Erosion and Nutrient Losses Estimates from a Large Watershed

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Abstract
On-site and off-site relationship in a large watershed (1987 km^2) draining from Pasoh region was assessed in terms of hill slope erosion and sedimentation at downstream. Soil erosion was modelled using the Universal Soil Loss Equation (USLE) in ArcVIEW-GIS. The land-use compositions were derived from satellite images. Forest makes up about 62% of the catchment area, followed by rubber (22.4%), oil palm (10.7%) and sundry crops (3.1%). Total estimated soil loss from the entire watershed was 7.15 mil t/yr or equivalent to 35.9 t/ha/yr. The highest soil loss was predicted for non tree sundry cultivation and the least for undisturbed forests. Consequently, nutrient loss from primary forest is low compared to the other land-uses. The observed sediment yield at the catchment outlet ranges from 0.58 to 6.44 t/ha/yr with a mean of 1.52 t/ha/yr. On an average only 4% of the soil eroded from hill slopes finally reach at the catchment outlet.

Introduction

Due to high storm intensity and relatively more fragile soil, erosion and sedimentation rates in the tropics are generally higher than in the temperate regions. Measurement of soil loss on hillslope requires the setting up of erosion plots with replication on different topography and vegetation type (Wischmeier & Smith 1978). Those measured at a catchment outlet is termed sediment yield which is usually less than on slope soil losses due to redeposition of soil particles as they travel downstream (Wasson et al. 1996). Soil erosion models such as Universal Soil Loss Equation (USLE) could offer great helps for estimating soil loss. With available geo-referenced spatial data, Geographic Information System (GIS) can expedite the processing time thus provides opportunities to test various land-use scenario.

This paper highlights soil and nutrient losses estimates from a reasonably large watershed using data-base from Pasoh region in Peninsular Malaysia. Erosion was estimated using USLE model run in ArcVIEW GIS. The incorporation of watershed functions in the overall quantification of ecosystem goods and services is crucial for policy reform to pursue sustainable management of tropical forests (Okuda & Ashton 2003).

Methods

Catchment Description

Modeling and analysis of erosion were carried in Triang Watershed (Figure 1). The total catchment area is 1987 km^2 or about 30% of the Pasoh Region. The river system emerges from the border of Selangor in the south-west and Pasoh Forest Reserve on the south-east. It flows towards the north east to join Pahang River. The forested catchments in the upstream are important sources for future potable water supply. Based on satellite images of 2003, the main vegetations in the Triang Watershed are primary forest (58.6%), rubber (22.4%) and oil palm (10.7%) Other land uses include orchards, secondary vegetation, grassland and urban. The topography at the downstream and middle parts of the watershed is generally flat to undulating with elevation between 40 and 500 masl. Toward upstream, the topography is steeper with a maximum elevation of 1440 masl. This region receives annual rainfall between 1469 and 2350 mm with a mean 1811 mm. Detailed climatic conditions of Pasoh area has been described by Noguchi et al. (2003).

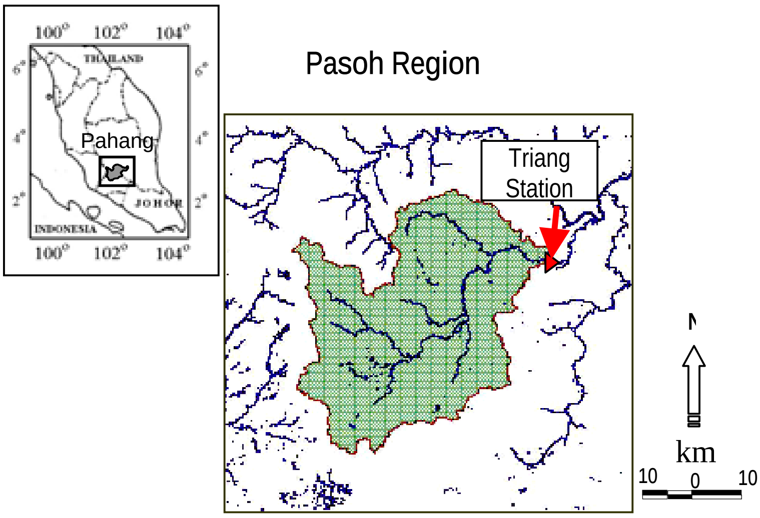

Figure 1: Location of Triang Watershed

Estimation of Soil Loss

Soil loss was estimated using Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1978) run in ArcVIEW GIS ver 3.1. This model was chosen because of its simplicity and relatively less data demanding. Moreover, USLE is widely used and in some countries accepted as an official tool for soil management and conservation (Lin et al. 2002; Moehansyah et al. 2004). In USLE, the potential erosion rate is calculated as:

