Development and Validation of the PLER (Predict and Localize Erosion and Runoff) Model

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Abstract

The development of simple models, which can be used even by those who do not have much knowledge about computers and/or modelling science is one major activity of the Management of Soil Erosion Consortium (MSEC). The PCARES (Predicting Catchment Runoff and Soil Erosion for Sustainability) model was the first model that was evaluated and tested for applicability to MSEC using the data from the Philippine catchment (Paningbatan, 2001). The model can predict the spatial and temporal distribution of soil erosion processes and rate and also the runoff and sediment discharge rates at the catchment outlet. Based on the concept developed by Rose and Freebairn (1985), it simulates overland flow and soil erosion for each erosive rainfall event. Predicted and observed values, however, were not close to each other. A second model (MSEC-1) was then developed, also based on the GUESS model (Eiumnoh, 2002). A major constraint, however, was a fixed runoff coefficient, which is not realistic according to the observations in the catchments. A further refined model, PLER (Predict and Localize Erosion and Runoff) has been developed in Bangkok considering the problems inherent in the first two models. It integrates the infiltration capacity of the soil and can simulate overland flow and soil erosion for each erosive rainfall event. The data on water discharge and soil erosion collected and monitored for two years in the Thai catchment were used to calibrate and validate the PLER model. Results showed closer agreement between the predicted and observed values of discharge and total runoff than the results using the first two models.

Introduction

Hydrology and soil erosion models could be a valuable tool in simulating hydrological processes and in planning land management strategies for a watershed. If properly validated, they can be used to great advantage in testing research hypotheses, seeking alternative intervention, and predicting results of management options before they are carried out or implemented in the field. Innovative interventions or mitigating measures could then be properly formulated and targeted to the critical areas in watersheds that require soil conservation treatments.

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The development of simple models that can be used even by those who do not have much knowledge of computers and/or modelling science is one major activity of the Management of Soil Erosion Consortium (MSEC). As such, the models should take into consideration the following: (a) compatibility of data input-output requirements of the model with the methodology of MSEC; (b) applicability to the MSEC approach; (c) user friendliness with minimum data input; and (d) cost of acquisition of the software needed to run the simulation model. Simple concept, structure, and operation of the models are positive indications of user friendliness considering that most MSEC researchers are computer literate but not necessarily simulation model users or model developers.

Spatial analyses of hydrological parameters and processes at a watershed scale have been limited to cartographic techniques or overlaying of thematic maps. However, recent advances in computer and information technology have enabled researchers to deal with these complexities. Advances in geographic information system (GIS), global positioning systems (GPS), and remote sensing, for example, have now facilitated not only cartographic but also dynamic modelling of the time- and space-dependent hydrological processes at a watershed scale.

This paper describes the development of soil erosion and hydrology models that are applicable on a catchment scale. It is expected that these will serve as tools to scale up to larger catchments if further refined and validated.

Model Development

Because it was important for MSEC to have a dynamic model (that means a model which gives a dynamic view of the erosion location and its importance), model development and evaluation were focused on those capable of running with PCRaster. PCRaster is a GIS software package capable of cartographic and dynamic modelling that allows easy simulation of the hydrologic and sediment transport processes occurring on a three-dimensional landscape. It was developed in the Netherlands by the University of Utrecht (van Deursen, 1995).

PCRaster has provided an infrastructure allowing the simple localized rules to be implemented in a way that formation and evolution of global virtual landscape structures can be observed. It is set up in a way that the researcher concentrates on the rule sets of the landscape itself in a high-level modelling language. By concentrating on processes rather than programming, one is able to make contributions to the science of landscape formation rather than computer science issues.

PCARES (Predicting Catchment Runoff and Soil Erosion for Sustainability) Model

Paningbatan, (2001) started the development of the soil erosion model for MSEC by conducting a search from the Internet and published literature. After testing the applicability of three of the existing erosion models to the MSEC research undertaking using the data obtained from the Philippine catchment, the PCARES (Predicting Catchment Runoff and Soil Erosion for Sustainability) model was selected. PCARES is a physical model that simulates runoff and soil erosion of a catchment during each erosive rainfall event (Paningbatan, 2001).

