Enhancing Water Quality through Better Land Management of Degraded Upland Regions in Northern Laos

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Abstract

Rural water supply and human health are primary development focal areas for many countries in Southeast Asia. In many water supply systems based on open water bodies, increased turbidity during periods of high rainfall is commonplace and reduces the quality of water for human consumption. The cause of this increased turbidity is invariably rapid land conversion that induces a change in the path through which water moves within the landscape. In this respect the ratio of surface (turbid) flow / sub-surface (clean) flow increases, resulting in a significant increase in sediment loads. Limited attention has been given to the downstream off-site impacts of elevated sediment and nutrient loads associated with waters emanating from these upper basins, and to their potential impact on water quality and the livelihoods of rural communities. Inappropriate land management in upland agricultural production systems can have negative effects on the life span of reservoirs and other structures through sedimentation, and lead to water quality deterioration and degradation of downstream aquatic ecosystems, resulting in a decline in fish catches. All these contribute to deterioration of the livelihoods and health of downstream communities. To provide data lacking at the catchment scale, outflow and sediment yield have been monitored at eight small (approximately 0.6 ha-60 ha) rural catchments in northern Laos since 2001. Soil conservation strategies were developed and tested on three of these catchments. Results clearly show that sediment yields can be reduced from 5-11 Megagrams (Mg) ha^{-1} yr^{-1} under the current swidden (slash-and-burn) system, to nearly nil when appropriate practices are used. Such practices include improved fallow systems based on legumes. These innovative methods rehabilitate degraded land and enhance water quality, and are currently disseminated by several organisations in the region.

Keywords: northern Laos, catchment, water quality, erosion, soil conservation strategies, slash-and-burn, improved fallow.

1. Introduction

Rural water supply and human health are primary development focal areas for most countries in Southeast Asia. It is well recognised that water-borne diseases are a significant issue in rural communities and have serious economic implications for developing and emerging countries. One of the goals of development in the Lao PDR is to reduce infant mortality rates in rural areas (Thammavongsa, 2004), which are currently unacceptably high at 87 per 1,000 live births (Apaylath and

Meadley, 2004). Despite the provision of improved water supply and sanitation systems, water borne parasitic and faecal diseases are commonly observed, the most frequent being diarrhoea, cholera, typhoid fever, and parasitic infections. Significant efforts have been made to eliminate bacterial pollution sources from urban areas. Many urban rivers, however, remain impaired with respect to microbial water quality. In many cases, upstream rural areas are the suspected sources (Murray et al, 2001; Jamieson et al, 2004).

In many water supply systems based on open water bodies, increased turbidity during periods of high rainfall is commonplace and reduces the quality of water for human consumption (Maniphousay and Souvanthong, 2004). The cause of this increased turbidity is invariably rapid land conversion that induces a change in the pathway in which water moves within the landscape. In this respect the ratio of surface (turbid) flow / sub-surface (clean) flow increases, resulting in a significant increase in sediment loads. Many of these water-based issues are directly associated with agricultural activities that lead to increased sediment loads and pollution from agrochemicals in the lowlands. Since existing surveys remain fragmentary and scattered, it is vital that changing trends in the quality of surface and ground water are monitored and evaluated from physical, chemical and biological perspectives. This is a pre-requisite for providing policy makers with sound information to identify appropriate land management strategies for upper catchments, and so address water quality problems that affect crop production and the health and livelihoods of communities that inhabit the lowlands.

Increased exploitation of land resources in upper catchments results in increased sediment discharge unless adequate interventions and precautions are made to prevent the discharge to water bodies (Maglinao et al, 2004). These suspended sediments, rich in organic components, are favourable niches for pathogen proliferation, especially where water is polluted by excreta (Characklis et al, 2005). Poor hygiene practices by farmers and increased suspended sediment load provide favourable conditions for the development of water-bore diseases. In headwater catchments, the cycle of natural water depuration (oxidation and dilution) is too short to be effective. Providing infrastructure in remote areas will not have a significant impact on health without improving awareness amongst the community and decreasing sediment yields. In uplands, sedimentation increases the operation and maintenance costs associated with small-scale irrigation infrastructure and fish ponds. Soil conservation strategies have been developed and promoted to eliminate or reduce sediment discharge from these upland systems, but even if their impact is well documented at the farmer-plot scale, their effects on a larger scale still need to be assessed, partly due to gully and bank erosion processes which are increasingly recognised as major sediment sources at the catchment scale (Valentin et al, 2005).

