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Flood Prediction due to Land Cover Change in the Ciliwung River Basin

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Abstract. Located in the Special Capital Region of Jakarta (DKI Jakarta), which serves as the government capital and national capital of Indonesia, the Ciliwung River plays a major role in Indonesia. The increasing population of the Jakarta and Bogor area has resulted in an increase in the level of land ownership, which has had an impact on increasing areas of settlement and decreasing green open spaces. This rapid urbanization and change in land use has directly affected the hydrological nature of the area, causing an increase in the flooding volume in this region. This research was conducted in four stages: hydrological analysis, hydraulic analysis, flood hazard mapping, and flood assessment of land cover. To estimate the impact of the land cover change that has occurred, the Soil Conservation Service Unit Hydrograph was used along with the West Java rainfall distribution method. Hydraulic modeling uses the Hydrologic Engineering Center-River Analysis System, with 1D for channel runoff and 2D for surface runoff. Two projected land cover changes from a previous study and spatial plan were used to analyze design discharges. The results found that, for every 13 km^2 of forest or agricultural area converted into urban or bare soil area, the flood peak discharge, flood area, and flood volume would increase by 3.6%, 15%, and 16%, respectively. The hydrological analysis showed that, based on historical data trends, the land cover change in 2030 would lead to an increase in peak discharge, flood area, and flood volume of 25%, 101.7%, and 91%, respectively. However, this impact could be minimized by following Bogor District Spatial Planning, which has a wider forest area than the future projection land cover.

Keywords: Ciliwung River Basin; Curve number; Flood; Land cover change

1. Introduction

The Ciliwung River Basin has a broad watershed area of 337 km^2, with the length of the main river being about 117 km, and it forms the West Flood Canal (Kanal Banjir Barat) system, which covers more than a quarter of the total area of Jakarta. Jakarta is the city with the largest population in Southeast Asia, at more than 10 million, and it has growth

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reaching 0.94% annually (BPS of Jakarta Province, 2020). The increasing population of the Jakarta and Bogor area has resulted in an increase in the level of land ownership, which has had an impact on increasing areas of settlement and decreasing green open spaces. In terms of urban planning and land use, Jakarta fulfills less than one-third of the ideal scale of the green environment and catchment areas needed as natural catchments in years of normal rainfall (Setiowati et al., 2018). This poor land use is shown in several locations designed as rain catchment areas, which are mostly used as luxury housing areas (Firman et al., 2011). Jakarta's rapid growth has affected the surrounding areas, particularly to the south, which have turned agricultural areas into industrial areas (Farid et al., 2011; Hidajat et al., 2013; Widiatmaka et al., 2016; Moe et al., 2018). This rapid urbanization and land use change has directly affected the hydrological nature of the area by reducing the rate of infiltration, baseflow, and lag time and by increasing surface runoff, peak discharge, runoff volume, and flood frequency (Hartono et al., 2010; Ogden et al., 2011; Emam et al., 2016; Tellman et al., 2016; Julian et al., 2019).

Jakarta's open areas over the past 20 years have been followed by an increase in the intensity and occurrence of floods, indicating a direct relationship between a reduction in green open spaces and the exacerbation of the condition in Jakarta as one of the most vulnerable cities facing flood disasters (Fuchs, 2010). Changes in land use and land cover (LULC) have also indicated the effects of the frequency and characteristics of rainfall (Boysen et al., 2014; Mitsova, 2014). In 2013, Jakarta experienced a major flood in which 124 villages were submerged, with a total of 20 fatalities. The floods in 2013 were estimated to cause losses of US$360 million. In addition to causing damage to the area around the river, flooding in the Ciliwung River Basin also had a direct impact on several vital national monuments. Nonstructural measures, such as hazard mapping and flood risk, can be very effective for land use planning and flood damage mitigation (Marfai et al., 2015; Kuntiyawichai et al., 2016; Darabi et al., 2019; Farid et al., 2020).

