Effects of Land Use and Management Systems on Water and Sediment Yields: Evaluation from Several Micro Catchments in Southeast Asia

F. Agus, T. Vadari, R.L. Watung, Sukristiyonubowo and C. Valentin

Abstract

In an effort to develop economically promising and environmentally benign catchment-scale upland management systems, the Management of Soil Erosion Consortium (MSEC) initiated intensive soil erosion studies in selected catchments in the Philippines, Thailand, Laos, Vietnam, Nepal, and Indonesia. Hydrological stations were equipped with automatic water level recorders and staff gauges to measure water and sediment yields from each catchment and sub-catchment. Rainfall data were collected using automatic weather stations and manual rain gauges. Sediment and water yields were analyzed as these relate to land use and management systems at the micro catchment scale. The analysis showed that land use and management techniques greatly affect sediment and water yields. Catchments with good landscape filter systems such as orchards and forest with natural undergrowth, and catchments with grass strips as hedgerows showed better control of erosion than those under intensive cultivation of annual crops, or perennial trees but no undergrowth cover. Smaller sub-catchments used intensively for annual crops exhibited a shorter lag time between the peak of rainfall and the peak of runoff. Moreover, their runoff coefficients were relatively higher than those of catchments with perennial trees and good undergrowth and litter cover. This translates to the higher flood mitigation functions of better-covered catchments. Erosion from paddy fields is negligible and usually higher during tillage operation. Better regulation in water flow between plots can significantly control the sediment outflow from terraced paddy fields.

Introduction

Poverty and land degradation exist in a vicious cycle largely affecting the marginalized upland poor farmers in Southeast Asia. High population growth, for example 1.6 percent per annum in Indonesia, results in a continued increase in food demand and increased encroachment on the less suitable steep lands to produce more crops. Contrary to soil conservation principles, these steep lands have been inappropriately managed, unintentionally increasing runoff and accelerating soil erosion and sedimentation.

Because of the undividable link among the biophysical, socio-economic, and cultural factors, they should all be considered in developing options for improved soil management. Lack of implementation of research results may have been caused by the failure to take into

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account these interdependent concerns. In many cases, conserving the soil is given low priority by farmers on steep lands because most recommended conservation technology options are expensive and do not provide direct and short-term benefits to them. They are not able to address the reality of the rural poor (Garrity and Agus, 1999; Agus *et al.,* 1998). Researchers in many parts of the world have not successfully developed on-farm technologies that integrate both increased agricultural production and income and secure the upstream and downstream natural resource base (Shaxson, 1999). In Indonesia, for example, there have been many research and development projects dealing with conservation. However, many introduced measures have not been sustained by the farmers beyond the project life because most of them cannot generate intrinsic rewards to the farmers and project incentives are at their best within the project's duration.

Past failures to develop integrated, two-pronged (both for better production and conservation) management systems, led us to re-examine approaches to research on sustainable land management. A participatory catchment management research using an integrated and interdisciplinary approach has evolved and been adopted by the Management of Soil Erosion Consortium (MSEC) project of the International Water Management Institute (IWMI). National agricultural research systems from six countries, namely the Philippines, Vietnam, Laos, Thailand, Nepal, and Indonesia have been involved in this project.

Sediment yield and runoff data are important indicators of how different soil management systems keep the soil in place and potentially sustain soil productivity. In the Indonesian site, the earlier study by Agus *et al.* (2002) indicated lower direct runoff (fast flow) and sediment yields in smaller catchments probably because of the longer travel time for the runoff water and sediments to reach the catchment outlet (where measurement is done). Catchments with intensive annual upland farming systems had high water and sediment yields.

This report presents an analysis of the effect of land use and management systems on water and sediment yields of a number of catchments and sub-catchments in the Philippines, Vietnam, Laos, Thailand, and Indonesia. The analysis enables us to appreciate and further recognize the commonality and differences in hydrological behavior of catchments and helps us when formulating appropriate strategies for better land management. The information further provides valuable support to developing policies to promote environmentally sustainable land management and land use systems in Southeast Asia.

Materials and Methods

The catchment-scale research of MSEC was initiated in 1999 in six countries in Asia, but this paper covers only the results from Laos, the Philippines, Vietnam, Thailand, and Indonesia. The study catchments are described in Table 1 and further explained in a later section. This report presents the analysis of the 2002 observations with some reference to the data of the previous years.

Table 1. Characteristics of MSEC catchments and hydrological features in four countries in 2002

