Distributed flood model for urbanization assessment in a limited-gauged river basin

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Abstract

A distributed model is commonly used to investigate the effects of land cover change on flood discharge due to urbanization. The model should have adequate spatial data parameters in order to resemble actual condition and to achieve good accuracy. Unfortunately, most of developing countries have limited and insufficient datasets. The circumstances can be a problem in distributed flood model simulation. The objective of this study is to develop a distributed flood model for simulating runoff-response change due to urbanization in a river basin by using limited available datasets which correspond to the availability of datasets in developing countries. A 2D shallow water equation is used to simulate surface runoff while hydrologic parameters are simulated based on a nearly calibration free (NCF) tank model. The infiltration rate in the urban area is accommodated by applying a spatial distributed urban density. The model is applied to the upstream of the Ciliwung River basin, located in West Java Province, Indonesia. This domain, with an area of 234 km^2 and a 46 km length of river, has contributed to flooding in its downstream area, Jakarta, the capital city of Indonesia. The urban area in this basin has increased by 183% while the forest area has declined by 52% from 1972 to 2002. The limitation of hourly rainfall data causes difficulty in producing spatial distributed hourly rainfall which is significant in flood simulations. Therefore, a method using simple linear interpolation is developed to solve this problem. Calibration and validation, conducted using events in 2002, showed good agreement to the observed data. In order to investigate runoff-response change due to urbanization, flood events in 2002 are simulated using 1972 land cover. The simulation results showed that urbanization during 1972 to 2002 has increased flood discharge significantly.
Keywords: urbanization, distributed model, flood simulation.

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1 Introduction

Land cover changes due to urbanization have been considered to give a contribution to flooding. Conversion of other land surface types to urban area changes the hydrologic characteristic. It will increase the area of impervious land surface, and decrease the rate of infiltration as well as the occurrence of interception loss. Hence, the amount of water on surface runoff will increase and intensify floods. A study by Liu *et al.* [1] concluded that runoff from urban areas is dominant for flood events. Sheng and Wilson [2] strengthened this finding by conducting statistical analysis to obtain a relation between urbanization and changing of flood behaviour in Los Angeles. They found a large percentage (90%) of rain become surface run off in urban areas, whereas it was only 25% in non urban areas.

Several studies have been conducted regarding the effect of land cover changes on flood discharge. Shi *et al.* [3] used a SCS (Soil Conservation Service) model to investigate the effect of land use/cover change on surface runoff in Shenzen region, China while a distributed hydrologic modelling system HEC-HMS was applied by Rongrong and Guishan [4] to analyze the influence of land use/cover change on storm runoff upstream of Taihu Lake watershed. They concluded that urbanization contributes to flood disaster and plays an important factor in intensifying the flood process. The results can be used to assess urbanization regarding disaster mitigation in water resources and planning management. Nonetheless, a fully distributed modelling approach should be applied in order to detail the characteristics of flooding [5]. For that reason, it is necessary to develop a distributed flood model for urbanization assessment.

An adequate dataset for input into a flood model is needed in order to represent the real condition of the flood event and to obtain good accuracy in simulation. Rainfall datasets input is essential for flood runoff generation. The spatial distribution of rainfall should be considered in a distributed flood model since it influences parameter estimation and leads to disagreement of calibration [6]. Segond *et al.* [7] and Pechlivanidis *et al.* [8] investigated the significance of spatial rainfall representation for runoff estimation. The results confirmed the importance of rainfall spatial variability. Unfortunately, the lack of distributed rainfall data is a common problem in most developing countries. Furthermore, rainfall stations with good temporal resolution, especially in hourly resolution, are very rare. Therefore, a solution to assess the spatial distribution of rainfall in good temporal resolution is needed.

