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Watershed Sediment Discharge Analysis as Revealed by Tank Model

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***Abstract* - Uncontrolled erosion and sedimentation will cause to substantial losses, either in the form of declining productivity of land as well as hydro structure damage and the occurrence of sediment in reservoirs. This is because the availability of sediment discharge data is quite limited, a number of models for the prediction of surface erosion and sediment discharge have been widely developed. The application of the model requires the availability of input data is sufficient, diverse and extensive, both for calibration and verification. The process of soil surface erosion and sediment discharges in watersheds affected by rain and surface runoff can be represented in the type of storage. In this research it conducted the approach uses Tank Model. The objective is to develop tank model for prediction of sediment discharge a Watershed. The steps are setting experimentation field for data acquisition as input data model, and setting model analysis by making the structure and formulation of the tank model. There are two proposed tank models: Tank Model 1 (three cascade tanks), and Tank Model 2 (one tank). The parameters of the model are determined by using the Genetic Algorithm method optimization approach program in MatLab. The results of the analysis show that 2 tank models can be developed for the prediction of sediment discharge in the Watershed. A good tank model configuration for the prediction of sediment discharge in a watershed is Tank Model 2, the model composed of 1 (one) tank consists of 2 (two) side holes, and 1 (one) bottom hole. This is based on the value criterion precision models in Kreo sub Watershed, the value of R between 0.77 - 0.88, the value of VE between 8.32 - 24.60%, the value of RE between 315.54 - 485.64%, the value of RMSE between 358 , 11 - 501.77. But the values of the parameters in the Watershed have different values according to the conditions of the Watershed observed. And the result of this analysis there is still the range of difference between simulated and measured sediment discharge value of varying magnitude, it is possible cause is the pattern of rain dispersion in the hydrological process, synchronization of measurement process and length of data and possible assumption of model parameters**

Keywords: sediment discharge, runoff, rainfall, tank model

1. INTRODUCTION

Several criteria for determining critical watersheds include the low percentage of land cover, high annual rate of erosion, the magnitude of the ratio of maximum river discharge and minimum discharge, as well as excessive sludge content (sediment load). These critical watershed indications indicate that the environmental system that supports the hydrological cycle process is being damaged and has been damaged, among others, reduced forest area in water catchment areas, increased levels of erosion and sedimentation, resulting in floods, landslides, and decreased soil fertility. And currently, there are 108 watersheds that are in critical condition [1].

A watershed can be viewed as a management system, where the watershed gets input which is then processed in the watershed to produce output [2, 3]. Thus, watershed is the processor of every input in the form of rain and human intervention (management) to produce output in the form of production, runoff and sediment. To analyze a watershed, there are at least four things that need to be considered [4]:

1. Land phase, considers the flow of water above the ground surface, both as runoff and surface runoff. In this case it does not view surface runoff as flow within the channel.
2. River phase, considers all aspects of the flow in the channel (river), including the scouring process, sedimentation, variations in flow through the river system, and all processes that occur and vary according to the nature of the flow.
3. The reservoir phase, including natural and artificial storage and processes involving inputs, outputs, sedimentation in

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reservoirs, density currents, water quality and biological processes.

4. The subsurface phase, involves all processes related to the flow and storage of water below the ground surface, the relationship between input and output, contamination and artificial and natural fill.

In this study, a tank model for prediction of sediment discharge in the watershed was carried out, the analysis refers to the land phase. In the land phase that considers the flow of water above the soil surface, both as runoff and surface runoff, it is important in this study, because runoff flow and runoff cause erosion and sedimentation processes as well as due to rain with an output in the form of sediment discharge. In the land phase, uncontrolled erosion and sedimentation results in decreased soil productivity and damage to water structures and reservoir sedimentation [5]. The process of determining the value of sediment discharge is very difficult because the process of erosion and sediment discharge is quite a complex mechanism. Sediment discharge analysis is usually performed using the Sediment Rating Curve which requires time, money and effort. A number of models or approaches for predicting erosion and sediment discharge have been developed, such as the WEPP model [6], the KINEROS model [7], the ANSWERS model [8], the AGNPS model [9,10] and the SWAT model [11, 12] include analysis of erosion and sediment discharge in watershed areas caused by rainfall and land runoff. Applied the Time-Area method to predict sediment yield with time variations [13]. With a lumped sediment runoff model to analyze sediment flow covering areas on sloping land and in rivers in watersheds [14, 15].

