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Proceedings of ninth International Conference on Hydro-Science and Engineering (ICHE 2010), IIT Madras, Chennai, India.
2 - 5 August 2010

EFFECT OF URBANIZATION DISTRIBUTION ON FLOOD SIMULATION

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***Abstract**: In this paper, a distributed model by combining hydraulic and hydrologic model is developed to simulate flood accurately without neglecting its physical process by accommodating urbanization distribution effect. Surface runoff is simulated using 2D shallow water equation while nearly calibration free (NCF) tank model is used to simulate hydrology parameters. Spatial distributed urban density factor is applied to accommodate physical based process for infiltration mechanism in urban area. This factor is used to adjust the value of infiltration coefficient in urban area (c_d) which is defined as ratio of permeable area in urban land cover. This coefficient determines the loss of water in urban area. The model is applied to the upstream Ciliwung River Basin, Indonesia with the area of 234 km^2 and 46 km length of river. This basin has been contributing discharge and causing flood in the downstream area, Jakarta which is the capital city of Indonesia. One day event of rainfall from wet season 2002 is selected to calibrate the model. For validation purpose, simulation is conducted by using flood event in 2002 which is considered to be one of the worst in city history. The result from both calibration and validation shows good agreement with observation data. To examine the effect of urbanization due to land cover change, simulation has been conducted for the same flood event in 2002 but with 1972 land cover. The result shows that urbanization from 1972 to 2002 has increased discharge significantly.*

***Keywords**: flood simulation; urban density; infiltration; distributed model.*

INTRODUCTION

Land use change due to urbanization is said to contribute in increasing flood discharge. Development has decreased permeable area, thus increased run off discharge. Deforestation has caused decreasing of tree canopy which also contributes to increase flood discharge. Statistical analysis has been studied to obtain relation between urbanization and changing of flood behavior in Los Angeles (Sheng and Wilson, 2009). It is found that a large percentage (90%) of rain become surface run off in urban area, whereas only 25% in non urban area.

The needs of new area for various developments can not be denied. Thus, it is important for decision maker to understand the correlation of urbanization to flood discharge. Flood

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simulation is considered to be an effective tool to study this phenomenon. Moreover, it has an important role in water resources and planning management especially in disaster mitigation and vulnerability assessment. Decision makers often rely on simulation result for those purposes. Therefore, it is necessary to have a good model that can represent the flood process itself in real condition.

GIS application in spatial modeling has been widely used for various purposes especially in spatial modeling. GIS method is relatively accurate and efficient. Furthermore, satellite data set is available in various formats. Recent studies lead to GIS application in land cover analysis. Satellite data such as Landsat images are available for this purpose. In general, land cover identification from satellite image can be approached using two methods, the supervised method and the unsupervised method. The unsupervised method provides an easier way to classified land cover with slightly reducing the accuracy (Thapa and Murayama, 2009). GIS analysis would be very helpful in studying the effect of land cover change to discharge production.

Investigation of land cover change using Landsat data has been studied in Xilin River Basin, Mongolia (Siqing et. al., 2003). The satellite images were analyzed and classified in to 5 types using the corresponding spectra. The results showed that the Landsat data is reliable for land cover change analysis. Further study of land use change related to the flood discharge has been done in Chomuvtoka basin, Czech Republic. Land cover change and hydrological analysis are conducted by using Soil Conservation Service Curve Number (Jenicek, 2007). Same method combined with GIS application was studied. The results show that changes in land use intensify the peak of flood discharge. Another method to simulate land use change effect in flood simulation by emphasizing the roughness value to the surface runoff and discharge production has been applied in Yasu River Basin (Kimaro et. al., 2003). An approach to assess urbanization was conducted by analyzing river network in urban area (Zhou et. al., 2007). However, this method requires river investigation to be applied.

