Applying GIS-Assisted Modelling to Predict Soil Erosion for a Small Agricultural Watershed within Sloping Lands in Northern Vietnam

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Abstract

GIS-assisted distributed modelling is particularly useful for supplying information to decision-makers regarding land-use, water management and environmental protection. This study deals with the prediction of soil losses by a simple distributed and GIS-assisted model within a small experimental agricultural watershed on sloping lands in northern Vietnam (<1 km^2). The Predict and Localise Erosion and Runoff (PLER) model predicts the spatial and temporal distribution of soil erosion rates; thus it can be used to identify erosion hot spots in a watershed. The model has been built specifically to take into account steep slopes. It is a conceptual erosion model on a physical base. Indeed, the model imitates soil erosion as a dynamic process which includes three phases: i) detachment, ii) transport and iii) deposition. In this study the PLER model was used for two complete years, 2003 and 2004. The disparity for the soil erosion quantity between the experiment and the run model was 5.1% in 2003 and 4.9% in 2004, even though these two years had a very different annual amount of rain. Indeed, 40% of the rainfall events were of a strong intensity (>75 mm hr^{-1}) in 2003 as apposed to only 4% in 2004. The amount of rainfall in 2003 and 2004 was 1,583 mm and 1,353 mm, respectively. The PLER model took into account this discrepancy in the rainfall characteristics between the two years. Between April to September, the disparity fluctuates between just 4.7%-5.3%. The maps drawn by the PLER model underline that the erosion process occurs mainly at the top of the landscape and highlights a different behaviour for detachability and soil erosion between the western and the eastern parts of the studied watershed.

Keywords: erosion, deposition, modelling, sloping land, Southeast Asia.

1. Introduction

Land degradation due to erosion processes incurs substantial costs both for individual farmers and for society as a whole (Pimentel et al, 1995; Johnson and Lewis, 1995). There is a growing need for tools that enable delineation of the spatial distribution of erosion within a watershed in order to locate sources of soil sediments that would facilitate strategic investments in soil water conservation efforts (Desmet and Govers, 1995; Jetten et al, 2003). Fundamental difficulties in distributed erosion modelling arise from the natural complexity of landscape systems, from spatial heterogeneity and from lack of available data (Merritt et al, 2003; Croke et al, 2004; El Nasr et al, 2005). Erosion processes consist of complex ecological interactions that are strongly scale-dependent (Jetten et al, 1999; Vigiak, 2005). Recent studies on soil erosion and soil conservation in Southeast Asia (i.e. by the Management of Soil Erosion Consortium (MSEC) and ASIALAND programmes) have demonstrated that land degradation brought about by soil erosion on sloping lands is a major constraint for sustaining upland agriculture and food security throughout Asia (Maglinao et al, 2003; Wani et al, 2003). Indeed, soil erosion by water is the major cause of soil degradation in Southeast Asia, especially on sloping lands. It decreases the overall arable area, reduces soil fertility and water quality, and results in the siltation of reservoirs and irrigated fields. Numerous studies on soil erosion associated with sloping lands have yielded a clearer understanding of the processes. However, in Vietnam these studies have been confined to plots of approximately 1 m^2. Scaling up results from plot scale to farming systems is dangerous because the erosion quantification is subject to thresholds that depend upon the scale level of study. How then, can reliable information be found on erosion consequences for sustainable natural resource management?

Various studies on erosion models have clearly demonstrated that the dominant factor contributing to sediment discharge is the erosive power of rainfall (Favis-Mortlock and Boardman, 1995; Valentin, 1998). The major variable appears to be rainfall intensity rather than the amount of rainfall. A second dominant pathway of influence is through changes in land cover. Hence, erosion is predominantly affected by changes in rainfall intensity and surface cover patterns, with both likely to have impact in similar ways (Nearing et al, 2005). Ground cover acts as a significant deterrent to rill erosion both by protecting the soil surface from the forces of flowing water and by dissipating energy of flow that would otherwise transport sediment (Valentin et al, 2005). Further, in the case of cultivated soils, tillage is a main factor strongly modifying surface-soil physical and hydraulic properties (Burwell et al, 1966; Battany and Grismer, 2000) and has a major influence on the hydrology of an agricultural system (Ahuja et al, 1998). It is well known that agricultural practices trigger runoff and soil erosion (Van Oost et al, 2000).

Geological, soil and land cover factors have often been incorporated into both empirical and process-based models for hydrological and erosion simulations. However, such models are often developed with data from relatively small (<50 km^2) headwater catchments and are usually only applicable at specific spatial and temporal scales (Wade et al, 1999). The non-linear response of models to spatial variability of particular parameters has been demonstrated by Boulet et al. (1999). The use of GIS-assisted distributed modelling is particularly useful for supplying information to decision-makers regarding land-use, water management and environmental protection. (e.g. Vanacker et al, 2002; Chaplot et al, 2005). In this respect this study deals with the prediction of soil losses by distributed modelling within an experimental watershed in Hoa Binh Province, northern Vietnam (Valentin, 1999; Tran Duc Toan et al, 2003). A methodology is proposed for investigating the cumulative effect of rainfall pattern, land use and land cover on erosion on sloping lands by incorporating hydrological soil parameters, which vary according to a specific land-use practice, in a simple process-based model. The study has three key components: i) validation of the first use of the new PLER model; ii) description of the influence of land-use patterns and rainfall distribution upon the soil losses on the slopes; and iii) quantifying of the resulting erosion within a small agricultural watershed (< 1 km^2).

