2). The floodplain delineation was automatically simulated in WMS by interpolation along a 100 m radius of the cross-sectional areas. This radius was obtained after sensitivity analysis of the model results.

The WMS is a powerful tool which is able to generate flood depth coverage that contains different polygons and contours of flood depth. To know the depth in a certain location, the users may click on any location of the flood depth coverage to obtain the depth of the flood, the elevation, and the x, y coordinates. Areas that were not inundated are shown by zero and minus values.

The minimum flood depth for all scenarios was almost zero, the maximum flood depth ranged from 2.37 to 2.77 m, while the average of the flood depth ranged from 0.91 to 1.14 m. Vertically, these values are not particularly different, but horizontally, the flood extent for each scenario showed considerable increase. The difference in flooded area between the 5 and

100 year return period is about 5 ha. All flood depths and areas showed a trend of increasing values with increases in peak discharge values as shown in Table 3 and Figs. 4 and 5.

A field survey to measure the flood depth during the flood event of January, 15th – 25th 2013 was carried out. Interviews of local inhabitants and information from the world wide web for news and video documentation to strengthen the findings based on field survey were conducted. The total of number of sampling locations is four, which were in the flooded areas that represents the study area as seen in Fig. 6.

Results from the 4 locations showed that for Location 1 (Cipulir Market) the observed flood depth was 1.5 m, which is close to Model 2 (10 year return period). Location 2 (Dense settlement), the observed depth was 0.5 m which is close to Model 3 (25 year return period). Location 3 (Downstream area of SMP 267) the observed depth was 0.7 m which is close to Model 3 (25 year return period). For Location 4, which is at a small road as a separator between regular housing (Perumahan Permata Mediterania) and irregular housing (kampung), the observed depth was higher than Model 5 (100 years return period).

Table 3. Results of flood modelling inundation

Area properties	Return period (years)				
	5	10	25	50	100
	MODEL (1)	MODEL (2)	MODEL (3)	MODEL (4)	MODEL (5)
Peak Discharge (m ³ /s)	151.30	177.70	215.50	228.90	242.40
Min depth (m)	0	0	0	0	0
Max depth (m)	2.37	2.50	2.66	2.72	2.77
Average depth (m)	0.91	0.98	1.08	1.11	1.14
Stand. Dev. (m)	0.51	0.53	0.57	0.58	0.59
Total inundated area (m ²)	600,500	618,400	639,900	648,000	654,400