Limited attention has been given to the off-site impacts of elevated sediment and nutrient loads associated with waters emanating from these upper basins, and their potential impact on water quality and the livelihoods of these rural communities. Inappropriate land management in upland agricultural production systems affects the life span of reservoirs and other structures through sedimentation, ansl also leads to water quality deterioration, sedimentation and eutrophication of downstream aquatic ecosystems with a subsequent decline in fisheries production. All these factors contribute to a deterioration in the livelihoods of downstream communities. Reduced quality and quantity of surface water directly affects community health, and means that alternative sources of drinking water must be found. The activities of upstream landholders, however, are often simplistically blamed for negative impacts on downstream communities. This often occurs without understanding the policy and institutional frameworks that lead to over-exploitation of upper catchments, the relative importance of various land uses in contributing to degraded water quality, or the constraints that limit the ability of upstream communities to adopt more sustainable practices. Integrated and cross-scale knowledge is therefore essential to the development of appropriate infrastructure that can support soil conservation land-use management practices, thus ensuring high quality water throughout basins in the region.

A comprehensive understanding of water quality issues requires consideration of many catchment factors including climatic conditions, hydrological parameters and land-use parameters. To provide data lacking at the catchment scale, this study monitored outflow and sediment yields. This article presents and discusses 1) sediment yield data collected from eight small (0.57-60.2 ha) rural catchments monitored since 2000 in northern Laos; and 2) soil conservation strategies that have been developed and tested on three of these catchments.

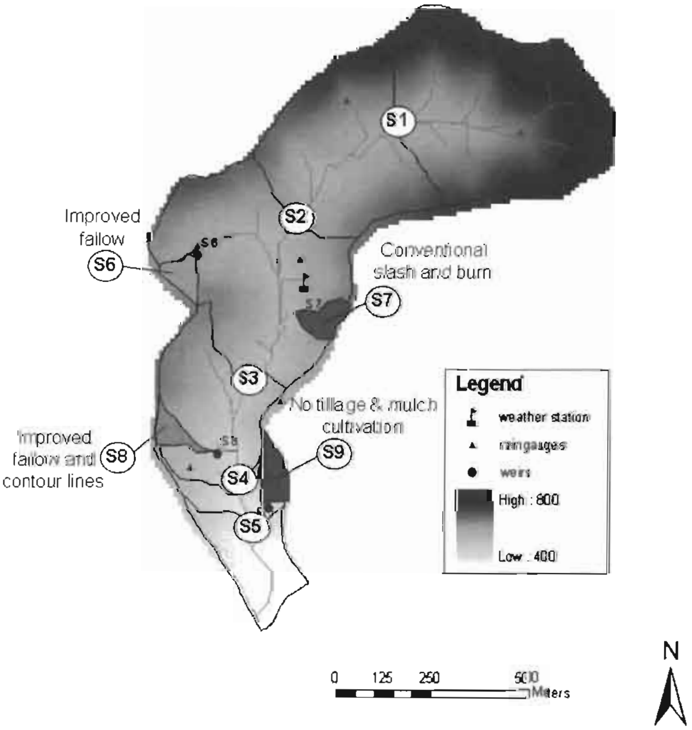

Figure 1: The Houay Pano catchments showing the eight weirs in the eight sub-catchments and areas used to trial soil conservation practices

