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Research Article

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GIS application for sediment delivery ratio assessment in tropical river basin

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Abstract Land degradation in form of erosion and sedimentation has been known as one ofthe critical issues in the last decade. Heavy erosion results a huge number of sludge and sediment in downstream, reducesthe capacity of the reservoir and destroys many public facilities. This study was focusing on sediment delivery ratio (SDR) assessment. A tropical river basin which is located in the upstream of a multi-purpose reservoir was selected as the study site. We calculated soil erosion, suspended load sediment and classified the basin into ten sub-basins to estimate the SDR. Erosion in each sub-basin was calculated using RUSLE model, integrated with Geographic Information Systems (GIS), meanwhile, suspended load was calculated by regression equation. The results shown that the mean SDR value of the study site was 0.14. Suspended load concentration in the south part was higher than the north part. This study provides useful references to estimate the suspended load yield and also provides reference forsedimentation studies, particularly in the tropics.

Keywords Erosion, suspended load, GIS, sediment delivery ratio, sub-basin

Introduction

Sediment delivery ratio (SDR) is the ratio of sediment yield toward erosion within an area or a river basin. Sediment yield is a result of interaction among the river basin components. Excessive sediment flow into downstream indicates problems in the river basin. Sediment yield which is mostly produced from erosion process has strong correlation with erosion. Hence, linking erosion and sediment is important to develop the better conservation practices and prevent the land degradation. Sediment flow causes many problems downstream such as decreasing water quality, reducing reservoir capacity, destroying water supply facilities, destroying aquatic environment and others [1-3]. Furthermore, the huge number of sediment yield may change the river morphology significantly [4]. The same problem was faced by tropical countries, where sediment yield which is resulted by river basins tend to high. Sediment formation in the tropics was accelerated by the effect of climate factor (rainfall) and human activities such as farming and mining [5-7]. High rainfall has become a challenge to control the sedimentation in the tropics.

Sediment production and transport were affected by some factors such as properties of the particles (size, density, volume and shape), river geomorphology, carrying capacity of stream flow or discharge, land cover and human activities. There are two types of sediment transportation i.e. suspended load and bed load. Bed load included sand, rock or others large particles which move along the river bed. Suspended load is commonly in form of suspension [8]. In this study, we calculated sediment delivery ratio by considering erosion and suspended load. Commonly, SDR is estimated by using suspended load because the measurement of this type sediment is easy. A tropical river basin which is located in Indonesia is selected as the study site. The basin has a vital function as the catchment area of a multi-purpose reservoir downstream which provides water for various needs. We used ArcGIS 10.1 to calculate erosion by RUSLE model and regression equation to calculate the suspended load. Information of sediment delivery ratio is required for river basin management and protection.

Materials and Method

This study was conducted in the upstream river basin of Wadaslintang reservoir, which is administratively located in Central Java Province Indonesia. The basin which is dominated by agricultural land, covers about 177.70 km^2 area, meanwhile, the reservoir has about 14.81 km^2 area. We divided the basin into ten sub-basins to calculate SDR (Figure 1). There are three main activities in this study: erosion assessment, suspended assessment and SDR assessment. Some data were required for SDR assessment those were sub-basins map, monthly rainfall, soil map, digital elevation model (DEM) or land slope map and land cover map. All maps which were used to calculate the erosion were presented in 30 m resolution (grid size).