Catchment	Area (ha)	Soil order/subgroup	Land use/farming system	Dominant slope (%)
INDONESIA (Sep 01 to -May 02)				
Tegalan	1.1	Andic Eutropepts	Cassava, maize, some trees in 2000 and 2001 and fodder grass and some trees starting in December 2001	45-47(46)
Rambutan	0.9	Andic Dystropepts	95% rambutan, 5% shrubs	22-55(40)
Kalisidi	13	Andic Dystropepts	100% rambutan, lower catchment encroached for annual crops	22-55(37)
Babon	285	Typic Tropaquepts	All above + rice field	0-55(30)
PHILIPPINES				
MC 1	24.9	Ultisols	Falcata, bamboo,. grassland (98%), veg. aAnd root crops (2%)	33
MC 2	17.9	Ultisols	Forest, grassland (85%), cropland, shrubs (10%)	27
MC 3	8	Ultisols	Grassland (75%), cultivated (15%), settlement (10%)	22
MC 4	0.9	Ultisols	Grassland, trees (60%), cultivated and bare (40%)	15
Whole	84.5	Ultisols	Grassland, bamboo, eucalyiptus, etc 80%; vegetablesable and rootcrops (20%).	25
VIETNAM				
W 1	3.7	Ultiosols	Cassava, grass	25-40
W 2	7.7	Ultisols	Cassava, A. mangium	30-35
W 3	10.8	Ultisols	Cassava, tarro, A. mangium	40-45
W 4	7.2	Ultisols	Cassava, A. mangium, sec. forest	35-40
MW	45.5	Ultisols	Cassava, arrow root, sec. forest	20-25
LAOS:				
S0	1.3	Ult, Alf	69% bush fallow 31% teak	25
S1	19.6	Ult, Alf, Ent	76% bush fallow, 14% forest and teak, 9% annual and 1% perennial crops	29
S2	32.8	Alf, Ult, Ent	80% bush fallow, 15% forest and teak 2% annual and 3% perennial crops	27
S3	60.2	Alf, Ent, Ult	60% bush fallow, 10% forest and teak 20% annual and 10% perennial crops	25
S4	63	Alf, Ult, Ent	53% bBush fallow, 43% forest, teak 2% annual and 2% perennial crops	28
THAILAND				
W1	11.8		46% annual, 7% fallow, 35% orchard, 11% forest	34.4
W2	9.6		68% annual, 1% fallow, 5% orchards, 26% forest	34.3
W3	3.2		41% annual, 59% forest	42.7
W4	7.1		71% annual, 8% fallow, 3% orchards, 18% forest	40.6
W5-Whole	93.2		63% annual, 3% fallow, 10% orchards, 23% forest	23.1

1) Fertilizer application for rambutan (Nephelium lappaceum) was ceased in 1999 until mid-2001 because of encroachment by villagers. In November 2001 the company planned to resume the fertilization as well as regenerating some of the trees
2) Only sediment load was included

Hydrological Characterization

The biophysical aspect of research was initiated with the construction of V-notch weirs and sediment traps, and for some catchments, with perennial flow streams, also Parshall flumes. The pairs of sediment traps and V-notch weirs were equipped with both automatic water level recorders (AWLR) (Orphimedes or Thalimedes type) and manual recording staff gauges for water level and discharge measurements.

Four to five hydrological gauging stations were installed in each country. The distribution of the gauging stations in Laos and Thailand is shown in Figures 1 and 2, respectively. In Laos, the measuring stations are located at points along a common stream while in Thailand, four separate small sub-catchments are distributed within one whole catchment. The Lao case typifies the catchments in Vietnam and the Philippines while the Indonesian catchment is similar to the Thai catchment in terms of distribution of gauging instruments.

For perennial flow canals that are equipped with Parshall flumes, water discharge (water yield per unit time) was determined as the product of water velocity (determined either with a current meter or a float) and the cross-sectional area of the flowing water through the flume. For intermittent flow systems with sediment traps and V-notch weirs, water discharge was estimated before and when the water level reached the base of the V-notch. Before the water level reached the V-notch, discharge was calculated as the change in the water volume in the trap divided by the time interval between measurements. When the water level reached the V-notch, the discharge (in the Indonesian case) was calculated using the following relationship:

$$Q = 8/15 \times SQRT\,(2g) \times CD \times \tan\,(q/2) \times h^{2.5} \times 60000 \qquad \text{Eq. 1}$$

Where,

8/15 - a constant depending on the design of the V-notch weir
Q - discharge (L minute^{-1})
g - acceleration due to gravity (9.8 m sec^{-2})
CD - the correction factor of discharge
q - angle of V-notch
h - the water level, measured from the base of the V-notch
60 000 - conversion factor from m^3 h^{-1} to L min^{-1}

Some countries use rating curves, developed as a relationship between the height of water flowing through the V-notch and the volume of outflowing water from the V-notch per unit time. Success in developing the rating curves depends on the capability to calibrate within a wide range of water debit (water height passing the V-notch).

Water level data were obtained from each automatic recorder at 1- or 5-minute intervals and verified for accuracy with the readings of the staff gauges. The staff gauge readings were done three times daily at 08.00, 12.00, and 16.00. A continuous record of rainfall amount and intensity was kept every five or six (in the Indonesian case) minutes using the automatic weather station and manual rain gauges.

Total soil loss or sediment yield was taken as the sum of bed load and suspended load. Suspended load was estimated from a rating curve of each catchment for the relationship between sediment concentration and water discharge passing the V-notch. It is calculated as the product of discharge and sediment concentration. The oven-dry weight of the sediments collected in the sediment trap after each rainfall event represents the bed load (coarse aggregates and particles).