2. Methods

2.1 Dong Cao watershed

The study area is located 30 km northwest of Hanoi (along the Lang-Hoalac road) in Tien Xuan Commune within Luong Son District, Hoa Binh Province. The experimental watershed covers three sub-catchments over a total area of 49.7 ha (figure 1). At each outlet a weir was built to collect soil losses and to continuously record the water levels using a Thalimedes recorder. An automatic meteorological station (from Cimel) recorded total rainfall, rainfall intensity at six-minute time intervals, air temperature, air humidity, and hourly wind speed. Elevation within the catchment ranges from 485 masl at its highest point to 120 masl at the main outlet. Slopes within the catchment vary from 10%-120%, with an average slope of 45%. The soils are mainly Ferralic Acrisols on shale parent material. Clay and silt tended to decrease from the top to the bottom of the watershed, especially where cassava was cultivated. Soil aggregate stability is an important parameter for evaluating the soil structure. Within the whole watershed, the soil aggregates useful for cultivation (>1 mm) tended to decrease from top to bottom, and soil aggregates not useful for cultivation tended to decrease from bottom to top. Some Leptosols can be found in limited areas in the lower part of the watershed and Cambisols and Fluvisols occur along the stream course (figure 1; Podwojewski, 2003; Renaud, 2003; Tran Duc Toan et al, 2004).

Soil legend:
Xf-d1: Epi-Lithi-Ferralic Acrisols; Xf-d2: Endo-Lithi- Ferralic Acrisols; Xf-h: Hapli-Ferralic Acrisols; CM: Cambisols; P: Fluvisols; E: Leptosols.

Figure 1: Soil map, rivers and sub-watershed limits.
Source: Do Duy Phai, MSc thesis.

Modelling of sediment and runoff were applied for two years, 2003 and 2004, since there were no changes in land use over this period (figure 2). Sub-watershed 1 (W1) covered an area of 7.7 ha and was mainly cultivated with a perennial crop of the pasture species *Bracharia ruziziensis* (4 ha). The upper part of the watershed was covered by degraded secondary forest (3 ha) with young fallow on the eastern side (1 ha). 2003 was the first year of grass cultivation, with the *Bracharia* being planted in May 2003. Sub-watershed 2 (W2). an area of 10.1 ha, was cultivated with cassava (*Manihot esculenta*) on 1.5 ha of the downstream portion of the catchment on sloping lands. In the upper portion of the catchment, corresponding to sub-watershed 3 (W3), there was an old fallow of 8.6 ha of *Chukrasia tabularis* and *Acacia mangium*. As shown in figure 2, the other parts of the experimental watershed also drained by the main weir (MW) were mainly covered with planted forest (*Eucalyptus camaldulensis, Acacia mangium, Venicia montana, Styrax tonkinensis, Canarium album, Chukrasia tabularis*) and a natural degraded secondary forest (Ministry of Agriculture and Rural Development, 2000). Several fallows established in 2003 were located near the main outlet.

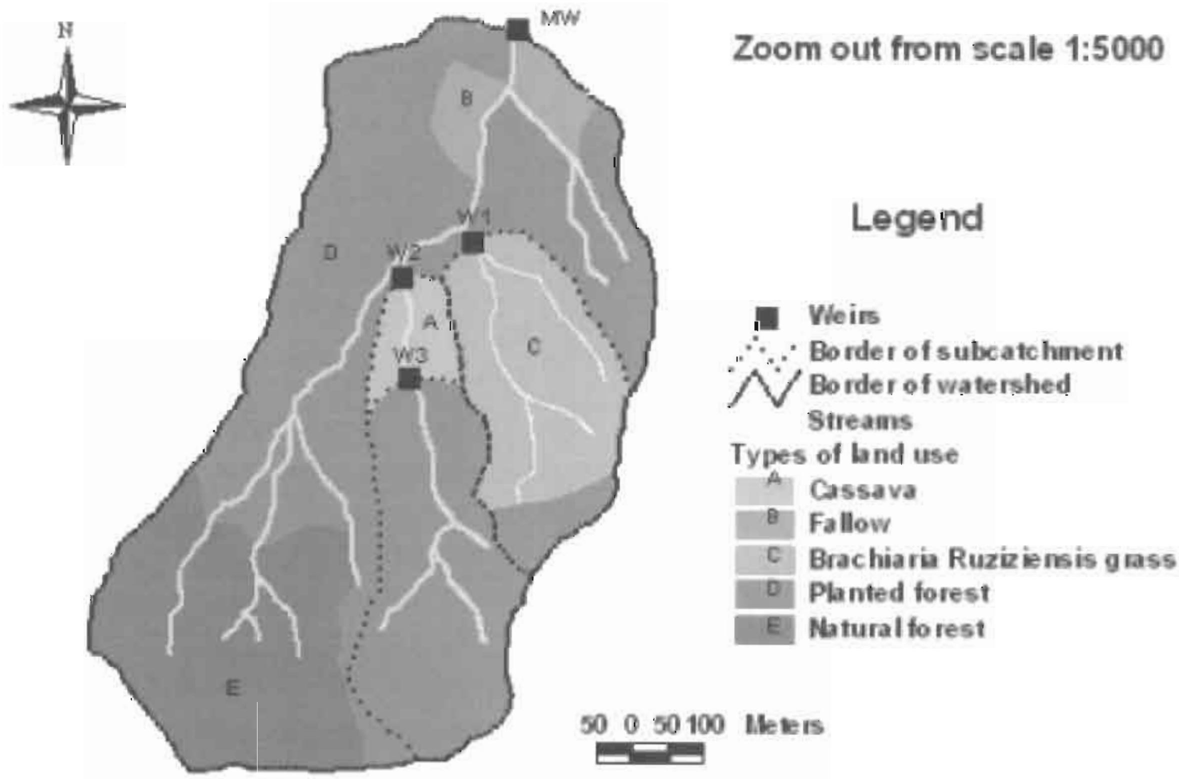

Figure 2: Land use map of Dong Cao watershed in 2003 and 2004 Source: Do Duy Phai, MSc thesis.

