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Application of Geographic Information System (GIS–IDRISI) for Assessing Land Use Risks on Sediment Yields

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The land use development on the catchment area have to consider the sustainability of the natural resources, particularly water and soil fertility. Therefore, the risks of land use development must be minimized. This paper presents a methodology and analysis of the land use risks on sediment yield from a catchment area and propose some suggestions to maintain the catchment area function. The universal soil loss equation (USLE) in combination with IDRISI software package was used in this study. Five thematic maps of USLE parameters; rainfall erosivity (R), soil erodibility factor (K), length–slope–steepness factor (LS), land use factor (C), and conservation factor (P) were constructed by digitizing them on computer data base with an element size of $200 \times 200\,m^2$. The spatial and temporal changes on catchment area (land use and sediment yield) were obtained by comparing two set of maps from different period. The proposed method is applied at Wonogiri catchment area in Indonesia. From this study, it was found that there are significant risks of the land use on the sediment yields and the existing land use have to be modified to reduce the sediment yields.

INTRODUCTION

The land use pattern is a critical aspect in the overall water resources project. The purpose of an appropriate land use planning is to maximize land productivity, in accordance with minimum risks of land use management. Land use risks analysis is an important task, particularly in medium to large catchment area in tropical, and especially in densely populated area like in most parts of Indonesia. In order to assess the effect of land use risks in a catchment area, the described in this paper methodology was developed. The integration of digitization map on computer data base with an element size of $200 \times 200\,m^2$ is used to assess the soil erosion in the study area. The spatial and temporal changes on catchment area (land use and gross erosion) were obtained by comparing two set of maps from different period.

STUDY AREA

The proposed method was applied in the Wonogiri catchment area, which is located in the Southeast part of the Central Java in the mountainous area of Upper Solo Catchment area (Figure 1). The catchment area covers an area of $1305\,km^2$, and

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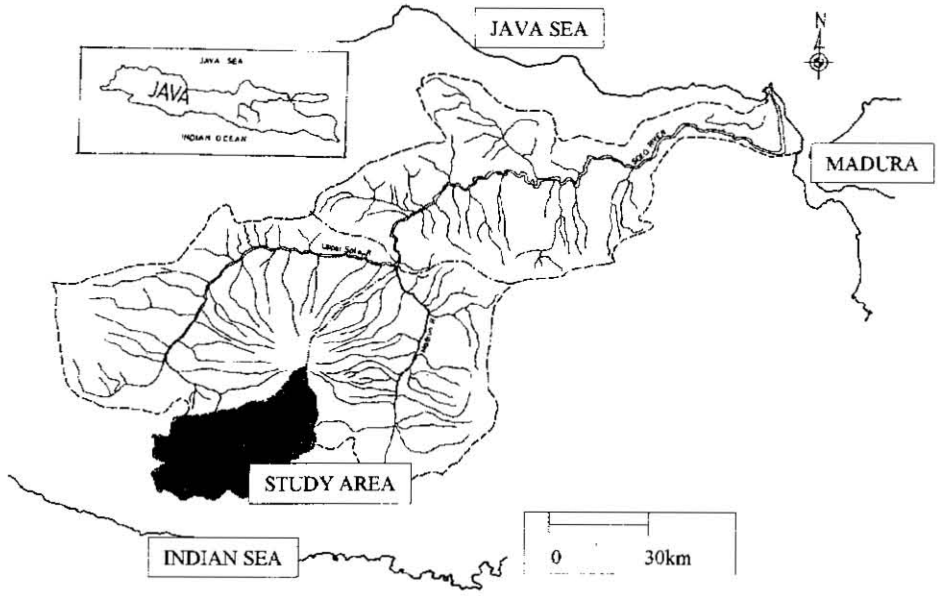

Fig. 1. Location map of the study area

composed of six sub-basins: Keduang (417.36 km²), Tirtomoyo or Wiroko (229.36 km²), Beling or Temon (65.04 km²), Upper Solo (203.52 km²), Alang (163.80 km²) and Wuryantoro-Ngunggahan (137.44 km²). It is closed catchment area, surrounded by continuous mountain ranges; Merbabu and Lawu Mounts in the West, South Mountain in the South, Willis Mount in the East and Kendeng Mountain in the North. The catchment area is located between 7°32' S – 8°12' S and 110°40' E – 111°18' E. It experiences an Indo-Australia monsoon with mean annual precipitation of 1850 mm, 85% of which fall during wet season (November-April).

