DEVELOPMENT OF RAINFALL RUNOFF MODEL FOR BOGOWONTO RIVER BASIN BY USING TANK MODEL

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ABSTRACT

As one of major rivers in Central Java Province, the Bogowonto River plays important roles for life in the river basin. the Bogowonto River Basin, extends over some 587 km^2 located between Latitude 7° 23' and 7° 54' South and Longitude 109° 56' and 110° 10' East. It is located on the Western side of the complex known as Kulon Progo Mountains, with river sources at the South-Eastern slopes of Sindoro and Sumbing volcanoes. The average annual precipitation over the Bogowonto basin reaches about 3,000 mm, but exceeds 5,000 mm at the slopes of Mount Sumbing. The annual precipitation in the coastal plain tends to be lower than the average over the basin. The mean annual flow at the river mouth amounts to about 35 m^3/s. Purworejo, one of the districts that are located around the Bogowonto River, is frequently flooded. Flood occurs not only from the main stream of the Bogowonto river, but also from overflow of the tributaries. For example, in 2004 there was big flood occur Purworejo. Inundation heights reach 50-100 cm and the flood inundates hundreds of houses in 21 villages. In order to determine the appropriate countermeasure to overcome flood in Bogowonto River Basin area, the characteristic of that river basin must be understood. For that purpose, rainfall-runoff modeling is used. By using tank model as the rainfall-runoff model, physical condition of the Bogowonto River basin is investigated. To determine 12 parameters of Tank Model, Shuffled Complex Evolution-University of Arizona (SCE-UA) is used as the optimization tools. By compiling the Tank Model and SCE-UA, the optimization process is runs well. The result of this study shows the physical condition of Bogowonto River Basin. It can be concluded that floods which occur every year around the Bogowonto River are derived from subsurface flow described by the second tank in this study. Water that comes from the upper part will be accommodated in this tank, while the infiltration out of this tank is very small. It causes the water surface in this tank will always be higher than the side outlet. Therefore, the discharge that comes out through the intermediate outlet is large enough to cause flooding.

Key words: *rainfall-runoff model, tank model, parameters, SCE-UA, optimization, hydrologic process.*

INTRODUCTION

Flooding in the Bogowonto River is not easy to overcome. Controlling the flood cannot be attained merely by constructing infrastructures in a flood prone area, but it must be carried out comprehensively and sustainably from upstream to downstream. And to understand the physical properties of the Bogowonto River is important as one of effort to control the flood. For that, rainfall-runoff model is needed. To determine the relationship between rainfall and runoff in a watershed and to investigate the characteristics of these watersheds, a hydrologic model is used for a simulation of rainfall-runoff. And a hydrologic model that describes the relationship between rainfall and runoff, will represents the characteristics of the watershed. Tank Model is one of them. To calibrate the parameters in Tank Model in this study, SCE-UA was used as the optimization method. Optimization process can be done by compiling Tank Model Fortran code with the SCE-UA method in a FORTRAN source code that has been developed by Tsuyoshi Tada (Tada, 2008). The final results are parameters in the tank model and physical condition of the tank model that can represent the characteristics of Bogowonto River Basin. Figure 1 shows the Bogowonto River basin with rain gauges and runoff measures station.

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DATA

Data that used in this research is data from Bogowonto River Basin in 2003, taken from different measurement station such as 3 rainfall gauge station, 1 discharge gauge station. These data were collected from Ministry of Public Works Directorate General of Water Resources Serayu Opak River Basin Organization, Yogyakarta, Indonesia in 2003. These data are daily rainfall data in each station and because of the data might be not uniformly distributed throughout the river basin, Thiessen Polygon method (Equation 1) is used to get the average rainfall data. The description of data in each rain gauge station is shown in Table 1.

$$\bar{P} = \sum_{i=1}^{N} \alpha_i . P_i \qquad (1)$$

Where $\bar{P}$ is average rainfall (mm), α is Thiessen weight, P is rainfall (mm).