In this paper, we proposed a distributed flood runoff model to assess urbanization by considering rainfall spatial variability in a limited-gauged river basin. The infiltration coefficient which is defined as the ratio of the permeable area in an urban land cover is introduced. This coefficient can be considered for assessing urbanization in the model. In order to overcome the lack of distributed rainfall data, a method using simple linear interpolation is developed by utilizing the available datasets. This model will be applied to the upper catchment of the

Ciliwung River basin. Urbanization in this basin is considered to be one of the contributing factors that causes flooding in Jakarta. This river basin is also known for its lack of spatial rainfall datasets with good temporal resolution.

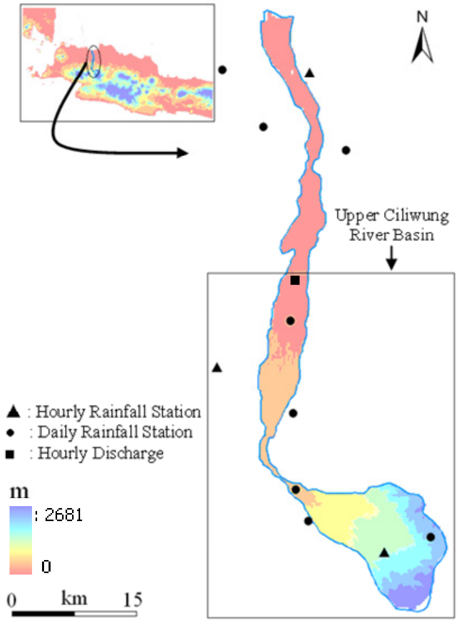

Figure 1: Location of study area.

2 Study area

The study was carried out for the upper catchment of Ciliwung River basin. It is located in West Java Province, Indonesia, fig. 1. This catchment has been developing rapidly during the last few decades which causes land cover change due to urbanization and has been considered to contribute in the occurrence of flooding in its downstream area, Jakarta, capital city of Indonesia [9]. The data of land cover in table 1, obtained from the Center for Regional System Analysis, Planning, and Development Indonesia, shows that during 1972 to 2002, urban area has grown by 1.8 times while the forest area has decreased by 0.5 times.

The domain covers an area of 234 km^2 with 46 km of river length. Hourly discharge can be obtained from Depok station located downstream of this domain. The climate is tropical with a dry season for the period from May until September and a wet season for the period from October until April. 11 scattered stations of rainfall gauge are available. However, only 3 of them measure hourly rainfall. The datasets were obtained from the Department of Meteorology, Climatology and Geophysics. The upstream part of the domain is covered by a slope with a steepness of 40% while a mild slope of around 2–15% covers the downstream part. A digital elevation model (DEM) was provided by SRTM (Shuttle Radar Topography Mission). Soil type is dominated by latosol with 1 meter on average for the effective top layer. The soil map is available at 1:250000 obtained from the Indonesian Center for Agricultural Land Resources Research and Development.

Table 1: Land cover area.

Year	Cultivated	Forest	Urban
	km^2		
1972	137.4	72.2	24.8
2002	151.1	37.8	45.5

3 Methodology

This study used a distributed model which combined a nearly calibration free (NCF) tank model and a two-dimensional runoff model. However, the limitation of the available data sets required an approach to assess the spatial data for the model. A spatial distribution for rainfall and urbanization assessment was applied to simulate runoff-response change due to urbanization in the study area.

3.1 Spatial distribution of rainfall

Lack of datasets is an important issue in most of developing countries. It becomes a problem when simulating a distributed flood model. Good resolution satellite/radar rainfall data is very difficult to find. Therefore, in the case of Ciliwung River basin, datasets of rainfall from 11 observation stations are used. Hourly resolution is only available in 3 stations. It is possible to produce good rainfall distribution for daily resolution, based on the data availability. However, a distributed flood model usually requires the spatial distribution of rainfall in hourly resolution. Therefore, a method, as can be seen in fig. 2, is proposed in order to assess the spatial hourly rainfall distribution by maintaining the daily rainfall distribution.

