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Bioretention Design Simulation for Efficient Urban Stormwater Reduction

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ABSTRACT The population increases, leading to extensive urbanization and the consequent rise in impervious surfaces. This urbanization trend has exacerbated stormwater runoff issues, necessitating sustainable stormwater management strategies. Low Impact Development (LID) techniques, such as bioretention, have emerged as promising solutions to mitigate the adverse effects of increased impervious surfaces on stormwater management. Through drainage simulation using Environmental Protection Agency Storm Water Management Model (SWMM) 5.2 software, this study assessed the effectiveness of bioretention in mitigating stormwater runoff within Pesona Regency Housing in Jember Regency. The effectiveness will be measured by comparing the amount of reduction to the evaluation of actual drainage conditions. In this approach, hydrological techniques use rainfall for a 2-year return period based on the typology of the study area. The bioretention scenarios used coverage of 5%, 10%, and 20% of the subcatchment area as Scenario 1, 2, and 3. The simulation revealed promising reductions in peak runoff discharge across various scenarios, with average reduction rates of 80%, 88%, and 92% for Scenarios 1, 2, and 3, respectively. However, the effectiveness of bioretention varied across different junctions and scenarios due to factors such as location, junction area coverage, soil properties, and local drainage patterns. While larger bioretention areas generally resulted in greater runoff reduction, the study underscores the importance of considering location and cost-effectiveness in bioretention design. Overall, this research provides valuable insights into the efficacy of bioretention as a stormwater management strategy in rapidly urbanizing areas, offering guidance for property developers in planning flood-resistant housing with LID bioretention.

KEYWORDS Bioretention; Drainage; Low Impact Develompent; Runoff; SWMM

1 INTRODUCTION

The 2020 population census of Jember Regency recorded the total population of Jember Regency as 2,536,729 people. This number increased by 204,003 people or 8.75% in the last 10 years, from 2010 to 2020 (Badan Pusat Statistik Kabupaten Jember, 2021). Population growth converts land surface into built-up land, as well as other impervious surfaces (Qin, 2020), resulting in an increase in stormwater runoff volume, peak flow, and flow velocity (Liu et al., 2022). To reduce stormwater runoff, impervious area management is required using sustainable management called Low Impact Development (LID) (Lee et al., 2022).

Over the past few years, LID has been recognized as a promising strategy for sustainable stormwater management (Tansar et al., 2022). LID is sustainable stormwater management that aims to reduce the impact of increasing population and impervious surfaces. LID refers to sustainable water conservation that includes reducing runoff (peak and volume), increasing infiltration, recharging groundwater, and maintaining water quality (Greksa et al., 2022). LID design can use Storm Water Management Model (SWMM 5.2) software, which is able to analyze water quantity and quality issues related to urban runoff (Amin, 2020). It contain some of LID features, including: infiltration trench, bioretention, rain garden, rain barrel, permeable pavement, green roof, and vegetative swale (Andajani and Hidayat, 2019).

One type of LID that is often used is bioretention (Stec and Słyś, 2023). Bioretention is a stormwater management system consisting of a shallow area covered by vegetation. The purpose of this system is to collect, store, and infiltrate rainwater and surface runoff into the ground so that it can fill the aquifer (underground water layer) and can then be controlled and utilized (Manto and Kadri, 2020). Bioretention consists of several layers: the first is a surface layer that functions as a runoff catcher. The second layer is the soil layer used for vegetation growth media. In the third layer, there is a storage layer consisting of rocks that function to drain water into the ground or drain pipes if there is a runoff (Rossman, 2016). Bioretention was chosen because it has several benefits: it can reduce discharge and runoff volume, can be adaptively applied into the urban landscape, and improves aesthetics. (Nazarpour et al., 2023).

The application of bioretention has been carried out in several previous studies Walega et al. (2018), conducted a bioretention study on a parking lot in Poland with a bioretention coverage of 3% of the total subcatchment and resulted in a 56% reduction in peak surface runoff discharge Stec and Słyś (2023), implemented a bioretention with installation position on the side of the road with a length of 100 m and a width of 0.3 m which was able to reduce the runoff discharge by 82%. Implementation of bioretention in Blacksburg and Weslaco, USA built in parking lots can reduce peak discharge by 84-98% (Willard et al., 2017; Mahmoud et al., 2019). Laying bioretention around sidewalks in Vaughan and Ontario, Canada can reduce 95% of peak discharges (Spraakman, Van Seters, Drake and Passeport, 2020; Goor et al., 2021). In addition, the implementation of bioretention specifically placed in residential areas in Xi'an Xianyang, China and Gold Coast City, Australia, was able to reduce 94.2-100% peak runoff (Jiang et al., 2017; Liu et al., 2022).