2. Materials and methods

2.1 Experimental catchment and sub-catchments

The Houay Pano catchment (figure 1) was selected as representative of an area under the shifting agriculture characteristic of northern Laos and has good accessibility to roads and transport facilities (Phommasack et al, 2003). It is located in northern Laos, 10 km south of Luang Prabang city. While the national population density is 23.8 inhabitants per km^2 (in 2000), the population density in this area increased from 19 to 115 inhabitants per km^2 between 1990 and 2004 due to a combination of natural growth and government resettlement policies (Lestrelin and Giordano, 2007). This catchment is approximately 0.6 km^2 in area; it belongs to the Mekong River watershed, with UTM 1983 coordinates (zone 48) of between 203245.14-204679.65 m and 2197318.4-2198825.04 m (Chaplot et al, 2005a). It is an area cultivated under a typical swidden (slash-and-burn) system without inputs and recently the fallow period was reduced from approximately five to two years (de Rouw et al, 2002). In addition to the main catchment, seven nested sub-catchments were equipped and monitored from 2001 onwards. The surface areas ranged from 0.57-60.2 ha (table 1). The outlets of sub-catchments one to four are located on the main, permanent, stream channel, whereas the outlets of the other sub-catchments (with a surface area of about 0.6 ha) are located on hillside gullies.

Table 1: Main physical characteristics of the eight study catchments

Catchment number	Area	Min Elev	Max Elev	Mean Elev	Slope	Perim	Ci	Slw	Lw
	(ha)	(m)	(m)	(m)	(%)	(m)	(%)	(%)	(m)
S1	19.6	558	718	623	61	1,745	0.10	24	439
S2	32.8	515	669	571	53	1,576	0.11	18	822
S3	51.4	488	621	544	51	2,163	0.13	14	1,304
S4	60.2	430	592	513	48	1,637	0.14	15	1,557
S6	0.64	530	585	562	52	358	0.11	59	30
S7	0.60	514	588	553	62	392	0.13	45	50
S8	0.57	477	580	534	54	452	0.15	58	30
S9	0.73	423	505	459	54	421	0.12	48	140

Columns display, for each catchment station (S), the surface area; the minimum (Min), maximum (Max) and mean elevation (Elev); the mean slope gradient; the catchment perimeter (Perim), the Gravelius (Ci) index of compactness, which is the ratio of the perimeter of the sub-catchment to the perimeter of a circle that has the same surface area (adapted from Chaplot et al, 2005a and unpublished data); the mean slope of the main waterway (Slw); the length of the main waterway (Lw).

2.2 Equipment and experimental procedures for hydrological & erosion monitoring

A rain gauge network consisting of six manual totalisers and one automatic weather station was set up at the field site in order to measure the spatial and temporal rain distribution and environmental variability. The weather station's rainfall recorder calculated rainfall intensity at a six-minute time-step interval. Weather data was collected and downloaded every week.

The water level in each weir was measured at a constant distance upstream of the flume using an automatic water level recorder associated with staff gauges. A rating curve (the relationship between water level and discharge) was determined for each stream-gauging station, using the velocity area method. Water-level data was collected from the eight catchments and downloaded every week. Water samples were collected manually in 2001 and then automatically from 2002 onwards from the weirs during flow events, even at night. The sampling step varied from 5 to 10 min depending on flow stage (rise, peak, rapid and slow decrease). In the laboratory each sample was then flocculated using alumina sulphate, filtrated, oven-dried at 60°C and weighed to assess the sediment concentration (g l^{-1}). Suspended load was calculated as:

Suspended load (g) = Mean sediment concentration (g l^{-1}) x Stormflow volume (l).

Bedload, namely the sediments trapped in the weirs, was collected after every main event. Five to ten samples were collected, starting from the upper section of the weirs, weighed, oven-dried and weighed again to assess their water content, and thus the total dry mass of sediments. The total sediment yield was calculated at the catchment level by adding the suspended load to the bedload.

