Soil erosion characterization in an agricultural watershed in West Sumatra, Indonesia

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ABSTRACT Quantitative evaluation of soil erosion rates provides important baseline data to investigate, manage and improve land use systems. However, soil erosion analyses have not been sufficiently conducted in Indonesia. In the present study, we investigated the spatial distribution of soil erosion rates in relationship to land use patterns in the Sumani agricultural watershed, the primary rice-producing region in West Sumatra. The soil erosion rate was estimated applying the Universal Soil Loss Equation (*USLE*) using representative soil survey data obtained in the watershed. Sediment delivery ratio (*SDR,* i.e. sediment yield / soil erosion rate) was determined from sediment yield data, which was generated in a previous study. Soil erosion rate in the Sumani watershed was estimated as 43.13 Mg $ha^{-1}y^{-1}$ in 1992 and 58.91 Mg $ha^{-1}y^{-1}$ in 2002 (annual averages). These values are far greater than the tolerable soil erosion rates (TER) for Indonesia i.e. 14 Mg $ha^{-1}y^{-1}$. Natural factors, including heavy rainfall and local soil properties in a landscape susceptible to soil erosion were the fundamental factors responsible for the high soil erosion in the watershed. In addition to these causes, changes in land use accelerated soil erosion. From 1992 to 2002, the soil erosion rate showed a 37% increase due to forest conversion to agricultural fields. *SDR* in five sub-watersheds exhibited relatively small values ranging from 6% to 15%, indicating an accumulation of eroded soil particles in flat areas in the lower part of the watershed where the land is primarily allocated to sawah.

Key words: *USLE*, Indonesia, land use change, erosion, sediments

INTRODUCTION

Soil erosion in Indonesia is one of the most serious environmental degradation problems the country faces (Kusumandari and Mitchell 1997). Watershed soil erosion and subsequent river deposition are of the utmost concern in circumventing erosional processes for two reasons. First, rich fertile soil is eroded from watersheds; and second, this results in a reduction in reservoir capacity and a degradation of downstream water quality (European Environment Agency 1995, Zhow and Wu 2008). Deforestation due to forest fires, grazing, legal and illegal logging, inappropriate methods of tillage or other agricultural practices accelerates soil erosion, resulting in large increases in sediment inflow into streams (Pimentel 1998). Approximately two million $ha^{-1}y^{-1}$ of Indonesian forest have been lost due to deforestation, including land use conversion to agriculture (World Resources Institute 2003). Deforestation increased the soil erosion rate from approximately six to 12 Mg $ha^{-1}y^{-1}$, which resulted in economic losses of US $340-406 million per year in 1989, caused by the reduction of agricultural production in Java Island (World Bank 1989).

The Sumani watershed is the primary rice-producing region in West Sumatra and faces Lake Singkarak (107.8 km^2, 364 m asl), which supplies hydroelectricity for West Sumatra and Riau Province. The watershed exhibits hilly topography and high yearly precipitation (> 2400 mm y^{-1}), indicative of a landscape susceptible to erosion. Heavy rainfall characteristic of the region has induced flooding and landslides, resulting in not only land degradation but also endangering human life in the watershed. In addition, population increases in Sumatra have accelerated a land use shift from forest to agricultural fields with intensive cultivation practices, exacerbating soil erosion in the watershed. Sharp fluctuations in the river water levels, and flooding in the lower parts of the watershed in recent years can be attributed to eroded materials sedimentation in the lower river streams and tributaries. These events have caused serious damage to downstream villages and the infrastructure of the Sumani watershed. In addition, Lake Singkarak hydroelectric power plant ceased operations due to high amounts of suspended soil in the water to avoid problems with facilities operations (personal communication).

Therefore, land management planning for the Sumani watershed must be reevaluated and new management instituted to mitigate natural and man-induced problems and reduce soil erosion. In order to achieve this, the present status of soil erosion in relationship to land use patterns in the watershed must be assessed. However, it is not practical to conduct direct measurements over the entire watershed due to its extensive area. Therefore, due to the time and financial constraints associated with such large field intensive studies, it is more common to estimate soil erosion using models. Several types of models to estimate soil erosion have been developed and applied worldwide, including Universal Soil Loss Equation (*USLE*, Wischmeier and Smith 1978), WEPP (Amore et al. 2004), ANSWERS (Ahmadi et al. 2006), AGNPS (Walling et al. 2003) and EUROSEM (Morgon et al. 1998). Among process-based models, WEPP, ANSWERS, AGNPS and EUROSEM provide logical results. However, these models require numerous input data that are generally not available and difficult to measure in most watersheds in Indonesia due to financial and technical limitations. *USLE* has been used as an evaluation tool for soil conservation throughout Indonesia (Kusumandari et al. 1997, Moehansyah et al. 2004) because it accepts rather small data sets and is easy to adopt. The Ministry of Agriculture and Ministry of Forestry in Indonesia set up a soil erosion standard based on a *USLE* estimated value (Indonesian Government Role No. 41 in 1999) to control soil erosion. In general, there is no single best model for all applications. Consequently, the most appropriate model depends on the purpose of the study and the characteristics of the watershed (Shamshad et al. 2008). In the present study, *USLE* was judged sufficient to estimate soil erosion rates as it provides a relative ranking of watershed soil loss risk when accurate parameter values are used. In addition, as mentioned above, *USLE* has been used as a soil conservation evaluation tool in Indonesia. However, despite its application, few studies have been conducted that measure or estimate soil erosion processes in Indonesia.

In the present study, we characterized soil erosion conditions under current land management systems in the Sumani watershed. We used *USLE* and applied the kriging method (Golden software 2002), with the aim of mapping the spatial distribution of soil erosion rates and dominant erosion factors influencing erosion. The results of our study served to generate data to provide discussion for better management of the Sumani watershed. This is the first study in Indonesia to map the soil erosion status at a watershed scale of the Sumani, 58,330 ha, based on detailed soil analyses data. We felt confident we could produce more precise estimate values than previous studies in Indonesia.

