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NUMERICAL EXPERIMENTS OF FUTURE LAND USE CHANGE FOR FLOOD INUNDATION IN JAKARTA, INDONESIA

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The risks associated with changes in land use are a common concern, especially in relation to their potential impact on many cities around the world. Jakarta, Indonesia is a typical urbanized Asian city where flooding presents a challenge. In this study, our main objective was to evaluate quantitatively the impact of changes in the use of land upstream of the city by using a flood inundation model to analyze several land-use-change scenarios. We considered four scenarios of future changes in land use in Jakarta based on the SLEUTH model: the worst-case, compact-growth, and controlled-growth-I and -II scenarios. The controlled-growth is a scenario to decrease the growth rate and delay the progress of urbanization compared to the compact-growth scenario.

According to our analyses, the predicted changes in land use with the land subsidence in the worst-case and controlled-growth-II scenarios would cause flood inundation volumes in 2050 to be 37% and 27% larger than in 2013, respectively. Thus, even under the controlled-growth-II scenario, the modeled changes in land use with the land subsidence would significantly increase flood inundation. Based on these results, we strongly recommend the Jakarta government to regulate land use in the forested upper regions and land subsidence in the lower regions as soon as possible to reduce future flood damage to the city.

Key Words: *flood inundation model, land-use changes, Jakarta, Indonesia*

1. INTRODUCTION

The risks associated with changes in land use are a common concern, especially in relation to their potential impacts on many cities around the world. Jakarta, Indonesia is a typical urbanized Asian city where flooding presents a challenge. Kure et al[1] emphasized that flooding in urban areas of Jakarta causes both human casualties and severe economic damage.

The factors that contribute to flooding in Jakarta include a variety of social issues and infrastructure problems, including changes in land use/cover, lack of capacity in the canals and rivers, land subsidence in coastal areas and garbage disposal problems[2],[3],[4],[5]. However, Moe et al[6] reported that changes in land use have had a far greater effect on the extent of flood inundation in Jakarta than the other factors.

There have been several studies on the impact of land-use changes on flooding in Jakarta. According to numerical simulations by Farid et al[7], the urbanization of Jakarta's upper catchment area has caused flooding to expand further and progress faster as a result of increasing effective rainfall and surface runoff. Moe et al[6] projected the worst-case scenario for future flooding when land-use changes and subsidence were taken into account and concluded that land-use changes in Jakarta and its surrounding areas should be regulated as soon as possible. However, they predicted the inundation only under the worst-case scenario, so their results are not considered valid predictions of the real situation.

Development is expected to continue in areas upstream of Jakarta, with accompanying changes in land use and cover. Hence, the expected impact of these changes on future flood inundation under various scenarios must be evaluated with a view to

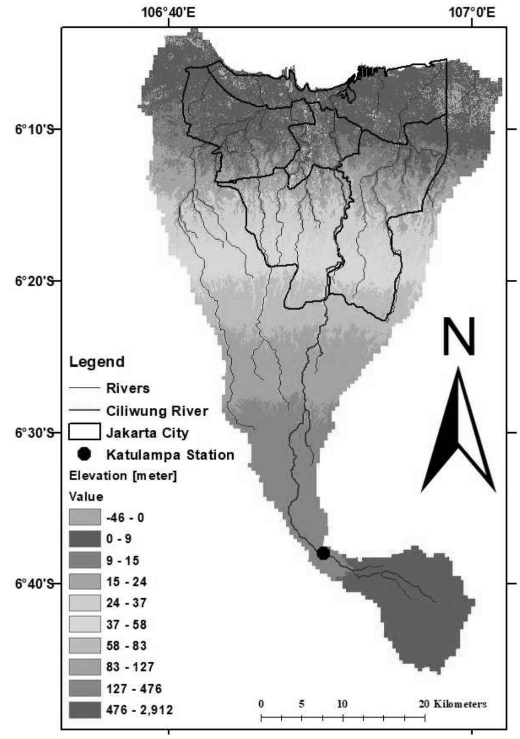

Fig.1 Study area

controlling changes in land use. The main objective of this study was to apply a flood inundation model to analyze quantitatively the impacts of various possible changes in land use upstream of Jakarta. Also, several land-use change scenarios were employed in this study in order to evaluate the uncertainty of the future land-use change.