Land-use maps were prepared every year from detailed field surveys. Observed land uses included fallow (Fw), degraded secondary forest (Forest), teak plantation, bananas, upland rice, Job's tears (*Coix lacryma-jobi* L.), sesame and maize. Four sub-catchments (S6, S7, S8 and S9) were equipped to compare four farming systems: (i) the present rotational swidden system being used as the control, and three innovative systems; (ii) improved fallow with pigeon pea and *Crotalaria micans*; (iii) improved fallow with contour planting; and (iv) mulch planting without tillage (de Rouw et al, 2003).

2.3 Statistical analyses

The team investigated the relations between annual runoff coefficient, suspended load, bedload and sediment yield recorded in each catchment, and a wide array of factors (those in table 1 plus annual rainfall, mean catchment slope, soil clay, silt, and sand content, soil depth, areal percentage of land cover for each land use) using correlation matrices for the Pearson correlation coefficient (r). In addition, stepwise linear regression analyses were performed with variables statistically significant at the 0.01 level.

3. Results

3.1 Rainfall, runoff coefficients and soil loss

Annual rainfall did not vary significantly over the five-year period: 1,403 mm in 2001, 1,414 mm in 2002, 1,325 mm in 2003, 1,378 mm in 2004 and 1,414 mm in 2005 (mean = 1,365 mm, standard deviation = 48 mm). The rainy season between April and October is clearly evident on a graph of monthly rainfall (figure 2).

