JMHT Vol. XVII, (2): 63–70, Agustus 2011

Artikel Ilmiah
ISSN: 2087-0469

Application of Tank Model for Predicting Water Balance and Flow Discharge Components of Cisadane Upper Catchment

Nana Mulyana Arifjaya[1]*, Cecep Kusmana[2], Kamarudin Abdulah[3], Lilik Budi Prasetyo[4], and Budi Indra Setiawan[5]

[1]Department of Forest Management, Faculty of Forestry, Bogor Agricultural University, Bogor 16680
[2]Department of Silviculture, Faculty of Forestry, Bogor Agricultural University, Bogor 16680
[3]Department of Agricultural Engineering, Faculty of Agricultural Technology, Bogor Agricultural University, Bogor 16680
[4]Department of Conservation Natural Resources and Ecotourism, Faculty of Forestry, Bogor Agricultural University, Bogor 16680
[5]Department of Civil and Environmental Engineering, Faculty of Agricultural Technology, Bogor Agricultural University, Bogor 16680

Abstract

The concept of hydrological tank model was well described into four compartments (tanks). The first tank (tank A) comprised of one vertical (q_{A0}) and two lateral (q_{A1} and q_{A2}) water flow components and tank B comprised of one vertical (q_{B0}) and one lateral (q_{B1}) water flow components. Tank C comprised of one vertical (q_{C0}) and one lateral (q_{C1}) water flow components, whereas tank D comprised of one lateral water flow component (q_{D1}). These vertical water flows would also contribute to the depletion of water flow in the related tanks but would replenish tanks in the deeper layers. It was assumed that at all lateral water flow components would finally accumulate in one stream, summing-up of the lateral water flow, much or less, should be equal to the water discharge (Q_o) at specified time concerns. Tank A received precipitation (R) and evapo-transpiration (E_T) which was its gradient of (R-E_T) over time would become the driving force for the changes of water stored in the soil profiles and those water flows leaving the soil layer. Thus tank model could describe th vertical and horizontal water flow within the watershed. The research site was Cisadane Upper Catchment, located at Pasir Buncir Village of Caringin Sub-District within the Regency of Bogor in West Java Province. The elevations ranged 512 –2,235 m above sea level, with a total drainage area of 1,811.5 ha and total length of main stream of 14,340.7 m. The land cover was dominated by forest with a total of 1,044.6 ha (57.67%), upland agriculture with a total of 477.96 ha (26.38%), mixed garden with a total of 92.85 ha(5.13%) and semitechnical irigated rice field with a total of 196.09 ha (10,8%). The soil was classified as hydraquent (96.6%) and distropept (3.4%). Based on the calibration of tank model application in the study area, the resulting coefficient of determination (R^2) was 0.72 with model efficiency (NSE)of= 0.75, thus tank model could well illustrate the water flow distribution of Cisadane Upper Catchment. The total water yield was 2.789 mm year^{-1} from 3,624 mm year^{-1} of total annual precipitation. The total water yield comprised of a total runoff of 47.39% and 49.23% of sub surface flow and base flow.

Keywords: tank model, Cisadane upper catchment, base flow, watershed

**Correspondense author, email: nmulyana@ipb.ac.id, phone: +62-251-8621244, fax: +62-251-8621244*

Introduction

Tank model has demonstrated a satisfactory performance in depicting characteristics and vertical and horizontal groundwater movement for watershed, sub-watershed and wet rice field (Setiawan *et al*. 2003). Water movement in an area is a dynamic process and very dependent on climate distribution, precipitation and combination of land coverage, evapotranspiration rate, soil type, contour and river network pattern to produce a complex dynamic balance. With the use of a tank model, vertical and horizontal water distribution can be easily and simply demonstrated, hence it can exhibit flow distribution at certain time for each layer of the watershed area.

The advantage of a Tank Model is that it is design with easy and simple software (MS Office excel) to use thus can model water distribution in four categories: run off, sub surface flow intermediate flow, sub base flow and base flow, as well as vertical water flow distribution of every watershed layer. Therefore, both vertical and horizontal distribution can be clearly modelled.

