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Modelling erosion and sedimentation in a small watershed, East Java, Indonesia

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Abstract: Changes in land use as a result of human activities may generate the alteration of hydrometeorological disasters. Erosion, sedimentation, floods and landslides frequently occur in the Sanenrejo watershed (±292 km^2), located in East Java, Indonesia. In this paper, the soil and water assessment tool (SWAT) model is used to evaluate the hydrological processes in this small watershed. The digital elevation model (DEM) is used as the primary input for deriving the topographic and physical properties of the watershed. Other input data used for the modelling processes include soil type, land use, observed discharge data and climate variables. These data are integrated into the SWAT to calculate discharge, erosion and sedimentation processes. The existing observed discharge data used to calibrate the SWAT output at the watershed outlet. The calibration results produce Nash–Sutcliffe efficiency (*NSE*) of 0.62 and determination coefficient (R^2) of 0.75, then the validation result of 0.5 (*NSE*) and 0.63 (R^2). The middle area faced the highest erosion and sedimentation that potentially contribute to hydrometeorological disasters.

Keywords: discharge, erosion, modelling, Sanenrejo watershed, sedimentation, SWAT

INTRODUCTION

Land degradation resulting from soil erosion and sedimentation is a severe problem in Asian countries such as Vietnam [Ngo *et al.* 2015], Thailand [Wijitkosum 2016], India [Bhattacharyya *et al.* 2015] and China [Li *et al.* 2014; Ouyang *et al.* 2018]. One of the trigger factors for these phenomena is the change in land use or land cover. Intensive agricultural activities also accelerate the processes [Sharma *et al.* 2011; Wijitkosum 2016]. In Indonesia, research conducted by Sutrisna *et al.* [2010]. Suyana and Muliawati [2014] show that the primary cause of erosion is agricultural activities, and similar phenomena are observed in many watersheds across the country. The USDA Forest Service [FS 2009] states that the main factors affecting erosion and sedimentation are local weather patterns, topography, vegetation and soil type.

Several models have been developed to predict erosion and sedimentation, including the universal soil loss equation (USLE), or USLE, developed by Wischmeier and Smith [1978], and the sediment delivery distributed model as proposed by Bhattarai and Dutta [2008], which adopted the main principles of USLE. The revised-USLE (RUSLE) model also uses the principles of USLE [Renard *et al.* 1991], and the modified universal soil loss equation (MUSCLE) [Sadeghi *et al.* 2014] also adopt USLE as the main idea for its modelling philosophy. Further models such as the water erosion prediction project (WEPP) and the soil and water assessment tool (SWAT) as published by Neitsch *et al.* [2011] have also been developed. Moreover, the soil and water integrated model (SWIM) published by Krysanova *et al.* [2015], WATEM/SEDEM as published by Bezak *et al.* [2015], and SEDNET as described by Hughes and Croke [2011] have contributed to the development of modelling tools for erosion and sedimentation.

The SWAT model has more comprehensive equations and features, making it able to calculate the discharge, erosion, sediment and nutrient-related to hydrological processes [Krysanova, Arnold 2008; Xu, Peng 2013]. The spatial unit of calculation set to hydrological response units (HRUs) rather than to pixels.

In SWAT, land characteristics are represented by the curve number (*CN*) value, ranging from 25 to 98, and the *CN* value is determined by land cover and hydrologic soil group. Dense land cover (such as a forest) will produce small curve number and lower overland flow values. The higher the value of *CN*, the higher the surface flow produced. The more coarse the soil texture, the less the surface flow, and vice versa [ZHANG *et al.* 2019].

The HRU concept is used for dynamically analysing and modelling hydrology from various structures into homogeneous structures based on their interactions with soil type, geology and crop cover [PIGNOTTI *et al.* 2017]. The HRU process describes the similarity of hydrological characteristics, resulting in more accurate erosion values. Each HRU will produce one hydrological value based on the characteristics of land cover, soil and slope [PIGNOTTI *et al.* 2017].

The eastern part of East Java has experienced frequent disasters [BPBD Jawa Timur 2020]. The floods and landslides that frequently occur in Tempurejo (one of the districts in East Java) are evidence of hydrometeorological disasters [DIANSARI 2018; WURYANINGSIH *et al.* 2019]. Tempurejo is a small agglomeration (at district level) in the centre of the Sanenrejo watershed area. Theses disasters thought to be caused by the conversion of land resources to agriculture in the upstream areas of the watershed [TASLIM *et al.* 2019].

