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Impact of land-use changes on water balance

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Abstract

Due to rapid population growth, Goseng catchment has been subjected to considerable land-use changes over the last decade. The main objective of this research is to find out the impact of land-use changes on the hydrological processes and river discharge using the simulation of land cover changes. GenRiver model is used to analyze and predict water balance change in Goseng catchment by proposing some scenario of land cover changes. GenRiver calibration was achieved by NSE analysis, comparing observed and simulation discharge data in the period of 1974 - 1994. Calibration and validation results showed that the satisfaction model using daily test has the coefficient correlation of 0.73. Furthermore, the land cover simulation of community forest in scenario 2 has the highest buffering indicator value and the lowest in paddy field. Thus, the land-use changes play an important role in the water balance changes in Goseng catchment, indicated by increasing surface run-off along with the decline of vegetation cover.

1. Introduction

Rapid population growth raises serious problem to land-use changes in Goseng catchment. The increase of population growth every year is always followed by the increasing demand of land, especially the needs for production, housing, agriculture and others. People tend to ignore land-use capability and suitability which cause land degradation and affect water balance [2][3]. Several studies [3][4][5] have

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shown that the land changes caused by the increase of urbanization, agricultural activities and devastated forests area are cause factors of water balance changes. The term of water balance is introduced to refer to the balance between input and output of water from precipitation and the outflow of water by evapotranspiration, groundwater recharge and stream flow.

Goseng catchment covers an area around 630,01 hectares wide, located in Karanganyar regency, the southern part of Central Java. Soil type is Mediteran Kromik, Latosol Distrik dan Latosol Eutrik. The average rainfall in this region is 2220 mm/year, and it is classified as type D of Schmidt-Ferguson climate classification.

Land-use in Goseng catchment consists of community forests, settlement, paddy field, moor and shrubs. Goseng catchment has been subjected to considerable land-use changes over the last decade due to intensive agriculture. Moreover, since it is located in the upper part of the land, it has an important role for water supply and agriculture.
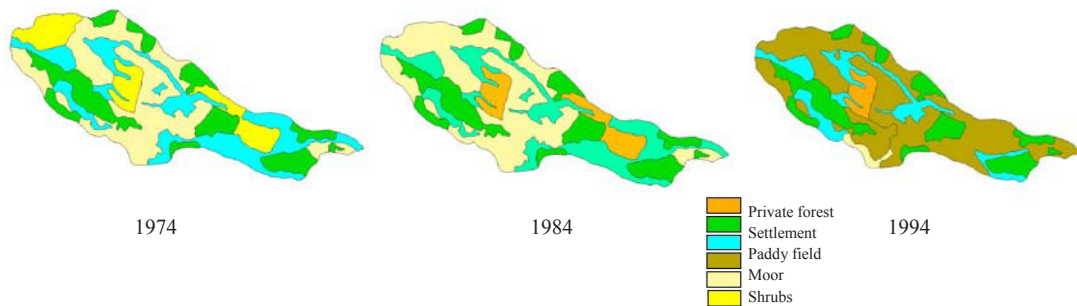

Fig. 1. Land-use changes in Goseng catchment

Table 1 Land-use changes in Goseng catchment.

No	Land-use	Area (hectares)		
		1974	1984	1994
1	Settlement	143.31	143.31	143.31
2	Paddy field	168.65	167.91	99.71
3	Shrubs	98.91	0	0
4	Moor	219.14	257.49	11.7
5	Community forest	0	61.31	25.89
6	Sugar Cane	0	0	349.33
Total		630.01	630.01	630.01

2. Objective

The objective of this research is to find out the impact of land-use changes on hydrological processes and river discharge using a GenRiver model. The GenRiver model can be used as a media to explore and understand the changes in the river flow due to the influence of land-use changes [6]

3. Methods

3.1. Dataset

The description of the main datasets to be analyzed using Genriver model is given in Table 2. The data were obtained from field surveys and scientific literature.

Table 2. Dataset collection.

No	Data	Description
1	Land-use maps	Historical land-use maps were collected from forestry research agency, for periods 1974, 1984, 1994.
2	Daily rainfall and temperature	Daily rainfall data were collected from Jumantono rainfall station, and temperature data were obtained from meteorological and geophysics agency (1974 – 1994). These data were used to check for potential evapotranspiration.
3	Daily river discharge	It was obtained from forestry research agency.
4	Soil map and it's characteristics	Characteristics of soil were collected from forestry research agency. It was used to obtain bulk density and fraction ratio.
5	River network	It was derived from contour map.