MATERIALS AND METHODS

Study area

The Sumani watershed occupies 58,330 ha and is located in Solok regency (latitude 0°36′08″ to 1°44′08″ S, longitude 100°24′11″- 101°15′438″ E) in West Sumatra, Indonesia (Fig. 1). The watershed outlet is Lake Singkarak. Average annual precipitation ranges from 1669 to 3230 mm, and the watershed occupies an elevation from 300 m to 2500 m above sea level (asl) (Farida et al. 2005). Average annual temperature ranges from 19 to 30 ℃, which varies along an altitudinal gradient. Average annual humidity varies from 78.1 to 89.4%. The Sumani watershed provides a range of land uses, including primary forests, tree crop gardens (mixed gardens, coconuts and tea gardens), vegetable gardens, sawah, bush (shrubs, grasses and *alang-alang* [land dominated by *Imperata cylindrica* (Poaceae)]) and settlements. The term sawah refers to a levelled and bounded rice field with an inlet and outlet for irrigation and drainage (Wakatsuki et al. 1998). Mixed garden refers to land where perennial crops, primarily trees such as coconuts, cloves, coffee, teak, mahogony, sawo (*Achras zapota* L.), avocados, melinjo (*Gnetum gnemon*), rubber, and cinnamon are planted in a combination with annual crops (Karyono, 1990). Chillies (*Capsicum annum* L.), onions (*Allium cepa* L.), soybeans (*Glycine max* L.), corn (*Zea mays* L.) and sweet potatoes (*Ipomea batatas L.*) are the major crops in vegetable gardens. The watershed is divided into eight geological types, i.e. breccia; andesites of Mt. Talang; alluvium from andesitic volcanic sources; colluvial deposits; welded tuff; quartz rich andesites; shale that are part of the Tuhur Formation; andesitic to basaltic lava (Farida et al. 2005). The Sumani watershed (SW) consists of five sub-watersheds including Sumani (S1), Lembang (S2), Gawan (S3), Aripan (S4) and Imang (S5).

Fields survey and analytical methods

Soil surveys were conducted at 81 sites (42 sites in 2002 and 39 sites in 2006) occupying a variety of geomorphic

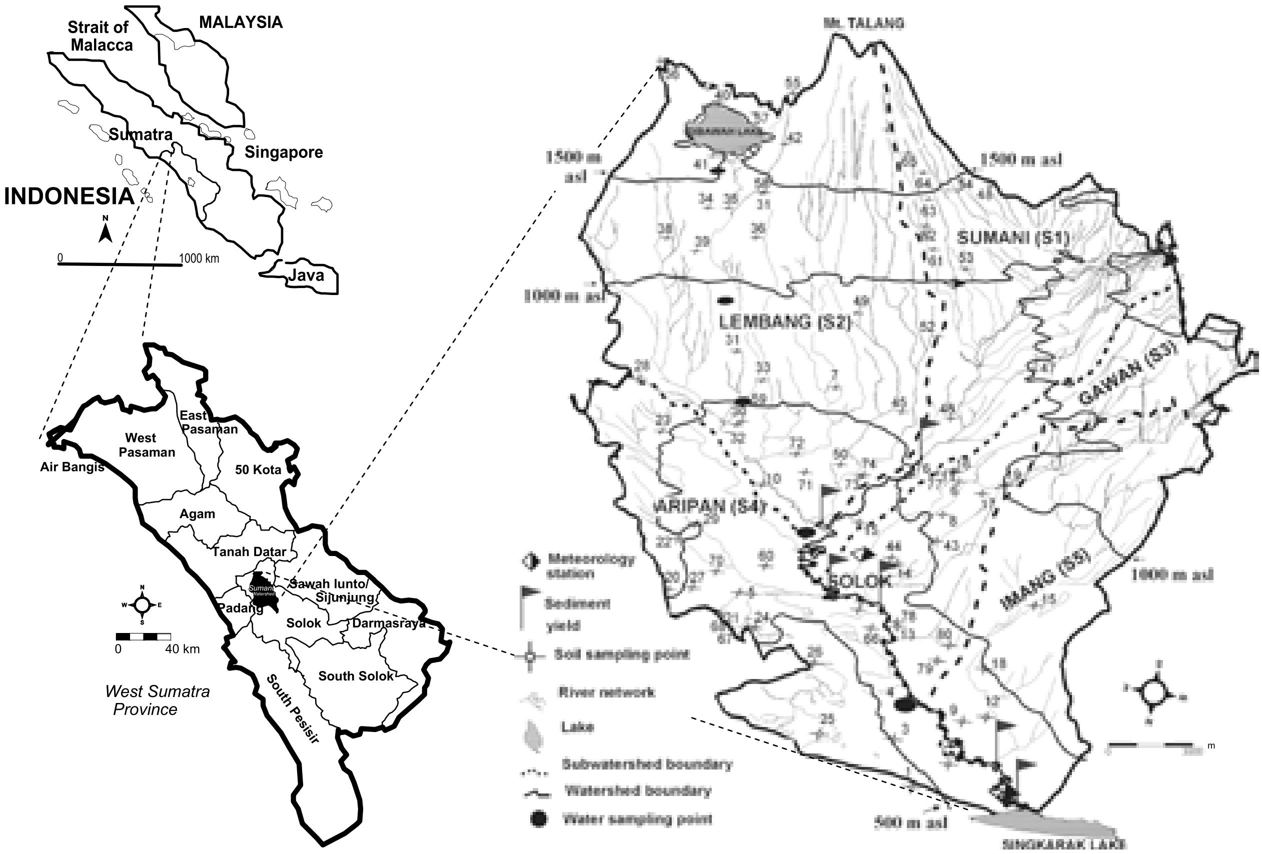

Fig. 1. Study site and distribution of soil sampling points sites in Sumani watershed, West Sumatra, coordinates bases on UTM coordinate system WGS 84 Zone 47 Southern Hemispire.

positions, land use types (Figure 1) and soil types (Table 1). Soils were collected at depths of 0-20 cm and 20-40 cm. Soil samples were air dried and sieved through a 2 mm mesh for physico-chemical analyses. The Walkley and Black type method (IITA, 1979) was used to determine organic carbon content. Soil permeability followed the protocol of Reeve (1965). Soil texture was determined by the pipette method (Gee and Bauder 1986), and bulk density was established by volumetric sample (Blake and Hartge 1986). During the field surveys, we also confirmed watershed soil, vegetation types and land uses.

In addition, we conducted a preliminary study of the water quality in the main rivers of the watershed, i.e. the Sumani and Lembang Rivers (Fig. 1). We collected water samples at five points along the main rivers and determined PO_4-P and NO_3-N concentrations every month from August 2006 to February 2007. Nitrate nitrogen concentration was determined using the diazotization method following the cadmium reduction protocol; and PO_4-P concentration was ascertained using the ascorbic acid technique following the standard methods of water analyses (American Public Health Association/American Water Works Association/ Water Environment Federation, 1995).

Data processing for mapping

USLE data processing was conducted in Surfer® 8 (Golden software, 2002) with factors obtained from meteorological stations, detailed soil surveys, topographic and land use maps, and satellite images.