The assessment of erosion and sedimentation are urgent for the management of water and land resources. This study aims to apply the SWAT to calculate discharge, erosion and sedimentation in the watershed. Future water and land-resource conservation activities on the watershed may be proposed through the interpretation of model results if calibration and validation processes for this model can be successfully conducted on this watershed.

MATERIALS AND METHODS

STUDY SITE

This research was conducted at Sanenrejo, a small watershed area (±292 km^2) located in the eastern part of East Java (Fig. 1).

The water balance at the Sanenrejo watershed calculated using the soil and water assessment tool (SWAT) model are summarised in Table 1. Annual flow coefficient is the ratio between the highest annual flow (*Q*, mm) and the highest annual rainfall (*P*, mm) in the watershed [MENHUT 2014].

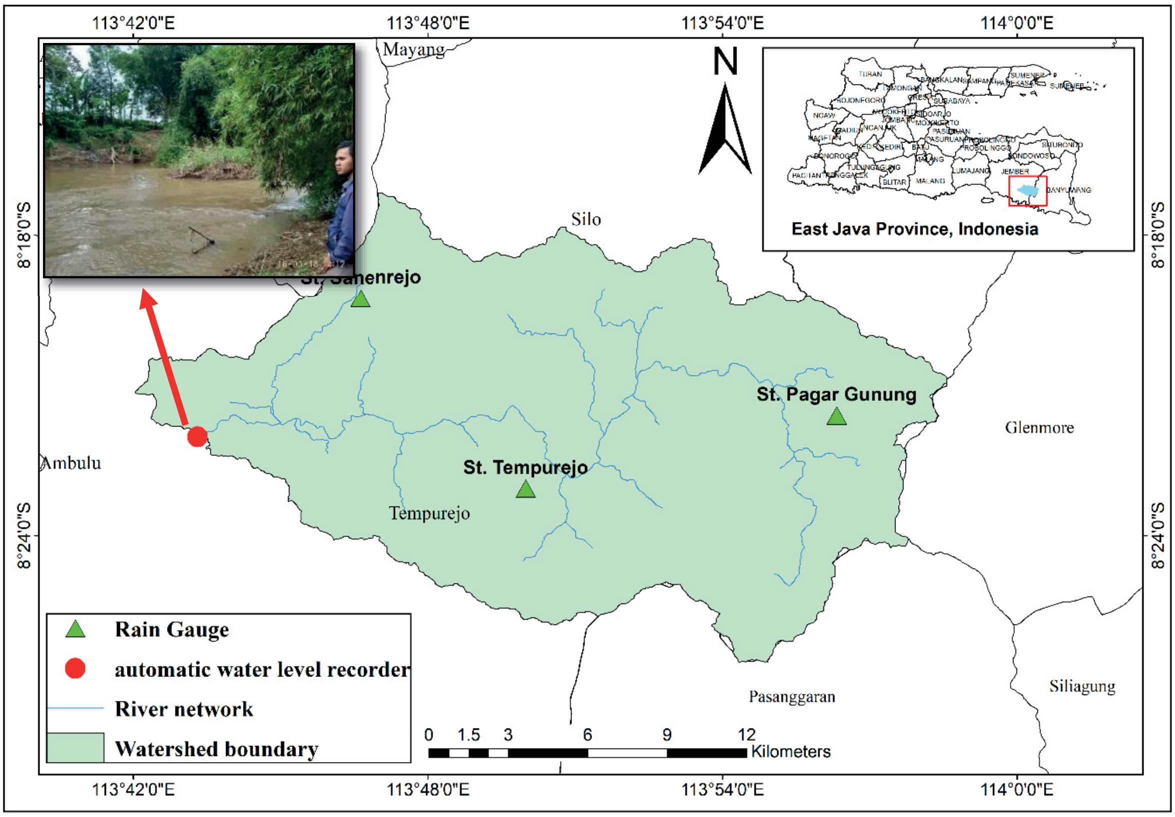

Fig. 1. Study area: the Sanenrejo watershed; source: own elaboration

Table 1. Water balance

Parameter	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 (Mg·ha^{-1})	66.6
Q_{max} (m^3)	111.4
Q_a (m^3)	7.0
Annual flow coefficient	0.4
Flow regime coefficient	15.8
Category	high

Explanations: Q_{max} = maximum discharge, Q_a = average discharge.
Source: own elaboration.