2. STUDY AREA

Jakarta, the capital of Indonesia, is an Asian mega-city that is currently undergoing rapid urbanization and development. Thirteen natural and artificial rivers flow through Jakarta, the main river being the Ciliwung River, which is also the longest. It flows from the upstream region on the border of the cities of Cianjur and Bogor through the city center, as shown in **Figure 1**.

The target area selected for this study included Jakarta and its surrounding river basins, covering an area of approximately 1346.6 km^2 in total. The problem of flooding in Jakarta is closely related to changes in land use upstream of the city. The area containing the city and its surroundings is almost covered by urbanized zones, but forested and agricultural areas can be found in the middle and upper regions of the target area, as shown in **Figure 2**.

3. METHODOLOGY

(1) Flood inundation model

In this study, we used a physical model of rainfall-runoff and flood inundation to simulate the flood inundation in Jakarta that would result from various changes in land use[6)]. The model consisted of modules representing the rainfall-runoff in each sub-basin, a hydrodynamic module representing the river and canal networks, and a flood inundation module for predicting the status of the floodplains.

The rainfall-runoff module applied the kinematic wave theory of a hillslope and computed surface and subsurface flows based on the geological and hydrological characteristics of each sub-basin[8),9)]. The hydrodynamic module used to simulate the river and canal networks was composed of a continuous equation, and an equation for the momentum at steady flow (Saint-Venant equation). The flood inundation module modeled the floodplains using unsteady two-dimensional flow equations derived by combining a continuity equation with a momentum equation. We used this model of flood inundation for Jakarta because it has previously been applied and calibrated to the study area[10), 11)] to analyze a 2013 flood event. The model is applicable to both highly urbanized areas and mountainous regions.

We calibrated the values of the soil parameters in the simulation based on four classes of land cover: forest, cropland, paddy field, and urban area. The calibration also included Manning’s roughness coefficients, which were set to between 0.02 and 0.4 for the beds of each river section and to 0.1 for the land surface of all floodplains. We could find several high values of the manning’s roughness coefficients around 0.1-0.4 in the river beds. This might be because of lack of information about the river cross sections used in the model and reduced capacity of the river by trash, sedimentation and so on.

(2) Data

The project authority of JICA provided cross sections of the rivers and details of the drainage systems of the rivers and canals. We obtained rainfall data from radar rainfall information provided by Badan Pengkajian dan Penerapan Teknologi (BPPT; the Agency for the Assessment and Application of Technology). The water levels of the Ciliwung River and the Jakarta flood inundation map were provided by Badan Penanganan Bencana Daerah (BPBD, the Jakarta Disaster Management Agency). In addition, the land-use maps from 2002 were supplied by the Ministry of Public Works (PU).

(3) Future Land-use/cover change scenarios

We investigated the effects of changes in land use on flooding in Jakarta by predicting future land use using the SLEUTH model[12)], which estimates urban growth based on historical slopes, land use,