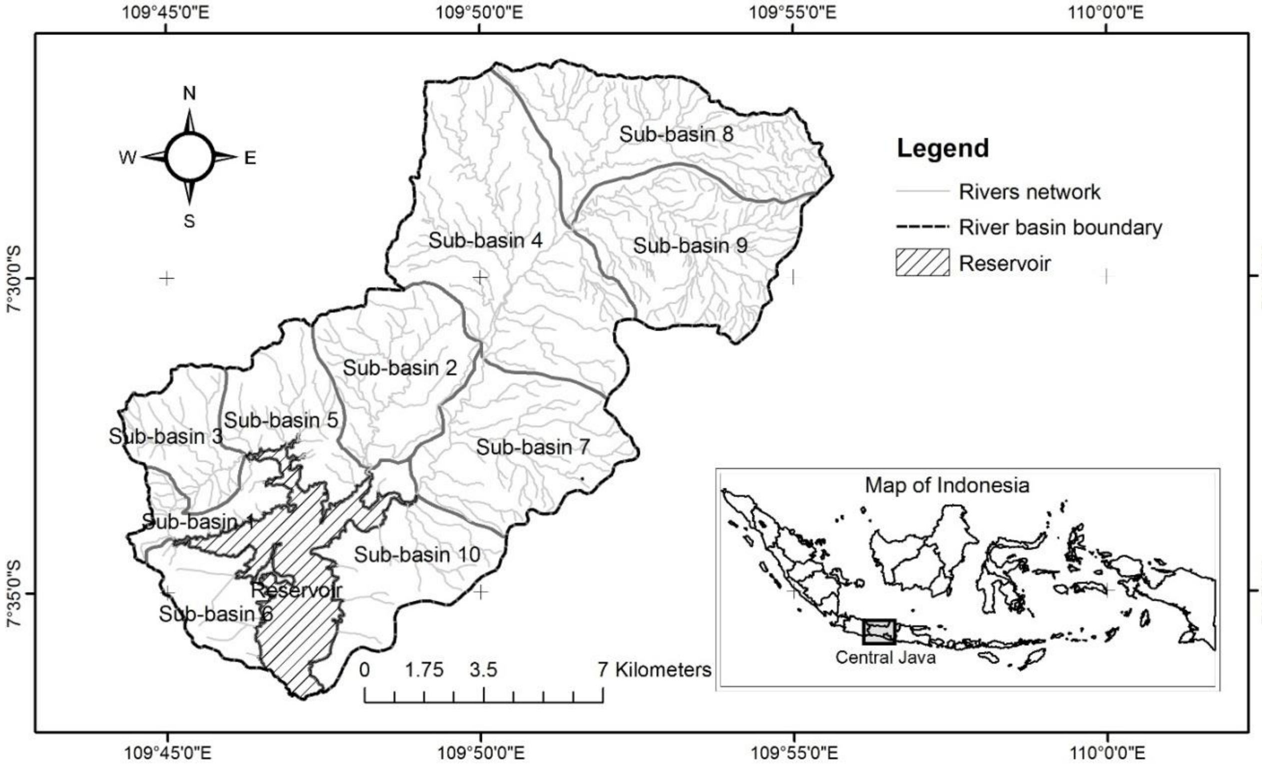


Figure 1: Location of the Study Site

Erosion was calculated by using RUSLE method [9]. RUSLE is easy and has proved good capabilities to apply in various climate condition [10-11]. The equation of RUSLE model expresses as:

$$A= R \times K \times LS \times C \times P \quad (1)$$

where:

- A is the average annual erosion (t ha^{-1} yr^{-1});
- R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}). We estimated R value by using equation: $R = 2.21 Pm^{1.36}$, where Pm is monthly rainfall in mm [12];
- K is the soil erodibility factor (t h MJ-1 mm-1). In this study, K estimated based on soil types [12,13];
- LS is the slope length-steepness factor (dimensionless). LS calculated by considering flow accumulation and land slope [14];
- C is the cropping management factor (dimensionless). C value was estimated based on land cover types in the study site [13]; and
- P is the erosion control practice factor (dimensionless). P value was estimated by considering land use type and land slope [13].

For suspended load, it was calculated by using water discharge and suspended load concentration in the river basin. Suspended load of the sub-basinswas calculated using two equations which are investigated in Medono

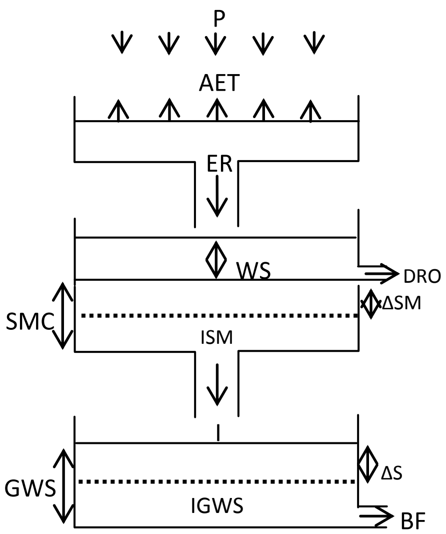
River (eq. 2) and Tritis River (eq. 3). These equations were used for some sedimentation studies in the study site [15].

$$Qs = 0.098\ Q_w^{1.339} \quad (2)$$

$$Qs = 0.260\ Q_w^{1.367} \quad (3)$$

where Qs is suspended load (Kg/s), Q_w is water discharge (m^3/s). In this study, the value of Qs was presented in unit m^3/s, converted by using bulk density of sediment in the study site, where the value was 2.65 ton/m^3.