2.2 Climate and rainfall amount description

The climate of northern Vietnam (situated between 16 and 18°N) is humid sub-tropical. The climate is marked by two seasons: a dry and cold season occurs from October to March, during which the average rainfall, evaporation and air temperature are 40 mm/month, 60 mm/month and 19°C, respectively. A rainy and warm season runs from April to September, during which time 87% of the total annual rainfall occurs, with a maximum in August and an air temperature of approximately 28°C. This season is also characterised by high intensity rainfall events that range from 20-60 mm hr^{-1}. There is a high monthly inter-annual variability. For each month of the year, the total monthly rainfall can vary by as much as 100%. This implies a large variation in water volumes during the rainy season. For example, in August, the variation of monthly total rainfall varies from 150-450 mm/month. Indeed, one of the characteristics of the northern Vietnamese climate is its high degree of variability, making weather forecasting difficult. Thus when monsoon winds from the southwest are weakened by winds coming from the Lao PDR, periods of dryness can occur during the months which are usually the wettest.

The total annual rainfall recorded at the site ranged from 1,583 mm in 2003 to 1,353 mm in 2004. While there is a large discrepancy in the rainfall characteristics of these two years, the number of significant rain events (rain events >20 mm) were quite similar, with 28 rainfall events in 2003 and 21 in 2004. In contrast, the number of rainfall events with intensities of more than 25 mm hr^{-1} totalled ten in 2003, but only one in 2004. Moreover, one typhoon occurred in July 2003, when more than 340 mm of rain fell in four days and rainfall intensity peaked above 125 mm hr^{-1}. According to Hudson (1985), only rainfall intensities above 25 mm hr^{-1} result in soil erosion. Thus in the Dong Cao watershed, the proportion of the total rainfall events that had the potential to cause erosion was 46% in 2003 and only 23% in 2004.

2.3 Model description

The development of a soil erosion model within the MSEC research project was initiated by Paningbatan (2001) and continued by Eiumnoh et al. (2003). The first version of the PLER model was presented by Bricquet et al. (2003). In order to address the first criterion required by MSEC, user friendliness, and to ensure compatibility of the model's data input-output requirements with the MSEC methodology, it was decided that any new soil erosion model should be simple in concept and structure.

The PLER model is a GIS-assisted model that simulates runoff and soil erosion in a small catchment scale (<1 km^2). It is built to predict the spatial and temporal distribution of surface runoff, soil detachment, and soil erosion rates. Thus it can be used to identify erosion hot spots in a watershed. This model was specifically built to take into account steep slopes. Models that the authors have applied to the catchment are empirical models that were developed for topography with limited slopes. The PLER model is a conceptual physically-based erosion model with two combined modules: One module addresses the surface runoff calculation and the second module deals with the erosion calculations. In terms of modelling, a PC-Raster language is used on a Nutshell platform. The advantage of this code language is that it is able to take into account both a dynamic modelling on time-steps and a cartographic database to produce serial and cartographic outputs. Then it allows easy simulation of land-use scenarios undertaking the hydrologic and sediment transport processes occurring in a three-dimensional landscape. The model outputs are time series with values of erosion quantity at the outlet selected by the user, and maps with soil detachment, sediment storage and erosion quantity within each cell (generated every time step/every hour/everyday according to the user's needs).

The hydrological component is based on the PCARES model (De La Cruz and Paningbatan, 2003). The hydrology comprises the interrelationships of rainfall, infiltration and runoff during each effective rainfall event (Western and Bloschl, 1999). The water discharged at the downslope portion of each cell area is calculated from the amount, direction and velocity of water inflow or outflow to the neighbouring cells. A water routing subroutine called Local Drain Direction of PC-Raster command calculates the direction of water flow while the velocity of overland flow is calculated using Manning's equation (Migraine and Orange, 2005). The erosion component is based on the integration of the Griffith University Erosion Sedimentation System (GUESS) model (Rose et al, 1983) within PC-Raster language (Eiumnoh et al, 2003). The model assumes soil erosion as a dynamic phase which includes three processes: i) detachment, ii) transport and iii) deposition. The calculation of the quantity of eroded soil in each cell is determined by the GUESS erosion equation. The concept of the model is to use the equilibrium of sediment in the area. It calculates the movement of sediment under current conditions and takes into account the deposition by runoff flow in each event. Two types of soil are considered: original soil and newly deposited soil. The original soil has different cohesion and aggregation attributes, while the newly deposited soil has no cohesion and aggregation. Therefore in each rainfall event the soil cohesion in the area will not be the same. The details of calculation are presented in Eiumnoh et al. (2003).

Currently, GIS is employed to manage and analyse data including watershed management and soil erosion in a static state, such as empirical models like USLE. PC-Raster is a GIS raster software that has both functional and operational packages for real dynamic water surface runoff and soil erosion modelling, which is a key attribute and advantage of the PLER model. The software is capable of performing cartographic and dynamic modelling to simulate soil erosion, on-site and off-site effects through surface water flow, and sediment transportation (Van Deursen and Wesseling, 1992; FGS, 2000).

This paper describes the use of the PLER model to predict erosion and soil detachment and to establish erosion maps. The model was calibrated by using data collected in 2003 and validated using the erosion-generated data from 2004.