In this study, the river basin has been divided into three sections—upper, middle, and downstream—based on the difference in the area slope and the availability of an automatic water level recorder (AWLR) for the needs of the early warning system. Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) software was used as a hydrological modeling tool to produce flood hydrographs at Depok AWLR, MT. A Haryono AWLR at the Manggarai flood gate, along with the Hydrologic Engineering Center-River Analysis System (HEC-RAS), was used as a hydraulic modeling tool to generate the flood inundation model in the Ciliwung River Basin. The purpose of this study was to assess the impact of estimated changes in land cover on future flood hazards with several land cover scenarios through changes in peak discharge, flood area, and flood volume in Jakarta. To quantify the detailed results, the magnitude of the change in flooding was compared to the change in forest area converted to settlement area.

2. Study Area

The study area is located in the Ciliwung River Basin, one of 13 rivers flowing in Jakarta. Geographically located at 106°45'E and 107°00'E and 6°05'S and 6°50'S, starting in the Bogor Regency, the Ciliwung River flows through Bogor, Depok, and Jakarta. The length of the main river is 120 km long, with a catchment area at the entrance of the Manggarai flood gate of 337 km^2. The topography of the basin ranges from +0 to + 900 above sea level. The downstream part of the river basin is categorized as a low-lying area, which is one of the reasons that is prone to flooding, while the upstream part of the river area is a plateau, especially in the Bogor Regency, with an average slope of 10%. The upstream soil area is dominated by hydrologic soil group (HSG) types C and C/D and is characterized by a composition of less than 50% sand and 20–40% clay, while both the middle stream and downstream areas are dominated by HSG types D and D/D and is characterized by a composition of less than 50% sand and > 40% clay (Ross et al., 2018). In terms of rainfall seasonality, the basin is classified as bimodal, having a long rainy season predominantly between the months of April and June and a short rainy season between September and December. The average annual rainfall depth is about 1,300 mm in a normal year devoid of extreme rainfall events due to climatic variations. Figure 1 shows the study location.

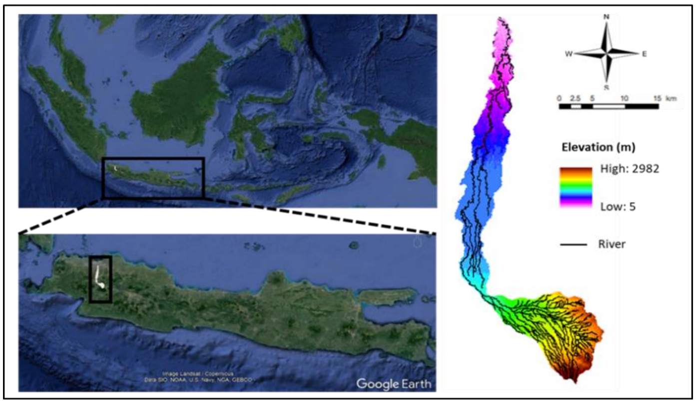


Figure 1 Location of the study area

3. Material and Methods

This research is based on the results of land use modeling projections done by Moe et al. (2017) and the Regional Spatial Plan (RTRW) for the Province of Jakarta and its surroundings in the Ciliwung River Basin area. Data collection included the digital elevation model (DEM) from the Indonesian Geospatial Information Agency, soil data from the United States Geological Survey (USGS), rainfall data from the Meteorology, Climatology, Geophysics Agency, and river discharge and channel geometry (Ciliwung River) provided by the River Basin Agency of Ministry Public Works and Housings.

This research was divided into four major parts: hydrological analysis, hydraulic analysis, flood hazard mapping, and flood assessment of land cover. By using rainfall and land cover data, hydrological analysis was conducted to obtain the calibration and flood design discharge that was used to generate flood maps through hydraulic analysis. The output of flood mapping on several land cover projections was then used to analyze the flood assessment of land cover changes. The framework of this study can be seen in Figure 2.