Mapping procedure

Regionalized variable theory successfully applied to soil properties interpolation for nearly 30 years was used in the present study. In this way, all *USLE* factor data described in the study could be successfully processed and mapped. Interpolation is a Surfer® 8 term for an optimal Delaunay triangulation. The algorithm generates triangles by drawing lines between data points. The original points are connected in such a way that no triangle edges are intersected by other triangles. The result is a patchwork of triangular faces over the extent of the grid. The method is an exact interpolator (Golden software 2002). The theory provides a convenient

Table 1. Soil properties and *K*- factors in soil groups in of the Sumani watershed

Soil group	Topographical position	Land use type	coarse sand (%)	very fine sand (%)	silt (%)	clay (%)	Organic matter (g kg^{-1})	Soil water Permeabily (x 10^{-5} m s^{-1})	Soil Structure code	*K*-factor
Aeric Tropaquept	Lower, n=13	Sw, Vg, Sr	16.05	2.81	55.27	25.86	38.4	2.67	2, 4	0.27
	Middle, n=1	Sr	5.70	5.81	54.20	34.30	40.0	1.86	2	0.21
Andic Humitropept	Middle, n=3	Vg, MG,	14.10	1.68	50.43	33.78	29.4	19.79	3, 4	0.25
	Upper, n=2	T, Sr	4.47	3.08	59.98	32.47	96.7	40.53	3, 4	0.06
Oxic Hapludand	Lower, n=2	F, MG,	2.65	5.35	65.10	26.90	45.5	0.12	3	0.39
	Middle, n=6	Sw, MG,	6.10	1.77	53.37	38.76	40.5	4.16	1, 2, 3	0.22
	Upper, n=19	Vg, Sw, MG, T, F	8.81	2.00	63.66	25.53	78.3	13.09	2, 3, 4	0.15
Typic Distropept	Lower, n=9	Sw, F, MG,	7.55	1.81	66.51	24.13	55.1	7.06	2, 4	0.28
	Middle, =12	Sr, Mg, F, Sw	9.87	1.98	48.95	39.20	45.4	1.95	2, 4	0.22
Typic Eutropept	Lower, n=1	MG	20.50	1.20	27.00	51.40	55.7	> 56	4	0.19
	Middle, n=2	MG	4.65	8.65	46.30	40.40	37.7	0.56	2, 4	0.31
Typic Kandiudult	Lower, n=9	Vg, MG,	4.09	1.87	45.94	48.10	51.7	2.63	2, 4	0.19
	Middle, n=3	Sw, Sr, F, Sr	2.80	3.00	40.73	53.47	51.7	1.49	4	0.21

Coarse sand (size 2-0.2 mm), very fine sand (0.05-0.02 mm), silt (0.02-0.002 mm), clay (< 0.002 mm).
Lower, 300-500 m asl; Middle, 500-1000 m asl; Upper > 1000 m asl. Sw, sawah; Vg, vegetable garden; Sr, shrub; MG, mix garden; T, tea; F, forest. Soil structure code 1, very fine granular <1 mm; 2, fine granular 1-2 mm; 3, medium – coarse granular 2 – 10 mm; 4, blocky, platy, massive.

summary of data variability (in the form of a semi-variogram) and an interpolation technique, i.e. a kriging method. From a theoretical point of view, kriging provides the best linear unbiased estimates, a more accurate description of the data spatial structure and valuable information regarding estimation error distributions (Kravchenko and Bullock 1999). Individual files for respective *USLE* factor parameters and land use pattern were constructed by grid modeling procedures in Surfer® 8 (Golden software 2002) to calculate soil erosion rates in a spatial domain.

A 1:50000 topographic map, including the Sumani watershed, was input to Surfer® 8 by manual digitization. This vector elevation map was converted into grid format with a spatial resolution of 125 m x 125 m. Based on kriging in Surfer® 8, an interpolation routine was employed to derive the elevation surface from the rasterized line data. Takata et al. (2008) details the kriging method and its applications. The digital elevation map (DEM) served as the foundation raster layer for other topographic-related analyses. The soil properties, land use types, and other related attributes were also input to Surfer® 8 by manual digitization and keyboard entry. Polygons and their attributes were connected with uniform code. Polygon is the command method to draw an irregularly shaped area. These vector maps were also converted into rasters, which had the same reference system and resolution as the DEM. The data sources were converted into a grid format. Each grid was defined based on an exact location in space determined by the grid orientation and grid size, and each grid was allocated its specific attributes. To predict soil erosion rate in the spatial domain, a map unit was set at 125 m by 125 m, which was the finest resolution size available with the given data set and authors' computational facilities. Each grid was assumed a single slope plane in order to apply a *USLE* to each grid.

USLE

USLE expresses mean annual soil loss as a function of six erosion factors:

$$E = R \times K \times L \times S \times C \times P \quad (1)$$

where E is estimated soil loss in Mg ha^{-1}y^{-1}, R is rainfall erosivity (dimensionless); K is inherent soil erodibility (dimensionless); L is slope length factor (dimensionless); S is slope factor (dimensionless); C is crop cover factor (dimensionless); and P is a factor that accounts for the effects of soil conservation practices (dimensionless). Distributions of respective factors in the watershed are summarized in Figure 2 (a-h).

The watershed was divided into 39316 grids of size 125 m x 125 m. Basic data were allocated or estimated in each grid by reading maps and a Landsat image for land use types and altitude or the kriging method for soil

Table 2. Monthly rainfall and rainfall erosivity (*R*-factor) in the Sumani watershed

Month	Monthly rainfall (mm)		Rainfall erosivity	
	1992-1993	1996-2007	1992-1993	1996-2007
Jan	249.0	275.4	166.20	212.43
Feb	192.7	160.4	187.76	115.16
Mar	221.3	221.4	172.04	172.06
Apr	162.3	246.2	131.98	187.01
May	336.0	186.2	269.77	135.94
Jun	170.3	114.9	197.52	75.70
Jul	216.3	158.2	181.29	113.36
Aug	106.3	142.0	56.17	99.38
Sept	110.3	180.2	61.98	127.92
Oct	109.3	199.9	64.39	135.53
Nov	288.0	281.3	243.56	203.61
Dec	248.0	296.5	168.44	223.93

properties. Based on these data, *USLE* factors were calculated in each grid unit. Among the above factors, *C*- and *P*-factors can be field modified to improve soil erosion and agro-economical conditions in the watershed.

Rainfall erosivity factor (*R*)

The *R*-factor is rainfall erosivity, which predicts the potential for precipitation to cause soil erosion. To compute the monthly *R*-factor value, the following equation proposed by Bols (1998) for Indonesia was applied:

$$R = 6.19(Rf)^{1.21}(Rn)^{-0.47}(Rm)^{0.53} \quad (2)$$

where *R* is monthly erosivity, *Rf* is total monthly rainfall, *Rn* is the number of days of rain per month, and *Rm* is the maximum rainfall during 24 hours in an observed month. Table 2 shows general monthly rainfall data and monthly *R*-factor values calculated with the above equation for two study periods. A clear dry season has not been observed in the study area, therefore the monthly rainfall and *R*-factors did not exhibit a seasonal pattern. The results indicated a highly fluctuating seasonal pattern on a yearly basis.