This method is mainly based on simple linear interpolation where the value of hourly rainfall data in a grid is estimated by using the 2 nearest hourly rainfall stations of the grid considering hourly rainfall deviation from daily average. The daily distribution from the estimated hourly rainfall must be equal to the daily distribution obtained from the measurement data in order to maintain the daily rainfall distribution. Measurement data of rainfall from all stations are used to make spatial daily rainfall. Estimation for hourly rainfall is conducted by means of linear regression based on the hourly stations as shown in eqn. (1) and fig. 3.

$$\left(P_{hX} - \overline{P_{hX}}\right) = \frac{A_X.\left(P_{hA} - \overline{P_{hA}}\right) + B_X.\left(P_{hB} - \overline{P_{hB}}\right)}{A_X + B_X} \qquad (1)$$

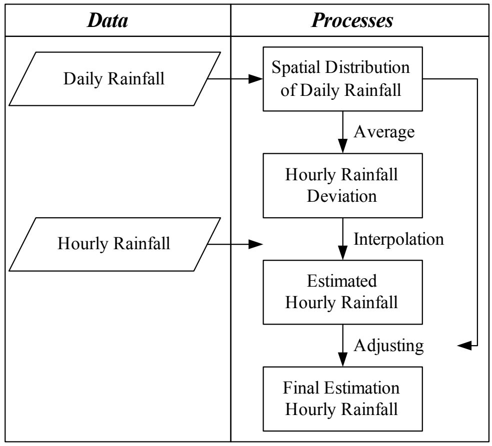

Figure 2: Rainfall estimation.

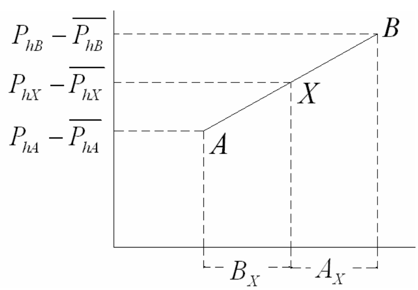

Figure 3: Linear interpolation.

where P_{hA} and P_{hB} are hourly rainfall data at station A and B, P_{hX} is the estimated hourly rainfall data at point X, A_X and B_X are the distance from X to B and A respectively. P_{hX}, P_{hA}, and P_{hB} are the daily average rainfall deviation at X, A, and B. The obtained value from the regression is adjusted to meet the daily rainfall data from measurement by using eqn. (2)

$$P_{hfX} = P_{hX} - \frac{P_{hX}}{P_{deX}}\left(P_{deX} - P_{dX}\right) \tag{2}$$

where P_{hfX} is the final adjusted value of the estimated hourly rainfall at X, P_{deX} is the estimated daily rainfall based on the sum of hourly estimated rainfall at X, P_{dX} is the measured daily rainfall data at point X which is obtained by interpolating all available observed daily rainfall stations. This final adjustment will ensure that there will be no deviation of the daily rainfall based on hourly estimation to the daily rainfall measurement.

3.2 Urbanization assessment

The amount and distribution of sealed surfaces, particularly in urbanized area, is also an important factor for the input in a distributed flood model [10]. In an urban area, there are some open spaces such as gardens or parks which are able to infiltrate the water. Therefore the infiltration rate can not be neglected. Unfortunately, detection of these open spaces requires very high resolution images which can be expensive and time consuming. In this study, this parameter is assessed by applying the spatial distributed urban density, such as that shown in fig. 4.