Applied a tank model for sediment yield, with analysis using an arrangement of 3 (three) cascade tanks [16,17]. The weakness of this model is the assumption that the sediment concentration undergoes infiltration, percolation, and this condition is actually unlikely to occur such a process. Research on tank models for predicting sediment discharge in watersheds until 2020 has not been followed up. Sediment discharge analysis based on the rainfall-flow model, namely the tank model by including sediment elements has not been carried out [18]. Based on the description of several existing models, a hydrological model in the form of a tank model can be developed to predict the sediment discharge in the watershed by modifying the arrangement of the tank based on the erosion process and sediment discharge in the watershed area and this has not been done.

There is a significant difference from the results of previous studies with the research offered, that this study represents the process of erosion - sediment discharges in the River Basin in the form of reservoirs that is modifying the tank model developed for prediction of sediment discharge, namely Tank Model 1 with 3 (three) cascade tanks, and Tank Model 2 with 1 (one) tank. Here this study aims to develop a tank model with predictive analysis of sediment discharges in watersheds by modifying tank structures based on erosion and sediment discharge processes in watersheds. Limitation of the study Sediment discharge referred to in this study is the result of erosion caused by rainfall and rainfall runoff in the River Basin (sloping land, grooves, and ditches). The implication of the model development is to provide supporting information, especially to the stakeholders of the watershed management in carrying out sediment discharge monitoring to determine environmental degradation in the watershed and the planning of water structures.

The theoretical basis used to develop a tank model for predicting sediment discharge in a watershed refers to the distribution-based physical lumped method for predicting sediment flow in a watershed, with the concept of including sediment elements in the rain analysis process into a rainfall-runoff.

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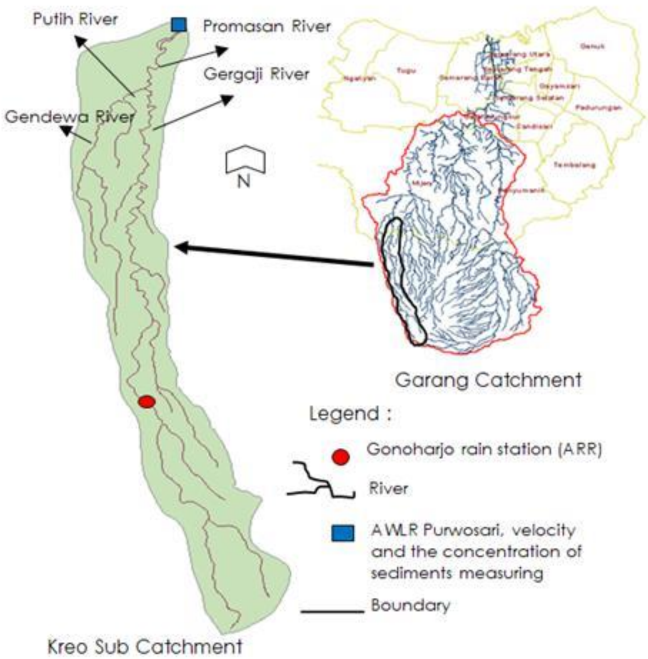