Soil erodibility factor (*K*)

K-factors represent soil susceptibility to erosion and the rate of run off measured under standard plot conditions. The *K*-factor value was computed using the following equation (Wischmeier and Smith 1978):

$$100K=2.713M^{1.14}(10^{-4})(12-a)+3.25(b-2)+2.5(c-3) \quad (3)$$

where *M* is given by $[(St - Svf)/100] - Cf$, *a* is the percentage of soil organic matter content, *b* is the structural code, *c* is the soil permeability class code, *St, Svf* and *Cf* are the percentage of silt, very fine sand and clay fractions, respectively. Soil data are shown in Figure 1 and Table 1.

In general, for successful application of the model *R*- and *K*-factors are the most important characteristics of local conditions that require evaluation (Chris and Harbor 2002). Not all of the grids possessed precipitation and/or soil data analyses to calculate *R*- and *K*-factors. In this case, interpolation by the nearest neighbor kriging method (Golden software 2002) assigned the value from the nearest grid possessing soil analyses data. This method is useful and provides robust results as reported by Goovaerts (2000) and Takata et al. (2008).

Slope length and steepness factor (*LS*)

Each grid was considered a single slope plane. The *LS*-factor was calculated using the equation presented by Wischmeier and Smith (1978). Liu et al. (2000) reported that the slope length exponent in the equation did not change with an increase in slope gradient from 20 to 60%, while it changed in the condition with that less than 20%. Therefore, in the present study, we used two equations according to slope gradient, i.e. (4) for slope gradient less than 20% and (5) for slope gradient >20% (Renard and Jeremy 1994, Irvem et al. 2007)

$$LS = (L/22)^{m}(65.41\sin^2 X - 4.56\sin X + 0.065) \quad (4)$$

$$LS = (L/22)^{0.7}(6.432\sin(X^{0.79})\cos(X)) \quad (5)$$

where *L* is the slope length in m, *S* is slope percentage, *X* is the degree of slope, and *m* is an exponent that varies with slope gradients, i.e. 0.2 for < 1%, 0.3 for 1 – 3%, 0.4 for 3.5 – 4.5% and 0.5 for > 5%.

Cover crop (*C*) and conservation practices (*P*) factors

Land use types in the Sumani watershed were investigated by interpreting Landsat TM 2002 images, which were confirmed with field surveys in August 2007 and 1992 land use maps based on aerial photographs. Abdurachman et al. (1984) (Table 3) indicated that *C*- and *P*-factors are land use features that do not vary widely among regions. Each land use type possesses a cover crop (*C*) factor value. Forest exhibited the smallest and vegetable garden the highest *C*-factors, with the exception of settlements. Major soil conservation practices used in the Sumani watershed were based on ground coverage by grasses or shrubs in vegetable, mixed and coconut gardens, and terrace in sawah (Table 3). The conservation practice (*P*) factor is the soil erosion ratio

Table 3. *C*- and *P*- factors and land use for soil conservation practices

Land use	Conservation measures	*C*-factor	*P*-factor
Vegetables garden	Ground coverage[a]	0.4 [b]	0.5 [b]
Mixed garden and tea	Ground coverage	0.2 [b]	0.5 [b]
Coconut garden	Ground coverage	0.32 [b]	0.5 [b]
Sawah	Terraces	0.01 [b]	0.4 [b]
Shrub and *alang-alang*	none	0.02 [b]	1.0 [b]
Pine plantation	none	0.002 [b]	1.0 [b]
Grass land	none	0.29 [b]	1.0 [b]
Forest	none	0.001 [b]	1.0 [b]
Settlement	none	0.95-1 [b]	0.4 [b]

[a] Grasses or shrubs covered land surface of 20-80%.
[b] Sources from Abdurachman et al (1984).

associated with a specific conservation practice (Renard et al. 1997). Farmers typically apply the same conservation practices for the same land use type in the Sumani watershed, therefore a *P*-factor was given to a land use type following the values suggested by Abdurachman et al. (1984) (see Table 3). The land use patterns in the Sumani watershed in 1992 and 2002 are depicted in Figure 3 (a, b).

Tolerable erosion rate (TER) for agricultural production

TER is defined as a maximum rate of soil erosion that permits crop productivity to be sustained economically (Renard et al. 1997) and is a fundamental indicator for soil conservation planning. However, in soil conservation planning activities in Indonesia, the TER value has been influenced by local government policies. For economic reasons, soil erosion in agricultural lands has often been permitted to exceed guidelines of soil erosion values set by local governments. Therefore, the Indonesian government decided to establish a TER related to sustainable agricultural production at the national level. According to the Indonesian government's technology manual for soil and water conservation, the TER cannot exceed 14 Mg $ha^{-1}y^{-1}$ and was based on plot experiments conducted in the country (Kusumandari et al. 1997, Department of Forestry 1985). It is higher than that of China, which is <10 Mg $ha^{-1}y^{-1}$ (Shi et al. 2004). In the present study, we used this TER as a criterion to evaluate the soil erosion status in the Sumani watershed.

Sediment delivery ratio (*SDR*)

Walling et al. (1994) reported that *USLE* calculates the total mass of sediment delivery, which will be approximately two to seven times higher than the sediment yields measured at watershed outlets. Sediment delivery ratio (*SDR*) is the amount of sediment that is actually transported from eroding sources to a measurement point, such as the watershed outlet compared to the total amount of soil that is lost over the same area above the point of detachment (Lu et al. 2006, Zhow et al. 2008). It is dimensionless and is conventionally expressed as follows:

$$SDR\ (\%) = Y/E \times 100 \quad (6)$$

where Y is the average annual sediment yield per unit area and E is the average annual erosion rate for the same area in Mg $ha^{-1}y^{-1}$. Sediment yield data for 1992 was obtained from Saidi (1995). Sediment samples were collected from the five sub-watershed outlets and one watershed outlet collection at a monthly time-step for a period of one year (August 1992-July 1993). The 1992 *SDR* was calculated based on the sediment yield values and soil erosion rates estimated in the present study; 1992 *SDR* was used to estimate 2002 sediment yield.

RESULTS AND DISCUSSION

Spatial distribution of *R*-, *K*-, *LS*-, *C*- and *P*- factors

The Sumani watershed was separated into three rain erosivity classes based on data derived from three climatology stations (Fig. 2a, b). *R*-factors were low in lowlands near Lake Singkarak and increased in upper topographical positions in the watershed, which were attributed to increases in precipitation.