The annual flow coefficient is closely related to the flow regime coefficient. The annual flow coefficient value shows that a large proportion of the rainfall is converted to flow. The storage capacity of the watershed is relatively low because the topography of the area is mostly steep and because of conversion of land use from forest to agriculture and settlements. Flow regime coefficient is the ratio between maximum discharge (Q_{max}) and average discharge (Q_a) in a watershed [MENHUT 2014].

The high value of the flow regime coefficient indicates that the watershed is subject to higher runoff during the rainy season. In contrast, in the dry season, the watershed produces a minimum of runoff. In other words, the watershed has low storage capacity and is prone to water deficit or drought risk.

INPUT DATA AND TOOLS

The primary input data for this study is digital elevation model (DEM) data derived from the digital elevation model at the national scale (DEMNAS) provided by the National Agency of Geospatial Information (Ind. Badan Informasi Geospatial – BIG).

DEMNAS has a spatial resolution of 8.3 m × 8.3 m, which is suitable for this watershed study. The DEMNAS data is available for free download through the official website [BIG 2020]. In this case, DEMNAS is used to determine the watershed boundary and river network (Fig. 2).

Figure 2a shows the variation of altitude in the watershed, varying from 21 m to 1194 m above sea level. The detailed slope map (Fig. 2b) is also derived from DEMNAS data. The morphometric parameters obtained for Sanenrejo include 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), 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) [SUJARWO *et al.* 2019].

Then, the land-cover map (Fig. 2c) was clipped with the watershed boundary to calculate the composition of land cover/land use within the watershed. It was obtained from the interpretation of Landsat 8 image from Watershed Management Center of Brantas Sampean (Balai Pengelolaan Daerah Aliran Sungai dan Hutan Lindung Brantas Sampean – BPDAS-HL). The major land conditions/uses are as follows: agriculture of mixed shrubs dry land (AGRC) – 0.26%; plantation (AGRL) – 25.47%; dryland agriculture (AGRR) – 9.67%; land clearing (FLAX) – 0.3%; planted forests (FRSD) – 3.6%; primary dryland forest (FRSE) – 0.82%; secondary dryland forest (FRST) – 38.51%; rice (RICE) – 2.42%; shrubs (RNGB) – 17.88%; and settlement (URBN) – 1.07%. Furthermore, the soil map layer from the Soil Research Institute (Ind. Pusat Penelitian Tanah) was digitised and clipped with the watershed boundary, revealing the soil-type composition of the watershed (Fig. 2d) as alluvial (6.21%), latosol (90.99%) and regosol (2.8%) soils.

Hydrometeorological (rainfall and discharge) data were obtained from public offices of the water management and watershed authorities. Meteorological and climate data (i.e. rainfall, temperature, solar radiation, wind speed and humidity) were collected from the nearest local station, located at Kalibaru, about 20 km from the study site. Meteorological data were also collected from the website of Agency of Meterological, Climatological and Geophysics (Ind. Badan Meteorology dan Klimatologi Geofisika), that located in Banyuwangi [BMKG undated].

Rainfall data obtained from three measurement stations: Sanenrejo, Tempurejo and Pagar Gunung. The recording period for the various climate variables is from 2006 to 2017 (12 years). Discharge data obtained from the existing automatic water-level recorder located at the outlet of the watershed. The monthly discharge and rainfall data (2006–2017) are shown in Figure 3.

