The role of green infrastructure in reducing runoff in urbanized catchment areas of Eastern Jakarta

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Abstract. Urbanization has changed the land use from pervious cover to impervious cover which have an impact on increasing runoff in urban areas. The objective of this study is to determine the effectiveness of spatial distribution of Green Infrastructure (GI) in reducing runoff under various design storms. Simulation of runoff reduction is carried out by implementing the GI in the catchment area located in Pondok Kelapa, Eastern Jakarta, Indonesia. EPA SWMM 5.1 was used to simulate the performance of GI on reducing runoff in the study site for two simulation scenarios: baseline scenario (current conditions) and GI scenario (implementing rain garden and rain barrel). The results show that GI compared to the baseline under various design storms 2-year, 5-year, 10-year, 25-year and 50-year return periods reduce the total runoff volume approximately 9.67%, 8.92%, 8.49%, 7.94%, 7.54%, respectively.

1. Introduction
The rapid development in Jakarta encourages economic growth to attract large urbanization from the surrounding areas to come to Jakarta. Urbanization increases human population in Jakarta. The population growth rate from 2010-2015 was around 1.09% [1]. This condition has triggered the increase of residential, commercial and urban facilities. Urban development involves the replacement of vegetated area with impermeable surfaces; this process can exert profound influences on the biogeochemical cycle, hydrological process, climate change, and biodiversity in terrestrial ecosystems at multiple scales [2].

Stormwater runoff is generated when rainfall does not infiltrate into the ground but flows over the surface then enters to drainage system. The increased impervious cover which reduce the amount of infiltration will increase total runoff volumes and peak flow and consequently causing floods in urban area. In many cities in the USA, UK, Canada, Germany and New Zealand, the green infrastructure (GI) has been used to mitigate urban flooding [3]. The GI is designed to minimize the generation of urban stormwater runoff and associated pollution by using and mimicking natural system to collect, treat, and infiltrate rain where it falls at the site level [4]. The GI is designed to reduce the quantity of runoff by adding storage (often pervious) with the capacity to capture, evapotranspirate, and infiltrate stormwater [5].

The hydrological performance and benefits of GI practices have been shown in numerous studies in-situ-scales and micro-scales [6]. GI such as rain barrel/cistern and bioretention/rain garden attenuate runoff peak flow and reduce runoff [7][8]. GI quantification can be made by hydrological modeling using Stormwater Management Model (SWMM). SWMM uses a sub-catchment based modeling approach to simulate runoff generated from rainfall, where the runoff is captured or diverted to different conveyances, storage, and/or treatment devices [9].

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In this research, implementation of GI in study area were evaluated using SWMM model. The objective of this study is to evaluate the effectiveness of GI spatial distribution to reduce runoff under different storm return periods.

2. Materials and Methods

2.1. Study area
The study area is an urban catchment part of Buaran Creek Watershed located in Pondok Kelapa, Eastern Jakarta, Indonesia which geographically located between 6°14'06”-6°14'58” S and 106°55'51”-106°56'33” E. The location of catchment and boundary of study area are represented in Figure 1(a) and Figure 1(b). The catchment area approximately 165.13 hectares which is occupied by densely residential, commercial, and some open space land uses.

![Figure 1](a) Study area: (a) The location of catchment in Pondok Kelapa, Eastern Jakarta. (b) Boundary of study area.

2.2. Data requirement
The following is required data in this study include:
- Daily rainfall data obtained from Balai Besar Wilayah Sungai Ciliwung-Cisadane and Perum Jasa Tirta II. Rainfall data collected from 2005 to 2014. This research using rainfall data from 2 meteorological stations: Cawang Station and Bekasi Station. Computation of areal average rainfall using Thiessen method.
- Digital Elevation Model (DEM) or topographic scale 1:25,000 obtained from Badan Informasi Geospasial (BIG). Catchment delineation process is performed using ArcGIS based on DEM.
- Soil type data. The soil type in site is sandy loam [10] classified as hydrologic soil group class B. The values of curve number (CN) based on soil type and land uses.
- Land use/cover data. Identifying homogeneous land use types (e.g., residential, commercial using base map data scale 1:1,000 and aerial photo (recorded 2014) data were provided by Dinas Cipta Karya, Tata Ruang dan Pertanahan DKI Jakarta. Land use types and its runoff curve number [11] in study area are shown in Table 1.
- Road network data provided by Dinas Bina Marga DKI Jakarta.
- Drainage system network data obtained from Dinas Sumber Daya Air DKI Jakarta. Drainage system in site using concrete open channel.
Table 1. Land use types in study area

| Land use type                                      | Area (ha) | Percentage of occupation (%) | CN |
|---------------------------------------------------|-----------|------------------------------|----|
| High density residential                          | 69.85     | 42.30                        | 85 |
| Very high density residential                     | 47.83     | 28.97                        | 92 |
| Commercial                                        | 13.20     | 8.00                         | 92 |
| Public facilities (e.g., school, government office)| 4.15      | 2.51                         | 75 |
| Open space                                        | 10.68     | 6.47                         | 61 |
| Roadway                                           | 19.14     | 11.59                        | 98 |
| Water Body                                        | 0.84      | 0.16                         | -  |
| Total                                             | 165.13    | 100                          | -  |

2.3. Hydrologic modeling

Storm Water Management Model (SWMM) version 5.1.013 was selected as the hydrologic model for this study. The SWMM was developed by U.S. Environmental Protection Agency (EPA). SWMM is popular software for urban/suburban rainfall-runoff model to compute the runoff from urban/suburban areas in response to simulated precipitation events. SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas [12].