The model can not only predict the spatial and temporal distribution of soil erosion processes and rates but also the runoff and sediment discharge rates at the catchment outlet.

It incorporates a sediment transport routine described by Rose and Freebairn (1985), which calculates the soil loss, SL (kg s^{-1}) from the product of sediment concentration, c (in kg m^{-3}) and water discharge rate, Q ($m^3 s^{-1}$). Sediment concentration was estimated using the simplified equation,

$$c = 2700 \lambda S (C_r) \quad (1)$$

Thus, the sediment loss (kg s^{-1}) at each cell was calculated from Eq. 2:

$$SL = 2700 \lambda S (1 - C_o)(Q) \quad (2)$$

where:
SL is soil loss (kg s^{-1}),
λ is the efficiency of sediment entrainment,
S is the sine of the slope angle,
$(1 - C_o) = C_r$ where C_o is the ratio of the area not exposed to runoff or the contact cover fraction,
Q is the water discharge rate ($m^3 s^{-1}$).

To run the model, time series rainfall rates (mm h^{-1}) for each rainfall event selected for model validation and calibration were set to a five-second time step. Calibration was done using the data from the Lao catchment. The results showed that the predicted and observed water discharge started at the same time (Figure 1). Despite showing similar values of maximum discharge (close to 400 L s^{-1}), predicted values sharply increased but also immediately decreased after the peak flow. The total discharge was highly underestimated probably due to the contribution of groundwater that is not taken into account in PCARES. Similarly, the predicted and observed erosion (kg L^{-1}) occurred simultaneously with maximum values of the same order of magnitude (close to 15 kg s^{-1}, Figure 2). However, total erosion was also underestimated.

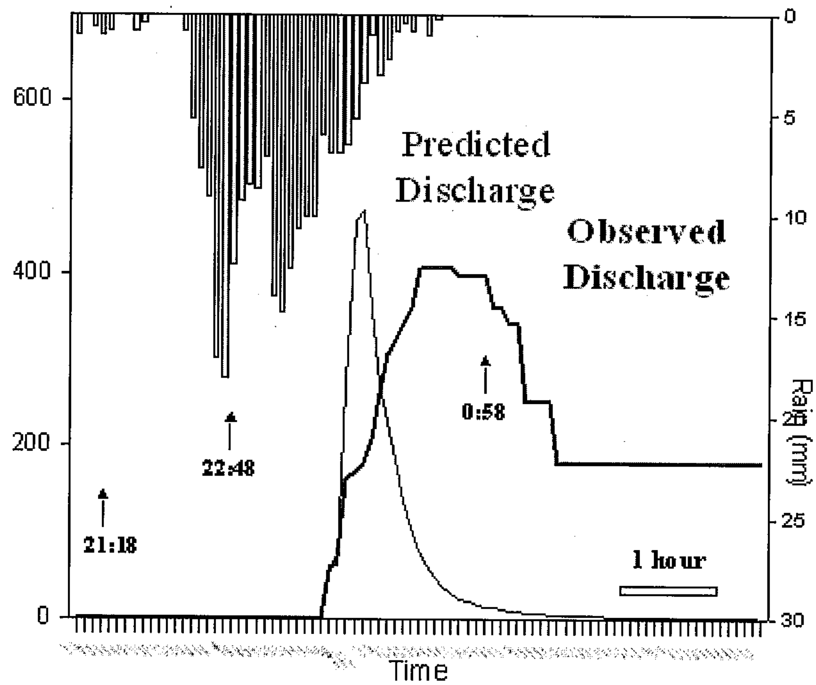

Figure 1. Predicted and observed discharge (L s-1) at the weir (Lao catchment) resulting from validation of the PCARES model using a rainfall event (September 3, 2001) of 90 mm and intensity of 90mm h^{-1}