2.4 Inputs and outputs

The inputs used to run the PLER model are presented in figure 3 and table 1 and include:

✓ A Digital Elevation Model map (DEM) in raster format (in this study a grid size of 2 m built from a measured topographic map with contour lines at 5 m intervals was used) and a Local Drain Direction map (LDD);

✓ A map with location of the chosen outlets (i.e. the measurement devices as the weirs in our study);

✓ A map with the river route, maps of soil units and land-use units in the same raster format;

✓ Seven parameters to define the soil units: soil density, soil depth, infiltrability, clay percentage, sediment velocity, sediment density and porosity efficiency;

✓ Two time series with the potential evapotranspiration (PET) and one with the effective rainfall (the time step and the duration of the model running are chosen by the user);

✓ Three parameters to define the land-use units: real evapotranspiration (RET) /PET ratio, Manning's coefficient, vegetation cover;

✓ Three calibration variables: two of them characterise the anteriority of the last rainfall (the initial infiltrability ratio and the initial water content in the soil), and one calibration variable defines the stream's capacity to transfer the surface water to the outlet (the ratio between effective water velocity and the computed water velocity, which depends on the mean hydraulic radius of the stream section, was calculated).

The outputs are as presented in figure 3 and include:

✓ Four types of map: runoff (m^3/s), soil erosion (t/ha), sediment storage (t) and soil detachment (corresponding to the sediment flux; t/ha). Each map is generated for every time step/hour/day according to the user's demand;

✓ Four types of time series corresponding to cumulated runoff, soil erosion, sediment storage and soil detachment (corresponding to the sediment flux).

The rainfall input uses the concept of effective rainfall (Shaw, 1994). By definition, effective rainfall is that portion of the total rainfall that ultimately reaches the receiving water body, and it is identical to the groundwater recharge. The process of transformation of total rainfall into effective rainfall is complicated and includes effects of evapotranspiration, interception, depression storage, infiltration, soil-moisture deficiency, land use, vegetation cover, slope and other catchment characteristics.

In the current study, effective rainfall was assumed to be a rain event >20 mm and a mean intensity >25 mm hr^{-1}. PET was calculated using the Penman-Monteith formula from data collected by the Cimel automated weather station set in the centre of the watershed.

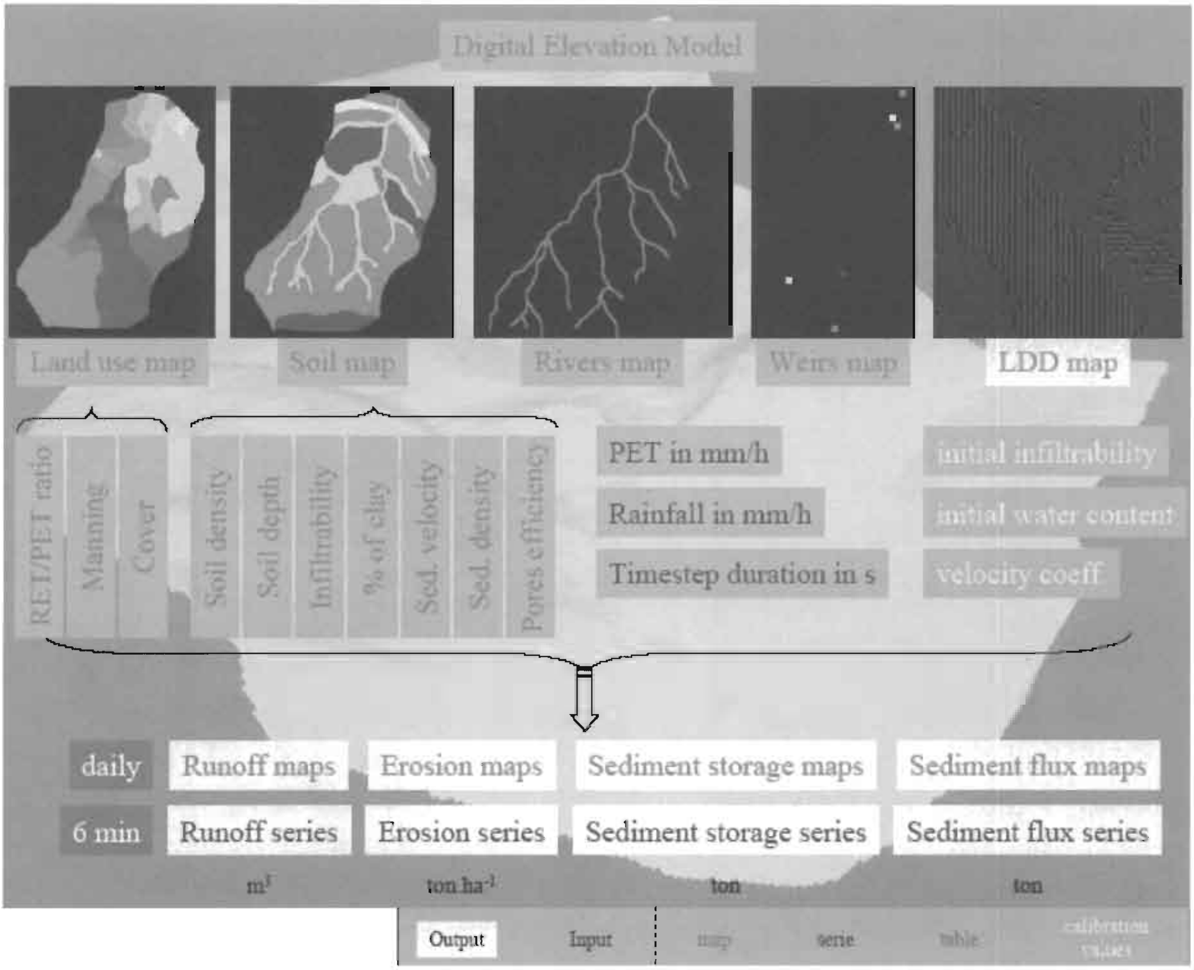

Figure 3: Inputs and outputs in the PLER model

All other watershed characteristics (defined for each cell) included in the calculations can be classified into two groups: those of a static or dynamic nature.

