Future projection of flood inundation considering land-use changes and land subsidence in Jakarta, Indonesia

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Abstract:

Jakarta is facing several issues related to flooding, including land subsidence in the coastal area and rapid land-use/cover changes in the upstream area. In this study, we analyzed the effects of future changes in land use and land subsidence using a rainfall-runoff and flood inundation model. The future land-use scenarios were projected based on the SLEUTH model, and land subsidence was projected based on an extrapolation of the current state in Jakarta.

Based on this analysis, land-use changes and land subsidence contributed to an increase in flood inundation volume of 36.8% from 2013 to 2050. Moreover, the effects of land-use changes on flood inundation in Jakarta were much greater than those of land subsidence. The government’s current target to stop land subsidence by 2020 would cause a 7.7% decrease in the flood inundation volume by 2050. Furthermore, controlling and regulating land-use/cover changes by 2020 would cause a 10.9% decrease in the flood inundation volume by 2050. From these results, we conclude that a flood mitigation plan should be made not only for land subsidence, but also for land-use changes.

KEYWORDS Jakarta; flood inundation simulation; land subsidence; land-use changes

INTRODUCTION

Jakarta faces various infrastructural, social, and water-related problems, such as land subsidence in coastal areas and rapid land-use/cover changes in the upstream region, which have resulted in an increase in the size of the area at risk of flooding. The Indonesian economy has grown in the past three decades, leading to new and expanding urbanized areas in Jakarta and its surrounding areas. Using a flood inundation model for Jakarta and the Ciliwung River basin, Farid et al. (2011) and Moe et al. (2016a) noted that flood inundation area and volume increased with increases in the urbanized area.

In addition to problems stemming from urbanization, land subsidence in Jakarta is another major issue. Abidin et al. (2011) reported that groundwater extraction in the urbanized area has resulted in significant land subsidence in Jakarta. They assessed the state of land subsidence in the city and evaluated the relationship between the flooded areas and areas affected by land subsidence, concluding that the impact on land subsidence has led to the expansion of flood-prone areas in Jakarta. Budiyono et al. (2016) suggested that land subsidence would be the greatest factor driving increases in the extent of future flood risk in Jakarta. Moreover, Takagi et al. (2016) concluded that land subsidence would be the main driver of coastal floods in the north coastal area of Jakarta by projecting the sea level rise under future climate change and land subsidence conditions.

Land subsidence and land-use changes are ongoing, and significant changes are expected to continue in the future (Moe et al., 2016b). Land subsidence in Jakarta exhibits spatial and temporal variations. From 1982–2010, rates were about 1–15 cm year−1, although a few locations had subsidence rates of up to 20–28 cm year−1 (Abidin et al., 2011). However, to the best of our knowledge, no studies have examined future trends in flooding with regard to both land-use changes and land subsidence in Jakarta. Therefore, it was important to examine how future changes resulting from continuous land subsidence and land-use/cover changes will affect flooding in Jakarta, and to quantify these effects to help mitigate future floods. The main objective of this study was to project flood inundation in Jakarta by considering future land-use changes and land subsidence.

STUDY AREA

Jakarta, officially known as the Special Capital Region of Jakarta, is located in the northwest part of Java Island, Indonesia. The main and longest river in Jakarta is the Ciliwung River, which passes through the central part of the city from an upstream mountainous region. The target area selected for this study included Jakarta and the Ciliwung River basin, covering a total area of 1,346.6 km² (Figure 1).
Jakarta has many infrastructure problems, including traffic jams and floods, caused by rapid economic growth and urbanization. Bricker et al. (2014) noted the reduced capacity of the drainage system due to trash clogging floodgates, which was one of the factors behind the 2013 flood. In addition, Kure et al. (2014) emphasized that a lack of capacity in rivers is a factor that can worsen flooding. As explained above, urbanization has contributed to increased flood damage (Farid et al., 2011; Moe et al., 2016a) and land subsidence is a serious problem that causes urban flooding in lowland areas (Budiyono et al., 2016).

**METHODOLOGY**

**Flood inundation model**

We applied a physically based rainfall-runoff and flood inundation model (Kure and Yamada, 2004; Kure et al., 2008) to simulate flood inundation scenarios in Jakarta for historical and future periods. The model consisted of a rainfall-runoff module for each sub-basin, a one-dimensional hydrodynamic module for the river networks, and a two-dimensional flood inundation module for the floodplains. The computed runoffs from each sub-basin were used for lateral inflows of the hydrodynamic module. The hydrodynamic module and the flood inundation module were laterally linked based on a weir equation for simulating overflow from a river channel onto a flood plain. We used this model to compute flood inundation in Jakarta because it was previously applied to the study area and calibrated (Moe et al., 2016a, b), and the model is applicable not only to mountainous regions, but also highly urbanized areas. Details of the model, including its parameters and datasets, are provided in Text S1.

