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Paper:

Effects of Urban Development on Regional Climate Change and Flood Inundation in Jakarta, Indonesia

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Flood risks associated with changes in land use and climate are a common concern, especially in relation to their potential effects on many cities around the world. Jakarta is a typical urbanized Asian city in Indonesia where flooding presents a consistent challenge. This study aimed to quantify the effects of land use and climate change using a flood inundation model to analyze future urban growth and climate change scenarios. The projected rainfall data of RCP2.6-SSP1 and RCP8.5-SSP3, based on the WRF simulation, were used as inputs for rainfall-runoff and flood inundation simulations in Jakarta. In addition, RCP2.6 and RCP8.5, without urban development scenarios, were investigated to determine the effects of urbanization in Jakarta. The results showed that rainfall intensity, peak discharge, and flood inundation generally increased in the high RCP and SSP future scenarios. Significantly, the RCP2.6-SSP1 scenario showed a higher peak discharge value than RCP8.5, owing to the combination of land-use change and increased rainfall. We conclude that the effects of urban development on atmospheric and runoff processes should be considered in climate change studies in urban areas.

Keywords: flood inundation model, Indonesia, Jakarta, climate change, urban development

1. Introduction

Floods are natural disasters that cause major disruptions to human activities, and their frequency has increased in recent years. In the past, the city of Jakarta has experienced many floods, and after 2013, floods have been occurring almost every year [1]. The 2013 flood resulted in more than 40 deaths, 45,000 refugees, and significant economic damage [2]. More than 60 people were killed during the most recent flood that occurred in January 2020, despite several countermeasures being implemented in the city [1]. Extreme and destructive flooding events may become more frequent in the future, owing to a combination of urbanization in the upstream region and climate change effects.

Many studies have projected that extreme precipitation will increase in tropical regions in the future (Scoccimarro et al. [3], Kure and Tebakari [4], Iwami et al. [5], Yamamoto et al. [6]). However, the projected urban area will grow by 66% by 2050 (United Nations [7]), which could lead to an altered percentage of urban areas, thereby increasing the area of the impervious zone. This condition could amplify the direct runoff (Leavesley et al. [8], Legesse et al. [9]). Thus, a flood mitigation plan that considers land-use change regulations and climate change adaptation is needed. Hence, a detailed future climate change impact assessment is required to consider future urban development.

The impacts of urbanization on precipitation extremes and flood risks in the catchment were analyzed by observations and numerical simulations (Burian and Shepherd [10], Gu et al. [11], Feng et al. [12]). Burian and Shepherd [10] indicated that diurnal rainfall distribution had changed significantly in urban areas, especially in the afternoon during the warm season, based on a comparison of the pre- and post-urban rainfall patterns. Feng et al. [12] investigated the sensitivities of urban flooding to urban land growth by simulating flood flows under different urbanization conditions and during different flooding stages based on HEC-HMS and HEC-RAS analyses. They concluded that urbanization creates higher surface runoff and river discharge rates, along with shortened times to achieve peak runoff and discharge. As such, urbanization may impact both extreme precipitation events and river flood characteristics.

In Jakarta, several studies have focused on urban development and climate change. Farid et al. [13, 14] and Moe et al. [15] reported that urbanization in the Ciliwung River Basin in Jakarta contributed to an increase in river flow.

Land subsidence problems due to urbanization in Jakarta were analyzed by Abidin et al. [16] and Park et al. [17]. Takagi et al. [18] projected the extent of coastal flooding in Jakarta by the year 2050, considering the sea level rise and land subsidence and reported that between 2000 and 2050, the potential extent of flooding would increase by 110.5 km^2, mainly due to land subsidence. Budiyono et al. [19] estimated future flood damage costs in Jakarta based on numerical simulations of climate change and urban development scenarios. Combining all future scenarios, they simulated the median increase in risk as 180% by 2030. Januriyadi et al. [20] showed that the combination of climate change and urban development could amplify the mean flood risk in the future by 322%–402% by 2050 in Jakarta, with a confidence interval of 95%. Notably, the difference in the increased risks between Budiyono et al. [19] and Januriaydi et al. [20] is due to the different methods for estimating the asset values used in their research [20].