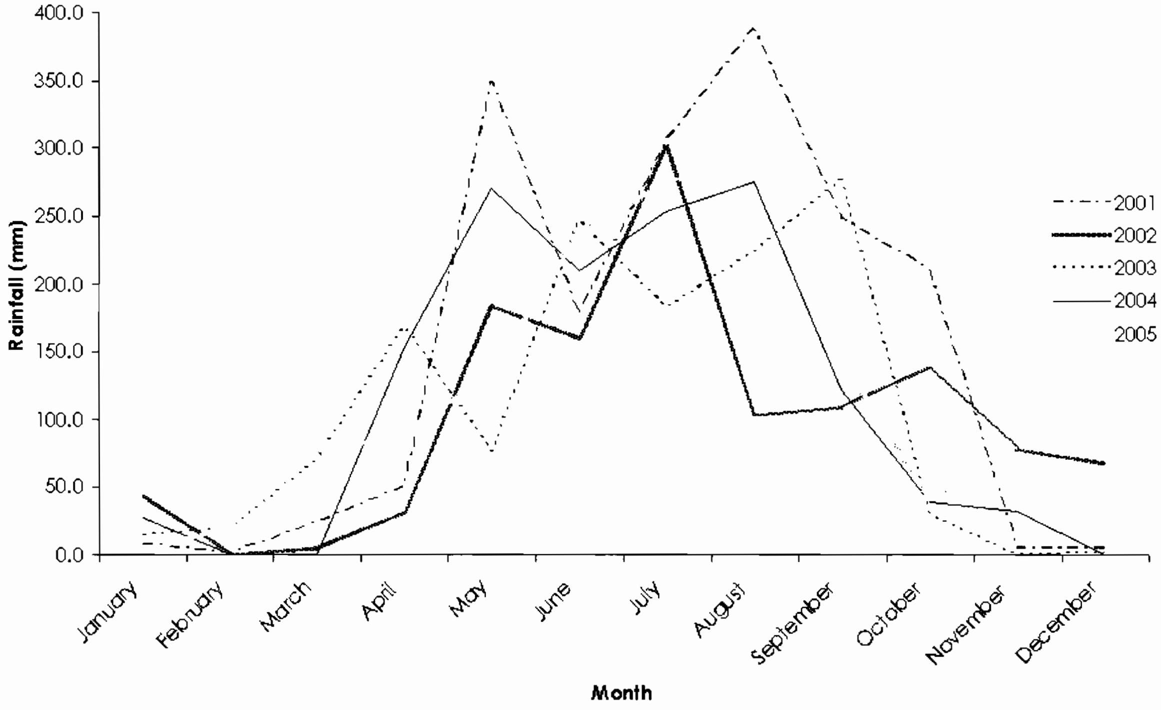

Figure 2: Monthly rainfall in the Houay Pano catchment, 2001-2005

Flows were permanent in the four catchments along the main stream (S1-S4) and sporadic in the hillslope sub-catchments (S7-S9). Runoff coefficients were much higher in the S1-S4 catchments than in the S7-S9 sub-catchments (figure 3). Along the main stream, suspended load decreased from S1 to S2 (mean: 2.05 to 1.11 Mg ha^{-1} yr^{-1}) and increased from S2 to S4 (mean: 1.11 to 2.63 Mg ha^{-1} yr^{-1}). Similar trends, but with much lower values, were observed for bedload, which decreased from S1to S2 (mean: 0.32 to 0.04 Mg ha^{-1} yr^{-1}) and increased from S2-S4 (mean: 0.04 to 0.90 Mg ha^{-1} yr^{-1}). By contrast, the suspended load was much lower in the hillslope sub-catchments than in the bigger catchments along the main stream. The suspended load peaked under swidden cultivation in 2005 (S5; 0.84 Mg ha^{-1} yr^{-1}). In contrast, bedload was much higher in the hillslope sub-catchments (figure 3), with the highest amounts recorded during swidden cultivation in S7 (4.74 Mg ha^{-1} yr^{-1} in 2002; 10.15 Mg ha^{-1} yr^{-1} in 2005). Bedload plummeted during the fallow period in S7 (0.02 and 0.38 Mg ha^{-1} yr^{-1} in 2003 and 2004 respectively). The alternative soil conservation systems tested were effective in reducing bedload with a mean of 0.11, 1.07 and 0.81 Mg ha^{-1} yr^{-1} for S6 (improved fallow), S7 (contour improved fallow) and S8 (no-till and mulch cultivation) respectively. Sediment yield (suspended load + bedload; figure 3) showed that improved fallow was efficient in reducing soil loss, (mean SY: 0.12 Mg ha^{-1} yr^{-1} in S6) when compared to the slash-and-burn system (4.45 Mg ha^{-1} yr^{-1} in S7). At the larger catchment scale (S4), mean annual sediment yield was also high (3.52 Mg ha^{-1} yr^{-1}).

3.2 Land-use changes

Until 1998 only upland rice was cultivated in the catchment but because of the increasing difficulty in controlling weeds, farmers started to diversify their crops by planting Job's tears (de Rouw et al, 2002) and more recently maize and sesame (figure 4). Between 2001 and 2005, secondary forest cover decreased from 18.3-6.5% of the whole catchment area (S4; figure 4), banana cover increased from 3.8-6.6%, and teak plantations remained the same (2.7%). Fallow ranged from between 64.9% in 2002 and 38.2% in 2002. Since 2002, the areal percentage of fallow tended to increase, but the fallow period continued to decrease from approximately 3-2.5 years.