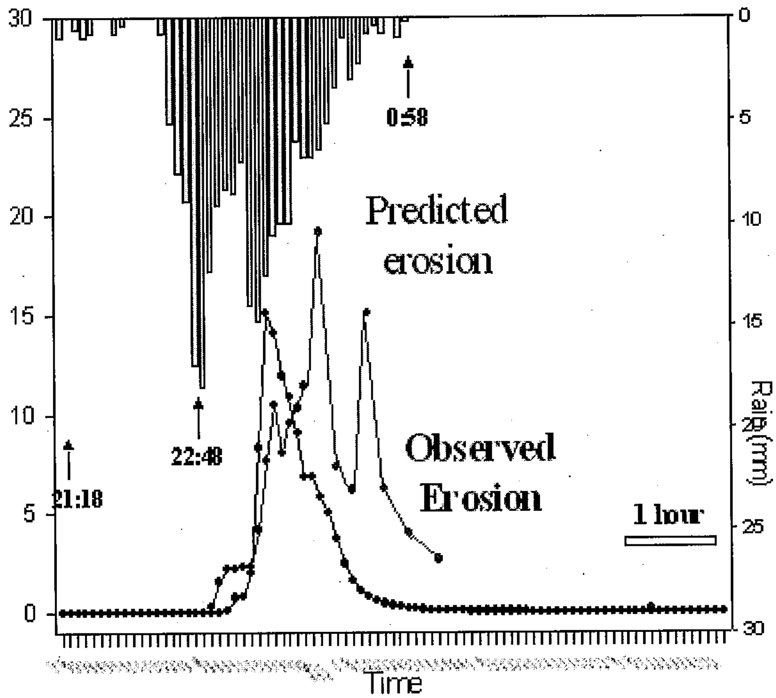

Figure 2. Predicted and observed erosion (kg s^{-1}) at the weir (Lao catchment) resulting from validation of the PCARES model using a rainfall event (September 3, 2001) of 90 mm and intensity of 90 mm h^{-1}

MSEC-1 Model

A second model, called MSEC-1, which is also an extrapolation of GUESS (Griffith University Erosion Sedimentation System) and integration within PCRaster language was later developed by Eiumnoh *et al.* (2001). The GUESS model for soil erosion, which was developed by Rose *et al.* (1983) illustrated the processes of soil erosion, transportation, and deposition. Therefore, the model can be used to predict on- and off-site effects. The concept of the model is to use the equilibrium of sediment in the area. It calculates the movement of sediment for each rainfall event by considering both the transport and deposition of the sediments during runoff. Generally, two types of soil are considered, original soil and newly deposited soil. The original soil has different cohesion and aggregation to the newly deposited soil. Therefore, in each rainfall event, the soil cohesion in the area will not be the same. The capability for leaching, eroding, and transporting of sediments varies according to Eq. 3.

$$\frac{\partial Q_{si}}{\partial \chi} + \frac{\partial (C_i h)}{\partial t} = e_i + e_{di} + r_i + r_{di} - d_i \qquad (3)$$

where;

Q_{si} = Sediment load of sediment class *i*

C_i = Concentration of sediment class *i* in the flow

e_i = The rate of detachment of particles of sediment class *i* in the original soil by raindrop impact

e_{di} = The rate at which recently detached soil of sediment class *i* is re-detached by raindrop impact

r_i = The rate of detachment of particles of sediment class *i* by flow

r_{di} = The rate at which recently detached soil of sediment class *i* is re-detached by flow

d_i = The rate of deposition

The idea behind integrating GIS-PCRaster in the GUESS model is to simulate soil erosion in a real situation or as virtual simulation in each rainfall event. Soil erosion is calculated by time steps or rainfall events. The results would then show the direction of flow according to the topography or DEM or LDD. Calculation starts from the first time step or the first rainfall event and sediments transported and deposited before the second time step or second rainfall event begins. The calculation process continues until the last time step or the last rainfall event. The amount of sediments transported and deposited may be obtained at the pit or outlet of the catchment or watershed.

The model also provides changes of sediments during each rainfall event according to the LDD. Therefore, it is possible to plan measures to reduce soil loss from the field. The raster format helps in the calculation of the movement or transportation of sediments through the LDD map.

The GUESS model, however, requires a runoff rate (Q) ($m^3 sec^{-1}$), which essentially is the total amount of runoff per event (åQ), since there are only event data. From the study of ICRAF (2001), the total amount of runoff per event, åQ is about 15 percent of the amount of rainfall per event. This value of runoff is used by the model. This is probably the main limitation of the MSEC-1 model. Using a fixed value of runoff could be unrealistic and dangerous as the runoff coefficient may vary from 2 to 60 percent. It is necessary to collect more information of each rainfall event to obtain the actual value of runoff.