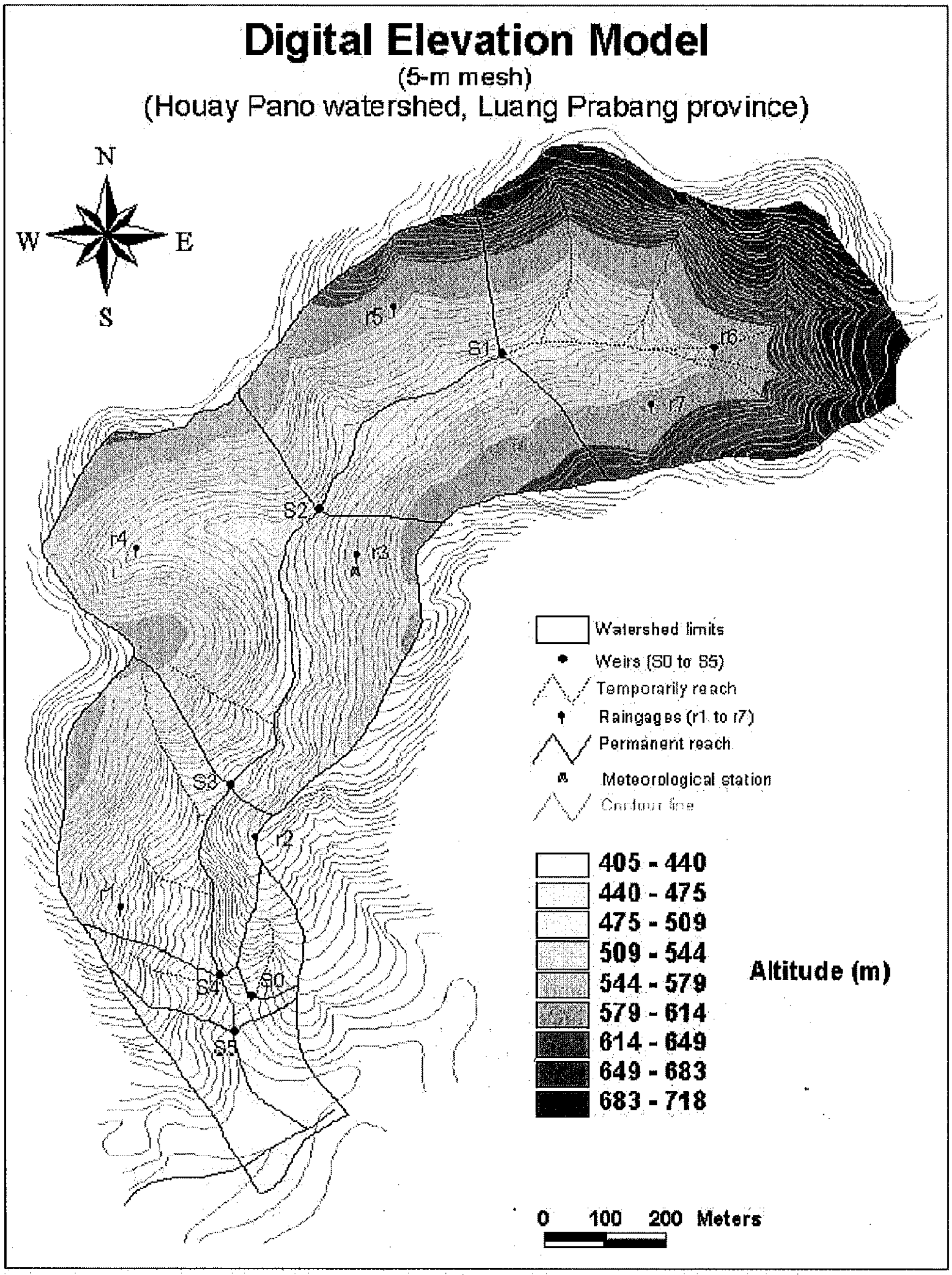


Figure 1. Digital Elevation Model (DEM) of the Houay Pano Catchment in Laos showing the different sub-catchments and the distribution of the weirs, rain gauges, and the meteorological station

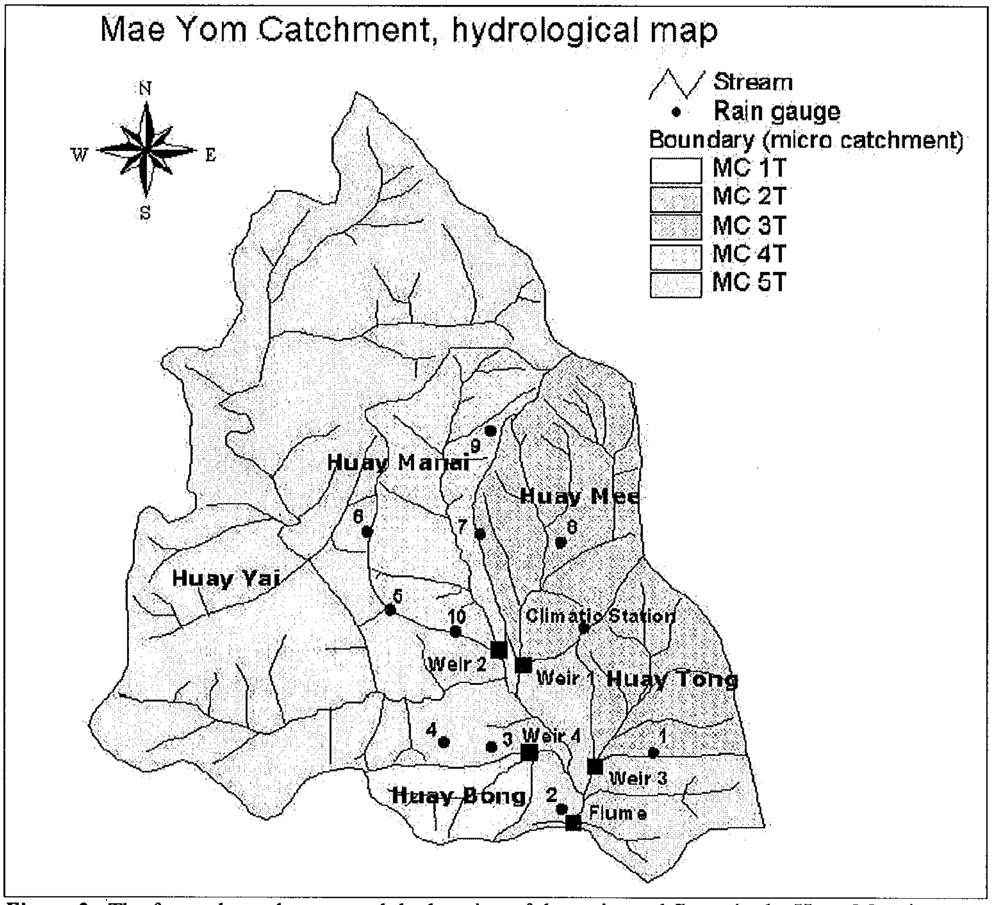


Figure 2. The four sub-catchments and the location of the weirs and flume in the Huay Manai Catchment in Thailand