The flood inundation model was applied to the flood event in January 2013, which caused severe damage in Jakarta. In this study, cells in the riverbanks were omitted from any flow calculations in the two-dimensional model to prevent inundated water from flowing cross the riverbanks into other rivers. The inundation flows generally do not cross into other rivers due to high riverbanks in the urbanized target area. However, previous studies did not take this step, and some discrepancies between simulated and observed flood inundation areas were found in previous results (Moe et al., 2016a, b). Figure 2 shows the observed and simulated inundation areas. The observed flooded area data were provided by the Badan Penanggulangan Bencana Daerah (BPBD; Jakarta Province Regional Disaster Management Agency). The simulated inundation area in the target area matched the observed area reasonably well. However, there were discrepancies between the reported and simulated inundation areas, especially in the north-central and northeast areas. This may have been caused by the numerous local fish ponds located in these areas. The local fish ponds are initially filled with water but this initial water was not captured by the land-use map used in this

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Figure 1. Study area and land-use/cover maps from 1983 to 2050

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Historical and future land subsidences were reconstructed and projected, respectively (Moe et al., 2016b), to evaluate the effect of land subsidence on flooding. Jakarta Coastal Defense Strategy (2011) measured land subsidence in Jakarta using a GPS, leveling surveys, and interferometric synthetic aperture radar technology, and reported a total land subsidence of up to ~4.0 m in the lowland areas from 1974 to 2010. Moe et al. (2016b) extracted this accumulated land subsidence data at each grid point and constructed a spatially interpolated land subsidence accumulation map of Jakarta. Then, from the 2009 base elevation data and the computed land subsidence rates at each grid, past and future land subsidence scenarios were reconstructed and projected using linear extrapolation.

This method of linear extrapolation for the projection of land subsidence should be considered as the worst-case scenario, as it assumes that the rate of land subsidence will continue due to ongoing groundwater extraction and high-rise building development. However, Takagi et al. (2016) and Budiyono et al. (2016) reported that the government has a target to stop land subsidence by providing all of Jakarta with a water supply system by 2020. Based on this target, we assumed two scenarios in this study: one in which land subsidence is stopped by 2020 and another in which it is stopped by 2030.

Historical and future land-use/cover changes

To evaluate the effect of land-use changes on flooding in Jakarta, we investigated historical and future land use. For the historical period, land-use change data obtained from the Ministry of Public Works were used. Figure 1 shows land-use/cover maps for 1983, 1996, and 2002 (Moe et al., 2016a).

In addition, Figure 1 shows the projected land-use changes in the target area from 2020 to 2050, while Table I shows the land-use by category (%) for each year. Future urban development was projected using the SLEUTH model. 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, 2006). All C language source code, libraries, and sample data for the SLEUTH computations are available for downloading through Project Gigalopolis (USGS, 2010), and SLEUTH has been applied to many cities (e.g. Guan and Rowe, 2016). In this study, urban growth was determined according to the assumption that historical levels of urbanization would be maintained. Varquez et al. (2017) applied SLEUTH to Jakarta under the RCP8.5-SSP3 scenario (Varquez et al., 2017), and the resulting projected land-use/cover maps were employed in this study. It should be emphasized that the land-use projection 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 region. In other words, this urban growth should be considered as the worst-case scenario (the RCP8.5-SSP3), as it assumes that...
the historical trend of uncontrolled growth of urbanization is maintained.

Based on this projection, Jakarta and its surrounding areas, especially the upstream region, would be fully urbanized by 2040, assuming that no future land-use controls are imposed by the government (Figure 1, Table I). Similar to land subsidence, we assumed two scenarios, one in which changes in land-use would stop by 2020 and another in which they would stop by 2030. We assumed that the government would implement land-use controls and that development would cease in the upstream region of the target area after 2020 or 2030. Furthermore, a mitigation plan based on controlling land use/cover to stop urbanization in the upstream region was evaluated by numerical simulations and is described in the following sections. These cases and scenarios are summarized in Table II.

