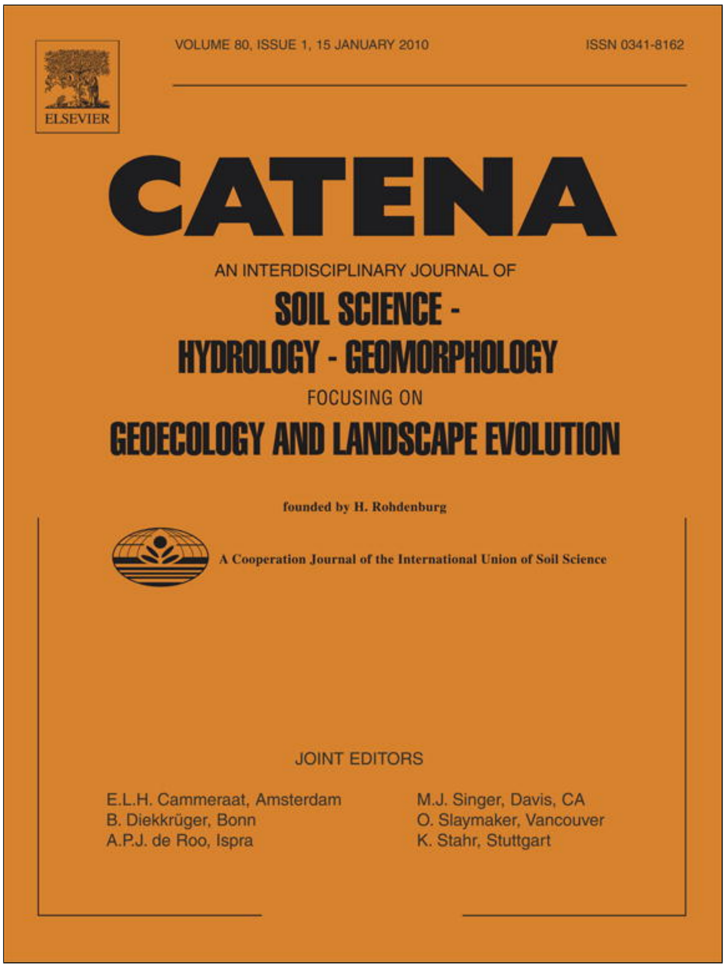
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Factors affecting soil loss at plot scale and sediment yield at catchment scale in a tropical volcanic agroforestry landscape

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ABSTRACT

Tropical deforestation and land use change is often perceived as the major cause of soil loss by water erosion and of sediment load in rivers that has a negative impact on the functioning of hydropower storage reservoirs. The Sumberjaya area in Sumatra, Indonesia is representative for conflicts and evictions arising from this perception. The purpose of this study as part of a Negotiation Support System approach was to assess sediment yield both at plot and catchment scale and to relate it to a variety of possible clarifying factors i.e. land use, geology, soil and topography. Sediment yield at catchment scale per unit area, was found to be 3–10 times higher than soil loss measured in erosion plots. A stepwise regression showed that the dominant factors explaining sediment yield differences at catchment scale in this volcanic landscape were a particular lithology (Old Andesites) and slope angle followed by the silt fraction of the top soil. In lithologically sensitive areas soil loss at the plot scale under monoculture coffee gardens decreases over time from on average 7–11 Mg $ha^{-1} yr^{-1}$ to 4–6 Mg $ha^{-1} yr^{-1}$, mainly because of the development of surface litter layers as filters and top soil compaction in the areas without litter, but remains higher than under shade coffee systems or forest. The runoff coefficient under monoculture coffee remains on average significantly higher (10–15%) than under forest (4%) or under shade coffee systems (4–7%). In lithologically stable areas soil loss remained below 1.8 Mg $ha^{-1} yr^{-1}$ and the runoff coefficient below 2.5% under all land use types, even bare soil plots or monoculture coffee gardens. Less than 20% of the catchment area produces almost 60% of the sediment yield. The reduction of negative off-site effects on e.g. the life time of a storage reservoir would benefit greatly from an improved assessment of the lithologies in volcanic landscapes and the consideration of potential sediment source and sink areas. In lithologically sensitive areas, a shift from sun to shade coffee systems may result in reducing surface runoff and soil loss, although water erosion at the plot scale is not the main contributor to sediment yield at the catchment scale. The quantification of land use effects on dominant erosive processes such as river bank and river bed erosion, landslides and the concentrated flow erosion on footpaths and roads can contribute to more targeted efforts and relevant incentives to reduce (or live with) sediment load of the rivers.

1. Introduction

Tropical mountain areas are very susceptible to soil erosion due to their rough topography and erosive climate (Dadson et al., 2003). This observation is not new as already at the beginning of the 19th century the high sediment load of the rivers in Java, Indonesia was considered a serious problem and was attributed to deforestation (Coster, 1937), slash-and-burn practices (De Voogd, 1937), landslides (De Voogd, 1937; Rappard, 1937), but also to poor land management practices (clean weeding) in coffee (and tea) gardens (Coster, 1941; De Haan, 1942). This focus on the effects of land use on the sediment load in rivers still resounds these days, not only at the policy level, but also in scientific literature e.g. (Valentin et al., 2008) and 'universal soil loss equations'.

Most erosion research in Indonesia is carried out at plot scale (40–500 m^2), mainly to quantify soil erosion rates under different land cover, slope and soil types. These research results have led to an impressive commitment to national level soil conservation programs. On Java in Indonesia, most upland agricultural land has now been terraced, but at the catchment scale the sediment yield problem persists and the effectiveness of these conservation programs has been challenged (Rijsdijk, 2005). These plot scale results have often been implicitly, but also explicitly scaled up to the catchment scale e.g. Nibbering and De Graaff (1998) and Schiettecatte et al. (2008). Many water erosion assessments were (and are still) based on the Universal

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Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its modifications. In the absence of reliable spatially distributed process-based models for the prediction of sediment transport at the drainage basin scale, area-specific sediment yield (SY; Mg $ha^{-1} yr^{-1}$) is often assumed to decrease with increasing basin area (Walling, 1983). However, scaling up soil losses measured at the plot scale can be notoriously inaccurate, as other soil erosion processes can be dominant at different scales (de Vente and Poesen, 2005). These processes can be gully erosion, bank erosion or mass wasting and they are not captured by plot measurements. Over the past two decades case studies have reported both positive and negative non-linear relation between basin area and SY (de Vente et al., 2007).

Multi-scale research (plot and catchment) allows to assess the SY resulting from these various erosive and filter processes (van Noordwijk et al., 2004). In Indonesia a large systematic monitoring effort of rainfall and runoff discharge Q at catchment scale was undertaken since the early seventies, when for many large basins (>250 km^2) the potential for irrigation and/or hydropower was assessed. The frequency of sediment load assessments is however much lower. The use of average daily runoff discharge values and the non-linearity between sediment concentration measurements and runoff discharge Q ($m^3 s^{-1}$) often leads to an underestimation of SY, especially during storm events that might only last a couple of hours.

Data collection at an intermediate scale (5–300 km^2) and hydrological modelling can provide more accurate estimations of sources of sediment and (temporary) deposition areas or changes in catchment response. Hydrological modelling has seen a rapid evolution on the last decades, nevertheless, the application of these models to small and meso-scale catchments is still limited in the tropics. Also in Southeast Asia studies at this intermediate scale are underrepresented, except for a few research studies e.g. in Northern Thailand and Malaysia (Chappell et al., 2004, 2006; Thanapakpawin et al., 2007).

The calculation of SY requires runoff discharge Q ($m^3 s^{-1}$) and sediment load data, consisting of suspended sediment concentration (SSC; mg l^{-1}) and bedload (BL). Continuous, or near-continuous, streamflow or runoff discharge data can be calculated from water level recorders, where the stage or water level is converted to discharge based on a site-specific stage–discharge relationship (Horowitz, 2003). SSC data are generally based on a limited amount of samples, while bedload is often based on an even smaller sample frequency. As the sediment load at a particular location generally increases with increasing runoff discharge Q, sediment rating curves have been developed to relate runoff discharge Q to sediment load.

Possible causes of high sediment loads at the catchment outlet and their perceived increase over time could be steep hill slopes, unstable lithologies, soil compaction, land use change and deforestation in particular. A comparison of SY at catchment scale with plot scale erosion data allows to explore the homogeneity of the area and the effects of spatial scale on SY.

The specific objectives of this case study in the Way Besai are

(1) to explore to what extent SY varies spatially between the most important subcatchments;
(2) to attribute measured differences in SY to variables related with topography, geology, soil and land use;
(3) to explore the effect of scale on SY measurements in a tropical environment;
(4) to explore to what extent there has been an increase in SY over the years affecting the Way Besai storage lake;
(5) to assess the effect of agroforestry practices on runoff and SY.