Many previous studies have conducted climate change impact analyses in Jakarta, considering future climate and land use changes, land subsidence, and sea level rise. In addition, several flood studies have been conducted in Jakarta, including flood inundation prediction [1, 14, 21], land use/cover change impact analysis [13, 15, 22], and future climate change projections [20]. However, the effects of urban development on the atmospheric environments of cities have not been considered in many previous flood and climate change studies conducted in Jakarta or in urban cities across the world. Local urbanization is expected to affect the atmospheric environments of megacities owing to the changing urban thermal environments, such as the heat island phenomena; however, this effect has not been quantitatively evaluated in previous studies. In general, local urbanization was considered only for land-use changes in runoff and flood inundation simulations. Darmanto et al. [23] coupled global climate change with distributed urbanization scenarios, based on projections of future urban morphology and anthropogenic heat emissions in a mesoscale weather model. They projected future air temperatures and rainfall in Jakarta, considering both climate change and local urbanization. However, Darmanto et al. [23] focused only on the projected air temperature, and the projected rainfall was not analyzed in the previous study. The effects of future changes on flood inundation, as a result of climate change and local urbanization in cities require detailed investigations. In this study, we aimed to quantify the effects of both land use and climate change on future rainfall and flood inundation in Jakarta, based on future urban growth and climate change scenarios.

2. Study Area

Jakarta, officially known as the Special Capital Region of Jakarta, is the capital and largest city in Indonesia, with a population of approximately 9.6 million. Central Jakarta is home to the national and provincial governments of Greater Jakarta.

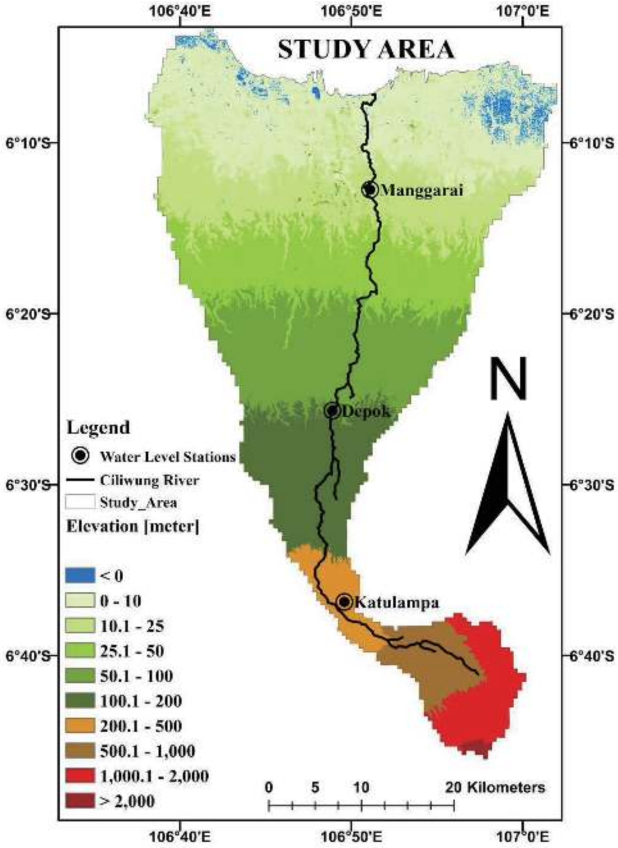

Fig. 1. Study area [1].

The rainy season in Jakarta begins in November and ends in March, and the peak rainfall intensity mostly occurs in January and February. Thirteen major rivers flow northward through Jakarta, into the Java Sea. The main river in Jakarta is the Ciliwung River with an upstream area in Mount Pangrango and a downstream area in Jakarta. The target area selected for this study included Jakarta and the Ciliwung River Basin, with a total area of 1346.6 km^2, as shown in **Fig. 1**. Five rainfall stations and three river water level stations are shown in **Fig. 1**. Hourly rainfall data from the stations were used for bias correction of the projected rainfall data, and the locations of the three water level stations were used as the peak discharge evaluation points, as discussed in later sections.

The area containing the city and its surroundings is almost entirely covered by urbanized zones; however, forested and agricultural areas can be found in the middle and upper regions of the target area. Many of these forested and agricultural areas are expected to be converted into urbanized areas in the near future [22].

3. Methodology

Figure 2 shows the schematic representation of the research method used in this study. The details are explained below.

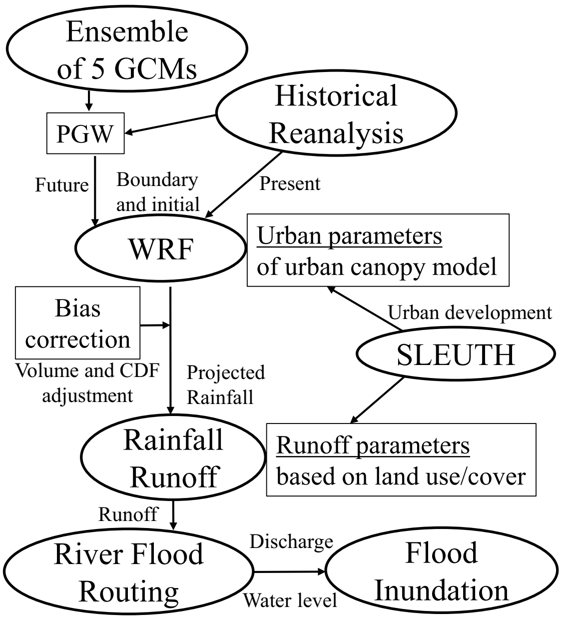

Fig. 2. Schematic representation of the method.