However, the use of large bioretention does not always result in significant runoff reduction (Putri et al., 2023). Meanwhile, the larger the bioretention, the greater the cost required. Thus, a bioretention design simulation is needed to get the most efficient design that provides great benefits at a low cost. Therefore, with the various percentages of bioretention coverage and the amount of reduction produced, the study sought to explore the efficiency of bioretention design using several coverage scenarios. The level of effectiveness will be assessed from the amount of reduction against the evaluation of actual drainage conditions.

2 METHODS

2.1 Study Area

The study area is in Pesona Regency Housing, Jember Regency, East Java Indonesia, which is close to one of the Bedadung tributaries as shown in Figure 1. The housing estate is bordered by railroad tracks to the east, residential areas to the south and north, and Bedadung creek to the west. The study area is almost 5.2 ha or 52,000 m^2, consisting of 3.9 ha of built-up area and 1.3 ha of undeveloped land. The eastern part of the study area is mostly residential buildings while the western part is mostly undeveloped areas. The regional climate is classified as tropical with rainy seasons from October to March and dry season from April to September. Considering the feasibility of LID practices for urban inundation mitigation, a bioretention system was selected to improve flood resilience in the study area. The bioretention planning in the study area was conducted using several scenarios presented in Table 1, with the regional rainfall used for a 2-year return period adjusted to the typology of the study area as shown in Table 2, with 63.8 mm day^{-1}.

Table 1. Bioretention Scenario

No	Scenarios
Existing	Without LID
Scenario 1	Bioretention 5%
Scenario 2	Bioretention 10%
Scenario 3	Bioretention 20%

Table 2. Regional Typology

City typology	Water Catchment Area (Ha)			
	<10	10-100	101-500	>500
Metropolis City	2 years	2-5 years	5-10 years	10 - 25 years
Big City	2 years	2-5 years	2-5 years	5 - 20 years
Medium City	2 years	2-5 years	2-5 years	5 - 10 years
Small City	2 years	2 years	2 years	2 - 5 years

2.2 Research Method

The study began by taking rainfall data from three rain gauge stations around the study area, namely Sembah station, Arjasa station, and Bintoro station, each with a position on a relatively flat elevation and close to each other with the range of distance between the nearest rain station being 3.7 km and the farthest being 7.3 km as shown in Figure 1. Thus, based on the position of the rain stations which are close to each other, in a relatively flat area, and where the rainfall height is almost the same, the average rainfall of the region can be used with the arithmetic method (Al-Timimi et al., 2020). These rainfall data were obtained from the Public Works Office of Bina Marga and Water Resources of Jember Regency, and include rainfall data for 20 years from 2003 to 2022 as daily rainfall data. However, the SWMM assesses hydrological modeling by using hourly rainfall data, therefore, the these rainfall data were then processed using the Mononobe formula in equation 1 (Limantara, 2018), to obtain the design rainfall and intensity–duration–frequency (IDF) curve. Mononobe formula is used because it is familiar in hydrological design to calculate the intensity of rainfall at any time in Indonesia (Priambodo et al., 2019). This formula can be used if there are limitations to the data obtained, namely only daily rainfall data, not short-term rainfall (Danasla et al., 2021).

$$I = \frac{R_{24}}{24}(\frac{24}{t})^{\frac{2}{3}} \quad (1)$$

where I is the rainfall intensity (mm hr^{-1}), R_{24} is the rainfall height for 24 hours (mm), t is the rainfall duration (hr).

Furthermore, direct data collection in the study area includes topographic data and soil infiltration. Topographic data includes elevation, channel dimensions, and water level. Elevation data are taken using a total station and ArcGIS data processing. Channel dimension data are taken using a total station and measuring tape, along with surface height data which are taken using measuring tape. The soil infiltration rate at the location was reviewed using two methods, namely direct