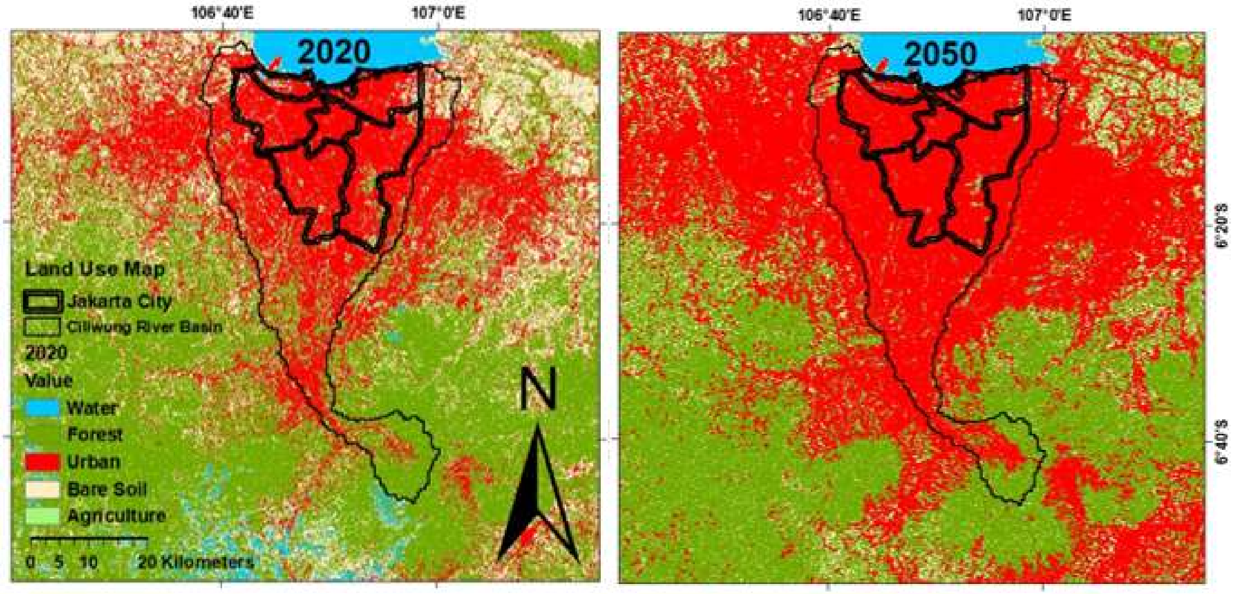

Fig.2 Projected future land-use map of the compact-growth scenarios for 2020 (left) and 2050 (right)

exclusion, urban growth, transportation, and hill-shade data. Varquez et al[13] applied SLEUTH to Jakarta under the RCP8.5-SSP3 (worst-case) and RCP2.6-SSP1 (compact-growth) scenarios, and we used the resulting projected land-use/cover maps in this study. Although a previous study by Moe et al[6] investigated the impact of land-use changes in the worst-case scenario, several additional scenarios must be evaluated to develop realistic strategies for future land-use management.

The necessary inputs are slope, land cover, excluded region, urban cover, transportation, and hill shade in the study area. Excluded region, means areas where urban growth is restricted (e.g. water bodies, parks). From the inputs, Varquez et al[13] calibrated the necessary growth coefficients (dispersion=1, breed=14, spread=89, slope=65, and road=28) for urban growth using 1000 iterations of the Monte Carlo Simulation. Under the RCP8.5-SSP3, direct application of the calculated growth coefficients provided the urban extents of 2050. To limit urban expansion (i.e. consistency with RCP2.6-SSP1), the coefficients (e.g. spread=22) were reduced. For more details, please see the reference[13].

In this paper, we consider four scenarios for future land use in Jakarta: the worst-case, compact-growth, and controlled-growth-I and -II scenarios. The worst-case scenario assumed that historical levels of urbanization are maintained. In the compact-growth scenario, we reduced the spread coefficients of the SLEUTH model to represent less urban growth than in the worst-case scenario.

We did not use the output from the SLEUTH model for the controlled-growth model. Instead, we reduced the total urbanization ratio obtained from the compact-growth model of the target area. We have 40 sub-basins for the rainfall-runoff simulations in the study area. Four land cover ratios of these sub-basins were calculated by the SLEUTH model under the worst-case and compact-growth scenarios, and then, these land cover ratios were used in the rainfall-runoff simulations. For the controlled-growth scenarios, some of the urban areas were uniformly converted to the forest areas over the upstream regions. These new urbanization and mountainous ratios in the sub-basins were used for the rainfall-runoff simulations of the controlled-growth.

The compact-growth and controlled-growth-I scenarios differed by a constant ratio (0.03) for every year (2020, 2030, 2040, and 2050) of urbanization between 2050 (0.90) and 2040 (0.87). Thus, the aim of the controlled-growth scenario was to decrease the growth rate and delay the progress of urbanization by 10 years compared to the compact-growth scenario in 2050. We set the constant difference ratio between levels of urbanization according to the compact-growth and controlled-growth-II scenarios in 2050 (0.90) and 2030 (0.81) to 0.09, based on the ratio of the compact-growth scenario to the controlled-growth-II scenario. This allowed us to increase our control of urban development in the upstream region. Relative to the compact-growth scenario, the controlled-growth-II scenario delayed development by 20 years and the controlled-growth-I and -II scenarios replaced urban areas in the upper region with forested areas.