The relationship between land coverage and water availability results in a complex problem due to the dynamic nature of the water and inter linkages between the two factors, hence no water balance model to date can model the flow distribution correctly. Cisadane Upper Catchment is purposely selected as the study area for Micro Watershed

Model (MWM) to study the relationship between land use pattern, water pattern and pattern between nature of the watershed and social factors in a broader sense. Once the effect of land cover, soil and water conservation efforts on watershed have been studied, correlation between the dynamic land use change pattern and surface and sub flows distribution can be established. The objective of this paper is to examine the vertical and horizontal water balance distribution to provide quantitative information on water movement characteristics of a watershed.

Methods

Tank model parameters The structure of a tank model according to Setiawan *et al.* (2003) is shown in Figure 1.

Water level change in tank A:

$$\frac{dH_A}{dt} = R - E_T - Y_{A0} - Y_{A1} - Y_{A2} \qquad [1]$$

where: $Y_{A0} = A_0 \cdot H_A$ [2]

$$Y_{A1} = A_1 \cdot H_A \cdot S\left(H_A, H_{A1}\right) \qquad [3]$$

$$Y_{A2} = A_2 \cdot H_A \cdot S\left(H_A, H_{A2}\right) \qquad [4]$$

S is the step function having a value of 0–1 depending on the differences between dependent variables.

Water level change in tank B:

$$\frac{dH_B}{dt} = Y_{A0} - Y_{B0} - Y_{B1} \qquad [5]$$

where: $Y_{B0} = B_0 \cdot H_B$ [6]

$$Y_{B1} = B_1 \cdot H_B \cdot S\left(H_B, H_{B1}\right) \qquad [7]$$

Water level change in tank C:

$$\frac{dH_C}{dt} = Y_{B0} - Y_{C0} - Y_{C1} \qquad [8]$$

where: $Y_{C0} = C_0 \cdot H_C$ [9]

$$Y_{C1} = C_1 \cdot H_C \cdot S\left(H_C, H_{C1}\right) \qquad [10]$$

Water level change in tank D:

$$\frac{dH_C}{dt} = Y_{C0} - Y_{D1} \qquad [11]$$

where: $Y_{D1} = D_1 \cdot H_D$ [12]

Discharge of water flowing into the river was equal to the total lateral flows (Q_c):

$$Q_C = Y_{A1} + Y_{A2} + Y_{B1} + Y_{C1} + Y_{D1} \qquad [13]$$

Total amount of stored water within soil profile (Ht):

$$H_T = H_A + H_B + H_C + H_D \qquad [14]$$

Potential evapotranspiration (ETP) was calculated using the FAO Penman-Monteith equation as follows:

$$ETP = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad [15]$$

where:

ETP = potential evapotranspiration (mm day^{-1})
R$_n$ = net radiation (MJ m^{-2}day^{-1})
G = soil heat flux (MJ m^{-2} day^{-1})
T = average air temperature at 2 m height (°C)
u$_2$ = wind speed at 2 m (m s^{-1})
D = water vapour pressure gradient (kPa °C^{-1})

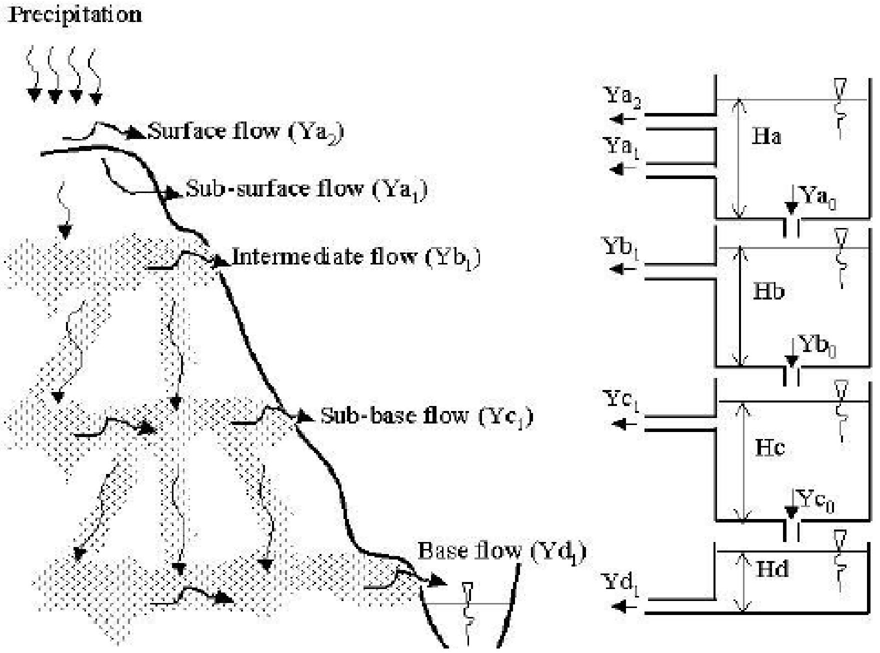

Figure 1 Diagram of water components flowing to river and its representation in a tank model.