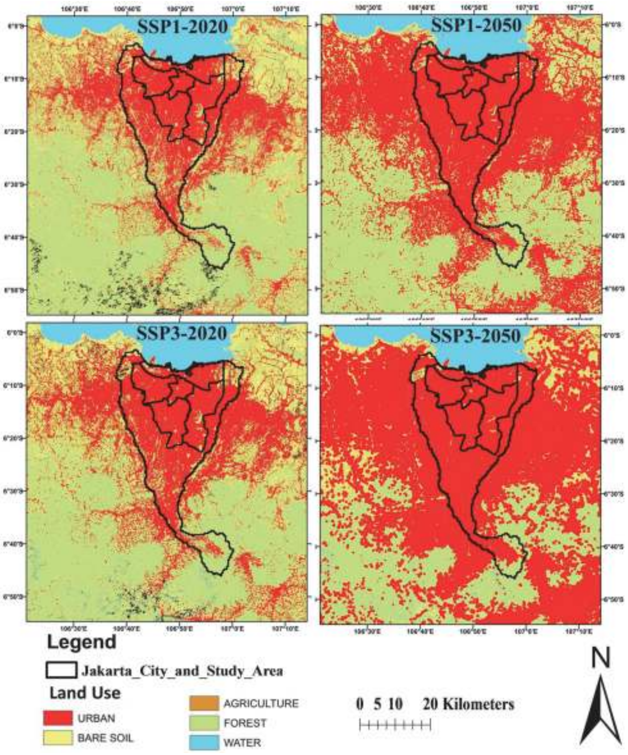

Fig. 3. Land use/cover in 2020 and 2050 (SSP1 and SSP3).

3.1. Future Projected Rainfall

Darmanto et al. [23] simulated the present and future urban climate in Jakarta, based on high-resolution 1-km regional climate modeling. The high-rainfall seasons in the present (2006–2015) and future (2046–2055) climates were simulated using the Weather Research and Forecasting (WRF) model, coupled with a modified version of the single-layer urban canopy model to represent important urban morphological parameters. In this single-layer urban canopy model, the estimations of the bulk transfer coefficients for each building facet have been revised, based on the simple urban energy model for mesoscale simulation (SUMM). In addition, actual urban fractions were considered rather than the constant values used in the default WRF model. Further descriptions of the modified WRF can be found in [23].

For future conditions, four scenarios were used, so that the month of January, in the last 10 years of the historical period, and the next 40 years (10 years × 4 scenarios), could be simulated in the WRF runs. For the present simulation, the historical re-analysis data of the NCEP-FNL were used for the boundary and initial conditions of the WRF simulation.

The future global climate scenario was downscaled using a pseudo global warming (PGW) method with ensembles of five CMIP5 global climate models (GCMs), namely HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M, and GFDL-ESM2M as inputs for RCP2.6 and RCP8.5. The PGW is a non-direct downscaling delta approach used to realize finer resolution and effective performance of future climate projections using a mesoscale regional climate model (Kimura and Kitoh [24]). This method has been validated in several studies. Using this approach, we considered the 10-year average of the future climate values of each GCM in January during the period 2046–2055. The values necessary for the PGW method include the three-dimensional wind components (3- and 6-hourly), temperature components (3-hourly, 6-hourly, daily, and monthly), pressure components (6-hourly), and humidity components (3-hourly, 6-hourly, and monthly). Ensemble averaging was performed for each meteorological component value from 2046–2055. The ensemble averages were subtracted from those for 2006–2015. The difference in the ensembles was added to the meteorological boundaries of the historical NCEP-FNL to be used as the meteorological boundary for 2046–2055. The specific details of the PGW method can be found in Kimura and Kitoh [24].

RCP2.6 and RCP8.5 were selected considering the best and worst emission scenarios, respectively. Urban parameters were projected based on the socio-demographic parameters from SSP1 and SSP3. SSP1 presents lower challenges for mitigation (resource efficiency) and adaptation (rapid development). In contrast, SSP3 presents high challenges for mitigation (regionalized energy/land policies) and adaptation (slow development) [25].