2. Study site

The Sumberjaya subdistrict, West-Lampung, Sumatra, Indonesia is situated in the humid tropics between 104°25′46.5″–4°26′51.4″ E and 5°01′29.9″–5°02′34.2″ S and comprises the upper Way Besai catchment (41,500 ha), a caldera of 20–25 km diameter in a volcanic landscape (Fig. 1). According to the Land unit and soil map for Sumatra (CSAR, 1989,1991) and after conversion of the units to the World Reference Base (WRB) (IUSS Working Group WRB, 2007) the soils are for 93.5% Cambisols (often with Andic properties), 6% Andosols and 0.5% Fluvisols and Gleysols.

The altitude ranges between 720 m and 1870 m asl, with an average of 987 m asl. The most important land cover types are coffee gardens on the slopes (70%), forest on the mountain tops (12%) and paddy rice in the valleys (9%). A past land use change study (Verbist et al., 2005) shows that forest cover declined from 46% in 1973 to 12% in 2006, while the percentage of coffee gardens increased from 7 to 70%. The last 20 years monoculture coffee gardens are gradually transformed into agroforestry systems with shade trees (Verbist et al., 2005). At an altitude of 987 m the average daily air temperature of the upper Way Besai catchment is 22.4 °C and average yearly rainfall is 2500 mm. About 55% of the average annual rainfall occurs during the rainy season between November and March, while the dry season lasts from May to September (Verbist, 2008).

State forest claims cover 46% of the upper Way Besai catchment of which 33% is protection forest and 13% the Bukit Barisan Selatan National Park. Private land covers 54% of the catchment (Fig. 1). Protection forest aims to protect watershed functions — important for the lifetime of the storage reservoir of the hydropower dam — and covers the highest elevations of the central Bukit Rigis and the steeper slopes at the edge of the caldera.

3. Data collection and methodology

3.1. Soil loss at plot scale

Soil loss due to sheet and rill erosion was measured at plot scale by the national Centre for Soil and Agroclimatic Research (CSAR) of Indonesia and the Soil Science Department of Brawijaya University between 2001 and 2006 in the Way Ringkih (WR), the Way Tebu (WT) and the Way Petai (WP) catchment (Dariah et al., 2004; Hairiah et al., 2005).

Plot size was 4 × 10 m in the Way Ringkih catchment and consisted of measurements of soil loss under 5 age classes of monoculture coffee (1, 3, 5, 7 and 10 years after coffee planting in 2000/2001) and measurements of soil loss under 5 land use types: monoculture sun coffee (SC), simple shade coffee with *Gliricidia*, simple shade coffee with *Paraserianthes falcataria*, multistrata coffee (with fruit and timber trees as well as nitrogen-fixing shade trees (*Erythrina* sp. and *Gliricidia sepium*) and old growth tropical forest (Table 1). A sun coffee system was categorised as such if the basal area of the shade trees was less than 20% of the total basal area, otherwise it was considered a shade coffee system. A multistrata coffee system was differentiated from a simple shade coffee system as having more than 5 different shade trees species. The coffee plants in the shade coffee systems were 7–10 years old (Hairiah et al., 2005). For each treatment there were 4 replications, but some replications were co-located in the same coffee garden where insufficient gardens of the required age were found in the study area. A similar experiment was set up in the WT and WP catchments on plots of 8 m wide and 15 m long in a randomised block design with 4 replications by CSAR. Treatments were (1) sun coffee; (2) coffee + Gliricidia; (3) coffee + Gliricidia + dead end trench; (4) coffee + Gliricidia + hedgerows of natural vegetation; (5) coffee + Gliricidia + ridging; and (6) remnant forest (Table 1). The slope of all these plots varied between 22° and 30°. Metal sheets, driven 20 cm in the soil and remaining 20 cm above the soil surface, delineated plot boundaries, avoided run-on and made sure that soil loss and runoff measured originated from the plot only. Plots were checked daily and runoff was collected after each rainfall event for measurement of suspended load and, in case of large events, bedload in the runoff trough.

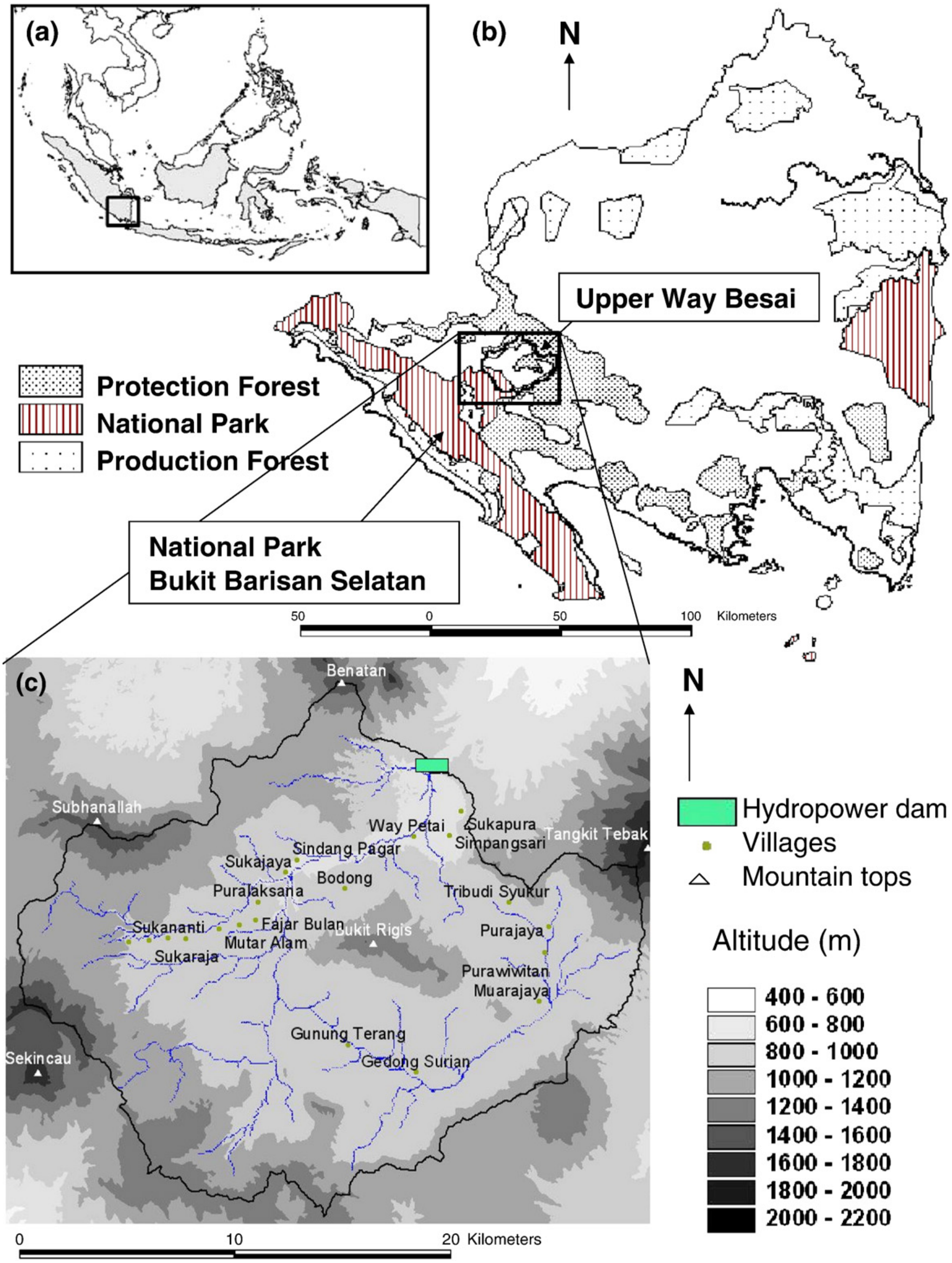

Fig. 1. a) Location of Lampung province on Sumatra island, Indonesia; b) Map of Lampung province with the delineation of state forest land and the location of upper Way Besai catchment; c) The upper Way Besai catchment with the most important villages and mountain tops.