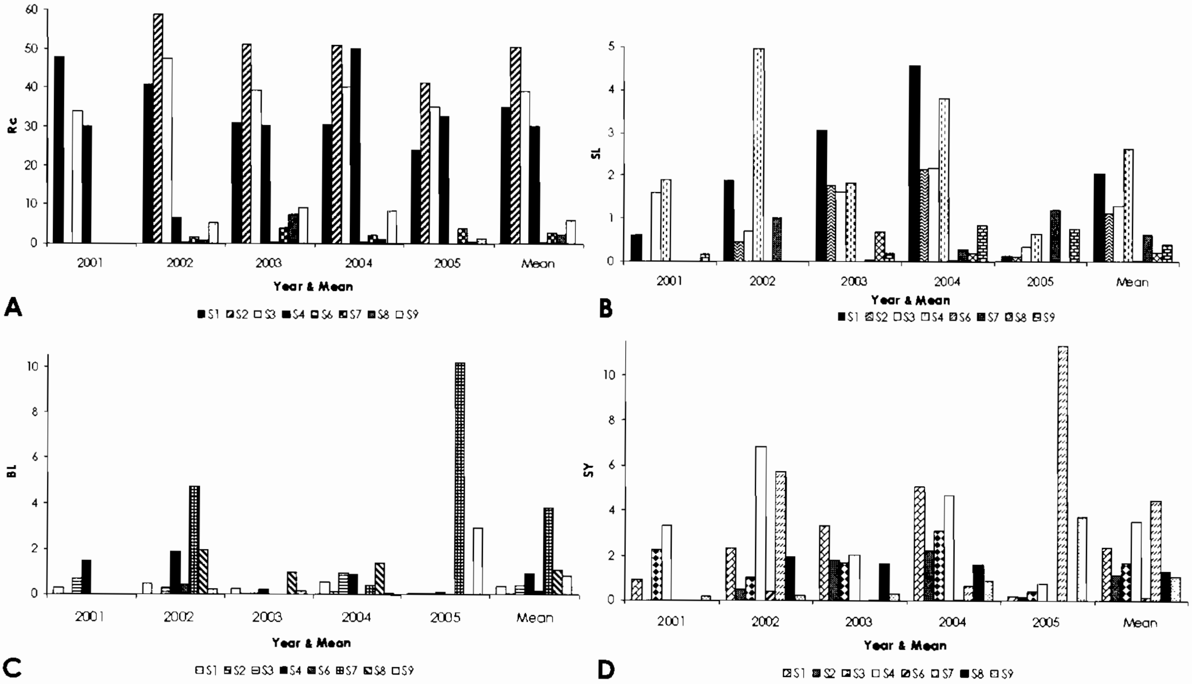

Figure 3: Hydrological and soil loss annual data (2001-2005)

A: **runoff coefficient** (Rc, %); B: **suspended load** (SL, Mg ha^{-1} yr^{-1}); C: **bedload** (BL, Mg ha^{-1} yr^{-1}); D: **sediment yield** (SY, Mg ha^{-1} yr^{-1}). S1, S2, S3, S4 are nested catchments along the same stream; S6, S7, S8 and S9 are hillslope sub-catchments; S6: improved fallow; S7: slash-and-burn (under fallow in 2003 and 2004, under cultivation in 2002 and 2005); S8: contour improved fallow, S9: no till and mulch.

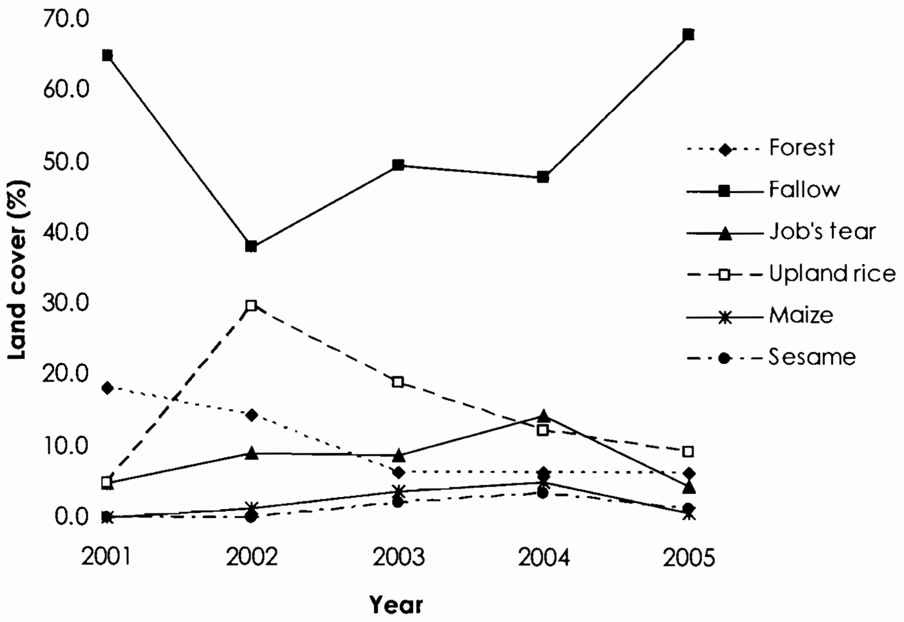

Figure 4: Change in land cover (%) between 2001 and 2005 by forest, fallow and annual crops within the Houay Pano main catchment (S4)