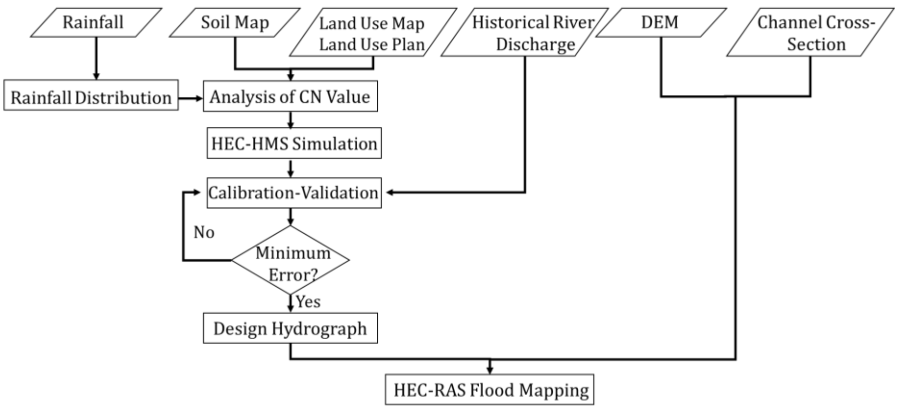


Figure 2 Framework methodology

3.1. Land Use Model

Four land cover models were used in this analysis: actual land cover in 2009 and 2019, and projected land cover in 2030 by local governments and according to trends in the past 30 years. The land cover was divided into five categories according to type 1 land cover categories by the Indonesian Ministry of Forestry: forest, agriculture, bare soil, settlement, and water body. The land cover information from 2009 and 2019 was generated using Landsat imagery with a 30 x 30 m grid provided by the USGS.

The Depok sub-basin experienced the majority of land change dynamics. In a period of 20 years, there was an increase in the area of settlement by more than 23 km^2 and a reduction in the agricultural area by 16 km^2, followed by a decrease in bare soil by 13.5 km^2. In contrast with the high dynamics of change in the Depok sub-basin, the M.T. Haryono sub-basin experienced only a few minor changes, which were dominated by an increase in the settlement area by 2.6 km^2, equivalent to 3.2% of the total area. There was also a decrease in the agricultural area and bare soil area of 3.2 km^2 and 1.7 km^2, respectively. The increase in residential area growth and decrease in bare soil area that has occurred can be observed moving from the direction of Jakarta to the upstream of the Ciliwung River Basin. The dynamics of the land cover of the Ciliwung River Basin can be seen in Figure 3.

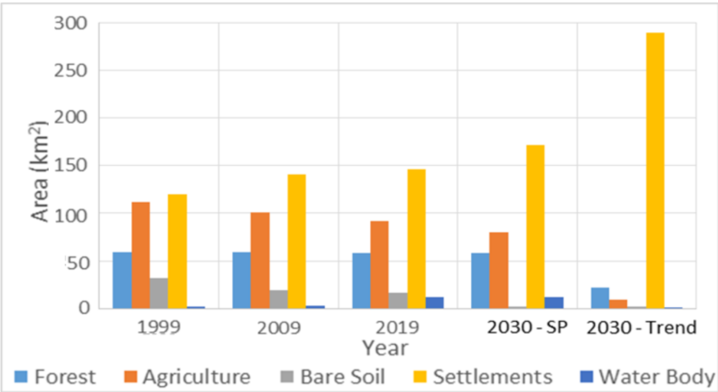


Figure 3 Land cover change in the Ciliwung River Basin

Projected land cover by local governments was based on the RTRW to reach long-term development goals. The spatial plan for Depok City and the Bogor Regency was prepared by considering the links between various aspects related to land cover, such as the location of certain infrastructure development and social development. In this spatial planning, the government ensures that sustainable development continues without sacrificing environmental aspects. Using the SLEUTH model, Moe et al. (2017) extrapolated trends in land cover change through land cover data from 1983 to 2002. SLEUTH stands for the spatial inputs used in the model (i.e., land cover, excluded regions, urban land cover, transportation, and hill shade) and is a cellular automata-based computer simulation model that utilizes historical LULC (Zhou et al., 2019). In this model, urban growth was determined according to the assumption that historical levels of urbanization would be maintained, and it ignored the occurrence of social growth and infrastructure growth. 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.

