Evaluation of Environmental Factors and Soil Erosion in MSEC Catchments

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Abstract

Although changes in land use or management practices most commonly modify surface runoff, soil erosion, and soil fertility, such processes are still very poorly documented at the scale of catchments. The Management of Soil Erosion Consortium (MSEC) initiated a research project in six countries of Asia. MSEC provides the data collected from catchments representative of a variety of situations. This study aims to test existing regression models (Phommasack et al., *2001) for the prediction of runoff and annual erosion amounts over the study catchments. The data set for model generation consisted of annual budgets for 2001 from five catchments and 21 sub-catchments located in five countries of Southeast Asia (Indonesia, Laos, the Philippines, Thailand, and Vietnam). Runoff and erosion budgets from the 2002 rainy season for these catchments constituted the validation set.*

The runoff (R) model showed a root mean square error (RMSE) of 18 percent. An error analysis revealed that accurate estimations occurred for larger catchments. At smaller catchments, R was overestimated in Laos where high infiltration capacity and sub-surface runoff occurred, and was underestimated in Thailand where eroded soils induced high surface runoff rates. The model for bedload prediction showed a mean error (ME) of 4.5 t ha^{-1}*, which is weak considering a bedload standard deviation of 5 t* ha^{-1}*. Accurate estimations occurred for suspended load (SL). These results confirmed the ability of prediction models to accurately estimate catchment outputs for runoff and partial sediment. These results also illustrate the real need to integrate erosion mechanisms acting at different spatial scales.*

Introduction

Water availability, water quality, and sediment delivery have become crucial for food security, human health, and the environment. In particular, most concerns stem from the rapid changes in land use patterns caused by demographic, economic, political, and cultural transitions (Ingram *et al.*, 1996). Inappropriate land use has long been recognized as one of the major causes of decreasing water supply, and accelerated soil erosion and nutrient loss, particularly

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in areas of recent land cover changes such as the tropical regions. The conversion of tropical rainforests to pastures or cultivated land commonly results in a reduction of surface soil porosity. Increased erosion removes the first top cm where most organic matter and nutrients are concentrated. In addition to decreased on-site productivity, these processes lead to off-site consequences including flooding; decrease in groundwater recharge; pollution by nutrients, heavy metals, and pesticides; siltation; and eutrophication of reservoirs (IGBP, 1995).

Despite the crucial need for a sound assessment of these processes, available data remain scarce and are usually based on a single process observed at a specific scale (e.g. soil loss from erosion plots). In the sloping lands of Southeast Asia, land use changes are very rapid due to strong demographic, economic, and political drivers. In many locations, the pristine forest has been cleared for slash-and-burn cultivation or for more intensified systems based on the use of pesticides, fertilizers, and machinery. At the onset of the rainy season, the tilled soil that is left bare tends to crust and generates runoff, which concentrates and generates gully erosion. Conversely, appropriate land use can lead to soil and water conservation.

To tackle these issues, the Management of Soil Erosion Consortium (MSEC) initiated a research project in six countries of Asia with the support of the Asian Development Bank (ADB). It aims at developing, adapting, and disseminating appropriate tools and methodologies to reduce the on- and off-site effects of erosion on land and water resources (Maglinao, 2001). Each participating country has selected a catchment of about 100 ha and equipped it and at least four sub-catchments to monitor runoff and sediment yield. These catchments are representative of the prevailing biophysical and socio-economic conditions in the area. The objectives of this particular study are: (i) to assess runoff and sediment yield annual budgets from the data collected in 2001 from five catchments and 21 sub-catchments; (ii) to assess the impact of land use, climate, and topography on runoff, bedload, and suspended load annual budgets; and (iii) to predict annual runoff and sediment yield using statistical models.

Materials and Methods

Data Acquisition

Rainfall, runoff, and sediment yields and other climatic data were collected in 2001 from five catchments and 21 sub-catchments in five countries in Southeast Asia. The landscape descriptions of the study sites in Indonesia, the Philippines, Thailand, and Vietnam are presented in Figure 1 and of Laos in Figure 2. In 2002, Indonesia studied four sub-catchments; Laos, eight; the Philippines, four; Thailand, four and Vietnam, four.

In 2001, catchment delineation and topographic features of the catchments were derived from Digital Elevation Models (DEM) with a 10 m mesh. In most cases, DEMs were available at 10 m resolution generated by interpolation from digitized contours of 5 m intervals in a 1: 50,000 topographic map. Some more accurate DEMs have been established by interpolation from field spot heights using a theodolite (e.g. Laos). Topographic characteristics such as slope angle and its standard deviation for each sub-catchment were estimated from DEMs using Arc-View® software (ESRI, 1994).