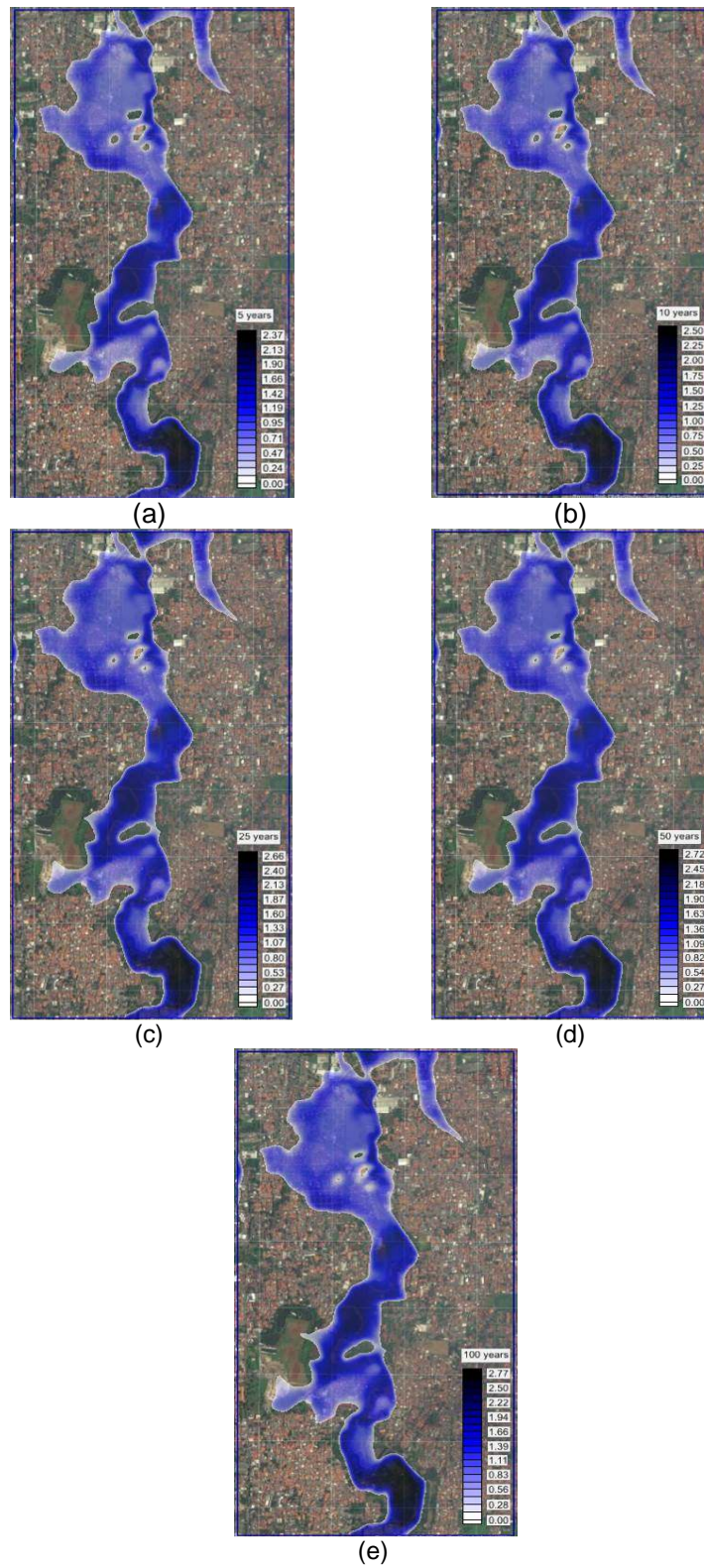


Fig. 4. Estimation of flood inundation for different return periods for runoff discharge for 5, 10, 25, 50, 100 years respectively

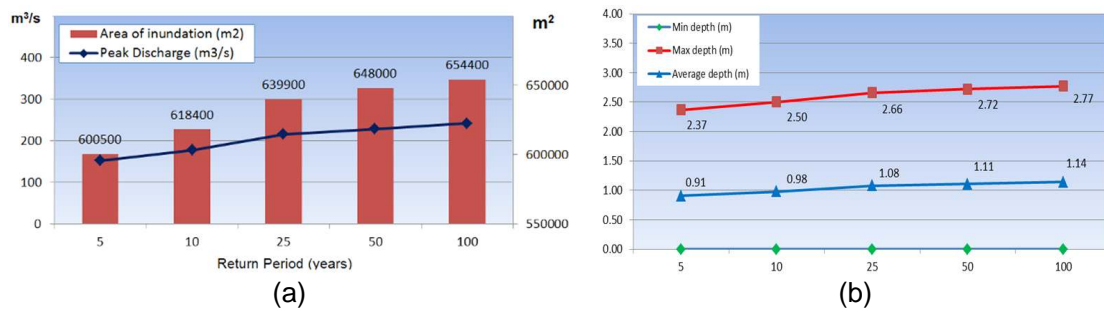


Fig. 5. (a) Area of flooding at different peak discharges; and (b) Flood depth characteristics at different return periods

