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RELIABILITY OF 2D HYDRODYNAMIC MODEL ON FLOOD INUNDATION ANALYSIS

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ABSTRACT: This paper presents a flood inundation analysis to determine the possibility of flooding in urban areas. Many studies have conducted flood simulations to generate inundation problems due to river overflow. Urban flood problems commonly occur because of rainfall in subcatchments that do not enter the channel effectively. Therefore, it is necessary to analyze the inundation that occurs owing to overland flow. This study investigates the usefulness of rain-on-grid boundary conditions compared to flow hydrographs to represent the overland flow. The 2D shallow water equation was applied using the HEC RAS 2D model to select suitable boundary conditions to describe watershed problems. The rain-on-grid boundary condition gives a direct rainfall–runoff calculation in the simulation. The flow hydrograph was calculated separately using the rainfall-runoff analysis based on the storm-water-management model. Although rain-on-grid represents the real physical condition, it is difficult for the 2D hydrodynamic model to assess the drainage channel. However, the flow hydrograph boundary condition shows good results compared qualitatively with historical data based on on-site observations obtained from the Department of Public Works, Highways, and Drainage Management. Furthermore, this research provides the capability of flow hydrographs and rain-on-grid boundary conditions for flood simulation in urban areas. The results can be used to conduct an appropriate future simulation of urban drainage planning.

Keywords: Flood, Watershed, Inundation, 2D model

1. INTRODUCTION

Urban flooding is a natural hazard that commonly occurs in developing countries, including Indonesia. It occurs mainly in major cities. People prefer to live in urban areas as there are more livelihood opportunities. Therefore, the population of big cities has increased rapidly, leading to land-use changes. These land-use changes increase surface runoff and trigger floods. However, the risk of flooding may be due to other factors such as sea level, heavy rainfall, and inadequate channel capacity [1]. This represents the uncertainty of flooding. Therefore, flood simulation must be conducted using a hydrodynamic model to analyze the possibility of flooding. The hydrodynamic model is used to perform flow fluctuation calculations and has already been implemented in assessing flooding risk [2]. Hydrodynamic models commonly used for flood simulation consist of 1D, 2D, and 3D models, among which the 2D model is more appropriate for flood detention on a large scale [3] and is widely used [4]. The 1D model is convenient and is mostly implemented to analyze the flow along the cross-section one dimensionally. However, the 2D model yields more accurate results [2] and is used to simulate floods caused by dam breaches, showing promising results [5]. A previous study conducted flood simulation to assess the hydraulic model's capability and compared it to a model experiment. Although the hydraulic model predicted the experimental results reasonably accurately, the uncertainty caused by channel modification must be evaluated [6]. Faudzi et al. [7] conducted a 2D simulation to analyze the maximum acceptable discharge to mitigate inundation. Farooq et al. [8] conducted a study in Nothern Pakistan using a 2D model to develop flood hazard maps for flood mitigation measurements in the Swat valley. The HEC RAS was also implemented for flood plain mapping in Segamat Town Malaysia to simulate the flood level to provide flood characteristics [9]. Furthermore, the HEC RAS was applied to develop the upcoming flood hazard in Thailand [10], and was used to verify the usefulness of preference planning as a mitigation scheme [11]. The HEC RAS 2D model was used to examine the consequences of topography and land cover to evaluate the flooding extent in Kilicozu Creek, Turkey. This shows that the resolution of topography and land cover to obtain a dependable model is not needed [12].

Faudzi [7] performed a 2D flood simulation using a flow hydrograph and normal depth as the upstream and downstream boundary conditions. The simulation results indicate the proper discharge from a dam to mitigate the flood. Furthermore, Yalcin [12] used 2D flood simulations to investigate the influences of data resolutions on the generation of flood inundation. The same types of boundary conditions were used to simulate floods. Urban flooding is commonly caused by overland flow through the subcatchment areas when rainwater cannot flow into the channel effectively. Therefore, investigating the influences of several types of schematizing boundary conditions in 2D flood simulations is necessary. The inundation in the watershed is mainly caused by local precipitation and insufficient drainage systems. The boundary condition should represent the actual hydrologic conditions in the watershed while providing a good result. The boundary conditions that provide suitable results can be used in future simulations.