To calculate suspended, discharge data of each sub-basin is required. This data is not available due to no measurement in a level of sub-basin. Direct measurement of discharge data was conducted in the reservoir which represent the total area of the basin. To solve this problem, we used hydrology model of Mock to calculate discharge data in each sub-basin (Figure 2). Mock model is a rainfall-runoff model which is containing three artificial tanks representing rainwater transformation processes in the atmosphere, soil and ground water system [16].



ER	=	P-AET	IGWS	=	GWS_{I-1}
WS	=	ER-ΔSM	DRO	=	WS-I
ΔSM	=	SMC-ISM	BF	=	I-ΔS
ISM	=	SM_{I-1}	ΔS	=	GWS – IGWS
I	=	Ci x WS	Q_{TOT}	=	DRO + BF
GWS	=	0.5 (1+K) I + K x IGWS			

P	=	precipitation	I	=	infiltration
AET	=	actual evapotranspiration	WS	=	water surplus
ER	=	excess rainfall	BF	=	base flow
DRO	=	direct runoff	Ci	=	infiltration coefficient
ΔSM	=	change of soil moisture	SMC	=	soil moisture capacity
ISM	=	initial soil moisture	K	=	recession constant
ΔS	=	change of ground water volume	Q_{TOT}	=	total water discharge
GWS	=	ground water storage			
IGWS	=	initial ground water storage			

Figure 2: Structure of the hydrology model of Mock

Results and Discussion

Soil erosion

Lack of data availability has become a challenge to conduct this study, hence, data were obtained from various sources such as Main Office of SerayuOpak River Indonesia (soil type map), Office of Probolo River System Central Java Province Indonesia (rainfall data), Geospatial Information Agency Indonesia (sub-basin map, land cover map) and United States Geological Survey (digital elevation model map). We used rainfall data from the period of 2007-2016 to calculate erosion in the study site. To eliminate error and to achieve the best result, we verified RUSLE and Mock model using observed data in the study site. For erosion calculation, RUSLE model verification was conducted using direct measurement data of sedimentation in 2004 and 2008 [17]. The verification proved that RUSLE model has good accuracy to use in the study site where there are no significant differences between observed data and calculated data of erosion, calculated using RUSLE. The RUSLE model was then used to estimate the soil erosion in the study site. Erosion value in each of sub-basin is presented in Figure 3. The highest and lowest value of erosion was found in sub-basin 4 (137,274.4 m^3) and sub-basin 1 (17,050.6 m^3) respectively. Erosion in the study site was mainly affected by land slope condition where in sub-basin 4, the slope tends to high. The same pattern was also found in sub-basin 7 and sub-basin 9. Various value of land slopes was significantly affecting the value of erosion [18].