The PLER (Predict and Localize Erosion and Runoff) Model

The MSEC-1 model was completely rewritten to address its limitation of using a fixed runoff coefficient and the need for clear code lines for the PCRaster. For the runoff calculation, the Curve Number as defined for the SWAT model (Arnold *et al.*, 1994) was used. This enables an estimation of the runoff at each time step or every rainfall event. The new model named the PLER (Predict and Localize Erosion and Runoff) model now combines the runoff determination of the PCARES model and the erosion calculation of the MSEC-1 model.

To further improve the prediction of erosion and runoff, the total infiltration capacity of the soil was incorporated as a new parameter. Thus the final model has five input maps, seven parameter tables, and two time series. The general design of the PLER model is shown in Figure 3. It is a distributed rainfall-runoff-erosion model taking into account the influences of topography, precipitation amount and intensity, antecedent soil moisture content, land use type, and soil type.

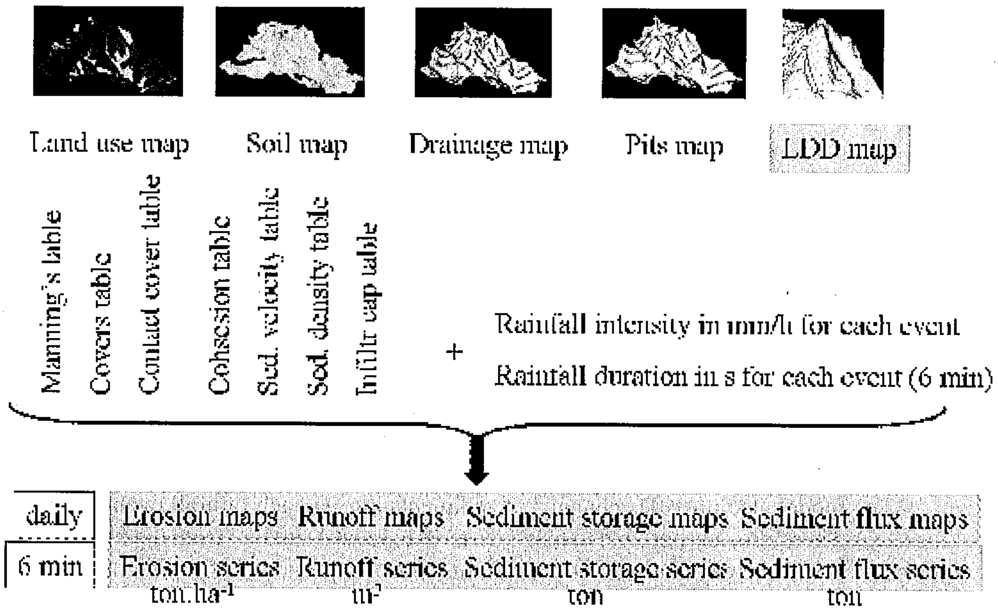

Figure 3. Flowchart of the PLER (Predict and Localize Erosion and Runoff) model

The model was built using the PCRaster Dynamic Modelling Language. Thus, it uses square grids to represent the landscape. The grid size is user defined and the maximum number of grids is limited by computer memory only. The simulation time step can also be defined by the user. The model has a very flexible structure and is easily adaptable. It contains about 250 code lines.

The outputs of the PLER model are hydrographs, total runoff, total erosion, and erosion fluxes at user-defined catchment outlets. Final maps of runoff and erosion and a series of maps showing changes in time can be produced.

PLER Model Calibration

The first calibration of the model was conducted with data gathered from a sub-catchment (Weir 1, 11.2 ha) in the Huai Ma Nai Catchment in Thailand. The DEM was built with a 2x2 m grid (Figure 4). Before running the model, the soil and land use parameters were defined as shown in Table 1. Manning's coefficients for the various land uses were derived from Morgan (1995).