3.2. Hydrologic Modeling

Daily precipitation data were retrieved from the Indonesian Meteorological and Geophysical Agency, along with the Ministry of Public Works and Housing. To calibrate the hydrologic model, the data were converted into hourly precipitation and matched with recorded flood discharges. The calibration of each flood event was conducted at three discharge points as measurement locations: Depok AWLR, MT; Haryono AWLR; and the Manggarai flood gate. Each location was divided into smaller sub-basins. The daily precipitation data were also used to estimate the precipitation of the 50-year return period. The curve number system by the United States Department of Agriculture (1986) was used to quantify the effect of land cover change on flooding, which was then used to calculate the amount of infiltration that occurs. This value was obtained from the relationship between soil composition and land cover type. The West Java Rainfall Trend and Soil Conservation Service hydrograph unit was used as the model for the hyetograph and hydrograph (Brotowiryatmo, 2016). The Soil Conservation Service – Curve Number (SCS-CN) method was chosen because of its many advantages compared to other infiltration quantification methods, especially because of its simplicity, accuracy, and ease of application (Singh et al., 2010; Verma et al., 2018), as further research showed that the SCS-CN method gives the most satisfactory calibration results (Pratama et al., 2021). The hydrologic model can be seen in Figure 4.

Some hydrological simulations were simulated with different sets of CN parameters and with other simulation parameters of a constant value. The SCS-CN method is based on calculating runoff from rainfall depth as seen in Equation 1:

$$Q = \frac{(P - I_a)^2}{(P - I_a) - S} \tag{1}$$

where Q is the direct runoff (m), P is the rainfall (m), S is the potential maximum retention (m), and Ia is the initial abstraction (about Ia = 0.2S). Potential maximum retention was defined by CN, as indicate by Equation 2.

$$S = \frac{25400}{CN} - 254 \tag{2}$$

while lag time was approached using Equation 3.

$$t_L = \frac{L^{0.8}(2540\text{-}22.86\ CN)^{0.7}}{14104\ CN^{0.7} I^{0.5}} \tag{3}$$

with peak discharge expressed in Equation 4.

$$Q_p = U_p A Q F_p \tag{4}$$

where t_L is lag time (hour), L is river length (km), I is river bed slope (m/m’), Qp is peak discharge (m^3/s), A is the river basin area (km^2), Q is discharge (mm), and Fp is the lake/swamp calibrating factor.

3.3. Hydraulic Modeling

The flood hydrograph from the hydrologic analysis was used as the flow input for the hydraulic modeling. To calibrate the hydrologic model, aerial pictures of several flooding events were retrieved from the Jakarta Regional Disaster Management Agency and compared to hydraulic simulation results using HEC-RAS. Hydraulic modeling uses the HEC-RAS coupling one-dimensional (1D) method for channel modeling and two-dimensional (2D) method for modeling land runoff. The governing equations used for 2D HEC-RAS modeling were the continuity equation, the mass conservation equation, and the momentum conservation equation, expressed in Equation 5, Equation 6, and Equation 7, respectively.

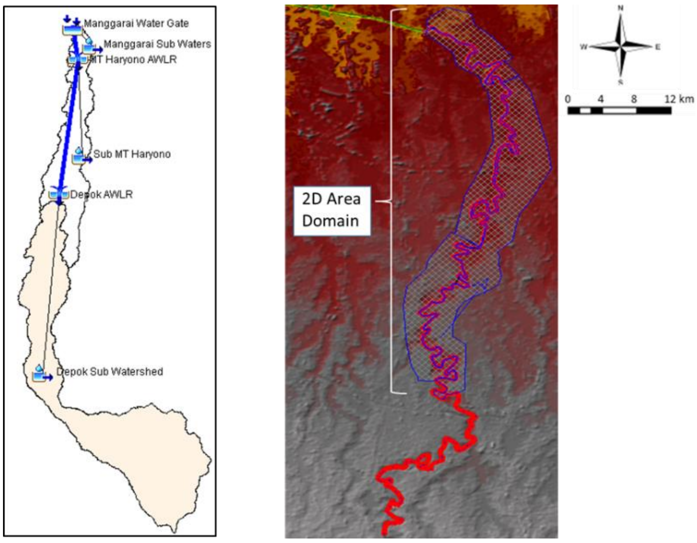
$$\frac{\partial H}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} + q = 0 \tag{5}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial H}{\partial x} + v_i\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u + fv \tag{6}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial x} + v_i\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v + fv \tag{7}$$

where t is time, u and v are velocity components in the x direction and the y direction, q is the inflow or outflow flux form, u and v are the velocity in the Cartesian direction, g is the acceleration due to gravity, v_i is the horizontal coefficient of Eddy viscosity, R is the hydraulic radius, and c_f is the coefficient of friction that occurs in the channel.