3.3 Main factors affecting runoff coefficients

As shown in table 2, the variables that statistically affected the annual runoff coefficient, at the 0.01 probability level, were mainly parameters describing catchment geometry and soil characteristics. Annual crops (upland rice and sesame) and fallow were found to be associated with high runoff coefficients while improved fallow and more generally 'total conservation practices' were associated with low runoff coefficients. Suspended load was highly correlated to runoff coefficient and is influenced by the same variables except for slope, silt content, bananas, Job's tears and total fallow.

Table 3 summarises the results of the step-wise linear regression analysis. It shows that the best predictors for runoff coefficient are Slp, the slope of the waterway of each catchment, and Impfw, the surface occupied by improved fallow (R^2=0.83, i.e. 83% of the explained variance). For suspended load, the best predictors are Slp, Tac (the total surface occupied by annual crop), and Ttree, the total tree cover (R^2=0.64). In the case of bedload, the best predictors are Jt and Fw, Job's tears and total fallow percentage respectively (R^2=0.77).

Table 2: Correlation coefficient (r) matrix including most significant factors of runoff and soil losses (n = 36)

Factors	Runoff and soil loss variables			
	log(Rc)	**log(SL)**	**BL**	**Log(SY)**
Surface	0.71**	0.58**	-	0.39*
log(Surface)	0.83**	0.63**	-	0.41*
Max Elev.	0.51**	0.33*	-	-
Elev. Range	0.84**	0.61**	-	0.45**
Slope	0.34*	-	-	-
Slope Stand. Dev.	- 0.72**	-0.55**	-	-0.39*
Perim	0.83**	0.61**	-	0.40*
log(Perim)	0.85**	0.63**	-	0.41*
Slw	-0.89**	-0.71**	-	-0.48**
log(Lw)	0.87**	0.69**	-	0.45**
Silt	0.42*	-	-0.35*	-
Sand	-0.53**	-0.36*	-	-0.37*
Forest	-0.35*	-0.41*	-	-
Fallow	0.64**	0.35*	-0.38*	-
Impfw	-0.77**	-0.63**	-	-0.60**
Bananas	0.34*	-	-	-
Jt	-	0.39*	0.85**	0.48**
Upland rice	0.45**	0.53**	-	0.46**
Sesame	0.45**	0.41*	-	-
Tac	0.39*	0.54*	0.62**	0.60**
Ttree	-0.38*	-0.48**	-	-
Total fallow	-	-0.35*	-0.60**	-0.57**
Tcp	-0.76**	-0.59**	-	-0.58**
log(Rc)		0.77**	-	0.59**
log(SL)	0.77**		-	0.81**
BL	-	-		0.44*
Log(SY)	0.59**	0.81**	0.44*	

* correlation significant at the 0.05 level

** correlation significant at the 0.01 level

-: non significant.

Table 3: Linear models from stepwise regression analyses (n=36), and linear regression coefficient (R^2)

Explained variables	Linear regression equation	R^2
Runoff coefficient	log(Rc) = [2.117 - (0.033xSlp)] - (0.007xImpfw)	0.83
Suspended load	log(SL) = [0.473 - (0.028xSlp)] + (0.014xTac) - (0.027 xTtree)	0.64
Bed load	Bd = [0.575 + (0.132xJt)] - (0.014xFw)	0.77
Sediment yield	log(SY) = [-0.345 + (0.016 xTac)] - (0.019xImpfw)	0.49

4. Discussion

The 'acceptable soil erosion' rate for maintaining balance between soil formation and soil erosion is currently considered to be 2 Mg ha^{-1} yr^{-1}. With a mean sediment yield of 3.52 Mg ha^{-1} yr^{-1} for the larger catchment of 60.2 ha, soil losses at Houay Pano largely exceeded this figure. A scenario with 100% annual crops would lead to an annual sediment yield of 18 Mg ha^{-1} yr^{-1}. Conversely, a scenario with 100% improved fallow would produce only 6 kg ha^{-1} yr^{-1}.