The relationship between land use, catchment size, and sediment and water yields was described by grouping catchments of different sizes, but with similar land use systems, and those of comparable sizes, but with different land use and management systems.

Erosion in Terraced Paddy Fields

The quantification of erosion from terraced paddy fields was conducted in connection with ongoing research on the Multifunctionality of the Paddy Farming System (Agus *et al.*, 2003). Measurements were done in 18 terraced paddy fields, ranging from 12 to 358 m^2 (total area of 2,515 m^2) in two rice cropping seasons (31 October 2001 to 31 January 2002 and from 16 March to 1 July 2002). V-notch weirs made of GI sheets were installed in the water inlets and outlets. The water level at the inlets and outlets of each plot was recorded two times daily and a rating curve for the relationship between water level and discharge was generated. During and after each field operation (plowing, puddling, transplanting, weeding, and fertilization), intensive water sampling was done and sediment concentrations were determined using gravimetric procedures. Less frequent (weekly) sampling was done during the rest of the season when sediment concentrations are expected to be low. From sediment concentrations and water discharge data, the amount of sediment debits entering and leaving the paddy fields was calculated.

Results and Discussion

Catchment Characteristics and an Overview of 2001 Results

The common features of the sloping upland agricultural land areas in the collaborating countries are the predominantly steep slopes and the poverty of the people. Land use intensity varies from a transition from shifting cultivation to a more permanent agriculture in Laos, to a very intensive farming system in Java, Indonesia. Rainfall patterns, land management systems, and catchment sizes vary within and among countries (Table 1).

The catchments and sub-catchments that were studied intensively varied from 0.9 ha in Indonesia and Philippines to 63 ha in Laos (Figure 3). In Indonesia, the Tegalan, Rambutan, and Kalisidi sub-catchments have intermittent flow and discharge in the drainage canals can only be observed during and shortly after heavy rainfall events. Discharge in Kalisidi is intermittent but continues to flow for a longer time after each heavy rainfall event, and is still observed for several consecutive days during the peak of the rainy season. Lao and Vietnamese catchments have perennial flow while those in Thailand and the Philippines have intermittent streams.

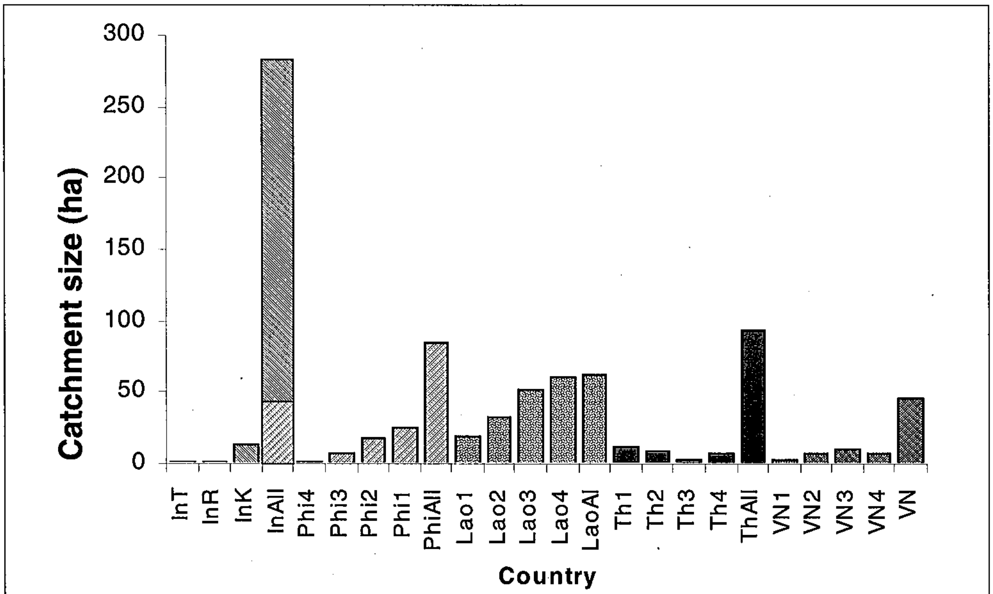


Figure 3. Size of the MSEC catchments in Indonesia (In), the Philippines (Phi), Laos (Lao), Thailand (Th), and Vietnam (VN). T, R, and K for Indonesia stand for Tegalan, Rambutan, and Kalisidi, and modifier 'All' means the overall catchment encasing all sub-catchments

The study site in Indonesia is located in Ungaran sub-district, Central Java Province. It is relatively close to urban development and farming constitutes the second or third source of income. The annual rainfall of about 2,800 mm and high intensity rains in the catchment typify the rainfall characteristics in the mountainous areas of West and Central Java. Despite the high rainfall, the proportion of runoff relative to rainfall (runoff coefficient) did not exceed 14 percent indicating the high infiltration capacity of the soil at the site. Sediment yields from the sub-catchments, except Tegalan (cultivated to annual crops) were less than 2 t ha^{-1} $year^{-1}$. Sediment yield of the Tegalan sub-catchment was about 20 t ha^{-1} $year^{-1}$. This higher yield can be attributed to the larger soil surface area exposed to raindrops, sparse litter cover, intensive tillage, steep slopes, and the small size of the sub-catchment (Agus *et al.*, 2001).