Tank model is commonly used for modeling the hydrology process in a basin or sub basins. Use of tank model for flood forecasting has been applied in two river basin areas in Japan, Shichikasuku and Ookawa (Kardhana and Mano, 2009). Nevertheless, tank model and kinematic wave routing are lack of ability to simulate the overland flow process. Generally, in flood simulation, infiltration effect in urban area is neglected assuming that the urban area is completely impervious. However, this assumption is slightly incorrect, since there is still some part of the area which is permeable. Therefore, infiltration should be considered though the amount of infiltration rate might not as high as in open area. Application of the urbanization in advanced hydraulic-hydrologic model such as shallow water model or tank model has not been studied widely yet.

The objective of this study is to obtain a model which can be used to simulate flood accurately without neglecting its physical process by accommodating urbanization distribution effect. A distributed model for flood simulation by combining hydraulic and hydrologic model to satisfy runoff process along with hydrology process is developed. Surface runoff is simulated using 2D shallow water equation while nearly calibration free (NCF) tank model is used to simulate hydrology parameters.

STUDY AREA

Ciliwung River flows to Jakarta, capital city of Indonesia. In fact, there are several rivers that flow to that city but Ciliwung River is the biggest. Moreover, this river flows through the middle part of Jakarta which is the central part of activities for government, business, and commercial area. The watershed area of this river has a catchment from Bogor District for upstream part up to downstream area which is the Jakarta city. The area of study for this paper is limited to the upstream part. Development in this area has been considered as one of the factors that caused flood in Jakarta. Urbanization has been increasing since 1972 especially in Bogor city, located in the upstream of Ciliwung River Basin.

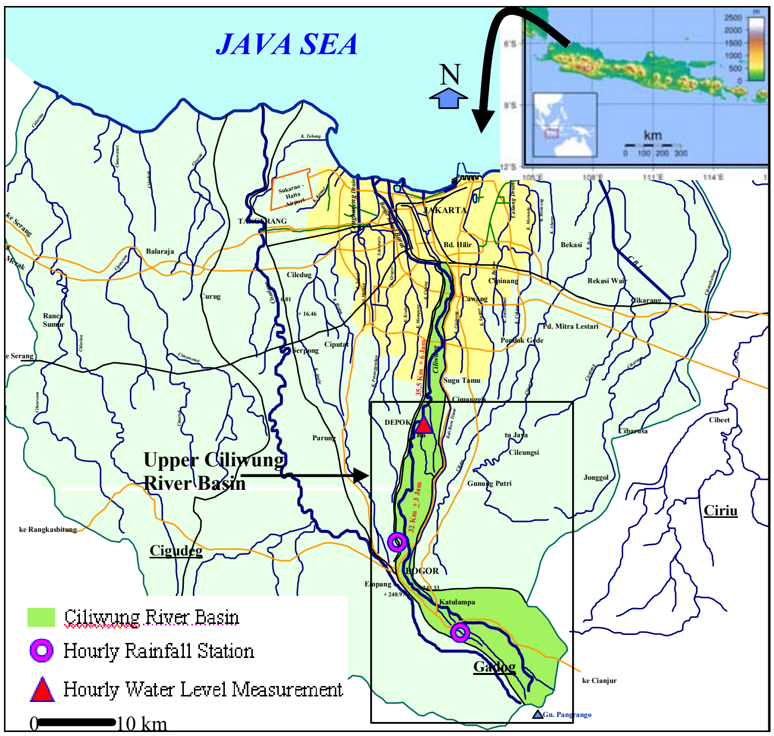

Fig. 1. Location of study area.

The upper part of Ciliwung River Basin is located in West Java, Indonesia, which only has 2 seasons per year, dry season (May – September) and wet season (October – April). The domain has 234 km^2 of catchment area with the 46 km length of river. Hourly rainfall data for this area is recorded at Citeko and Darmaga Station while hourly water level is measured at Depok Station.