Soil properties and *K*-factors for respective soil groups classified in field surveys are shown in Table 1, and *K*-factor distributions are depicted in Figure 2c. Four soil orders including six groups, i.e. Oxic Hapuldant, Andic Humitropept, Typic Kandiudult, Aeric Tropaquept, Typic Distropept and Typic Eutropept (Soil Survey Staff

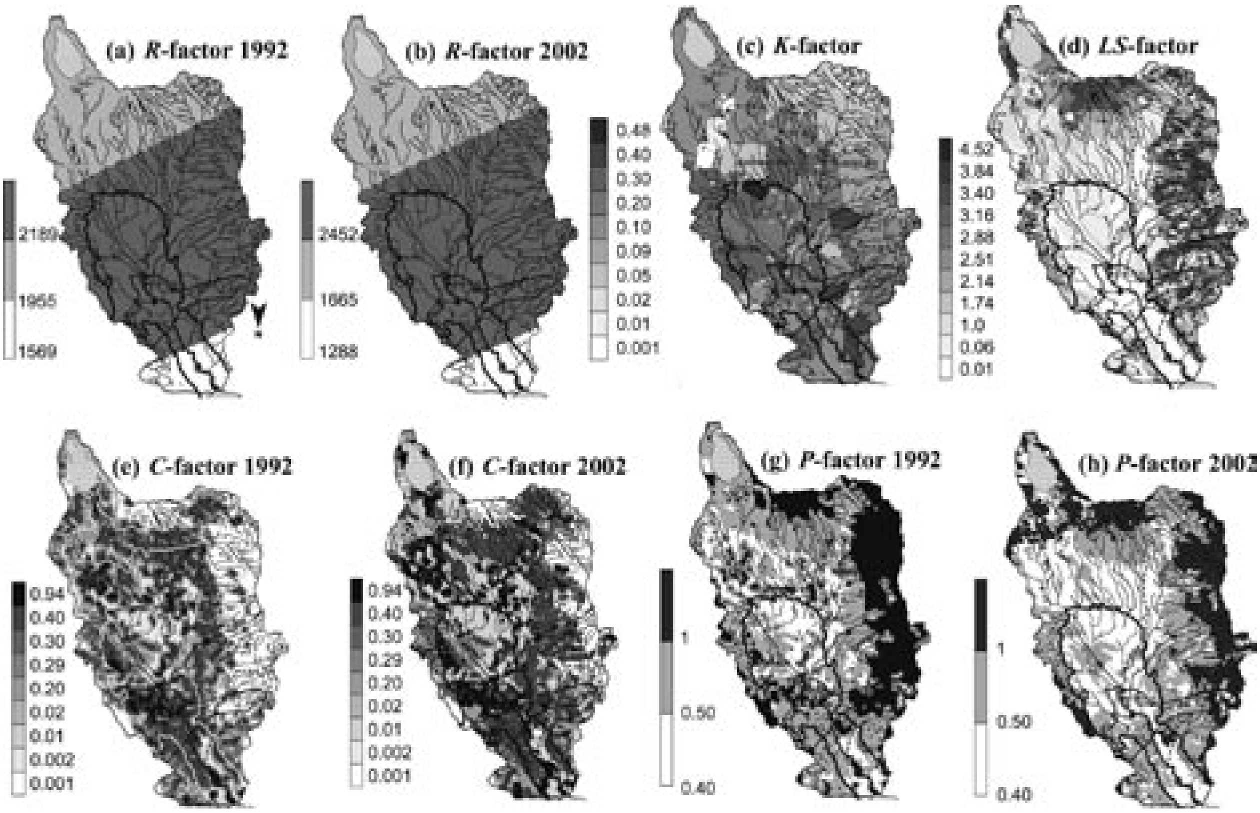

Fig. 2. Spatial distribution of resolute USLE factors in Sumani watershed.
a: *R*-factor 1992, b: *R*-factor 2002, c: *K*-factor, d: *LS*-factor, e: *C*-factor 1992, f: *C*-factor 2002, g: *P*-factor 1992, h: *P*-factor 2002

1990) were identified in the watershed. Soil group distribution was dependent on the type of parent material and topographical position. Both Oxic Hapuldant and Andic Humitropept are derived from volcanic ash materials and are distributed in the upland area of Lembang and Sumani sub-watersheds, where are closed to Mt. Talang. Typic Kandiudult is derived from colluvial deposits of andesitic to basaltic lava, and is distributed in the lowlands and uplands of the Aripan sub-watershed and in the mid-Lembang sub-watershed. Aeric Tropaquept is derived from alluvium and the colluvial deposits distributed in the lowlands of the Sumani, Lembang, Aripan, and Gawan dan Imang sub-watersheds. Typic Distropept is derived from the colluvial deposits and is distributed in the Imang, Gawan and Sumani sub-watersheds. Typic Eutropept is derived from the colluvial deposits and is distributed only in the Aripan sub-watershed.

The *K*-factor ranged from 0.001 to 0.48 and was clearly not attributed to soil groups, land use or topographical positions, but soil properties at specific sites in the watershed. Soils with low infiltration exhibited *K*-factors higher than 0.04 and were generally susceptible to soil erosion (Wischmeier and Smith 1978, Cassel and Lal 1992). Approximately 96% of the soils investigated in the Sumani watershed showed *K*-factors higher than 0.04, indicating the soil property of the watershed was largely susceptible to soil erosion.

Figure 2d depicts the distribution of *LS*-factors in the watershed. The values ranged from 0.001 to 4.52, and its average and standard deviation were 1.4 ± 1.3, respectively. Lowland areas with an altitude less than 500 m asl and land use of terraced sawah in middle to upper topographical areas showed relatively small *LS*- factors.

In terms of land use change in the Sumani watershed, forest area decreased by 13% from 1992 to 2002 (Table 4 and Fig. 3), and was primarily converted to agricultural fields, such as mixed and vegetable gardens. Some agricultural fields were converted to shrub and settlements during the ten-year period. The increase in mixed and vegetable gardens varied in sub-watersheds, as the original land use patterns differed. The agricultural fields increased by 18.2% in S5, and decreased by 6.9% in S2. Details on sub-watershed land use change are