The Philippine catchment is located in Mindanao and ranges in size from 0.9 to 85 ha. Annual rainfall in 2001 was 2,574 mm. An annual sediment yield of 52 t ha^{-1} was observed from the smallest sub-catchment (MC4) of 0.9 ha and 40 percent being cultivated or bare. The higher yield was also because the bare and cultivated portion was relatively close to the sediment trap. For larger sub-catchments, sediment yields were not more than 1 t ha^{-1} $year^{-1}$.

The Vietnamese catchment where Dong Cao village is sited represents the typical cultivated mountainous uplands with slopes ranging from 15 to 60 percent. The altitude varies from 125 to 700 m above sea level. The main crops are cassava, taro, peanut, rice, maize, forest plantation such as eucalyptus, *Acacia mangium*, cinnamon, etc. The sub-catchments varied from 4.8 to 96 ha. With an annual rainfall of 2,000 mm in 2001, sediment yields ranged from 1.6 to 4.4 t ha^{-1} in 2001 (Toan, 2001).

The MSEC study site in Laos is located in Luang Prabang Province in the northern part of the country. Luang Prabang is predominantly mountainous, consisting of hills, steep and very steep slopes (8 to more than 55 percent). Gentle slopes (0 to 2 percent) lie on narrow foothills and at the valley bottom. Elevation varies from 290 to 2,257 m above sea level. The most common soil order is Ultisol, found on slopes ranging from 8 to 50 percent. The province has a wet-dry monsoon tropical climate. The dry season (November to March) is cold and mostly dry, while the wet season (April to October) is hot and humid. The annual rainfall in 2001 was 1,230 mm, lower than the average of 1,403 mm. The sub-catchment of 1.3 ha is planted to teak and covered by bush; it had sediment yield of only 0.01 t ha^{-1} $year^{-1}$. The other larger sub-catchments of between 20 to 65 ha and cultivated to annual upland crops, yielded sediments of 2.1 to 6.4 t ha^{-1} $year^{-1}$.

In Thailand, four sub-catchments namely, Huay Mee, Huay Ma Nai, Huay Bong, and Huay Tong were delineated within the study catchment. They are approximately 10.4, 8.6, 3.7, and 6.5 ha, respectively and dominated by annual upland crops and some patches of orchard and forest.

Rainfall and Water Yield in 2002

In 2002, among the sites, the Dong Cao Catchment in Vietnam had the lowest annual rainfall of 1,090 mm. The Indonesian site had the highest at 3,136 mm (Figure 4).

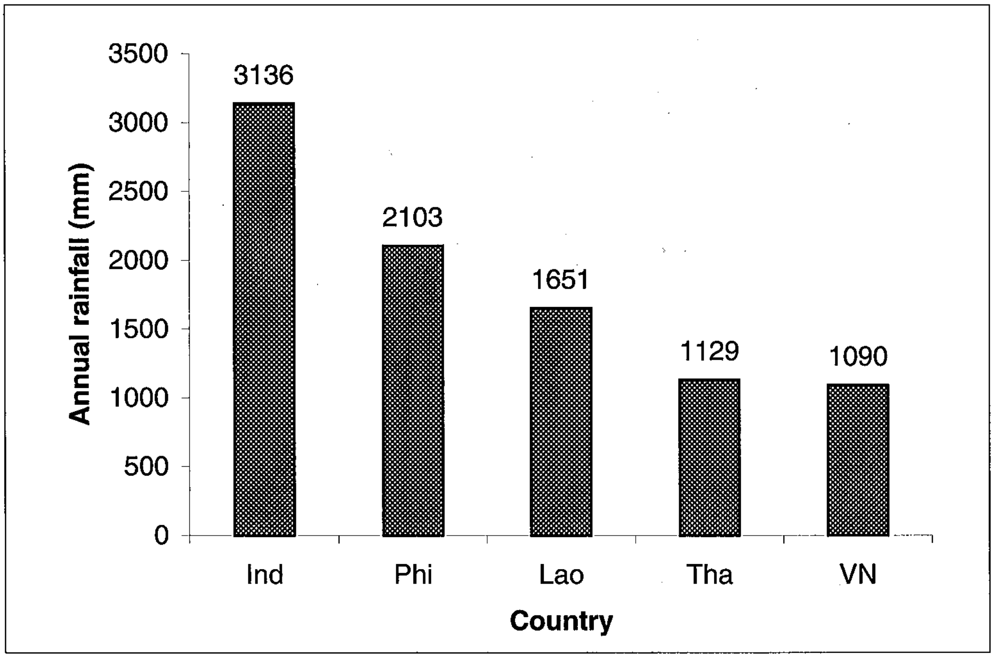


Figure 4. Annual rainfall (mm) at the different MSEC catchments in 2002

Figure 5 shows the variation in water yields expressed as runoff coefficients, R (%), or the fraction of rainfall that flows as runoff and reaches the measuring gauges of the different catchments and sub-catchments. They represent the sum of the direct runoff and the sub-surface flow and thus direct comparison of the management system and catchment size effects could not easily be made.