We employed two urban expansion scenarios based on the SLEUTH model, namely, compact and business-as-usual (BaU) adaptation strategies, where the compact scenario was derived from SSP1 and the BaU scenario was derived from SSP3 (**Fig. 3**). Details of the SLEUTH model are explained in the next section. The urban ratios of SSP1 and SSP3 in 2050 were 0.89 and 0.93, respectively. The urbanization rate in the study area was high; therefore, there were no significant differences between SSP1 and SSP3 in the study area [22]. Global and ur-

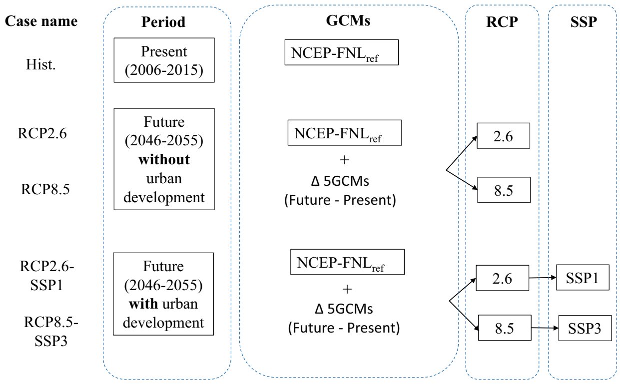

Fig. 4. Experiment cases.

banization scenarios were then coupled in the WRF simulation runs. In addition, RCP2.6 and RCP8.5 were simulated without urban development. Finally, rainfall data were projected for future periods, based on four scenarios (RCP2.6, RCP8.5, RCP2.6-SSP1, and RCP8.5-SSP3) and the historical period [23]. **Fig. 4** summarizes the experimental cases used in this study.

A bias correction was conducted for projected rainfall to obtain a realistic magnitude of the rainfall in the basin and flood discharge in the rivers because the rainfall data of the downscaled NCEP-FNL by the WRF simulation had a bias in volume and frequency compared to the observed data. It is noted that the NCEP-FNL is historical re-analysis data simulated considering historical atmospheric observations, but rainfall values have biases at the local basin scale. First, the monthly rainfall volume in the historical and future periods was adjusted based on the values of the observation rainfall data for 30 years, as used in a previous study [20]. The volume adjustment was conducted as there was an over-estimation of the simulated monthly rainfall volume compared with the observed rainfall, which might be due to the accuracy of the NCEP-FNL re-analysis data at the basin scale in Jakarta and the short span of the simulation period used for the analysis (10 years). It is noted that the bias information of the previous study was used in this study because it was obtained from much longer simulation periods (30 years). Second, the empirical cumulative distribution function (CDF) for the downscaled historical GCMs and hourly observed rainfall data for 10 years (2006–2015) were calculated, and the projected rainfall bias was corrected using the inverse of the CDF of GCMs with observation distribution parameters [20] to adjust the frequency of high-intensity rainfall. These adjustments were extended to the future projected rainfall data. This bias correction was based on CDF analysis for the rainfall intensity distribution to adjust the frequency and magnitude of extreme rainfall events in the historical period. However, it was noted that further analysis and bias correction based on the longer simulation periods of WRF simulations were required because the 10-year simulation periods were too short to compute long-term climate situations.

After this bias correction, the projected rainfall data were used as inputs for the rainfall-runoff and flood inundation models to project future flood inundation situations.

3.2. Future Land Use and Cover Change

SLEUTH is a tool that can predict urban growth by using historical slope, land use, exclusion, urban growth, transportation, and hill shade data (SLEUTH; Dietzel and Clarke [26]). All C language source codes, libraries, and sample data for SLEUTH computations are available for downloading through Project Gigalopolis [27]. SLEUTH has been applied to many cities (e.g., Guan and Rowe [28]). In this study, urban growth was determined according to the assumption that historical urbanization levels would be maintained. Varquez et al. [29] applied SLEUTH to Jakarta under the RCP8.5-SSP3 (BaU) and RCP2.6-SSP1 (compact-growth) scenarios, and the resulting projected land-use/cover maps were employed in this study. It should be emphasized that land-use projections for future periods ignored social and infrastructural developments, such as land reclamation in the northern coastal area of Jakarta, high-speed railways, and any scenario related to future conservation efforts in the city and upstream regions.

This study also used land-use/cover maps for 2050, based on the RCP8.5-SSP3 and RCP2.6-SSP1 scenarios for rainfall-runoff and flood inundation simulations, by changing the runoff model parameters based on land use/cover changes [15]. **Fig. 3** shows the land use/cover maps for 2020 and 2050 (RCP2.6-SSP1 and RCP8.5-SSP3). Land subsidence in Jakarta, which affects inland and coastal flooding, was not considered in this study.

3.3. Rainfall Runoff and Flood Inundation Model

We modeled flood inundation in Jakarta based on rainfall-runoff [30, 31] and flood inundation modeling [21]. The flood inundation model comprised a rainfall-runoff module for each sub-basin, a hydrodynamic module for rivers and canal networks, and a flood inundation module for flood plains. Rainfall-runoff and flood inundation models were applied to the 2013 flood event based on radar rainfall data and validated against observations [15]. For the model validations, the high Nash Index of 0.75 and 0.95 at Depok and Katulampa stations and correlation coefficients of 0.8 and 0.81, respectively, were simulated in the river discharge comparisons. Additionally, the visual-graph comparisons between the simulated flood inundation distribution and the observed inundation map indicated an acceptable agreement, as shown in **Fig. 5** [15]. The observed flooded area data were provided by the Badan Penanggulangan Bencana Daerah (BPBD), the Jakarta Province Regional Disaster Management Agency.