2. RESEARCH SIGNIFICANCE

This research investigates suitable boundary conditions for 2D flood simulations to represent the overland flow. The study provides the capability of flow hydrographs and rain-on-grid boundary conditions for flood simulation in urban areas. A rain-on-grid boundary condition setup gives direct rainfall–runoff calculations, meanwhile the flow hydrograph boundary conditions, the rainfall–runoff modeling must be performed separately. The model was verified by comparing the simulation results with historical data. The obtained results can be used to conduct an appropriate future simulation of urban drainage planning.

3. STUDY AREA

The research location is Surabaya, Indonesia (Fig. 1), located 7°21 south latitude and between 112°36 and 112°54 east longitude, with an area of approximately 326.81 km^2 [13]. Surabaya has published its drainage master plan (SDMP), which is used as a guide for drainage planning; it was conducted twice—in 2000 and 2018. According to the SDMP, Surabaya's drainage systems are divided into five districts consisting of Wiyung, Tandes, Jambangan, Gubeng, and Genteng [1]. Each district consists of several drainage channels, as listed in Table 1 [14].

Several watersheds are known to be located in flood-prone areas. This was one of the main factors for selecting the research location. The flood-prone areas obtained from SDMP 2018 [14] are illustrated by the orange area in Fig. 2, which shows the shaded polygon as the chosen area of the Kedurus watershed.

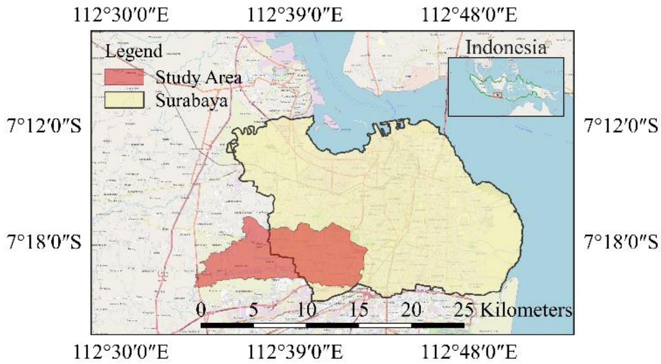

Fig. 1 Research location. (the base map was obtained from openstreetmap.org)

Table 1 The main drainage system of each district

No	Drainage System
1	Wiyung district: Kedurus drainage system
2	Tandes district: Gunung Sari drainage system and West Low Level drainage system
3	Jambangan district: Kali Perbatasan, Kalisumo, Wonorejo - Rungkut, Kebon Agung, Medokan Semampir, Kali Mir drainage sub system
4	Gubeng district: Pegirian - Tambak Wedi, Jeblokan, Lebak Indah, Kali Kepiting, Kalibokor, Kalidami, Kenjeran drainage system.
5	Genteng district: PA Darmo Kali & Ciliwung, Greges, PA Dinoyo and Keputran, Kayun and PA Kenari, Peneleh.

By overlaying the Kedurus watershed on a flood-prone map, it shows that several areas within the Kedurus watershed are vulnerable to inundation. Moreover, the drainage master plan indicates that the inundation problem in several areas is caused by land elevation, which is lower than that of the inlet. This condition prevents surface runoff from passing through the subcatchment into the channel. Furthermore, it triggers inundation in several areas surrounding the Kedurus Channel.

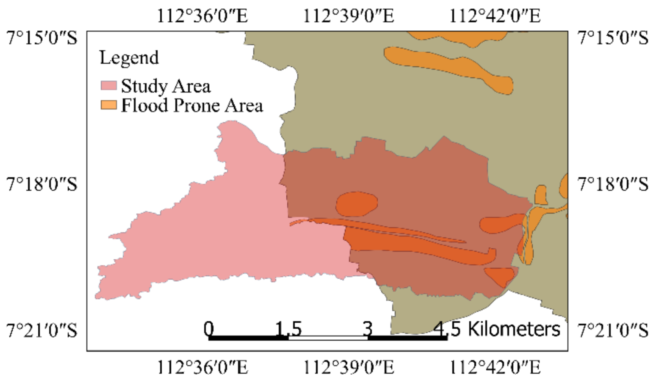

Fig. 2 Surabaya's Flood Prone Area

4. DATA AND METHODS

4.1 Data Availability

The proposed 2D model was constructed using the HEC RAS model. Several data were required to build the model: a digital elevation model (DEM), rainfall, drainage network, and land use. Because each datapoint was obtained from several sources, it influenced the model accuracy, as shown in Table 2.