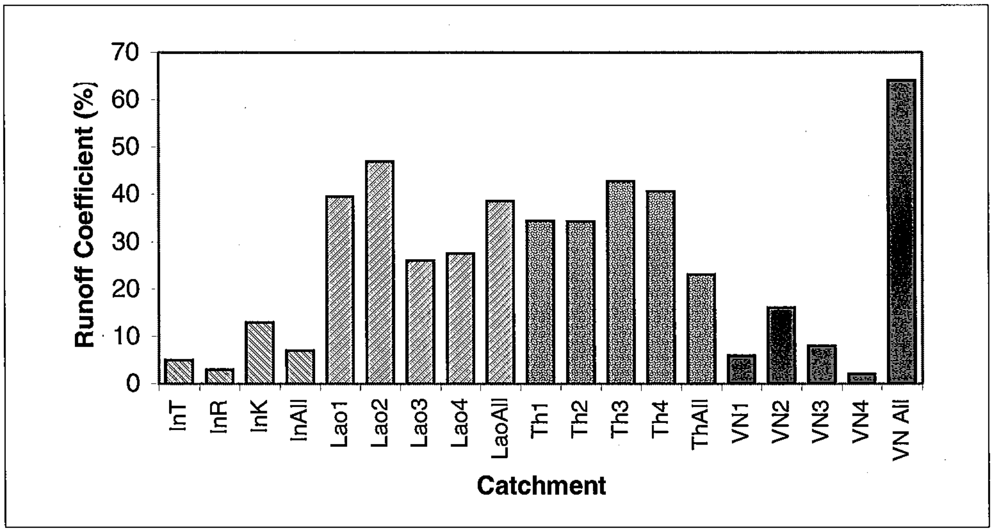


Figure 5. Runoff coefficient values (%) of the different MSEC catchments in 2002

The Indonesian sub-catchments were among the lowest, especially the Tegalan (InT) and Rambutan (InR) sub-catchments with R values values of 5 and 3 percent, respectively. With a land use system similar to the Rambutan sub-catchment, the Kalisidi sub-catchment had a much higher runoff coefficient of 13 percent. This seems to have reflected only the direct runoff because there was almost no tailing observed in the hydrographs of these two small sub-catchments (Figure 6). The hydrograph of Kalisidi was skewed indicating the effects of the long travel time of runoff water and/or the presence of sub-surface flow that reappeared on the soil surface near the measuring gauge Agus *et al.* (2002). The Babon Catchment (InAll) has a perennial stream, and its small total flow may have resulted from the unaccounted volume of water piped out for household use in the nearby village.

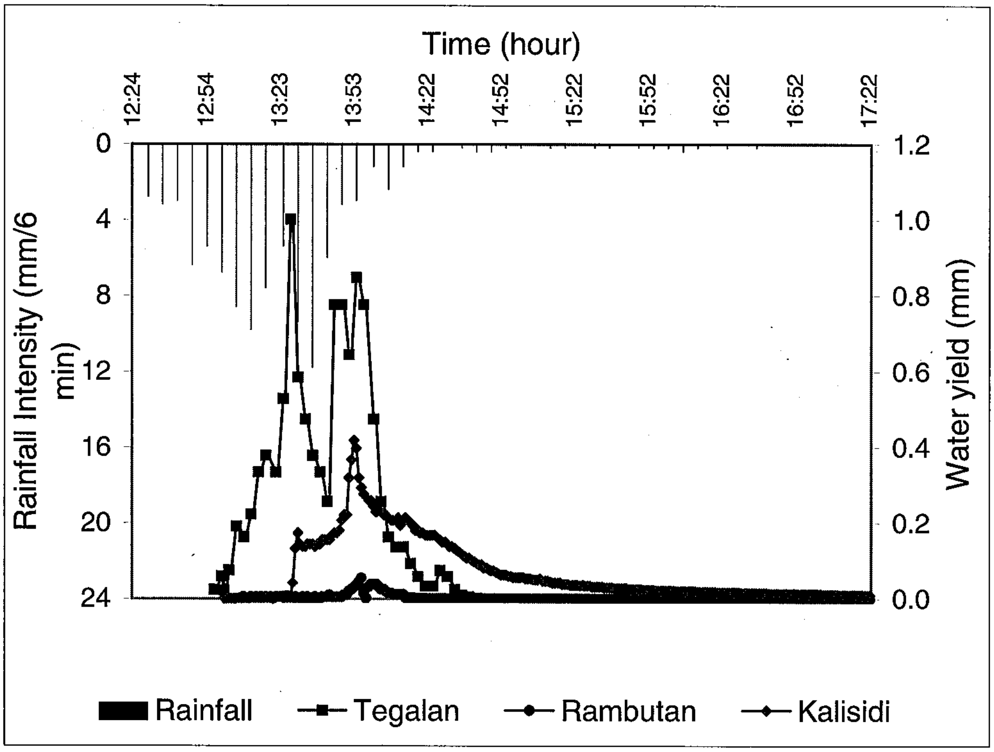


Figure 6. Hydrographs of Tegalan, Rambutan, and Kalisidi sub-catchments in Indonesia (rainfall event on 15 December 2001 with 102 mm)

The runoff coefficient of the Lao catchments was expected to be relatively high because of the perennial nature of the stream combining base flow and direct runoff. However, for the intermittent stream of the Thai catchment, the runoff coefficients seem to be high and the data currently available are insufficient to explain this phenomenon. Inclusion of soil property data and hydrographs of selected rainfall can better explain this observation. Although annual rainfall in the Vietnamese catchments was much smaller than that in the Indonesian catchment, the runoff coefficient was higher.