### RESULTS

Reconstructed and projected land surface elevations were used for each grid elevation of the flood inundation model for all years. In addition, historical and future land-use/cover information were used to compute the land-use categories by area and proportion (%) in each sub-basin. The other inputs, such as the rainfall and model parameters for each land-use category, were the same as those used for the calibration simulation of the 2013 event. Simulated hydrographs at the Katulampa and Depok stations (Figure 1), under each land-use/cover scenario, are shown in Figure 3. Based on the results, the flood peak and volume increased with future increases in the size of the urbanized area.

###Effects of land subsidence (Case 1)

The flood inundation simulations were conducted based on the land-use/cover conditions of 2013, using land surface elevation data from 1983 to 2050, to evaluate the effects of land subsidence (Case 1). The total flood inundation volumes in Jakarta, in 2013 and 2050, were calculated as 2,960,121 m³ and 3,228,087 m³, respectively, suggesting that the city’s flood inundation volume would increase by 9.1% from 2013 to 2050 due to the impact of land subsidence. Figure S1 shows the simulated flood inundations of 1983 and 2050, and the difference between them. It should be emphasized that the increase in flood inundation shown in Figure S1 is strongly related to high-subidence areas.

###Effects of land-use changes (Case 2)

The impacts of land-use changes were evaluated with the flood inundation simulation based on the 2013 elevation data and land use/cover data from 1983 to 2050 (Case 2). The total flood inundation volumes in Jakarta, in 2013 and 2050, were calculated as 2,960,121 m³ and 3,604,572 m³, respectively. Figure S2 shows the simulated flood inundations of 1983 and 2050, and the difference between them. The land use pattern in 2050 would increase the flood inundation volume by 21.8% compared to that in 2013. It should be emphasized that there is high demand for urban development in Jakarta and its surrounding areas, and resulting land-use changes would affect future flood inundation significantly.

###Effects of land-use changes and land subsidence (Case 3)

Both land-use changes and land subsidence effects were evaluated with the flood inundation simulations using land-use and elevation data from 1983 to 2050 (Case 3). Figure 4 shows the time series of the simulated flood inundation

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**Table II. Different land-use/cover change scenarios**

| Case | Situation                          | Land Use/Cover | Elevation   |
|------|-----------------------------------|----------------|-------------|
| 1    | Only land subsidence              | 2002           | 1983–2050   |
| 2    | Only land use change              | 1983–2050      | 2009        |
| 3    | Both                              | 1983–2050      | 1983–2050   |
| 4    | Land use change stops at 2020     | 1983–2020      | 1983–2050   |
| 5    | Land use change stops at 2030     | 1983–2030      | 1983–2050   |
| 6    | Land subsidence stops at 2020     | 1983–2050      | 1983–2020   |
| 7    | Land subsidence stops at 2030     | 1983–2050      | 1983–2030   |

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**Figure 3. Impacts of land-use changes on river discharge at the Depok and Katulampa stations, Ciliwung River basin**

**Figure 4. The time series of the simulated flood inundation**
area and volume, with and without consideration of land-use changes and land subsidence from 1983 to 2050. The inundation area and volume increased with increasing urbanization and land subsidence. The flood inundation volumes, considering both land-use and elevation changes (Case 3) in 2013 and 2050, were calculated as 2,960,121 m$^3$ and 4,050,171 m$^3$, respectively, showing a 36.8% increase.

The impact of land-use changes was much greater than that of land subsidence (Figure 4). This is because land-use changes affect the flood runoff volume. It should be emphasized that there was no significant difference in the impact of land-use changes on the flood inundation volume and area for the future period between 2040 and 2050 (Figure 4), because there would be no more space for the urbanized area in the city (and its surrounding areas) to expand into (Figure 1).

**Scenarios whereby land subsidence and land-use/cover changes are assumed to stop by 2020 or 2030 (Cases 4–7)**

The government plans to stop land subsidence in Jakarta by around 2020; therefore, we analyzed this scenario. Assuming that land subsidence would stop by 2020, constant elevation data in 2020 and land-use data from 2020 to 2050 were used for additional simulations (Case 6). The results are shown in Figure 4. The flood inundation volumes in 2013 and 2050 were calculated as 2,960,121 m$^3$ and 3,739,564 m$^3$, respectively. The flood inundation volume of Jakarta would increase by 26.3% by 2050 because of land-use changes and land subsidence, even if land subsidence were to stop by 2020 (Case 6). In the case in which land subsidence stopped by 2030 (Case 7), the city’s flood inundation volume would still increase by 29.8% by 2050.