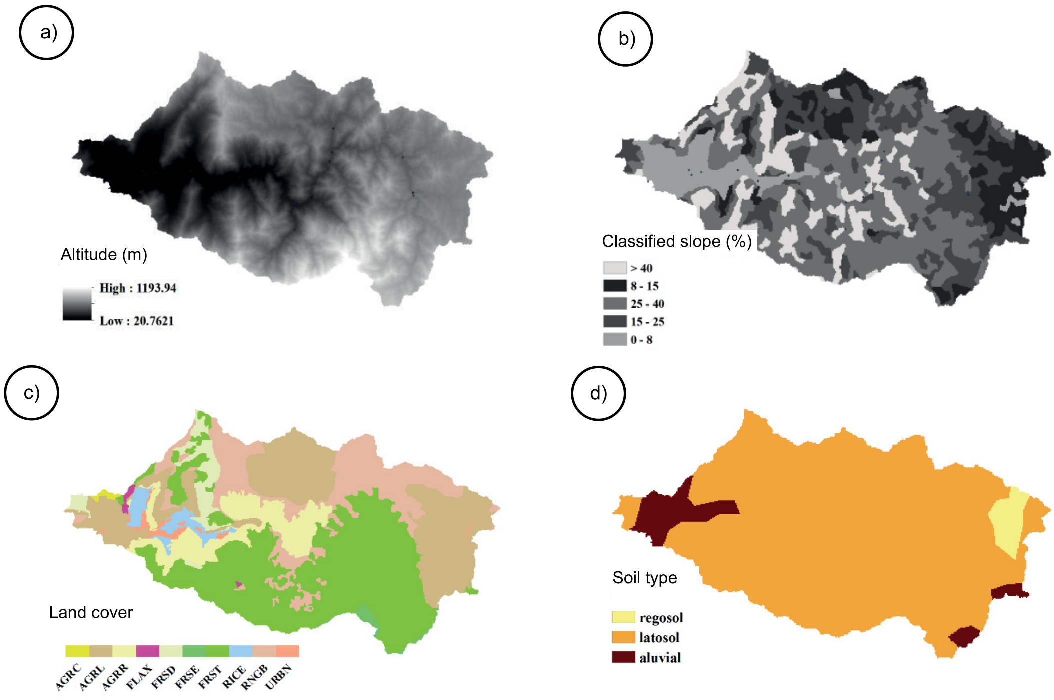

Fig. 2. Input for the SWAT model: a) altitude (m), b) slope (%), c) land cover, d) soil type; land cover codes as in Tab. 3; source: own study

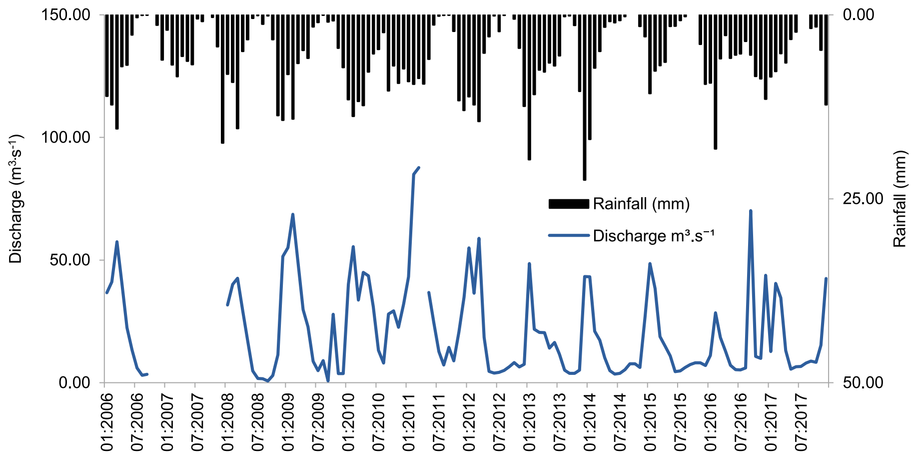

Fig. 3. Monthly discharge and rainfall (2006–2017); source: own elaboration

Table 2 presents all data used as inputs for the modelling process.

PROCEDURE

Preparing input data to the model. In this study, the erosion is estimated using the MUSLE method, as published by NEITSCH *et al.* [2011]. The hydrological cycle is simulated by the SWAT model based on water balance (Eq. 1):

$$SWt = SW0 + \sum_{i=1}^{i=t}(R\text{day} - Q\text{surf} - Ea - W\text{perc} - Q\text{gw}) \quad (1)$$

where: *SWt* and *SW*0 are, respectively, final and initial soil-water content (mm·d^{-1}); *t* is the time (day); *R*day is the precipitation (mm·d^{-1}); *Q*surf is the runoff (mm·d^{-1}); *Ea* is the evapotranspiration (mm·d^{-1}); *W*perc is the percolation (mm·d^{-1}); *Q*gw is the return flow (mm·d^{-1}).

The necessary input information in the SWAT model is DEMNAS data, land cover, soil characteristics, climate variables (rainfall, temperature, solar radiation, relative wind speed and humidity), and land management. All input data is in raster format. The general procedure of the modelling task consists of (1) hydrological response unit (HRU) processes; (2) climate input; and (3) running the model.

1. HRU processes

The number of HRUs generated was 628 and formed to 32 sub-basins.

2. Climate input

The climate variables are formatted and then entered into the weather stations in the SWAT model. The parameters determined for modelling processes are shown in Table 3.