γ = psychrometric constant (kPa °C^{-1})
e_s = saturation water vapour pressure (kPa)
e_a = actual water vapour pressure (kPa)
e_s - e_a = saturation vapour pressure deficit (kPa)

Acceptability process of the model use the discharge observation and output model was calculated using Nash-Sutcliffe efficiency (Nash-Sutcliffe 1970):

$$NSE = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad [15]$$

where:
NSE = 1 indicates a perfect model (without error)
O_i = observed discharge at ith time interval
õ = average observation data
P_i = simulated discharge at ith time interval
n = total data

Graph from simulation results and observation data were compared toward 1:1 line (y=x).

Description of the study area The study area is the Cisadane Upper Catchment located at coordinates of 6° 45’ 29.5" latitude and 106° 49’ 30.8" longitude. Administratively, it is located at Pasir Buncir and Cinagara Villages, within the Caringin Sub distric of Bogor Regency. The total area was 1,811.5 ha, with a total length of main river of 14,340.7 m.

Materials The hydrological data that were used to run the model were the 2008 data. The equipments used and installed in the field consisted of automatic weather station (AWS), and water level logger. The AWS comprised of automatic rainfall recorder, digital wind direction sensor, digital air temperature sensor, digital humidity sensor and water level sensor with precision of < 0.01 m at interval of 15 minutes. The softwares that were used to process and analyze spatial data were Arc View 3.X and tank model GA Optimizer (Setiawan *et al.* 2007).

Results and Discussion

Based on land cover interpretation, the distribution of land cover types of the study area were listed at Table 1. Based on USDA Classification System, there were two major soil types within the study area, namely *dystropept* and *hydraquent*. *Dystropept* was a slightly weathered soil, found in hot climate and low in base content. *Hydraquent* was a non-weathered soil, poorly drained, soft when stepped on and mostly had soft texture. *Dystropept* contributed only a small coverage, *i.e.*, (56.2 ha/3.1%), found along the southern part, while most of the area were covered by *hydraquent* (1,755.3 ha/96.9%).

The elevation of the study area ranged between 512.5–2,235.4 m above sea level whereas distribution of land slope around the outlet was less than 15%. Towards the upper area, the topography was very steep (> 40%) and mostly found around Cibedug Village. Percentage of each slope class of Cisadane Upper Catchment is shown in Table 2.

Table 1 Land coverage types of Cisadane Upper Catchment

Land coverage	Total	
	(ha)	(%)
Shrubs	477.96	26.38
Forest	1,044.60	57.67
Garden/plantation	116.11	6.41
Settlement	13.47	0.74
Grassland/open area	2.70	0.15
Irrigated rice field	23.18	1.28
Rain-fed rice field	40.64	2.24
Dry agriculture land	92.85	5.13
Total	1,811.50	100.00

Source: interpretation from image SPOT 5-2004

Table 2 Percentage of each slope class of Cisadane Upper Catchment

Slope class	Total	
	(ha)	(%)
0–8%	91.8	5.07
8–15%	109.2	6.03
15–25%	384.1	21.21
25–40%	1,031.0	56.91
> 40%	195.5	10.79
Total	1,811.6	100.00

Based on Bogor Geological Map, the geological structure of the study area comprised of volcanic rocks. The geological formation around the study area comprised of mature volcanic rock (Qvt) consisted of lithic tuff. The total area of Qvt was found to be 101.4 ha (5.6%). The southern part consisted of Gunung Pangrango volcanic rock with lava deposits and more mature lahar (Qvpy), comprising of basaltic andesite with oligoklas-andesin, labradorit, olovin, piroxene and hornblende. This type of rock covered only 179.7 ha (9.92%) of the whole area. The study area was dominated by Gunung Pangrango volcanic rock with younger *lahar* deposits (Qvpo) consisted of about 84.49% (± 1,530.5 ha) andesite.