Figure 1 Location of research in Kreo Sub catchment

A. METHODS

The Kreo Sub-watershed is a research location with an area of 1692,812 hectares. This area has a tropical climate which is influenced by the rainy season. The rainy season occurs from November to May and the dry season from June to October. The method in this study is a computational simulation to obtain sediment discharges with optimum tank model parameters, through calibration with measured sediment discharge data on the watershed, to produce the best value of sediment discharge from the model output. Computational simulations are carried out on tank models using the Genetic Algorithm method. Computational simulations for tank models are carried out to analyze the prediction of sediment discharges in the Watershed in the Kreo sub-watershed with model input data in the form of measured rain and measured sediment discharges The steps are setting the field experiment for data retrieval as the model input data, and

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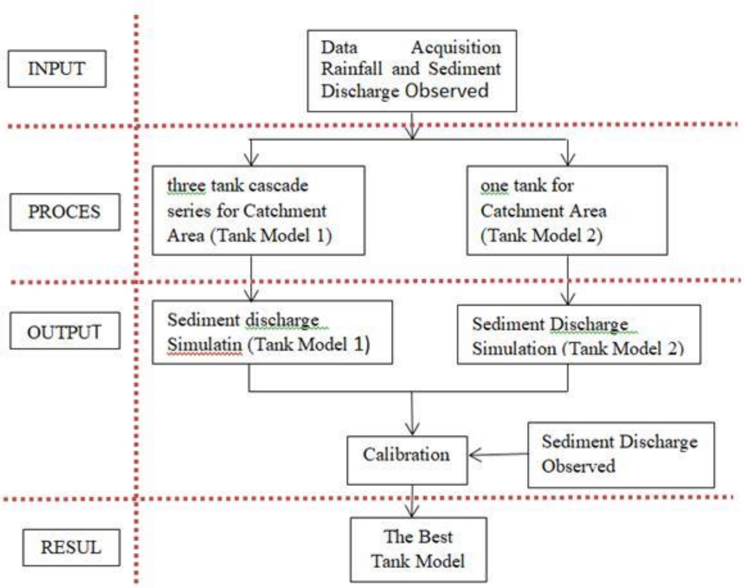

Figure 2. Research steps

Data collection includes rain data Automatic rainfall recorder (ARR) at Sta. Gonoharjo and measured sediment discharge Gunungpati District, Semarang City. The examples of rain data and sediment discharge data that are used as model input data are shown in Table 1.
data at an estimated post or river flow observation station (SPAS) in Purwosari Village

Table 1. Rain data and sediment discharge data

Time (minutes)	0	60	115	125	135	145	210	222	232	242	252
Rainfall (mm)	0	0	0.5	0	1	6.5	7.5	8.5	1.5	1	0.5
Sediment Discharge (ton/day)	3.73	3.49	4.5	4.29	6.68	314.33	526.56	1057.94	227.6	52.76	32.99

Time (minutes)	262	292	352	412	472	482	492	502	512	522	532
Rainfall (mm)	0.5	1.5	0.5	0	0.5	0.5	0	0	0	0	0
Sediment Discharge (ton/day)	22.3	24.3	14	13.2	12.4	11.52	10.17	10.54	6.7	5.16	4.19

There are 2 tank models with the proposed parameters, namely Tank Model 1 (three cascade series tanks), Tank Model 2 (one tank), Figure 3.

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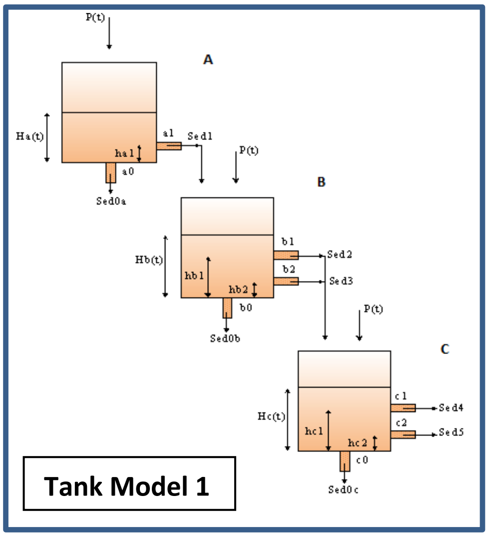