Runoff and erosion data were collected at the outlet of each catchment and sub-catchment where measuring devices had been installed. Runoff data were gathered both manually using staff gauges and automatically using automatic water level recorders. Water level in the weirs

Figure 1. Landscape characteristics and land management in Indonesia (4 sub-catchments), Philippines (4 sub-catchments), Thailand (4 sub-catchments), and Vietnam (4 sub-catchments).

was automatically recorded at a time step lower than 10 minutes. In Laos, Thailand, and Indonesia, water samples were collected during the main rainfall events to assess the sediment concentration. The time interval for water sampling differed among sites. Samples were collected at time intervals from two minutes to one hour depending on water discharge peaks. Bedload sediments, i.e. the sediments trapped in the weirs, were collected and weighed after each main rainfall event or once at the end of the rainy season depending on the amount accumulated. Runoff and sediment yield data were computed to obtain yearly means. Mean annual suspended sediment concentration was combined with water flux data to assess the annual suspended load, using data interpolation between the sampling periods.

Rainfall data were collected using manual rain gauges and an automatic weather station installed in each catchment site. Data from the manual rain gauges were recorded with a daily time step while six-minute data acquisition was recorded by an automatic weather station.

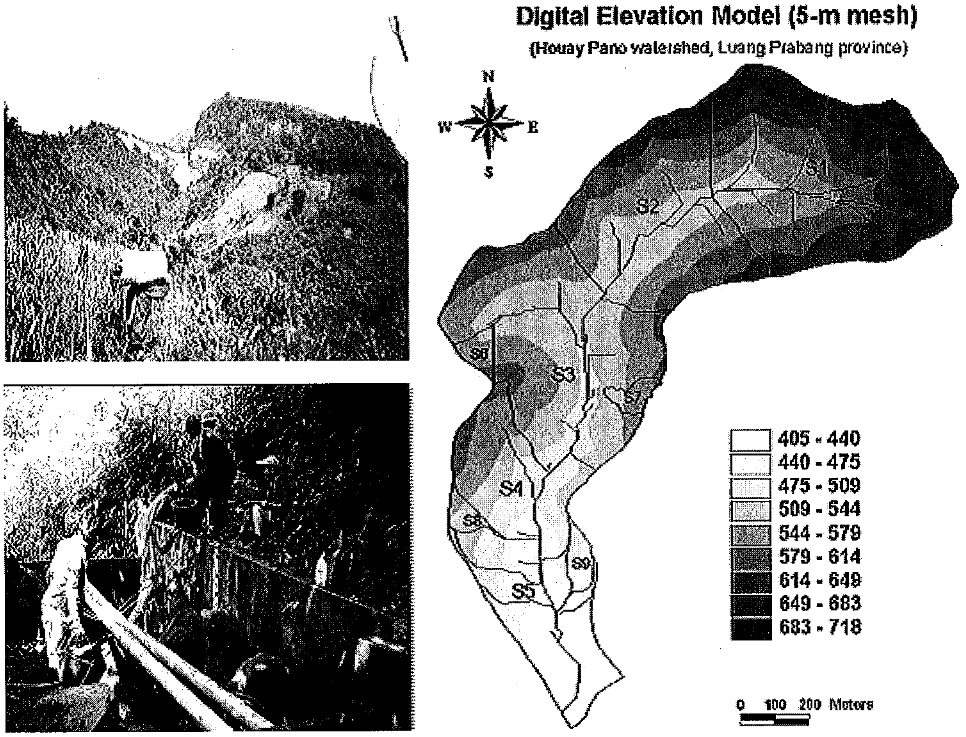

Figure 2. The Lao PDR site: landscape and land management of the main catchment and bedload collection at the outlet of one sub-catchment (pictures, left); digital elevation model with a 10-m mesh, channel network distribution, and location of the 9 sub-catchments

Land use was assessed from field surveys. Land use types included: forest (Fo), annual crops (C), fallows or pastures (Fa). Crops associated with conservation practices (Cp) were mainly coffee and agroforestry techniques with annual crops. Teak, eucalyptus tree plantations, and orchards were placed in a single category (O).