Land cover type data for the year 1972 and 2002 were obtained from Center for Regional System Analysis, Planning, and Development (P4W) Indonesia. It is clearly shown in Figure 2 that urbanization has changed the face of this basin within 1972 to 2002. Further analysis reveals that the urban area in 2002 has grown by 1.8 times than in 1972 while the forest area in 2002 has decreased by 0.5 times than in 1972 (Figure 3).

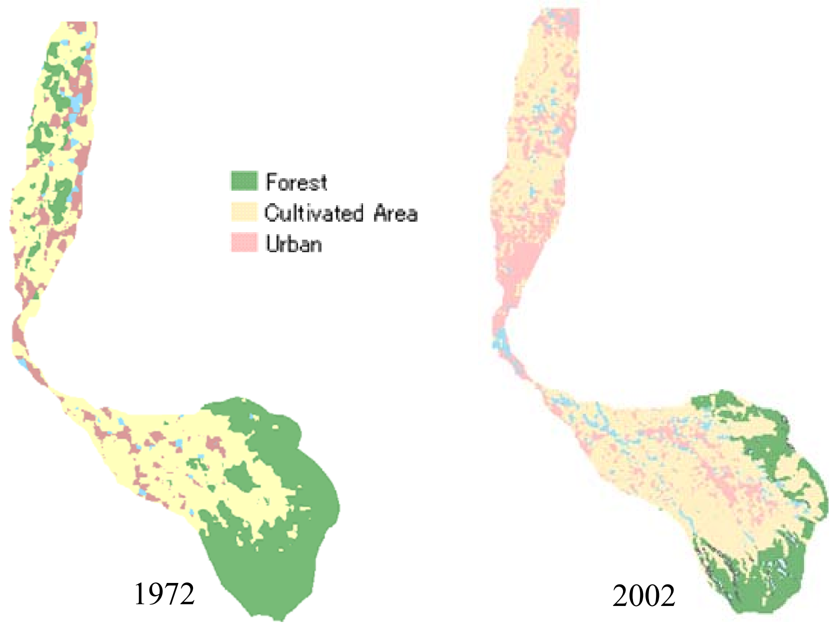

Fig. 2. Upstream Ciliwung land cover.

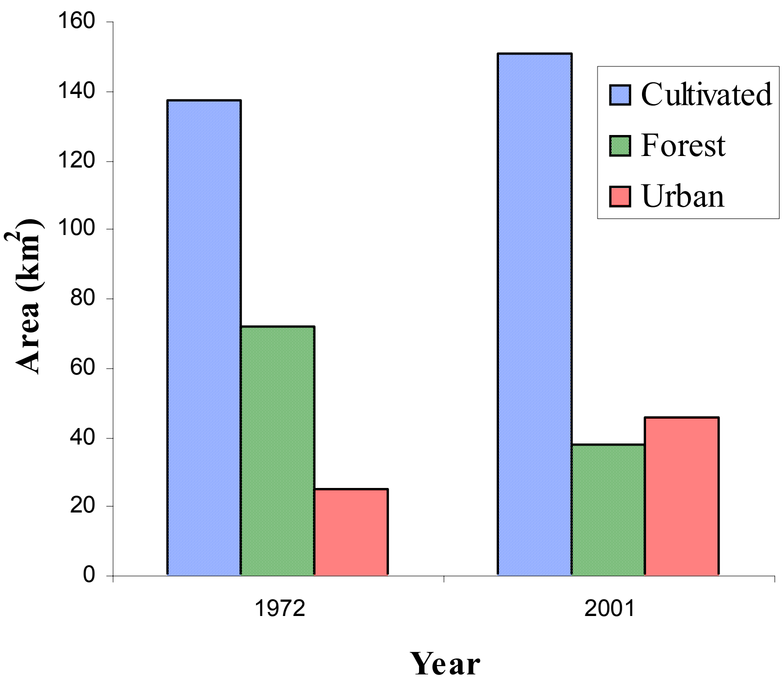

Fig. 3. Upstream Ciliwung land cover area.