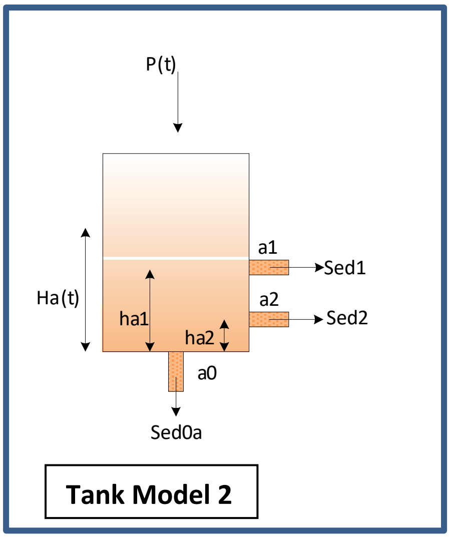

Figure 3. Tank Model Structure with parameters for Prediction Sediment Discharge in Kreo Sub Catchment

where: P(t) is rainfall (mm); Sed_1 (t), Sed_2 (t), Sed_3 (t), Sed_4 (t), Sed_5 (t) is the Sediment Discharge (ton/day); Sed_{0a}, Sed_{0b}, Sed_{0c} is Sediment Discharge deposition (ton/day); Ha(t), Hb (t), Hc(t), is storage height the Sediment Discharge (mm); a_1, a_2, b_1, b_2, c_1, c_2 are parameters model sediment discharge; a_0, b_0, c_0 is the parameters model sediment deposition; ha_1, hb_1, hc_1 is high of upper hole the sediment discharge on a model (mm); ha_2, hb_2, hc_2 is high of bottom hole the sediment discharge on a model (mm).

The process of obtaining sediment discharge is stimulated by the release of soil by rain and surface runoff. The basic assumption of this model is that sediment is transported and generated when surface runoff occurs. Thus, the carrying capacity of the surface flow is estimated to simulate the sediment discharge process. Soil release, sedimentation, and sediment discharge are handled with the equation of sediment flow continuity as in Equation 1 [19, 20, 21].

$$\frac{\partial(h_a C)}{\partial t} + \frac{\partial(q_a C)}{\partial x} = e(x,t) \qquad (1)$$

Where :
C = sediment concentration in the flow (kg/m^3)
h_a = depth of surface flow (m)
q_a = discharge per unit width (m^2/second)
e (x,t) = erosion by rainfall and surface runoff (kg/m^2/hour)

To calculate the sediment discharge from the two tank models using equations 2 through equation 14 which is the development of equation 1

1). Tank Model 1

$Sed_1(t) = [((Ha(t)+P(t)) \times C_h) - ha_1] \times a_1$ (2)
$Sed_2(t) = [(Sed_1(t)+ ((Hb(t)+P(t)) \times C_h)) - hb_1] \times b_1$ (3)
$Sed_3(t) = [(Sed_1(t))+ ((Hb(t)\ P(t)) \times C_h)) - hb_2] \times b_2$ (4)
$Sed_4(t) = [(Sed_2(t)+Sed_3(t)+((Hc(t)+P(t)) \times C_N)) - hc_1] \times c_1$ (5)
$Sed_5(t) = [(Sed_2(t)+Sed_3(t)+((Hc(t)+P(t)) \times C_N)) - hc_2] \times c_2$ (6)
$Sed_{0a}(t) = [(Ha(t)+P(t)) \times C_h] \times a_0$ (7)
$Sed_{0b}(t) = [(Hb(t)+P(t)) \times C_h] \times b_0$ (8)
$Sed_{0c}(t) = [(Hc(t)+P(t)) \times C_N] \times c_0$ (9)
Total sediment discharge on the right side of the tank
$= Sed_{total} = Sed_4(t)+Sed_5(t)$ (10)

