Effects of Settlement Development and Green Drainage Facility to Surface Runoff in Bodo River Basin Malang

Ratih Indri Hapsari, Syahrul Muhamad Ilham, Utami Retno Pudjowati, Suhartono

ABSTRACT--- The rapid urban development in Malang sub-urban area in Indonesia has increased the vulnerability of river basins to water-related disas-ters. Water sustainability in Malang, which is located in upper Brantas River Basin, becomes an important issue as the river serves as the most important source of water supply in East Java Province. The objective of this study is to evaluate the impact of a housing area (0.069 km2) and the green drainage facility in Malang Regency to the hydrological characteristic in Bodo River (4.937 km2), a tributary of Brantas River. The sustainable drainage system applied in this study is detention pond. This study requires land terrain data, daily rainfall data from Karangploso, Dau, and Singosari rain gauges, hourly rainfall data from JAXA global dataset, soil bore log and cone penetration data, and land use data. The designed rainfall is analysed by Log-Pearson Type III frequency distribution with 10 years return period. SCS hydrograph method from HEC-HMS software is applied to analyse the surface runoff and infiltration. Curve number is spatially analysed based on the soil properties and land use data, which has value of 83.37 and 96.9 for Bodoriver and housing area respectively. The hourly rainfall is assumed to have triangular distribution with 7 hours duration within a day. The analysis reveals that the existence of housing area increases the runoff of 0.46 m3/s. The designed flood in Bodo River for 10 years return period is 26.243 m3/s with 14 hours duration, while the runoff with contribution from housing area is 26.701 m3/s. In order to reduce the peak flood and extend the flood lag time as well travel time, the detention pond is designed in the housing area based on the land availability. The pond dimension is 67.25 m width, 205.83 m length, and 0.8 m depth. The pond could retain the water of 685.705 m3 volume and reduce the peak flood in the river 0.0013 m3/s. The results demonstrate the benefit of constructing green drainage facilities to complement urban development aggregately.

Keywords—Sustainable drainage, flood discharge, detention pond, HEC-HMS

1. INTRODUCTION

Rapid development, particularly in developing countries, affects the water security in many ways. There are increasing risks of flooding, ground water scarcity, and water pollution, recognizing the necessity of environmentally sound approach for managing water sustainably. Instead of applying conventional system which conveying the water as rapidly as possible to the end outlet, implementation of sustainable drainage system leads to significant reduction of surface runoff, groundwater recharging, and enhanced the landscape of the site (Kennedy et al. 2007).

The drainage paradigm has switched from removing the stormwater quickly to the sustainable design that allows the water conservation by cost-effective solutions. Bio-absorption hole, retention pond, and infiltration well are among the sustainable drainage constructions that have been introduced by past studies (Charlesworth, 2010; Zhou, 2014). Retention pond is utilized to prevent downstream from runoff by reducing peak and extending the rising limb as well as to provide recreation facility. However, it requires the maintenance and specific structure.

Over the years, Indonesia has seen many flood disasters that have brought about great losses (Hapsari and Zenurianto, 2016). With 30% increasing of municipal water demand in 2015 and flooding problem in many regions, promotion of stormwater infiltration through the construction of a million biopore absorption holes is set on Malang development agendas. A case study in Bodo River catchment in Malang, Indonesia is presented to evaluate the hydrological characteristic. This river is a tributary of upper Brantas River that serves as the most important source of water supply in East Java Province. Located in the Malang sub urban area, this region has increasingly rapid growth of human settlements. Taking into account the local physical features, topography and zoning regulation, the selected sustainable drainage component is detention pond supplementing traditional drainage channels.

There have been some studies reviewing the impact of land-use change to natural surface runoff in urban river basin (Niehoff et al., 2002; Naef et al., 2002). However, the consideration of including green drainage facilities to the flood risk reduction has not been adequately studied (Harrel and Ranjithan, 2003; Harbor, 1994). Furthermore, there is lack of the study in upper Brantas River (Rizkiana et al., 2017). Regarding the research on detention pond, Guo (2001) and Chen et al. (2007) have elaborated the feature of detention pond as well as the modeling of hydrological characteristic especially to reduce the flood impact.