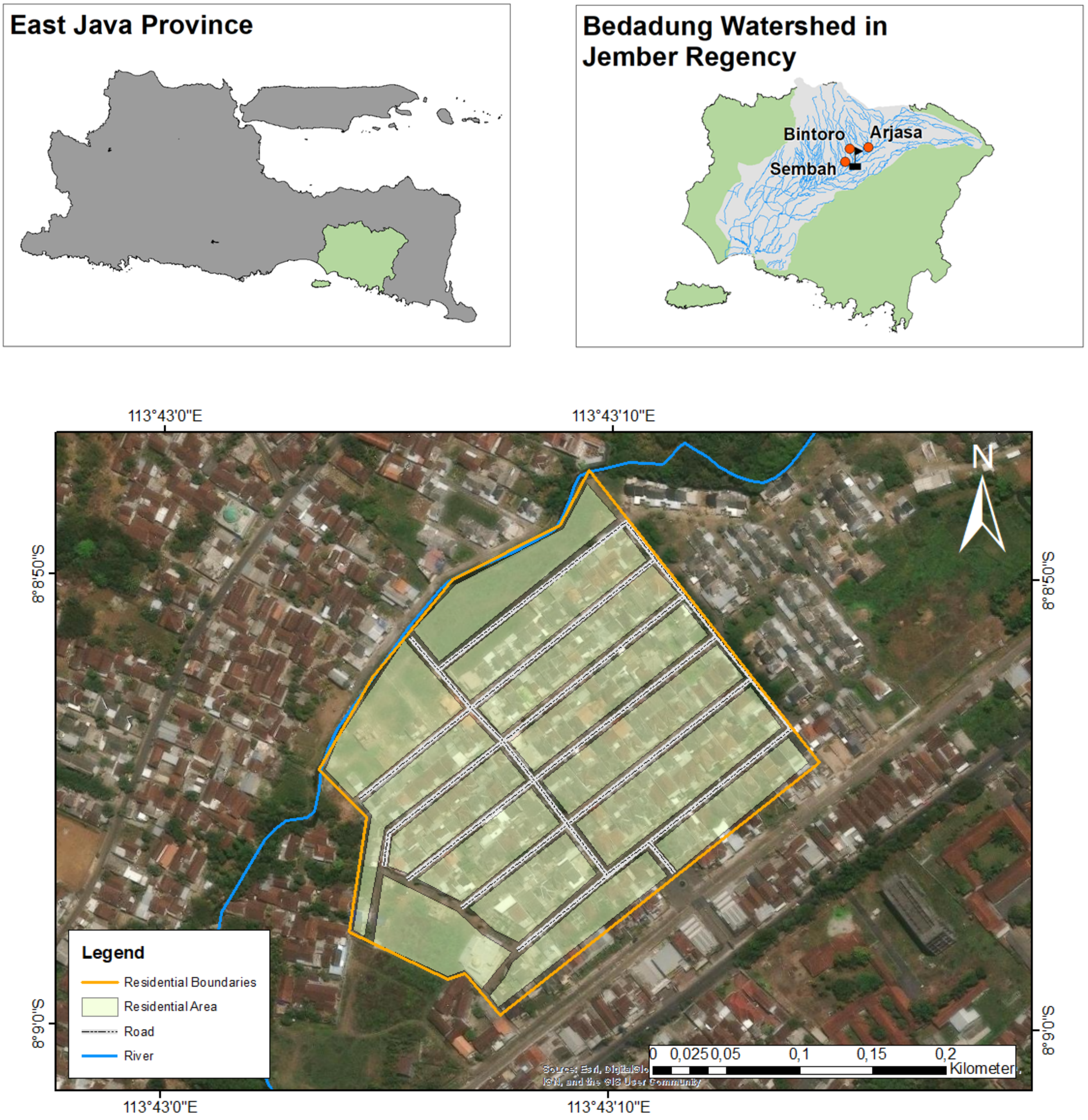

Figure 1 Study area

measurement and SCS curve number. Direct measurement using a double ring infiltrometer obtained a soil infiltration rate of 0.12 m h^{-1}. Based on the Food and Agriculture Organization (FAO) map, the vitric andosol soil type was obtained and used to calculate soil infiltration using the SCS curve number method. Rain intensity data, topography, and soil infiltration were then used as parameters in SWMM modeling as shown in Figure 2.

2.3 SWMM Modeling

EPA SWMM 5.2 is used in urban areas to simulate the quantity or quality of surface runoff. EPA SWMM 5.2 calculates the quantity and quality of surface runoff in each catchment, velocity, depth, discharge, and other variables in each channel during the simulation period with a certain time step. Objects required in the application of EPA SWMM 5.2 software include subcatchment, junction, conduit, outfall, and rain gage. EPA