The main river structure in this area is Gajah Mungkur (Wonogiri) reservoir, which was built in 1976 and essentially completed in 1982, while the reservoir impoundment was started in July 1980 (DGM, 1981). The reservoir is a multi-purpose project, majoring on flood control and irrigation (Citra Mandala Agrritrans, 1993). The dam was rock-fill with an impervious core, 40 meter high with a total capacity of $720 \times 106\,m^3$ at elevation 138.30 m (Virama Karya, 1992). Dead storage of $120 \times 10^6\,m^3$ is provided below elevation of 127.00 m. A bottom outlet of 1.95 m in diameter and completed with a hollow jet valve was installed at an invert level of 116.00 m. This outlet is used only during the case of reparation of power generation facilities, having a maximum capacity of $35.0\,m^3/s$.

Based on several hydrographic surveys (echo-sounding and/or terrestrial survey), it was found that the reservoir is silted up seriously (P4-PU, 1992). During 14 years in operation (1980-1993) the total capacity has lost 18%, or 1.3% annually (Table 1). It is much higher than that estimated in the design ($1.5 \times 10^6\,m^3$). So, the proposed life time of 100 years would hardly be achieved.

Table 1. Reduction of Gajah Mungkur reservoir capacity

Date of survey	Remaining capacity (10^6. m^3)	Accumulative deposition (10^6. m^3)	Deposition rate (10^6. m^3/yr)	Equivalent sediment yield t/ha/year
July 1980 (initial)	720.00	0	–	–
October 1984	678,32	41,68	9.62	84.6
September 1985	654,57	65,43	12.46	109.6
August 1987	635,62	84,38	11.77	103.5
December 1992	610,61	109,39	8.75	76.9
December 1993	588,13	131,87	9.77	85.9

Sources: P4–PBS (1989), UGM (1992), Virama Karya, PT (1992), Citra Mandala, PT (1993).

METHOD

Construction of computer data base

A Computer Data Base (CDB) system is a computer–assisted system for the acquisition, storage, analysis and display of land use and soil erosion. The element size of data base for this study is $200 \times 200\,m^2$. Map digitizing system is the component that one can take existing paper maps and converted them into digital form. In IDRISI, digitizing and editing the digital maps can be supported by some software packages like TOSCA, ArcInfo and AUTOCAD (Eastman, 1992). Image processing system is allows to take raw remotely sensed imagery (such as LANDSAT, SPOT satellite imagery) and convert into interpreted map according to classification procedure.

The CDB system is constructed for processing and managing of the land use and erosion data on the study area. The input data sets are entered to the system via keyboard or through the digitization of map information. The maps which are necessarily digitized and on which the GIS is structured are the thematic maps of USLE parameters; rainfall erosivity (R), soil erodibility factor (K), length slope–steepness factor (LS). land use factor (C), and conservation factor (P). Each grid–cell has an element size of $200 \times 200\,m^2$. The parcel and identification number is collected and stored in attribute tables. Identification number is the reference code for the retrieval of information.

Estimation of soil erosion

In this study, the universal soil loss equation (USLE) suggested by Wischmeier and Smith (1978), was used to determine gross soil erosion in the Wonogiri catchment area. The USLE is given as:

$$E = R \times K \times LS \times C \times P \qquad (1)$$

where E is gross soil erosion (t/ha/yr), R is rainfall erosivity (KJ/ha), K is soil erodibility (t/KJ), LS is length–slope–steepness factor, C is crop management factor, and P is soil conservation practice factor. Determination of each factor is discussed below.

Rainfall erosivity, R–factor: The R–factor was calculated by using equation developed in Java based on various plot studies carried out by the Soil Research Institute–Boggier, supervised by Belgian Technical Assistance under Bols (1976) as:

$$R = \sum_{i=1}^{n} EI_{30,m} \tag{2}$$

$$EI_{30,m} = 6.119 R_m^{1.211} N^{-0.474} R_{MAX}^{0.526} \tag{3}$$

where $EI_{30,m}$ is mean monthly erosivity factor (KJ/ha), R_m is monthly rainfall (cm) N is number of rainfall–days in a month, R_{MAX} is maximum–daily–rainfall in a month (cm).

Soil erodibility K–factor: The soil data in the study area were identified by using soil map from the Soil Research Institute, Bogor. It was found that, the soil in the study area are mainly composed of Lathossols, Meditranians, Lithossols and Grumusols. The texture of the soils are composed of 15–65% of sand and 40–75% of very fine sand and silt. Organic matter content varies from 0.05% to 6.5%. The soil structures are mostly fine granular, with a permeability ranges between slow and moderate. Using these information, the soil erodibility factor was computed following the nomograph prepared by Wischmeier *et al* (1971).