METHODOLOGY

Model concept for this study can be seen in Figure 4. Canopy intercept the precipitation, nevertheless, for the urban zone, this interception process is neglected. In surface, the remaining precipitations become surface runoff. However, some of these precipitations will be infiltrated through the soil layer and recharge the sub surface water.

The soil layer in the model is for top layer only. The top layer is considered to be 1 meter thick for the whole domain. The surface run off is simulated by the shallow water equation and the super tank model is applied at each grid.

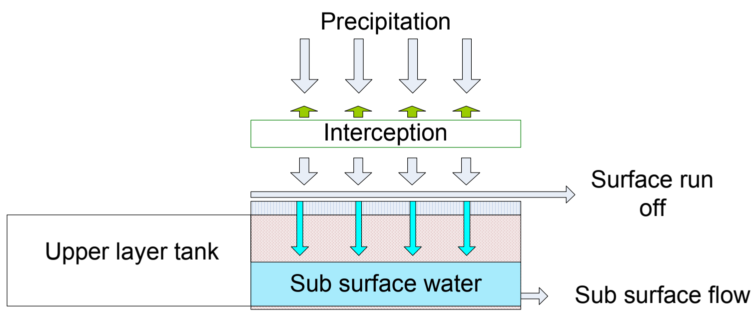

Fig. 4. Model concept.

The governing equation for the shallow water equation consists of continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=q \tag{1}$$

and momentum equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+gh\frac{\partial (h+z)}{\partial x}=-ghS_{fx} \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+gh\frac{\partial (h+z)}{\partial y}=-ghS_{fy} \tag{3}$$

where u and v are velocities in the corresponding axes, h is the water depth, q is the outsource term, and S_f is the friction slope calculated with manning equation as follows:

$$S_{fx}=n^2u\left(u^2+v^2\right)^{1/2}/h^{4/3} \tag{4}$$

$$S_{fy}=n^2v\left(u^2+v^2\right)^{1/2}/h^{4/3} \tag{5}$$

The governing equations for the surface run off above are solved using the Mc Cormack predictor and corrector scheme. The hydrology parameter will be added into outsource term which covers infiltration, precipitation, and interception. Interception is calculated using this following equation:

$$P=KEt_D+S \tag{6}$$

where P is the amount of intercepted precipitation for 1 period of rain. KE is vegetation interception rate during rainfall. This value depends on land use type, for forest the value is 0.2 and for cultivated area the value is 0.1 (Hattori et al., 1982., Tsukamoto, 1998). t_D is rainfall duration, while the canopy storage is symbolized by S with values of 1.5. So the interception rate can be obtained by P/t_D.

Infiltration and sub surface flow calculation are based on tank model concept, applied to each grid point. The infiltration rate is determined by soil hydraulic conductivity and water content in top tank. Relation between the precipitation rate (q_{re}), hydraulic conductivity ($k_{h_1}^*$), and infiltration rate ($q_{\inf}$) is governed based on the amount of precipitation and the hydraulic conductivity. A new coefficient is added to accommodate the urban density, assuming that there is still some recharging in the urban zone.

$$q_{\inf} = c_{density}(1-\lambda_1)q_{re} \tag{7}$$

$$q_{re} > k_{h_1}^* \rightarrow q_{\inf} = c_{density} k_{h_1}^* \tag{8}$$

$$\lambda_i = \frac{H_i}{H_{i\max}} \tag{9}$$

where λ is water content in the top tank (H is water depth in soil layer and $H_{\max}$ is soil thickness), and $c_{density}$ is the density rate of impervious area. The subsurface flow is calculated by using Darcy approach.

$$q_i = c k_{h_i}^* I \lambda_i \tag{10}$$

with c is the interflow coefficient and I is the surface slope.