In addition, we evaluated scenarios to control and stop the land-use changes by 2020 or 2030. If the land-use changes were stopped by 2020 (Case 4), the increase in the flood inundation volume by 2050 would be 21.9%. Meanwhile, if land-use changes were stopped by 2030 (Case 5), the increase in the volume by 2050 would be 33.6%. From these assumptions, it can be concluded that stopping land-use changes by 2020 (Case 4) would result in the lowest increase in flood inundation volume and thus represents the best mitigation plan to minimize future flood damage.

**DISCUSSION**

Several studies have evaluated flooding in Jakarta, which has become more frequent in recent years. Budiyono et al. (2016) evaluated the river flood risk in Jakarta with a flood inundation model, and observed that land subsidence would be the main factor influencing flooding in the near future. However, their study did not consider the effects of historical and future land-use changes. As mentioned in the previous section, the extent to which Jakarta is urbanized is expected to continue to increase in the future. Moreover, land-use changes would have a greater impact on flooding compared to land subsidence based on the model results. However, it should be noted the results presented in this study are highly affected by the future land-use change projection. In this study, we initially investigated the urban situation under the RCP8.5-SSP3 scenario (Varquez et al., 2017) as the worst socio-economic future scenario but other urban distribution scenarios assuming various combinations of RCP and SSP should be investigated in the next study.

Land subsidence is a major issue in Jakarta from the perspective of coastal flooding, because high tides and large waves are expected to become more significant in the future. For example, Takagi et al. (2016) simulated flood scenarios in Jakarta by projecting future relative sea level increases and land subsidence. They emphasized that future flooding from the ocean would significantly increase because of land subsidence in Jakarta. It should be noted that, in this study, we did not consider water from the ocean or coastal flooding due to high tides and large waves.

The government has a mitigation plan to stop land subsidence in the near future, although there is no policy in place to stop future land-use changes. Furthermore, extreme...
flooding could become more frequent over time (e.g. Kure and Tebakari, 2012; Iwami et al., 2017) due to climate change. Iwami et al. (2017) reported that the Solo River basin, located on the east side of Java Island, will become wet in the future, with more inundation areas and specific peak discharges in extreme flood events. However, this was not considered in the present study because, as reported by Budiyono et al. (2016), the impact of climate change on floods in Jakarta may be much smaller than that of land-use changes and land subsidence. Based on this, we conclude that the government should control and regulate land-use changes in upstream regions of Jakarta as soon as possible. Several mitigation plans to control land-use changes and land subsidence are discussed in this paper, which would contribute to reducing flood damage in the future. In addition, there are many other options for reducing flood damage that consider various countermeasures, including increasing the flood capacity of rivers by dredging sediment, widening rivers, and increasing the height of levees; constructing diversion tunnels to the East and West Canals; constructing infiltration wells in elevated regions; and increasing the capacity of both natural and artificial ponds or lakes in elevated regions. Such countermeasures should be quantitatively evaluated in future studies.

CONCLUSIONS

We used a rainfall-runoff and flood inundation model to project future flood inundation scenarios in Jakarta and its surrounding areas by considering land-use changes and land subsidence. Based on this analysis, land-use changes and land subsidence contributed to an increase in flood inundation volume of 36.8% from 2013 to 2050. In addition, the effects of land-use changes on the extent of flood inundation in Jakarta were much greater than those of land subsidence. The government’s plan to stop land subsidence by 2020 would cause a 7.7% decrease in the flood inundation volume by 2050. Furthermore, controlling and regulating land-use/cover changes by 2020 would cause a 10.9% decrease in the flood inundation volume by 2050. Based on these results, flood mitigation plans should be implemented not only for land subsidence, but also for land-use changes. We strongly recommend that the Jakarta government create land-use change regulations for Jakarta and its surrounding areas as soon as possible to reduce future flood damage in the city.

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SUPPLEMENTS

Text S1. Supplementary information on the flood inundation model and dataset used in this study

Figure S1. Flood inundation simulation results based on land subsidence in 1983 and 2050, and the differences between them

Figure S2. Flood inundation simulation results based on land use/cover in 1983 and 2050, and the differences between them

Figure S3. Study area and locations of the observation stations

Figure S4. Bias-corrected daily accumulated rainfall on January 15, 2013 (Moe et al., 2016a)

Figure S5. Land-use/cover map for 2002

Figure S6. Time series of observed and simulated discharges at the Katulampa and Depok stations (Moe et al., 2016a)

Table S1. Calibrated soil parameters

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