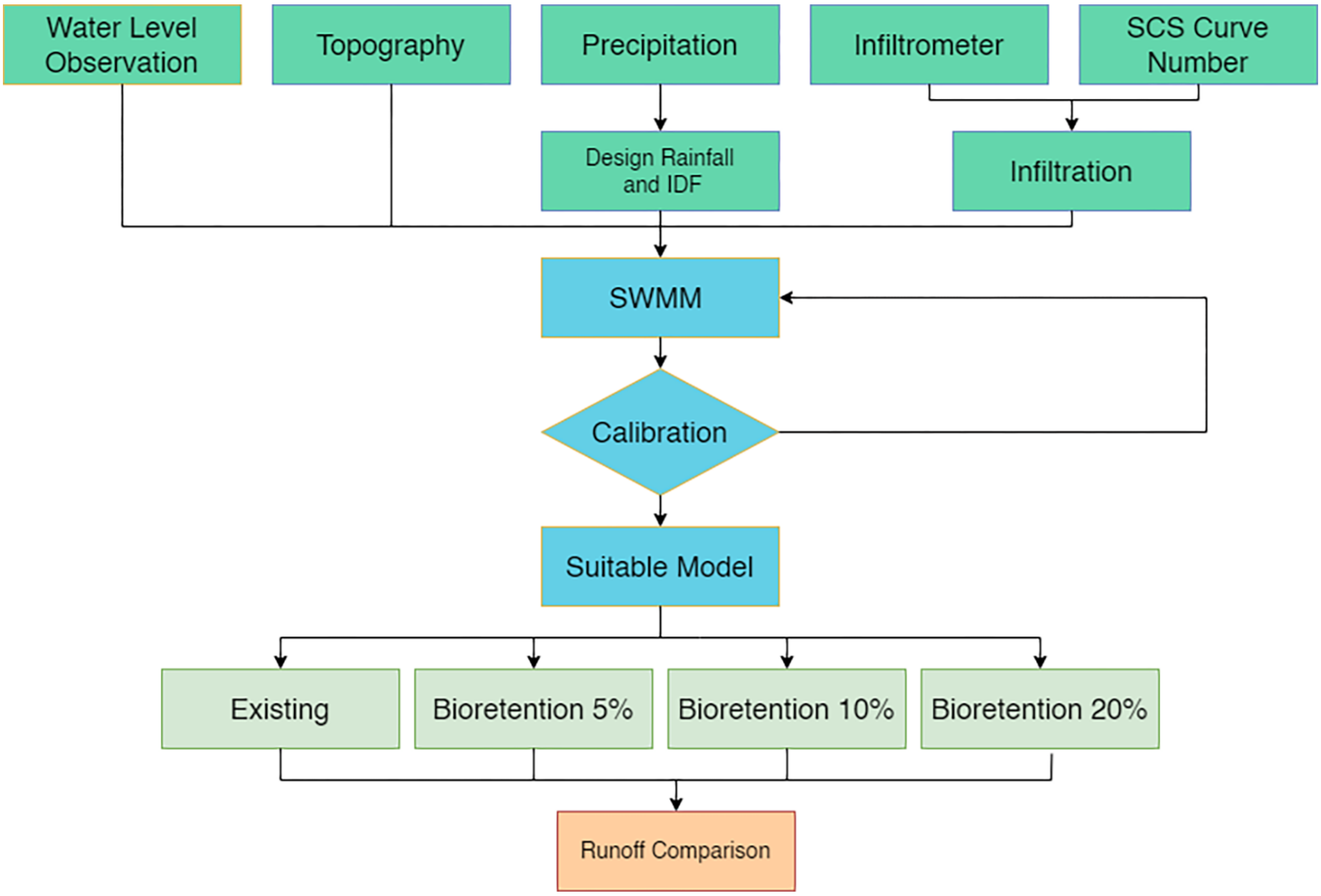

Figure 2 Flowchart of the study

Table 3. Bioretention Parameters

Parameters	Amount
Surface	
Berm height (mm)	250
Vegetation Volume	0.1
Surface Roughness	0.3
Surface Slope (%)	1
Soil	
Thickness (mm)	600
Porosity	0.45
Field Capacity	0.121
Wilting Point	0.057
Conductivity (mm h^{-1})	91
Conductivity Slope	44
Suction Head (mm)	50
Storage	
Thickness (mm)	400
Void Ratio	0.54
Seepage Rate (mm h^{-1})	2.6
Clogging Factor	0

SWMM 5.2 provides a LID control menu which is used for the application of sustainable stormwater management. Based on the results of infiltration tests, the soil type in the study area is classified as sandy soil. Thus, this study uses bioretention by inputting the parameters (Bond et al., 2021), presented in Table 3, which have similar soil characteristics.

2.4 Calibration

Modeling calibration is carried out to adjust the water level in actual conditions to match the water level in the EPA SWMM 5.2 modeling application. Calibration is done by comparing the height of the water level measured at the research location as shown in Figure 3, and the results of the EPA SWMM 5.2 software simulation. In the calibration simulation, the water level data are used in rain event on December 13, 2023, with rainfall of 76 mm day^{-1} for 3 hours.

3 RESULT AND DISCUSSION

3.1 Design Rainfall and IDF

The design of the drainage system requires estimating the peak discharge by analyzing the IDF graph that describes the rainfall intensity over time. The IDF curve graph can be seen in Figure 4. It shows the average rainfall over 20 years to be 68.7 mm day^{-1} with the highest

Figure 3 Measurement of Water Level in the study area

Table 4. Simulation calibration

Code	Height in Study Area (cm)	Height in SWMM (cm)	%Error
C36	28	28	0
C51	39	43	9.3
C63	43	42	2.3

rainfall in 2022 at 132 mm day^{-1} and the lowest rainfall in 2015 at 39 mm day^{-1}. In terms of the typology of the study area, the rainfall used is the 2-year return period because the study area has an area of less than 10 ha or 100,000 m^2. The value of the 2-year return period for the Jember area, based on several studies, is 82.9 mm day^{-1} in the Kaliurang Street area (Amrulloh et al., 2021), and 78.7 mm day^{-1} at Srikoyo Street area (Tamimi et al., 2016). These results are similar and can be used as a reference for evaluating the drainage network system in the Pesona Regency Housing Estate, Jember Regency.