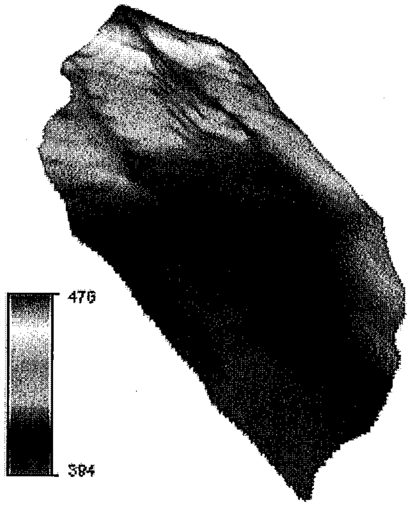

Figure 4. DEM of Weir 1 of Huai Ma Nai Catchment in Thailand

Table 1. Soil and land use parameters used in running the PLER model

	Manning's n	Cover	Cont cover
Forest	0.200	0.700	0.700
Abandoned trees	0.150	0.680	0.680
Bamboo/bananas	0.100	0.650	0.650
Fallow/grass	0.040	0.500	0.500
Orchard	0.700	0.600	0.600
Maize	0.090	0.350	0.350
Soybean	0.010	0.200	0.200

Figure 5 shows that the predicted and observed flow discharge started at the same time, but the decrease in the hydrograph was faster for the observed discharge. This implies that the model underestimates the rapid decrease in the soil humidity. However, the total volume of the runoff was similar. The observed runoff was 3,132 m^3 as compared to the simulated runoff of 3,018 m^3.

The second calibration was done for the whole Huai Ma Nai Catchment to also evaluate the capability of the model to work at a larger scale without introducing any changes. The whole Huai Ma Nai Watershed has an area of 93.2 ha. The DEM was built with a 5x5 m grid (Figure 6). The input tables were similar to the previous run.

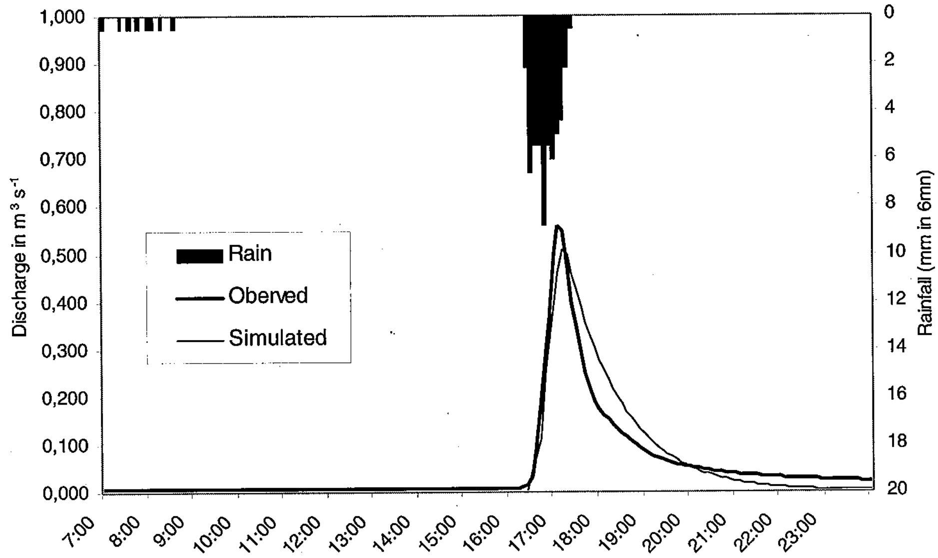

Figure 5. Comparison between the predicted and observed discharge (m^3 s^{-1}) at Weir 1 using the PLER model after calibration of a rainfall event (September 10, 2002) of 52 mm and intensity of 80 mm h^{-1}