Table 1. Rainfall Data in Each Rain Gauge Stations

No	Name of Station	Sub Catchment Area (KM^2)	Thiessen Weight
1.	Sapuran	76.3	0.221
2.	Kepil	130.8	0.378
3.	Guntur	138.9	0.401
TOTAL		346	1.000

The discharge data are in daily which has unit in m^3/s and it was obtained from Boro station.

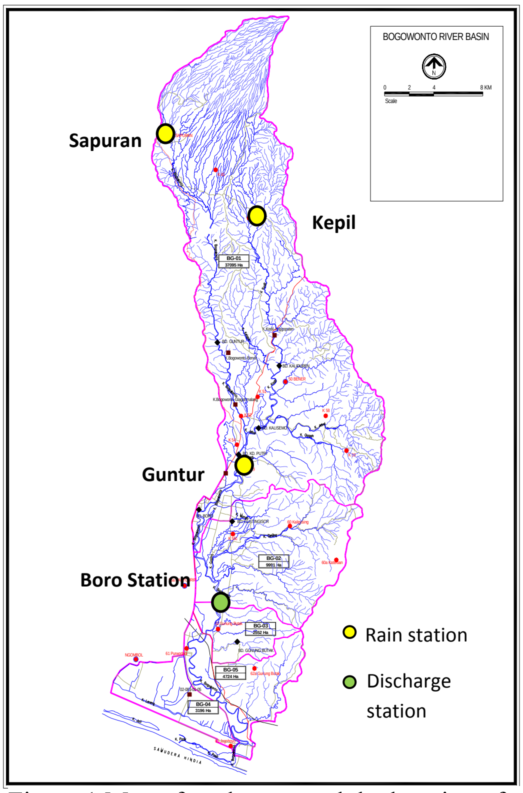

Figure 1.Map of study area and the location of gauge stations.

THEORY AND METHODOLOGY

Tank Model Design

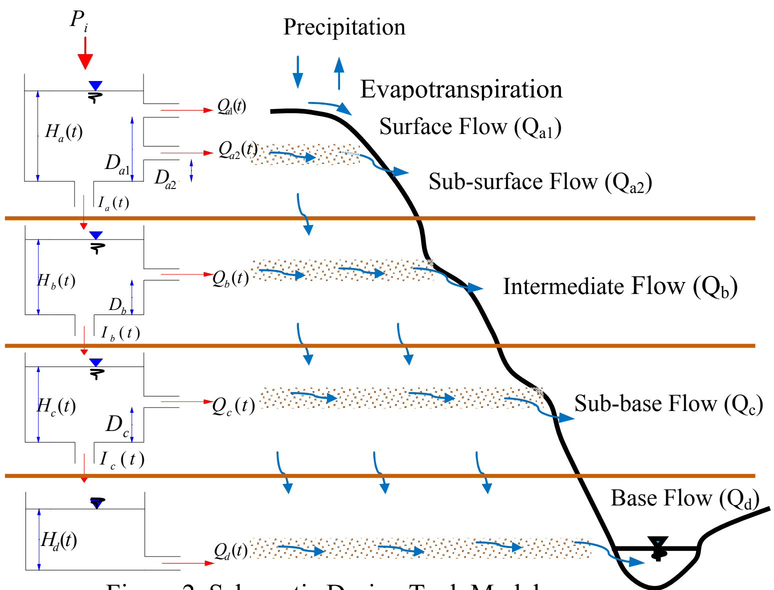

Figure 2. Schematic Design Tank Model

Figure 2 shows the schematic of design Tank Model which has 4 tanks. Consists of Surface Tank (A), Intermediate Tank (B), Sub-Base Tank (C), Base Tank (D). Rainwater that precipitates on the catchment area is the main input after deducting the amount of water that evaporates because of evapo-transpiration process. In the concept of Tank Model, water can fill the reservoir that lies beneath it, and water flows out at horizontal outlet in each reservoir, which is represented as Outflow Discharge (Runoff Flow).

- Tank A has two horizontal outlets and a vertical outlet. Horizontal outlets consist of Surface Flow (Q_{a1}) and Subsurface Flow (Q_{a2}). Horizontal flows only occur if the water level in the Tank A (H_a) is higher than its outlet (D_{a1} and D_{a2}).

