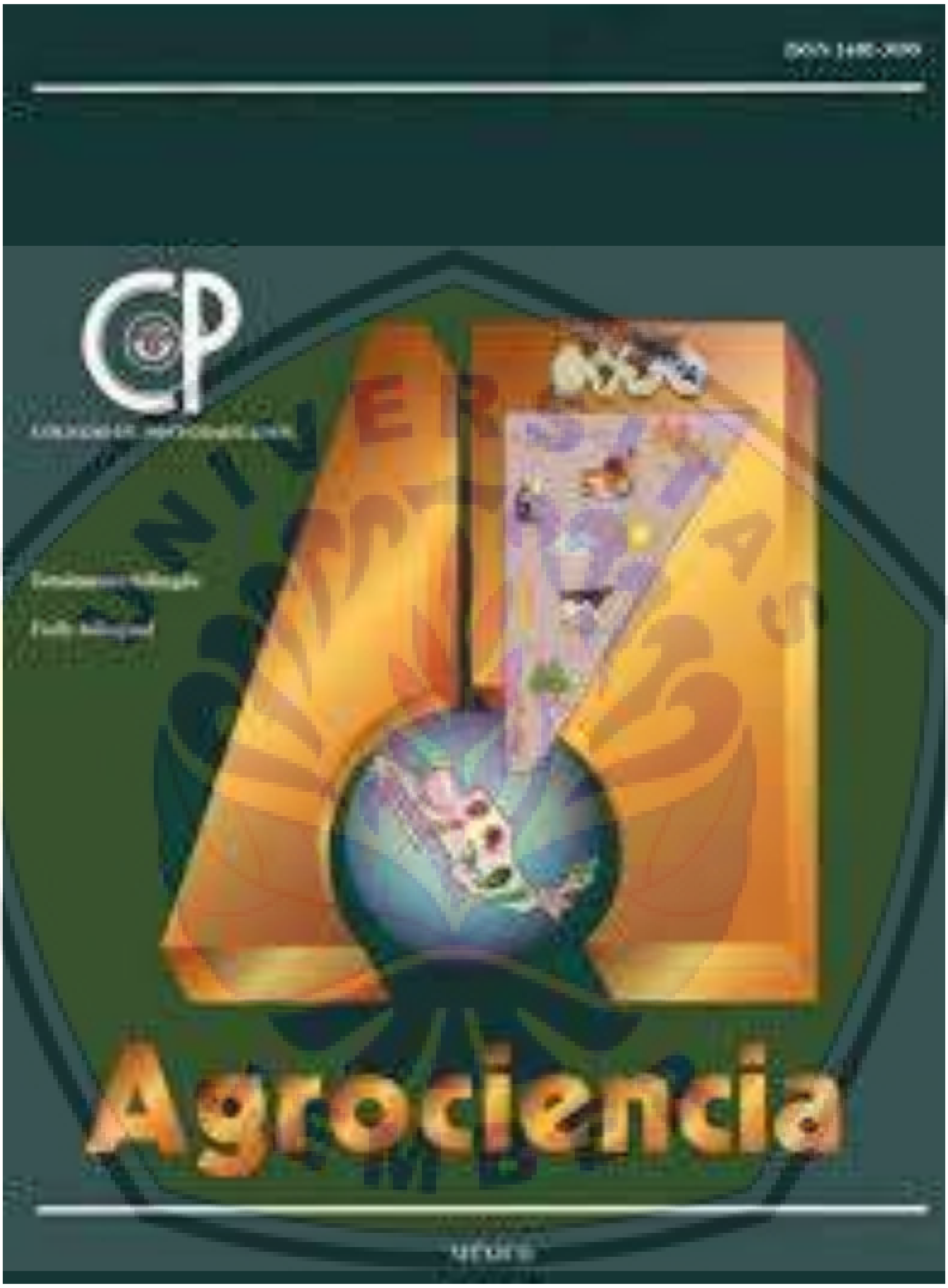
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Modelling Discharge, Erosion and Sedimentation at Small Watershed in East Java

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ABSTRACT

The land-use change due to human activities and agricultural practices propagate the intensity of hydro-meteorological related disaster (erosion, sedimentation, landslide). Therefore floods and landslides are frequently occurring at Sanenrejo Watershed (±292 km^2). In this paper, the SWAT (Soil and Water Assessment Tool) model used to evaluate the hydrological processes. The Digital Elevation Model use as the primary input for deriving topographic and physical properties of the watershed. Other input data used for the modelling processes include the soil layer, land-use layer, discharge and climate variables. All of these data are integrated into SWAT to calculate discharge, erosion and sedimentation processes. The existing observed discharge used to calibrate the SWAT output at the watershed outlet. The calibration results obtained an NSE and R^2 of 0.62 (satisfactory) and 0.75 (good). NSE validation of 0.5 (satisfactory). This parameter indicates a good model performance to describe the hydrological process in the Sanenrejo watershed. The SWAT than used for the prediction of erosion and sedimentation processes on the watershed.

Keywords: SWAT, Erosion, Sedimentation, Sanenrejo.

INTRODUCTION

Land degradation due to soil erosion and sedimentations are become serious problem in various Asian countries, for example in Vietnam (Phuong *et al*., 2012) in Thailand (Wijitkosum, 2016), in India (Bhattacharyya *et al*., 2015) and China (Li and Liu, 2014; Ouyang *et al.,* 2018). The trigger factors for these phenomena are changes in land-uses. Then, intensive agricultural-activities also accelerate the phenomena(Phuong *et al*., 2012; Sharma *et al*., 2011; and Wijitkosum, 2016). Similarly in Indonesia, research conducted by Widiriani *et al*. (2009), Sutrisna *et al*. (2010), Suyana & Muliawati (2014) also show that the primary cause of erosion is agricultural activities. The same phenomenon observed in many watersheds in Indonesia. USDA Forest Service (USDA Forest Service, 2009), states that the main factors affect erosion and sedimentation are local weather patterns, topography, vegetation, and soil types.