The runoff coefficient data (Figure 5) and hydrographs for the Indonesian case (Figure 6) clearly show the effect of land use systems on the hydrological response of each catchment.

The Tegalan Catchment planted to intensive annual crops had a higher R value and was more responsive (transmitting rainfall into runoff more readily) to rainfall than the Rambutan and Kalisidi sub-catchments with perennial tree cover. There was a shorter lag time between the peak of rainfall and the peak of discharge in the Tegalan Catchment than in the other two sub-catchments. Runoff also stopped earlier after the rain. The Rambutan sub-catchment was very nicely covered, not only by rambutan trees, but also by natural vegetation and a tree litter layer on the floor. Near its outlet, an area of about 5 percent of the sub-catchment was bush fallow. These conditions have resulted in high infiltration and low runoff even with a high amount (102 mm) and intensity of rainfall during this particular event.

Sediment Yield and Land Use

Sediment yields vary from catchment to catchment, with the highest of 24 t ha^{-1} year^{-1} observed in the small (0.9 ha), cultivated, partially bare and grassland sub-catchment in the Philippines. This was followed by the Tegalan sub-catchment (InT) planted to annual upland crops (partially converted to fodder grass planting in 2002) in Indonesia, with sediment yield of 10 t ha^{-1} year^{-1} (Figure 7). Sediment yield from InT was much greater than InR and slightly higher than InK; the latter two are dominated by rambutan trees. Although the Kalisidi Catchment in Indonesia was also covered by rambutan trees, about 30 percent of the orchard floor had been intensively cultivated to annual crops by the local villagers. This has created an erosion-prone zone as indicated by the higher sediment yield of the Kalisidi Catchment. The high proportion of suspended sediment in InK is an indication of the more dispersed aggregates in the exposed (intensively tilled) lower part of the catchment.

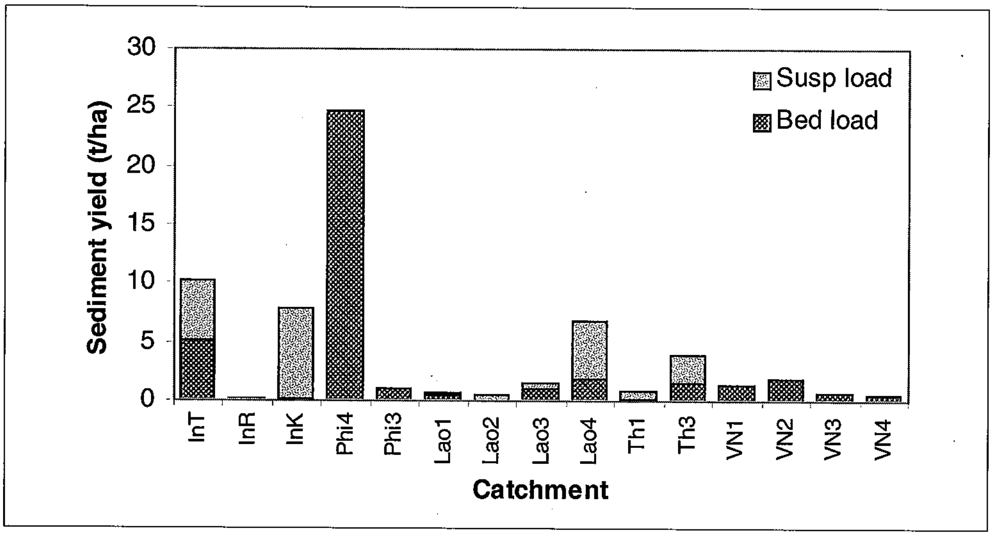


Figure 7. Sediment yields of selected MSEC catchments in the rainy season of 2002 (Nov. 2001 to April 2002 in the case of Indonesia)

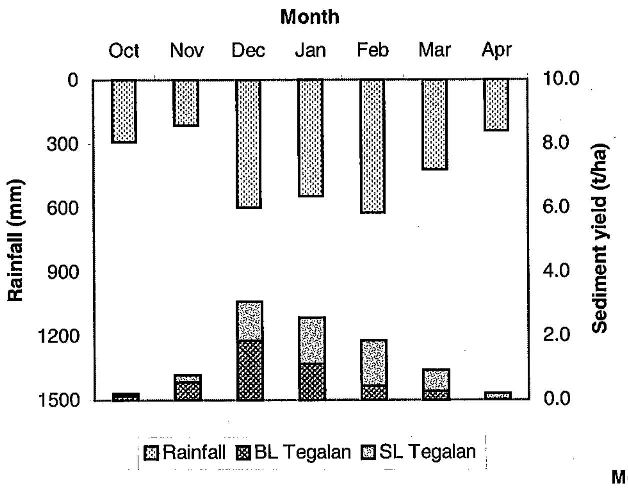
Lao catchments in general were used for shifting cultivation and bush fallow, especially in the lower sub-catchments (Lao3 and Lao4) and therefore sediment yields were relatively high for these two catchments compared to other Lao catchments.

In general, intensively cultivated catchments were observed to have higher sediment yields than other land uses. However, more specific and localized conditions, such as those in the Kalisidi sub-catchment in Indonesia, determine to a large extent the land susceptibility to erosion and this fact reemphasizes the importance of integrating the human dimension in formulating policies for natural resource management. As in the case of Lao4 and InK sub-catchments, equal attention should be given to the more open/exposed areas near the catchment outlet which greatly affect the total sediment yield. In developing soil conservation recommendations, this area near the catchment outlet (and this translates to the zone along the stream) should be paid more attention.