During the observation period in 2008, there were 195 rainy days with a total rainfall of 3,624 mm. The number of rainy days that was less than 10 occurred in the months of May, July, and September whereas the peak rainy days occurred in February and March. A complete rainfall and potential evapotranspiration data is presented in Tabel 3.

Table 3 showed that the total evapotranspiration within the study area from 1st of January–31st of December 2008 was 1,211 mm out of the total rainfall of 3,624 mm year^{-1} or in other words, 33.41% of rainfall was returned to the air. In July, the average evapotranspiration was more than 100 mm month^{-1} and the highest occurred in October with a total of 110.94 mm month^{-1}. The total ET during January–April was relatively lower than other months. The net rainfall indicated that during October–April there was a surplus of more than 100 mm month^{-1}, while during May, June, and September, although there were still surplus of net rainfall, but occurred below 100 mm month^{-1}, while the months of July–August experienced a deficit of 71–77 mm month^{-1} as shown on the Figure 2. The potential evapotranspiration dynamics during the measurement period is given in Figure 3. The relative humidity ranged between 85.8–100% with wind speed between 0.02–0.716 m s^{-1}. Data on solar radiation was taken from rainfall data with values between 13.99–21.07 MJ m^{-2}.

Hydrology Measurement of water level (H) and water discharge (Q) for the study area followed the following equation:

$$Q = 37.254\, H^{2.9162} \qquad R^2 = 0.967 \qquad [17]$$

where: Q = discharge ($m^3\, s^{-1}$)
H = water level (m)

Since the tank model required input of discharge unit in mm day^{-1}, hence the river discharge (Q_{obs}) equation became:

$$Q_{obs} = \frac{(86400\, Q)}{A} \qquad [18]$$

where A = area of watershed (m^2)

Based on the observation of discharge for 12 months (Table 4), it was revealed that the total river discharge has increased during rainy period and decreased during drought period. The minimum river discharge occurred during alteration from rainy season to drought, in July–September, around 88–96 mm. Peak discharge occurred on March 19th with a total of

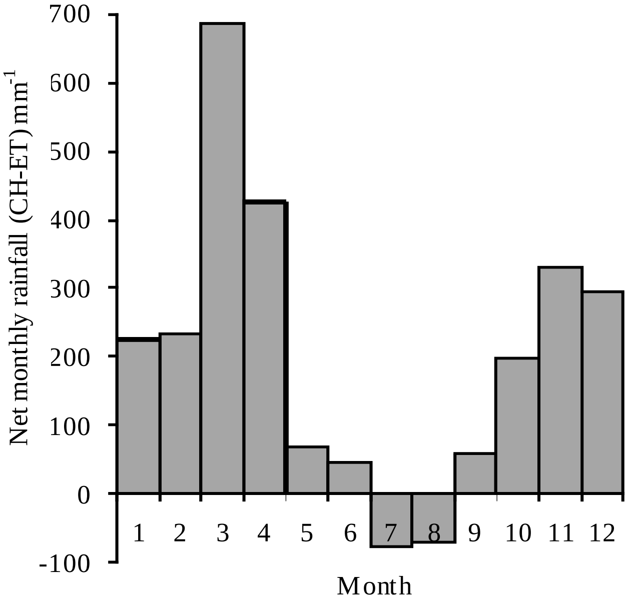

Figure 2 Net monthly rainfall in the study area.

Table 4 Monthly discharge (Q) of the study area

Month	Max Q (mm day^{-1})	Min Q (mm day^{-1})	Average Q (mm day^{-1})	Total Q (mm)
January	28.86	1.8	6.73	208.52
February	29.10	5.49	8.62	249.99
March	78.17	5.91	20.06	621.81
April	33.39	5.42	15.07	451.95
May	13.79	5.31	7.24	224.42
June	8.42	3.42	4.92	147.49
July	3.42	2.85	3.10	96.05
August	5.19	2.08	2.85	88.31
September	7.95	2.27	3.09	92.63
October	20.89	2.34	3.80	117.89
November	20.65	4.83	9.81	294.34
December	17.64	2.62	6.34	196.46
Total				2789.86

Table 3 Characteristics of monthly precipitation and evapotranspiration in the study area