3. Setup and simulation

The simulation period is set on a daily and annual basis, covering the period 2006–2017. The SWAT is then run through the GUI to get the simulation outputs such as HRU (USLE and SYLD) to show erosion and sediment model and RCH (FLOW_OUT) to show simulated discharge at sub-basin scale in m^3·s^{-1}.

Table 2. Description of input data

Data type	Source	Description
DEM	Geospatial Information Agency of Indonesia [BIG 2020]	pixel size 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 [BMKG 2020]	2006–2017 (12 years)
Rainfall	Sanenrejo, Tempurejo and Pagar Gunung stations	2006–2017 (12 years)

Source: own elaboration.

Calibration and validation. This study uses a manual calibration method. The calibration and validation uses only discharge data because of the limited availability of measured hydrological data. The calibration process uses 2014 data, and validation uses data from 2015. Several studies assumed that daily data for one year is sufficient to represent and to calibrate the SWAT model [SKHAKHFA, OUERDACHI 2016; YUSTIKA *et al.* 2012].

Sensitive parameters were determined from previous research results. According to 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 baseflow (i.e. GW_ALPHA, GW_REVAP, GW_DELAY, GW-QWN, REVAP-MN, RCHARG-DP).

Eight parameters may be adjusted to approach the discharge value, i.e., OV_N, CN2, SOL_AWC, SOL_K, GW_DELAY, ESCO, ALPHA_BF, CH_K2 [WAHDANI 2011]. 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 to process discharge optimisation. 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. A trial and error method was then used to find the best parameter values. Two statistical tests, coefficient of determination (R^2) and *NSE* [MORIASI *et al.* 2007] were applied to compare the accuracy of modelling processes.

Table 3. Details of the input model

No	Land cover	SWAT code	CP factor	Area (ha)	Percentage (%)
1	primary dry-land forest	FRSE	0.001	241.66	0.82
2	secondary dry-land forest	FRST	0.005	11,325.05	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	dryland 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 factor**	**Area (ha)**	**Percentage (%)**
1	alluvial	NINIGRET	0.16	1826.6	6.21
2	latosol	ENCHANTED	0.28	26,761.16	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			11,625.81	39.53
5	>40			4160.05	14.14

Explanations: *CP* factor = crop management and conservation practice factor, *K* = soil erodibility factor.
Source: own elaboration.

Table 4. Description of parameter changes

No.	Parameter	Information	Initial	Modified	Operation
1	CN2	SCS curve number	25–82	30–98	add
2	CH_N2	Manning's *n* value for the tributary channels	0.014	0.07	replace
3	CH_K2	effective hydraulic conductivity in main channel alluvium (mm·h^{-1})	0	7	replace
4	GW_DELAY	groundwater delay (days)	31	27	replace
5	ALPHA_BF	baseflow alpha factor (dm^3·day^{-1})	0.048	0.8	replace
6	GWQMN	threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0	200	replace
7	ESCO	soil evaporation compensation factor	0.95	0.65	replace
8	EPCO	plant uptake compensation factor	1	0.75	replace
9	ALPHA_BNK	factor alpha baseflow for "bank storage"	0	0.56	replace

Source: own study.

RESULTS AND DISCUSSION

CALIBRATION

The calibration process was conducted by changing the values of sensitive parameters such as CN2, CH_K2, CH_N2, ESCO, EPCO, ALPHA_BNK, GW_DELAY, and ALPHA_BF by trial and error until the results were better than the previous initial setting (Tab. 4).

Figure 4 visualised the hydrographs result of calibration period using adjusted parameter values. The *NSE* and R^2 calculated using the initial parameter settings show *NSE* = 0.08 and R^2 = 0.56. The adjustment of sensitive parameters created an increase in R^2 to 0.75 and in *NSE* = 0.62 (Figs. 4, 5).

Noor *et al.* [2014] revealed his research of the calibrated model was most sensitive to snowmelt parameters and *CN2* (curve number). Therefore the treatment added 20% *CN* value (*CN*·1,2) to each value aimed at increasing surface flow. CH_N2 parameter is the Manning's coefficient value of the main channel adjusted to the field conditions. The main-river condition of the Sanenrejo watershed is still natural (Photo 1) and dominated by grasses, trees and gravel around the channel.

Therefore the value is adjusted from 0.014 to 0.07 (refer to the Manning table).

