Modelling Water Flow Hydraulic in Open Channels with Green Drainage Facility

Ratih Indri Hapsari, Roikhatul Jannah, Moh. Charits, Agus Suhardono, Mona Shinta Safitri

ABSTRACT---High increasing of urban area in greater Malang Indonesia has been raising the water availability issues in surrounding river basins. Providing the green drainage system in residential area would be expected to contribute to the water sustainability in the sub-basin where the area is located. This study aims to design and evaluate the effectiveness of sustainable drainage channels and structures in a housing area in Malang Regency with area of 75,000 m2. The green drainage facilities includes pervious channel, permeable pavement, and retention pond. The data required are topographical map with 0.25 m interval, daily maximum rainfall rate from Lawang, Singosari, and Tumpang rain gauges, and soil properties. The design rainfall is analysed by Gumbel frequency distribution with ten years return period. Rational method is applied to calculate the design flood in conjunction with Kirpich and Mononobe method to analyse concentration time and rainfall intensity. Manning formula is used to design the channel dimension based on open channel hydraulic and uniform flow theories. The retention pond is planned by analysing the design capacity from the flood inflow and designed outflow hydrograph of the pond. The complexity of the hydraulic analysis considering the unsteady flow motivates the application of HEC-RAS one-dimensional hydraulic software. The analysis shows that the flood discharge in the primary channel is 5.007 m3/s using full asphalt pavement and 4.560 m3/s using permeable pavement. The dimension of the primary channel is designed as typical channel with 1.4 m width and 1.4 m height. Should the concrete channel is applied, the retention pond is designed to extend the flood timing of 3.578 minute and reduce the primary channel discharge of 0.070 m3/s. The analysis reveals that the adequate pond dimension is 30 m width, 20 m length, and 0.61 m depth. The pond could retain the water of 368.252 m3 volume, infiltrate the water of 26.280 lt/year to the ground water, and reduce the peak flood in the channel from 5.007 m3/s to 4.328 m3/s. The water level profile of steady flow is evaluated through HEC-RAS simulation. This analysis is important to assess the flow velocity, energy, and regime of the continuous channel in steady manner, which cannot be obtained directly from the initial Manning calculation. In addition, the unsteady flow caused by the existence of pond is simulated by HEC-RAS. The results demonstrate that the water stage and energy variation could be accommodated in the designated channels. This research is expected to provide benefit as consideration of the utilization of sustainable drainage facilities in development of urban area.

Keywords—Detention pond, HEC-RAS, flood discharge, drainage channel

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1. INTRODUCTION

Recent development of urban drainage system has been switched the paradigm from discharging the storm water as quickly as possible to retaining the water in the basin to allow more infiltration. This concept is called sustainable drainage system which includes green drainage infrastructures. The good practices of green drainage system are green roofs, filter drains, permeable pavement, swales, detention basin, retention pond, and wetland (Charlesworth et al., 2003). Unlike the traditional drainage system, these solutions generally keep the water on the surface and release the water as natural as possible. This approach is highly encouraged as complement to the conventional drainage system. Providing the green drainage system in residential area would be expected to contribute to the water sustainability in the sub-basin where the area is located.

The performance of green drainage system sustainability can be assessed not only through the technical aspects, but also environment, social, and economic aspects (Ellis et al., 2004). Water quantity matters including the reduced flood, prolonged flood time travel, groundwater recharge, and flow regime are some criteria in determining the project feasibility. There have been numerous researches that study the effect of sustainable drainage facilities to reduce the peak flow (Stovin et al., 2007, Davis et al., 2011). However, the studies on their impacts on the hydrology and hydraulic aspects simultaneously are limited (Abbott and Mateos, 2007).

Retention pond in a built up area provides temporary storage of storm water in the reservoir and thus attenuate the flood. However, its presence may consume a large portion of the site. Therefore, its combination with other facilities, like permeable pavement would compensate the disadvantage of land occupancy. In addition, the permeable pavement along with the retention pond would provide a sustainable landscape with green space and recreational facilities for increasing the value added. Permeable pavement is alternative material for road, parking, or pedestrian space that could significantly maximise the infiltration and minimize the flow as well as delay the flood if it is applied in wide space (Ndon 2017).