Month	Total day	Max rainfall (mm)	Rainfall (mm)	ET (mm) calculated	Max ET (mm day^{-1})	Min ET (mm day^{-1})	Mean ET (mm day^{-1})
January	16	57	324	98.85	3.88	2.41	3.19
February	27	71	320	87.08	3.44	2.31	3.00
March	25	99	772	87.05	3.59	2.26	2.81
April	19	128	524	98.09	3.83	2.27	3.27
May	8	82	168	101.11	3.65	2.66	3.26
June	10	27	140	95.31	3.49	2.76	3.18
July	3	22	26	102.83	3.60	3.00	3.32
August	10	11	38	108.59	3.79	3.28	3.50
September	5	67	166	108.11	3.99	2.89	3.60
October	22	44	309	110.94	4.08	2.91	3.58
November	25	78	435	104.87	3.87	2.87	3.50
December	25	71	402	107.78	3.97	2.86	3.48
Total	195	128	3,624	1,211.00			

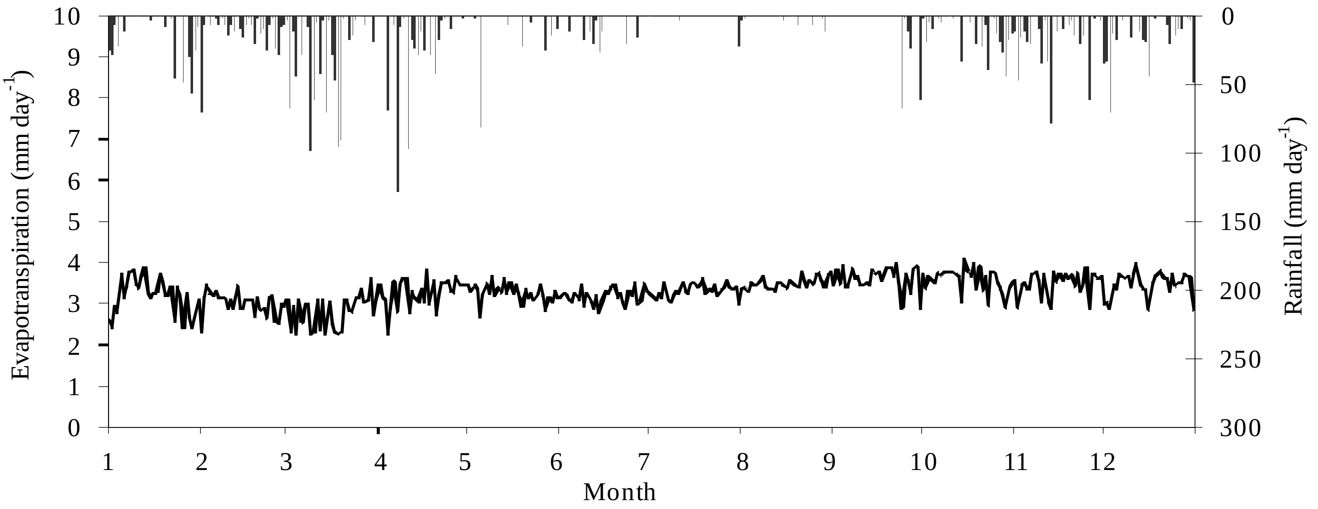

Figure 3 Evapotranspiration and rainfall dynamics. Rainfall (▬), evapotranspiration (—).