The model simulation started from the upstream Ciliwung River Basin, which is located south of Jakarta. Several lateral discharges were placed along the river. In this modeling, calibration, validation, and flood planning used the channel cross-sectional dimensions of 2015. The accuracy of the model was measured using the Nash-Sutcliffe efficiency (NSE) and root mean square error (RMSE) of the area of flooding, which was provided by Jakarta's Regional Agency for Disaster Management, and the water depth in the Manggarai flood gate for the simulation results. The hydraulic model can be seen in Figure 4.



(a) (b)

Figure 4 Model setup of the study: (a) hydrologic model and (b) hydraulic model

4. Results and Discussion

4.1. Calibration and Validation

To calibrate the hydrological and hydraulic models, the results of the modeling were compared to the actual flooding in 2015. Hydrograph lag time and initial soil abstraction were used as calibration parameters for the hydrological model, while the Manning coefficient of the river banks and floodplains were used as parameters for the hydraulic model. Calibration showed satisfactory results for both the hydrologic and hydraulic models, especially in the area around the riverside. Hydrograph modeling, with a lag time of 280 min, obtained a peak hydrograph of 117.5 m^3/s, while the peak observed discharge was 116.7 m^3/s. The NSE value of the hydrologic model was 0.69, and the RMSE value was

0.4. The NSE value of the hydraulic model was 0.562, and the RMSE value was 0.21. The calibrated model results for the hydrograph in 2015 can be seen in Figure 5.

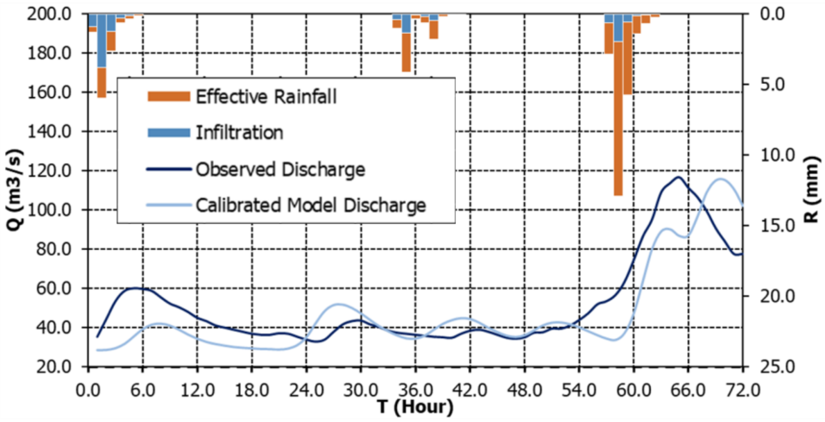
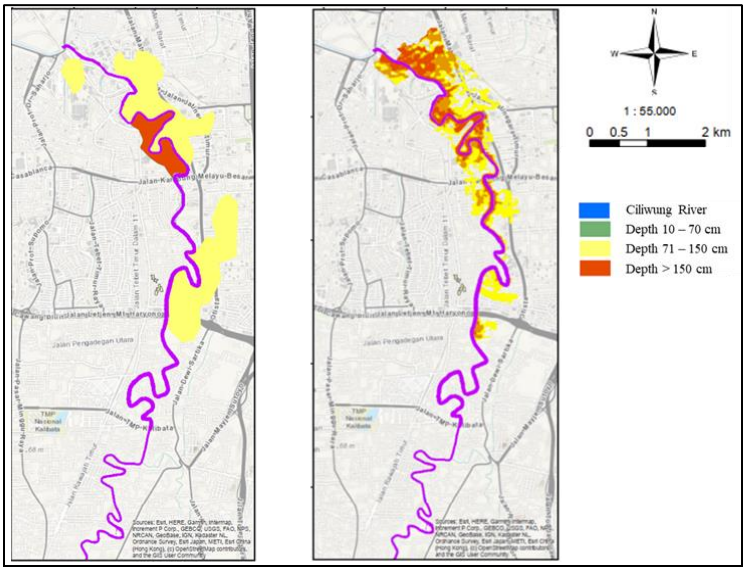


Figure 5 Hydrologic model calibration for the 2015 flood event

The 1D hydraulic calibration model obtained a record maximum depth of 8.5 m at the Manggarai flood gate, while the observation data showed a maximum depth of 8.75 m, a difference of 0.25 m. While the flooding area for the 2D model showed a good result, there were differences in the depth of flooding at several points on the map, which could have been caused by differences in ground elevation and differences in the water flow direction due to the presence of buildings. The calibrated 2D model results for flooding in 2015 can be seen in Figure 6.