3.2 Performance of Existing Drainage Simulation

The actual drainage simulation performance was obtained by using a 2-year return period rainfall. It shows that there are overflowed points in the channel, including J17, J24, J31, J34, J38, J45, and J53 that are unable to accommodate rainwater runoff in the study area as presented in Figure 6 with red dots. Based on the survey, the junction with the largest associated area is junction J38, which belongs to subcatchment S15 and has an area of 1800 m^2. Junction J31 and J34, which belongs to subcatchment S10 and S13 are the second largest area with 1800 m^2 and 1600 m^2. Junction J31 and J34 that covers subcatchment S10 and S13 have an area each of 1600 m^2. Junction J24, which serves subcatchment S9 has an area of 1500 m^2. Junction J45 which serves subcatchment S16, has an area of 1300 m^2. On the other hand, the junction with the smallest associated area is junction J53 , which is linked to subcatchment S20 and, with an area of 500 m^2.

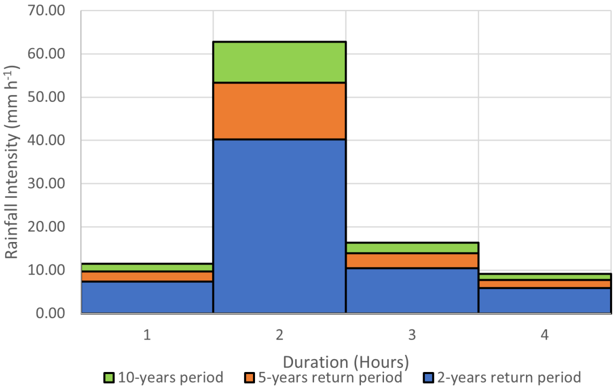

Figure 4 IDF Curve

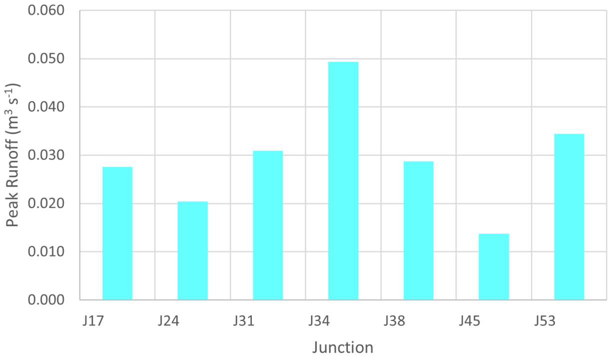

Figure 5 Peak Runoff at Channel

The runoff discharge in the channel that is unable to accommodate rainwater is presented in Figure 5. It shows the peak runoff in the channel that is unable to accommodate water when it rains. The smallest peak runoff at junction J45 is 0.014 m^3 sec^{-1}, while the largest peak runoff at junction J34 is 0.049 m^3 sec^{-1}. Although J45 only covers a small area, field observation shows that the minimal slope of the channel and the confluence of several channels can contribute to higher runoff.

Based on the calibration results presented in Table 4, the modeling process demonstrates an acceptable level of accuracy, given that the error values are all below 10%. Specifically, for code C36, where the observed and simulated heights align at 28 cm with a 0% error, the simulation accurately represents the real-world scenario. Although slight disparities are observed for codes C51 and C63, with percentage errors of 9.3% and 2.3%, respectively, these discrepancies fall within an acceptable range.

3.3 Comparison of Bioretention Scenarios

Simulation of bioretention scenarios was conducted using EPA SWMM 5.2 by filling in the parameters (Table 3) in the LID control menu. Bioretention scenarios were carried out in several selected subcatchments considering the availability of impermeable land and near channels where inundation occurs. There are 15