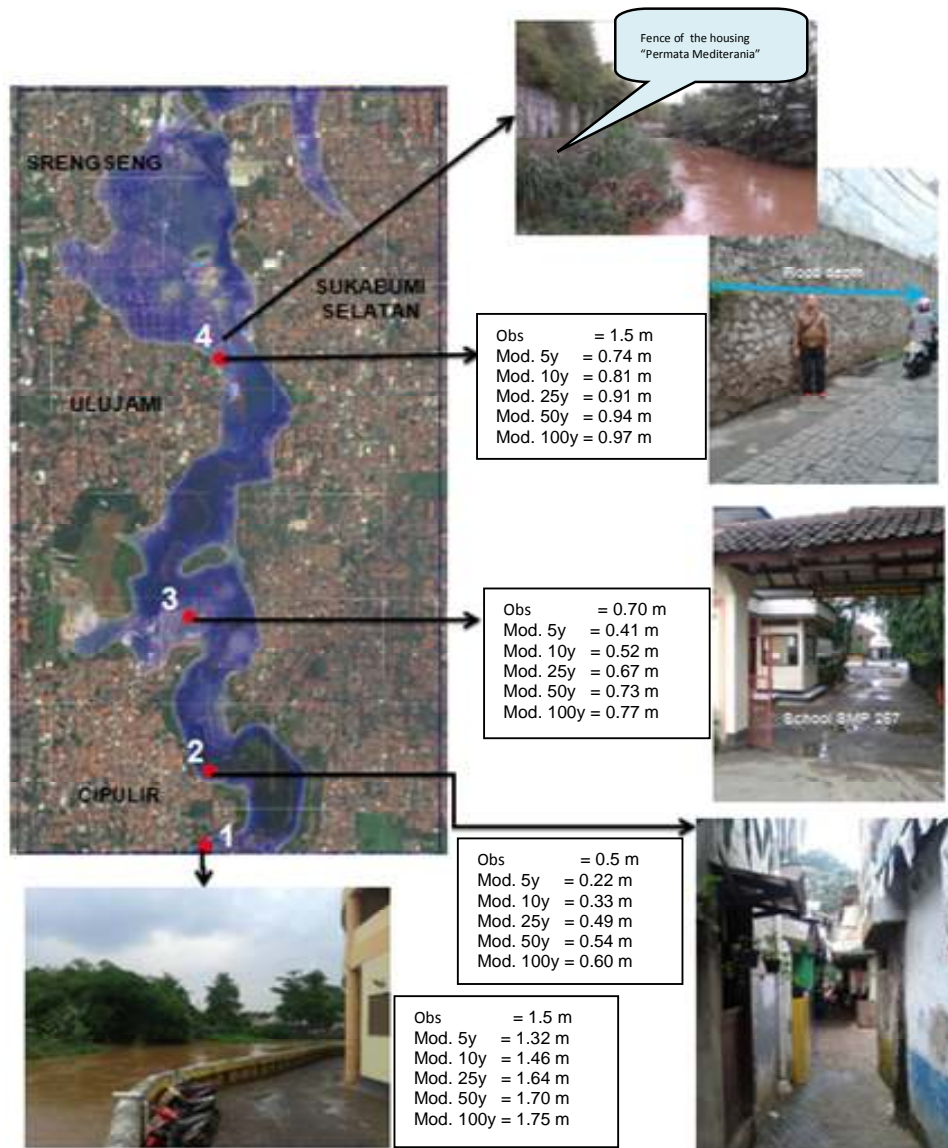


Fig. 6. Comparison between observed and modelled inundation locations

At location 4, the observed flood depth was higher than the highest model depth. This result is quite different from the model because of land surface changes. In 2000 a regular housing development, Permata Mediterania, was built. Based on the local inhabitants report, before its construction the depth of flood was about 50 cm and the water spread out to many places that did not have barriers. Once the housing was constructed some fences were built along the Pesanggrahan River banks. Consequently, the water course of Pesanggrahan became narrow and this lead to an increased depth of flood of 1.5 m even though the flood event in January 2013 was not the largest on record. The other condition that created a greater flood depth at location 4 was that the land surface of Permata Mediterania housing has been raised about one to two meters and this was not captured in the existing contour map. Therefore based on the four measured locations the flood event of January 2013 was close to the flood with a 25 year return period.

4. CONCLUSIONS AND RECOMMENDATIONS

Flood inundation modeling was successfully executed using the coupled HEC-RAS and WMS software for a watershed in the Jakarta region. The main objective of this study was to estimate the inundation areas due to the flood event of January 2013. Several data have been used including a 10x10 m TIN as a topographic representation which is derived from 1 m digital contours, land use which was derived by on screen digitizing based on Google Earth satellite imagery to determine the Manning's roughness coefficients (n), geometric data derived from topographic maps, satellite imagery during the flood event, and the peak discharges obtained from a previous study as input to perform the simulation scenarios.

WMS has an ability to simulate the floodplain delineation in a 2-D model using water surface elevation data as input in a scatter point data set with stream stage values that contain x , y , z coordinates where z is the elevation of the water surface. The results showed that the maximum flood depth values increased when the peak discharge values increased. The maximum flood depths reached 2.77 m, while the averages of the flood depths were similar for the 5-100 year return periods (0.91 to 1.14 m). The spatial extent of flooding ranged from 60.00 ha to 65.44 ha or about a 5 ha increase from the 5 to 100

year return period. The modeled results were compared to observations to assess the validity of the modeled results. The model results were close to the observed results, particularly in the areas where there was no construction such as housing and fences. Some technical adjustments need to be done in relation to the newly built-up areas to improve model results.

This study is very useful for inhabitants who live in the floodplain area which is affected by flooding. It is also useful for the government and stakeholders that must relocate the inhabitants from those locations to safer areas. In addition, the function of floodplain area should be restored as storage and conveyance, recharge of groundwater, and protection of water quality. Thus, the development conducted by humans must consider sustainability for the future.

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DISCLAIMER

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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