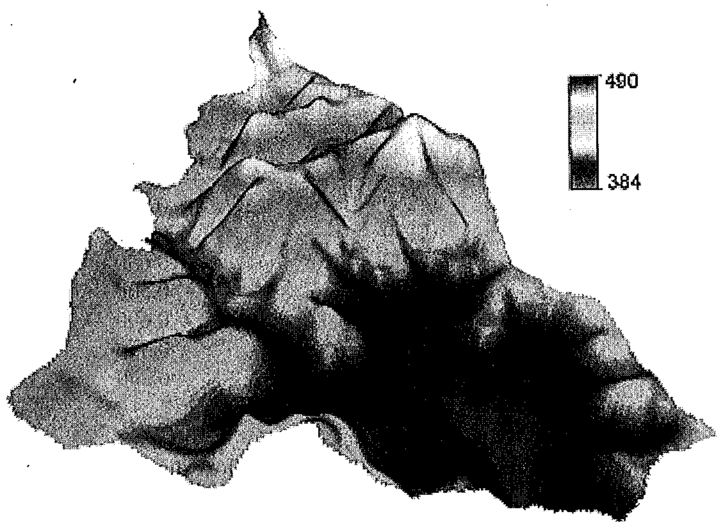

Figure 6. DEM of the whole Huai Ma Nai Catchment in Thailand

Figure 7 shows the result of the calibration of the PLER model for the whole catchment. Both the predicted and observed discharge started at the same time and reached almost the same maximum values (close to 2.5 m^3 s^{-1}). However, the predicted hydrograph increased and then decreased relatively slower than the observed hydrograph. Again, the total observed volume of 20,761 m^3 was close to the simulated volume of 19,240 m^3.

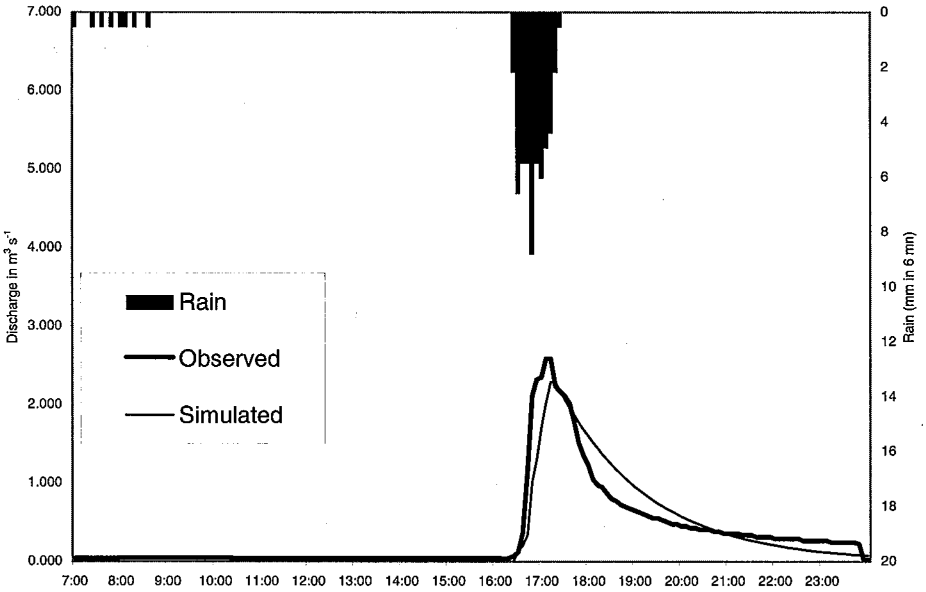

Figure 7. Comparison between the predicted and observed discharge (m^3 s^{-1}) at the flume (whole catchment) using the PLER model after calibration of a rainfall event (September 10, 2002) of 52 mm and intensity of 80 mm h^{-1}

Summary and Conclusion

The development and application of simple models for soil erosion is one major activity of the Management of Soil Erosion Consortium (MSEC). The PCARES (Predicting Catchment Runoff and Soil Erosion for Sustainability) model was first developed in the Philippines for very steep slope conditions to simulate overland flow and soil erosion for each erosive rainfall event. This was later refined by the Asian Institute of Technology (AIT) in Bangkok and termed the MSEC-1 model for dynamic soil erosion. The limitation was that it treated the runoff coefficient as a constant even under varying conditions. The latest version, named PLER (Predict and Localize Erosion and Runoff) model combined the first two versions and has now addressed the problem of the fixed runoff coefficient by integrating soil infiltration capacity as one parameter in the model. The model is able to simulate soil erosion and sedimentation patterns within a given catchment (< 100 ha) provided data on climate, soil type, topography, and land use are fed into the system. Modelling outputs include static and dynamic scenarios of distribution and intensity of erosion, sediment storage, and flux.