Table 2 Data Source

No	Type of Data	Data Source
1	Digital elevation model (DEM)	Badan Perencanaan Pembangunan Kota (BAPPEKO) - Surabaya
2	Rainfall	Tropical Rainfall Measuring Mission (TRMM)
3	Drainage network	Surabaya Drainage Master Plan (SDMP): SDMP 2000; SDMP 2018
4	Flood prone area	Surabaya Drainage Master Plan (SDMP) 2018
5	Land use area	Rencana Tata Ruang Wilayah (RTRW) 2014 - 2034

In this study, a digital elevation model was used to create the terrain model in the RAS mapper. The terrain model was used to obtain the flood extent. The rainfall input data were represented as precipitation within the watershed boundary condition. The rainfall data is used to generate runoff through the subcatchments. The discharge is defined by a flow hydrograph under upstream boundary condition. The flow hydrograph was generated based on a hydrology analysis using the storm-water-management model (SWMM). The drainage network was used to build the 2D area of the Kedurus watershed, which is bound with the manning value to delineate the land use types.

Several studies have used rainfall data based on rain-gauge observations to simulate floods. In this study, because one of the rainfall gauges influencing the watershed did not possess the observed data, the rainfall data were obtained from the Tropical Rainfall Measuring Mission (TRMM), as shown in Fig. 3. A rainfall correlation analysis was conducted to determine the dependency of both data.

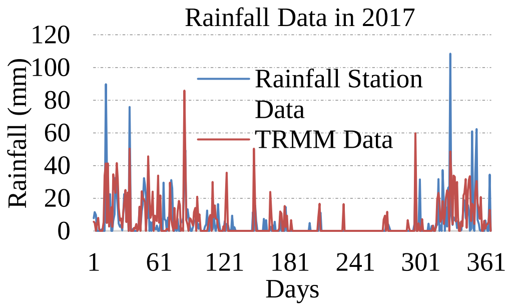

Fig. 3 Observed and TRMM rainfall data in 2017

The results show that the correlation values for both sets of data were 0.57, which is acceptable.

4.2 Numerical Simulation

This research assessed the flood simulation to obtain the flood extent of the Kedurus primary channel. Flood simulation was conducted using the HEC RAS, which a hydraulic model developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers; it enables the execution of 1D, 1D2D, and 2D models [15]. The flood simulation was aimed at validating the 2D model with the historical data.

The preprocessing of the flood simulation was initiated by creating a 2D flow area on the geometry. The 2D flow area was determined based on SDMP 2000 and SDMP 2018. However, confirming the watershed's edge was difficult because there was an undeveloped area with no drainage channel near the watershed. This could have impaired the creation of the 2D flow area, because these undeveloped areas could be included in the watershed. Therefore, the 2D flow area boundary was determined by considering terrain analysis using QGIS for spatial analysis. This was performed to obtain the channel network according to the DEM. The channel network was used to ensure the watershed boundary, as shown in Fig. 4. The figure shows the improvement of the watershed boundary, as demarcated by polygon areas. It was used to create a 2D flow area for flood simulation.

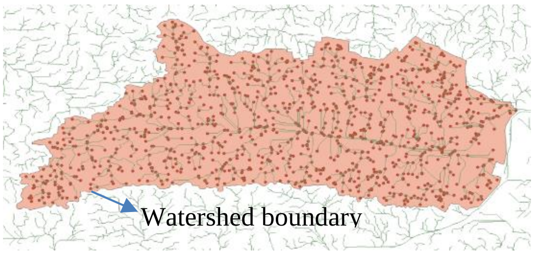

Fig. 4 Watershed boundary based on terrain analysis according to DEM

Moreover, the DEM was adjusted based on the 2D flow area to ensure a mild simulation. DEM data are required to create a terrain model within the RAS mapper. The terrain model was used to support mesh construction to establish the computation point spacing within the 2D flow area.