Some models developed to predict erosion and sedimentations. The first model used is USLE or Universal Soil Loss Equation, initiated by Wischmeier and Smith (1978). Then, the SEDD model that means Sediment Delivery Distributed model as proposed by Bhattarai and Dutta (2008) adopt the main-principle of USLE. Furthermore, RUSLE or Revised-USLE, also use the principle of USLE (Renard *et al*., 1991). Similarly, the MUSLE or Modified Universal Soil Loss Equation (Sadeghi *et al*.,2014) is still used USLE as the main idea for modelling philosophy. Furthers model has also developed such as WEPP or Water Erosion Prediction Project (Ampofo et al., 2002) and SWAT (Soil And Water Assessment Tool) as published by Arnold *et al.* (1993). Moreover, the SWIM (Soil and Water Integrated) model published by Krysanova *et al.* (2015), WATEM or SEDEM as published by Bezak *et al.* (2015) and SEDNET described by Hughes and

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Croke (2011) have contributed to the development of modelling tool for erosion and sedimentation.

The USLE method calculates the erosion rate by multiplying the factors that affect erosion such as rainfall erosivity, soil erodibility, slope-length and slope, as well as vegetation and conservation factors. The MUSLE calculate the erosion rate using a similar principle of USLE and estimate the sedimentation process using an empirical equation adjusted to USLE. The WATEM/SEDEM design as spatially distributed soil erosion and sediment delivery model (Quijano *et al.*, 2016; Pal and Galelli, 2019).

The SWAT model (Krysanova and Arnold, 2008; Xu and Peng, 2013) has a more comprehensive equation and features able to calculate the discharge, erosion, sediment and nutrient (N, P) related to hydrological processes. The spatial unit of calculation set to an HRU (Hydrological Response Unit) rather than pixels. The SWAT proposed more flexible calculation and flexible to the data availability. The SWAT model also offers attractive Graphical Unit Interface (GUI), free-open-source software, multi-platform and compatible with many GIS (Geographical Information System) platforms. The SWAT model has become more popular than others and applied all over the world.

In Indonesia, the widely used methods are USLE (Wischmeier & Smith, 1978), RUSLE (Renard *et al.* .,1991), MUSLE (Sadeghi And Mizuyama, 2007) and SWAT (*Soil and Water Assessment Tool*) (Arnold *et al.*, 1993; Krysanova and Arnold, 2008; Memarian *et al.*,2014). These three models can predict erosion and sediment quite well (Hajigholizadeh *et al.*, 2018).

METHODS

Study site, input data and tools

This research conducted at the Sanenrejo Watershed (Figure 1).

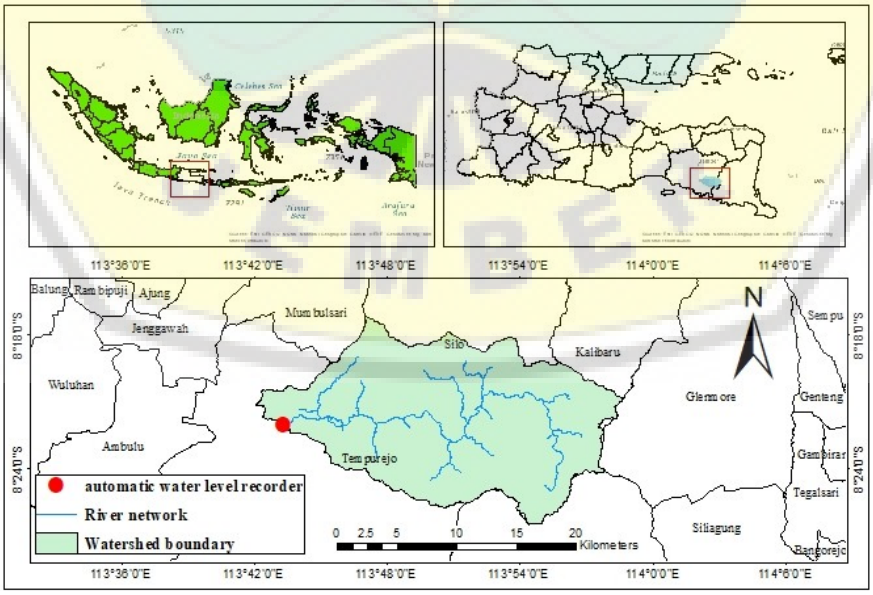

Figure 1. Study Area: the Sanenrejo Watershed

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Sanenrejo is one of the small watershed (±292 km^2) and located in the eastern part of East Java. The watershed has a significant potential of a hydro-meteorological disaster such as erosion, sedimentation (Figure 2), flooding and landslides (Kabupaten Jember, 2009).

(a) River condition (b) Landslide event

Figure 2. River "Kalisanen" Condition at Sanenrejo Waterhsed.

The phenomena are proved by flood events that frequently occur in Tempurejo and its surroundings. Tempurejo is a small city (at district level) at the middle of the watershed areas. These hydro-meteorological disasters are supposed due to land conversion to agriculture in the upstream areas (Pradana *et al.,* 2018). Therefore, the assessment of erosion and sediment are necessary for the management of water and land resources.