URBANIZATION DISTZRIBUTION

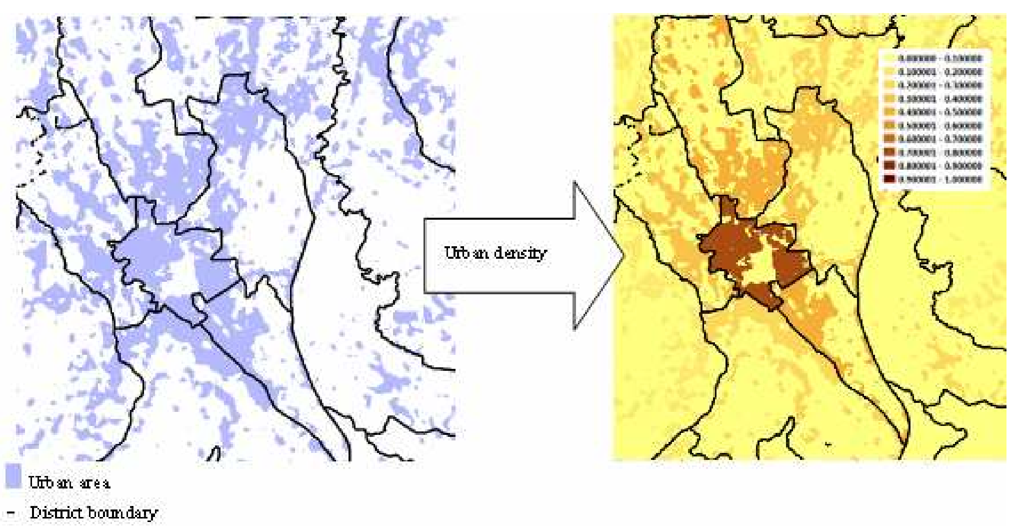

Fig. 5. Urban density spatial mapping.

The infiltration coefficient ($c_{density}$) in the model is defined as the ratio of the permeable area in an urban land cover. A detail map of urban area would be required to analyze the exact value of this coefficient. However, due to lack of data, this study used different approach to assess the value of $c_{density}$. The $c_{density}$ would be analyzed per district area. Spatial analysis is conducted per district area to determine the urban density. Urban density can be defined as the percentage of urban land cover in a district area. This value is further adjusted by introducing an adjusting parameter (c_{urban}) to obtain $c_{density}$ value. The c_{urban} is defined as the ratio of un-infiltrated area in urban land cover. This adjusting parameter will be multiplied to urban density. Therefore, the relation between the urban density value and the $c_{density}$ value can be defined as follows:

$$c_{urban} \cdot urban_{density} + c_{density} = 1 \tag{11}$$

$$c_{density} = 1 - c_{urban} \cdot urban_{density} \tag{12}$$

The ratio of urban land cover per district area will be much higher in the urbanized area than rural area. Therefore, a spatial map of this ratio can be produced. The spatial map will contain information of this ratio for each urban land cover zone within a district.

Two types of map data set are used for analysis. The district boundary map and the land cover map. Both maps are intersected to obtain a district map containing urban area land cover. Furthermore, the urban area is divided with its district area to obtain the urban density ratio which will be used to asses the $c_{density}$ using Equation 12.

SIMULATION

The computational domain for the study area is divided in to grids with spacing of 250 meter. The domain is bounded to the outlet measurement discharge at Depok Station. Simulation is conducted with 0.5 second time step. Nash–Sutcliffe Index (NSI) value is used to evaluate the model performance in comparison to the measured discharge data. The NSI value can be calculated using the following formula.

$$NSI = 1 - \frac{\frac{1}{n}\sum\left(Q_{observation} - Q_{simulation}\right)^2}{\frac{1}{n}\sum\left(Q_{observation} - \overline{Q_{observation}}\right)^2} \tag{13}$$

One day event of rainfall in the study area for the period of 1/2/02 13:00-1/3/02 13:00 is used to calibrate the model. The following parameters are set based on this simulation: Manning value of 0.08 for urban area, 0.03 for forest area, 0.025 for cultivated area and others. The adjusting parameter c_{urban} is determined as 0.9. The interflow coefficient is set at 10 as the standard value of NCF TANK MODEL. The spatial $c_{density}$ value for the corresponding year is used. The result from the simulation is shown in Figure 6. The NSI index of 0.82 shows the good performance of the model in simulating the discharge.