Figure 2 shows the predicted changes in land use in and around the target area in 2020 and 2050 based on the compact-growth scenario, as an example. **Figure 3** shows a time series of the total urbanization ratios in the target area for each scenario. These figures imply that the entire target area would be almost fully urbanized by 2050, even in the compact-

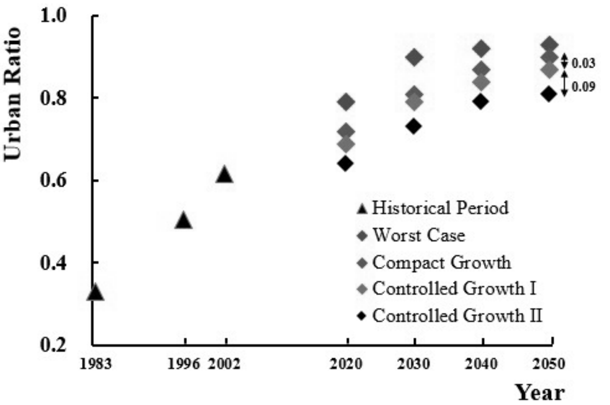

Fig. 3 Time series of the total urban ratio of each scenario in the historical and future periods

growth and controlled-growth scenarios.

It should be noted that the urbanization speed in **Figure 3** is gradually decreasing even in the worst-case scenario that assumed historical levels of urbanization are maintained. This is because there is no more space for the urbanization in the study area except for the excluded areas or steep mountainous areas that are not suitable for the urban development.

We used the land elevation data provided by Moe et al[7] to evaluate land subsidence. We assumed that historical land-subsidence speeds in the target area varied linearly over time. The historical land-use data were provided by PU. Models with entirely forested or entirely urban target areas were also simulated in two further numerical experiments.

We then applied the rainfall-runoff and flood inundation models using these land-use conditions and elevations. The results are discussed in the next section.

4. RESULTS

For the rainfall-runoff simulation, projected-land-use information was used to compute the land-use categories in each sub-basin by area and percentage (%). We used the values used for the calibration simulation[10), 11)] of the 2013 flood event for other inputs such as rainfall and the model parameters for each land-use category. It is noted that the same rainfall input data of the 2013 flood event was used as the input for the future and historical simulations. It means that we did not consider the impacts from the climate change on the flood inundation in this paper.

Figure 4 shows simulated hydrographs at Katulampa Station (**Figure 1**) in 2020 and 2050, under each land-use scenario. The flood peak and volume increase with future increases in the size of the urbanized area. Examples of the simulations are shown in **Figure 5**. This indicates the flood inundation in 2020 and 2050 according to the historical calibration simulation (2013) together with observations and the compact-growth scenario with the land subsidence. Each of the urban and forest situations is also presented in the figure. These figures clearly show that in the compact-growth scenario, extensive flooding occurs in 2050, whereas flooding is limited in the scenarios in which forest is retained.

Figure 6 shows a time series of the areas and volumes of historical and future flood inundation under each land-use condition with the land subsidence. The inundation area and volume increase with increasing urbanization under each scenario. The largest inundation area and greatest volume occur in the worst-case scenario, but the other scenarios also result in extensive inundation. We calculated the total worst-case-scenario inundation volumes in 2013 and 2050 as 4,050,171 and 2,960,121 m^3, respectively. The flood inundation volume in 2050 in the controlled-growth-