This study aims to apply SWAT *(Soil and Water Assessment Tool)* to calculate the discharge, the rate of erosion and sedimentation at the watersheds. The future scenario of water and land resources conservation activities on the watershed may be proposed through the interpretation of modelling model results if the calibration and validation processes of this model successfully conducted on this watershed.

The primary input data for this study is DEM (*Digital elevation model*) derived from DEMNAS. The DEMNAS is Digital Elevation Model at National Scale provided by the Indonesian Agency of Geospatial Information or *Badan Informasi Geospatial* (BIG). The DEMNAS has spatial resolution 8.3m x 8.3m, and it is sufficiently excellent for watershed study. The DEMNAS is accessible for free download through its official website, i.e., http://tides.big.go.id/DEMNAS/Jawa.php. In this case, the DEMNAS use to determine the watershed boundary and river network (Figure 3). Figure 3a shows the variation of altitude on the watershed. The altitude varies from 21 to 1194 m above sea level. The detailed slope map (in Figure 3b) also derived from the clipped DEMNAS.

In the previous study, Sujarwo et al. (2019) have derived some morphometric parameters based on the DEMNAS for small watersheds in East Java. Some morphometric parameters obtained for Sanenrejo includes: perimeter (94 km), total stream length (285 km), stream order (5), bifurcation ratio (1.82), Mean stream length (0.89), stream length ratio (1.16), stream length ratio (1.16), infiltration index (1.15), basin relief (1.17), relief ratio (0.03), ruggedness number (1.15), drainage density (0.98), stream frequency (1.17), texture ratio (1.84), form factor (0.24), circulation ratio (0.13), elongation ratio (0.65), length of overland flow (0.51), constant channel maintenance (1.02), and compactness constant (0.19) .

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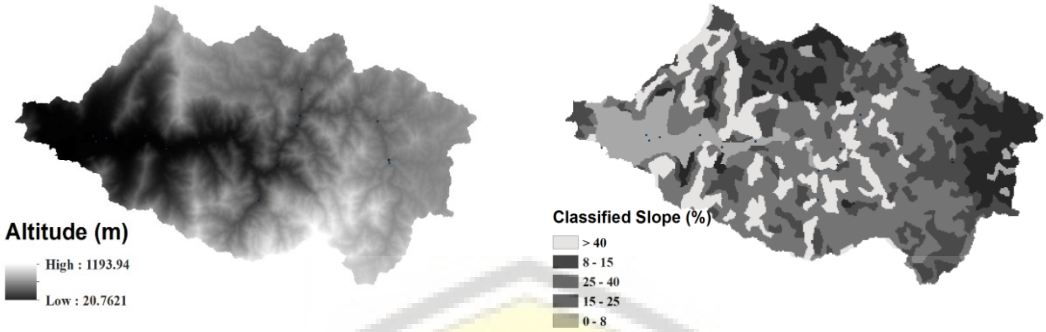
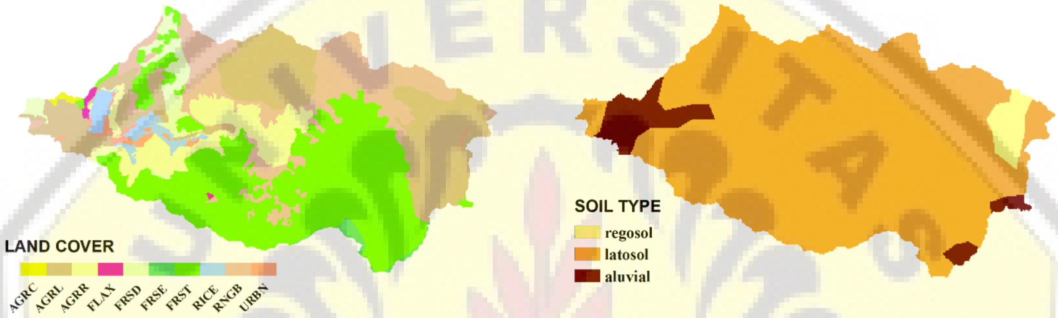


(c) Altitude (m) (d) Slope (%)



(c) Land cover (d) soil type

Figure 3. Input for SWAT Model

Then, Land cover map (Figure 3c) clipped with the watershed boundary to calculate the composition of land cover or land-use on the watershed. The major land-occupations are: Agriculture of Mixed Shrubs Dry Land 0.26% (AGRC), Plantation 25.47%(AGRL), Dryland Agriculture 9.67% (AGRR), land clearing 0.3% (FLAX), Planted forests 3.6%(FRSD), Primary Dryland Forest 0.82% (FRSE), Secondary Dryland Forest 38.51%(FRST), Rice 2.42% (RICE), Shrubs 17.88% (RNGB), and Settlement 1.07% (URBN). Furthermore, the soil map layer from the Soil Research Institute (1966) is digitised and clipped with the watershed boundary to obtain soil type composition of the watershed (Figure 3d). The watershed composed of alluvial (6.21%), latosol (90.99%), and regosol (2.8%).

The hydro-meteorological (rainfall and discharge) data obtained from public offices of the water management and watershed authorities. The meteorological or climate variable data (i.e., rainfall, temperature, solar radiation, wind speed and humidity) obtained from the near-by climatological station located at Kalibaru-Banyuwangi (about 20 km from study site). The meteorological data also collected from the website of Meteorological Agencies (BMKG Online).