Length–slope–steepness LS–factor: The project area is located almost entirely in fairly steep mountainous terrain, which varies from smooth until undulating/hilly with elevation of +127 up to +1500 m. The slope of the land surface in the watershed varies from 2% to steeper than 45%. Combined LS–factor for all land units was computed following the formula suggested by (Williams and Berndt, 1972):

$$LS = \sqrt{\frac{L}{22.13}}\,(0.065 + 0.0453S + 0.0065S^2) \tag{4}$$

where L is slope length in m, and S is slope steepness in m/m. L is determined from:

$L = \dfrac{0.5A}{LCH}$, LCH is the total length of channels (m) in the watershed, and A is basin area (m^2).

Land use C–factor: The digitally classified land use was used to determine the C–factor values for each sub–unit land following the table provided by BPS (1989). About 85% of the total study area composed of arable land and homestead, while forests occupy less then 15%. The land use are generally composed of wet rice (paddy), upland rice (gogo), soybeans, maize, groundnuts and cassava. Settlement area usually developed among the agricultural area as homestead. The C–factor for unit of land was estimated based on the dominant land use. The C–value ranges from 0 to 1. The C is highest for bare land (1.0), and lowest for lands which are fully covered with straw mulch (0.005).

Conservation practice P–factor: The P–factor refer to the practices on site that reduces the effects of topography, slope length and steepness, contour strip–crop system, contouring, and terracing. The P value for unit land composed of various land treatment can be estimated using formula from Williams and Berndt (1972) as:

$$P = 1.0 \times SR + 0.30\,SRWW + P_T \times T \tag{5}$$

where P is control practice factor for unit land, SR is the portion of the watershed farmed with straight rows, $SRWW$ is the portion of the watershed farmed with straight rows and grassed waterways, P_T is the erosion–control–practice factor for terracing, and T is the portion of the watershed that is terraced.

Each of the USLE factor with associated attribute data was digitally encoded in GIS data base eventually to construct five thematic layers. Using multilayer procedure, gross soil erosion was computed.

Sediment delivery ratio

Originally USLE was developed based on plot scale. The application of USLE on basin scale have to be corrected with the so–called Delivery Ratio (DR) (Williams and Berndt, 1972), which is defined as the ratio of sediment actually delivered (sediment yield=SY) at the basin outlet to the gross erosion (E). The magnitude of the ratio for a particular basin is influenced by a wide range of geomorphological and environmental factors including the nature, extent and location of the sediment sources, the relief and slope characteristics, the drainage pattern and channel conditions, the plant cover, land use and soil texture. For the case of Wonogiri watershed, Suripin (1997) found that the DR (in %) is function of bifurcation ratio (R_b), mean basin slope (S in %), and percentage of wet land and forest (W_L+F_L) as expressed:

$$DR=203\,R_b^{3.068}\,S^{0.4144}\,(F_L+W_L)^{-1.257} \tag{6}$$

Implementation of bench terraces adjust the mean basin slope as expressed in:

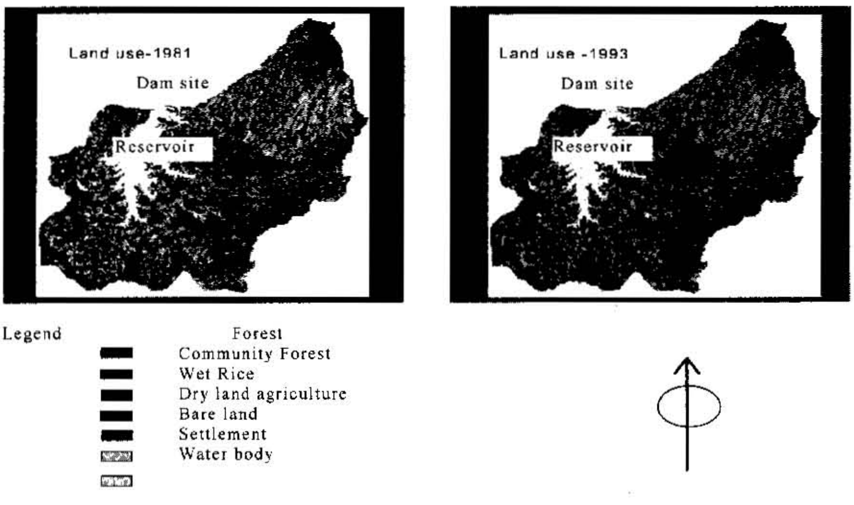

Fig. 2. Land use map of the Wonogiri watershed for the years, 1981 and 1993

$$S_{adj} = \frac{\sum (A - A_{ef})_i \, S_i}{\sum A_i} \quad (7)$$

where: S_{adj} is adjusted mean basin slope, A is sub–basin area (ha), A_{ef} is effective area of terraced land within sub–basin (ha), A_i is sub–area of land plot having a slope S_i (ha).

Land use changes in the study area

Two digital land use maps for the Wonogiri watershed for the year of 1981 and 1993 have been digitized, as presented in Figure 2. These maps were developed on the basis of aerial photographs of corresponding year at a scale of 1:50.000. The land use was classified broadly into 6 categories; forests (natural and community), wet land (paddy field), dry agricultural land, water body, and bare land.

The land use changes were then analyzed according to Figure 2. The results are presented as shown in Table 2. Using Table 2 above, the matrix of land use change in the study area can be arranged as shown in Table 3 below:

Table 2. Land use changes in the Wonogiri catchment area, 1981 and 1993

Land Use Category	Area in 1981		Area in 1993		Change in ha	
	ha	%	ha	%	Decrease	Increase
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Forests	11904	9.79	11876	9.76	28	
Wet Rice	22908	18.83	22912	18.83		4
Dry Agr. Land	62400	51.29	58744	48.29	3656	
Settlement and Homestead	22484	18.48	22664	18.63		180
Water Body	168	0.14	168	0.14		
Bare Land	1788	1.47	760	0.62	1028	
Comm. Forests	0	0.00	4528	3.72		4528
Total	121652	100.00	121652	100.00	4712	4712

Table 3. Matrix of land use change in the Wonogiri catchment area (in ha) for the years, 1981 and 1993.

Land use Category		Change to				
		(1)	(2)	(3)	(4)	(5)
Forests	(1)	0	0	0	28	0
WetRice	(2)	0	0	0	0	0
Dry Agr. Land	(3)	0	4	0	152	0
Settlement and Homestead	(4)	0	0	0	0	0
Bareland	(5)	0	0	0	0	0
Comm. Forests	(6)	0	0	0	0	0
Total		0	4	0	180	0

RESULTS AND DISCUSSION

The gross erosion resulting from the spatial overlay of various USLE factors in the Wonogiri watershed for the period of 1981–1985 and 1990–1994 are presented in Figure 3. Table 4 represents overall erosion classes in the Wonogiri watershed for the period of 1981–1985 and 1990–1994.

From the gross erosion data (Table 4), it can be seen that the watershed experiences a very high erosion, however there has been reduction of erosion rate between the two periods. The area with gross erosion within tolerance limits (0 – 10 ton/ha), and slight erosion increased from 14.04% to 14.72%, and 22.40% to 24.77%, respectively. While the area with moderate and very severe erosion decreased. This improvement was figured clearly from the average gross erosion for the whole of the Wonogiri watershed as given in Table 5. Figure 3 revealed that the steep sloping of dry agricultural land with no management practice are severely eroded (>100 ton/ha). It is also revealed that the reduction of erosion was mostly due to land use change from bare land to community forest, and due to implementation of bench terraces.

A great reduction of soil erosion was occurred in the Tirtomoyo and Upper Solo sub–basins. It is understandable since the improvement of land cover mostly took place in this two sub–basins, besides soil conservation activities were concentrated in these two sub–basins.

Table 4. Estimated gross erosion in the Wonogiri watershed for the period of 1981–1985

Gross erosion ton/ha	Erosion class	Area in % 1981–1985	Area in % 1990–1994
000 – 010	within tolerant limit	14.04	14.72
010 – 050	slight erosion	22.40	24.77
050 – 100	moderate erosion	13.98	13.63
100 – 250	severe erosion	12.12	18.39
>250	very severe erosion	37.46	28.49