3.2. Input Parameter and Model Evaluation

3.2.1. Input Parameter

GenRiver is a model developed based on hydrological processes (process-based model). The simulation for this model used Stella software associated with Microsoft Excel file, and then Microsoft Excel file is used for data input. In its structure, this model comprised of several patches, and the interconnected patches and the models composition were built using STELLA software.
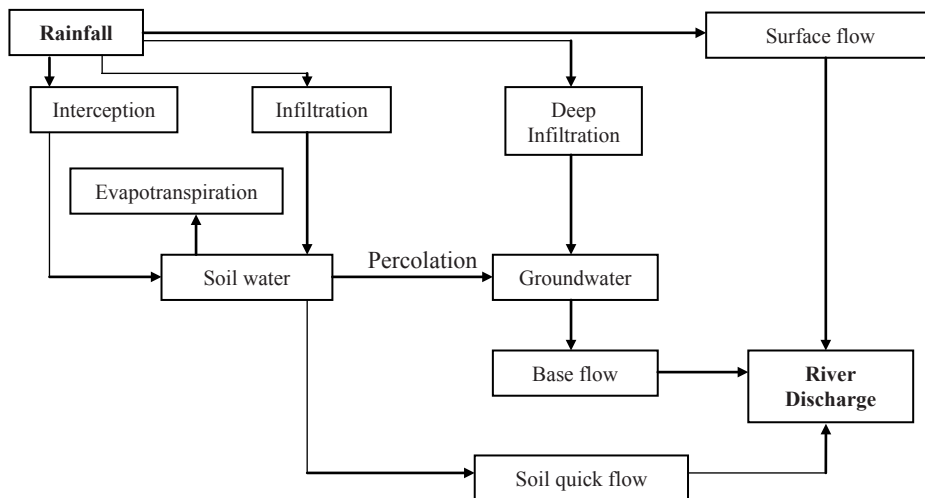
Fig. 2. Hydrological processes

Using GenRiver Model, it was found that the main components formed the river discharge including runoff (surface flow), groundwater, base flow and water flow in the soil that occurs after rain (soil quick flow).

3.2.2. Model Evaluation

Model evaluation is an effort made to determine the ability of the model in predicting the river flow. To test the ability of this model, this research employed several statistical indicators by using the Nash-Sutcliffe Efficiency Test (1970).

$$NSE = 1 - \left[\frac{\sum\limits_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum\limits_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2} \right] \tag{1}$$

Where Y_i^{obs} is observed discharge data, Y_i^{sim} is simulation result, Y^{mean} is mean observed discharge data and n is the number of observation. Then the criteria are $0,75 < NSE$ is very good, $0,65 < NSE \leq 0,75$ is good, $0,50 < NSE \leq 0,65$ is satisfactory, $NSE \leq 0,5$ is unsatisfactory.

The correlation coefficient test showed the relationship between simulation results and observed data. Correlation coefficient was calculated using the following equation

$$r = \frac{\sum (x_i - x_{mean})(y_i - y_{mean})}{\sqrt{\sum (x_i - x_{mean})^2 (y_i - y_{mean})^2}} \tag{2}$$

Where x_i is observed data, y_i is simulation result, x_{mean} is mean observed data and y_{mean} mean simulation result.

3.2.3. Simulations

Hydrologic simulation models can be done if the simulation model can produce discharge patterns that are relatively similar to or insignificantly different from the presented data [2]. The simulations of land-use were conducted by making some changes to the closure and treatment scenario of land management to study the relationship between land-use changes and river discharge. Land-use changes scenario is based on the current condition of land cover and the land cover development trends in the region, assuming that in the future, the condition of the structure and pattern of each land cover will not change or be the same as the current condition. The scenario is described in Table 3.

Table 3. The scenario of land-use changes.