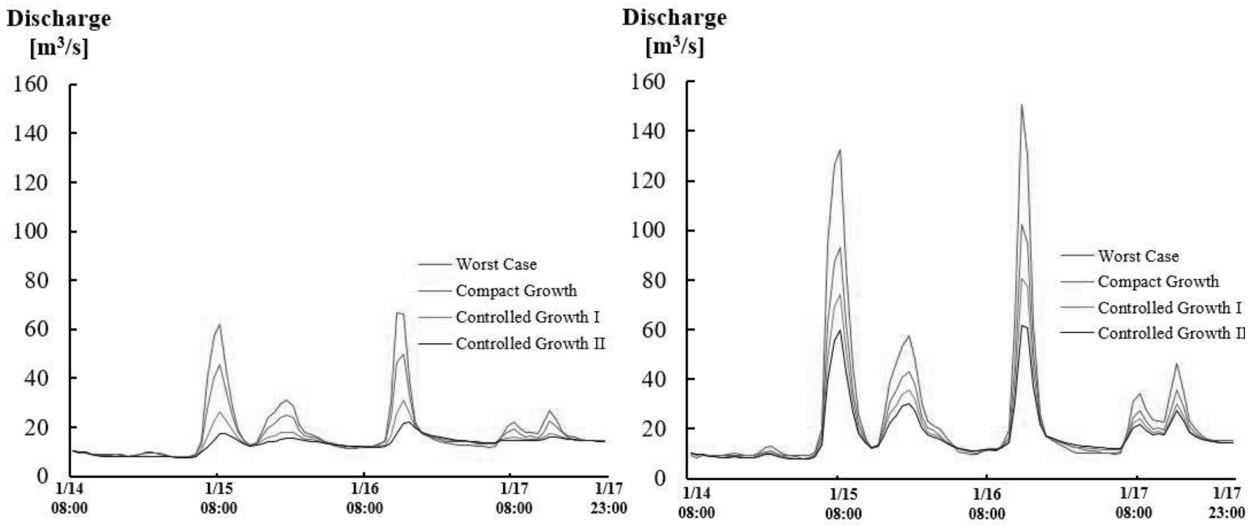

Fig. 4 Simulated river discharge [m^3/s] of each scenario at Katulampa Station in 2020 and 2050