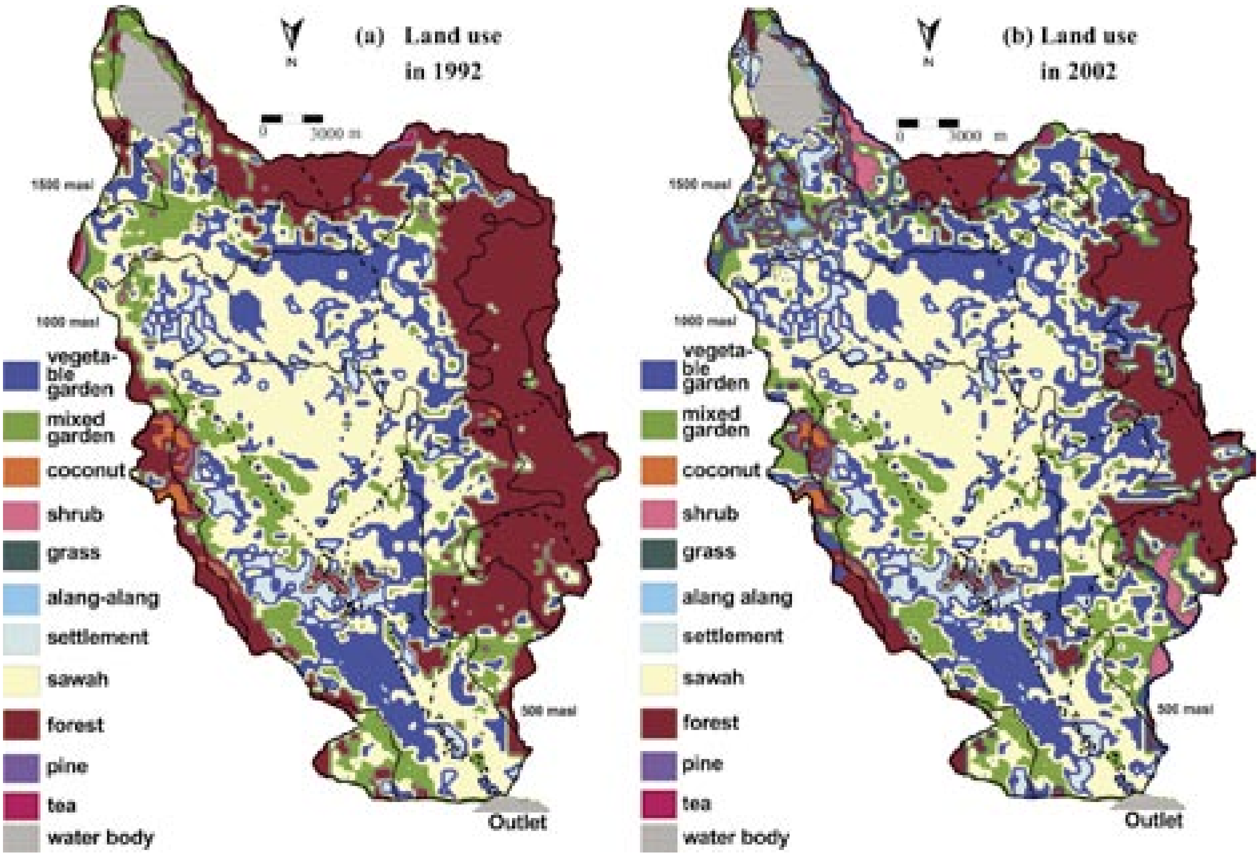

Fig. 3. Spatial distribution of land use patterns in Sumani watershed. a: 1992, b: 2002

Table 4. Change in land use type in the Sumani watershed during 1992 - 2002

Location	Area	Land use type												*C*-factor	
		Mixed garden		Forest		Vegetable		Sawah		Bush[a]		Settlement			
		1992	2002	1992	2002	1992	2002	1992	2002	1992	2002	1992	2002		
	(km^2)	(%)												1992	2002
S1	134.7	5.7	8.6	51.0	35.0	21.4	32.4	15.2	15.2	0.0	0.1	5.2	7.0	0.15	0.22
S2	201.8	12.2	6.3	12.7	5.4	21.7	20.7	39.6	37.4	2.1	13.6	11.4	16.5	0.22	0.26
S3	84.0	7.8	10.3	41.2	25.2	24.8	35.9	16.7	16.8	0.0	0.7	8.2	11.1	0.19	0.28
S4	107.9	22.5	25.9	12.6	6.6	22.9	22.9	16.8	15.9	0.4	1.6	16.8	19.0	0.32	0.35
S5	54.8	11.7	20.5	48.1	12.2	16.0	25.4	18.0	15.8	0.0	16.8	5.3	8.6	0.14	0.24
SW	583.3	11.9	12.2	28.9	15.9	21.7	24.9	24.4	23.3	0.9	3.7	9.9	13.3	0.21	0.27
Average soil erosion		44.60	66.90	0.62	0.64	110.6	132.27	0.99	1.04	43.28	38.60	45.75	72.01		

S1= Sumani, S2= Lembang, S3= Gawan, S4= Aripan, S5= Imang sub-watershed, SW= Sumani watershed,
[a] Bush includes shrub, grass and *alang-alang*

discussed below in relationship to soil erosion rates. Land use change experienced extensive progression in the period of economic crisis in Indonesia during 1997-1999. These land use changes affected *C*-factors (Fig. 2e, f and Table 4) and *P*-factors (Fig. 2g, h). The average *C*-factor in the Sumani watershed increased from 0.21 in 1992 to 0.27 in 2002 (Table 4) due to a decrease in forest cover, which exhibited the lowest *C*-factor of 0.001. The *P*-factor decreased from 1992 to 2002 (Fig. 2g, h) due to forest conversion to agricultural fields. Soil conservation practices were applied, resulting in a lower *P*-factor relative to forests (*P*-factor = 1.0). Although decreased

P-factors contributed to a reduction in soil erosion, values multiplied by *C*- and *P*- factors were still lower in forest than other land use areas. Therefore, the soil erosion rates in 2002 had increased due to land use changes relative to 1992. It should be noted that between 1992 and 2002, most of the sawah area was not changed (Fig. 3a, b). This was because very high priority was given to developing and maintaining sawah in the watershed, as it remains the main rice-producing region in Indonesia.

Soil erosion rates in the Sumani watershed

USLE estimated soil erosion rates for 1992 and 2002 are depicted in Figure 4. Soil erosion rates were classified into seven ordinal classes (Fig. 4a, b). The annual average soil erosion rate in the Sumani watershed (SW) was estimated at 43.13 Mg ha^{-1}y^{-1} in 1992 and 58.91 Mg ha^{-1}y^{-1} in 2002 (Table 5). Soil erosion rates greater than 100 Mg ha^{-1}y^{-1} were detected in areas of steep slope during both years. These areas exhibited the highest *R*-, *K*- and *LS*-factors in the watershed (Fig. 2a, b, c, d), indicating the strong influence of natural factors on soil erosion. In addition, land use types influenced on soil erosion rates (Figs. 3 and 4). Soil erosion rates were generally very high in areas of vegetable and mixed garden land use types, especially with steep slopes, indicated by high *LS*-factors (Fig. 2d). In contrast, soil erosion rates less than 0, indicating deposition, were found in lowlands where sawah was the major land use type. In 1992, 57.1% of the watershed area, including sawah, mixed and vegetable gardens in flat areas and forests exhibited soil erosion rates less than the TER (<14 Mg ha^{-1}y^{-1}). According to the erosion risk class criteria of Odura (1996) and Irvem et al. (2007), 7.2, 8.8, and 26.9% of the watershed areas were classified into low (14-28 Mg ha^{-1}y^{-1}), medium (28-56 Mg ha^{-1}y^{-1}), and high (>56 Mg ha^{-1}y^{-1}) level classes, respectively.