Here, we quantified the agreement based on the following fit index [32]:

$$\text{Fit [\%]} = \frac{IA_{obs} \cap IA_{sim}}{IA_{obs} \cup IA_{sim}}, \quad \dots\dots\dots\dots \quad (1)$$

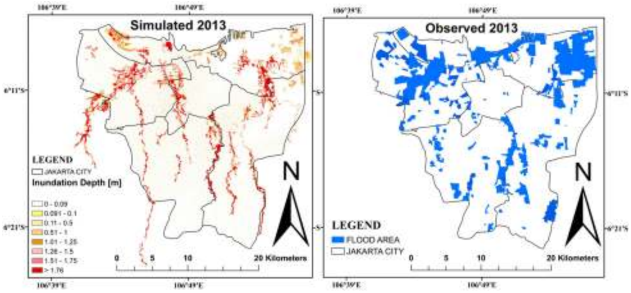

Fig. 5. Comparison of the simulated (left) and observed (right) inundation areas [15].

where IA_{sim} is the inundated pixels predicted by the model (we assumed a depth greater than 0.1 m as the simulated flood extent in this study) and IA_{obs} is the identified flooded pixels by the observation map. To obtain the area of the IA_{obs}, the map shown in **Fig. 5** was digitized and converted to a raster dataset with the same grid size as the model simulation. From Eq. (1), the fit value was 0.21, which was relatively low. For this reason, it should be emphasized that the observed flooded area was based on eyewitness reports in each district by government officers during the flood event and interviews with local residents after the event, although there were some uncertainties. For example, only a small area was actually inundated, but the entire district was judged as the inundated zone in **Fig. 5**. In addition, there were discrepancies between the reported and simulated inundation areas, particularly in the northern and northeastern areas. This may have been caused by the numerous local fish ponds in these areas. The local fish ponds were initially filled with water, but this initial water was not captured by the land-use map used in this study, leading to the under-estimation of the flood inundation simulation.

It should be noted that the rainfall-runoff model used in this study is assumed to be applied to mountain regions [30, 31], so that it can be improved to represent urban flooding in lowland areas in Jakarta. In addition, the flood inundation model needs to be improved to simulate local urban situations like sediment deposition and low embankment points, along with zones in canals and rivers. However, to consider these urban effects and local situations, fine-resolution DEM and river cross-sectional data are required.

These calibrated models and parameters were validated based on their application to other historical flood events from 2015 to 2020 [1]. It is noted that satellite-driven rainfall data were used as the input to the model in these simulations because the weather radar in Jakarta used in the model calibration was not operated and the radar rainfall data were not available after 2014 because of its high maintenance cost. Even when using satellite-driven rainfall data, acceptable simulation results were reported by Priyambodoho et al. [1]; thus, we concluded that the model and parameters were applicable not only to historical floods but also for future projected flood events.

During the model application to the 2013 event, soil parameter values, such as the soil depth and saturated hydraulic conductivity, were calibrated based on four classes of land cover (forest, cropland, paddy field, and urban area). Forty sub-basins in the study area were analyzed for rainfall-runoff simulations. Four land cover ratios for these sub-basins were calculated using the SLEUTH model under the RCP2.6-SSP1 and RCP8.5-SSP3 scenarios. Moreover, future land use changes were considered in the rainfall-runoff simulations.

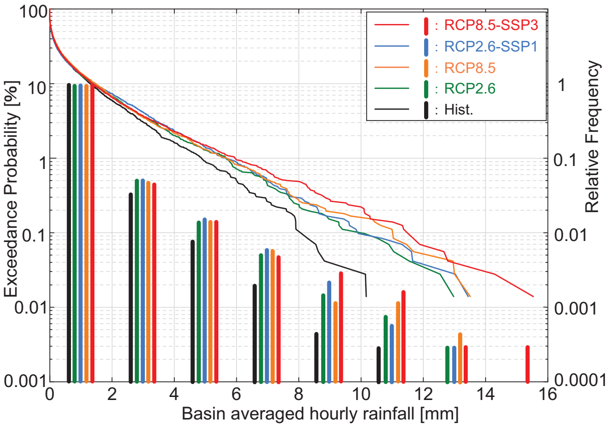

Fig. 6. Comparison of the relative frequencies of hourly rainfall in each scenario.