✓ **Parameters with static characteristics:** topographic parameters such as slope, slope length, downstream direction; land-use parameters including RET/PET ratio (%), Manning roughness coefficient and vegetation cover (%); soil parameters including soil density (kg m^{-3}), soil depth (m), minimum and maximum infiltrability (mm hr^{-1}), % of clay (%), mean sediment velocity of deposition in stable water (m s^{-1}), mean sediment density (kg m^{-3}) and pore efficiency ratio (efficient pores/total pores, %);

✓ **Parameters with dynamic characteristics:** pores available for water storage (mm), infiltrability (mm hr^{-1}, fluctuating between a minimum and a maximum), water volume stored in the cell (m^3), mean efficient velocity of surface and subsurface water runoff (m s^{-1}), time needed for runoff generated to reach the outlet of the watershed(s).

Table 1: Description of inputs for running the PLER model

No.	Name	Description	Units
1	depth.tbl	Table with soil depth for each soil unit	m
2	soilden.tbl	Table with soil density for each soil unit	kg m^{-3}
3	sedden.tbl	Table with sediment density for each soil unit	kg m^{-3}
4	sedvel.tbl	Table with sediment velocity of deposition for each soil unit	m s^{-1}
5	cohesive.tbl	Table with soil cohesion for each soil unit	% of clay
6	infilmin.tbl	Map with min. (waterlogged) infiltration capacity	mm hr^{1}
7	infilmax.tbl	Map with max. (dry) infiltration capacity	mm hr^{1}
8	rains.tss	Rainfall	mm hr^{1}
9	etp.tss	Value of ETP	mm hr^{1}
10	pitchs.tss	Length of timepitches	s
11	cover.tbl	Table with cover for each LU unit	% of coverage
12	transpir.tbl	Table with water consumption for each LU unit	% of ETP
13	manning.tbl	Table with Manning practice and root-effect coefficient for each LU unit	0.05-0.5

Input values for the soil parameters were previously determined by Podwojewski (2003; table 2). Values for the land-use parameters were measured (for the vegetation cover) or estimated from literature documents by Do Duy Phai (2005; table 3).

Table 2: Values of soil parameters used in the simulation

No.	Parameters	Soil units*					
		Xf-d1	Xf-d2	Xf-h	CM	P	E
1	Soil density (kg m^{-3})	2,700	2,700	2,700	2,600	2,600	2,500
2	Soil depth (m)	0.5	1.5	1.5	0.8	0.3	0.2
3.1	Min. infiltration (mm h^{-1})	15	15	15	7.5	2.5	3.7
3.2	Max. infiltration (mm h^{-1})	67	67	67	30	18	56
4	Soil cohesion (% clay)	45	45	45	37	37	37
5	Sediment velocity (m s^{-1})	0.63	0.63	0.63	1.12	1.12	1.12
6	Sediment density (kg m^{-3})	3,080	3,080	3,080	2,600	2,600	2,600
7	Pore efficiency (%)	90	90	90	90	90	90

* Xf-d1: Epi-Lithi- Ferralic Acrisols; Xf-d2: Endo-Lithi- Ferralic Acrisols; Xf-h: Hapli-Ferralic Acrisols; CM: Cambisols; P: Fluvisols; E: Leptosols.

Table 3: Values for the land-use parameters

Kind of land-use	Vegetation Cover (%)		Water Consumption (% of ETP)[1]		Manning's Coefficient[2]	
	2003	2004	2003	2004	2003	2004
Cassava	52	51	0.21	0.20	0.10	0.10
Fallow	45	47	0.13	0.15	0.16	0.16
Brachiaria	79	90	0.20	0.26	0.32	0.36
Artificial forest	81	89	0.25	0.25	0.18	0.20
Natural forest	83	90	0.25	0.27	0.32	0.34

[1]Hanoi Water Resources University (1998); [2]Morgan (1985).

3. Results and discussion

3.1 Results: calibration and validation of the PLER model

The PLER model was run with time-steps of six minutes from early April to end of September in 2003 and 2004. The 2003 and 2004 outputs were used to calibrate and validate the model respectively. The results of the simulations and the measured sediment discharge from the catchment are presented in table 4.

Despite the typhoon in 2003, the calibration coefficient was quite good for each month, varying from 4.9%-5.3% (table 4). It is normal that the largest discrepancy was recorded for the month of July, when soil loss reached a maximum value (3.6 t ha^{-1} measured and 3.8 t ha^{-1} simulated). The average discrepancy between simulated and actual value of soil erosion was 5.1%. However, it should be noted that in this case the values of the calibration variables were fixed to assure a good model of erosion output, since the response in soil loss was a priority in this study. In contrast, output associated with generated runoff indicated a poor relationship between predicted and measured values. In spite of the poor prediction of water discharge from the catchment, the simulation based on the 2004 data gave excellent predictions of sediment discharge, with an average discrepancy of 4.9% between measured data and simulated results. The monthly variability of difference between observed and simulated data ranged from 4.7%-5.2% (table 4).