$$A = R.K.LS.CP \quad (1)$$

where *A* is soil loss (t/ha/yr), *R* is rainfall erosivity factor, *K* is soil erodibility factor, *LS* is slope length factor, *C* is cover management factor and *P* is erosion control practice factor. For forested sites and tall trees (e.g. rubber, oil palm and orchard) *VM* factor (Baharuddin et al. 1999) was used instead of *CP*. The *VM* factor was calculated based on three sub-factors: i) canopy cover, ii) mulch and ground vegetation cover and iii) bare ground with fine root. Layers of GIS inputs were constructed based on 30x30 m grids.

Sediment Yield

Sediment yield was computed using sediment-discharge rating curve following method described by (Walling 1978)

$$C = aQ^b \qquad (1)$$

where C is suspended sediment concentration (mg/l) and Q is water discharge (m^3/s). The analysis used eleven years (1980-1990) data of sediment concentration and daily flow measured at Triang Station by the Department of Irrigation and Drainage (DID). However, complete record of daily stream flow and sediment concentration data were available only for 1981 and 1982 data sets. Missing stream flow was filled in using regression equation relating mean monthly discharge and monthly rainfall. The decision to choose monthly data instead of daily values was because the daily discharge-concentration relationship produced weak correlation for prediction purposes.

The sediment yield to soil loss ratio per unit area or sediment delivery ratio (SDR) was compared with that proposed by Quyang & Bartholic (1997):

$$SDR = a.AREA^b \qquad (2)$$

where a and b are coefficients and $AREA$ is catchment area in km^2. Values of a and b range from 0.4 to 0.6 and -0.2 to -0.1, respectively.

Carbon and Nutrient loss

Losses of C, N, P and K from the top soil were calculated as the product of area-weighted concentration mean of each nutrient and the estimated soil loss for each land use. The area-weighted concentration mean, $\overline{C}$ was determined as follows:

$$\overline{C} = \frac{\sum_i^n C_i A_i}{\sum_i^n A_i} \qquad (3)$$

where C_i and A_i are nutrient concentration and area belong to soil series i, respectively. This technique, however, is only appropriate when variation in nutrient concentration is small.

Results

Soil Loss

The topography and layers of USLE factors for calculating soil loss are shown in Fig. 2. Total soil loss from the entire watershed was estimated at 7.15 mil t/yr. Rubber plantation which constituted 22.4% of the catchment area contributed about 2.70 mil t/ha or equivalent to 37.8% of the total soil loss (Table 1). This is followed by oil palm plantation – 1.7 mil t/yr. Undisturbed forest which makes up about 59% of the watershed only contributes 19.7% of the soil loss budget. Rate of soil loss on a per area basis was highest for non tree sundry vegetation amounted to 477 t/ha/yr followed by hill rice, sundry trees, rubber and oil palm. Forest area is the least eroded (12.1 t/ha/yr) or only one fifth and one seventh of the rates in rubber and oil palm, respectively.

Table 1 : Soil loss by land-use from Triang Watershed based on 1995 satellite image

Landuse	Soil loss (t/yr)	% of the total loss	Soil loss (t/ha/yr)
Primary forest	1 407 526	19.69	12.1
Secondary forest	413 256	5.78	69.3
Sundry tree cultivation[1]	466 180	6.52	82.1
Sundry non tree cultivation[2]	207 581	2.90	477.2
Hill paddy	158 688	2.22	240.2
Rubber	2 704 054	37.83	60.8
Oil palm	1 692 511	23.68	79.8
Others	98 444	1.39	26.4
Total	**7 148 240**	**100.00**	**35.9**[#]

1: Sundry tree are mostly perennial crops such as durian, mango, rambutan, mangostine etcs.
2: Non tree sundry trees are short rotation crop such as banana, vegetables, corn etcs.
#. Area weighted average