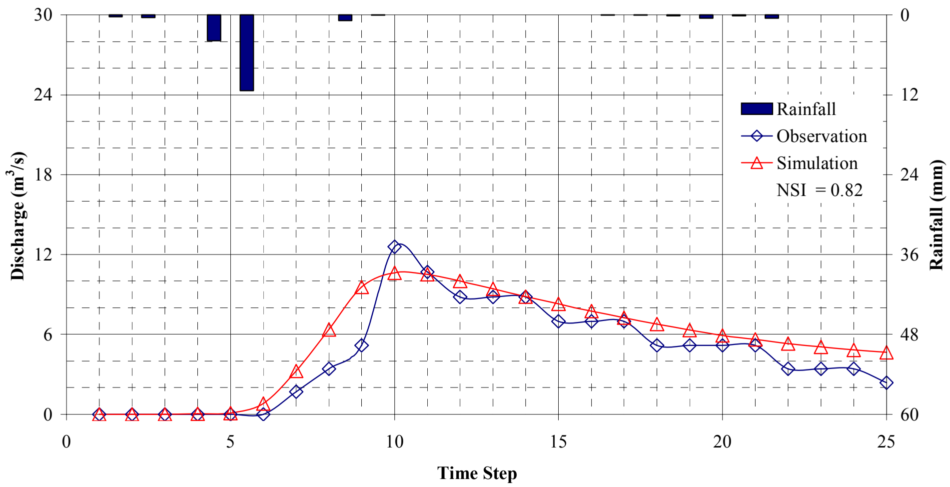

Fig. 6. Model calibration for one day rainfall event.

The parameters above are used to simulate discharge reproduction in the study area during the flood event. For this purpose, the flood period between 1/29/02 0:00 to 2/3/02 7:00 is simulated. The result from this simulation can be seen in Figure 7. The simulation result gives a good comparison to the measurement data which is also shown by the NSI index of 0.83.

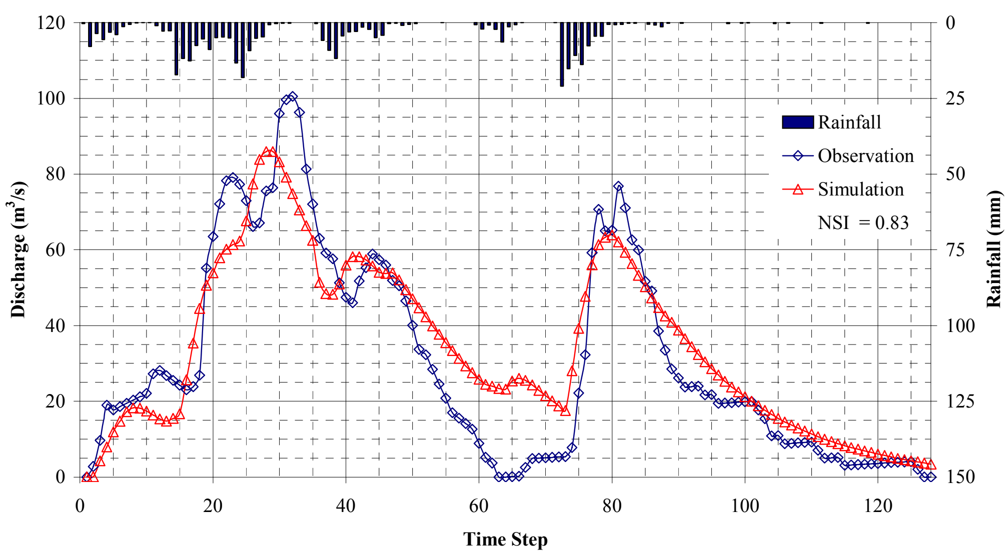

Fig. 7. Model validation for 2002 flood event.