Rainfall data also obtained from 3 measurement stations (Sanenrejo, Tempurejo, Pagar Gunung). The recording period for all the climate variables ranges from 2006 to 2017 (12 years). The discharge data obtained from existing AWLR (Automatic Water Level Recorder) located on the outlet of this watershed. Figure (3) show the plot of monthly discharge and rainfall data (2006-2017).

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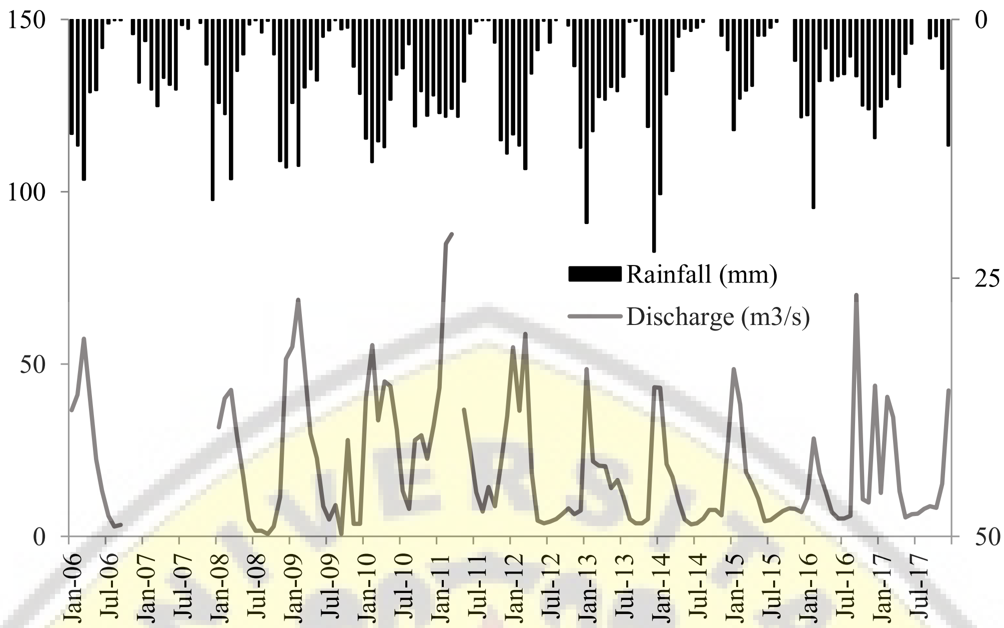

Figure 4. Discharge and rainfall (2006-2017)

Table 1 summary the water balance at sanenrejo watersheds as calculated using the SWAT model. Annual Flow Coefficient is the ratio between the highest annual flow (Q, mm) and the highest of annual rainfall (P, mm) in the watershed (Menteri Kehutanan Republik Indonesia, 2014).

Table 1. Water balance

Parameters	Value
Rainfall (mm)	1672,2
Surface runoff (mm)	340,9
Lateral flow (mm)	316,9
Groundwater (mm)	153,3
Water yield (mm)	778,2
Sediment yield (t/ha)	66,6
Qmaks (m^3)	111,4
Qa (m^3)	7,0
Annual flow coefficient	0,4
Flow Regime Coefficient	15.8
Category	High

The annual flow coefficient is closely related to the flow regime coefficient. Annual flow coefficient value shows that a large portion of rainfall converted to flow. The storage capacity of the watershed is quite low because the topography of the area is mostly steepest and conversion of land-use from forests to agriculture and settlements. Flow regime coefficient is the ratio between maximum discharge (Qmax) and average discharge (Qa) in a watershed (Menteri Kehutanan Republik Indonesia, 2014). The high value of flow-regime coefficient indicates the watershed that subject to the higher value of runoff during the rainy season. The flood discharge frequently occurs. Contrary, in the dry seasons, the watershed subject to minimize runoff. In other words, this condition shows the watershed that less storage capacity. The watershed is prone to water deficit or drought risk. Finally, Table 2 presents all data used as input for the modelling process.

Table 2. Description of model input

Data Type	Source	description
DEM (Digital elevation model)	Geospatial Information Agency of Indonesia http://tides.big.go.id/DEMNAS/Jawa.php	Resolution 8,3 m
Digital map of soil	Soil Research Institute, 1998 Bogor, Indonesia	Scale 1:250.000
land use/land cover	Directorate general of forestry	Scale 1:250.000 (satellite image)
Climate /meteorological	Badan Meteorology dan Klimatologi Geofisika Banyuwangi	2006-2017 (12 years)
Rainfall	Sanenrejo, Tempurejo, Pagar Gunung Stations.	2006-2017 (12 years)

The processing and analysis conducted at the Laboratory of Environmental Control and Conservation (*Laboratorium Teknik Pegendalian dan Konservasi Lingkungan*) - Faculty of Agricultural Technology – The University of Jember. The analysis conducted using ArcSWAT (2012), Excel and GIS software. GIS used to visualise the spatial maps and running the SWAT program.

Procedure

Create a model SWAT

The USDA Agricultural Research Service develops the SWAT model. The model is semi-distributed. Some parameters spatialized, while others are determined globally (lumped). SWAT used to analyze the impacts of climate, soil, vegetation and agricultural activities on the river flows. The erosion is estimated using the Modified Universal Soil Loss Equation (MUSLE) method, as published by Neitsch et al. (2011).