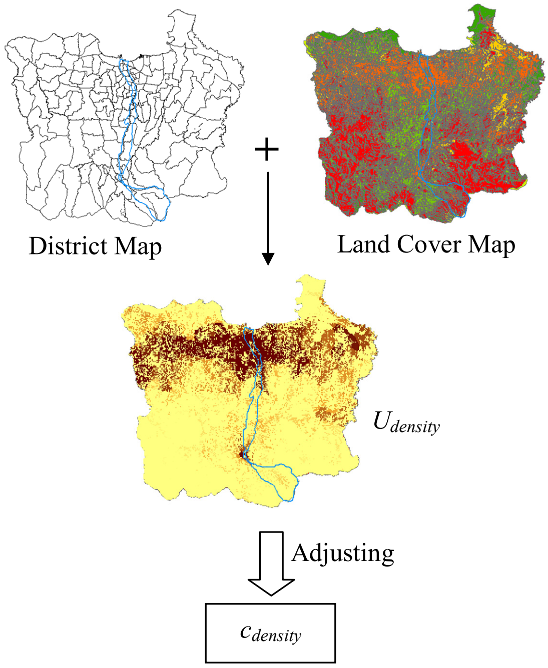

Figure 4: Urbanization analysis.

The idea in the developed method is to apply an infiltration coefficient ($c_{density}$) in the distributed flood model to accommodate the ratio of the permeable area in an urban land cover. This coefficient is analyzed in every district area. Spatial analysis is conducted per district area to determine the urban density ($u_{density}$) which 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 the $c_{density}$ value. c_{urban} is defined as the ratio of un-infiltrated area in urban land cover. The relation between $u_{density}$ and $c_{density}$ can be expressed in eqns. (3) and (4).

$$c_{urban} \cdot u_{density} + c_{density} = 1 \tag{3}$$

$$c_{density} = 1 - c_{urban} \cdot u_{density} \tag{4}$$

3.3 Distributed flood model

The model concept is shown in fig. 5. Precipitation will be intercepted by the canopy. However in the urban zone this process is neglected. The rest of the precipitation will fall to the surface and become surface runoff, but some will be infiltrated through the soil layer and recharge the sub surface water. Surface run off is simulated by a two-dimensional shallow water equation while a NCF tank model [11] is applied at each grid of the domain.

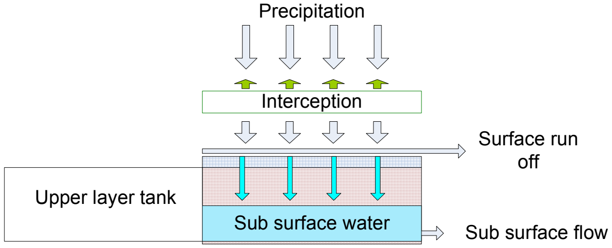

Figure 5: Model concept.

The governing equation for the shallow water equation consists of a continuity equation shown in eqn. (5) and a momentum equation shown in eqns. (6) and (7).

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = q \tag{5}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial (h+z)}{\partial x} = -gS_{fx} \tag{6}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial (h+z)}{\partial y} = -gS_{fy} \tag{7}$$

where u and v are the 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 roughness (n) using eqns. (8) and (9).

$$S_{fx} = n^2 u \left(u^2 + v^2\right)^{1/2} / h^{4/3} \tag{8}$$

$$S_{fy} = n^2 v \left(u^2 + v^2\right)^{1/2} / h^{4/3} \tag{9}$$

Hydrologic parameters will be added into the outsource terms which cover infiltration, precipitation, and interception. Interception is calculated using eqn. (10).

$$P = KEt_D + S \tag{10}$$

where P is the amount of intercepted precipitation for a period of rain. KE is the vegetation interception rate during rainfall. This value depends on land cover type, for forests the value is 0.2 and for cultivated areas the value is 0.1. T is rainfall duration, while the canopy storage is symbolized by S with values of 1.5.

The infiltration rate is determined by soil hydraulic conductivity and water content in the top tank. The 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, eqns. (11), (12), and (13). $c_{density}$ accommodates the value of infiltration in the urban land cover

$$q_{\inf} = c_{density} (1 - \lambda_1) q_{re} \tag{11}$$

$$q_{re} > k_{h_1}^* \rightarrow q_{\inf} = c_{density} k_{h_1}^* \tag{12}$$

$$\lambda_i = \frac{H_i}{H_{i\max}} \tag{13}$$

where λ is the water content in the top tank (H_i is the water depth in the soil layer and $H_{\max}$ is the soil thickness). The subsurface flow (q_i) is calculated by using the Darcy approach, as in eqn. (14).