3.2. Sediment yield at catchment scale

3.2.1. Hydrological data

To obtain insight into the spatial variability of SSC in the Way Besai river system, a sediment-monitoring program was set up in the Way Besai catchment early 2005. In order to assess the spatial variation in sediment response, 10 sampling sites were selected along the Way Besai and its major tributaries. The sampling points were selected as much as possible on bridges along the road that encircles Bukit Rigis, allowing rapid access to collect river water samples (with suspended sediment) and to carry out streamflow velocity measurements. Automatic water level sensors (Hobo Onset U20-001-01) were installed in January 2006 at (Fig. 4) the outlet of Way Tebu (WT), Way Besai4 (WB4), Air Hitam (AH), Way Campang (WC), Way Lirikan (WL), Way Petai (WP) and Talang Nangka (WB8) catchments. Automatic water level sensors (WIKA-IL) were used at Way Ringkih (WR) and WB7. Flow velocity measurements were regularly taken at 60% of the water depth (0.6D) at regular intervals along the cross-

Table 1
Number of erosion plots and land use and management per location.

Land use	Number of plots in Way Ringkih catchment	Number of plots in Way Petai and Way Tebu catchments
SC1 (age = 1 year)	4	
SC3 (age = 3 years)	4	
SC5 (age = 5 years)	4	
SC7 (age = 7 years)	4	
SC10 (age = 10 years)	4	
SC		4
SShC with *Gliricidia sepium*	4	4
SShC with *Gliricidia sepium* and dead end trench		4
SShC with *Gliricidia sepium* and hedgerows		4
SShC with *Gliricidia sepium* and ridging		4
SShC with *Parserianthes falcataria*	4	
Multistrata coffee	4	
Forest	4	4
Total	36	24

SC: sun coffee, SShC: simple shade coffee.

section using a flow probe (Global Water FP201) to establish a stage–discharge rating curve.

Runoff discharge data *Q* were calculated at an hourly timestep and rainfall data were available from 19 automatic tipping bucket raingauges installed in the study area. Missing runoff discharge data were filled in based on rainfall data using the VHM rainfall–runoff model (Willems, 2000).

3.2.2. Suspended sediment load

Accurate measurement and calculation of suspended sediment transport is dependent on the timing and frequency of data collection and this has been the subject of many discussions and controversy e.g. Edwards and Glysson (1988), Horowitz et al. (2001) and Phillips et al. (1999). In this research both monthly samples as well as event-based samples were taken during the rainy season. The event-based samples were taken during the peak of the rainy season (7 days in 2005 and 10 days in 2006), with 15 minute intervals between 12.00 and 18.00, when the probability of rain and increased sediment load is highest and there is still daylight. River water samples were also collected outside this time span when there was a flood or the water was turbid. In 2005, river water grab samples were taken from 12 to 18 of February. In case the water was not well mixed, grab samples (mainly taken from the top layer of the river water) could underestimate the SSC. In January 2006, a simple home-made depth-integrating sampler was developed and both grab samples and depth-integrated samples were taken since then at all locations. On the wider Way Besai river (WB4 till WB8) samples were taken from 3 positions along the river cross-sectional profile (Fig. 2).

All river water samples were first visually screened. In case the variation in turbidity during the day was small only 3–5 samples were selected for further analysis. When there was a clear rise and fall in turbidity all 15 minute river water samples were selected and their SSC measured.

3.2.3. Bedload

Bedload assessments are notoriously variable and difficult to assess. Consultants in Indonesia often use a fixed percentage of 10% of the total sediment load, a figure that was confirmed in an intensive study in the Konto catchment in East-Java, Indonesia using slot-type traps (Rijsdijk and Bruijnzeel, 1990). As the Sumberjaya study area is quite similar to the Konto area regarding annual rainfall (2500 mm), soils (both study sites are dominated by Andosols and Cambisols), steep slopes and size of the catchments (245–2162 ha in the Konto area and 738–35,825 ha in Sumberjaya), we estimated the bedload to be 10% of the total sediment load (SY; Mg $ha^{-1} yr^{-1}$). We also present SY results for a bedload percentage of 26% of the total sediment load, a percentage suggested in the Way Besai hydrological investigation report.

3.3. Establishment of sediment rating curves

In contrast to continuous measurements of rainfall and runoff discharge, suspended sediment samples generally only cover a limited number of events. Linking suspended sediment concentration

Fig. 2. Collection of depth-integrated runoff and suspended sediment samples at Talang Nangka (WB8).

measurements and discharge is generally done using a power sediment rating curve e.g. Asselman (2000), Phillips et al. (1999) and Walling (1977).

$$SSC = c\ Q^d \varepsilon \tag{1}$$

where SSC is the suspended sediment concentration (mg l^{-1}), Q is the water discharge ($m^3 s^{-1}$), the parameters c and d are regression coefficients and ε a lognormal distributed error. In this study we used four versions of this formula, as was also done in a study by Asselman (2000). In version (1) the regression coefficients are obtained using a linear least squares regression on the logarithm of the concentration and discharge data. In version (2) a bias correction factor (Ferguson, 1986) is introduced, based on the degree of scatter around the rating curve. In version (3) a power function with additive error (with zero mean and variance s^2) is assumed and a non-linear least squares regression is used to determine the parameters c and d. In version (4) an additive constant term p is added to version (3). More details about the procedure are provided in Verbist (2008).

The SSC was then weighted for discharge and expressed as a suspended sediment yield (SSY; Mg $ha^{-1} yr^{-1}$). The analysis was event based. When more samples were taken during the same event, the average was taken of the discharge weighted SSY, to give equal weight to each sampled event.

The four versions of the suspended sediment rating curves were calculated for all 10 catchments and evaluated with the Nash–Sutcliffe efficiency Eq. (2). The Nash–Sutcliffe modelling efficiency (NSE) determines the relative magnitude of the residual variance ('noise') compared to the measured data variance ('information') (Nash and Sutcliffe, 1970).

$$NSE = 1 - \frac{\sqrt{\sum_{i=1}^{n} (SS_{obs,i} - SS_{mod,i})^2}}{\sqrt{\sum_{i=1}^{n} (SS_{obs,i} - \overline{SS})^2}} \tag{2}$$

where $SS_{obs,i}$ is the observed value for suspended sediment at time i, $SS_{mod,i}$ is the modelled value for suspended sediment at time I, $\overline{SS}$ is the mean value of the observed data.

Sediment rating curves are often characterised by a lot of scatter and this study is no exception. A possible improvement is to separate the discharge data in rising and falling limbs and to develop separate sediment rating curves for each limb type (Asselman, 2000; Walling, 1977). As for several catchments the number of data points for the rising limb was limited, it was decided to use a single sediment rating curve in order to increase comparability between catchments.

3.4. Assessment of catchment characteristics

A digital elevation model (DEM) provided by the spatial analysis unit of ICRAF (the World Agroforestry Centre) was derived from the 1:50,000 scale topographic map. The 25 m contour lines had been converted to a raster format and were then interpolated at a resolution of 10 by 10 m. After a first delineation of the catchments using ESRI's ArcGIS 9.x and ArcView 3.2 desktop GIS-software, inconsistencies appeared during the field campaign regarding catchment delineation, flow direction and aspect. This DEM was hydrologically corrected incorporating data from field observations and from a more accurate second DEM that was derived by ICRAF from 1993 aerial photographs that covered 60% of the upper Way Besai catchment. The Shuttle Radar Topographic Mission (SRTM) 90 m digital elevation data (http://srtm.csi.cgiar.org) allowed for the construction of a third, more coarse, but homogeneous DEM (Jarvis et al., 2008).

For three nested catchments along the Way Besai (WB4, WB7 and WB8) the SY of mutually exclusive areas, called net catchment areas was calculated. For each catchment 27 variables belonging to 4 main factors (i.e. topography, soil, geology and land use) were compiled. In the next section we briefly discuss how each variable was calculated. More details are given in Verbist (2008).

3.4.1. Topography

Many variables can be used to describe topography. In this study the upslope contributing area, average slope, topographic index, stream power index, relief ratio and hypsometric integral were calculated.

In a grid-based DEM the upslope contributing area A_j is

$$A_j = \frac{\sum_{i=1}^{n} a_i}{b} \tag{3}$$

where a_i is the grid cell area, n is the number of grid cells draining into grid cell j and b is the contour width approximated by the grid resolution (Moore et al., 1991).

The topographic index T (Beven and Kirkby, 1979) was calculated using

$$T = \ln\left(\frac{A_j}{\tan\beta_i}\right) \tag{4}$$

where β is the slope of each grid cell.

The Deterministic Infinity (D-Inf) flow algorithm (Tarboton, 1997) was used to derive the slope, flow direction and the topographic index T. For these calculations the Terrain Analysis Using Digital Elevation Models (TauDEM) software was integrated in ESRI's ArcGIS software. It contains a wetness index W that is the inverse of the topographic index.