Table 4: Comparative soil erosion amount between measurements from field and results from model

Months	Soil erosion amount (kg ha^{-1})				Disparity (%)	
	Measurements from field		Results from model		*2003* calibration	*2004* validation
	2003	*2004*	*2003*	*2004*		
April	29.3	28.6	30.9	30.1	5.2	5.0
May	317	82.0	334	86.3	5.1	4.9
June	157	15.5	165	16.3	5.0	4.7
July	3,578	128	3,779	135	5.3	5.2
August	1,151	81.6	1,211	85.6	4.9	4.7
Sept.	926	32.5	975	34.2	5.0	4.9
Rainy season	6,158	369	6,495	387	5.1	4.9

3.2 Discussion

The model enabled not only calculation of total soil loss from the catchment, but also the establishment of dynamic maps of soil erosion and soil detachment (e.g. the four cumulative maps for the April-September period in 2003 and 2004 presented in figures 4a, 4b, 5a and 5b). The soil detachment maps indicate where the soil losses are generated, while the soil erosion maps show the sum between soil loss and soil sedimentation in each cell. The soil erosion maps, therefore, give the final image of soil loss impact within the watershed.

The soil detachment maps (figures 4a and 5a) were very similar in 2003 and 2004, while the soil loss maps (figures 4b and 5b) were very different. Indeed the soil loss value was highest in 2003 for the same range of soil detachment for the two studied years. This suggests that the spatial distribution of areas of sediment generation was similar over the two years. The areas with high soil detachment are the upper parts of the watershed, especially within W3 and the south western part where the slopes are steepest, are covered by planted or natural forest (figure 2). Another place with a high soil detachment was the fallow area near the main outlet MW.

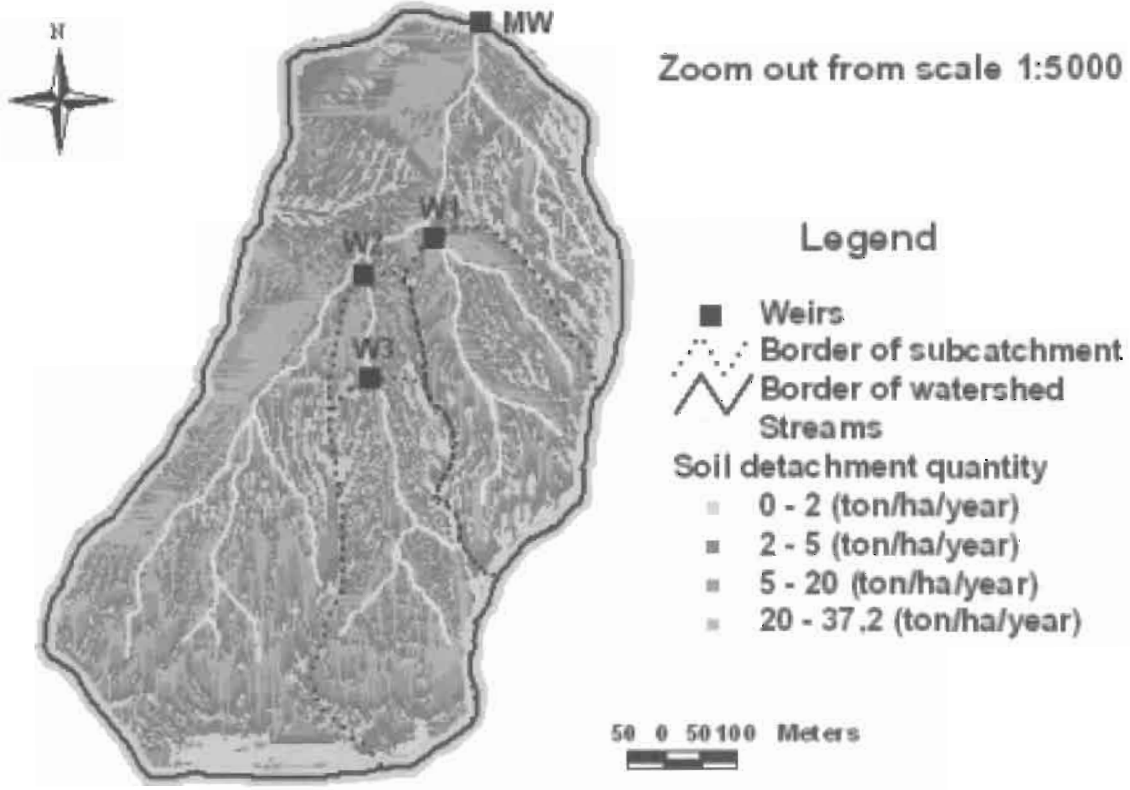

Figure 4a: Cumulative soil detachment map after the April-September period in 2003 in Dong Cao
Source for figures 4 and 5: Do Duy Phai, MSc thesis.

The soil loss per cell ranged from zero to up to 37.2 t $ha^{-1}yr^{-1}$ in 2003 (figure 4a), and from zero to up to 24.6 t $ha^{-1}yr^{-1}$ in 2004 (figure 5a). In addition, 18 ha were affected by soil loss of over 20 t $ha^{-1}yr^{-1}$ as opposed to only 12 ha in 2004. In terms of erosion, the difference between the two years is far more significant due to the sedimentation process. Indeed, the erosion amount per cell reached 19.8 t $ha^{-1}yr^{-1}$ in 2003 (figure 4 b) but only 2.1 t $ha^{-1}yr^{-1}$ in 2004 (figure 5b). In addition, 33.4 ha were affected by erosion of more than 2 t $ha^{-1}yr^{-1}$ in 2003 and only 14.3 ha in 2004. An analysis of the spatial distribution of the erosion spots within the catchment between 2003 and 2004 underlines the influences of the typhoon on the observed variability in erosion. The typhoon in 2003 resulted in a seven-fold increase in stream discharge at the main outlet (i.e. 28.7 l/s in 2003 for only 7.4 l/s in 2004) whilst the annual rainfall was similar (1,443 mm in 2003 and 1,151 mm in 2004) in both years.