The conversion of forest into agricultural fields, i.e. mixed and vegetable gardens in the Sumani watershed in 1992 and 2002 was more evident in sub-watersheds S1, S3 and S5, where forest coverage was relatively high in 1992. In S5, forest area was reduced by more than 70%. Mixed and vegetable gardens exhibited an increase, with subsequent abandonment as indicated by an increase in bush between 1992 and 2002 (Table 4). Some S2 mixed garden was reduced and converted to bush. The human population in the watershed increased by 6716 people between 2000-2002 (Solok statistical agency 2002). The 1992 and 2002 data show that settlements increased in all

Table 5. Sediment yields in sub-watersheds and the Sumani watershed in August 1992 to July 1993

Location	Soil Erosion Rate (Mg ha^{-1}y^{-1})		Study area (km^2)	Measured Sediment Yield	Estimated Sediment Yield	SDR (%)
				1992	2002	
	1992	2002		(Mg ha^{-1}y^{-1})		
S1	33.55	49.39	177	5.17	7.61	15.41
S2	38.5	40.49	192	3.88	4.09	10.1
S3	59.44	98.81	80	3.49	5.80	5.87
S4	45.14	57.08	70	3.85	4.87	8.53
S5	53.73	91.64	64	6.64	11.32	12.35
SW	43.13	58.91	583	4.53	6.18	10.50
Malaysia in 2005[a]						
B. Teh (0.37)	93.76		30.27	10.87		12
B. Cempedak (0.37)	152.72		31.74	18.13		12
Kuala Tasek (0.37)	123.19		63.09	14.50		12
France in 2001[b]						
Lautaret (0.03)	28.34		12.92	0.87		30
Belgium in 2001[b]						
Hangeland (0.24)	11.14		12.92	7.29		65
Portugal in 1990[b]						
Amedoria (0.15)	20.52		10.75	2.89		14
Greece in 1993[b]						
Lagadas (0.13)	12.65		0.24	6.93		55

S1= Sumani, S2= Lembang, S3= Gawan, S4= Aripan, S5= Imang sub-watershed, SW= Sumani watershed
Number in parentheses indicate of *C*-factor, [a] Shamsyad et al. 2008, [b] Bakker et al. 2008

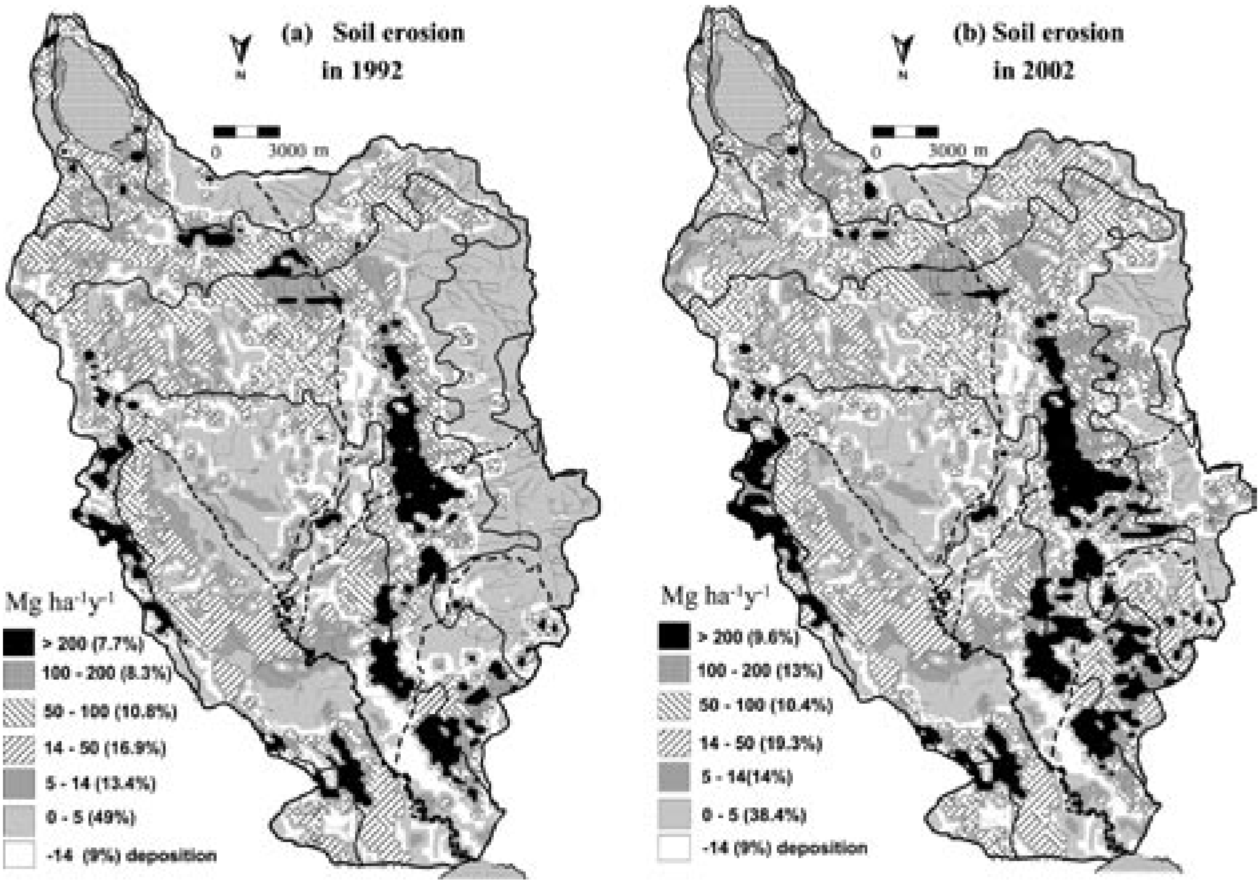

Fig. 4. Soil erosion rate in 1992 (a) and 2002(b)

sub-watersheds. As the consequence of these land use changes, the average *C*-factor increased, particularly in S1, S3 and S5, which further resulted in average soil erosion rate increases in the sub-watersheds and the Sumani watershed (Table 5). In S3 and S5, the soil erosion rate exceeded 90 Mg $ha^{-1}y^{-1}$, indicating the results of land use change in the absence of proper planning.