$$q_i = ck_{h_i}^* I \lambda_i \tag{14}$$

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

4 Results and discussions

The model was simulated in three scenarios; calibration, validation, and land cover change effect investigation. The model domain was divided using 250 m of grid size with 0.5 second time step and bounded to the outlet discharge measurement at Depok Station. The Nash–Sutcliffe Index (NSI), expressed in eqn. (15), is used to evaluate model performance.

$$NSI = 1 - \frac{\frac{1}{n}\sum\left(Q_{observation} - Q_{simulation}\right)^2}{\frac{1}{n}\sum\left(Q_{observation} - \overline{Q_{observation}}\right)^2} \qquad (15)$$

4.1 Calibration

This scenario was conducted in order to get the appropriate parameter for the model. One day's event of rainfall from the 2002 wet season in the study area for the period of 1/2/02 13:00-1/3/02 13:00 is used to calibrate the model. Manning values are set to be 0.08 for the urban area, 0.025 for the forest area, 0.03 for the cultivated area and others. The adjusting parameter for urbanization (c_{urban}) is set to be 0.9 which means that there is only 10% permeable area in urban land cover. The interflow coefficient is set at 10 as the standard value of the NCF tank model. The result is shown in fig. 6. The NSI index of 0.93 shows the good performance of the model.

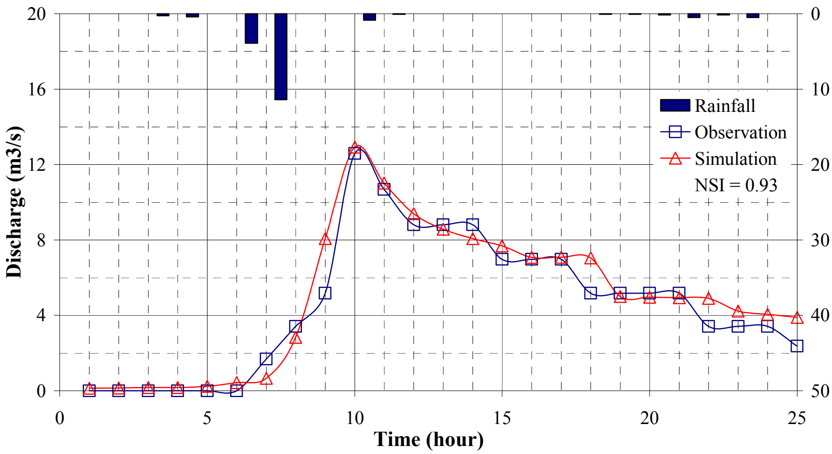

Figure 6: Calibration by the rainfall event in January 2–3, 2002.

4.2 Validation

The purpose of validation is to verify the parameters obtained from calibration process. This scenario used a 2002 flood event when Jakarta experienced one of the most severe floods in its history, which caused widespread damage and affected more than 75% of the total population of the city [12]. The flood period was from 1/29/02 0:00 to 2/3/02 7:00.

The simulation result as can be seen in fig. 7, gives a good agreement to the observed data with a NSI index of 0.91. Therefore, the parameters that were determined in the calibration process are acceptable to be used in other scenarios.