3. Modeling in SWMM

3.1. Design storm

After obtaining the areal average rainfall, furthermore, frequency analysis was conducted to determine the type of distribution and the suitability of frequency distribution is tested using the Smirnov-Kolmogorov and Chi-Square methods [13]. Based on the frequency analysis, resulting Log Pearson Type III as the suitable of frequency distribution. The test results of the suitability of frequency distribution are Do (0.11) < Dcritical (0.41) for Smirnov-Kolmogorov and X² (1.00) < Xcritical (3.81) for Chi-square. It mean Log Pearson Type III can be accepted. The calculation results for return period of rainfall are shown in Table 2. To obtain a design storm, the daily rainfall value is changed into rainfall intensity. In this study, the rainfall hyetograph in West Java [14] is used to compute the design storm for 4 hour duration of rainfall [15] under various return periods of rainfall as shown in Table 3.

Table 2. Return period of rainfall depth

| Return period (year) | Depth (mm) |
|----------------------|------------|
| 2                    | 88.77      |
| 5                    | 111.74     |
| 10                   | 128.15     |
| 25                   | 150.32     |
| 50                   | 167.91     |

Table 3. Design storm for return period of rainfall

| Duration (hour) | Rainfall intensity distribution for return period (mm/hr) |
|-----------------|---------------------------------------------------------|
| 2nd             | 23.08  29.05  33.32  39.08  43.66                      |
| 3rd             | 54.15  68.16  78.17  91.69  102.42                     |
| 4th             | 8.88   11.17  12.82  15.03  16.79                       |
| 5th             | 2.66   3.35   3.84   4.51   5.04                       |
3.2. Sub-catchments division
The catchment area is divided into several sub-catchments according to road network and drainage network. The catchment area in this study is divided into 85 sub-catchments as shown in Figure 2. The parameters value of sub-catchment such as area, percent slope, percent impervious, and curve number values were estimated based on the Digital Elevation Model (DEM) and the land use/cover using ArcGIS. The related parameters for sub-catchment for SWMM modeling were selected using the reference data from SWMM User’s Manual. The sub-catchment properties were parameterized for the SWMM hydrologic module and shown in Table 4. The ground water is negligible for this study.

![Figure 2. Sub-catchment division for SWMM Model](image)

Table 4. Sub-catchments properties

| Name          | Units | Value |
|---------------|-------|-------|
| N-Imperv      |       | 0.012 |
| N-Perv        |       | 0.15  |
| Dstore-Imperv | mm    | 2.54  |
| Dstore-Perv   | mm    | 1.27  |
| % Zero-Imperv | %     | 15    |
| % Slope       | %     | 0.2-1.85 |
| Percent Routed| %     | 100   |

3.3. Low impact development (LID) controls
Rain barrels (RB) and Rain garden (RG) are two forms of retrofit LID technologies has been used to infiltrate, store and detain water runoff in residential housing [16]. RG and RB were selected as LID controls in this study due to the land use of catchment area is dominated by residential housing. RB is used to treat rooftop runoff, whereas RG is used to treat runoff from impervious cover in study area. RB are deployed on each building in High Density Residential area and on each building in Public Facilities area. RG was estimated 30% from total area of Open Space in each sub-catchment. Parameters for RG and RB are presented in Table 5. The total area of RG in catchment approximately 3.20 hectares covering 1.94% of total catchment area and total of RB is 8,225 units. The capacity of each RB is 200 liters [17].
Table 5. Parameters for RB and RG

| Layer     | Parameter                  | Unit | RG  | RB |
|-----------|----------------------------|------|-----|----|
| Surface   | Berm height                | mm   | 150 | -  |
|           | Vegetation volume fraction | -    | 0.1 | -  |
|           | Surface’s roughness        | -    | 0.12| -  |
|           | Surface slope              | %    | 0.3 | -  |
| Soil      | Thickness                  | mm   | 500 | -  |
|           | Porosity                   | -    | 0.3 | -  |
|           | Field capacity             | -    | 0.2 | -  |
|           | Wilting point              | -    | 0.1 | -  |
|           | Conductivity               | mm/h | 500 | -  |
| Storage   | Thickness                  | mm   | -   | -  |
|           | Seepage rate               | mm/h | 200 | -  |
|           | Height                     | mm   | -   | 930|
|           | Bottom area                | sqm  | -   | 0.26|
| Drain     | Flow coefficient           | -    | -   | 0.68|
|           | Flow exponent              | -    | -   | 0.5 |
|           | Offset height              | mm   | -   | 125|
|           | Drain delay                | hr   | -   | 5.8|

3.4. Simulation scenarios
The study area was evaluated under the condition before and after implementation LID. Two scenarios were simulated: 1) no LID/baseline (BL); 2) GI scenario. RG and RB were implemented in the catchment for the GI scenario. The scenarios are simulated for various return periods of design storm: 2-year, 5-year, 10-year, 25-year, and 50-year. For simulation option in SWMM, the simulation time was 8 hours, the Dynamic Wave routing model and Curve Number infiltration model were selected in this study.