Vertical flow (I_a) is represented as an infiltration. The amount of Q_{a1}, Q_{a2} and I_a are influenced by the characteristic of each outlet.

- Tank B has a horizontal outlet and a vertical outlet. Horizontal outlets represent Intermediate Flow (Q_b). It only occurs if water level in Tank B (H_b) is higher than its outlet (D_b). Vertical flow (I_b) is represented as an infiltration. Q_b and I_b are influenced by the characteristic of its outlet.
- Tank C has a horizontal outlet and a vertical outlet. Water flows out through horizontal outlet or we can call it Sub-Base Flow (Q_c). It only occurs if water level in Tank C (H_c) is higher than it outlet (D_c). Vertical outlet (I_c) is represented as an infiltration. Q_c and I_c are influenced by the characteristic of its outlet
- Tank D (Base Reservoir) only has a horizontal outlet. Water flows only through this outlet and it represented as Base Flow (Q_d). It is influenced by the characteristic of the outlet.

The total outflow from the side outlet (Q) from each tank is considered as the accumulation of the outflows from a system in the watershed and the equation is as follows:

$$Q(t) = \{Q_{a1}(t) + Q_{a2}(t) + Q_b(t) + Q_c(t) + Q_d(t)\} \tag{2}$$

Water Balance

Water balance equation is :

$$\frac{d}{dt}H(t) = P(t) - Q(t) \tag{3}$$

Where P is rainfall (mm/day), E is evapotranspiration (mm/day), Q is total runoff (mm/day), H is water storage level (mm), t is time (day). At the initial time (t=1), the initial conditions of water level storage in tank A ($Ha_{(1)}$), tank B ($Hb_{(1)}$), tank C ($Hc_{(1)}$) and tank D ($Hd_{(1)}$) are given. For the next time step ($t+1$) the storages in each tank are updated as follows:

$$\mathrm{Ha}(t+1) = \mathrm{Ha}(t) + \mathrm{P}(t) - \mathrm{Qa1}(t) - \mathrm{Qa2}(t) - \mathrm{Ia}(t) \tag{4}$$
$$\mathrm{Hb}(t+1) = \mathrm{Hb}(t) + \mathrm{Ia}(t) - \mathrm{Qb}(t) - \mathrm{Ib}(t) \tag{5}$$
$$\mathrm{Hc}(t+1) = \mathrm{Hc}(t) + \mathrm{Ib}(t) - \mathrm{Qc}(t) - \mathrm{Ic}(t) \tag{6}$$
$$\mathrm{Hd}(t+1) = \mathrm{Hd}(t) + \mathrm{Ic}(t) - \mathrm{Qd}(t) \tag{7}$$

Calibration of Tank Model

Table 2. Parameters in Tank Model That are going to be Calibrated

No	Coef.	Functions	Description
1.	C_{a1}	$Q_{a1}(t) = C_{a1} \times (H_a(t) - D_{a1})$	Surface runoff coefficient
2.	C_{a2}	$Q_{a2}(t) = C_{a2} \times (H_a(t) - D_{a2})$	Sub-surface runoff coefficient
3.	C_{a0}	$I_a(t) = C_{a0} \times H_a(t)$	Infiltration Coefficient
4.	C_{b1}	$Q_b(t) = C_{b1} \times (H_b(t) - D_b)$	Intermediate runoff coefficient
5.	C_{b0}	$I_b(t) = C_{b0} \times H_b(t)$	Infiltration Coefficient
6.	C_{c1}	$Q_c(t) = C_{c1} \times (H_c(t) - D_c)$	Sub-base runoff coefficient
7.	C_{c0}	$I_c(t) = C_{c0} \times H_c(t)$	Infiltration Coefficient
8.	C_{d1}	$Q_{d}(t) = C_{d1} \times H_d(t)$	Base runoff coefficient
9.	D_{a1}		Height of upper surface outlet
10.	D_{a2}		Height of subsurface outlet
11.	D_b		Height of intermediate outlet
12.	D_c		Height of sub-base outlet

The SCE-UA method was developed by Duan et al. in 1992. It is a global optimization method designed to handle the various response surface problems encountered in the calibration of nonlinear simulation models, particularly the multilevel optima problem encountered with Conceptual Rainfall-Runoff (*CRR*) models. This method combines deterministic and stochastic strategies and it is based on a synthesis of the best features from several existing methods, including the genetic algorithm and simplex downhill search scheme. On the base of competitive evolution, the SCE-UA method introduces a new concept of complex shuffling. This method is capable of finding global optimum and it does not rely on the availability of an explicit expression for the objective function or the derivatives (Wu, et al., 2006).