The hydrological cycle simulated by SWAT model based on the water balance (eq. 1):

$$SWt = SW0 + \sum_{i=1}^{i=t}(Rday - Qsurf - Ea - Wperc - Qgw) \qquad \text{eq.1}$$

where :

*SW*t, *SW*0 are respectively, final and initial soil water content (mm/d);
t is the time (day);
*R*day is the precipitation (mm/d);
*Q*surf is the runoff (mm/d);
Ea is the evapotranspiration (mm/d);
*W*perc is the percolation (mm/d);
*Q*gw is thereturn flow (mm/d).

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The SWAT model developed from the SCS (Soil Conservation Service) hydrological model. The SCS model created firstly by the United States Department of Agriculture. The output of the SCS model is the discharge or runoff in the watershed. The SCS hydrological model determined by rainfall and land characteristics. Land characteristics calculated by the CN value (curve number) ranging from 0 to 100. The CN value determined by land cover and HSG (Hydrologic Soil Group). The dense land-cover (such as a forest) will produce small the CN number and less overland flow values. The higher the value of CN, the higher the surface flow produced. The more coarse the soil-texture will produce less surface flow and vice versa (Zhang *et al*., 2019).

The necessary inputs information in the SWAT model is digital elevation model (DEMNAS), land cover, soil characteristics, climate variables (rainfall, temperature, solar radiation, relative wind speed and humidity), and land-management. All input data formatted in raster. The general procedure of the modelling task consists of (1) HRU Processes, (2) Climate Input, (3) Running Model.

1. HRU Process

The HRU concept is a requirement for dynamically analyzing and modelling hydrology from various structures into homogeneous structures based on their interactions with soil type, geology and cover crop (Pignotti *et al*., 2017). The HRU process starts from the watershed delineation to obtain watershed boundaries, determines the river network, determines river outlets using DEM Raster and then inputs HRU data on land use maps, soil type maps, and determines slope classes. The HRU describe the similarity of hydrological characteristics resulting in more accurate erosion values. SWAT model will distribute hydrological flow to each HRU based on elevation and river network. Each HRU will produce one hydrological value and distributed to other HRUs based on the characteristics of land cover, soil and slope (Pignotti *et al*., 2017).

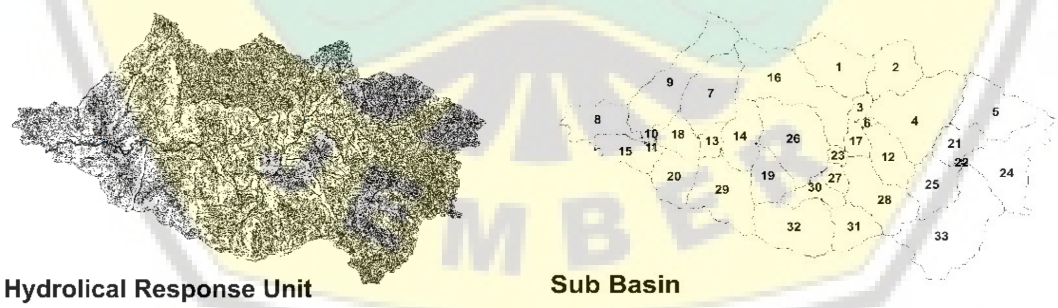

Figure 5. HRU and Sub Basin Result

2. Climate input

The data input requested by the SWAT is the climatological station's coordinate point and daily climates variables (i.e., rainfall, maximum and minimum temperature, average humidity, the intensity of solar radiation, and wind speed). The climate variables are formatted and then enter to the GUI (Graphical User Interface). Table 3 summary the parameter determined for modelling processes.

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Table 3. Details of the Input model

No	Land Cover	SWAT Code	CP	Area (ha)	Percentage (%)
1	Primary Dry land Forest	FRSE	0.001	241.66	0.82
2	Secondary Dry land Forest	FRST	0.005	11325.05	38.51
3	Planted forests	FRSD	0.005	1057.42	3.6
4	Settlement	URBN	1	315.69	1.07
5	Plantation	AGRL	0.3	7490.64	25.47
6	Dry land Agriculture	AGRR	0.02	2843.01	9.67
7	Agriculture of Mixed Shrubs Dry Land	AGRC	0.02	76.17	0.26
8	Rice	RICE	0.028	712.8	2.42
9	Shrubs	RNGB	0.3	5259.32	17.88
10	clearing	FLAX	0.4	88.32	0.3

No	Soil Type	SWAT Code	K	Area (ha)	Percentage (%)
1	alluvial	NINIGRET	0.16	1826.6	6.21
2	latosol	ENCHANTED	0.28	26761.16	90.99
3	regosol	DEERFIELD	0.29	822.33	2.8

No	Slope	Area (ha)	Percentage (%)
1	0 - 8%	2485.71	8.45
2	8 - 15%	3748.35	12.75
3	15 - 25%	7390.17	25.13
4	25 - 40%	11625.81	39.53
5	> 40%	4160.05	14.14

3. Running the SWAT Model

The running model starts with the setup process to determine the simulation period. In this model, the simulation period is set on a monthly and annual basis, starting from 2006-2017, depending on the climate data input period. Then running the SWAT model trough the GUI. After the model has been run-out, then read the simulation results by determining the required outputs such as (HRU: USLE, SYLD) to show erosion and sediment model and (RCH: FLOW_OUT) to show discharge on sub-basin scale in m^3/s.