This paper presents the analysis of surface runoff in Bodo River basin and the impact of housing area development with including the green drainage facility, i.e. detention

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pond. At the first part, the hydrograph at Bodo outlet with the absence of settlement area is analyzed. The flood discharge at the same outlet without the existence of settlement area is compared. Finally, the practical designs of detention pond is described and the surface runoff, infiltration, lead time, and other hydrological characteristic are compared between the existing design and the inclusion of detention pond. The designed storm is analyzed by Log-Pearson Type III frequency distribution with 10 years return period. SCS hydrograph method from HEC-HMS software is applied to analyze the surface runoff and infiltration considering the soil properties and land use data to obtain curve numbers. The hourly rainfall is assumed to have triangular distribution with 7 hours duration within a day. This study is expected to contribute to the consideration of housing development in urban river basin.

2. STUDY AREA AND DATASETS

The study is conducted in Bodo River Basin in Malang Regency. Figure 1 shows the situation of the study site. This watershed is covered by paddy field, forest, and grass land in the upstream and combination of housing area with grassland in the downstream. The development of Mayla housing area in the west-downstream (-7.898672, 112.608695) is analyzed to assess the impact to the Bodo River flow features. The basin outlet is shown by red square in Figure 1. The catchment area in this outlet 4.937 m2, while the area of housing region is 0.069 km2. The land use or land cover map is obtained from Google Earth satellite image. The soil type is mainly clayey silt which is obtained from soil bore log and cone penetration data. Three closest rain gauges are employed to derive the precipitation data, i.e. Karangploso, Dau, and Singosari Stations. Daily maximum rainfall rate from 2008 to 2017 in these three station is used for calculating design rainfall. The minimum and maximum daily maximum rainfall rate are 62 mm/hour and 153 mm/hour respectively. The discharge observation station is available along this river as indicated by blue dot in Figure 1. Though thelocation of the station is not exactly on the targeted basin, this data will be used for verification. The discharge of Bodo River at southern part ranges from to 0 to 145 m3/s.

3. RESEARCH METHOD

3.1. Rainfall Frequency Analysis

The maximum daily rainfall data is processed to obtain the most probable stormwater that will contribute to the surface runoff. Beforehand, several quality control procedures are done, which include generating the missing data and consistency test with double mass curve method. Areal rainfall as calculated by mean aver- age method, as the catchment scale is categorized as small size or less than 500 km^2. Considering the skewness and kurtosis value, the available data fit with Log Pearson Type III distribution. It is calculated using the general equation:

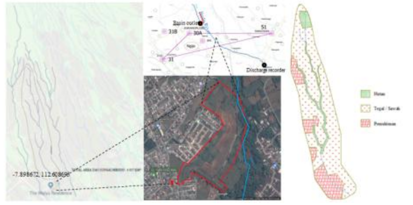

Fig. 1: Site map of study area (accessed from Google Maps February 5, 2018), location of rain gauges and river discharge observation station, land use map

$$\log X_{TR} = \overline{\log X} + G_{TR} \cdot S_{\log X} \tag{1}$$

where, X_{TR} is the designed rainfall with TR return period, $\overline{\log X}$ is the average of rainfall logarithmic value, G is the frequency factor from table for TR return period, and $S_{\log X}$ is the standard deviation of rainfall logarithmic value. Ten years return period is taken considering this main function of the river is drainage system and the catchment has low to medium level of risk. The goodness of fit test is conducted by Smirnov-Kolmogorof and Chi-Square methods.

3.2. Spatial Data Preparation

The land use map (Figure 1) and soil and are processed to obtain the runoff generation coefficient. Here, the coefficient is represented as curve number. The ratio of impervious surface to total area for Bodo catchment and housing area are 0.19 and 0.94 respectively. The soil test shows that the cone resistance, q_c is 16.33 kg/m^2 and the friction ratio, FR is 4.68%. According to the soil classification chart (Robertson, 1986), the soil type is categorized as clay. SCS curve number gives the runoff coefficient of 79 for forest, 80 for paddy field, and 98 for housing area (NRCS, 1986). This data is used to determine the SCS curve number. The topographical data is used to calculate the catchment gradient. The average terrain slope of Bodo catchment is 0.132.