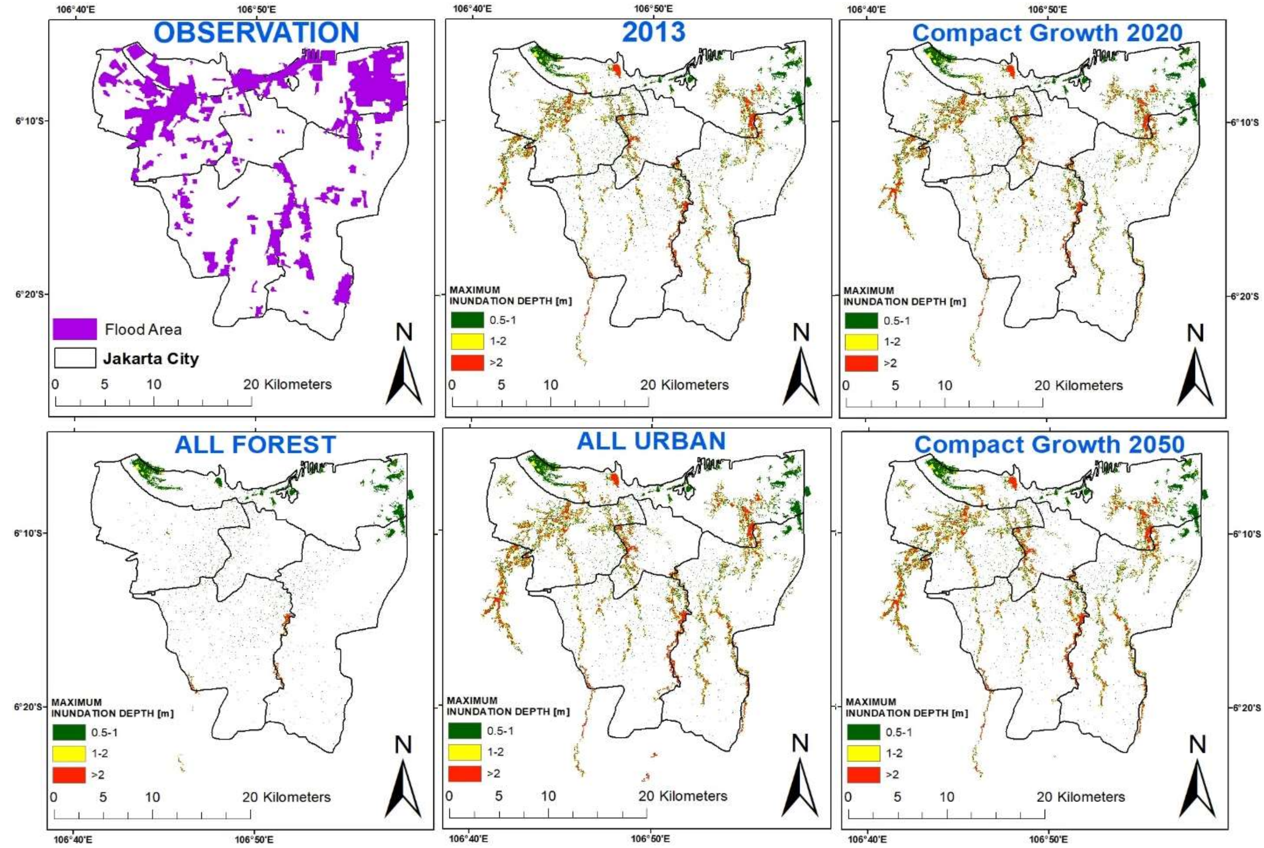

Fig. 5 Simulated flood inundation areas of the example scenarios

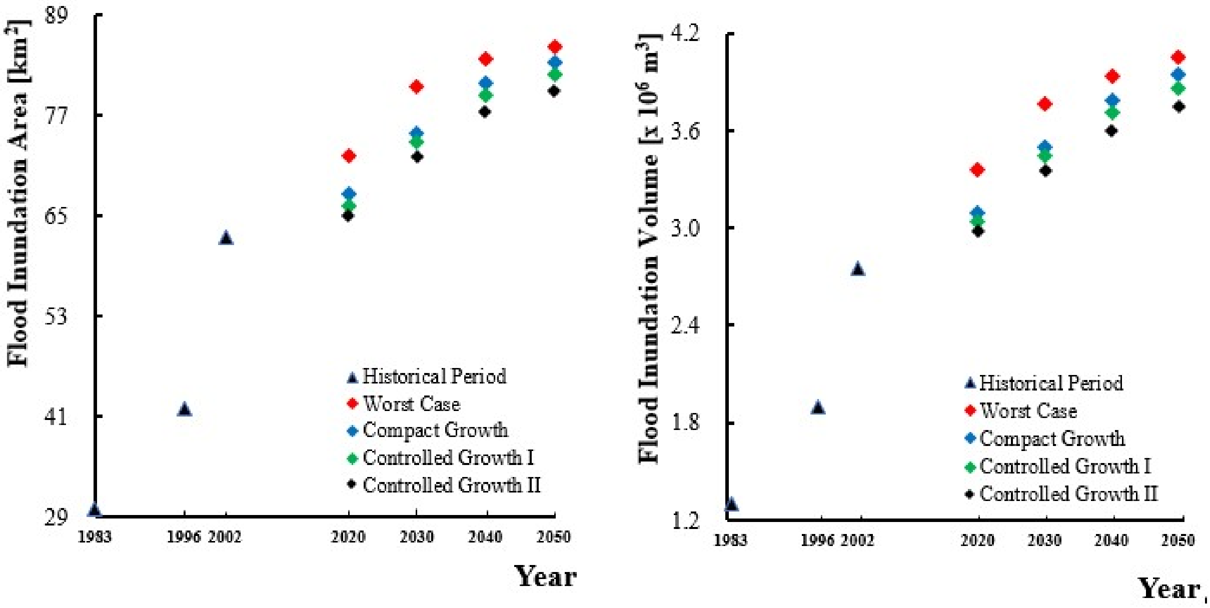

Fig. 6 Time series of the simulated flood inundation areas and volumes of each scenario in the historical and future periods

II scenario would be 3,752,756 m^3. The changes in land use between 2013 and 2050 would increase the flood inundation volume in the worst-case and controlled-growth-II scenarios by 37% and 27%, respectively. It should be emphasized that flood inundation would increase significantly due to changes in land use with land subsidence even if urban development in the upper region were delayed, such as in the controlled-growth-II scenario. This is because, except for some areas in the upper forest, much of the study area was already occupied by urban areas in 2013. The impact on flood inundation of converting the remaining forested areas into urban areas would be significant. Based on this, we conclude that the government should control and regulate changes in land use in the regions upstream and land subsidence in the regions downstream of Jakarta as soon as possible.