Calibration and Validation

The calibration and validation of the model using only discharge data because of the limited availability of measured hydrological data on the watershed. In this study, some considerations used for calibration and validation processes.

a. Sensitive parameters determined from previous research results. According to

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Arnold et al. (2012), some parameters are sensitive to the change in surface runoff such as CN2, AWC, ESCO, EPCO, SURLAG, and OV_N. Others parameters are sensitive to the change in base-flow (i.e., GW_ALPHA, GW_REVAP, GW_DELAY, GW_QWN, REVAPMN, RCHARG_DP). According to Wahdani (2011), nine parameters should be adjusted to approach the discharge value, i.e., OV_N, CN2, SOL_AWC, SOL_K, GW_DELAY, ESCO, ALPHA_BF, CH_K2.

b. Some parameters are sensitive to the discharge of the watershed. If there is a change in discharge from the model output, then the parameter is used for the process of discharge optimization. Some sensitive parameter values change by adjusting to natural conditions in the watershed such as CH_N2 (Manning coefficient on the main channel), CH_K2 (hydraulic conductivity on the main alluvium channel and others). Then proceed with the trial and error to find the best value of parameters.

c. Two well-known statistical tests usually used in hydrology (i.e., coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) to compare the accuracy of modelling processes. The value of R^2 describes the distribution of observed and calculated. The higher value of R^2 indicates a low error. Value R^2 = 0, means there is no correlation, whereas if R^2 = 1 means that the distribution of calculated and observed value is similar. Moriasi et al. (2007) revealed that the range of NSE values lies between $-\infty$ to 1, NSE = 1 is the optimal value. NSE values between 0.0 and 1.0 are generally seen as acceptable levels of model performance, while NSE $\leq$ 0.0 indicates that model performance is unacceptable.

RESULT AND DISCUSSION

CALIBRATION

The calibration process uses 2014 data (Figure 6), and validation uses data in the year 2015. Several studies such as those conducted by Susanto (2015); Surahman (2016); and Hutomo (2017) assumed that daily data for one year is sufficient to represent and to calibrate the SWAT model.

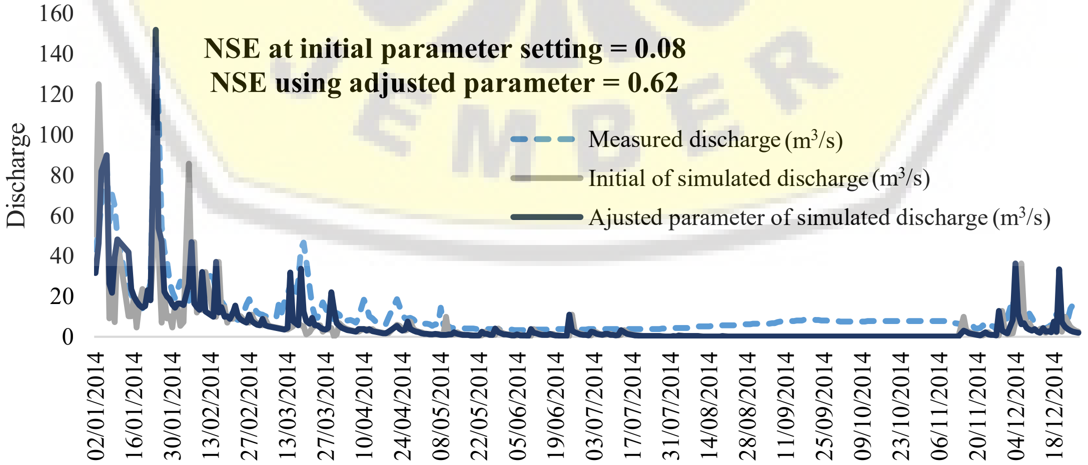

Figure 6. Calibration result.

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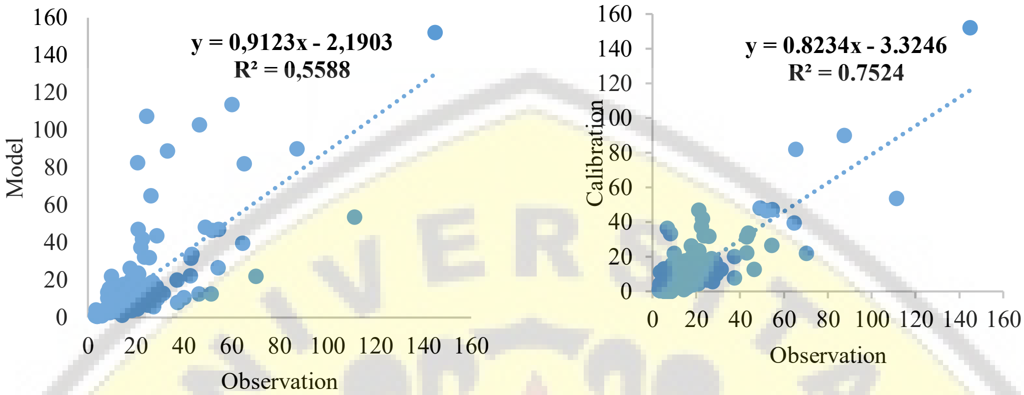
The NSE and R^2 calculated using the initial parameter setting show the value of NSE = 0.08, and $R^2 = 0.56$ (Figure 6). The calibration process conducted by changing the value of sensitive parameters such as CN2, CH_K2, CH_N2, ESCO, EPCO, ALPHA_BNK, GW_DELAY, ALPHA_BF, by trial and error until the results better than the previous initial setting. The adjustment of sensitive parameter done an increase in R^2 until 0.75 and NSE = 0.62 (Figure 6 & 7).



(a) R^2 using the initial value

(b) R^2 using adjusted value

Figure 7. Comparing of R^2 Calibration.