3.3. Rainfall-runoff Simulation by Conceptual Model

In this study, the hydrological process in the watershed is simulated by HEC-HMS (USACE, 2005) conceptual model. In this model, the response of a dendritic watershed system with specific properties to the precipitation is simulated. Basically, it is a physically-based model that includes all hydrological component. It allows unit hydrograph and hydrologic routing with capabilities of linear-quasi distributed runoff transform (ModClark) for use with precipitations, continuous simulation with one to five layers soil moisture method. In terms of spatial process, this model is a non-distributed model. The main advantage are the graphical user interface, continuous process generation, and inclusion of spatial data. The model range includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

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In this simulation, the loss rate is calculated with SCS curve number method. The transform of rainfall to runoff uses SCS unit hydrograph method. The baseflow is assumed zero for simplicity. The flood is routed by kinematic wave method. The time interval is 1 hour. The precipitation data is input as single rainfall data which is uniformly distributed spatially all over the watershed. The hyetograph is developed to represent the time variability of rainfall. As the continuous hourly rainfall data is unavailable, the hyetograph is developed triangular hyetograph based on the hourly satellite data. JAXA Global Rainfall Watch-GSMAP (Global Satellite Mapping of Precipitation) during high rain is used to define the common rainfall duration in the study site. Triangular hyetograph assumes the rainfall depth is distributed in triangle pattern (Chow, 2010) shown below:

$$I_p = \frac{2P}{t_d} \quad (2)$$

Where, *Ip* is peak hourly rainfall (mm/hour), *t* is rainfall duration (hour), *P* is daily rainfall intensity for specific return time (mm/day), t_d is rainfall duration (hour) shown below:

$$t_p = r.\, t_d \quad (3)$$

Where, t_p is time of peak (hour), *r* is constant (0.3 – 0.5)

Lag time, T_p (minute) which is required by the model as governing parameter, can be defined as the time between beginning of the flood to the peak runoff. The lag time is calculated following SCS method by including the concentration time. The concentration time, T_c which is the time needed for water to flow from the most remote point in a watershed to the watershed outlet, follows the Kirpich method shown below (Natakusumah et al., 2011):

$$T_p = \frac{2}{3} T_c \quad (4)$$

$$T_c = T_0 + T_d \quad (5)$$

$$t_o = \left(\frac{2}{3} x 3{,}28 x L_0 x \frac{n}{\sqrt{s}} \right)^{0{,}167} \quad (6)$$

$$t_d = \frac{Ls}{60v} \quad (7)$$

Where, T_0 is time needed for water to flow from the most remote point in a watershed to the channel upstream (minute), T_d is time needed for water to flow from the channel upstream to the watershed outlet (minute), L_0 is the distance of flood plain (m), *n* is Manning roughness coefficient of the flood plain, *S* is the slope of flood plain, L_d is the length of channel (m), *V* is the designed channel velocity (m/s).

The basin model is prepared by developing the map of delineated catchment. Three scenarios are included: a) river without residential area, b) river with additional area from residential area, and c) river with residential areathat applying retention pond. Figure 2 depicts the basin model for three scenarios.

3.4. Application of Sustainable Drainage

The concept of retention pond is store the water during the maximum flood and gradually release when the river discharge is normal. Specifically, the pond reduces the peak flood in order to decrease the overtopping risk. Firstly, the pond location is selected, which is recommended at the low-lying site. In this study area, the pond is located at the lower part of the residential area to allow for receiving drained storm water. The outlet of the drainage system is Bodo River. The pond capacity is calculated based on the topographical map. Afterward, the influence of the pond to the simulated discharge is calculated by HEC-HMS. Figure 3 illustrate the design of retention pond and the elevation-capacity curve. The pond dimension is 67.25 m width, 205.83 m length, and 0.8 m depth. The maximum capacity is 685.705 thousand m3. As the spillway is not designed with control gate, the highest water storage is 376.127 thousand m3. The pond is treated as reservoir in the model.