The most important thing in the tank model is how to determine the parameters by comparing the *Q calculated* with *Q observed* using particular objective function. For the parameters in this tank model that are going to be calibrated as shown on the Table 2.

The general description of SCE-UA method is given below:

1) To initialize the process, select $p \geq 1$ and $m \geq n+1$, where p is the number of complexes, m is the number of points in each complex, and n is the dimension of the problem. Compute the sample size $s = p \times m$.
2) Generate a sample. Sample s points $x_1, \dots, x_s$ in the feasible space. Compute the function value f_i at each point x_i. In the absence of prior information, use a uniform sampling distribution.
3) Rank points. Sort the s points in order of increasing function value. Store them in an array D = $\{x_i, f_i, i = 1, \dots, s\}$, so that i = 1 represents the point with the smallest function value.
4) Partition D into p complexes $A^1, \dots, A^P$, each containing m points, such that $A^K = \{A_j^K, f_j^K \mid x_j^K = x_{K+p(j-1)}, f_j^K = f_{k+p(j-1)}, \quad j = 1, \dots, m\}$
5) Evolve each complex. $A^K, K = 1, \dots, p$ according to the Competitive Complex Evolution (CCE) algorithm.
6) Shuffle the complexes. Replace $A^1, \dots, A^P$ into D, such that $D = \{A^K, K = 1, \dots, p\}$. Sort D in order of increasing function value.
7) Check the convergence. If the convergence criteria are satisfied, then stop; otherwise, return to step (3).
8) Check the reduction in the number of the complexes. If the minimum number of complexes required in the population, P_{min}, is less than p, remove the complex with the lowest ranked points; set $p = p-1$ and $s = p \times m$; return to Step (3); If $P_{min} = p$, return to step (3).

To start optimization process, there are several initial parameter values that should be decided. And the initial parameters are shown in Table 3.

Table 3. Initial Condition of Tank Model

No	Parameters	Initial	Min	Max
1.	C_{a1}	0.01	0	1
2.	C_{a2}	0.01	0	1
3.	C_{a0}	0.02	0	1
4.	C_{b1}	0.05	0	1
5.	C_{b0}	0.05	0	1
6.	C_{c1}	0.01	0	1
7.	C_{c0}	0.01	0	1
8.	C_{d1}	0.01	0	1
9.	D_{a1}	40	0	100
10.	D_{a2}	15	0	100
11.	D_b	15	0	100
12.	D_c	15	0	100

Objective Function

Efficiency Index (EI):

$$EI = 1 - \frac{\sum_{i=1}^{i=n}(Qo_i - Q_i)^2}{\sum_{i=1}^{i=n}(Qo_i - \overline{Qo})^2} \qquad (9)$$

Logarithmic Values of Efficiency Index (*ln EI*):

$$lnEI = 1 - \frac{\sum_{i=1}^{n}(\ln Qo_i - \ln Q\ )^2}{\sum_{i=1}^{n}(\ln Qo_i - \overline{\ln Qo})^2} \qquad (10)$$

Where Q_{oi} is observed discharge at time i, Q_{ci} is calculated discharge data at time i, $\overline{Qo}$ is mean of the observed discharge data, and n is number of data.

RESULTS AND DISCUSSION

Optimization Process

The results show that design models provide a fairly good result, although less satisfying. Performance tank design model shows the value of coefficient of correlation (R^2) of 0.732, the Efficiency Index (*EI)* is 0.694. Optimization results for the Hydrograph of the Bogowonto River in the year 2003 can be seen in the Figure 3.