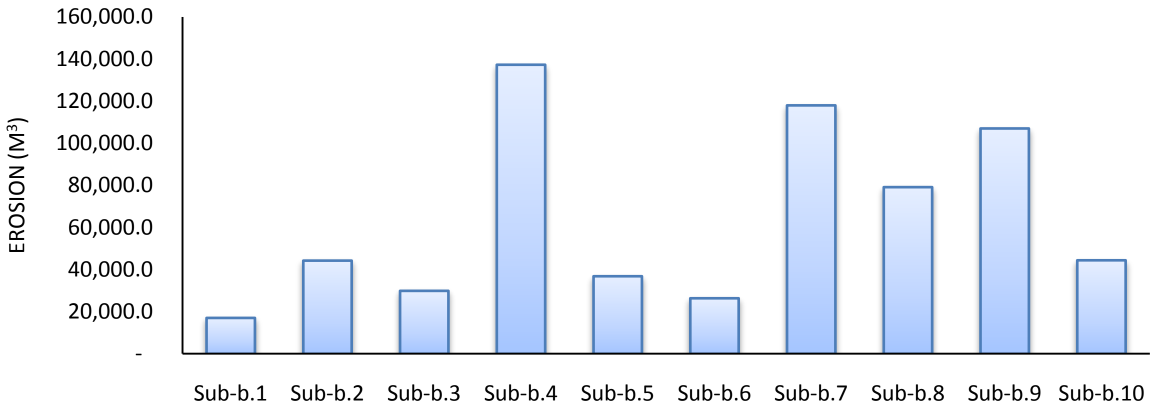


Figure 3: Erosion value (m^3) in each sub-basin of the study site

Suspended load

Discharge data of each sub-basin were required to calculate suspended load. A Mock model which is used to calculate discharge was verified by using observed discharge data in 1999/2000. The result of Mock model verification shows that the Mock model has good capabilities to estimate discharge data in the study site, indicated by the value of correlation coefficient (R) was 0.91, volume errors (VE) was 0.04 and efficiency coefficient (E) was 0.93. Average monthly discharge of sub-basins which is calculated for the period of 2007-2016 is presented in Table 1. The highest average value of discharge was found in sub-basin 4 which has the largest area.

Table 1: Average monthly discharge of sub-basins (m^3/s)

Month	Sub-basin									
	1	2	3	4	5	6	7	8	9	10
Jan	1.72	5.19	2.85	11.30	4.10	2.42	6.24	7.02	6.72	4.38
Feb	2.37	7.18	3.94	15.63	5.67	3.35	8.64	9.71	9.30	6.06
Mar.	3.14	9.51	5.22	20.70	7.51	4.43	11.44	12.87	12.32	8.02
May	1.60	4.86	2.67	10.57	3.84	2.26	5.84	6.57	6.29	4.10
June	0.94	2.84	1.56	6.18	2.24	1.32	3.41	3.84	3.68	2.39
July	0.69	2.09	1.15	4.54	1.65	0.97	2.51	2.82	2.70	1.76
Aug.	0.48	1.45	0.79	3.15	1.14	0.67	1.74	1.96	1.87	1.22
Sept.	0.35	1.06	0.58	2.32	0.84	0.50	1.28	1.44	1.38	0.90
Oct.	0.24	0.74	0.41	1.61	0.58	0.34	0.89	1.00	0.96	0.62
Nov.	1.58	4.77	2.62	10.37	3.77	2.22	5.73	6.45	6.17	4.02
Dec.	3.04	9.20	5.05	20.01	7.26	4.29	11.06	12.44	11.91	7.76

Rating curve of sediment which reflects the correlation between suspended sediment and discharge provide an easy way to estimate suspended load. Obtaining good rating curve by using regression analysis need to consider climate condition, where mostly the peak of sediment transport as occurred during the rainy season. In this study, suspended load was calculated by using regression equations which are obtained from two main rivers of the basin i.e. Medono river and Tritis river. Medonoriver has about 107.00 km^2 catchment area (55.7% of total area) which covers the sub-basin 4, sub-basin 7, sub-basin 8 and sub-basin 9. Meanwhile, Tritis has about 9.7 km^2 catchment area (5.1% of total area) which covers sub-basin 2. For sub-basin 1, sub-basin 3, sub-basin 5, sub-basin 6 and sub-basin 10, suspended load was estimated using eq. 3 due to the physical characteristic in this sub-basin is tend to be the same with the catchment area of Tritis river. The suspended load of each sub-basin is presented in Figure 4.