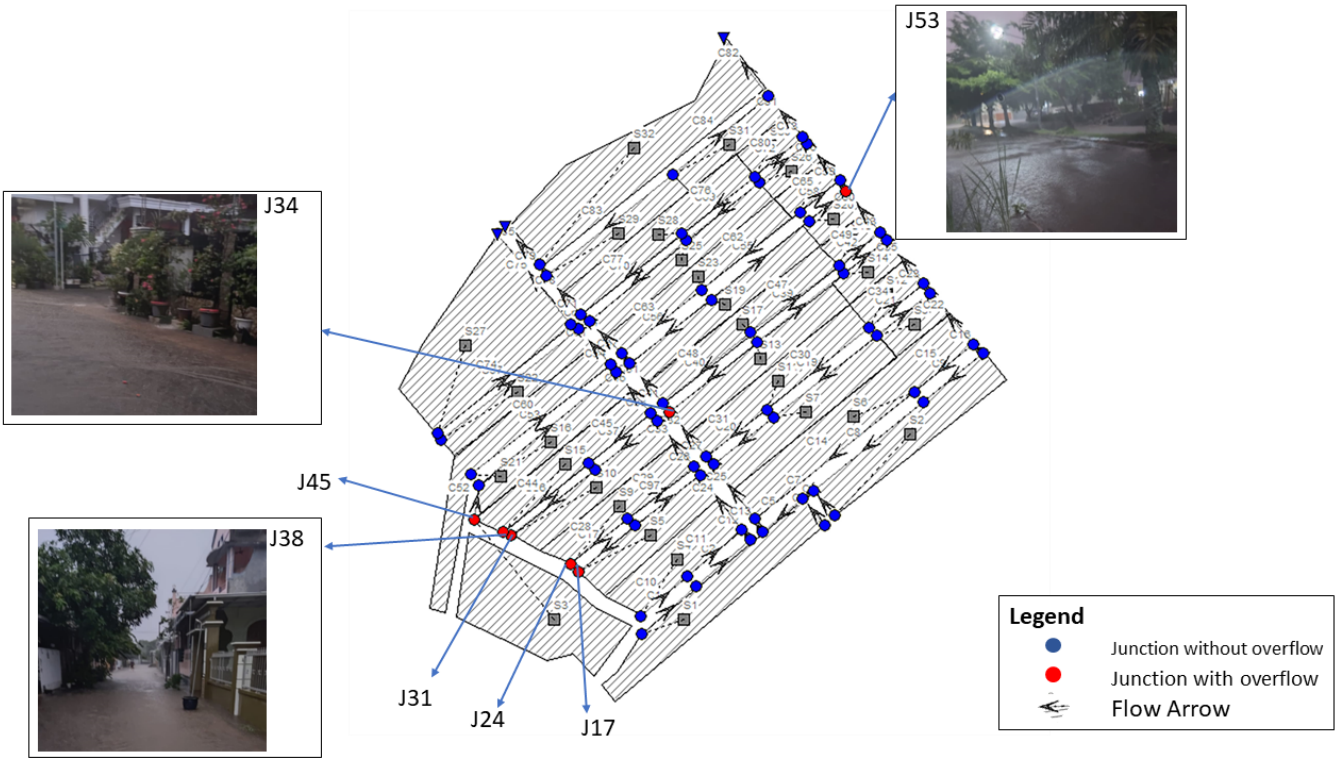

Figure 6 Runoff Points in the Study Area

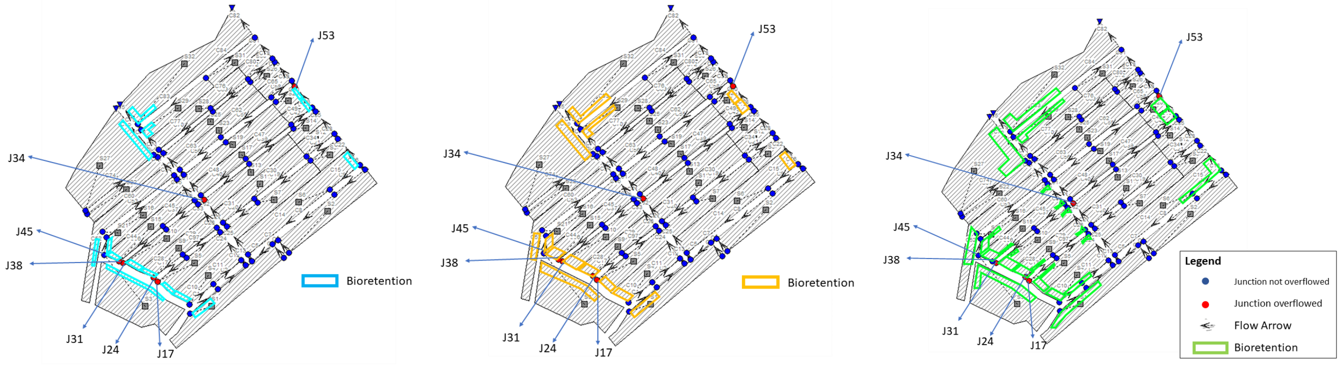

Figure 7 Bioretention location in selected subcatchments

bioretention units in each scenario to simulate in the study area, as shown in Figure 7.

The comparison was conducted following the simulation of bioretention scenarios in the study area to assess the effectiveness of runoff reduction in each scenario. Variances in peak runoff discharge in the channel that was incapable of accommodating rainwater were observed after the simulation of bioretention scenarios, as shown in Figure 8.