The CN2 parameter is the SCS curve number. The CN2 refers to the land use and soil hydrology group (Hydrology Soil Group). CN2 optimised by changing the CN value according to the land cover and soil hydrology (Neitsch *et al.*, 2011). The CH_N2 parameter is the value of the manning's coefficient of the main-channel. It is adjusted to the condition in the field. The main river in the Sanenrejo watershed is still natural and dominated by grasses, trees and rocks around the canal. Therefore the value is adjusted to 0.014 (refer to the manning table).

The CH_K2 parameter represents the value of hydraulic conductivity in the main channel. The river flow classified into four class based on the interaction between the river flow and the ground-water system (Munggaran, 2017). In this case, the initial value of CH_K2 = 0, and the adjusted value by trial and error = 7. This value illustrates that the condition of water loss in the alluvium channel is quite low. The bed material characterised by a mixture of gravel, sand and high silt-clay content (J.G. Arnold *et al.*, 2012).

The ESCO parameter is the coefficient of water requirements taken from the lowest soil layer for the evaporation process. The ESCO parameter value adjusted from 0.95 (initial) to 0.65 (final adjusted). The EPCO parameter represents the amount of water required for transpiration and the amount of water available in the soil. The value adjusted from 1 to 0.75. ALPHA_BNK or alpha baseflow factor for 'bank storage' is a parameter that contributes to the flow of the main channel or channel in the sub-basin. The ALPHA_BNK value used is 0.56.

The GW_DELAY parameter represents the time interval required for water to flow from the soil profile to the saturation zone. The value adjusted from 31 (initial) to 22. The GWQMN describe the water depth threshold in shallow aquifers. Groundwater flow to the river can occur if the depth of the water in shallow aquifers is equal to or greater than (>=) the GWQMN. The initial value = 0 and adjusted to 200 mm. The ALPHA_BF parameter is a land-surface response index that describes the groundwater response to the changes inflow.

The ALPHA_BF index varies from 0.1 to 0.3 for land-surface having a low response to flow, from 0.3 to 0.9 for a reasonable response, and an interval of 0.9-1 for the quick response. The ALPHA_BF value adjusted from 0.048 to 0.8. It describes the reasonable response of the watershed to the change in groundwater flow. The calibration results show an increase of the NSE to 0.63 and R^2 to 0.75. NSE values> 0.5 and R^2> 0.6 in the SWAT model show that the model is quite useful in simulating the hydrological process of the watershed (Santhi *et al.*, 2001; Munggaran, 2017).

VALIDATION

The validation uses data starts from January 1 to December 2015 (Figure 8). The validation results show that the performance of the model still performs (NSE = 0.5 and R^2 = 0.632). This value is still acceptable, and the model can be applied to assess erosion and sedimentation in the Sanenrejo sub-watershed.

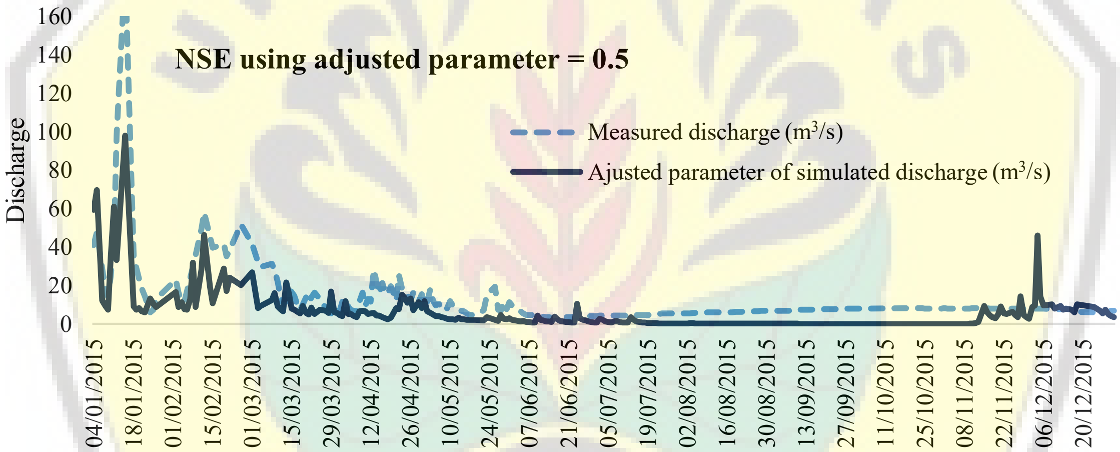


Figure 8. Validation Result

ASSESSMENT OF EROSION AND SEDIMENT

The SWAT shows a significant effect of rainfall on sediment yield. The higher the rainfall, the greater the discharge produced. The effect of land-use changes interferes with the infiltration process, therefore the water carrying sediment into streams. The erosion calculated based on the HRU scale. 76.5% of the watershed area classified as slight and very-slight erosion rate. Only 5% of the area classified in the severe erosion rate.

In the middle stream area, the erosion classified as a moderate or severe class. This middle area has contributed to an increase in discharge and sedimentation in the downstream areas (Figure 9). The highest erosion finds in HRU 402 = 396.34 tons/ha/year in the middle-stream area. The plantations, dry-land agriculture, mixed dry-land agriculture in slopes areas (of more than 40%) contribute to the erosion and sedimentation in the middle areas. The area converted from forest to agricultural.

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Conservation program to reduce sedimentation and hydrometeorological disasters is necessary for this area.