The application of sustainable drainage technology affects the hydraulic parameters including channel flow, water depth, flow velocity (Paredes, 2018), and flow profile. Before conducting the hydraulic physical modelling, it is necessary to calculate the model by computational model.

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The hydraulic modelling is indispensable to address the performance and safety of the structure. The application of retention pond has causes the unsteady flow in the channels. In the case of open channel that is a part of sustainable drainage, the calculation require as the flow may be and non-uniform flow.

The objective of this study is to evaluate the alternatives of sustainable drainage that applies conventional stormwater channels and green infrastructures in a housing area in Malang Regency. The assessed criteria are reduced flood discharge in drainage outlet and some hydraulic parameters. The complexity of the hydraulic analysis considering the unsteady flow motivates the application of HEC-RAS one-dimensional hydraulic software. This research is expected to provide benefit as consideration of the utilization of best practice sustainable drainage facilities in development of urban area that assures the technical feasibility and construction safety.

2. RESEARCH METHODOLOGY

2.1. Designing the Dainage System

The permeable pavement is included by applying the concrete block in the road and pedestrian pathway. The impact is obvious in hydrological matter, that is i.e. reducing the storm water flow volume as the runoff coefficient is lower. In addition to permeable pavement, the pervious drainage channel is applied by using the earth lining material.

Retention pond is a system that store the storm water temporarily to be slowly released after the heavy rain. The pond that being filled up with the flood volume controls the impact on the downstream. Usually, it is placed in the area that will effectively reduce the flood magnitude, i.e. in the downstream of particular basin. It can be constructed either in a low-lying site or in a flat area by excavating a flat area (DPURI, 2012). Retaining wall is designed in the excavated retention pond. The height of retaining wall should be less than 2 meter for stability and artistic reasons. The walls should not occupy more than 50% of the pond perimeter. The pond capacity is decided according to the desired reduced flood magnitude and timing. The dimension of the pond is then calculated according to the topography and the designed capacity.

2.2. Flood Frequency Analysis

The designed rainfall with 10% occurrence or 10 years return period that will contribute to the surface runoff is analyzed considering the catchment has low to medium level of risk. Extreme high-flow analysis uses maximum rainfall data to analyze the flood frequency. Data preparation procedures including selecting three closest rain gauges, interpolating the missing data, and consistency test with double mass curve method are conducted before the rainfall data processing. For small catchment with size less than 500 km, areal rainfall as calculated by mean average method. The rainfall frequency analysis in processed by Gumbel Type I distribution following general equation (Chow, 2010):

$$X_{TR} = \overline{X} + \left(Y_t - Y_n\right)\frac{S}{S_n} \tag{1}$$

$$Y_T = -\ln\left(-\ln\frac{T_R - 1}{T_R}\right) \tag{2}$$

where, X_{TR} is the designed rainfall with TR return period, $\bar{X}$ is the average of rainfall, Y_t is the reduced variate, Y_n and S_n are Gumbel parameters, and S is the standard deviation. The goodness of fit test is conducted by Smirnov-Kolmogorof and Chi-Square methods.

The designed flood discharge is calculated by rational method (French et al., 1974), a simple method to determine peak flow from drainage system:

$$Q = C \cdot I \cdot A \tag{3}$$

where, Q is runoff (m3/s), I is rainfall intensity (mm/hour), A is catchment area. Empirical Mononobe method is used to calculate rainfall intensity:

$$I = \frac{R}{24}\left(\frac{24}{t}\right)^{\frac{2}{3}} \tag{4}$$

where, R is design rainfall (mm/day) and T_c is concentration time, which is the time needed for water to flow from the most remote point in a watershed to the watershed outlet. T_c is calculated by Kirpich method as follows (Suripin, 2004):

$$t_c = t_0 + t_d \tag{5}$$

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

$$t_d = \frac{Ls}{60v} \tag{7}$$

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

2.3. HEC-RAS for Evaluating Water Flow Regime

Open channel simulation is used to study the flow pattern along the channels. HEC-RAS is a software to mimic the hydraulic physical phenomena of flow in real channel through series of mathematical relationship of flows variables, e.g. geometric, kinematic, and dynamic (USACE, 2010). In this study, the flow simulation is treated as both steady and unsteady flow. Steady flow modelling is calculated as steady gradually or rapidly varied flow. In HEC-RAS, the flow module is solved by one dimensional energy equation. The energy loss is calculated by friction and contraction/expansion constants using Manning formula.