After simulating the bioretention scenario, there was a decrease in peak runoff within the channel. Junction J45 consistently achieved a 100% reduction in peak runoff across all three scenarios, indicating the effectiveness of bioretention measures in these locations. Junctions such as J17, J24, and J38 demonstrated varying degrees of reduction, with notable improvements in peak runoff observed as the bioretention coverage increases from Scenario 1 to Scenario 3. For instance, junction J17 showed a significant difference in Scenarios 1,2 and 3 with 18% in scenario 1 to 44% in scenario 2 and 90% in scenario 3. Junction J24 experienced a rapid increase from Scenario 1 to scenario 2 by 17% to 87% but showed no significant difference with using scenario 3 at 89%, while junction J38 increased from 6% under Scenario 1 to 100% under Scenario 3, highlighting the significant impact of enhanced bioretention coverage on runoff mitigation, where there is a relationship between bioretention coverage and peak runoff reduction, with greater bioretention coverage resulting in greater peak runoff reduction. However, junctions like J53 showed comparatively lower reduction percentages, indicating the challenges associated

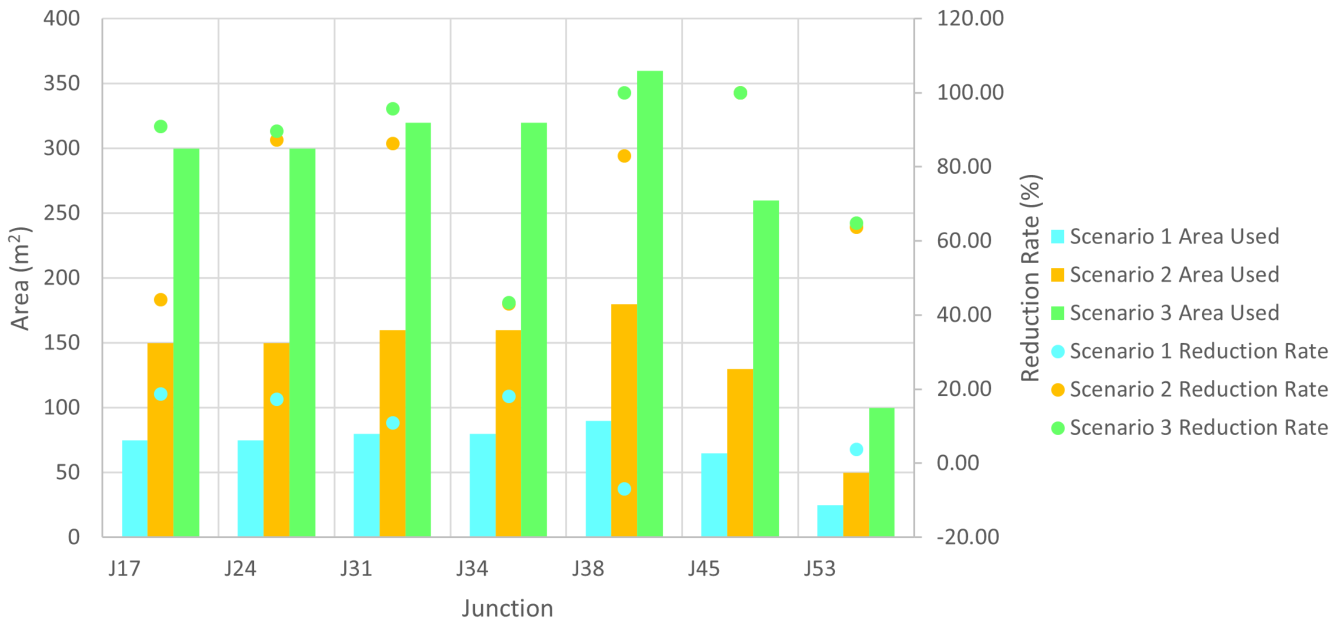

Figure 8 Peak runoff reduction at channel

with mitigating runoff in areas with smaller bioretention coverage or other contributing factors. Even so, the average peak runoff reduction rate in Scenarios 1, 2, and 3 were 23%, 72%, and 83%. This indicates the potential of implementing bioretention at this site.

4 DISCUSSION

4.1 Peak Runoff Generation in Relation to Junction Area Coverage in Existing Drainage System

There is a clear pattern where larger junction areas coverage tends to correspond with larger peak runoff values within the existing drainage system (Guzha et al., 2018). This association suggests that a greater surface area for water collection leads to increased runoff production, as observed in J45, J24, J31, J34, and J38, while a smaller coverage area produces less peak runoff as seen in J53. However, junction J17 belongs to subcatchments S5, respectively. Despite their large areas, these subcatchments still have a significant amount of green land or pervious surface. Pervious surfaces, such as grasslands, can effectively reduce surface runoff by allowing water to infiltrate into the soil (Liu et al., 2020). Moreover, bioretention practices implemented in these areas can enhance soil infiltration, further reducing surface runoff (Putri et al., 2023). Consequently, J17 demonstrates low peak runoff values and the highest reduction rates.