The stream power index S (Moore et al., 1991)

$$S = \ln(A_j \tan\beta_i) \tag{5}$$

The relief ratio RR is the ratio between the difference in elevation H between the highest and lowest point of the catchment and the horizontal distance between those two points.

The hypsometric integral HI was calculated as:

$$HI = \frac{H_{mean} - H_{min}}{H_{max} - H_{min}} \tag{6}$$

(Willgoose and Hancock, 1998) with H_{mean}, H_{min} and H_{max}, being the mean, minimum and maximum elevation of the catchment.

3.4.2. Geology

The most detailed geological map of the area was produced by Van Bemmelen (1933). The most important lithologies in the study area are Quaternary Andesites, propylitised old andesitic tuff layers (on Bukit Rigis), dacites on the eastern and western part of the Bukit Rigis, pre-tertiary granite (at the foot of Bukit Rigis), alluvium in the western part of the upper Way Besai catchment and Ranau tuff pockets of largely eolian origin from the Ranau volcano 70 km to the west of the study area. The area covered by all dominant lithologies is expressed as a fraction of the catchment area.

3.4.3. Soil

Representative top soil samples were collected over a depth of 0–20 cm at 162 locations by the Bogor-based National Centre for Soil and Agroclimatic Research (CSAR) and their physical soil properties, i.e. bulk density (BD) and particle size distribution (Clay, Silt, Sand), characterised (Subagyono et al., 2005). For each of the 10 catchments the average BD and particle size distribution was calculated.

3.4.4. Land use

The land use map derived from the SPOT-XS image of 19/08/2002 (K/J 279/360) is used for this analysis. The SPOT-XS image was not affected by haze as was the case with the Landsat ETM 2000 image used in an earlier publication (Verbist et al., 2005). Distinguished land use classes are forest, horticulture, multistrata coffee, paddy rice, settlement, shrub, simple shade coffee and sun coffee.

3.5. Stepwise regression

As all the catchment variables are expressed numerically, a stepwise linear regression was used to assess which of the above variables has a dominant impact on the SY. Some variables (e.g. the various descriptors of topography) are correlated, hence causing collinearity. Unnecessary predictors will add noise to the estimation of the variables and waste degrees of freedom (Faraway, 2002). As the variables are part of four thematic groups (topography, geology, soil and land use), a backward elimination procedure within each thematic group allows a reduction of the number of variables per group. To avoid removal of potentially relevant variables, a rather low threshold value p of 20% was used to withhold variables in a first iteration. The AIC or Akaike Information Criterion (Bozdogan, 2000; Faraway, 2002) was implemented in R (R Development Core Team, 2006) and used in each step. A second iteration of these steps on the number of remaining variables allows a further reduction of the number of variables and the identification of the most relevant variables. In addition partial correlation coefficients were calculated using SPSS 13.0.

3.6. Changes in sediment yield over time

Historical data were collected in 1983 during a feasibility study as well as in 1989–1990 for the hydrological survey of the Besai Electric Power Project (Indra Karya and Nippon Koei Co, 1990). Using a depth-integrated sampler river water samples were collected at 2 points: at Sukajaya, WB7 (28,900 ha) and the location Petai (38,900 ha), which is 1 km downstream of Talang Nangka, WB8 (35,825 ha) on the Way Besai. Because the historical measurement place Petai is now covered by the storage reservoir, the nearby upstream Talang Nangka site (WB8) was used instead to collect runoff discharge and SSC data. Changes in SY over time can be explored by comparing rating curves based on current and historical SSC data.

4. Results

4.1. Soil loss at plot scale

Soil loss data reported for the erosion plots in the Way Ringkih catchment are rather high and range from 33 to 37 Mg ha^{-1} yr^{-1} for 1–4 year old coffee (Widianto et al., 2004). These very high values were based on data obtained during the first two years of measurements. Graphs of cumulative soil loss for the full timespan of 5 years that measurements were made (not shown) illustrate that for each erosion plot, soil loss was very high during the first year, but then remained rather constant during the 4 subsequent years. The data for the first years were thus omitted in the analysis as these high vales were likely representative of the disturbance of the soil, when the metal sheets bordering the plots were installed and the trough collecting runoff below the plot was established.

A one way ANOVA ($n = 129$) confirmed that significant differences in average soil loss and runoff could be detected for various land use types. Tukey's Honest Significant Difference (HSD) test shows that sun coffee has a significantly higher soil loss and runoff coefficient compared to the other shade coffee systems and forest ($p < 0.001$). Soil loss under multistrata coffee was significantly higher than forest ($p < 0.05$). No significant difference could be detected in soil loss and runoff coefficient between plots under forest or plots under simple shade coffee systems with *Gliricidia sepium* or *Paraserianthes falcataria* ($p < 0.1$). Average soil loss under forest was 0.28 Mg ha^{-1} yr^{-1} and the runoff coefficient never higher than 6%.

Combining the results of the soil loss measurements over 4 years on monoculture coffee gardens of various ages, allows the construction of a so-called 'false time series' (Fig. 3), which shows that over time soil loss in the coffee monoculture gardens reduces from on average 7–11 Mg ha^{-1} yr^{-1} for 3–5 year old coffee to between 4 and 6.3 Mg ha^{-1} yr^{-1} after year 6, while the average runoff coefficient fluctuates between 8 and 16%, but without any clear decreasing trend (Fig. 3). These results suggest that especially monocultures of young sun coffee are prone to surface erosion.

Again leaving out the first year of soil loss measurements on erosion plots in the Way Tebu and Way Petai catchment, the highest recorded soil loss was only 1.8 Mg ha^{-1} yr^{-1} for the most erosion sensitive land use classes (three year old coffee and bare soil), while the runoff coefficient was never higher than 2.5% (Dariah et al., 2004). This suggests that the site effect (Way Petai and Way Tebu versus Way Ringkih) is more important than the age of the coffee gardens or the presence of shade trees. Soil loss under paddy rice was not measured in Sumberjaya, but was estimated as less than 2 Mg ha^{-1} yr^{-1} in micro-catchments in Java (Agus et al., 2002). Here SY was assessed in a cascade of paddy rice fields where V-notches and water level recorders were applied in between terraces to measure runoff discharge and SSC samples were taken at regular times. Most of the measured soil loss occurred during puddling operations.

4.2. Sediment yield at the catchment scale

4.2.1. Hydrological data

For each of the 10 catchments a continuous hourly runoff discharge series was constructed between 1 March 2006 and 28 February 2007. This corresponds with the period with the highest percentage of measured hourly streamflow data (Q_{obs} in Table 2). Missing streamflow data were filled in using the VHM model and the rainfall data.

4.2.2. Suspended sediment load

For each of the 10 catchments, around 30 independent runoff events with SSC measurements could be obtained, which was considered sufficient to develop sediment rating curves. Variability between catchments appeared to be rather high. A SSC as high as 5000 mg l^{-1} was measured in tributaries of the Way Besai like Way Kabul and Way Lirikan that otherwise had low base values of less than 60 mg l^{-1}. In contrast the average SSC of the main river Way Besai fluctuated between 250 and 500 mg l^{-1}, but peak values never exceeded 1000 mg l^{-1}.

4.3. Establishment of sediment rating curves

In a first step the sediment rating curves with the highest NSE were selected to estimate the SSY. In the Way Ringkih (WR) catchment estimations ranged between 12.3 and 17.3 Mg ha^{-1} yr^{-1} depending on the choice of the sediment rating curve, although the NSE for both values was very similar (0.94 and 0.95). Two estimations are provided: (1) maximising the NSE; (2) minimising differences in SY estimations between catchments, when the NSE between sediment rating curves was very similar (e.g. WR catchment). This latter, conservative approach increased the probability that, if there were differences in SY, these were true differences that did not have to be attributed to artefacts in the rating curves or measurement errors, although the 'true' SY is likely in between these two estimates. A SY for mutually exclusive areas (net catchment area in Table 2) was obtained by multiplying the catchment area with the SY per ha and subtracting that with the SY of the catchments included. Note that