In order to reduce soil erosion in the Sumani watershed, the application of soil conservation measures must be considered, especially in vegetable and mixed gardens that have moderately high *C*-factors. Soil conservation measures have been applied to agricultural fields in the watershed. A stone terrace was in place at the sawah and vegetable gardens in upper topographical areas around Mt. Talang and Lake Dibawah. Stone embankments were also built in hillside slope areas. However, these conservation measures have been practiced in limited areas by farmers and not instituted by local governments. It is necessary to develop soil conservation plans for the entire watershed at the local or higher-level government scales. According to the Indonesian Soil and Water Conservation Act, agricultural fields developed on slopes greater than 45 percent should be reforested, and those developed on slopes from 25 to 45 percent can be controlled for erosion by terraced sawah and agroforestry. Shi et al. (2004) reported that as slope gradients increased above 10%, the spacing between terraces decreased, which made construction cost more expensive and limited the adoption of terrace development. Consequently, priority is typically given to other soil conservation measures, including irregular strip planting, contour planting and hedgerow systems in soil conservation on steep sloping areas in the Sumani watershed. Terracing is considered only if the other practices are not practical or effective for use with the agricultural system.

Land use types meeting the TER for a given area could in fact be most suitable to the region (Figs. 3 and 4). For example, mixed and vegetable gardens, and sawah were recommended as suitable land use types in the S1, S2 and S4 lower topographical areas (300 – 500 m asl), particularly because these land uses produce agro-economical benefit. In the sloping middle to upper topographical positions of the watershed, steepness and length of slope were decisive factors for specific land use types. In the sloping areas, soil conservation measures are essential regardless of the land use type, with the exception of forest, in order to maintain soil erosion rates under the TER. Under the present conditions, some areas with vegetable and mixed gardens or shrubs in mid- to upper topographical positions of the watershed exhibited soil erosion rates exceeding 100 Mg $ha^{-1}y^{-1}$. These areas were located on steep 35% to 50% slopes. *USLE* simulation recommended forest as the only suitable land use type (data not shown).

Sediment delivery ratio (*SDR*)

Sediment yield data measured in 1992 to 1993 (Saidi 1995) and *SDR* values in the Sumani watershed (and in other countries for comparison) are shown in Table 5. Sediment yields ranged from 3.49 to 6.64 Mg $ha^{-1}y^{-1}$ in sub-watersheds, and SW sediment yield was 4.53 Mg $ha^{-1}y^{-1}$. *SDR* ranged from 5.87 to 15.41% in sub-watersheds and 10.50% in the SW. *SDR* was low in the SW compared with the value reported by Walling et al. (1994), i.e. ranged from approximately 15 to 50%. The inconsistencies between the two measures might be due to deposition of eroded soils in lowland sawah in these study sites. Sediment yield in the SW was estimated at 6.18 Mg $ha^{-1}y^{-1}$ in 2002 and reached a soil erosion rate of 360.5 Gg y^{-1} for all the SW. It is widely demonstrated that (e.g. Shively 2006) soil erosion and sedimentation in water reservoirs degrades the quality of drinking water, increases the risk of flash floods, and reduces aquatic ecosystem productivity. Moreover, the Sumani watershed sediment load negatively impacted the hydroelectric power plant operations in Lake Singkarak (personal communication).

Average soil erosion and sediment yield in the Sumani watershed were lower than watersheds investigated in Malaysia, and higher than those in European countries (Table 5). In the Malaysian watersheds, rubber plantations occupied 50% of the watershed areas in terms of land use (Shamsyad et al. 2008), which resulted in an average *C*-factor of 0.37 and high soil erosion rates ranging 93.76 to 152.72 Mg $ha^{-1}y^{-1}$ in the Malaysian watersheds. In Greece and France, respectively low levels of precipitation; approximately 500 mm y^{-1} and 965 mm y^{-1} were the main reason for minimal average soil erosion rates. However, the difference in sediment yields was relatively small among all the watersheds compared in Table 5. *SDR* in the Sumani and Malaysian watersheds was smaller than European sites (Table 5). This can be explained by the deposition of eroded soils in lowland sawah in Indonesia and Malaysia, where agricultural practice uses lowlands as sawah. Although we did not directly determine eroded soil deposition into the sawah, we speculate that a quantity of soil particles that eroded in upper topographical positions in the watershed were transported and accumulated into lowland sawah.

River water quality

Land use change from forest to agricultural fields accelerated soil erosion and increased sediment yield (as described above). This is likely to cause water quality degradation downstream, including eutrophication. Nitrogen and phosphorous are the major nutrients lost from agricultural fields that can be non-point sources of these nutrients, and are the cause of lake eutrophication (Ekholm 2005, Woli et al. 2008). Average concentrations of PO_4-P and NO_3-N in river and irrigation water in the SW ranged from 0.09 – 1.8 mg L^{-1} and 3.9 – 5.4 mg L^{-1} from August 2006 to February 2007, respectively. According to Daniel et al. (1998), total P and N concentrations should not exceed 0.05 and 1.1 mg L^{-1}, respectively, in rivers entering lakes and reservoirs to control eutrophication. Both P and N exceeded these levels, which has probably resulted in eutrophication in the lower streams and in Lake Singkarak. In fact, abnormally high levels of algal and aquatic plant blooming have been observed in the Sumani watershed (personal communication). Although we have no quantitative data on the contribution of soil erosion to the nutrient loss from agricultural fields, soil erosion has surely accelerated the loss.

CONCLUSIONS

Overall, soil erosion rates in the Sumani watershed were high due to precipitation and soil properties in a landscape susceptible to soil erosion. In addition to these natural conditions, recent conversion of forest ecosystems to agricultural fields, i.e. mixed and vegetable gardens have likely accelerated soil erosion processes. Soil erosion status exceeded the TER in 2002 and was characteristic of a "high" erosion class (Odura 1996, Irvem et al. 2007). Soil erosion results in watershed degradation, including both soil and water resources, which has and likely continues to occur in the Sumani watershed. Nitrate-N and PO_4-P contamination in river water can be explained by soil erosion, which can ultimately lead to lake/reservoir eutrophication. It is vital to control soil erosion in the watershed to reduce the risks of resource and environmental degradation that are directly related to risks to human health. It is a complex balance to manage, because we must develop a means to maximize the benefits of agricultural production, while reducing the risk of soil erosion in the watershed. The Sumani watershed sustains human life and is a viable, functioning ecosystem. Natural environmental factors affecting erosion such as rainfall and soil cannot be changed, however better land use planning and management for the Sumani watershed can be implemented. This is the focus of our next study.

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