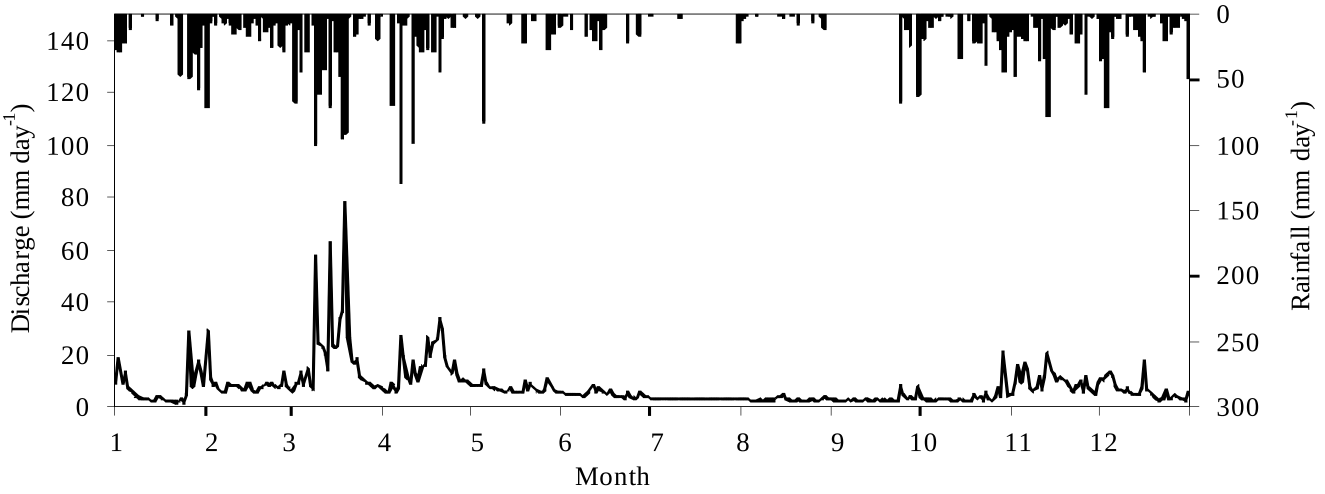

Figure 4 Relationship between rain occurrence and river flow discharge. Rainfall (▬), discharge (—).

78.1 mm day^{-1}. Compared to other months, the maximum river discharge occurred lowest in July, with a value of only 3.42 mm day^{-1}. The total water yield for 1 year was amounted to 2,789.86 mm year^{-1} or equalled to 76.9% out of the total rainfall during observation period. Figure 4 showed the graph for rainfall and discharge during measurement period.

Tank model simulation Recapitulation of observation data and simulation results before and after calibration using the Tank Model calculation, as well as the parameters used in the simulation were tabulated in Table 5 and 6.

After calibration, the simulation result was closer to observation data where the total discharge for the period of measurement was only 1.18% higher than observation data. Discharge components were dominated by surface flow (47.39%) followed by sub base flow (46.23%). Intermediate and base flows contributed only small amounts, *i.e.*, 2.78% and 3.6% respectively. The dynamics of each discharge

Table 5 Recapitulation of simulation results and observation data before and after calibration

Variables	Unit	Before calibration		After calibration	
		(mm day^{-1})	(%)	(mm day^{-1})	(%)
Surface flow	mm day^{-1}	1,356	47.74	1,338	47.39
Intermediate flow	mm day^{-1}	1,265	44.53	78	2.78
Subbase flow	mm day^{-1}	143	5.03	1,305	46.23
Base flow	mm day^{-1}	77	2.70	102	3.60
Total flow	mm day^{-1}	2,841	100.00	2,823	100.00

Table 6 Parameters used in the simulation

Symbol	Note	Unit	Before calibration	After calibration
a0	Parameter in outlet 0 of Tank A	-	0.18226	0.14349
a1	Parameter in outlet 1 of Tank A	-	0.13273	0.14343
Ha1	Level of outlet 1 of Tank A	mm	6.25421	14.4055
a2	Parameter in outlet 2 of Tank A	-	0.07467	0.91407
Ha2	Level of outlet 2 of Tank A	mm	40.7251	198.628
b0	Parameter in outlet 0 of Tank B	-	0.00188	0.01660
b1	Parameter in outlet 1 of Tank B	-	0.01972	0.00100
Hb1	Level of outlet 1 of Tank B	mm	19.2737	0.49431
c0	Parameter in outlet 0 of Tank C	-	0.00020	0.00099
c1	Parameter in outlet 1 of Tank C	-	0.17690	0.42396
Hc1	Level of outlet 1 of Tank C	mm	0.67060	0.00033
d1	Parameter in outlet 1 of Tank D	-	0.00024	0.00033
Initial condition (t~0)				
Ha	Water level in Tank A	mm	10.476	48.506
Hb	Water level in Tank B	mm	28.765	292.412
Hc	Water level in Tank C	mm	14.423	6.679
Hd	Water level in Tank D	mm	889.862	791.166
Total			943.526	1138.759

component based on simulation results after calibration were shown in Figure 5. Nash-Sutcliffe efficiency (NSE) value or efficiency model was found to be 0.75 and coefficient of determination (R^2) between simulation and observed data was 0.7215 setting the intercept equal to 0. Comparison between simulated data after calibration and observed data on 1:1 line (y=x) is given in Figure 6 while data series of river discharge based on observation and simulation.