The maximum computation point spacing used in this simulation was 50 × 50. Fig. 5 shows the additional break line used to represent the primary channel for refining mesh construction. The mesh construction was used to simulate the flood extent. Moreover, to improve the flood simulation, the selected time step and boundary conditions were considered.

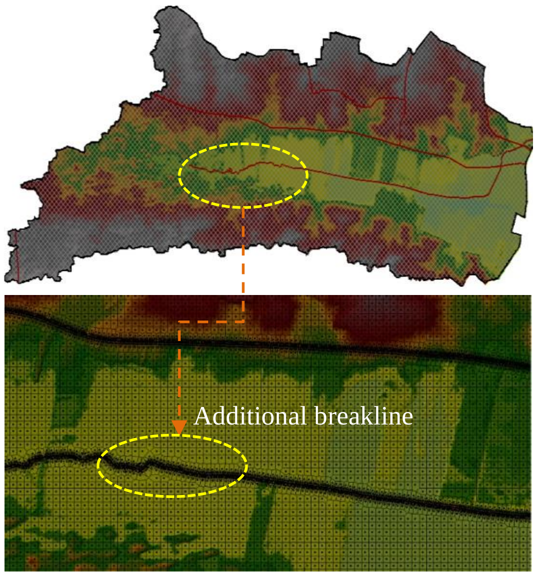

Fig. 5 Mesh construction on 2D flow area

Flow hydrographs, rating curves, lateral flows, stage hydrographs, normal depths, and precipitation are among the several types of boundary conditions that can be simulated. Accordingly, several scenarios were simulated to obtain an appropriate model, as illustrated in Fig. 6. This simulation considered the precipitation boundary because the inundation problem in the Kedurus watershed is not only generated by the channel overflow but also from rainfall through subcatchments that does not enter the channel effectively.

5. RESULT AND DISCUSSION

Every scenario applied to simulate the extent of flooding was able to predict inundation accurately. However, an appropriate model must be evaluated according to historical inundation based on municipal government data and SDMP 2018–2038. In this study, the model that provided the closest inundation results to the municipal government data and SDMP 2018–2038 was considered the most suitable. Fig. 7 shows the comparison of simulation results for three scenarios. Fig. 7.a illustrates the simulation results of the 1st scenario, which was simulated using the flow hydrograph as the upstream boundary. The flow hydrograph represents the discharge from the upstream catchment area that was analyzed based on SWMM. Fig. 7.b shows the simulation result for the 2nd scenario, using the base flow as the upstream boundary. This is different from the 1st simulation because there is an additional precipitation boundary within the watershed. It is assumed that the discharge flowing into the channel was caused by rainfall. Because of the precipitation, which is already used as the watershed boundary, the upstream boundary condition only uses base flow within the river channel. The aim of this scheme is not to provide a double-input discharge. The watershed problem is caused by rainfall–runoff, which does not flow into the channel inlet effectively. Therefore, the precipitation within the watershed boundary condition was chosen to represent the rainfall simulation through the subcatchment. Fig. 7.c shows the 3rd simulation, in which the discharge that flowed into the channel was assumed to be caused by precipitation only.

Overall, the simulation results showed that the appropriate model, which is approximately close to the historical data, is the 1st scenario model based on the extension location of inundation, similar to the historical data.