Momentum formula is applied in rapidly varied flow, that includes hydraulic jumps, hydraulics of bridges, hydraulics of channel confluences. Below is the energy equation as governing formula of HEC-RAS one-dimensional model:

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$$Z_2 + Y_2 + \frac{a_2 V_2^{\ 2}}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^{\ 2}}{2g} + h_e \quad (8)$$

Where, Z is elevation of the main channel inverts, Y is depth of water at cross sections, a is velocity weighing coefficients, V is average velocities, g gravitational acceleration, and he is energy head loss. The dynamic flow is calculated based on 1-D Saint Venant Equation using an implicit and finite difference method. In this study, the channel geometric is input based on the channel designing procedure using Manning formula prior to the hydraulic simulation:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \quad (9)$$

where, V is flow velocity (m/dt), R is hydraulic radius (m), and S is slope. The hydraulic features of applying each drainage system is evaluated by HEC-RAS, i.e. water surface profile, flow profile, and flow velocity.

2.4. Case Study Area

The framework is evaluated through a case study in Zhafira residential are in Malang, Indonesia. It is located at $112^0$40'47.74"E and $7^0$52'49.14"S. The area of this housing is 7500 m2. The data used are topographical map with 0.25 m interval, daily maximum rainfall rate from Lawang, Singosari, and Tumpang rain gauges, and soil properties. Figure 1 shows the study site, site map, topographical map, and location of rain gauges.

3. RESULT AND DISCUSSION

3.1. Designe of sustainble drainage and runoff attenuation

In this chapter, we describe the advantage of applying sustainable drainage against conventional system in terms of the flood and drainage outlet channel capacity. At first, the drainage network system to allow the water flowing in gravity. Figure 2 shows the drainage system including the retention pond. Should the traditional system is applied, the pond is replaced by the housing lots. The time concentration of the pond inflow is 2.687 minute for t0 and 2.422 minute for td giving 5.109 minute for time concentration. The lead time of pond is design 6 minute. With this pond, the required capacity is 368.252 m3. Figure 3 is the inflow and outflow hydrograph of retention pond.

Table 1 provides the comparison of the scenario performance to assess the effectiveness of proposed system. From the results, it is obvious that implementation of retention pond and permeable pavement could reduce the peak flood to 4.328 m3/s and 4.560 m3/s respectively from 5.007 m3/s. These values are equivalent to 16.6% and 8.93% respectively. By comparing the results from Meierdiercks (2016), a similar conclusion is reached that decreasing 33% of impervious surface would reduce the peak discharge of 24.4%, while adding retention pond would decrease the peak flood to 357.6%. Though the reduction of peak flood using the proposed facilities in this study is somewhat smaller, it is important to note that the impervious surfaces have the most contribution to the storm runoffs of the community as stated by Liu et al. (2014) compared to swale and green roof. In the case of pond, the reduction is much smaller to the expected value as the size of the pond itself, which is the main factor determining the reduction, is small due the space availability. It is important to note that the reduction capacity for single facility is limited. Therefore, it is suggested to integrate some facilities at once to allow for more effectiveness.

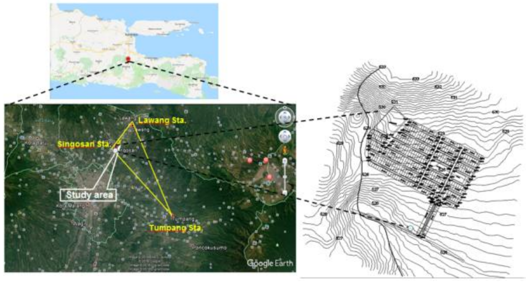

Fig. 1: Study site, site map, topographical map, and location of rain gauges.