4. RESULTS AND DISCUSSION

4.1. Hydrological Assessment of the Existing System

The frequency analysis reveals that the designed rainfall with 10 years time return is 120,41 mm/hour. This magnitude is similarwith the one calculated by in Ciliwung Basin Malang (Pandulu and Widodo), i.e. 137.27 mm/hour. This amount implies the probability of a rain of equal or greater magnitude than 120.941 mm/hroccurring in any one year period is 10%. This amount is approximately similar with the rainfall on October 10, 2016. According to the evaluation of hourly rainfall from JAXA, the duration of the rain is 7 hours that occurred at 00:00 to 07:00 LST. When comparing our results to those of older studies (Limantara et al., 2018), it must be pointed out that the rainfall duration in Lesti as tributary of Brantas River Basin is 4 hours. This discrepancy might be attributable to the method difference, in which Limantara et al. (2018) applies effective rainfall duration instead of actual recorded rainfall duration.

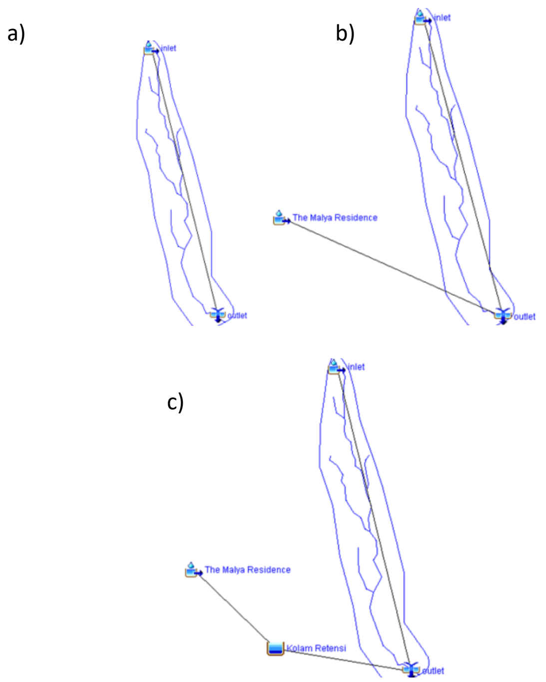

Fig. 2: Basin model with a), b), and c) scenario

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Once the rainfall peak and duration are known, the hyetograph can be developed as depicted in Figure 4. From the triangular hydrograph analysis, the peak hourly rainfall, I_p is 34.6 mm/hour that occurs at, t_d 2.8 hours from beginning. As the simulation is done in hourly scale, t_d is rounded to 3 hours. This data will be input as time series data for precipitation gage in the model.

The calculation of curve number from spatial data give results of 83.37 for Bodo watershed and 96.9 for residential area. Here we compare the curve numbers with those of other reference (Setyorini et al., 2017) who found that the curve number of upper Brantas River is 35 to 92. The lag time which is required by the model as governing parameter, is calculated and gives the value of 86.32 minute and 91.5 minute respectively for Bodo watershed and residential area.

From the simulation, it is obtained that the discharge at drainage outlet from the housing area applying conventional drainage system is 0.460 m^3/s that occurs at 05:00 LST or 5 hours after the peak rainfall (Figure 5). It can be inferred that the depth of total precipitation in the basin is 120.941 mm/day. In the watershed system, this volume is partially infiltrated to the soil with amount of 35.64 mm, while the excess water of is then transformed as runoff.

The results of the simulation at Bodo outlet are shown in Figure 6. In the case of existing river basin and river basin with residential area, the runoff volume is 85.26 mm and 85.63 mm respectively. This result highlights that that the inclusion of residential areaincreases the volume of water in the basin outlet, as the basin areaalso increases. As consequences, the runoff discharge in the outlet also increases from 26.243 m3/s to 26.701 m3/s.