The *CN2* parameter is the SCS curve number. The *CN2* refers to the land use and hydrology soil group. *CN2* is optimised by changing the *CN* value according to the land cover and soil hydrology Neitsch *et al.* [2011].

The CH_K2 parameter represents the value of hydraulic conductivity in the main channel. River flow is classified into four classes based on the interaction between river flow and the groundwater system [Arnold *et al.* 2012]. In this case, the initial value of CH_K2 = 0, and the adjusted value by trial and error = 7, illustrating that the water-loss condition in the alluvium channel is relatively low. The bed material (Photo 2) is characterised by a mixture of gravel, sand and high silt-clay content [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 was adjusted from 0.95 (initial) to 0.65 (final adjusted). EPCO parameter represented the amount of water required for transpiration and the amount of water available in the soil and was adjusted from 1.0 to 0.75. ALPHA_BNK or alpha baseflow factor for "bank storage" is a parameter that contributes to the flow of the main channel in the sub-basin. The ALPHA_BNK value used was 0.56.

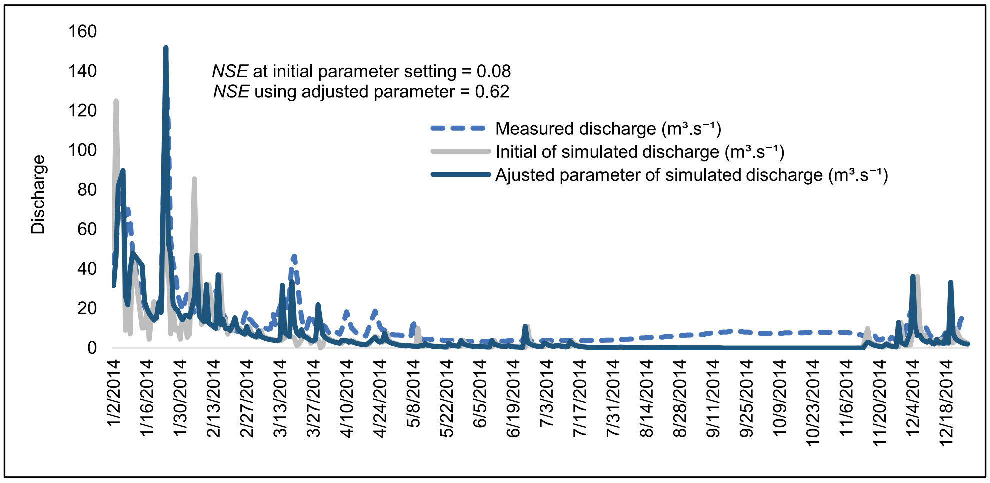

Fig. 4. Daily calibration results; source: own study

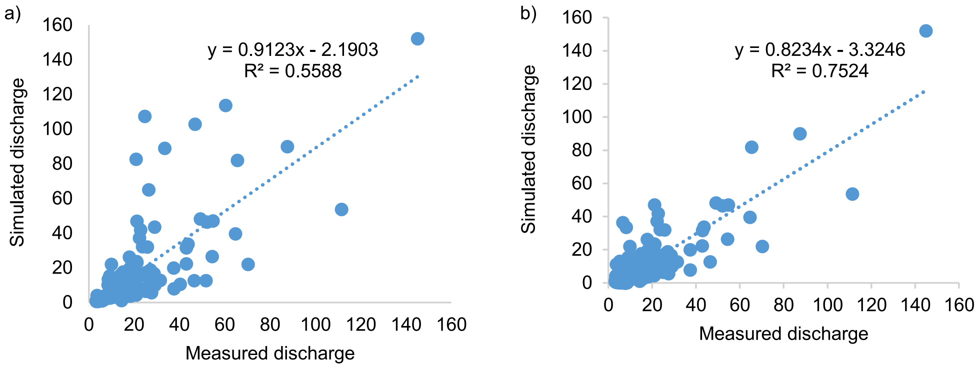

Fig. 5. Comparison of R^2 calibration: a) using initial values, b) using adjusted value; source: own study

Photo 1. One section of the stream channel (phot. *M.W. Sujarwo*)

Photo 2. Main channel stream (phot. *M.W. Sujarwo*)

The GW_DELAY parameter represents the time interval required for water to flow from the soil profile to the saturation zone and was adjusted from 31 (initial) to 22. The GWQMN describes 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 was 0 and was adjusted to 200 mm. The ALPHA_BF parameter is a land-surface response index that describes the groundwater response to changes inflow. LPHA_BF index varies between 0.1 and 0.3 for land surfaces with a low response, from 0.3 to 0.9 for a reasonable response and between 0.9 and 1 for a quick response. In this study, the ALPHA_BF value was adjusted from 0.048 to 0.8.