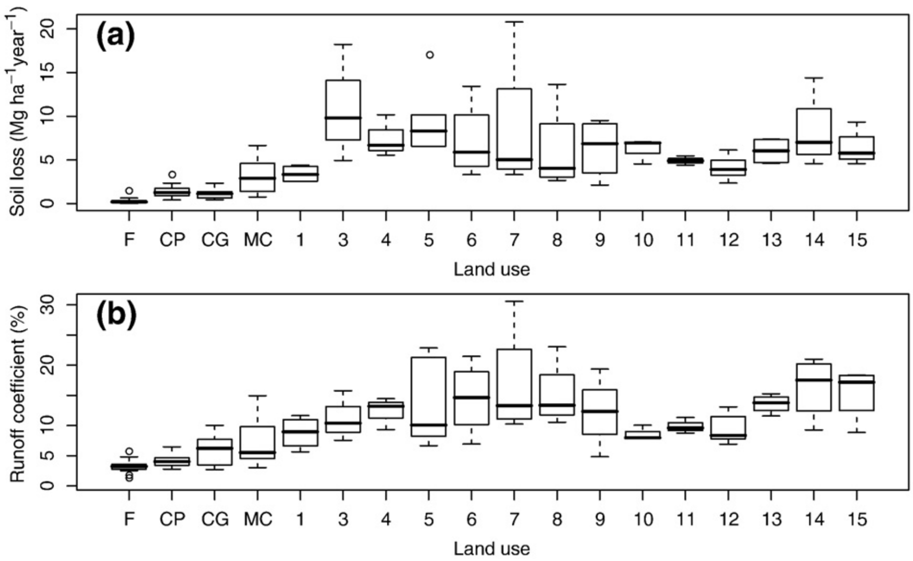

Fig. 3. Plot level data of soil erosion by water (a) and runoff coefficient (b) in the Way Ringkih (WR) catchment for old growth tropical forest (F), coffee multistrata (CM), simple shade coffee with Paraserianthes (CP) and Gliricidia (CG) as shade trees and a time series of monoculture sun coffee gardens (from age 1 years till 15 years). The whiskers of the boxplots represent or the maximum (resp. minimum) value or 1.5 times the interquantile range (IQR), which is the range between the first and the third quartile.

these SY are indicative as they are only based on data collected during one year. They are however homogeneous and allow comparison between catchments (Table 2).

As the difference in SY between catchments is rather large (one order of magnitude!) robust conclusions can be drawn on which catchments deliver on average more sediment. It appears that only a relatively limited area (18% of the sampled area) is responsible for almost 60% of the SY (Fig. 4). In the southern half of Sumberjaya (WB4, WB7 and AH) total SY is always less than 4 Mg ha^{-1}yr^{-1}, except for the WT catchment. Irrespective of what sediment rating curve is used, the highest SY (>4 Mg ha^{-1}yr^{-1}) is measured in a belt covering the northern half of the upper Way Besai catchment.

4.4. Catchment characteristics

A large, but almost linear difference appears between the topographic indexes derived from the SRTM-DEM or from the topographic map DEM. The index is scale and resolution dependent in absolute terms, but is consistent in a relative sense. For further analysis the SRTM-derived wetness index and stream power index were used, as computational limitations did not allow the generation of the average wetness index for catchment WB8 for the DEM derived from the topographic map. A Spearman rank correlation analysis (no data presented) showed that most topographic characteristics were highly correlated, except the hypsometric integral.

All land use classes are expressed as a fraction of the catchment area, where the non-classified areas covered by clouds and shadow were discarded. Only 86% of the pixels of the WP catchment were classified, but field observations and a visual inspection of the satellite image led to the assumption that this is still sufficiently representative to quantify the land use fractions in this catchment. Correlation between residential area (villages, roads) and paddy rice is high as these land use classes appear clustered in the landscape.

4.5. Stepwise regression and Akaike Information Criterion

From the 4 main factors (topography, geology, soil and land use) 27 variables could be calculated (Table 3). In a first iteration of the stepwise regression ($p<0.2$) and application of the AIC, Andesites, Old Andesites, Ranautuff and Alluvium for the factor geology, silt for the factor soil and forest, horticulture, multistrata coffee and paddy rice for the factor land use were kept (Table 4). For the factor topography slope angle, hypsometric integral and stream power were kept in the case suspended sediment yield rating curves with maximum NSE were chosen and slope angle, wetness index and stream power in case differences in SY between catchments were minimised.

Table 2
Estimated sediment yield for 10 catchments in Mg ha^{-1}yr^{-1} for SY rating curves with highest NSE and if differences between catchments would be minimised.

Cat	Q_{obs} (%)	Cat area (ha)	SSY (Mg ha^{-1}yr^{-1})	SY (Mg ha^{-1}yr^{-1}) BL = 10%	SY (Mg ha^{-1}yr^{-1}) BL = 26%	Net cat area (ha)	SSY (Mg ha^{-1}yr^{-1})	SY (Mg ha^{-1}yr^{-1}) BL = 10%	SY (Mg ha^{-1}yr^{-1}) BL = 26%	NSE
WT	38.5	771	7.4	8.2	10.0	771	7.4	8.2	10.0	0.32
WB4	99.8	8428	2.5	2.8	3.4	7657	2.0	2.2	2.7	0.83
AH	100.0	5501	1.1	1.2	1.5	5501	1.1	1.2	1.5	0.70
WK	52.7	3037	2.9	3.2	3.7	3037	2.9	3.2	3.7	0.77
WR	88.5	738	17.3	19.2	23.4	738	17.3	19.2	23.4	0.95
			12.3	13.7	16.6		12.3	13.7	16.6	0.94
WB7	65.0	26809	1.7	1.9	3.2	9105	2.4	2.7	3.2	0.52
			2.4	2.7	3.2		2.2	2.4	2.9	0.37
WCP	45.0	4258	3.0	3.3	4.1	4258	3.0	3.3	4.1	0.94
WL	66.6	669	5.1	5.7	6.9	669	5.1	5.7	6.9	0.99
WB8	99.8	35825	4.2	4.7	5.7	4089	12.2	13.5	16.5	0.63
			3.5	3.9	4.7		11.0	12.2	14.8	0.63
WP	97.2	1391	11.6	12.9	15.7	1391	11.6	12.9	15.7	0.78

Cat: Catchment, Q_{obs}: Available measured hourly discharge values in one year, missing discharge data Q were filled in with the VHM model, SSY: Suspended sediment yield, SY: Total sediment yield, BL: bedload (% of the total SY), NSE: Nash–Sutcliffe Efficiency.

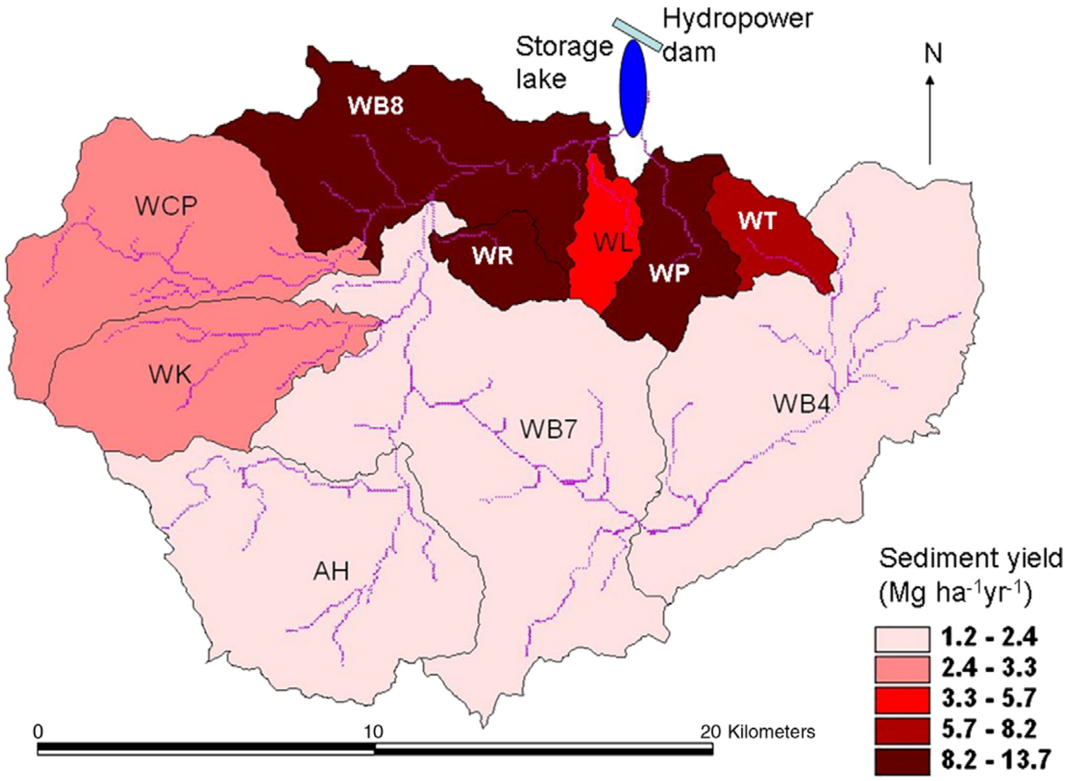

Fig. 4. Mean annual area-specific sediment yield (Mg ha^{-1}yr^{-1}) for mutually exclusive areas of the catchments in the upper Way Besai using a bedload percentage of 10 % of the total SY. For catchments WB4, WB7 and WB8 the area and sediment yield of the nested catchments were subtracted.