Carbon and Nutrient Loss

Estimates of C, N, P and K losses from the entire Triang Watershed were 184 929, 12 607, 3 739 and 3 963 t/yr, respectively. On a per area basis, carbon loss ranges from 0.312 t/ha/yr for undisturbed forest to 2.12 t/ha/yr for non tree sundry cultivation. Similarly the highest depletions of N, P and K were observed for non tree sundry vegetation with the corresponding losses of 0.84, 0.25 and 0.26 t/ha/yr. As expected undisturbed forests maintain the least level of nutrient loss compared to other ecosystems. The equivalent amount of fertilizer required to replenish site productivity due to losses of N, P and K are presented in Table 2. Urea, rock phosphate and muriate of potash were selected as sources of N, P and K because these fertilizers are widely used in Malaysia. Based on the carbon cost of USD 8 per ton, the total carbon loss due to erosion amounted to USD 1.48 mil per year. Fertilizer cost to replenish N is USD 4.88 mil, P - USD 3.4 mil and K - USD 1.07 mil.

Sediment yield

Average monthly stream flow was moderately correlated against rainfall (r^2=0.51, $p<0.001$). This relationship was used to fill in missing monthly stream flow which is subsequently used for calculating sediment load. To improve sediment load prediction, the load-discharge rating curve was constructed using Reduced Major Axis Line (RMAL) regression technique which produces the following equation:

$$L = 0.0237Q^{3.01} \quad (r^2=0.85,\ p<0.001) \tag{4}$$

where L is average loading (t/day) and Q is average discharge (m^3/s). Annual sediment yield between 1980 and 1990 varies so much ranging from 0.56 to 6.44 t/ha/yr with a mean 1.52 t/ha/yr. These gave SDR values between 1.6% and 17.9% with a mean 4.2%.