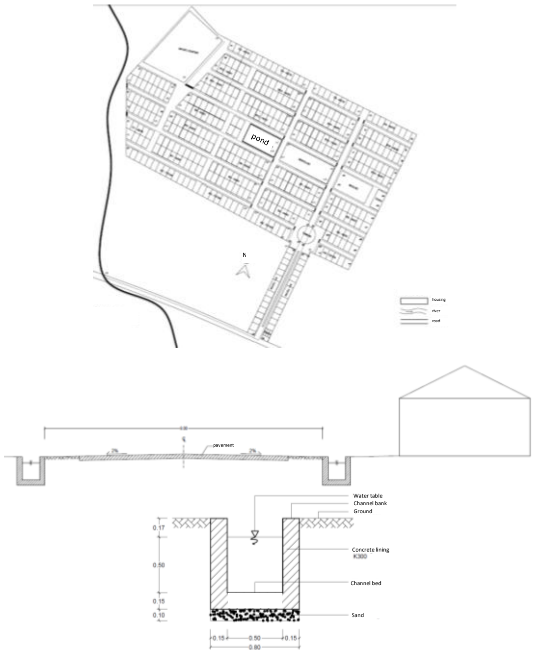

Fig. 2: Design of sustainable drainage infrastructure

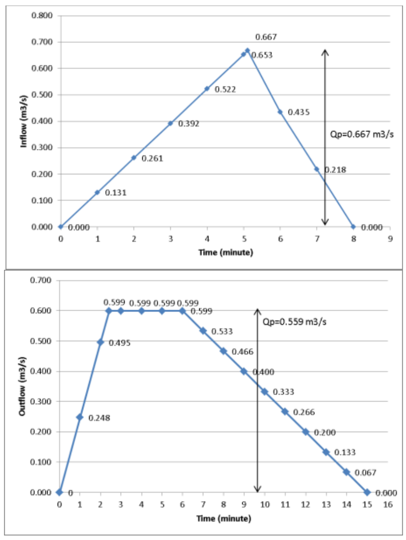

Fig. 3: Inflow and outflow hydrograph of retention pond

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By reducing the runoff at primary drainage, in fact, it is possible to construct more economical channel. However, in this study we use same concrete channel dimension for easiness of construction method. Infiltration is simply said as a portion of rain water that is not converted to surface runoff and soak to the ground. In this study, all calculation of water balance has been subtracted by evapotranspiration. In line with reduced runoff, the retention pond and permeable pavement promote more infiltration and in turn enhance groundwater recharge.

3.2.Hydraulic simulation

Hydraulic simulation requires correct definition of boundary condition and initial condition. In steady flow, the boundary condition is discharge and water level. The discharge is varied in each channel reach because the junction is assumed does not exist and the channel tributaries are treated as different reaches (see Figure 4).

Table 1: Performance of traditional and sustainable drainage in terms of flood feature and construction

Scenario	Runoff at primary drainage	Channel dimension	Extension of flood lead time	Infiltration
Conventional	5.007 m3/s	B=1.4m H=1.4m	N/A	3.007 m3/s
With retention pond	4.328 m3/s	B=1.4m H=1.4m	3.578 minute	3.007 m3/s and additional 2.601 m3/s
With permeable pavement	4.560 m3/s	B=1.4m H=1.4m	N/A	3.384 m3/s
With pervious channel	5.007 m3/s	B=1.5m H=1.5m	N/A	3.007 m3/s

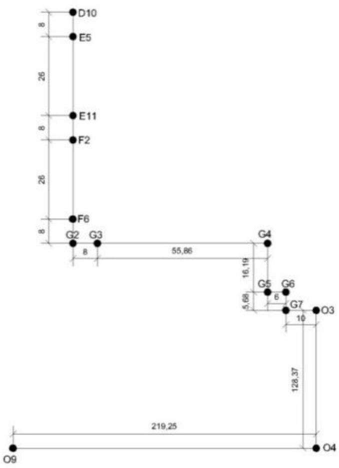

Fig. 4: Schematic diagram of channels network for hydraulic simulation

The water level is set 1.4 m in the channel inlet and outlet. In unsteady flow, the boundary condition is the outflow hydrograph from the retention pond and the channel slope in the outlet of 0.005. The initial condition is the maximum discharge rate from pond outflow.