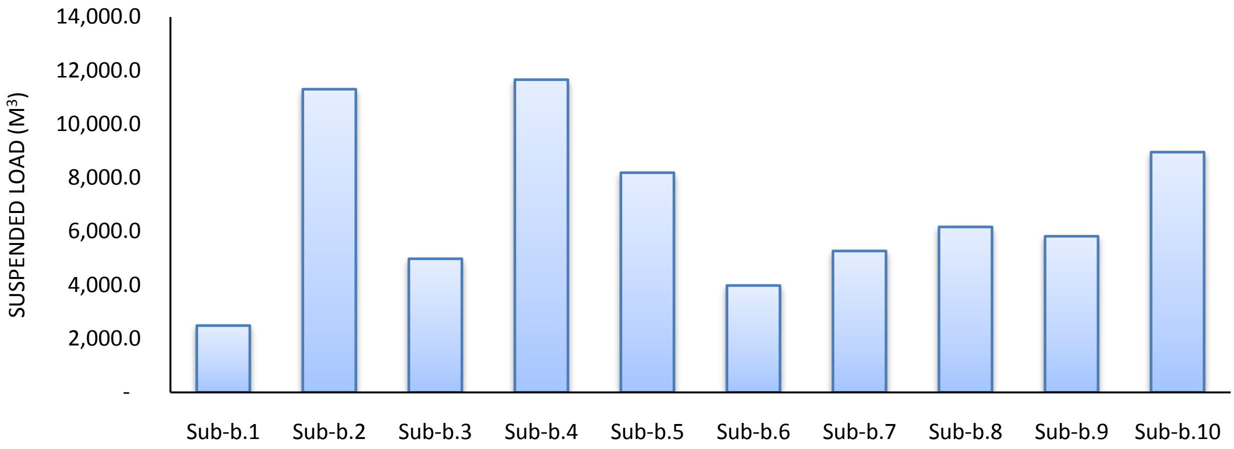


Figure 4: Suspended load value (m^3) in each sub-basin of the study site

The highest and lowest value of suspended load was found in sub-basin 4 (11,658.9m^3) and sub-basin 1 (2,488.4m^3) respectively. Suspended load in those sub-basins has a linear correlation with soil erosion. Suspended load in sub-basin 7 and sub-basin 9 has a small value, whereas the erosion was high. It means that the effect of the land slope was not strong in sub-basin 7 and sub-basin 9. There are some others factors exclude land slope which is strongly affecting the value of suspended load in the study site.

Sediment delivery ratio

SDR reflects the ability of basin to transport sediment into downstream. The high value of SDR means that the sediment carrying capacity of the basin is high. Carrying capacity of the basin has a strong correlation with the discharge. High stream discharge has high carrying capacity of sediment. This phenomenon can be used to estimate the possibility of degradation and aggradation in rivers bed, which is recognized as one of sediment source. In this study, the value of river basin SDR was calculated as the average SDR value of sub-basins. SDR value in each sub-basin is presented in Table 2. The value of SDR was various from 0.04 (lowest) to 0.26 (highest), whereas average value SDR of the basin was 0.14.Various rivers network and physical conditions in each sub-basin affect the value of SDR. The high value of SDR in the present study was mainly caused by the effect of suspended load. This finding indicates the contribution of sediment from landslide load or river bed degradation was significant enough.

Table 2: SDR value in each sub-basin

Sub-basin	Erosion(m^3)	Area(km^2)	Suspended load(m^3)	SDR
1	17,050.6	5.9	2,488.4	0.15
2	44,258.3	17.8	11,302.6	0.26
3	29,905.5	9.7	4,979.2	0.17
4	137,274.4	38.7	11,658.9	0.08
5	36,840.0	14.0	8,188.8	0.22
6	26,378.8	8.3	3,982.3	0.15
7	117,974.7	21.4	5,269.9	0.04
8	79,144.2	24.0	6,166.7	0.08
9	107,008.5	23.0	5,818.6	0.05
10	44,414.5	15.0	8,956.0	0.20
			Average	0.14

Understanding sediment sources is important to determine appropriate strategies for sediment control. Mostly, sediment source was from soil erosion, landslide load or streambed degradation. This study reveals that in sub-basin 4 and sub-basin 1, erosion and suspended load correlation was linear. It could indicate that erosion has significant contribution in this two sub-basin but not in others sub-basins. The lowest and highest value was found in sub-basin 7 and sub-basin 2 respectively. The value of SDR in the south part of the river basin tends to higher than in the north part, whereas the land slope of south part tends to lower than the north part. Investigation of SDR provides useful information for river-basin management and protection planning, particularly to design conservation practices in upland and rivers.

Conclusion

GIS has proved a good performance to calculate SDR in the study site. Average SDR of the study site was 0.14, where the lowest and highest value was found in sub-basin 7 (0.04) and sub-basin 2 (0.26) respectively. The study reveals that suspended load concentration in the south part of the study site was higher than the north part. Erosion in the study site has a strong correlation with land slope, whereas, for suspended load, the value was also strongly affected by other factors such as particles properties and river morphology. Sedimentation control is required by using engineering approach in the river with the high value of SDR. Meanwhile, land use types or land cover management using vegetation combined with engineering approach could be applied in upland to reduce the soil erosion as one of the sediment source.

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