No	Type of Land –use	Percentage of Land-use change (%)			
		1	2	3	4
1	Settlement	23	23	23	30
2	Paddy field	16	0	77	20
3	Moor	2	0	0	5
4	Community forest	4	77	0	10
5	Sugar cane	55	0	0	35
Total		100	100	100	100

Model validation was conducted by comparing the daily discharge of simulation results against the daily observed discharge data. Model validation using Nash-Sutcliffe Efficiency (NSE) was 61,9%. It showed minimum significant differences between the observed data and the simulation result. Therefore, average correlation value was 0.73. Thus, the scenario of land-use changes could be done
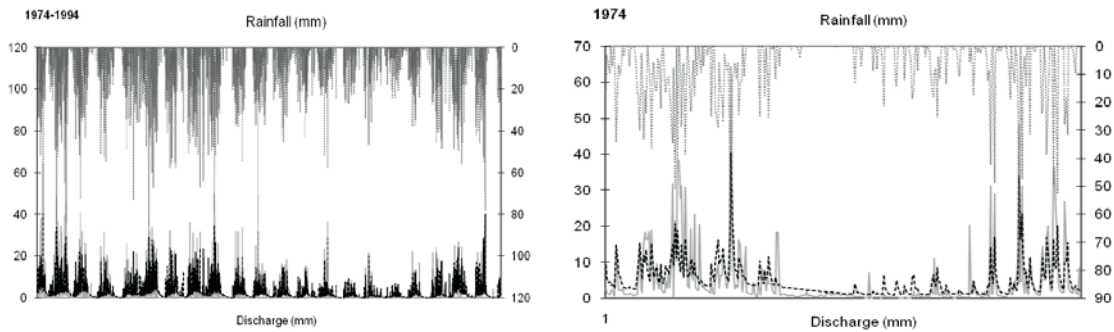

Fig. 3. (a) Overall Simulation results, (b) yearly simulation result

Figure 2 shows that in general the discharge pattern between simulation results and observed data is relatively similar from the period of 1974 to 1994. However, the comparison of simulation results and observed data cannot be done by just looking at the proximity of any point on the graph generated. This is because the results of simulation models have not been able to approach some GenRiver peak and the base flow of observed discharge although it has a similar pattern. The discharge data from the simulation process was based on the simulated discharge pattern read by the model. Therefore, the rain and the observed discharge which were abnormal or extreme could not be explained and predicted by the model. This was the cause why simulation results have not been able to approach the peak discharge or similar / identical to the actual condition.

Water balance in the region highly depends on the amount of precipitation, solar radiation, interception, surface runoff, evaporation and evapotranspiration. The precipitation and solar radiation are the X factor that cannot be manipulated by human. Therefore, hydrological processes in the catchment

affected by the condition of vegetation including stand structure, stand density and canopy vegetation types making up the stand [1]

Table 4. The simulation results

No	Indicator	Scenario			
		1	2	3	4
1	Rainfall	1,535.64	1,535.64	1,535.64	1,535.64
2	ETp	531.3	529.56	511.35	512.73
3	Discharge	1,012.93	1,013.27	1,034.53	1,031.22
4	Surface runoff	587.06	557.01	630.98	594.02
5	Soil quick flow	2.31	6.22	3.15	2.31
6	Base flow	425.63	454.83	403.15	437.01
7	Buffering indicator	0.63	0.65	0.61	0.63

Trees function as a media to transfer rain water to soil through the process of temporary detention of rainwater by interception, stemflow, and throughfall, indicated by the high value of base flow in Scenario 2. Water infiltrated into soil and increased the water storage to ensure the continuity of water discharge. This condition will improve the ability of the region in controlling the surface runoff rates during the rainfall events (buffering indicator).

The current land cover conditions (the scenario 1), dominated by sugar cane (55%) was the highest evapotranspiration rates compared to others amounting to 531.30 mm. On the other hand, the scenario 2 which was dominated by community forests (77%), had the lowest surface runoff. The presence of vegetation in the community forests increased the interception and soil infiltration. Moreover it can alter soil properties in relation to water and can affect the condition of the soil surface as well as the surface runoff. Therefore the land cover simulation output of scenario 2 of community forest (77%), had the highest buffering indicator value. The lowest was paddy field (77%) in the Scenario 3

4. Conclusion

The findings of this research show that land-use changes play an important role in water balance, indicated by increasing the surface runoff and river discharge due to lower extent and the rate of vegetation cover. Scenario 2 was the optimal scenario of land cover in terms of hydrological processes in Goseng catchment. The following land covers were Scenario 4, Scenario 1 and Scenario 3 respectively.

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