Figure 5 illustrates the result of hydraulic simulation of steady flow in long section view without applying green infrastructure. The water level ranges 0.647 to 1.440 m. Generally, the flow velocity and Froude number increase by the distance from the upstream. The velocity varies from 1.241 m/s to 3.287 m/s with Froude number of 0.491 to 1.005, which means the channels are characterized as subcritical flow with Froude number less than one. The flow velocity meets the requirement, i.e. no more than 3 m3/s for concrete channel.

The result of hydraulic simulation of steady flow in long section view with applying permeable pavement is shown in Figure 6. The water table in the open channel varies from 0.587 to 1.330 m. The simulated velocity varies from 1.264 m/s to 3.182 m/s with Froude number of 0.502 to 1.005. These parameters meet the requirement of drainage open channel. The flow velocity and Froude number progress to the downstream. This is attributable to the discharge, which also increases by the distance from the upstream.

In Figure 7, we show the steady hydraulic simulation with applying pervious channel. The water depth ranges between 1.042 and 1.619m. Froude number as the indicator of flow profile, varies from 0.232 to 1.005. The Froude number varies from 0.232 to 1.000 which is categorized as subcritical flow. This flow type is preferable in drainage channel as it behaves in a slow or stable way due to gravitational forces. In order to avoid the channel lining scouring that may cause the erosion, the flow velocity is checked, which results in 0.752 m3/s to 3.212 m3/s speed for all sections.

In Figure 8, we show the unsteady hydraulic simulation with installing retention pond. The water depth is changed dynamically, that ranges from 0.264 m to 0.441 m. Froude number varies from 0.017 to 1.007 which means the flow is categorized as subcritical flow. Subcritical flow is preferable as it behaves in a slow or stable way due to gravitational forces. The flow velocity ranged from 0.036 m3/s to 1.622 m3/s for all sections, which means it meet the maximum permissible velocity of concrete lined channel of 3 m3/s. It can be concluded that the presence of retention pond has decreased the flow discharge as well as the velocity. This is because of the flood discharge that decreases as the surface runoff is stored by the reservoir.

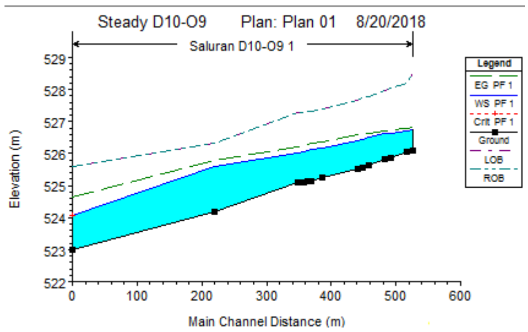

Fig. 5: Hydraulic simulation of steady flow in primary channel for conventional design (*EG* is energy gradient, *WS* is water surface, *Crit* is critical water depth, *LOB* is left channel overbank, and *ROB* is right channel overbank)

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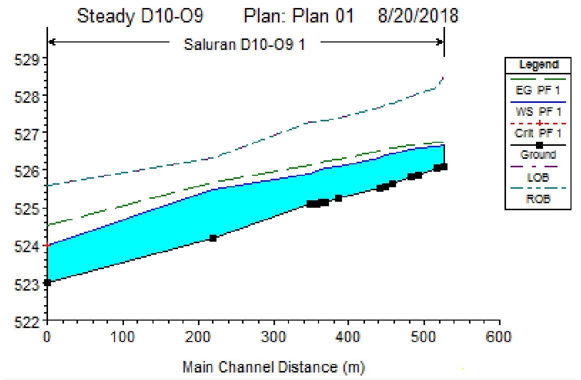

Fig. 6: Hydraulic simulation of steady flow in primary channel with permeable pavement

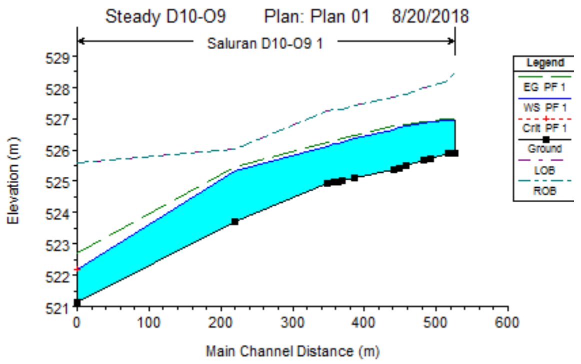

Fig. 7: Hydraulic simulation of steady flow in primary channel with pervious lining