On the other hand, Junction J53, situated in subcatchment S20, presents a different result. Despite its smaller area, this subcatchment is predominantly covered with impervious surfaces, such as houses and roads. The presence of impervious surfaces significantly restricts water infiltration, leading to increased surface runoff. Additionally, J53 shows a minimal slope in the channel and is located at the confluence of several channels, which further amplifies runoff. Thus, despite its smaller size, J53 generates a higher peak runoff. Due to the prevalence of impervious surfaces, the effectiveness of bioretention measures in reducing runoff is limited compared to areas with more pervious surfaces (Zhang et al., 2021).

4.2 Peak Runoff Reduction in Relation to Bioretention Size

The relationship between bioretention size and peak runoff reduction is predominantly positive, as the size of bioretention areas increases, the magnitude of peak runoff reduction also increase, which isshown in Figure 8. While the trend generally suggests that larger bioretention areas result in increased peak runoff reduction, it's essential to acknowledge that the rate of increase may not always be substantial. In some cases, the incremental benefits of expanding bioretention coverage might plateau. For instance, at junction J34, the reduction rates show incremental changes from 18% in Scenario 1 to 43% in Scenario 2, and remain 43% in Scenario 3. Based on this result, the consideration of scaling up bioretention infrastructure needs to be considered (Vijayaraghavan et al., 2021). In addition, the reconfiguration of the bioretention composition at this location also needs to be reviewed, in order to maximize the potential of bioretention in reducing runoff (Butcher, 2021).

Similarly, junctions J17 and J24 exhibit minimal variations in reduction rates between scenarios. Junction J24's reduction rate increases only slightly from 87% in Scenario 2 to 89% in Scenario 3, while J53 only increases from 63% in Scenario 2 to 64% in Scenario 3. These marginal shifts suggest that factors other than bioretention coverage size may be influencing the peak runoff reduction effectiveness at these junctions. This implies that additional considerations such as land use (de Macedo et al., 2019), soil properties (Wang et al., 2021), vegetation types (Nowogoński, 2021), or location and local drainage patterns (Putri et al., 2023), might be playing significant roles in determining the extent of peak runoff reduction, highlighting the complexity of stormwater management strategies. Therefore, while expanding bioretention coverage remains essential, a comprehensive approach that addresses various site-specific factors is necessary to achieve optimal peak runoff reduction outcomes (Spraakman, Rodgers, Monri-Fung, Nowicki, Diamond, Passeport, Thuna and Drake, 2020).

4.3 Efficient Bioretention Design

In the implementation of bioretention, it is important to consider the construction costs involved (Öhrn Sagrelius et al., 2022). The larger the bioretention area used, the higher the costs incurred (Hidayah et al., 2024). Therefore, it requires careful decision-making in the design phase to ensure that bioretention can provide maximum benefits with minimal costs, known as an efficient design and cost-effective (Zeng et al., 2020). Thus, this study analyzed the efficiency of bioretention design across various coverage scenarios. The effectiveness will be measured by comparing the amount of reduction to the evaluation of actual drainage conditions. This implies that not all designs from Scenario 3 need to be universally applied. For example, in the areas of junctions J45, the implementation of bioretention design from Scenario 1 can be considered adequate, as it is capable of reducing peak runoff by up to 100%. In contrast, in the areas of junctions J24, J31, J38, and J53, the implementation of bioretention design from Scenario 2 is already sufficiently adequate, as there is no significant increase in reduction compared to the design from Scenario 3. However, in the area of junction J17, it is necessary to consider implementing the bioretention design from Scenario 3, as this design provides significantly greater benefits compared to other scenarios. Therefore, this finding can be a guide for housing developers to implement sustainable strategies and provide urban flood resilient for the communities.

CONCLUSION

The population growth observed in Jember Regency over the past decade, including in Pesona Regency Housing, requires innovative approaches to managing stormwater runoff. LID techniques such as bioretention have been tested using EPA SWMM 5.2 software, identifying critical points in the drainage network that require intervention. Simulations of bioretention showed peak runoff reductions of 23%, 72%, and 83% for Scenarios 1, 2, and 3, respectively. Areas with impervious surfaces have higher runoff, while bioretention increases soil infiltration, especially in green fields. The relationship between bioretention size and peak runoff reduction is generally positive, with larger areas resulting in greater levels of reduction. However, there may be stagnant results with increasing size, requiring careful consideration of bioretention design and cost-effectiveness. Factors such as location, land use, soil properties, and local drainage patterns affect the effectiveness of peak runoff management, so a customized approach to site-specific conditions is required. This study is useful for property developers in planning flood-resistant housing with LID bioretention.

DISCLAIMER

The authors declare no conflict of interest.

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