(a) (b)

Figure 6 2D Hydraulic calibration results for 2015 flood: (a) observation data and (b) simulation results

4.2. Hydrologic Modeling Results

In the simulation of flood discharge in the Depok watershed with a 50-year return period, four hydrograph models were generated: a peak discharge of 412 m^3/s for the land cover of 2009, 431 m^3/s for the land cover of 2019, 451 m^3/s for the land cover of 2030 based on the spatial plan, and 529 m^3/s for the land cover of 2030 based on the trend. The simulation results found that an increase in CN by 1 point caused an increase in discharge generation in the Manggarai sub-basin by 3.6%, with an extreme discharge difference of up to 120 m^3/s between the land cover of 2009 and the 2030 trend. Adhering to the RTRW that was formulated, the plan slows down growth, decreasing the likelihood of a flooding impact. The results can be seen in Figure 7.

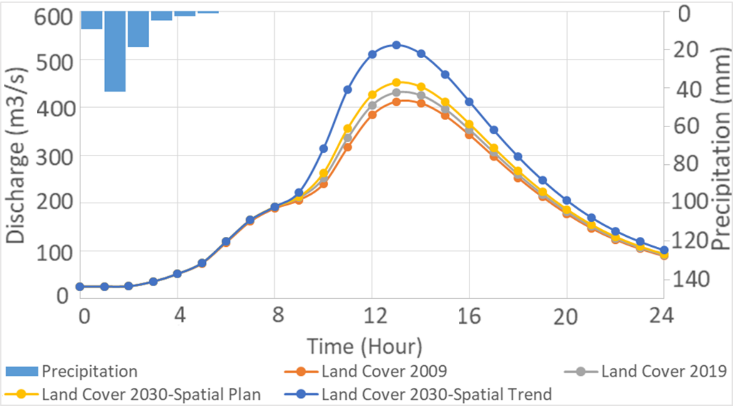
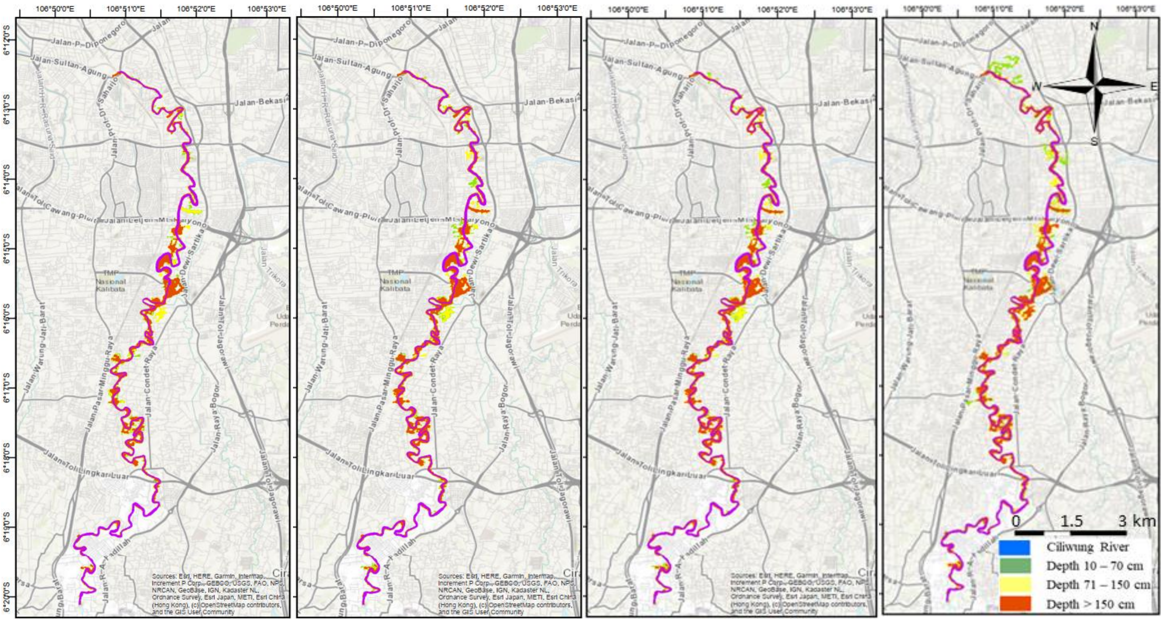