References

Arnold, J.G.; Williams, J.R.; Srinivasan, R.; King, K.W.; and Griggs, R.H. 1994. *SWAT, soil and water assessment tool.* USDA, Agriculture Research Service, Temple, TX 76502.

Eiumnoh, A.; Somnuck, P.; and Sewana, A. 2002. A dynamic soil erosion model (MSEC-1): An integration of mathematical model and PCRaster-GIS. In *Integrated catchment management for land and water conservation and sustainable agricultural production in Asia.* Compilation of MSEC papers presented at the IWMI-ICRISAT-ADB Joint Annual Review and Planning Workshop. 10-14 December 2001. Hanoi, Vietnam. CD-ROM.

ICRAF. 2001. Modeling soil erosion at different scales – A primary "virtual exploration of the Sumber Java Watershed. Final Report, ICRAF Indonesia.

Morgan, R.P.C. 1995. *Soil erosion and conservation.* 2nd ed. Longman Scientific and Technical.

Paningbatan, E.P. 2000. Hydrology and soil erosion models for catchment research and management. 5th MSEC Assembly, Semarang, Indonesia on Nov. 7-11, 2000.

Rose, C.W.; and Freebairn, D.M. 1985. A new mathematical model of soil erosion and deposition processes with application to field data. In El Swaify, S.A., W.C. Moldenhauer and A. Lo (eds.), *Soil erosion and conservation..* Iowa: Soil Conservation Society of America.

Rose, C.V.; Williams, J.R.; Sander, G.C.; and Barry, D.A. 1983. A mathematical model of soil erosion and deposition process. I. Theory for a plane element. *Soil Science Society of America Journal,* 47: 991-995.

Van Deursen, W.P.A. 1995. *Geographical information systems and dynamic models: development and application of a prototype spatial modelling language.* PhD thesis, Utrecht University, NGS 190, 206 pp.

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Organized by
National Agriculture and Forestry Research Institute (NAFRI)
Vientiane, Lao PDR
Institute of Research for Development (IRD)
Vientiane, Lao PDR
International Water Management Institute (IWMI)
Southeast Asia Regional Office (IWMI-SEA)
Bangkok, Thailand

With support from
The Asian Development Bank (ADB)
Manila, Philippines

Held at Vientiane, Lao PDR
2-7 December 2002

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International Water Management Institute (IWMI)
Southeast Asia Regional Office
7th Floor, Institute of Food Research and Product Development (IFRPD)
Kasetsart University, Jatujak, Bangkok 10903, THAILAND

December 2003

IWMI receives its principal funding from 58 governments, private foundations, and international and regional organizations known as the Consultative Group on International Agricultural Research (CGIAR)

The editors: Amado R. Maglinao is a Senior Researcher and Frits Penning de Vries is the Theme 2 Leader of the International Water Management Institute, Southeast Asia Regional Office, Bangkok, Thailand and South Africa Regional Office, Pretoria, South Africa, respectively. Christian Valentin is a Principal Scientist seconded to IWMI from the Institute of Research for Development in Vientiane, Lao PDR

IWMI gratefully acknowledges the financial support from the Asian Development Bank (ADB) for the project

Maglinao, A. R.; Valentin, C.; Penning de Vries, F.; (Eds). 2003. From soil research to land and water management: Harmonizing people and nature. Proceedings of the *IWMI-ADB Project Annual Meeting and 7th Management of Soil Erosion Consortium (MSEC) Assembly,* held at Vientiane, Lao PDR, 2-7 December 2002. Bangkok, Thailand: International Water Management Institute. 250 p.

watershed management / soil management / land management / natural resources / soil conservation / erosion / development projects / rain / agricultural research / water management / tillage / hydrology / rainfall-runoff relationships / catchment areas / statistical analysis / Asia / South East Asia / Indonesia / Laos / Nepal / Philippines / Thailand / Vietnam

ISBN – 9290 90 533 6

Cover Photograph: Gullies formed on cultivated steep slopes, Houay Pano catchment, Lao PDR, photo. A. de Rouw.