This describes the reasonable response of the watershed to the change in groundwater flow. The calibration results show an increase of *NSE* to 0.63 and R^2 to 0.75. *NSE* > 0.5 and R^2 > 0.6 in the SWAT model show that the model is reasonably useful for simulating the hydrological processes of the watershed [SANTHI *et al.* 2001].

VALIDATION

The validation uses data from 1 January 2015 to 31 December 2015 (Fig. 6). The validation results show *NSE* = 0.5 and R^2 = 0.632, and these values are deemed to be acceptable. So the model can be applied to assess erosion and sedimentation in the Sanenrejo sub-watershed.

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 effects of land-use changes interfere with the infiltration process, and therefore with the water carrying sediment into streams.

Erosion is calculated based on the HRU scale. It indicates that 76.5% of the watershed area is classified as having slight or very slight erosion rates while only 5% of the area is in the severe erosion category. In the mid-stream area, erosion is classified as moderate or severe. This middle area has contributed to an increase in discharge and sedimentation in the downstream areas (Fig. 7, Tab. 5).

The highest erosion, found in HRU 402, is 396.34 Mg·ha^{-1}·y^{-1} in the mid-stream area. The plantations, dryland agriculture and mixed dryland agriculture in slope areas (comprising more than 40%) contribute to the erosion and sedimentation in the middle areas. The area has been converted from forest to agricultural use and a conservation programme to reduce sedimentation, and hydrometeorological disasters are necessary for this area.

The sedimentation value at the watershed outlet is relatively small, at less than 3 Mg·ha^{-1}·month^{-1}. In general, the sediment rate increases during the wet season (October–April) because rainfall significantly affects erosion and sedimentation (Fig. 8).

Average sediment yield is higher than 10 Mg·ha^{-1} in the watershed, and this is a very high value for average watershed sedimentation. The maximum sediment yield of more than 50 Mg·ha^{-1} is found in HRU 610 (sub-basin 26), an area covered by dryland agriculture vegetation and regosol soil.

Figure 9 shows that more than 50% of erosion is converted to sediment, indicating that the erosion in the watershed determines the quality of the river flow. The slope and valley areas of the watershed accelerate sediment deposit. The mid-stream and downstream of the Kalisanen River are surrounded by hilly and valley areas.

CONCLUSIONS

Calibration produces *NSE* = 0.62, while validation done the *NSE* = 0.5. Coefficient of correlation (R^2) for calibration periods = 0.75 and for validation = 0.63 respectively. This study shows the application of the soil and water assessment tool (SWAT) model to simulate hydrological process on the watershed. In this case, the model used to calculate discharge, erosion and sedimentation. Average sediment yield in the watershed is relatively high (>10 Mg·ha^{-1}). More than 50% of