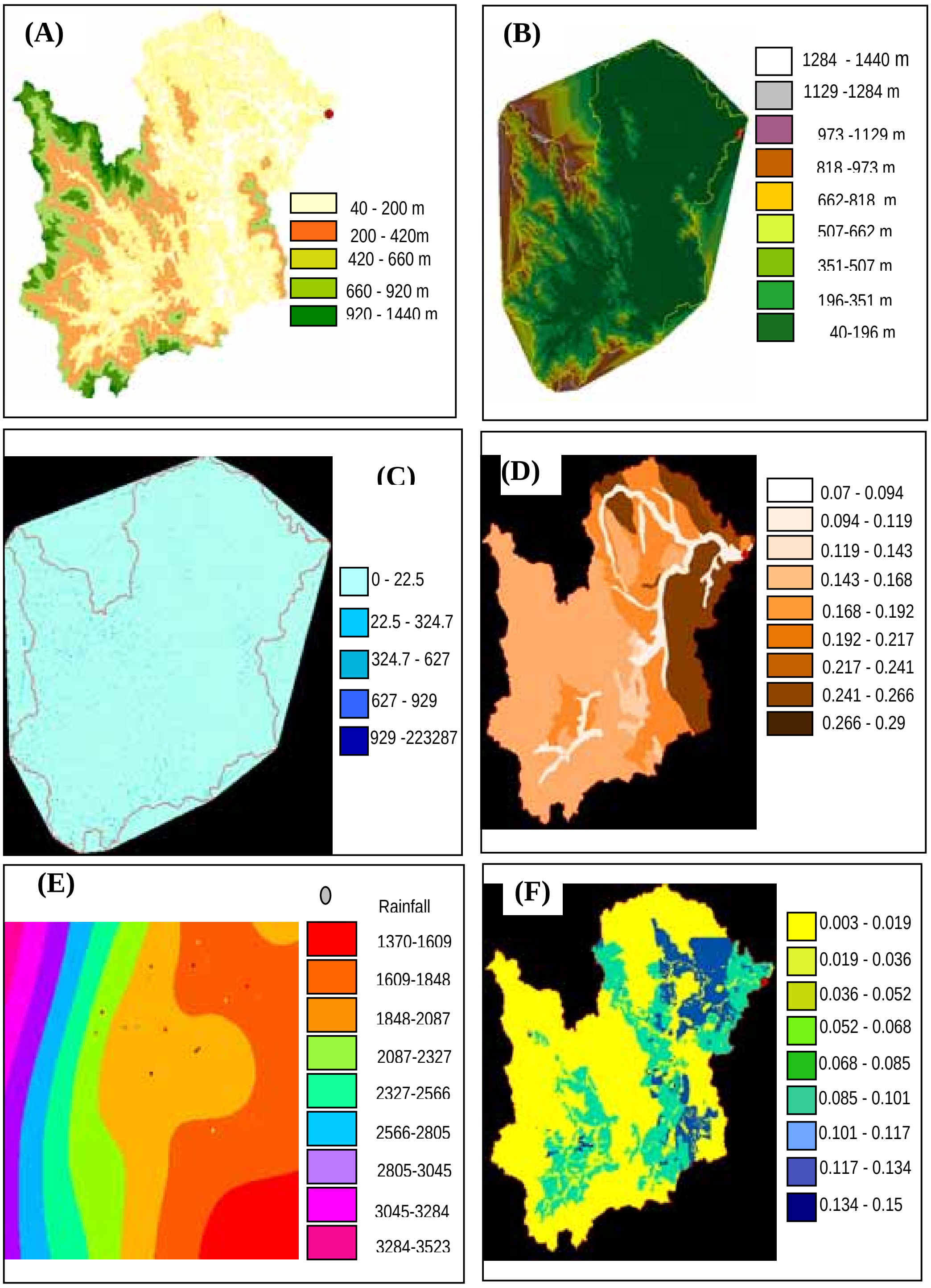

Figure 2: GIS inputs and layers for calculating soil loss in Triang Watershed. (A)- topo map, (B) – Triangulated Irregular Network (TIN); (C) – Length slope factor, *LS* ; (D) – erodibility factor, *K*; (E) – isohyetal map; (F) – Crop and management practice *CP* and Vegetation management, *VM* factor.

Table 2: Carbon and fertilizer equivalent to replace annual losses of nutrients from Triang Watershed

Landuse	C	Urea	CIRP	MP	C[1]	Urea[2]	CIRP[3]	MP[4]
	Equivalent loss (t/y)				Replacement cost (USD)			
Primary forest	36413.5	5396.5	6 197.2	1 567.1	291 307.8	960 576.0	669 300.4	211 560.7
Secondary forest	1069.2	1584.4	1 819.5	460.1	85 529.3	282 029.5	196 509.6	62 115.2
Sundry tree cultivation	12060.3	1787.4	2 052.6	519.0	96 482.7	318 147.8	221 675.8	70 070.0
Sundry non tree cultivation	5370.2	795.9	914.0	231.12	42 961.9	141 665.1	98 708.0	31 200.8
Hill paddy	4105.3	608.4	698.7	176.7	32 842.8	108 297.7	75 458.6	23 851.9
Rubber	69955.4	10 367.4	11 905.7	3 010.7	559 642.6	1 845 400.7	1 285 819.5	406 437.7
Oil palm	43786.2	6 489.1	7 452.0	1 884.4	350 289.6	1 155 066.0	804,815.1	254 395.9
Others	2546.8	377.4	433.4	109.6	20 373.4	67 183.8	46 811.6	14 796.8
Total	184 928.9	31 473.1	31 473.1	7 958.7	1 479 431.4	4 878 366.6	3 399 098.6	1 074 429.1

1- Carbon price of USD 8.00/ton
2- Urea contains 46% N; cost USD 178/ton
3- CIRP is Christmas Island Rock Phosphate contains 27% P2O5; average cost USD 108/t
4- MP is Muriate of Potash contains 60% K_2O; average cost USD 135/t.

Discussion

As soil loss from undisturbed forest is the least compared to other land use, conserving the forest is expected to provide the best protection to soil resources and subsequently minimize loss of nutrient and deterioration of water quality. Logging activities are anticipated to increase soil loss by 6-fold. Forest conversion to oil palm and rubber plantation on steep terrains would increase soil losses by 5- and 6.5-fold, respectively. The highest soil loss was predicted for non tree sundry vegetation amounted to 477 t/ha/yr. This was due to higher CP values adopted in this study to reflect intensive soil practices involving weeding and plowing. These activities increase soil exposure to rain drop impacts. Application of USLE model on shifting cultivation plots in Sabah by Gregersen et al. (2003) provides estimates of soil loss of 269 t/ha/yr for hill rice planting and 337 t/ha/yr for ginger. They also found higher soil loss of up to 580 t/ha/yr on steep slopes.