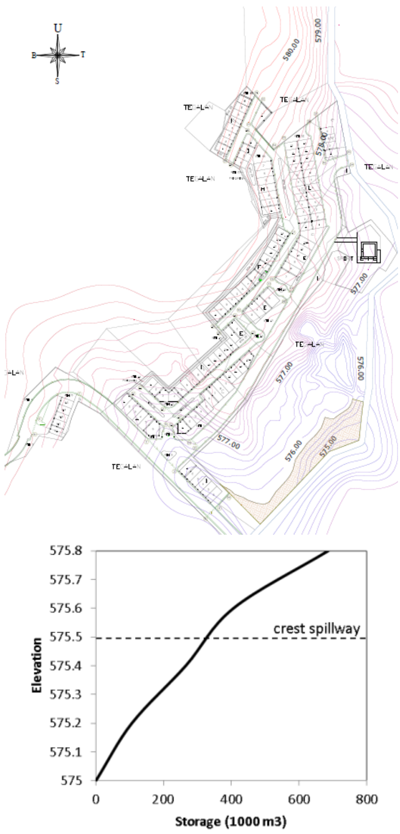

Fig. 3: Design of retention pond and the elevation-capacity curve

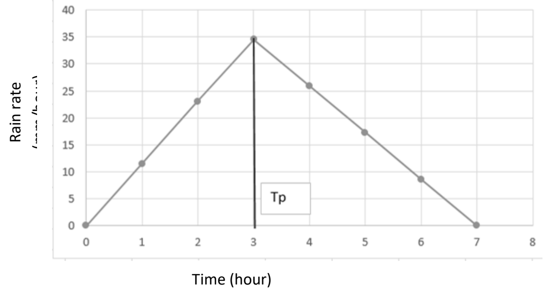

Fig. 4: Hyetograph showing the hourly rainfall distribution

The model simulation requires verification to ensure the correct representation of the watershed system by the input parameter and the selected method inside the model. As the available discharge measurement is limited in downstream of Bodo River, the validation is conducted by evaluating the plausibility of the simulated with the observed discharge in upstream and downstream respectively. The observed discharge ranges from 10 m3/s to 145 m3/s (Leonita et al., 2017). With the catchment area of 67.680 km² in the downstream compared with that of 4.937 km2 in the upstream, the simulated discharge of 26.243 m3/s is shows reasonable reproducibility by the model.

4.2.Evaluation of the Sustainable Drainage Application

In this section, we evaluate the impact of the housing area that applies the sustainable drainage system to the river runoff. The**conventional drainage system**outflow hydrograph from housing area as shown in Figure 4 becomes an inflow of the retention reservoir. Figure 7 bottom shows the outflow hydrograph of the pond simulated by HEC-HMS. The peak runoff is 0.453 m3/s that occurs on 05:00 LST. During the peak flood, the retention pond could store the water to the maximum level. The water surface variation is shown in Figure 7 top. From the figure, it can be seen that the overtopping of 575.5 elevation occurs at 05.00 LST. The water surface at this elevation equals to 343.16 m^3 volume of water.

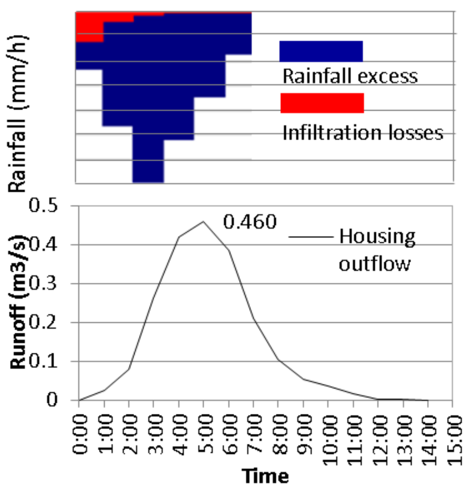

Fig. 5: Outflow hydrograph in the housing area applying

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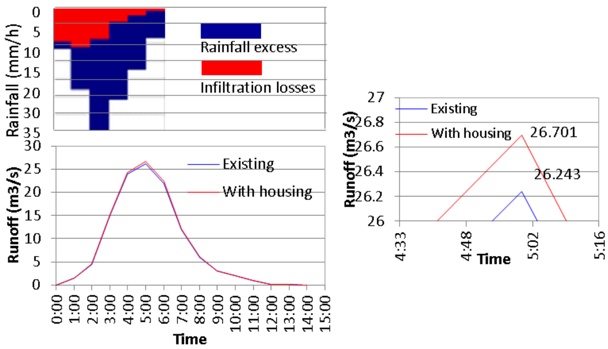

Fig. 6: Rainfall-runoff simulation of the watershed system applying conventional drainage system

By adding the green drainage facilities in the residential area, the discharge can be reduced from 26.701 m3/s to 26.230 m3/s, which is nearly the same as existing condition (Figure 8). Though the amount is somewhat insignificant because of the tiny basin, the finding has strengthen the importance of considering green drainage facilities in the overall basin.