Calibration of the tank model showed that water flow in Cisadane Upper Catchment was dominated by water movement of the surface flow (tank A) as much as 47.39% and of sub base flow (tank C) as much as 46.23%. The water depth of the model when the model was first initiated witha total outlet of tank Ha_1 of 14.4 mm and outlet Ha_2 of 198.62 mm, meaning that water movement on the surface layer was greater than that of the sub surface. The vertical water storage in tanks A, B, C, and D were 48,506; 292,412; 6.679; and 791.166 mm respectively. These suggested that water movement was dominated by sub base flow and groundwater layers. Tank model analysis showed that the surface flow accounted for 47% out of the total, and filling of intermediate flow occurred between January–August with a rate of 0.1–0.5 mm day^{-1} and there were no filling between September–October, although the river was still flowing and only come from the spring (base flow) as much as 0.3 mm day^{-1}, while on the sub base flow (tank C) water rate was dominant between 1–10 mm day^{-1} between January–September and ranged between 1–5 mm day^{-1} in November–December. Therefore, the rate of surface runoff in Cisadane Sub Watershed was still considered as high (47.39%) thus it was necessary to reduce the ratio of runoff to rainfall by carrying out replantation on areas dominated by dryland agriculture such as corn, ground nuts and cassava, to return them back to hard wood areas since the area was previously consisted of rubber and tea plantations.

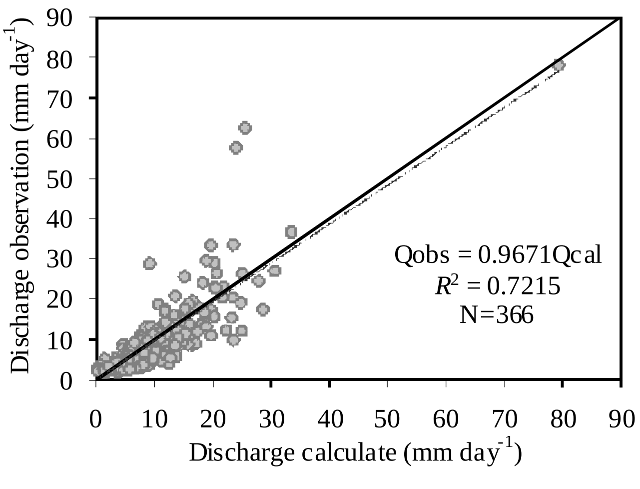

Figure 6 Comparison between simulation result and observation after calibration.

Conclusions

Tank model is very practical to use for estimating the water balance and water flow pattern in a watershed area because it provides a detailed information on vertical and horizontal water movements of each layer of the watershed and this model can be use in the study area because it has a coefficient correlation value between model and measurement (R^2) of 0.72 with acceptability value (NSE) of 0.75. Water movement in Cisadane Upper Catchment has a rainfall to surface flow ratio of 47.39% where 49.23% originates from sub base flow and 2,789 mm year^{-1} of base flow from the total rainfall of 3,624 mm year^{-1}. Water movement in Cisadane Upper