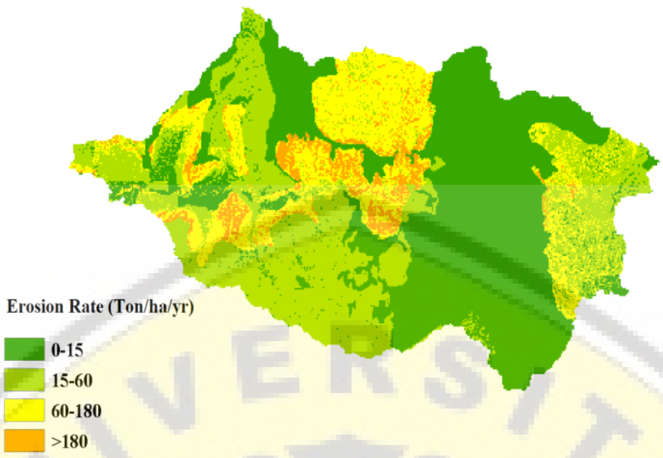

Figure 9. Distribution of erosion SWAT at 2017

Table 4. Value of erosion SWAT and USLE at 2017

Erosion rate (ton/ha/yr)	SWAT		Category
	Area (Ha)	Area (%)	
0-15	12,557.7	44.01	Very slight
15-60	9,298.2	32.59	Slight
60-180	5,175.6	18.14	Moderate
180-480	1,495.9	5.24	Severe
>480			Very severe

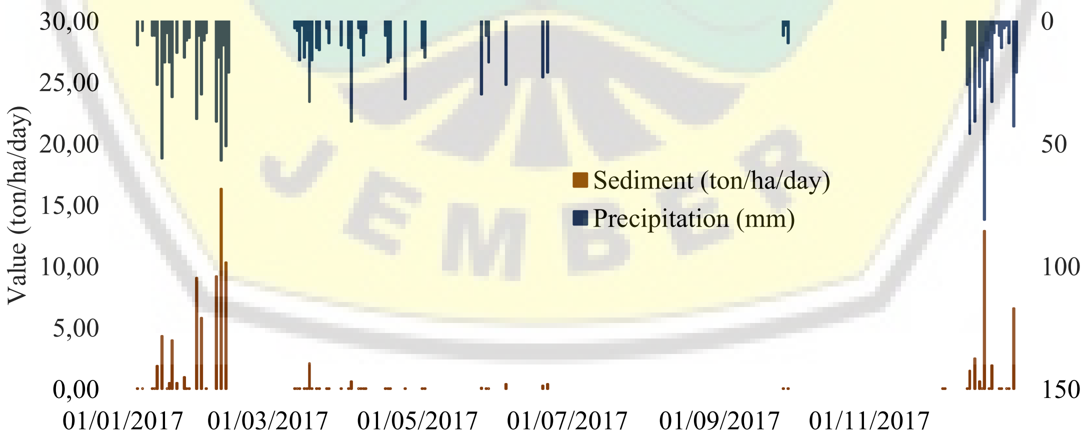

Figure 10. Sediment Outlet SWAT

The sedimentation value at the watershed outlet is quite small. It is less than 3 tons/ha/month. In general, the sediment rate increases during the wet season, from

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October to April, because rainfall significantly affects erosion and sedimentation (Figure 10).

Average sediment yield is higher than ten metric tons per ha in watersheds. It is very high for the average watershed sediment. The maximum sediment yield of more than 50 metric tons per hectare found in HRU 610 (Sub-basin 26). This area covered by dry-land agriculture vegetation and regosol soil.

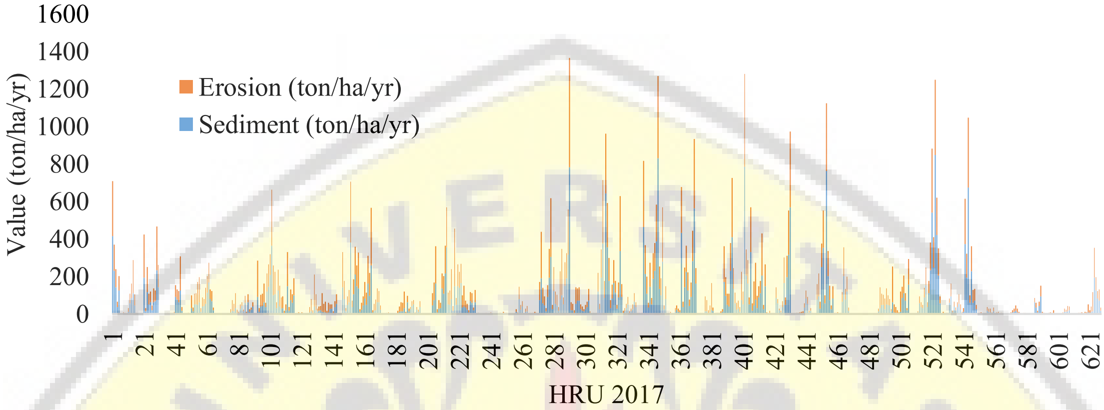

Figure 11. Sediment and erosion value of HRU SWAT

Figure 11 shows that more than 50% of erosion converted to sediment. It indicated that the erosion in the watershed determines the quality of the river flow. The slope and valley area of the watershed accelerate sediment deposit. The middle-stream and down-stream of the Kalisanen river are surrounded by the formation of hilly and valley areas.

CONCLUSION

Calibration analysis produces NSE and R^2 values of 0.62 (satisfactory) and 0.75 (good) then validation of 0.5 (satisfactory) and 0.63 (good), therefore the SWAT model can simulate erosion and sedimentation in the Sanenrejo watershed. The middle stream area produces the highest erosion and causes sedimentation and hydrometeorological disasters in the downstream area.

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