The same flood event is re-simulated using 1972 land cover dataset. This simulation is conducted for analyzing the land cover change effect to flood discharge.

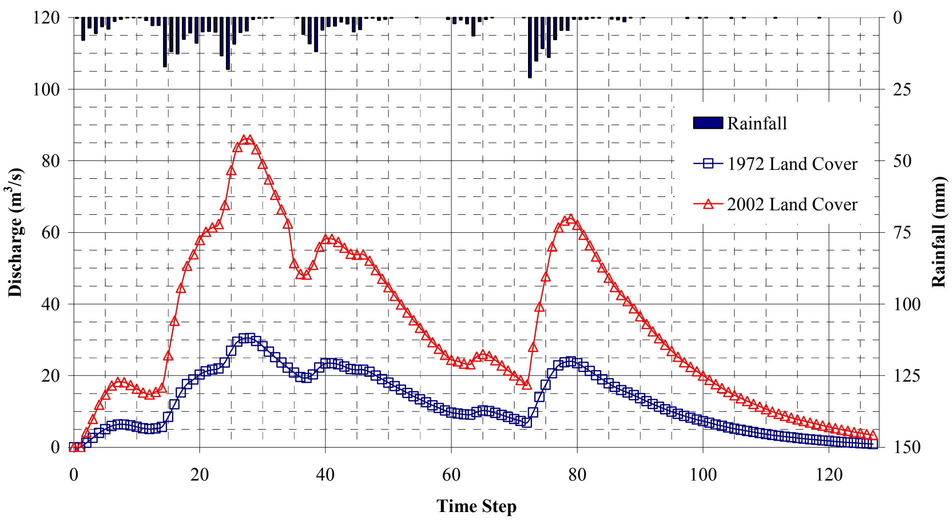

Fig. 8. 2002 flood simulation with two different land cover.

It can be seen that the peak flood discharge is significantly reduced in the flood simulation using 1972 land cover. Urban area in 1972 is 55% of that in 2002. The peak discharge is decreased to 30.5 m^3/s from 86 m^3/s, nearly 65% of reduction. It is also observed that the down curve of hydrograph has milder slope. Volume of hydrograph in simulation using 2002 land cover is bigger than another one using 1972 land cover. It is related to the amount of surface runoff. In 1972 land cover, forest has larger than urban. Therefore, the amount of water intercepted and infiltrated is more than in 2002 land cover.

CONCLUSIONS

Urbanization effect to flood has been studied in this study with the case study of Ciliwung River Basin, Indonesia. The study was conducted using shallow water overland flow model coupled with the tank model. A new parameter ($c_{density}$) is introduced. It is used to approach infiltration rate in the urban area. Spatial distribution analysis is conducted to obtain this parameter.

The model was used to simulate several scenarios. Model accuracy was determined using the NSI value. Comparison to the observation data shows that the model can reproduce discharge with good accuracy. Simulation of the same flood event using two different years (1972 and 2002) of land cover data was conducted. Spatial analysis shows that urban area in 2002 has grown by 1.8 times than in 1972 while the forest area in 2002 has decreased by 0.5 times than in 1972. This changes lead to the different flood discharge. It is found that peak discharge in the flood event of 2002, is reduced by 65% when re-simulated using the land cover of 1972.

The method proposed in this study would be helpful in assessing the urban condition for flood modeling. The model can be further developed by applying a spatial distribution of rainfall, for a more realistic approach.

ACKNOWLEDGEMENTS

The author would like to express gratitude to Indonesian Ministry of Education for financial support in this research.

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