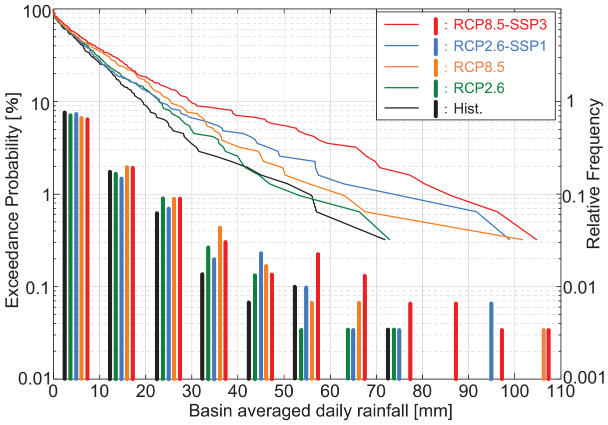

Fig. 7. Comparison of the daily total rainfall exceedance probability in each scenario.

4. Results

In this study, we focused on the effects of urban development on rainfall and flood inundation in Jakarta. Hence, the differences between RCP2.6, RCP2.6-SSP1, RCP8.5, and RCP8.5-SSP3 were considered as the urbanization effects, and the results were mainly evaluated based on the hourly and daily time scales.

4.1. Rainfall Comparisons

Figures 6 and **7** show a comparison of the relative frequency and changes in the exceedance probability of

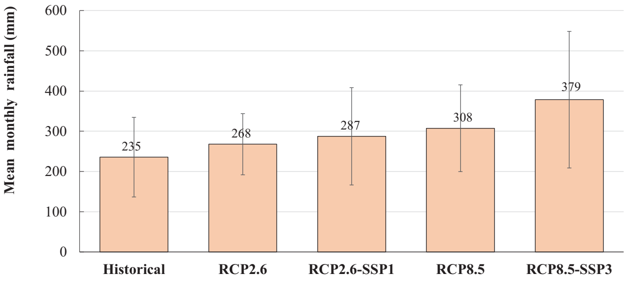

Fig. 8. Comparison of the average monthly rainfall in each scenario.

hourly and daily rainfall in the target area and over the studied time periods. The projected rainfall was spatially and temporally averaged over the target area in January over 10 years in both historical and future periods. Generally, high rainfall was projected toward high RCP and SSP scenarios. The RCP8.5-SSP3 scenario was found to show the highest rainfall intensity. RCP2.6-SSP1 and RCP8.5-SSP3 showed higher rainfall values with higher probabilities than RCPs alone. **Fig. 8** shows the monthly rainfall in both the historical and future periods under each scenario. In this figure, the error bars for each scenario show the 95% confidence intervals. Monthly rainfall clearly increased in the high RCP and SSP scenarios. The average monthly rainfall of RCP2.6-SSP1 was approximately 7% higher than that of RCP2.6, whereas that of RCP8.5-SSP3 was approximately 23% higher than that of RCP8.5. As such, the increase in rainfall in RCP8.5-SSP3 was significant compared to that in RCP2.6-SSP1.

4.2. Flood Peak Discharge Comparisons

Figure 9 shows comparisons of the hourly simulated peak river discharge at the three stations (**Fig. 1**) of the Chiliwung River during both the historical and future periods under each scenario. As shown in the figure, the peak discharge generally increased toward the high RCP and SSP scenarios in the future, owing to the high rainfall and land use change. Significantly, RCP2.6-SSP1 showed higher peak discharge values than RCP8.5, owing to the combination of land-use change and increased rainfall.

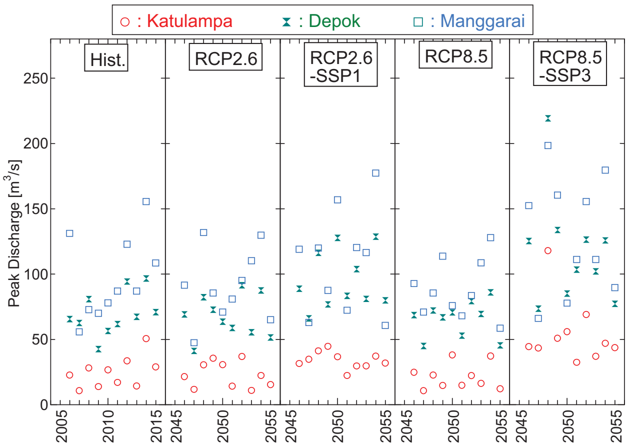

Fig. 9. Comparison of simulated peak river discharge at 3 stations in each scenario.