It is clearly seen that the tank design model to simulate one year (2003) were almost successful to calculate for the low flow but is less successful in calculating the maximum flow. For the low flow, it is seen that the calculated discharge almost fit with the observed one. To increase the value of EI, another objective function is used. This objective function is Nash-Sutcliffe Efficiency with Logarithmic Values (*ln EI*). The result is shown in Figure 4. According to the result using *ln EI*, the value of the model performances are increasing with value of R^2 is 0.75 and *EI* is 0.71.

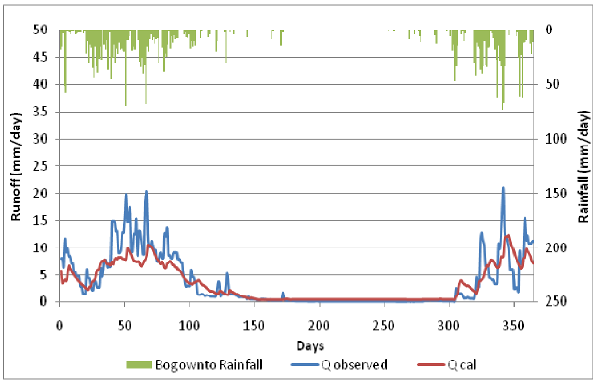

Figure 4. Hydrograph for One Year Optimization in Bogowonto River with EI Objective Function

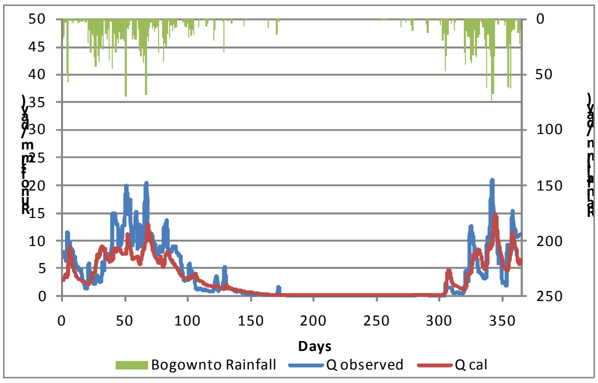

Figure 4. Hydrograph for One Year Optimization in Bogowonto River with Logarithmic Value of EI (ln EI) Objective Function.