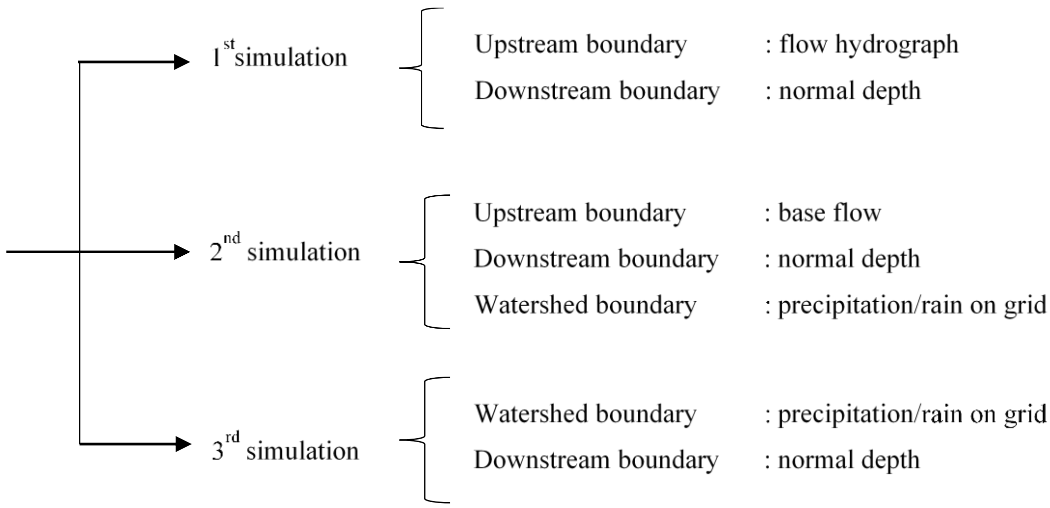

Fig. 6 The several scenarios of boundary condition

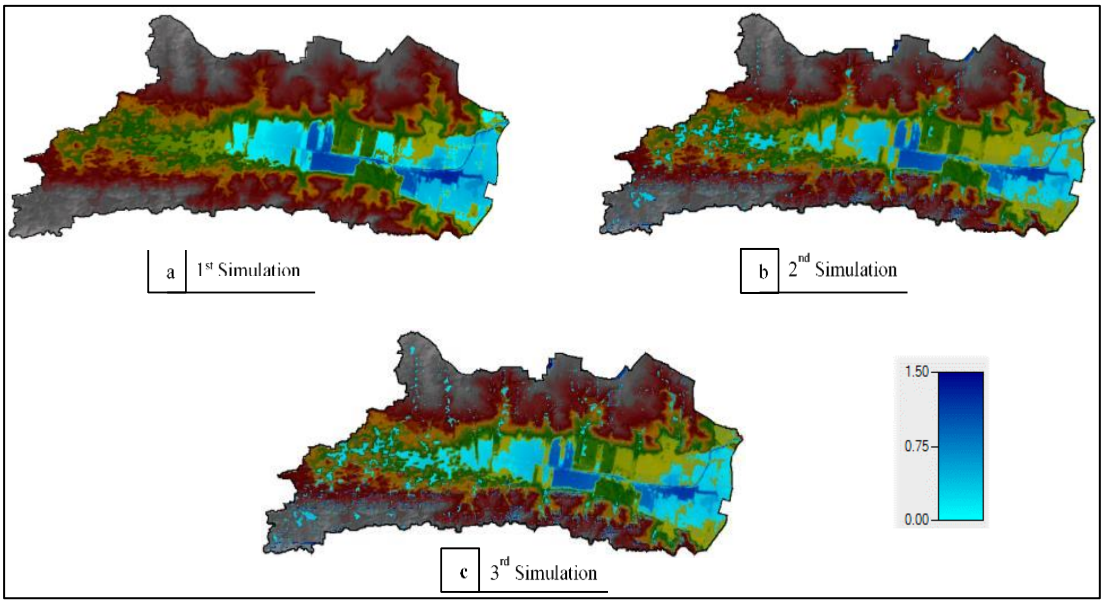

Fig. 7 The 2D simulation result

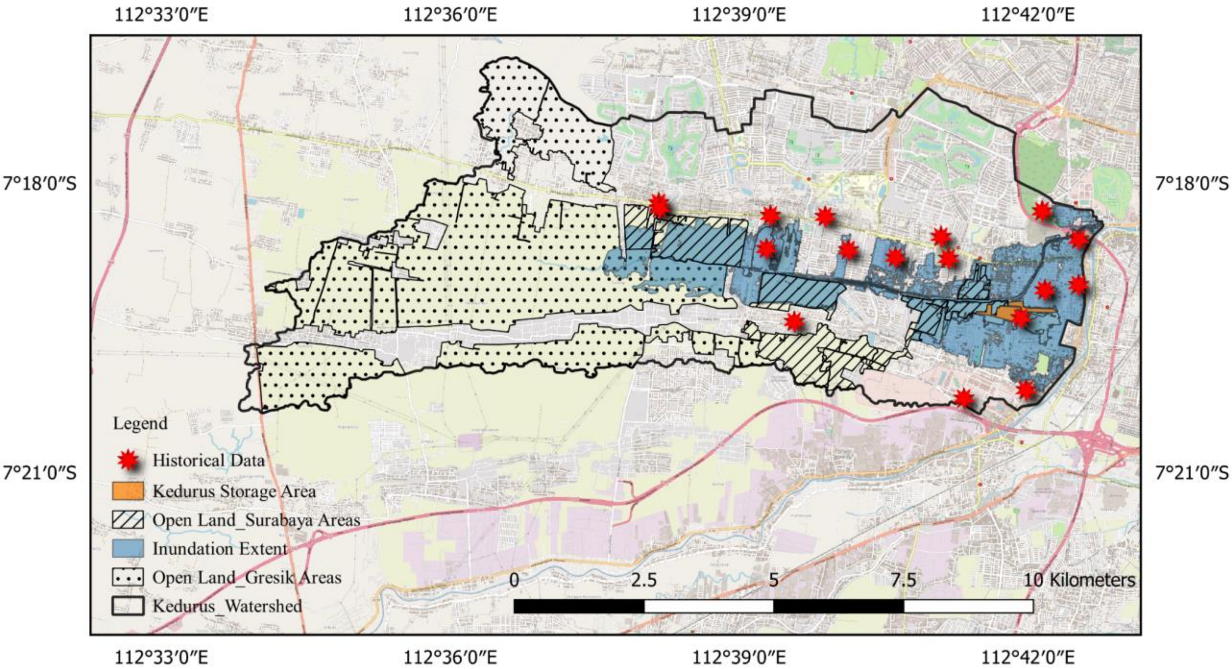

Fig. 8 The flood extension compared to the data. (the base map was obtained from openstreetmap.org)

Fig. 8 shows the location of the inundated area based on the simulation model results (represented by the blue colored areas) compared to the historical data (represented by the drop shadow marks). Because the watershed boundary of the historical data is slightly different from the simulation, the comparison result in this figure was adjusted according to the historical data and SDMP. This adjustment was aimed at exposing the inundation results to the same watershed border as the SDMP and historical data. The shortcoming of this simulation result is the storage location and undeveloped areas/open land as the inundation area. This is owing to the elevation, which is lower than that of the surrounding area. Therefore, it is necessary to adjust the location that is excluded from the investigated area, in which the storage area is undoubtedly inundated, and the adjustment can also be applied to the undeveloped areas.

6. CONCLUSIONS

A 2D urban flood simulation was performed using HEC RAS model packages. It aims to study the performance using the boundary condition based on the hydrological conditions in the area. Two types of boundary conditions representing flow were used in this simulation: flow hydrograph and rain-on-grid. This boundary condition was determined by considering a schematic of the drainage system schematic, in which the flow hydrograph represents the discharge from the upstream. The rain-on-grid was chosen to represent the rainfall simulation through the subcatchments. This study provides more information regarding the requirements of each boundary condition. Therefore, it can be used as a reference to set up boundary condition parameters.

The flood simulation was conducted using the two aforementioned boundary conditions. The flow hydrograph represents the rainfall–runoff and was obtained from SWMM. The simulation could obtain the optimal model when the flow hydrograph was used as the boundary condition. This shows that the simulated inundation extent is accurately representative of the historical data.

Although the rain-on-grid represents the real physical condition, several aspects should be considered when using this boundary condition. The simulation results showed that the rain- on-grid is less accurate than the historical data. The terrain data does not represent the drainage channel, and the model of the drainage channel in the 2D simulation required a fine grid, which is not effective. Furthermore, the precipitation boundary condition assumed no infiltration or evaporation. Therefore, rainwater, which falls in a catchment area, is assumed to be the overall surface runoff.

Overall, the simulations revealed that assessing the contribution of the cross-section capacity is difficult. However, this 2D model can be used in urban flooding because it can obtain acceptable results and address the watershed problems. Therefore, this 2D model is applicable and reliable for simulating inundation with limited channel cross-section data.

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