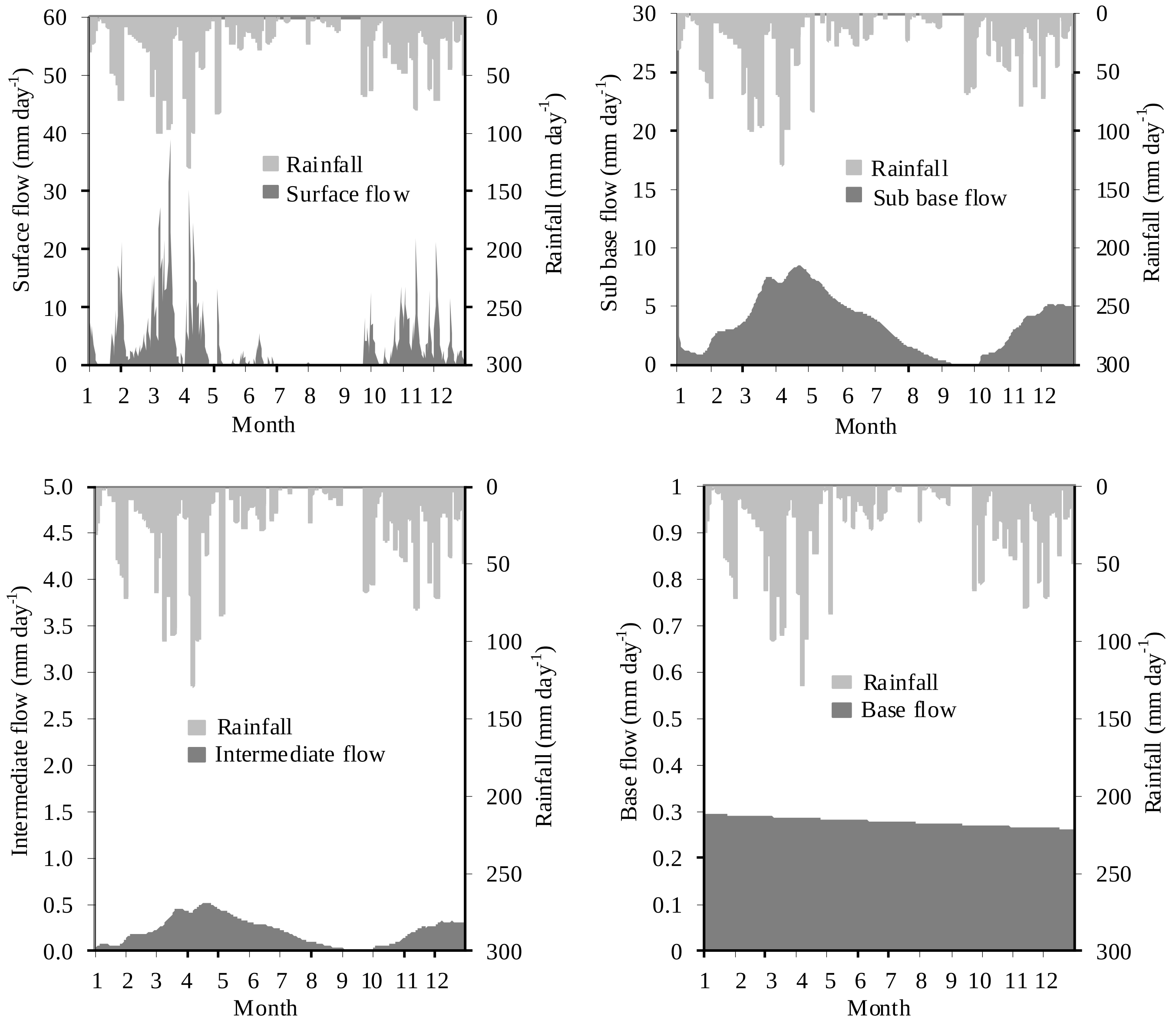

Figure 5 Dynamics of each streamflow component in the study area.

Catchment is more dominant in tank A and tank C. This suggests that the role of forest in controlling water is very significant because land coverage and roots provide real influence in water movement and balance within a watershed area.

Acknowledgements

On this occasion, we would like to show our particular gratitude to the Head of Citarum Ciliwung Watershed Regional Office, Directorate General of Land Rehabilitation and Social Forestry (RLPS) of Ministry of Forestry Government of Indonesia who has been of great help in providing and collaborating in the use of data as materials for this paper.

References

Elhassan AM, Goto A, Muzutani M. 2001. *Combining a Tank Model with Ground Water Model for Simulating Regional Ground Water Flow in Alluvial Fan. Trnas. Of JSIDRE*. Japan: Utsonomiya University. pp 21–29.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models part I-a discussion of principles. *Journal of Hydrology* 10(3):282–290.

Setiawan BI, Rudiyanto. 2007. *Optimization of Hydrologic Tank Model's Parameter. Discrete and Continues Step Function Optional Objective Error Function Microsoft Excel and Visual Basic Editor rete and Continuous Step Functions.* Bogor: Department of Agricultural Engineering Bogor Agricultural Technology.

Setiawan BI, Rudyanto, K Abdullah. 2005. Perancangan model pendugaan efekftivitas waduk resapan. *Jurnal Alami: Air, Lahan, Lingkungan dan Mitigasi Bencana* 10(1):48–54.

Setiawan BI, T Fukuda, Y Nakano. 2003. Developing procedures for optimization of Tank Model's Parameters. Agricultural Engineering International: The CIGR Journal; manuscript LW 01 006.

Setiawan BI. 2003. Optimasi parameter tank model. *Jurnal Keteknikan Pertanian* 17(1):8–20.

Tingsanchhali T. 2001. *Application of Combined Tank Model and AR Model in Flood Forecasting*. Thailand: Asian Institute of Technology.