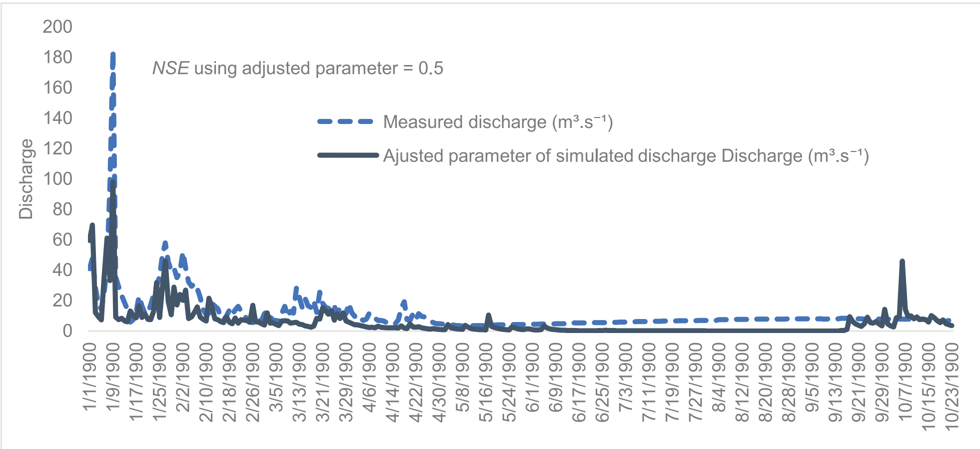

Fig. 6. Daily validation results; source: own study

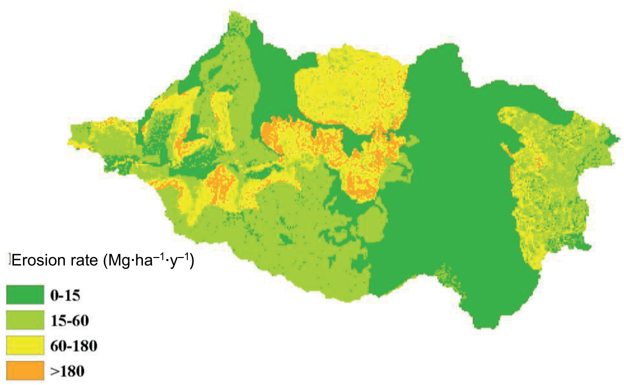

Fig. 7. Distribution of erosion – 2017; source: own study

Table 5. Erosion values – 2017

Erosion rate (Mg·ha^{-1}·y^{-1})	Values acc. to soil and water assessment tool		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

Source: Peraturan Nomor : P. 32/Menhut-II/2009.

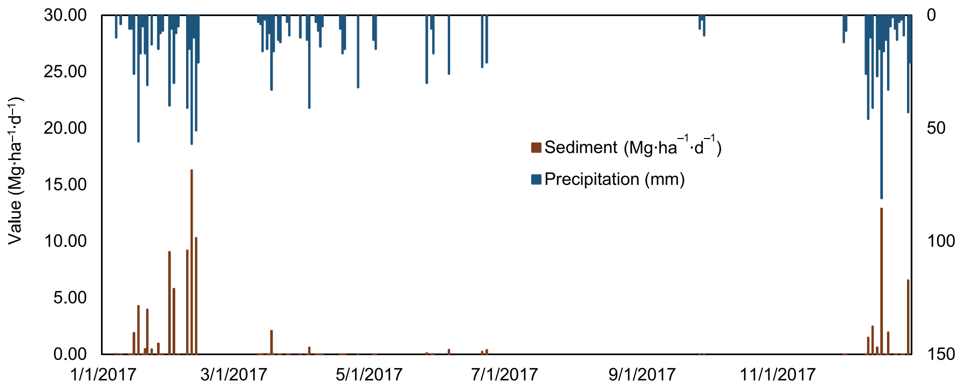

Fig. 8. Sediment outlet – soil and water assessment tool; source: own study

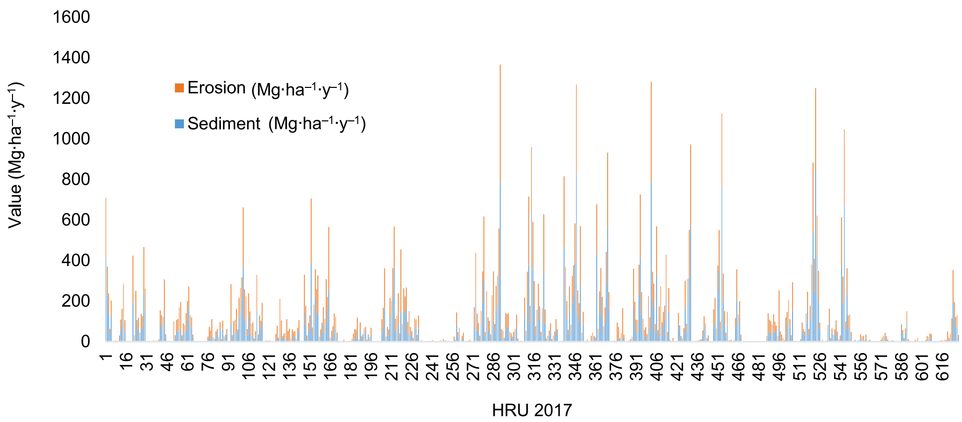

Fig. 9. Sediment and erosion value of hydrological response unit – soil and water assessment tool; source: own study

erosion is converted to sediment, indicating that the erosion in the watershed determines the quality of the river flow.

The model can serve the stakeholder as recommendations for disaster information, adaptation, and mitigation in the study area. This research would be better if it added socio-economic aspects to get human influence on natural resources.

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