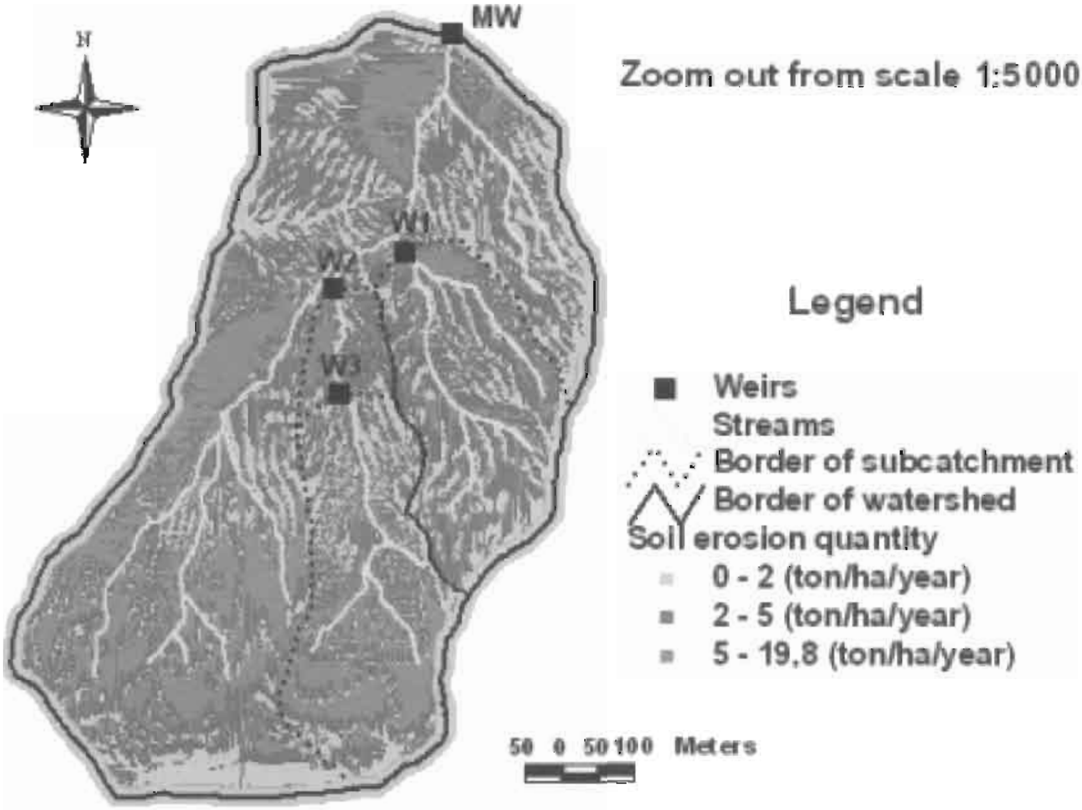

Figure 4b: Cumulative soil erosion map after the April-September period in 2003 in Dong Cao

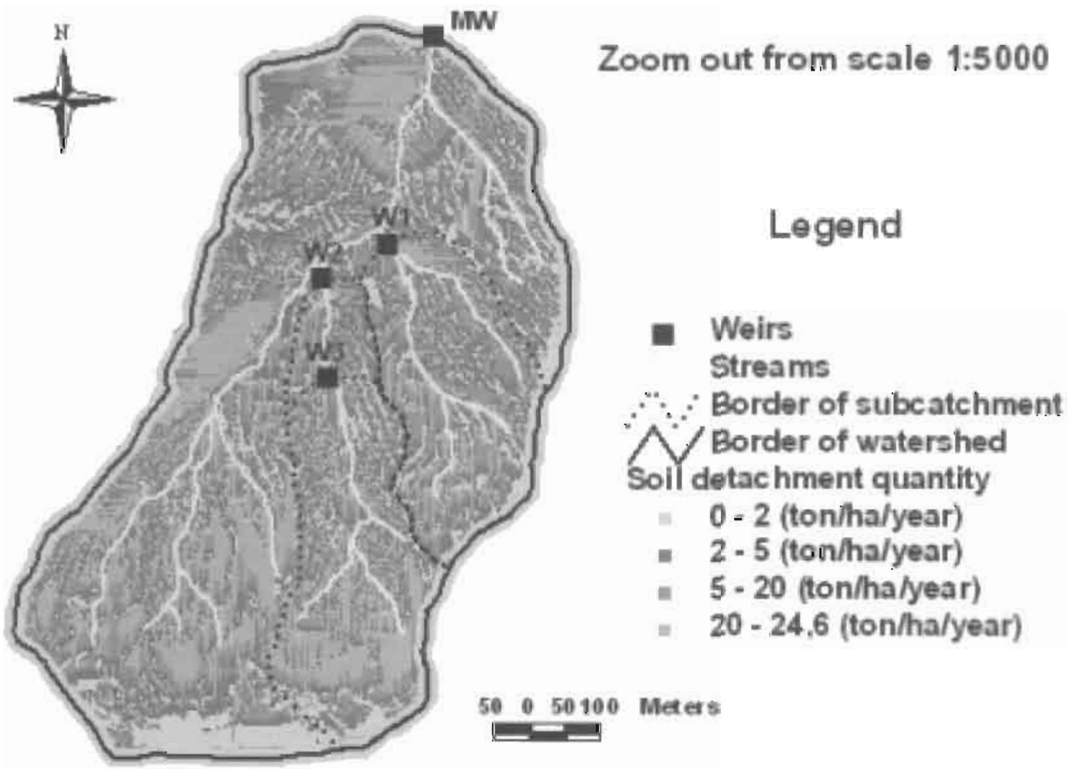

Figure 5a: Soil detachment map after the April-September period in 2004 in Dong Cao