4.3. Flood Inundation Comparisons

Figure 10 shows a comparison of the 10-year average of the annual maximum flood inundation depths and the computed values of the flooded volumes. The simulated annual maximum flood inundation depths were averaged for each grid during this period. The difference between the cases with and without SSPs is shown in the figure. A high maximum flood inundation depth was computed for the RCP8.5-SSP3. However, in a simulated event from RCP2.6-SSP1, a large inundation on the west side of Jakarta was observed, as shown in **Fig. 10**. Hence, the spatial distribution of rainfall is also important for analysis, but only this case showed high rainfall in West Jakarta. Moreover, the ensemble numbers of the simulations may have to be increased to analyze the spatial distribution patterns of rainfall. The largest flood inundation was simulated under the RCP8.5-SSP3 scenario, and the second largest flood inundation was simulated under the RCP2.6-SSP1 scenario but not in RCP8.5, because urban development was not considered in the RCP8.5-only scenario.

Figure 11 summarizes the monthly rainfall, runoff, and flood inundation volumes for both historical and future periods under each scenario. In **Fig. 10**, the flood inundation volume [m^3] is computed by multiplying the inundation depth [m] at each grid and inundation area [m^2]. The largest flood inundation was simulated under the RCP8.5-SSP3 scenario, and the second largest flood inundation was simulated under the RCP2.6-SSP1 scenario, but not RCP8.5, owing to the urban development that had not been considered in the RCP8.5-only scenario. These simulation results clearly indicate that the urban development scenario should be considered in the climate change assessment of cities, not only for atmospheric conditions, but also for flood inundation situations. We conclude that the combined effects of urban development on the atmosphere and flooding should be considered in the climate change analysis of cities.

5. Discussion

In this study, the effects of urban development on the atmosphere and flood inundation were discussed. Jakarta and its surroundings are highly urbanized areas, and convectional rainfall typically occurs in the urban areas of humid tropical regions. Additionally, the heat island phenomenon has been progressing significantly in Jakarta; moreover, the urban thermal influence on the background environment of convectional rainfall prevails in the region [33]. This type of heat island effect has not been considered in many previous climate change studies, because of the difficulties in modeling urban heat environments in course grid simulations. In this study, urban development was considered for both the rainfall and flood projections.

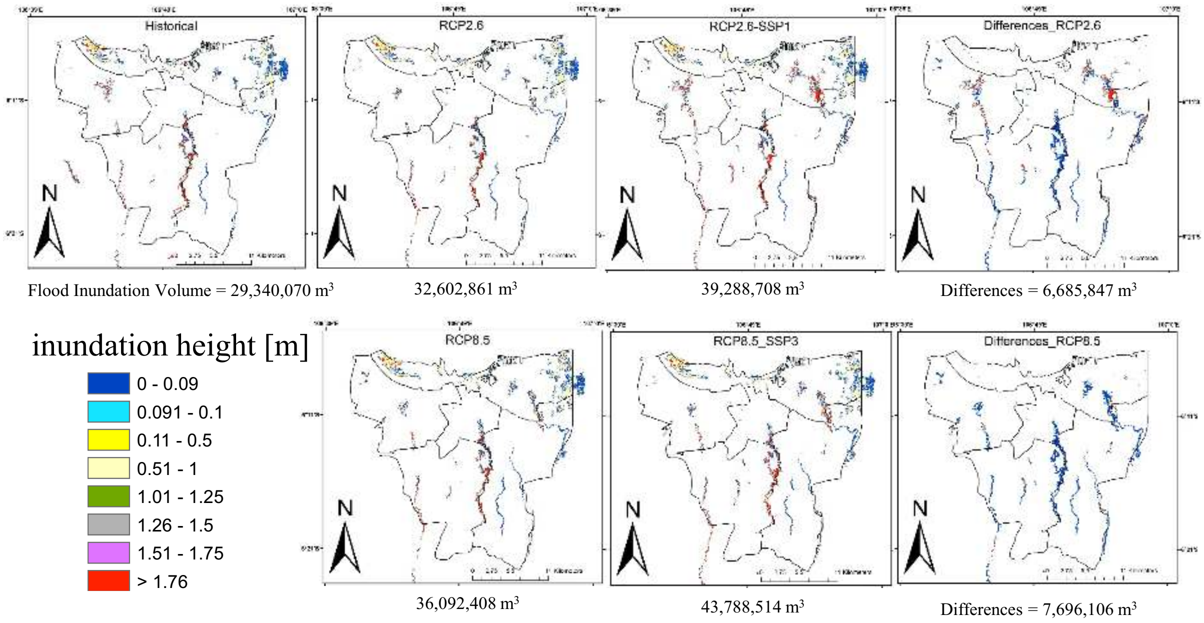

Fig. 10. Comparison of the simulated 10 years averaged maximum flood inundation depths in each scenario and the differences of w/wo SSPs.