2). Tank Model 2

$Sed_1 (t) = [((Ha(t)+P(t)) \times C_h(t)) - ha_1] \times a_1$ (11)
$Sed_2 (t) = [((Ha(t)+P(t)) \times C_h(t)) - ha_2] \times a_2$ (12)
$Sed_{0a} (t) = [(Ha(t)+P(t)) \times C_h(t)] \times a_0$ (13)
Total sediment discharge on the right side of the tank

$= Sed_{total} = Sed_1 (t)+ Sed_2 (t)$ (14)

All of parameters non negatif : $0 < a_0+a_1+a_2 \le 1$; $0 < b_0+b_1+b_2 \le 1$; $0 < c_0+c_1+c_2 \le 1$; $a_1 \ge a_2$; $b_1 \ge b_2$; $c_1 \ge c_2$; $ha_1 \ge ha_2$; $hb_1 \ge hb_2$; $hc_1 \ge hc_2$
To get a tank model for prediction of sediment discharges that represent actual watershed conditions using the research criteria volume error (VE), relative error (RE), correlation coefficient (R) and root mean squares error (RMSE) shown by equations 15 through equation 18, with a limit value of research criteria for VE < 5%, RE -10% to 10%, R > 0.7 and RMSE close to 0. Its formula is as follows:

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$$R=\sqrt{\frac{Dt^2-D^2}{Dt^2}} \tag{15}$$

$$Dt^2=\sum_{i=1}^{N}\left(Sed^i_{obs}-\overline{Sed}\right)^2$$

$$D^2=\sum_{i=1}^{N}\left(Sed^i_{obs}-Sed^i_{sim}\right)$$

$$VE=\frac{\sum_{i=1}^{N}Sed^i_{obs}-\sum_{i=1}^{N}Sed^i_{sim}}{\sum_{i=1}^{N}Sed^i_{obs}}\,x\,100 \tag{16}$$

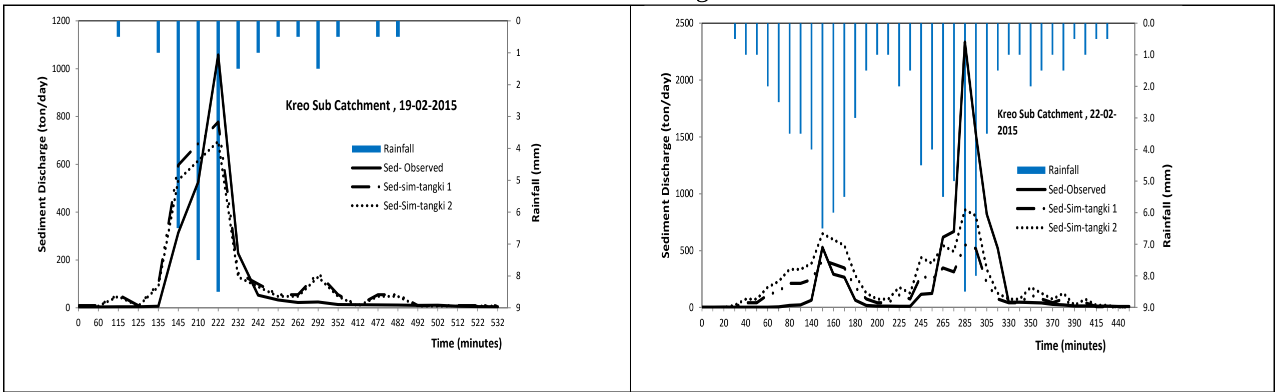
$$RE=\frac{1}{N}\sum_{i=1}^{N}\frac{\left|Sed^i_{sim}-Sed^i_{obs}\right|}{Sed^i_{obs}} \tag{17}$$

$$RMSE=\sqrt{\frac{\left(\sum Sed^i_{sim}-Sed^i_{obs}\right)^2}{N}} \tag{18}$$

where: VE is volume error [%]; RE is relative error [%]; R is correlation coefficient; RMSE is the root mean squares error; Sed_{sim} is the production of surface erosion simulation period-i [t/d]; Sed_{obs} is the production of surface erosion measurable period-i [t/d]; N is the number of data; is average of the production of surface erosion simulation period-i [t/d]; $\overline{Sed^i_{obs}}$ is the average of surface erosion production measurable period-i [t/d].