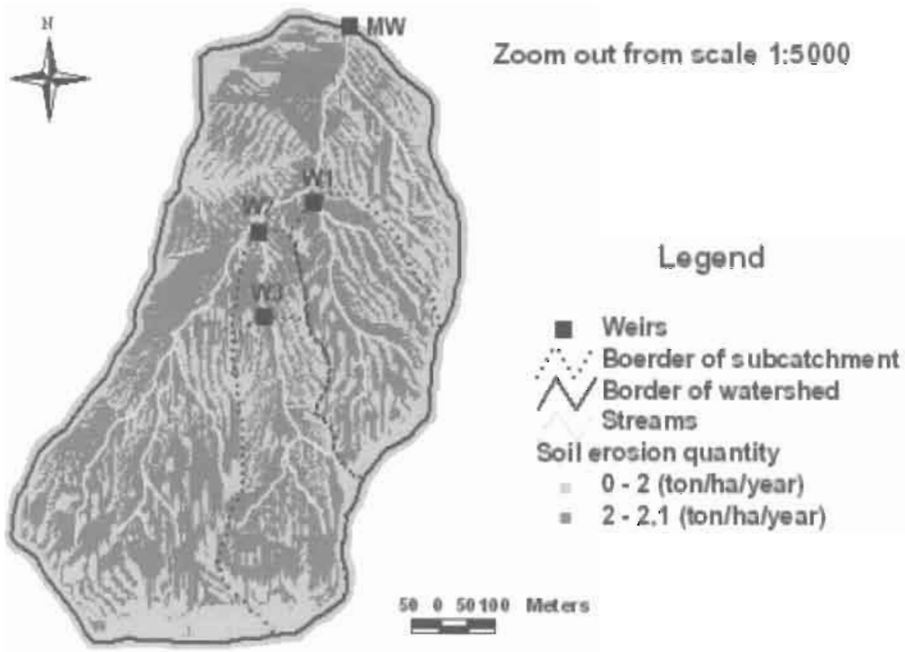

Figure 5b: Soil erosion map after the April-September period in 2004 in Dong Cao

The impact of the typhoon on the running of the PLER model meant that it was not possible to analyse differentiation of the impact of vegetation cover, notably for the *Bracharia* crop within W 1. However, the difference in land use between 2003 and 2004 did not seem important and was not significant for the PLER model (table 3), although this may have been due to an inaccurate value assessment of some parameters such as water consumption and the Manning's coefficient. It is argued that the dramatic increase in discharge associated with the typhoon in 2003 transported significant amounts of sediment directly to the stream with little sediment distribution within the catchment. This would explain the observed difference between the soil detachment map and soil erosion map.

4. Conclusion

The PLER model has been used for the first time in this study. It has been validated by using two different years of contrasting rainfall intensity. Comparison of soil erosion results from the modelling with field measurements shows an adequate fit of the two data sets with an average difference of 5% over the two years. Indeed, 40% of the rain events in 2003 were of a high intensity (>75 mm hr^{-1}) as opposed to only 4% in 2004. Outputs included erosion flux and deposition dynamic maps (one map every hour for example) and a temporal series for sediment flux. Consequently, the PLER model has satisfactorily accounted for the difference in the rainfall characteristics between the two years. In addition, the PLER model has allowed the identification of high risk areas for soil erosion at the watershed scale.

The capability for leaching, erosion and transport of sediment varies according to the period tested. In 2003, soil detachment (i.e. for each cell) was relatively high, reaching a maximum of 37.2 t $ha^{-1}yr^{-1}$, and the soil erosion quantity for each cell fluctuated from 0 19.8 t $ha^{-1}yr^{-1}$. In 2003, the surface areas with weak, average, strong-average and strong levels of detachment covered 12.9 ha, 11.8 ha, 7.0 ha and 18.0 ha respectively, across the whole watershed. The maps drawn by the model underline that the erosion process occurs mainly at the top of the landscape and also highlight differences in behaviour for detachability and soil erosion between the western part and the eastern part of the studied watershed – as verified by field observation. In 2004 the soil detachment quantity was lower than in the previous year, reaching a strong grade by cell (0-24.6 t $ha^{-1}yr^{-1}$), while soil erosion by cell reached 2.1 t $ha^{-1}yr^{-1}$. In 2004, the surface area with weak, average, average-strong and strong detachment was 21.4 ha, 8.5 ha, 7.9 ha and 11.9 ha, respectively, while erosion had only two classes (weak and average): 35.4 ha and 14.3 ha respectively.

This first running of PLER on erosion calculation within a small and sloping agricultural watershed has shown a satisfactory agreement between predicted and measured soil loss from the watershed. Consequently, PLER could be a useful tool to study the effect of land-use change and management options on water and soil management. However, there is a need to continue these studies by running the model in other watersheds and for longer time series. In addition, there is a need to improve the parameterisation of the model through better estimates of input attributes.

Even though the values assessed for some parameters still need refining, the PLER model can be used to predict and locate erosion changes under land-use and climate changes. Comparison of the model's outputs under contrasting scenarios would enable assessment of the efficiency of soil conservation practices. This could assist decision support systems, with many socio-economic attributes being introduced to compare the impact of land-use practices with farmers' strategies.

In short, the distributed PLER model provides a satisfactory compromise solution between conceptual models and physical models. Upscaling, downscaling and transfer to other watersheds should be possible through a cell-based approach to the flux processes. It can be concluded that a rather simple model with only elementary process descriptions can be used to predict sediment delivery by surface runoff from hill slopes to rivers in small catchments with acceptable accuracy (Van Rompaey et al, 2001).

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