The Special Case of Indonesian Land Management Systems

Grass strips for annual upland crop-based catchment vs. cultivation at the floor of the orchard

Figure 8 illustrates more clearly the positive effect of grass cover in controlling erosion as exemplified by the Tegalan sub-catchment. As opposed to the cultivation of the orchard floor of the Kalisidi sub-catchment, there was less sediment yield in the former sub-catchment.



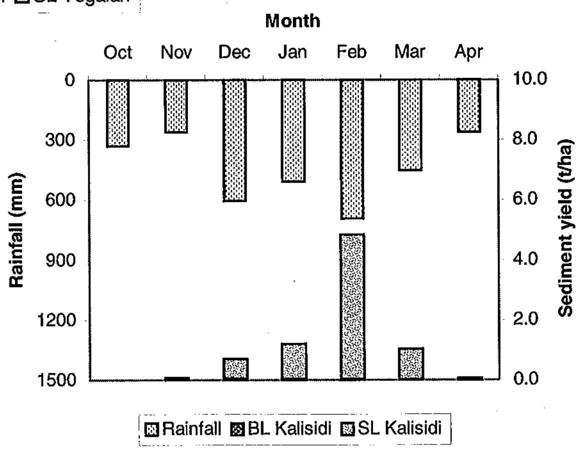


Figure 8. Monthly rainfall and sediment yields in the Tegalan and Kalisidi sub-catchments in Indonesia (measured from October 2001 to April 2002)

In December 2001, there was 600 mm of rainfall in the area, about 450 mm in January 2002 and 620 mm in February 2002. It was observed that the corresponding monthly water discharge from the sub-catchments followed the same pattern as the rainfall, also increasing from December 2001 to February 2002. Monthly sediment yields, however, did not follow the water yield pattern but showed the influence of the management systems. The planting of fodder grass in December 2001 (as part of the introduced option) combined with zero tillage in the Tegalan sub-catchment improved the catchment filter function with time as shown by the decrease in sediment yields in the succeeding months. For the Kalisidi sub-catchment, the monthly sediment yields followed those of the water yield pattern. These results confirm the effectiveness of the grass system in improving the filter function of the catchment. The planting of grass hedgerows in combination with cattle fattening, not only decreased erosion, but also promises higher profits. Hence, the system became the most preferred practice by the farmers (Watung *et al.*, 2003).

Soil Loss from Terraced Paddy Fields

Paddy fields, because of the terrace and dike system (Figure 9) can function as a filter for transported soil sediment in a landscape. In many cases, runoff from the upland system feeds into cutoff drains or irrigation canals. From here, it feeds into the terraced paddy system where the sediments and nutrients contained could be deposited. Despite this possible conservation function of paddy fields, not much is known about quantifying sediment transport into and out of a paddy field system.

Figure 9. Terraced paddy field, shortly after tillage (puddling), showing suspended sediment in a few terraces down slope

A recent study by Kundarto *et al.* (2002) showed that sediment transport in the paddy system is very small (<1.5 t ha^{-1} $season^{-1}$) and more than 50 percent of the paddy field erosion was associated with tillage operation (Table 2). Water flow in the system only occurred when the water level in the fields exceeded the normal water level (5-10 cm) during tillage and the vegetative stage of the rice plant. Thus, regulating and keeping the water from flowing to the lower terraces can further minimize sediment transport especially during tillage.

Table 2. Amount of sediment entering and leaving a series of 18 terraced paddy fields (size between 12 to 358 m2 and total area of 2,515 m2) during two rice cropping seasons (31 October 2001 to 31 January 2002 and from 16 March to 1 July 2002).

Variable	Cropping sSeason	
	First	Second
Duration of observation (day)	62	69
Sediment budget:		
Total sediment entering the system from irrigation canal (t /ha-1)	3.4 1)	6.2 1)
Total sediment leaving the system (t /ha-1)	1.4	0.8
Total sediment leaving the system during tillage operation (t /ha-1)	0.7	0.6
Net sediment deposition (t /ha-1)	2	5.4

Source: Adapted from Kundarto et al. (2002)
1) These values may have been overestimated because of the difficulty in controlling the water level in the erosion canal and that in the first terrace.

During and a few hours after tillage, mud from tilled terraces was transported to only a few terraces downslope. This means that particles reaching the stream originated from only a few plots/fields nearby. The general slope of this terraced paddy field is about 25 percent, but the level bench terraces and dike system could have minimized its effect on erosion. Table 2 also shows that if the irrigation water is loaded with sediments, most of these sediments would be deposited in the field, implying the filtering ability of the paddy fields to erosion in a landscape.

Conclusions and Recommendations

- Catchments with good filter systems such as orchards and forest with natural undergrowth or catchments planted to grass showed better control of erosion as compared to catchments used for intensive annual crops or perennial trees, but with cleared undergrowth. Tree cover *per se* without floor contact-cover such as litter and undergrowth cannot guarantee good erosion control.
- Mitigating sedimentation is very much influenced by the location of the erosion control measures which serve as filters. The zone along the stream is critical and needs to be covered with a good filter for stream protection. Conservation recommendations should emphasize the improvement of vegetative filters along the streams.
- Erosion from paddy fields is negligible compared to that from annual upland farming systems of similar general slope, and paddy fields can function as sediment filters in a landscape.

Acknowledgement

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