Physical Condition in Each Tank

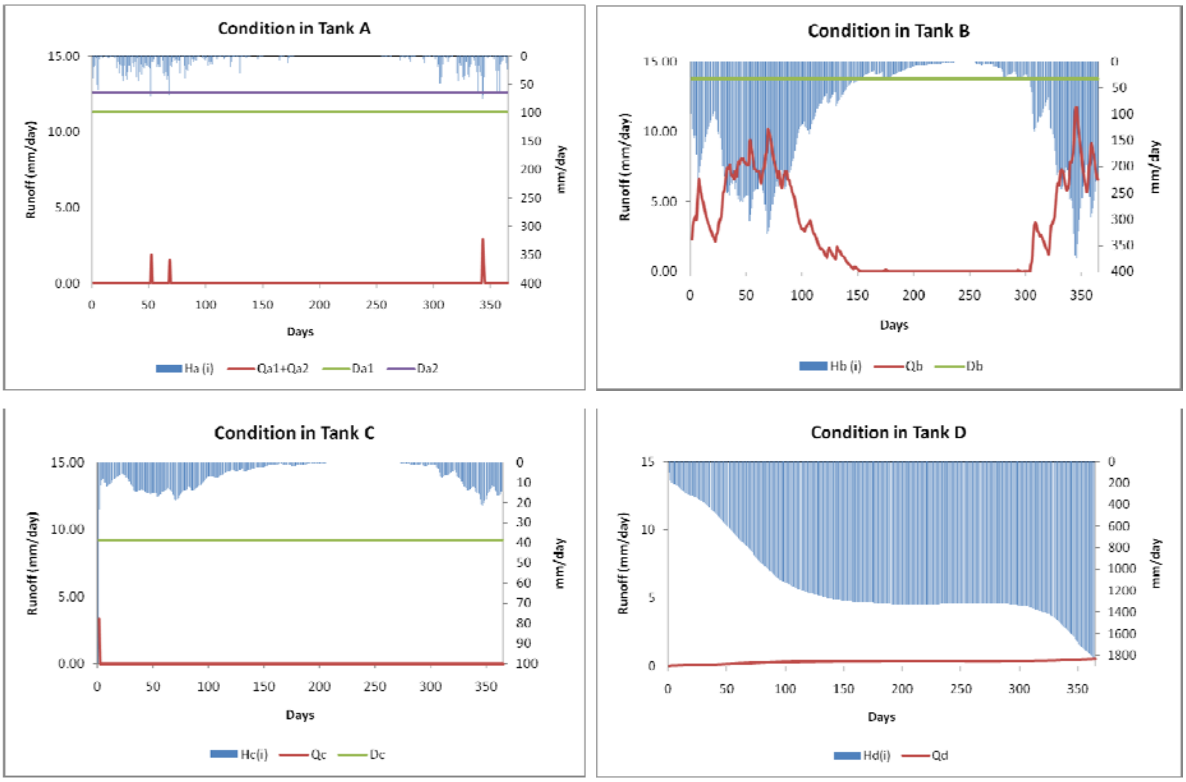

Figure 5. Physical Condition of Bogowonto River Basin

According to Figure 5, it shows the physical condition of the Bogowonto River Basin. In Tank A, the rain water that falls to the ground surface is absorbed directly into the soil, and surface runoff is very small. With a maximum water level in tank A of 75.58 mm, while height of the surface outlet (D_{a1})= 98.06 mm and sub-surface outlet (D_{a2}) = 64.16 mm. In Tank B, the maximum water level in the tank B is 375.561 mm and the height of the outlet (D_b) is 32.04 mm. Side outflow from this outlet mostly occurs throughout the rainy season. Because the water level is higher than the outlet, discharge water that coming out of this outlet is big enough even though the coefficient of the outlet was not so high (C_{c1} = 0.0544). In Tank C, there is practically no side outflow from Tank C. The only one outflow occurs in day 1. It happens because the initial condition (H_{c1} = 100) of water storage in tank C is higher than the side outlet (D_c= 38.54). For the infiltration process, vertical outflow occur from tank C to tank D. Although the water level in tank C not so high, but the parameter of infiltration outlet is quit high with the value of C_{c0} = 0.7751. Condition in tank D reflects that all rainwater that falls to the ground, will be accommodated in this section. A very small coefficient of the outlet is found in tank D (C_{d1}), which is only 0.0003, although the water level in the tank D is very large. Tank D contribute the outflow to the Bogowonto river during the dry season. Because of this condition the Bogowonto River never gets dry through the year.

CONCLUSION

By using observed hydrology data of Bogowonto River Basin in 2003, the tank model is calibrated and gives good results that represented the physical condition of Bogowonto River Basin. Because optimization process by using SCE-UA algorithm needs 3000 computational time of iterations applied to 365 rainfall and runoff data as well, it takes time to run the model and to get the results. In this model, setting of more than 12 parameters is also made possible. According to the result of tank model in this study, the following hydrologic mechanisms are inferred. It can be concluded that floods which occur every year around the Bogowonto River are derived from subsurface flow described by the second tank in this study. Water that comes from the upper part will be accommodated in this tank, while the infiltration out of this tank is very small. It causes the water surface in this tank will always be higher than the side outlet. Therefore, the discharge that comes out through the intermediate outlet is large enough to cause flooding.

RECOMMENDATION

Data set used in this study is only of the 2003 and only from 3 rainfall stations. To build a good rainfall-runoff modeling using tank model more than 3 rainfall gauge stations data are required in order to represent the whole watershed and provide better result. Further, more than one year data with good quality is also necessary. In this study, the initial water level in each tanks are decided before the optimization process started. For the future study, it is better to optimize the initial condition of the tank model (set the water level in each tank as the parameters that should be determined), so it can give the best result of parameters although it will need more time to calibrate it.

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