In respect to the flood timing, the time at which the peak runoff is occurring is 05:00 LST or the time to peak is 5 hours. The base time, or the total duration of flood is 14 hours. The travel time which is also known as lag time, is 2 hours. This parameter means the time between the gravity center of rainfall hyetograph and the peak of the hydrograph. All of these time parameters are the same for three scenarios. This is because the simulation is run in hourly based, which is not possible to display the temporal variation in minute scale.

The present study confirmed the findings about the reduction of flood discharge resulted from upstream retention pond. The decreasing of peak flow in the nearby river is obvious if the newly developed housing applies the green drainage facility. We have verified that using the result from Soong et al. (2019) that confirms the similar finding. As for the performance of the system in decreasing the time to peak as well as time travel, a more research is needed particularly by running the model in minute scale. Further study is recommended to include other sustainable drainage facilities in the urban area for managing surface water and groundwater recharge which is expected to contribute to water resources sustainability.

5. CONCLUSION

This paper has demonstrated the impact of the built-up area with applying conventional and green drainage facility to the flood in urban river basin. The analysis reveals that the housing drainage discharge is 0.460 m3/s that is likely to increase the flood discharge at the Bodo River with the same amount. The designed flood in Bodo River for 10 years return period is 26.243 m3/s with 14 hours duration, while the flood in Bodoriver with the inclusion of housing area is 26.701 m3/s. The study has confirmed the advantage of developing the retention pond as a part of green drainage facility that store the water from the housing drainage outlet. The performance of the pond is shown by the decreasing of the river flow from 26.701 m3/s to 26.230 m3/s, which is nearly the same as existing condition. Constructing green drainage facilities is obviously essential to lessen the flood risk in rapidly developed urban area. For improvement of the study, it is advised to include various green drainage components, to calibrate and validate the model by observed hydrograph, and evaluate the overall benefit of sustainable drainage such as ground water and water quality.

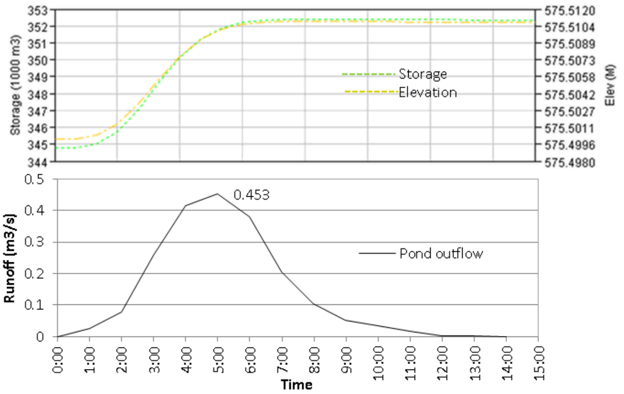

Fig. 7: Outflow hydrograph in the housing area applying green drainage system (bottom), the variation of water storage in the pond (top)

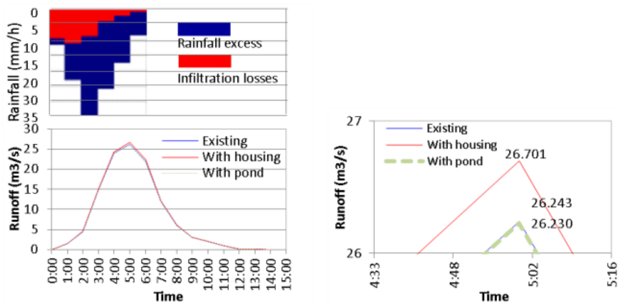

Fig. 8: Rainfall-runoff simulation of the watershed system applying green drainage system

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