3. Results and discussion

The results of the simulation of 2 tank models (Figure 3) for prediction of sediment discharge in the Kreo sub-watershed based on rain input data and sediment discharge data (Table 1), on February 19, 2015, and February 22, 2015, is shown in Figure 4:



(a)　　(b)

Figure 4. Calibration Results of Observation and Simulation Sediment Discharge using 2 Tank Models in Kreo Sub-watershed on (a) 19 February 2015, (b) 22 February 2015 Calibration results of parameters using 2 tank models are shown in Table 2

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Table 2 Parameter 2 tank models

Parameters	February 19, 2015		February 22, 2015	
	Tank Model 1	Tank Model 2	Tank Model 1	Tank Model 2
a0	0,010	0,056	0,365	0,322
a1	0,0195	0,345	0,319	0,651
a2		0,057		0,018
b0	0,019		0,023	
b1	0,582		0,533	
b2	0,199		0,118	
c0	0,093		0,029	
c1	0,364		0,629	
c2	0,211		0,173	
ha1	0,849	56,124	0,553	55,639
ha2		0,634		0,136
hb1	42,94		49,604	
hb2	0,294		0,008	
hc1	41,046		50,582	
hc2	0,021		0,232	

The value of the research criteria for the calibration results of the two tank models to show an accurate tank model is shown in Table 3.

Table 3 Value Criteria Accuracy of the two tank models

Rainfall	**Correlation Coefisien (R)**		**RMSE**		**Relatif Error (RE)**		**Volume Error (VE)**	
	Tank Model 1	Tank Model 2	Tank Model 1	Tank Model 2	Tank Model 1	Tank Model 2	Tank Model 1	Tank Model 2
19/02/2015	0,91	0,91	101,38	100,47	239,31	197,45	25,20	11,11
22/02/2015	0,75	0,75	347,85	317,78	657,46	934,31	24,17	6,25

The results showed that the tank model 2 is better than the tank model 1. This is evidenced by the results of the calibration using the parameter values in Table 2, with the sediment discharge values and the accuracy criteria values are shown in Figure 4 (a), (b) and Table 3. The calibration results on the two tank models show that tank model 2 is less representative of the actual watershed conditions.

The results of the analysis of the tank model for prediction of sediment discharge, the rising limb value of the simulation sediment discharge is greater than the measured sediment discharge value, and and peak value of the simulation sediment discharge is lower than the measured sediment discharge value, this rainfall tends to be high, of course, the amount of surface flow increases so that the output value of sediment discharge in the tank model becomes lower (Figure 4 (a) and 4(b)) and recession limb simulation sediment discharge value decreases, this is because rainfall tends to decrease and surface flow also decreases so that the output value of sediment discharge in the tank model becomes small. Except for Figure 4 (b) there may be a disturbance upstream of the tentative measurement, the measured sediment discharge value is greater than the simulated sediment discharge value. Another cause is the pattern of rainfall distribution in the hydrological process, synchronization of the measurement process, and the length of the data and the possible assumptions of the model parameters.

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4. CONCLUSION

By representing the process of erosion - sediment discharges in watershed, the two tank models can be used for prediction of sediment discharges: Tank Model 1 with 3 (three) cascade tanks, and Tank Model 2 with 1 (one) tank. The arrangement or configuration of the tank model that provides predictive results of sediment discharges close to the measured sediment discharge is Tank Model 2, composed of 1 (one) tank consisting of 2 (two) side holes, a representation of the output size of the sediment discharge and 1 (one) lower hole, a representation of the amount of sediment deposits. But it still has a different range for sediment discharge values. This is possible because the factors are the pattern of rainfall distribution in the hydrological process, synchronizing the measurement process and the length of the data as well as the possible assumptions of the model parameters.

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