4. Results and discussion
4.1. Total runoff volume
Table 6 compares total runoff volume for two scenarios under different return periods of rainfall. Under 2-, 5-, 10-, 25-, and 50-year return period on BL scenario resulting in total runoff volumes were 139,060, 176,320, 203,000, 239,060 and 267,810 m³ respectively. For GI scenario resulting in total runoff volumes of 125,610, 160,590, 185,770, 220,070 and 247,630 m³ respectively for the same return periods.

As seen in Table 6, the total runoff volume was reduced by using LIDs. With the increasing design storm return periods, the percent effectiveness of total runoff decreased gradually. The percent reduction of total runoff volume GI scenario compared to BL are 9.67%, 8.92%, 8.49%, 7.94%, 7.54% for 2-, 5-, 10-, 25-, and 50-year return periods, respectively.
Table 6. Comparison of total runoff volume for two scenarios

| Return periods of rainfall | Total runoff volume (m$^3$) |
|---------------------------|------------------------------|
|                           | Scenario 1 (BL)               | Scenario 2 (GI)               |
| 2-year                    | 139,060                      | 125,610                       |
|                           | (9.67%)$^1$                  |                               |
| 5-year                    | 176,320                      | 160,590                       |
|                           | (8.92%)$^1$                  |                               |
| 10-year                   | 203,000                      | 185,770                       |
|                           | (8.49%)$^1$                  |                               |
| 25-year                   | 239,060                      | 220,070                       |
|                           | (7.94%)$^1$                  |                               |
| 50-year                   | 267,810                      | 247,630                       |
|                           | (7.54%)$^1$                  |                               |

$^1$Values inside parenthesis indicate the percent reduction compared to BL.

4.2. Peak flow

Figure 3 shows the peak flow hydrographs for two scenarios under different return period of rainfall. As shown Figure 3, the peak flow hydrograph for two scenarios almost coincide. Table 7 shows under 2-, 5-, 10-, 25-, and 50-year return period on BL scenario, the maximum rainfall intensities were 54.15, 68.16, 78.17, 91.69, and 102.42 mm/hr, respectively, resulting in peak flows of 4.96 m$^3$/s, 5.40 m$^3$/s, 5.72 m$^3$/s, 6.15 m$^3$/s, 6.49 m$^3$/s, respectively. Whereas the peak flow for GI scenario are 4.85 m$^3$/s, 5.26 m$^3$/s, 5.55 m$^3$/s, 5.97 m$^3$/s, 6.33 m$^3$/s, respectively. The peak flow is reduced by LID implementation on GI scenario compared to BL scenario. The percentile effectiveness reduction of GI scenario for 2-, 5-, 10-, 25-, and 50-year return periods are 2.22%, 2.59%, 2.97%, 2.93%, 2.47% compared to BL scenario, respectively.

Table 7. Peak flow for two scenarios under various of the design storms

| Return periods of rainfall | Peak flow (m$^3$/s) |
|---------------------------|---------------------|
|                           | Scenario 1 (BL)     | Scenario 2 (GI)     |
| 2-year                    | 4.96                | 4.85                |
|                           | (2.22%)$^2$         |                     |
| 5-year                    | 5.40                | 5.26                |
|                           | (2.59%)$^2$         |                     |
| 10-year                   | 5.72                | 5.55                |
|                           | (2.97%)$^2$         |                     |
| 25-year                   | 6.15                | 5.97                |
|                           | (2.93%)$^2$         |                     |
| 50-year                   | 6.49                | 6.33                |
|                           | (2.47%)$^2$         |                     |

$^2$Values inside parenthesis indicate the percent reduction compared to BL.
5. Conclusion

This paper was explored the effect of GI implementation in reducing runoff and peak flow in urbanized catchment areas of Eastern Jakarta. The total runoff volumes and the peak flow were
simulated by SWMM to evaluate the effectiveness of GI in the catchment. Two scenarios were compared under different return periods of rainfall. The results indicated that rain barrel and rain garden implementation resulted in 2.22%–2.97% reduction of peak flows and 7.54%–9.67% reduction of runoff volume for different return periods of rainfall. The effectiveness of GI in reducing runoff volume and peak flow decreasing with increasing return periods of rainfall.

The performance of rain barrels can be improved by increasing the capacity of rain barrel and the roof treatment area. The performance of rain garden can be improved by increasing the percentage of pervious area treated or by optimizing parameter of rain garden i.e., surface, soil, and storage. The implementation of rain barrel and rain garden are good option for stakeholders for managing stormwater in urbanized catchment areas. However, for practical uses of the results, more detailed modeling and field studies should be considered to identify perception of stakeholders prior to implementation.

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