SY is positively correlated with the average slope angle of catchments and the relative area under Old Andesites, and negatively correlated with the area under multistrata coffee. SY being positively correlated with the forested area of the catchment area appears odd at first sight, but remaining forest is not randomly spread over the landscape and co-locates with steep slopes and erodible soils.

Table 3
Summary of the catchment characteristics.

Catchment characteristics	Avg	S.d.	Min	Max
Area (ha)	8743	12,338	669	35,825
Average slope (%)	19.7	2.7	16.8	23.7
Topographic index SRTM (D-Inf)	12.5	1.7	10	15
Topographic index from map (D-Inf)	346.0	72.5	247	437
Stream power index *S* (SRTM)	6.44	2.97	1.20	10.16
RR (%)	0.06	0.03	0.02	0.10
HI (%)	0.37	0.14	0.15	0.59
Andesites (%)	64.6	21.2	36.0	92.0
Dacites (%)	1.1	2.0	0.0	6.0
Old Andesites (%)	7.4	11.0	0.0	35.0
Granites (%)	0.1	0.3	0.0	1.0
Ranau Tuff (%)	3.6	3.9	0.0	9.0
River and lake alluvium (%)	22.8	20.1	5.0	64.0
BD (g cm^{-3})	0.93	0.07	0.83	1.02
Sand (%)	19.6	3.3	14.0	24.0
Clay (%)	43.5	8.2	31.0	57.0
Silt (%)	37.0	7.2	26.0	46.0
F (%)	18.1	11.0	4.0	37.0
H (%)	2.3	1.5	1.0	6.0
MC (%)	42.3	12.2	25.0	58.0
R (%)	9.4	4.8	5.0	18.0
S (%)	2.5	1.7	0.0	6.0
Sh (%)	4.4	1.4	1.0	6.0
SShC (%)	11.7	2.6	7.0	16.0
SC (%)	9.0	2.7	6.0	14.0

HI: Hypsometric Integral, RR: Relief Ratio, BD: Bulk density (g cm^{-3}), F: Forest, H: Horticulture, MC: Multistrata coffee, R: Paddy rice, S: Settlement, Sh: Shrub, SShC: Simple shade coffee, SC: Sun coffee.

In a second iteration of stepwise regressions and application of AIC on these 12 remaining variables, Old Andesites, slope angle and silt fraction appeared in descending order as the most significant variables related to SY, in case sediment rating curves with the highest NSE were chosen (Table 5a).

When minimising differences in SY between catchments slope angle and Old Andesites appeared consistently as the most significant variables related to SY (Table 5b). The silt fraction of the topsoil appeared more important than any landuse class, but in combination with the variables slope angle and Old Andesites, was not significantly related with SY, just like any single land use class (Table 5). The Old Andesites correspond with the central Bukit Rigis, from which the sediment rich rivers Way Ringkih, Way Lirikan, Way Petai and Way Tebu originate. The addition of the land use class forest results in a lower adjusted *R*-squared (0.67), than when only 2 variables (Old Andesites and slope angle) are used (0.72).

4.6. Changes in sediment yield over time

The difference between the sediment rating curves for WB8 (2005–2007) and Petai (1983–1989) suggests that the sediment load has increased significantly (Fig. 5a). In the period 2005–2007 water samples were collected at Talang Nangka (WB8) from 112 independent events allowing a rather robust sediment rating curve. No noticeable difference could be detected in sediment rating curves, derived for Sukajaya in 1989–1990 and in 2005–2007 (Fig. 5b).

5. Discussion

Surprisingly, the SY was higher for those catchments with the highest forest cover. This is likely due to the fact that these catchments (WR, WP, WT and WL) are also the ones that are situated on Bukit Rigis. The Air Hitam catchment with only a forest cover of 4% had the lowest SY of 1.2 or 1.5 Mg ha^{-1}yr^{-1} depending if a bedload percentage of 10 or 26% was taken (Table 2).

Table 4
Most important linear regression results with SY = c + dX for a bedload of 10%.

X	*c*	*d*	Multiple R^2	Adjusted R^2	*p*
a) For SY rating curves with highest NSE					
Old Andesite	2.94	0.45	0.79	0.77	0.00053
Andesite	13.39	−0.11	0.16	0.06	0.24
Ranautuff	7.74	−0.31	0.04	−0.07	0.56
Alluvium	6.24	0.00	0.00	−0.12	0.97
Slope	−26.79	1.68	0.64	0.60	0.0053
Hypsometric integral	4.05	6.03	0.02	−0.09	0.67
Streampower	7.78	−0.23	0.01	−0.11	0.74
Silt	20.11	−0.37	0.22	0.12	0.17
Forest	−0.46	0.37	0.52	0.46	0.018
Horticulture	0.25	2.57	0.37	0.29	0.062
Multistrata coffee	20.76	−0.34	0.54	0.48	0.01
Paddy rice	6.45	−0.01	0.00	−0.12	0.97
b) After minimising differences in SY between catchments					
Old Andesite	3.40	0.32	0.65	0.61	0.0046
Andesite	11.07	−0.08	0.16	0.05	0.26
Ranautuff	6.98	−0.33	0.09	−0.03	0.49
Alluvium	5.45	0.01	0.00	−0.12	0.86
Slope	−20.70	1.34	0.69	0.65	0.0029
Wetness index	−11.41	210.52	0.39	0.31	0.06
Streampower index	7.37	−0.25	0.03	−0.09	0.64
Silt	16.97	−0.30	0.24	0.15	0.15
Forest	0.20	0.31	0.59	0.54	0.009
Horticulture	2.48	1.39	0.18	0.08	0.22
Multistrata coffee	17.20	−0.27	0.57	0.51	0.011
Paddy rice	5.36	0.04	0.00	−0.12	0.90

Table 5
Multiple regression results with SY with 10% bedload.

a) For SY rating curves with highest NSE					
$R^2=0.847$	$R^2_{adj}=0.803$				
SY = −9.809 + 0.332 Old Andesite + 0.693 Slope					
p	0.27	0.0185	0.17		
R^2_p=		0.452	0.229		
$R^2=0.909$	$R^2_{adj}=0.864$				
SY = −25.572 + 0.409 Old Andesite + 0.936 Slope + 0.281 Silt					
p	0.048	0.0057	0.053	0.087	
R^2_p=		0.514	0.294	0.251	
$R^2=0.912$	$R^2_{adj}=0.841$				
SY = −27.915 + 0.414 Old Andesite + 1.132 Slope + 0.270 Silt − 0.062 Forest					
p	0.082	0.011	0.158	0.136	0.729
R^2_p=		0.516	0.220	0.236	−0.049
b) After minimising differences in SY between catchments					
$R^2=0.78$	$R^2_{adj}=0.718$				
SY = −11.94 + 0.17 Old Andesite + 0.83 Slope					
p	0.16	0.13	0.084		
R^2_p=		0.54	0.61		
$R^2=0.81$	$R^2_{adj}=0.719$				
SY = −20.63 + 0.21 Old Andesite + 0.97 Slope + 0.15 Silt					
p	0.122	0.096	0.067	0.35	
R^2_p=		0.63	0.67	0.38	
$R^2=0.78$	$R^2_{adj}=0.672$				
SY = −12.90 + 0.17 Old Andesite + 0.90 Slope − 0.02 Forest					
p	0.32	0.17	0.28	0.92	
R^2_p=		0.54	0.44	−0.04	
$R^2=0.78$	$R^2_{adj}=0.673$				
SY = −9.51 + 0.17 Old Andesite + 0.76 Slope − 0.02 MC					
p	0.56	0.19	0.24	0.86	
R^2_p=		0.51	0.47	−0.08	

MC: Multistrata coffee (%); R^2: multiple regression coefficient; R^2_p: part R^2; p: *p*-value of parameter estimate.

The high SY from catchments originating from Bukit Rigis suggest that Bukit Rigis is not located on an old Andesitic formation as mentioned by Van Bemmelen (1933, 1979), but coincides more likely with a lava dome that originated at a later stage. It would be logical that younger soil material of a more recent geological formation is more prone to various erosion processes like surface erosion, bank erosion, landslides and mass wasting, as the older formations would already have stabilized after a much longer exposure to erosive processes. Additional geological research would be required to confirm this hypothesis.