Table 5. Average gross erosion in sub–basin

Sub–basin	Area ha	1981–1985			1990–1994		
		E t/ha/yr	DR %	SY t/ha/yr	E t/ha/yr	DR %	SY t/ha/yr
Keduang	41736	167,98	19.55	32.84	159,33	19.24	30.66
Tirtomoyo	22936	544,10	45.09	245.33	354,04	38.40	135.95
Beling	6504	261,17	13.47	35.18	213,50	11.60	24.76
Uppe Solo	20352	616,97	36.88	227.44	335,35	29.42	98.66
Alang	16380	176,45	27.21	48.01	159,81	22.98	36.72
Wuryantoro	13744	337,55	12.38	41.79	297,06	10.81	32.11
Wonogiri Basin	121652	323,26	33.61	108.64	228,43	27.38	62.55

E=gross erosion from the GIS technique, DR=deposition rate, SY=sediment yield

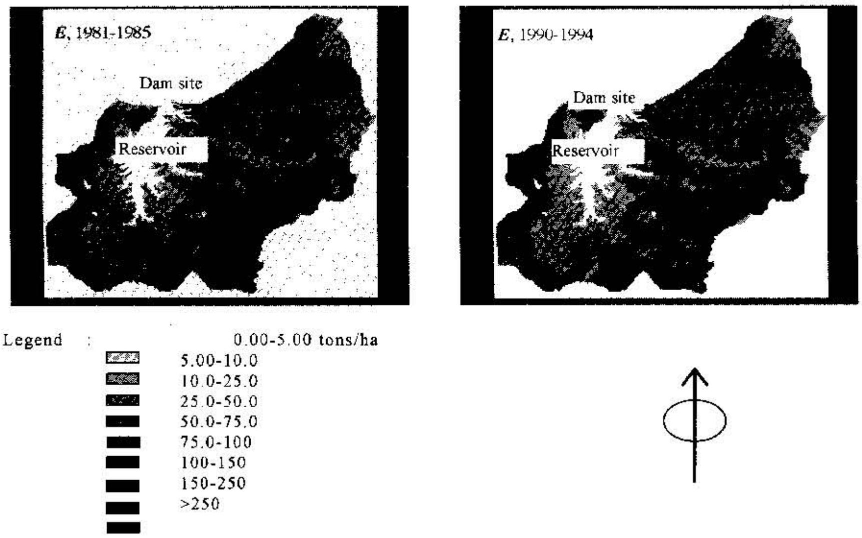

Fig. 3. Spatial and temporal gross soil erosion E (tons/ha/year) of the Wonogiri watershed for the period 1981–1985 and 1990–1994

Land cover improvement reduces not only soil erosion but also surface runoff (Banasik, 1989; Roger *et al.*, 1996). Analysis of streamflow in the Wonogiri watershed shows that the five–year moving average of the ratio of runoff–rainfall decreased from 0.71 in 1981–1985 to 0.54 in 1990–1994. The subsequent effects of this phenomena is than to reduce sediment delivery ratio, on the other words to reduce sediment yield.

The results of the present study are in line with the measured reservoir deposition (Table 1). The reduction of reservoir deposition rate was in accordance with the decreasing erosion rate on the catchment. This decrease may be overestimated if only caused by land use changes. The deviation in gross erosion may much due to soil conservation which took place during the period of 1988–1994.

CONCLUSION AND SUGGESTION

Land use/cover plays a critical role in the overall catchment area management project. Population pressure, however, has broken the golden rule of soil conservation: keeping continuous land cover. As consequence, soil is degraded seriously; soil erosion rises remarkably, and soil fertility decreased. Further consequence, the Gajah Mungkur reservoir was silted up seriously.

The results of this study more or less fit with the measured reservoir deposition. The rate of deposition was decreased during the last decade in accordance to the land use improvement and the effort of land rehabilitation/soil conservation. The alteration of land cover from bare land/dry agricultural land has reduced soil erosion/sediment yield and improve water conservation as well. Population pressure and food demand, however, limit further alteration of existing farmland (dry agricultural land) to nonfarm land that provides land cover permanently.

The results of this study can be used as guidelines to implement various soil conservation measures for different sub–catchment on priority basis, and to improve the strategy of watershed management.

It is suggested that the soil conservation should be focused not only on physical measures, but also non–physical activities. The latter is aimed to improve the farmer income as well as their awareness to the natural resources and the environment. The constrains faced in this area are the high pressure population with low income and low skill (education level), and limitation of the agricultural land. They are shortage of food and fire wood, and therefore, destruction of land by men is apparent as they cultivate, graze, and cut–down trees indiscriminately. Continuous guidance and counseling to improve farmers skill and awareness on the sustainability of natural resources have to be carried out. Without participation of the local community, the conservation efforts would be ineffective.

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