Statistical Analysis and Modelling

A factorial analysis was done to evaluate the effect of climate, topography, and land use on runoff and sediment yield. The relation between environmental factors and runoff amount (R), bedload (BL), and suspended load (SL) was first investigated using correlation analysis. Variance analysis was done between runoff and sediment yield as dependent variables and environmental factors as independent variables. These environmental factors included the yearly precipitation amount (P), the precipitation ratio (Pr) between the minimum monthly precipitation (Pn) and the maximum monthly precipitation (Px), the slope gradient (S), the catchment area (Surf) and the areal percentage of each land use type. Forward stepwise regression analyses (Neter *et al.*, 1989) were established using 2001 data to predict runoff and sediment yield using environmental factors as predictors. Regression analyses were performed using the Statistica® package for use on a personal computer (Statsoft, 1996). Parameters with statistical significance at the 0.01 level were considered for computing predictive equations and reporting results. The analysis considered data from 16, 21, and 11 sub-catchments for R, BL, and SL, respectively. The data in 2002 from 23, 18, and 25 catchments and sub-catchments were used to validate the generated regression models for R, SL, and BL, respectively.

Results and Discussion

Environmental Factors, Annual Runoff, and Sediment Yield

The main topographic and land use factors of the five catchments and 21 sub-catchments studied in 2001 are shown in Table 1. These same factors studied in 2002 for five catchments and 24 sub-catchments are shown in Table 2. The mean catchment area was 40.1 ha in 2001 (min. 0.9 ha, max. 290 ha) and 23 ha in 2002 (Tables 3 and 4, respectively). The decrease in the mean surface area in 2002 was due to the increase in the number of study catchments with a small surface area. This was the case in Laos with the construction of three new weirs at the outlets of S6, S7, and S8 with a surface area of 0.64, 0.60, and 0.57 ha, respectively.

Table 1. Main topographic and land use factors of the 5 catchments and 21 sub-catchments in 2001

Country	Local name	Study name	Surf (ha)	S (degree)	C (%)	Fa (%)	Cp (%)	O (%)	Fo (%)
Indonesia	Babon	Ib	290.0	10.0	0.0	0.0	0.0	100.0	0.0
	Sill	Is	150.0	8.0	10.0	0.0	90.0	0.0	0.0
	Tegalan	It	3.0	14.0	50.0	0.0	0.0	50.0	0.0
	Rambutan	Ir	2.0	12.0	0.0	0.0	0.0	100.0	0.0
	Kalisidi	Ik	38.0	8.0	0.0	0.0	0.0	100.0	0.0
Laos	S0	L0	1.0	25.0	0.0	69.0	0.0	31.0	0.0
	S1	L1	19.1	29.0	9.2	76.0	0.0	0.8	14.0
	S2	L2	32.8	27.0	1.7	19.7	0.0	7.0	11.6
	S3	L3	51.4	25.0	18.6	61.2	0.0	9.5	10.2
	S4	L4	60.2	28.0	2.3	52.7	0.0	9.9	35.1
	S5	L5	63.0	17.0	0.0	55.7	0.0	31.0	13.4
Philippines	Main	Po	84.5	14.0	23.7	44.9	16.8	0.0	15.4
	MC1	P1	24.9	14.0	10.0	60.2	12.1	0.0	16.1
	MC2	P2	17.8	14.0	47.7	39.3	5.6	0.0	11.2
	MC3	P3	7.9	14.0	15.2	75.9	12.7	0.0	12.7
	MC4	P4	0.9	25.0	42.5	31.9	0.0	0.0	21.3
Thailand	W1	T1	7.5	14.1	30.0	0.0	30.0	30.0	0.0
	W2	T2	7.8	11.6	80.0	0.0	0.0	10.0	10.0
	W3	T3	2.2	12.7	3.0	2.0	2.0	92.0	0.0
	W4	T4	7.5	14.6	60.0	0.0	15.0	15.0	10.0
	Flume	Tf	79.5	11.4	70.0	5.0	12.0	8.0	5.0
Vietnam	W 1	V0	4.6	28.0	80.0	0.0	20.0	0.0	0.0
	W 2	V1	9.4	29.0	0.0	5.0	95.0	0.0	0.0
	W 3	V2	6.2	27.0	0.0	35.0	65.0	0.0	0.0
	W 4	V3	11.7	31.0	0.0	60.0	40.0	0.0	0.0
	MW	V4	59.5	25.0	28.0	22.0	20.0	30.0	0.0

Surf (ha) is the catchment area; S, the slope angle (?); C, the areal percentage for annual crops; Fa, the areal percentage for fallows or pastures; Cp the areal percentage for crops with conservation practices; O, the areal percentage for orchards; Fo, the areal percentage for forest