Fig. 6 illustrates that the SY at catchment scale is 3 (for WR) to 10 times (for WP and WT) higher than soil loss measured at plot scale. The SY estimations at catchment scale in Fig. 6 are based on sediment rating curves that minimised differences between catchments.

The observed SY at catchment scale in this study fit in the range of values compiled by Bruijnzeel (2004) for both soil loss and catchment SY in volcanic areas in Southeast Asia. The conservatively estimated SY at catchment scale in Way Ringkih (13.7 Mg ha^{-1} yr^{-1}) is considerably higher than the measured soil loss at plot scale under the most erodible land use of sun coffee gardens of 3–5 years old (Fig. 3). In 2005–2006, when the sediment load measurements at catchment scale were carried out, most coffee gardens in the Way Ringkih catchment were older than 10 years with an average surface erosion of 4–6 Mg ha^{-1} yr−1, while the fraction of the catchment covered by 3–5 year old coffee gardens was quite limited (<5% of the catchment area).

If 'sediment delivery ratio' (SDR) is defined as the SY at catchment scale divided by the soil loss at plot scale, both expressed per unit area, we obtain SDRs of 300–1000%. Empirical SDRs have been used to scale up USLE-based estimates to catchment level soil loss, but there is little predictive power on SDRs as yet and values as high as we found are not commonly reported.

Walling (1983) suggests that SY decreases with area and thus SDR is less than 100%. Our results suggest that SDR between any levels of the nested scales depends on the scales compared. On the right side of Fig. 7 SY indeed decreases with increasing area. On the left side of the graph no meaningful trend appears. De Vente and Poesen (2005), based on SY data collected in Spain, suggest that SY increases with area from plot scale to a catchment scale of 10–100 of ha largely due to the appearance of gully erosion, bank erosion and landslides, and then decreases again with increasing area. The top of the 'bell' in the graph suggested by De Vente and Poesen (2005) is not clear in Fig. 7, because of the wide range of soil losses at plot scale that is largely due to the geological heterogeneity in the study area. The per catchment comparison in Fig. 6 shows a clear difference between soil loss at plot and catchment scale and thus confirms the trends suggested by De Vente and Poesen (2005), as long as observations are made within the same lithology.

Rodriguez-Iturbe and Rinaldo (1997) found that, across published data sets, maximum runoff discharge scales with (area)$^{0.7}$, while annual discharge scales with (area)$^{1.0}$. Spatio-temporal patterns of peak rainfall may explain these scaling rules, but they suggest that the sediment transport capacity of river scales such that sediment builds up in lower parts of the landscape untill even larger rainfall events transport it further down. The main effect of land use change on sediment transport may well be the increased sediment transport capacity through a switch from interflow to surface runoff.

The sequence of sediment source and sink areas may be important in this respect. From the DEM it is clear that south of Bukit Rigis the slope of the meandering Way Besai is very low (Fig. 1). The sediment transport capacity of the meandering part of the river between WB4 and WB6 is limited: the maximum flow velocity measured during the highest peakflow recorded at WB4 (22 m^3 s^{-1}) was 0.9 m s^{-1}. The VHM modelling illustrated that above a runoff discharge of 16 m^3 s^{-1} the river increasingly floods the alluvial plain that effectively operates as a sediment trap and can be considered an effective landscape filter (Verbist, 2008). This fact — combined with the low SY of the almost completely deforested AH catchment — is reflected in the fact that

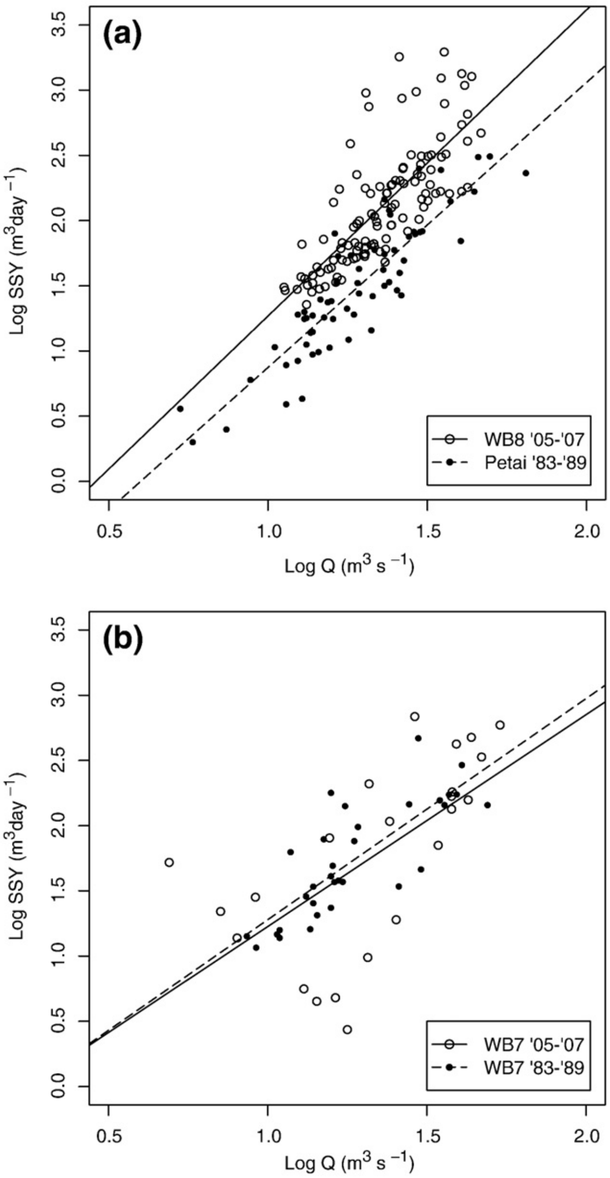

Fig. 5. (a) Runoff discharge weighted suspended sediment rating curves based on the historical set collected at Petai (in 1983 and 1989-1990) and at the Talang Nangka site (WB8) (2005- 2007); (b) Runoff discharge weighted suspended sediment rating curves based on the historical dataset collect at WB7 in 1989-90 and between 2005-07.

historical and current sediment rating curves for WB7 did not change (Fig. 5b).

From the above data it is clear that in the case of Sumberjaya an extrapolation of the plot scale results to the catchment scale as e.g. done in a study in Java (Nibbering and De Graaff, 1998) is thus very likely to underestimate the SY at catchment scale.

Four other erosion processes can be listed to explain the difference in SY at plot and at catchment scale: (1) landslides, (2) concentrated flow erosion on footpaths and motorcycle trails, (3) river bed and bank erosion and (4) gully erosion.

(1) Field observations point to the presence of landslides, especially nearby the forest edge on Bukit Rigis and next to the main road north of Bukit Rigis (Fig. 8a).
(2) Within the study area a relatively dense network of small footpaths and motorcycle trails exists (Fig. 8b). The impact of concentrated flow erosion on dirt roads and footpaths is mentioned as an important sediment contributing factor in studies in Northern Thailand (Turkelboom et al., 2008; Ziegler and Giambelluca, 1997) and in the Virgin Islands (Ramos-Scharron and MacDonald, 2007). A preliminary study on the impact of small footpaths as a source of sediment in the Way Ringkih catchment showed a high runoff and sediment load often with a very good connectivity with the river system (pers. comm. Alaik In'ami, Brawijaya University).
(3) Many tributaries of the Way Besai (and especially those originating from the Bukit Rigis) show signs of significant river bank erosion. Clear symptoms are river bank undercutting. In some parts the undercut river bank is 5–6 m high. River bank erosion was far less present on the main Way Besai river itself.

During the field campaign the river channel cross sections were regularly measured between February 2005 and June 2006. An additional 20 cross sections were measured in the Way Ringkih catchment in March 2005 and again in October 2005. In that time span of 7 months most of these cross sections in the Way Ringkih had widened between 5 and 50 cm, while riverbeds in former ash layers had also deepened. For the main river Way Besai, the cross-profiles kept more or less the same width, although the riverbed would sometimes rise and fall (in the order of 10–15 cm) after large floods when sediment pulses were passing through. These measurements provide extra evidence about the importance of river bank erosion.

The relatively limited soil loss of paddy rice at plot scale (Agus et al., 2002 suggests that paddy rice fields have the potential to operate as a filter for sediment. A quarter of all paddy rice fields is 'strategically located' within 50 m from a river. Many of these fields expand every year a little bit, until the vegetated riparian strip separating the paddy rice field and the river, becomes as narrow as 0.5 m. Under these irrigated rice fields, soils are often saturated down to the bedrock at a depth of 1–2 m. Most river bank slumping occurs after a few consecutive days of high water level and where stream power is high. Paddy rice could thus be a major contributor to bank erosion, depending on where it is located in the landscape. Over a stretch of many kilometers large tracts of paddy rice fields along the Way Ringkih and Way Petai were severely damaged in the large flood of 14 January 2005 (Fig. 8c). At the Way Petai measuring point the river bed rose by almost 0.5 m after the 14 January 2005 storm. It took more than 6 months until the river bed had returned more or less to its initial situation, being a considerable sediment source during that period of time.