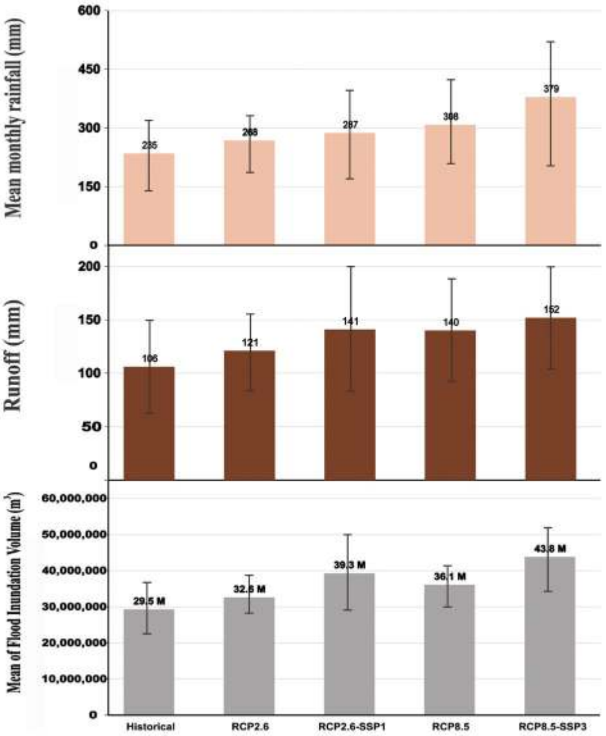

Fig. 11. Comparison of average monthly rainfall with the simulated runoff and flood inundations in each scenario.

From the comparisons with and without SSPs (**Figs. 6** and **7**), it is evident that the extreme rainfall events of the hourly and daily time scales were enhanced due to urbanization. These urbanization and heat island impacts on rainfall were reported from several previous studies [34, 35]. Urban land-use changes also lead to high river flood discharges in urbanized areas. The peak river flood discharge and inundation volume in RCP2.6-SSP1 were larger than those in RCP8.5 (**Figs. 9–11**). Moe et al. [15] analyzed the impact of land use change on flood inundation without considering climate change and reported that the flood inundation volume increased from approximately 30 Mm^3 in 2013 to 35 Mm^3 in 2050. We assumed that only land-use changes may have contributed to the 5 Mm^3 increase in flood inundation. In the current study, much higher increases were computed while comparing RCP2.6-SSP1, RCP2.6 (6.7 Mm^3), and Historical (10 Mm^3); these increases were also observed while comparing RCP8.5-SSP3, RCP8.5 (7.7 Mm^3), and Historical (14.5 Mm^3) as specified in **Fig. 8**. It can be inferred from the results herein and in Moe et al. [15] that the urbanization impacts on atmospheric rainfall contributed to the flood inundation volume of 1.7 Mm^3 in RCP2.6, 2.7 Mm^3 in RCP8.5. We assumed that if land use change could increase the flood inundation volume by 5 Mm^3, as reported by Moe et al., then a similar increase was applicable in this study. These increases amount to approximately 5%–10% of the current flood inundation volume; hence, we speculated that the urban development effects on the increases in rainfall would contribute to an increase in the flood inundation volume by approximately 5%–10% in a target area. Based on these results, urban development was found to affect increase in rainfall because of changes in the urban thermal environment and flood inundation associated with land use and rainfall changes in the future.

However, in this study, simulations for only a 10-year period were performed within a scenario owing to the requirement of extremely heavy computations for high-resolution urban atmospheric simulations. Thus, the relatively large flood inundation result on the west side of Jakarta was only simulated under RCP2.6-SSP1. However, only ten events were insufficient for discussing the spatial distribution patterns of rainfall. Moreover, because of the smaller number of ensemble members in future projections, we could not analyze the statistical significance of future changes caused by urban development. In future studies, the simulation period must be increased to evaluate the uncertainty of the impact of future climate and urban development in Jakarta. Furthermore, the statistical significance and more physical patterns, such as the spatial distribution of rainfall, must be assessed, and a more realistic bias correction that may be applicable under future land use and urban environment situations, should be evaluated.

6. Conclusions

In this study, future flood inundation scenarios were projected, considering both climate change and the effects of urban development. The future projected rainfall data of RCP2.6 and RCP8.5, without urban development, and RCP2.6-SSP1 and RCP8.5-SSP3, based on the WRF simulation, were used as inputs for the rainfall-runoff and flood inundation simulations in Jakarta. Future land use change was also considered in the rainfall-runoff simulations based on the SLEUTH model outputs in Jakarta and surrounding areas in 2050. Based on the results of this analysis, urban development was clearly seen to increase not only the rainfall intensity and volume in the future, but also the runoff from the basin, river flow discharges, and flood inundations in Jakarta. This happened due to the combination of land use change and increased rainfall. We conclude that the effects of urban development on both atmospheric and runoff processes should be considered in climate change studies in cities.

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