Soil erosion primarily affects top soil and fine particles and thus has a major effect on soil fertility within the catchment (Chaplot et al, 2005c). The results of this study also clearly show that annual crops can have off-site impacts. The 53 Mg trapped each year on average in the main weir (S4) would normally be trapped downstream in irrigation canals. More importantly, 156 Mg of suspended sediment is exported downstream annually from the catchment. At the catchment level, mean carbon enrichment by a factor of 1.5 in the eroded sediment was found compared to the bulk soil (Rumpel et al, 2006), with likely consequences on downstream water quality. The lack of a statistically significant relationship between annual rainfall or maximum monthly rainfall and runoff and soil loss parameters can be ascribed to the absence of any major variations in rainfall within the study period (figure 2). In addition, no exceptional rain event, such as a typhoon, was recorded. Our results appear to substantiate projections suggesting that climate change is likely to have less of an impact on soil losses than land-use changes (Chaplot et al, 2005b).

It was found that runoff coefficient was more affected than soil loss by parameters describing catchment geometry. These depend primarily on land use. Runoff coefficient and suspended load decrease where the stream slope increases. This surprising result can be explained by the observation that hillslope catchments with steep slopes are much more permeable than valley bottoms with lower slopes. Likewise, hillslope catchments produce more bedload than suspended load compared to the nested catchments along the stream. Increases in water infiltration on steep slopes are a consequence of soil crusts not developing as readily on these surfaces, this was shown on small plots in Thailand and in the same catchment in Laos (Janeau et al, 2003). The observed increased runoff production from the catchment with a lower stream slope is probably occurred because between weirs S1 and S2 (figure 1), suspended load is trapped in a swampy zone, where it accumulates and retains water. Geophysical studies are currently underway which, it is hoped, will confirm that this wetland acts as a water storage reservoir (water table).

As mentioned above, soil loss, reflected by bedload and sediment yield, depends predominantly on land use. In particular, annual crops are the major cause of soil erosion at the catchment level. These results are consistent with those obtained i) from studies on gully erosion in the same catchments (Chaplot et al, 2005a); and ii) from studies by the Management of Soil Erosion Consortium in catchments located in five Southeast Asian countries where annual cropping also appeared as the major factor contributing to soil loss at the catchment scale (Phommasack et al, 2003). Cropping of Job's tears, which is often planted after upland rice on fertility-depleted soil, appears to be a major cause of bedload. In contrast, fallow and improved fallow tend to limit soil loss. Current studies indicate that improved fallow systems are more readily accepted by farmers than hedgerows. Improved fallow that rehabilitates degraded land and enhances water quality is currently disseminated by several organisations in the region.

5. Conclusion and recommendations

This study clearly showed how rapid land-use change can have a huge impact on soil loss at the catchment scale. If the observed trend continues in the Houay Pano catchment, sediment yields may reach 18 Mg ha^{-1} yr^{-1} at the catchment scale. To combat soil erosion, and thus off-site effects, mainly in the form of suspended load, improved fallows appear to be a promising alternative to the current situation.

Acknowledgements

This research was carried out within the framework of the Management Soil Erosion Consortium, which aims to gain a better understanding of water erosion within catchments in Southeast Asia. The authors gratefully acknowledge the Asian Development Bank, the Institut de Recherche pour le Développement and the International Water Management Institute for co-funding this project with the five national partner institutions.

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Correct citation for this work:

Gebbie, L., Glendinning, A., Lefroy-Braun, R. and Victor, M. (editors). 2007. *Proceedings of the International Conference on Sustainable Sloping Lands and Watershed Management: linking research to strengthen upland policies and practices.* Vientiane: NAFRI.

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