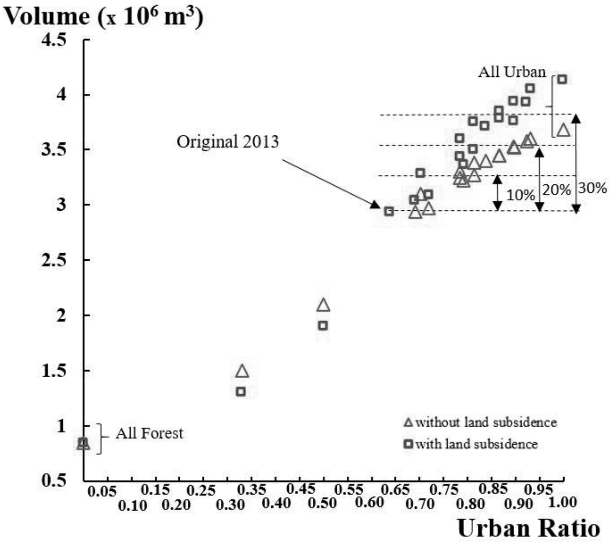

Fig. 7 Relationship between total urbanization ratios and flood inundation volumes with and without land subsidence

Figure 7 shows the relationship between the urbanization ratio of the whole area and flood inundation volumes, with and without land subsidence. We analyzed the impact of land subsidence by simulating flooding both with and without land subsidence. High urbanization ratios are clearly associated with high flood inundation volumes, with the figure showing that the urbanization ratio varies linearly with the flood inundation volume. We found that land subsidence also would have the impact to the flood inundation. The land subsidence itself has small impacts as reported by Moe et al.[6] but the combination of the land-use change and land subsidence would have a much greater impact to the flood inundation than only land subsidence or land-use change.

5. DISCUSSION

Since becoming more frequent in recent years, flooding in Jakarta has been investigated by several studies. Moe et al[6] reported that the extent of flood inundation in Jakarta was much more sensitive to land-use changes than to other factors. However, they considered only urban areas in a future scenario with the worst-possible socio-economic conditions, namely the RCP8.5-SSP3 scenario. They suggested that further investigations to evaluate other future land-use scenarios, and stated this would be the subject of their next study. Accordingly, in this study, we analyzed the compact-growth scenario as in the RCP2.6-SSP1 scenario together with other controlled-growth scenarios (controlled-growth I and II). The simulated flood inundation volume under the several scenarios in this study and the previous study[6] are summarized in **Table 1**. It is also noted the flood inundation model used for these simulations was developed through our previous studies[6),10),11)].

It should be emphasized that, even the controlled-growth-II scenario, which delayed urban development in the upper region of Jakarta, resulted in significantly increased flood inundation because of the additional impacts from land subsidence. Hence, land use in the upper region and land subsidence in the lower region of Jakarta should be urgently controlled or regulated. **Figure 7** implies that the urbanization ratio in the target areas should be maintained at below 0.7 (70% of the target area is urbanized) and 0.8 in the future to restrict the increase in flood inundation volumes to within 10% and 20% of present levels (2013), respectively. The urbanization ratio is currently 0.63, implying that there is little or no more space available for urbanization in upstream regions, and an urgent need to regulate changes in land-use/cover.

It should be noted that we did not consider the impact of climate change on flood inundation in Jakarta. Possible effects should be investigated in our next study. Also, it should be emphasized that we did not consider the counter measures for the flood inundation such as a development of a drainage system in the study area. These future possible counter measures should also be evaluated in the next study.

6. CONCLUSIONS

In this paper, we examined four possible scenarios for future changes in land use and used a flood

Table 1 Percentages of the flood inundation volume increase compared to the original 2013 flood.
(LU: only land-use change, LS: only land subsidence, and LU+LS: land-use change with land subsidence)

Year	LS[6]	Worst Case[6]		Compact Growth		Controlled Growth I		Controlled Growth II	
		LU	LU+LS	LU	LU+LS	LU	LU+LS	LU	LU+LS
2020	8	9	14	1	3	-3	3	-3	1
2030	9	19	27	11	18	7	16	5	13
2040	13	21	33	17	28	12	25	10	22
2050	15	22	37	19	33	14	30	12	27

inundation model to evaluate their impact. The results indicate that by 2050 changes in land use with land subsidence would cause flood inundation volumes to increase by 37% and 27%, respectively, relative to those of 2013, in the worst-case and controlled-growth-II scenarios. Of the scenarios modeled, the worst-case scenario had the greatest impact on flood inundation. However, flooding increased significantly even in the controlled-growth-II scenario. In addition, the effects of changes in land use on the extent of flood inundation in Jakarta were increased by land subsidence even under the delayed urban developments scenarios.

Based on these results, we strongly recommend that the Jakarta government specify regulations for changes in land use in the forested upper regions and land subsidence in the lower regions as soon as possible to reduce future flood damage in the city.

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