Table 2. Main topographic and land use factors of the 5 catchments and 24 sub-catchments in 2002

Country	Local name	Study name	Surf (ha)	S (degree)	C (%)	Fa (%)	Cp (%)	O (%)	Fo (%)
Indonesia	Babon	Ib	35.0	10.0	51.0	0.0	49.0	40.0	0.0
	Sill	Is		8.0					
	Tegalan	It	3.2	14.0	60.0	0.0	40.0	0.0	0.0
	Rambutan	Ir	2.0	12.0	0.0	0.0	100.0	100.0	0.0
	Kalisidi	Ik	38.5	8.0	0.0	0.0	100.0	100.0	0.0
Laos	S1	L1	19.6	29.0	49.5	36.0	0.0	0.7	13.8
	S2	L2	32.8	27.0	27.5	7.6	0.0	0.0	5.8
	S3	L3	51.4	25.0	8.9	15.8	0.0	4.6	3.4
	S4	L4	60.2	28.0	1.1	7.1	0.0	0.2	5.4
	S5	L5	63.0	23.8	0.1	1.6	0.0	0.0	1.5
	S6	L6	0.6	25.6	54.7	6.3	54.7	9.4	29.7
	S7	L7	0.6	28.8	76.3	0.0	0.0	0.0	19.9
	S8	L8	0.6	22.6	52.9	0.0	52.9	0.0	77.6
	S9	L9	0.7	25.5	86.7	0.0	86.7	0.0	13.8
Philippines	Main	Po	84.5	25.0	24.8	40.6	7.4	11.8	15.4
	MC1	P1	24.9	33.0	15.1	56.8	8.0	4.0	16.1
	MC2	P2	17.9	27.0	57.0	16.9	9.8	4.4	11.9
	MC3	P3	8.0	22.0	65.5	7.9	12.7	1.3	12.7
	MC4	P4	0.9	15.0	56.7	33.3	0.0	0.0	10.0
Thailand	W1	T1	11.8	15.4	46.2	7.2	0.0	35.3	11.3
	W2	T2	9.6	13.5	67.6	1.2	0.0	4.8	26.4
	W3	T3	3.2	17.8	40.9	0.0	0.0	0.2	58.9
	W4	T4	7.1	13.7	71.0	7.9	0.0	3.2	17.9
	Flume	Tf	93.2	15.1	63.4	2.8	0.0	10.4	23.4
Vietnam	W 1	V0	3.7	20.0	0.0	67.0	0.0	0.0	0.0
	W 2	V1	7.7	24.0	44.0	38.0	0.0	0.0	0.0
	W 3	V2	10.8	24.0	0.0	63.0	0.0	0.0	0.0
	W 4	V3	7.2	24.0	0.0	26.0	0.0	0.0	0.0
	MW	V4	45.5	21.0	5.9	57.7	0.0	0.0	5.2

Surf (ha) is the catchment area; S, the slope angle (?); C, the areal percentage for annual crops; Fa, the areal percentage for fallows or pastures; Cp the areal percentage for crops with conservation practices; O, the areal percentage for orchards; Fo, the areal percentage for forest

Table 3. Main statistics (mean, minimum, maximum, standard deviation) for environmental factors in 2001

	Surf (ha)	P (mm)	Pm (mm)	Pr %	S (degree)	C %	Fa %	Cp %	O %	Fo %
Mean	40.15	2,019	466	16	18.8	22.4	27.5	16.8	24.0	7.2
Min	0.94	1,385	275	3	8.0	0.0	0.0	0.0	0.0	0.0
Max	290.00	3,840	672	31	31.0	80.0	76.0	95.0	100.0	35.1
SD	62.08	938	151	9	7.7	26.8	28.4	27.1	34.8	8.9

Surf (ha) is the catchment area; P, the yearly precipitation amount; Pm, the maximum monthly precipitation; Pr (%) the ratio between Pn, the minimum monthly precipitation and Pm; S, the slope angle (?); C, the areal percentage for annual crops; Fa, the areal percentage for fallows or pastures; Cp the areal percentage for crops with conservation practices; O, the areal percentage for orchards; Fo, the areal percentage for forest

Table 4. Main statistics (mean, minimum, maximum, standard deviation) for environmental factors in 2002