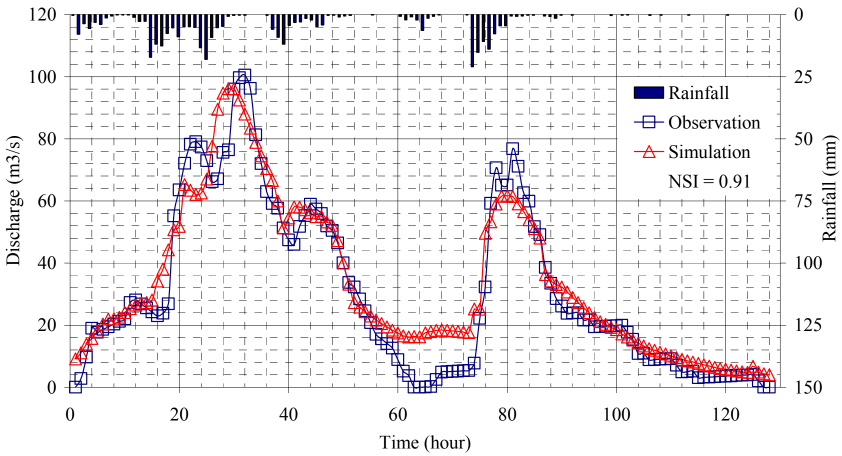

Figure 7: Validation by the flood event in January 29 to February 3, 2002.

4.3 Effect of land cover change

Effect of land cover change due to urbanization during 1972 to 2002 is investigated by simulating the 2002 flood event using different years of land cover condition. An increase in terms of peak discharge and volume of hydrograph was indicated based on the results shown in fig. 8.

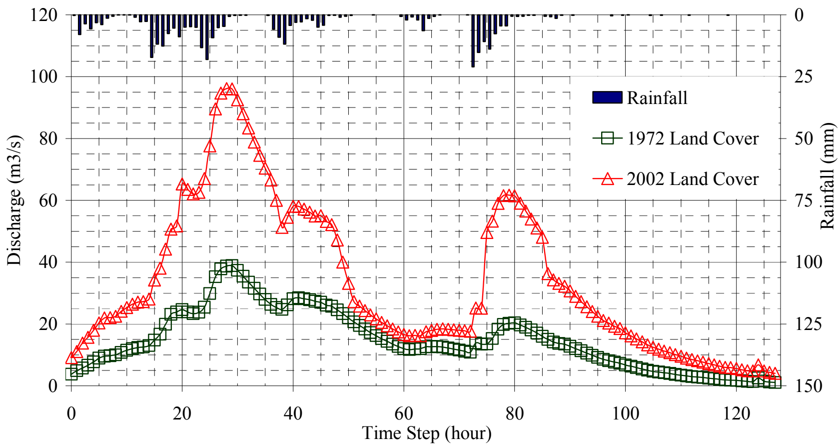

Figure 8: Effect of land cover change for the flood event in January 29 to February 3, 2002.

The peak discharge increased from 25.4 m^3/s up to 96.8 m^3/s. In terms of the hydrograph volume, the result using 2002 land cover is bigger than the result using 1972 land cover. Further analysis revealed that the amount of precipitation which becomes the outflow discharge increases from 19% in 1972 to 46% in 2002. In the end of the computation time, using the 2002 land cover data, it is found that 45% of soil layer is filled by water. This number increased to 60% for simulation using 1972 land cover. Another factor that influenced the change in hydrograph volume is the amount of water lost to interception which decreased from 21% in 1972 to only 9% in 2002. All of these circumstances correspond to the significant increase of impermeable area along with deforestation.

5 Conclusions

A distributed flood model which can be used to assess urbanization has been developed. Spatial distributed parameters for model input were provided by utilizing a spatial distribution assessment method that was developed to overcome the lack of datasets. A spatial distributed urban density is developed to accommodate the infiltration rate in the urban area based on land cover and district boundary data. A spatial distribution of hourly rainfall data is developed using a linear interpolation approach by considering hourly rainfall deviation from daily average. Both methods do not require a detailed data set; on the contrary, they are developed to assess detailed information based on limited data. The model has been calibrated and verified to field observation data with good comparison, shown by the high value of the NSI index.

The effect of land cover change due to urbanization in the study area has been investigated by simulating a flood event in 2002 using 2 different types of land cover. Based on the results, it can be concluded that urbanization during 1972 to 2002 has increased flood discharge significantly. Urbanization reduces the amount of interception and soil storage, moreover, higher surface water volume is observed in simulations with more recent land cover.

Acknowledgements

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