This part summarises the findings and contributions made by this study. Summary of hydraulic performance of sustainable drainage design is given in Table 2. Evaluating the water depth is necessary to ensure the water is maintained in the freeboard level and no risk of overtopping. The stream velocity is needed to evaluate if the flow may cause the sedimentation due to low speed or erosion due to high speed (Chow, 1959). High velocity may exhibit supercritical flow, which is unfortunate for drainage channel. Supercritical flow is dominated by inertia forces which is characterized by fast and unstable flow. One concern about the findings of hydraulic parameters is that the alternative 3 and 4 do not meet the require- ment. This limitations can be overcome by modifying the channel slope and simulating again the alternative design. Finally, by using this method, the technical feasibility and construction safety can be evaluated to provide reliable infrastructure for community.

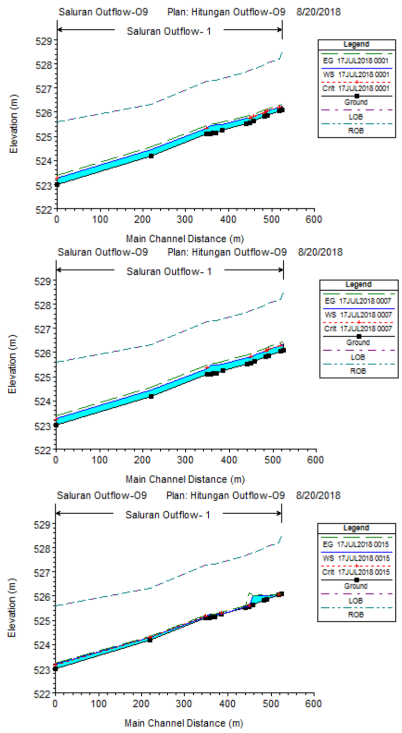

Fig. 8: Hydraulic simulation of unsteady flow in primary channel for conventional design with retention pond for 1, 7, and 15 minute

Table 2: Summary of hydraulic performance of sustainable drainage design

Alternative	Pavement	Channel	Pond	Water depth (m)	Flow velocity (m/s)	Froude number	Energy (m)
1	Asphalt C= 0.7	Concrete lining 1.4mx1.4m	N/A	0.647 to 1.440	1.241 to 3.287	0.478 to 1.005	0.647 to 1.440
2	Asphalt C= 0.7	Concrete lining 1.4mx1.4m	368.252 m3	0.264 to 0.441	0.036 to 1.622	0.017 to 1.007	0.264 to 0.441
3	Permeable pavement C= 0.5	Concrete lining 1.4mx1.4m	N/A	0.587 to 1.330	1.264 to 3.182	0.502 to 1.005	0.587 to 1.330
4	Asphalt C= 0.7	Pervious lining 1.5mx1.5m	N/A	1.042 to 1.619	0.752 to 3.212	0.232 to 1.005	1.042 to 1.619

4. CONCLUDING REMARKS

In this study, the design and evaluation of the effectiveness of sustainable drainage infrastructures in a housing area in Malang Regency with area of 75,000 m2 are presented. The green drainage facilities includes pervious channel, permeable pavement, and retention pond. The results show that the peak flow in drainage outlet is 5.007 m3/s using full asphalt pavement, and 4.560 m3/s using permeable pavement, and 4.328 m3/s with applying retention pond. The dimension of the primary channel is designed as typical channel with 1.4 m width and 1.4 m height. The retention pond extends the flood timing of 3.578 minute and decrease the primary channel discharge of 0.070 m3/s. This conclusion follows from the fact that the sustainable drainage facilities is environmentally beneficial, especially by treating stormwater to prevent urban flooding. Hydraulic simulation is able to show the water stage, flow profile, and flow velocity that could be accommodated by

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the designated channels. By using this approach, the technical feasibility and construction safety can be evaluated to provide reliable infrastructure in urban area. Future research should consider the potential effects of combining several drainage facilities more carefully. This provides a good starting point for further performance multicriteria measures, for example amenity and water quality.

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