	Surf (ha)	P (mm)	Pm (mm)	Pr %	S (degree)	C %	Fa %	Cp %	O %	Fo %
Mean	23.01	1,745	371	2	20.6	36.7	17.9	18.6	11.8	13.6
Min	0.57	1,090	145	3	8.0	0.0	0.0	0.0	0.0	0.0
Max	93.20	3136	548	14	33.0	86.7	67.0	100.0	100.0	77.6
SD	26.55	647	127	4	6.8	28.5	22.0	32.2	26.8	17.9

Surf (ha) is the catchment area; P, the yearly precipitation amount; Pm, the maximum monthly precipitation; Pr (%) the ratio between Pn, the minimum monthly precipitation and Pm; S, the slope angle (?); C, the areal percentage for annual crops; Fa, the areal percentage for fallows or pastures; Cp the areal percentage for crops with conservation practices; O, the areal percentage for orchards; Fo, the areal percentage for forest

The yearly precipitation amount (P) ranged from 1,385 to 3,840 mm in 2001 and from 1,090 to 3,136 mm in 2002; the precipitation ratio (Pr) ranged from 0.03 to 0.31 in 2001 and from 0.03 to 14 in 2002 (Tables 3 and 4). The slope gradient (S) varied from 8 to 33°.

In 2002, the runoff coefficient was estimated for all sub-catchments except in the Philippines and the Sill sub-catchment in Indonesia. SL was not estimated in the Philippines, the four small sub-catchments of Vietnam, the Sill Catchment of Indonesia, and the main flume of Thailand. The BL was not estimated at the outlet of the Lao catchments (as in 2001 due to the configuration of the weir with no trapping area), the Sill, and the main catchment of Thailand.

The mean runoff coefficient (R) was 22 percent in 2001 (with a range from 0.4 to 48 percent) and 22 percent in 2002 (with a range from 0.3 to 64 percent); mean bedload (BL) was 3 t ha^{-1} (0.01-20 t ha^{-1}) in 2001 and 1.9 t ha^{-1} in 2002 (Tables 5 and 6). The mean suspended sediment load (SL) was 1.8 t ha^{-1} (0.04-6.4 t ha^{-1}) in 2001 and 1.9 t ha^{-1} in 2002. The mean sediment concentration (SC) was 1.6 g L^{-1} (between 0.3 and 3.5 g L^{-1}) in 2001 and 1 g L^{-1} in 2002. These results indicate that the mean runoff coefficient (R) and suspended sediment load (SL) did not significantly vary from 2001 to 2002. On the contrary, BL was greatly reduced in 2002.

Table 5. Main statistics (mean, minimum, maximum, standard deviation) for runoff and sediment yield variables in 2001

	R (%)	BL (t ha^{-1})	SL t ha^{-1})	SC (g^{-1})
Mean	22.3.	3.0	1.8	1.6
Min	0.4	0.0	0.0	0.3
Max	48.0	20.0	6.4	3.5
SD	17.8	4.9	2.0	1.0

R is the runoff ratio; BL, the bedload; SL, the suspended sediment load; SC, the sediment concentration.

Table 6. Main statistics (mean, minimum, maximum, standard deviation) for runoff and sediment yield variables in 2002

	R (%)	**BL** (t ha^{-1})	**SL** (t ha^{-1})	**SC** (g^{-1})
Mean	21.6	1.9	1.9	1.0
Min	0.3	0.0	0.0	0.0
Max	64.0	24.7	7.6	3.4
SD	18.0	4.7	2.3	0.9

R is the runoff ratio; BL the bedload; SL the suspended sediments load; SC the sediment concentration.

The comparison between the observed data collected in 2002 and predictions from the statistical models established in 2001 (Phommasack *et al.,* 2001) showed a root mean square error (RMSE) for runoff of 18.3 percent (Table 7). In the case of runoff, the regression model provided higher prediction errors. Maximum errors occurred for smaller catchments. For instance S6, S7, S8, and S9 in Laos showed ME of 46, 57, 31, and 49 percent respectively. In the case of Thailand, smaller catchments revealed an underestimation. The low runoff amount in Laos may be explained by the high infiltration capacity and sub-surface runoff on hillslopes as revealed by hydrologic investigations. In Thailand, higher runoff amounts may result from the large amount of tillage and water erosion that has occurred during the past 30 years under intensive agriculture, which in turn affect infiltration and runoff.

Table 7. RMSE[§] for runoff, bedload. and suspended sediment.