Figure 7 Comparison of the flood hydrograph from different land cover at the Manggarai flood gate

4.3. Hydraulic Modeling Results

The results of the flood simulation for the 50-year return period for the 2019 land cover were 120.05 ha for the inundation area and 2.06 million m^3 flood volume, which is an increase in the volume and area of flooding by 7.61% (0.16 million m^3) and 7.32% (8.8 ha) of the flooding estimation from 2009. The flood simulations for 2030 with land cover in accordance with the spatial plan showed an increase in the volume and area of flooding by 18.2% (0.38 million m^3) and 15.85% (19 ha), while for land cover in accordance with the trend for 2030 showed an increase in the volume and area of floods by 101.7% (2.1 million m^3) and 91% (109 ha). With every 13 km^2 of forest or agricultural area, the flood area and volume would increase by 15%, and 16%, respectively. The flooding in the downstream area of the Ciliwung River Basin was found to be very sensitive to the changes that occur in the upper stream area.

For extreme land cover according to the trend in 2030, the prediction of inundated areas would not change much according to the map of flood-prone areas. However, there would be flood distribution at a new point. The area around the Manggarai flood gate and the Bidara Cina sub-district would be the areas most affected, with the increase in flood area and flood depth in projected future flood events. In the recorded historical flood events, the trend of flooding before the Manggarai flood gate was mainly caused by the closing of the floodgates by garbage or debris from upstream so that the gate's capacity decreased, whereas the simulation that was conducted showed that, even before the closure of the Manggarai flood gate, there was flooding in the floodplain. However, based on information from residents in several flood events, most of the floods were caused by the inability of the river, which was already full of discharge from upstream, to receive additional discharge from urban areas. This modeling can help conclude that, in the event of a 50-year return period for flooding in the land cover in 2030, the trend of using water pumps on the riverside, which are usually used as the main "weapon" to minimize the impact of flooding, will become ineffective. The hydraulic modeling results can be seen in Figure 8.



(a) (b) (c) (d)

Figure 8 Flooding in the Ciliwung River based on different land cover: (a) 2009, (b) 2019; (c) 2030 based on the spatial plan; (d) 2030 based on the historical trend

5. Conclusions

The present study attempted to estimate the impact of land cover changes on the evolution of flood peak discharge, inundation area, and volume in the Ciliwung River Basin, Indonesia. HEC-HMS was used to generate a flood hydrograph to calibrate and design flood discharges, while HEC-RAS was used as the hydraulic tool. To estimate the impact of land cover changes that occur, the Soil Conservation Service Unit Hydrograph was used along with the West Java rainfall distribution method. The hydrological analysis shows that land cover change based on historical land cover trends would lead to an increase in peak discharge, flood area, and flood volume in 2030 by 23%, 101.7%, and 91%, respectively. However, by following Bogor District Spatial Planning, the increase in flood effects for peak discharge, flood area, and flood volume would be 4.7%, 18.2%, and 15.85%, respectively. With every 13 km^2 of forest or agricultural area converted into urban or bare soil area, the flood peak discharge, flood area, and flood volume would increase by 3.6%, 15%, and 16%, respectively. The results of this study demonstrate that further detailed studies on the impact of the LULC on flood hazards are necessary, especially in urbanized areas. The study would be useful in spatial planning and can indicate areas that are currently or potentially flood prone and are also likely to be subject to future development. Such areas should be of special consideration in the formation of spatial planning policy to avoid economic losses in the future.

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