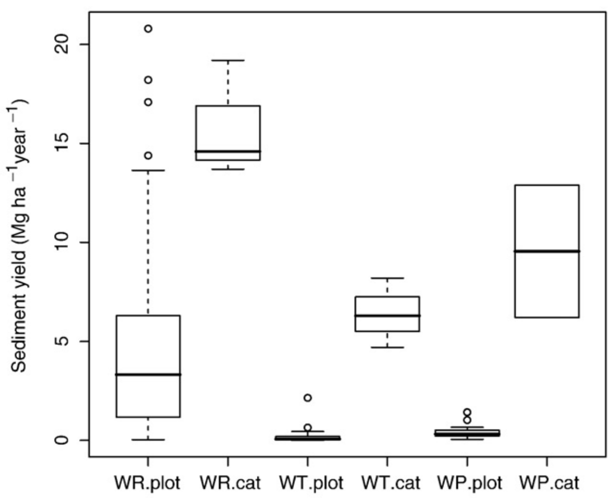

Fig. 6. Comparison of the range of measured sediment yields (Mg ha^{-1} yr^{-1}) at plot level (0.004 – 0.012 ha) and catchment level (cat) for catchments of Way Ringkih (WR; 738 ha), Way Tebu (WT; 771 ha) and Way Petai (WP; 1391 ha) in Sumberjaya.

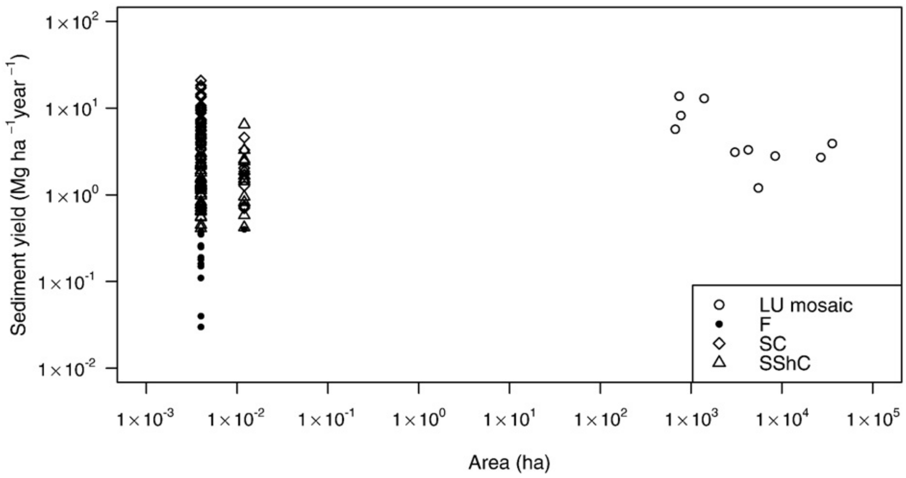

Fig. 7. Relation between drainage area and sediment yield at plot level (0.004 – 0.012 ha) for forest (F), sun coffee (SC) and simple shade coffee (SShC) and at catchment level (771- 35,825 ha) for land use (LU) mosaics.

(4) Gully erosion is not very common in Sumberjaya, but when it occurs, it is nearly always associated with the main roads (Fig. 8d). The lack of maintenance of the road drainage canals — or the lack of a drainage system altogether — triggers off large and deep gullies at points where the water converges.

After accounting for all other influences, plot scale soil loss does matter on soils derived from sensitive geological complexes. Forest and shade coffee systems, with their permanent litter layer, are clearly the most effective land cover to reduce soil loss and runoff.

In the Way Ringkih catchment soil loss at plot scale under sun coffee reduces over time with a factor 2, while the runoff coefficient does not show a meaningful decrease. This suggests that on a sensitive lithology soil armouring or compaction takes place in sun coffee gardens, in between the litter layer that tends to remain patchy. The presence of shade trees like *Paraserianthes falcataria*, *Gliricidia sepium*

Fig. 8. Landsliding next to the main road north of Bukit Rigis; b) Footpath erosion in the Way Ringkih (WR) catchment on the northern slope of Bukit Rigis; c) River bank erosion of the Way Petai (WP) after the storm of 14 January 2005. The dotted line illustrates where the river bank was before the storm; d) Gully erosion in Sumberjaya.

and other species not only further reduces soil loss but also surface runoff. This is likely due to the restoration of a surface litter layer and the resulting increase of soil organic matter that improves soil infiltration capacity (Hairiah et al., 2006).

Both plot and catchment results point towards a hierarchy in causal factors for soil erosion. In this tropical volcanic environment topography and lithology are clearly the most dominant factors, limiting or even masking the impact of land use. Not a single land use class appeared to be significantly related to SY in combination with the parameters slope angle and Old Andesites (Table 5). This corresponds to the results of the first large catchment study carried out in Indonesia (Mohr, 1908). However, they are in contrast with the recent results presented by Valentin et al. (2008), who presented in-field impacts of land use change as dominant factor controlling SY.

Bruijnzeel (2004) summarized erosion and sediment transport studies in the Konto catchment in E. Java, an area of similar size, climate, land use and geological origin as the Way Besai. In the Konto catchment roads, settlements and trails (together occupying ca. 5% of the total area) contributed approximately 54% of total SY, while mass wasting and bank erosion were estimated to contribute only 9%. The remaining 37% of the sediment came from the ca. 20% of the area occupied by rainfed agriculture. Open-field agriculture is a more important land cover type than in the Way Besai. The contribution of roads, settlements and trails may still depend on the geological substrate. The Air Hitam catchment has a much lower SY than the Way Ringkih although the area covered by roads and trails is comparable. Data on the relative contributions of in-field processes, riverbank and settlement/road related processes may thus be difficult to extrapolate. A focus on the 'anthropogene' aspects of changes in sediment transport may have to look considerably beyond the soil loss at plot scale that has received most attention so far. It seems likely that the relationship of SY with scale is non-linear, and thus conclusions on the relative importance of land use, lithology, climate or road infrastructure cannot be trusted outside of the area, internal heterogeneity and scale of study.

It is clear that the earlier delineation of protection forest (Fig. 1) did not very well capture, at least from a SY perspective, the risk-prone areas in Sumberjaya (Fig. 4). Criteria that have been used in Indonesia in the land use planning procedures for identifying protection forest include slope angle and climatic zone, but not the inherent erodibility of the soil linked to its geological origin. In the absence of spatial information at the relevant scale of this property, a stronger role for local terrain information may be needed to fine-tune the designation of areas where protection forest can be realistically expected to reduce sediment loads of rivers.

6. Conclusion

Catchment scale SY, per unit area, exceeds plot scale soil loss in this case study by a factor 3 to 10. Comparing SY at plot and at catchment scale shows that sheet and rill erosion in coffee gardens is not the most dominant process controlling SY. The Way Besai tributaries originating from the northern side of the central Bukit Rigis mountain are the largest net sediment contributors to the sediment load in the upper Way Besai. Landslides, river bank erosion and the concentrated flow erosion of small footpaths are the dominant erosive processes explaining the difference in soil loss at plot scale and SY at catchment scale. The flood plain along the meandering Way Besai, south of Bukit Rigis, operates effectively as a sediment filter at the landscape scale.

This study illustrates that topography and lithology control sediment production and override land use. Lithology, although one of the two most important factors, is in many studies not tested for because of the small area occupied by plots or small catchments or the lack of geological variability within the study area.

On erodible lithologies and steep slopes forest cover and shade coffee systems are the best land use types to reduce sheet and rill erosion. Although soil loss decreases over time in sun coffee, the higher runoff coefficient will contribute to off-site effects like increased peak runoff flows and bank erosion. This increase in peak flows is not only due to the presence of monoculture coffee gardens and their associated higher runoff coefficient, but also — and perhaps mainly — to the construction of roads, footpaths and impervious surfaces without proper drainage, causing concentrated flows that can result in landslides and gully erosion.

The currently promoted forest protection and 're-treeing' by converting sun coffee to agroforestry systems with shade trees will reduce over time soil loss and surface runoff at plot scale in lithologically sensitive areas. The impact at catchment scale is likely less, because these measures will affect only partly gully erosion, river bank and river bed erosion, landslides, and concentrated flow erosion on footpaths and roads.

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