	Runoff %	**Bed lLoad** t ha^{-1}	**Suspended lLoad** t ha^{-1}
ME	8.20	3.82	3.24
RMSE	18.27	5.06	3.24

[§] root mean square error

$$RMSE = \left\{ \frac{1}{n}\sum_{i=1}^{n} [(\text{estimation})^{*}\_\,\text{observation}]^{2} \right\}^{0.5}$$

$$ME = \frac{1}{n}\sum_{i=1}^{n} [(\text{estimation})^{*}\_\,\text{observation}]$$

Accurate estimations occurred for SL for most of the sites and sub-catchments. However, high underestimation was observed in Laos, especially at S2 and S9 (the ME for SL was 8.3 and 10.2, respectively). Lower erosion may be explained by the presence of clay soil and limited tillage depth. In addition, the presence of flat areas downstream of S2 and S9 sub-catchments induced a decrease of flow velocity which in turn allowed sedimentation processes. The model for bedload prediction showed a mean error of 4.5 t ha^{-1}, which is a very weak prediction considering the bedload standard deviation of 4.73 t ha^{-1}. The worst estimation occurred at MC4, the smallest catchment of the Philippines with an ME for BL of -17. This illustrates that high erosion rates may be related to high rainfall intensities or land management conditions not captured in the data set of model generation.

Conclusion

The data generated from monitoring the five catchments and 24 sub-catchemnts in five countries of Southeast Asia in 2002 were used to validate the regression models generated from 2001 data. These models were used for the prediction of runoff and erosion annual budgets.

When considering large catchments, generated models were accurate for runoff and erosion amount predictions. In the case of smaller catchments, high prediction errors (both over- and underestimations) occurred. This illustrates that at these small areas, the areal percentages of crops, the mean slope angle of hillslopes, and the rainfall characteristics are not enough to explain runoff and erosion features as in the case for larger areas. Other factors which may need to be studied are soil aggregate stability, soil tillage, soil infiltration, and topographic conditions downstream of catchments. Other site specific factors may include surface stoniness, soil resistance to shear stress, or the mean depth of soil. Thinner soil with low soil water storage may also affect sediment losses (Burt, 2001).

The percentages of annual crops, rainfall characteristics, and topographic conditions were confirmed as the main factors controlling sediment yield, both in terms of suspended load and bedload under these sloping land conditions. Such statistical prediction models must, however, be based on data from catchments with different sizes that include a longer time series than two years, one for calibration and one for validation.

Finally, the modelling approach, aiming at better prediction of water and sediment loads at the catchment scale should further integrate mechanisms involved at different spatial scales.

References

Burt, T.P. 2001. Integrated management of sensitive catchment systems. *Catena,* 42 275-290.

EPA. 2000. http://www.epa.gov/ost/ftp/basins/system/BASINS3

ESRI. 1994. *Understanding GIS. The ARC/INFO method.* ESRI, 380 New York Street, Redlands, CA USA 92273, 300 pp.

IGBP (International Geosphere-Biosphere Programme). 1995. *Land-use and land cover change.* Science Research Plan, Stockholm, 123 p.

Ingram, J.; Lee, J.; and Valentin, C. 1996. The GCTE soil erosion network: a multidisciplinary research program. *Journal of Soil and Water Conservation,* 51 (5), 377-380.

Maglinao, A. 2001. The management of soil erosion consortium (MSEC): linking land and water management for sustainable upland development in Asia. In *Proceedings of integrated watershed management for land and water conservation and sustainable agricultural production in Asia* (ADB-ICRISAT Annual Meeting and 6th MSEC Assembly), 10-14 December 2001. Hanoi, Vietnam.

Phommasack, T.; Agus, F.; Boosaner, A.; Bricquet, J.P.; Chantavongsa,A.; Chaplot, V.; Ilao, R.O.; Janeau, J.L.; Marchand, P.; Toan, T.D.; and Valentin, C. Forthcoming. Factorial analysis of runoff and sediment yield from 5 catchments and 21 sub-catchments of South-East Asia. In press. Proceedings of MSEC workshop, Hanoi, 10 December 2001.

Quinn, P.; Beven, K.; Chevallier, P.; and Planchon, O. 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrol. Processes* 5, 59-80.

StatSoft, Inc. 1995. Statistica for windows. Computer program manual. Tulsa, OK: Stasoft, Inc., 2325 East 13th Street, Tulsa, OK 74104, USA.

Valentin, C. 1996. Soil erosion under global change. In Walker, B.H. and W.L. Steffen (eds.) *Global change and terrestrial ecosystems*, Cambridge University Press, International Geosphere-Biosphere Programme Book Series, no. 2, pp. 317-338.