Predicted soil loss for forested catchment of 12.1 t/ha/yr is apparently higher compared to plot measurements (Baharuddin 1992). However, Roslan & Tew (1997), also using USLE, reported soil loss estimate of almost triple than the present value for forested catchment in Peninsular Malaysia. Many researchers cautioned on analytical error in *LS* factor when computed using GIS especially on steep slopes (e.g. Kinnell 2001; Lin et al. 2002). Auto calculation of *LS* often exceeded actual value, thus erosion may be overestimated. USLE was designed for application on field size areas with slope length limit of about 300 m. Field measurement suggests that slope length is generally less than 130 m for agricultural plots (Renard et al. 1996, Lin et al. 2002). In forested area, a shorter slope length can be expected as overland flow for carrying soil particle is virtually non-exist (Bruijnzeel 1990). In addition USLE does not account for redeposition of particle along the hillsope and stream channel. Nearing (1998) on examining the performance of erosion models concluded that most models over predict small measured values but under predict large measured erosion values. Perhaps, the biggest limitation in applying USLE for tropical area is the lack of calibrated *C* values especially for tall trees.

Average sediment yield of 1.52 t/ha/yr estimated from measured sediment concentration and flow seems reasonable for a large watershed. Douglas (1968) working on a catchment in Selangor with quite similar land uses compositions (57% forest, 24% rubber, 12% villages) but smaller size (140 km^2) reported sediment yield of 1.68 t/ha/yr. In another pioneering study, a catchment with 64% forest but on steeper topography recorded sediment yield of 2.57 t/ha/yr (Shallow 1956). Reported sediment yield values for undisturbed forest catchments generally less than 0.5 t/ha/yr (Leigh & Low 1973, DID 1986, Baharuddin 1988, Lai 1993). Sediment yield from forested catchments affected by recent logging ranges from 6.6 to 28.3 t/ha/yr with higher values were obtained on steep terrains especially when the logging operations did not comply with harvesting guidelines (Lai 1993, Douglas et al. 1993). Variation in yearly sediment yield for Triang Watershed is quite large (0.56 to 6.44 t/ha/yr) which may indicate temporal influence of land-use activities. However, this is difficult to confirm without detail information on the land-use history. Other possible contributing factors include variation in rainfall regime and unequal sampling intensity especially during storm events. As cautioned by (Douglass et al. 1993), inadequate storm event sampling could grossly underestimate sediment yield value.

The low sediment delivery rate obtained in this analysis corresponds to the high estimate of soil loss from Triang Watershed (35.7 t/ha/yr) compared to the sediment yield (average 1.52 t/h/yr). The resulted SDR (average 0.04) is much lower when compared with estimated value of 0.15 based on catchment area as proposed by Quyang & Bartholic (1997) (eq. 2). However, a comparable SDR of 0.06 was obtained when calculated using formula by Stewart et al. (1975). Therefore, the apparently low SDR for Triang watershed is still reasonable for a large watershed. Many researchers expressed concern over the uncertainties in determining SDR for a large catchment (Lane et al. 1997). They highlighted difficulties of getting reliable estimates for both gross erosion and sediment yield.

The losses of C, N, P and K are directly proportional to the estimated soil loss. This is to be expected since nutrient loss is the product of soil mass and average nutrient concentration. As a result, forested catchments leach the least amount of these nutrients on a per area basis and in increasing order followed by rubber, oil palm, tree sundry cultivation, hill rice and non-tree sundry cultivation. Nutrients eroded or leached from soil are also subjected to redeposition and uptake by vegetation as they travel downslope (Auerswald, 1989). This issue needs to be taken into consideration when estimating nutrient loss over a long term. As such the present estimates are likely to be overestimated.

Conclusion

Quantification of watershed services and function requires reliable estimate of hydrological parameters. Despite limitation of the USLE model for application in large tropical landscapes, the present analysis provides logical land-use options for considerations in sustaining watershed functions. The analysis highlights the importance of forested ecosystem for protecting soil and minimizing site degradation. Forest conversion to oil palm and rubber would increase the soil loss between 5 and 7 folds. The highest rate of soil loss was obtained for non-tree vegetation and hill rice. With about 60% of the watershed still forested, measured sediment yield at downstream is still reasonably low. The calculated sediment yield falls within the reported values for catchment having more or less similar land-use compositions. Estimates of nutrient loss, thus fertilizer cost to replenish site productivity should be revised toward smaller values to take into account redeposition and uptake by vegetation.

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