Hydrology and Soil Erosion Models for Catchment Research and Management

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INTRODUCTION

In watershed research and management, there is a need to develop and use quantitative methods for predicting the impact of land use and land use changes on hydrology and soil erosion at a landscape scale. With appropriate methodology, the on-site effects of soil erosion and runoff on soil productivity and the off-site effects on water quality and quantity are better understood and evaluated. Consequently, innovative interventions or mitigating measures could be properly formulated and targeted to the critical areas in watersheds that require soil conservation treatments.

Modelling could be a valuable tool in simulating hydrological processes and in planning land management strategies for a watershed. If properly validated, these hydrology and erosion models could 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.

Modelling soil erosion at a landscape level is a complex and difficult task because one has to consider the spatial and temporal interactions of weather, terrain, and crops on the hydrological and biophysical processes occurring in a landscape. This may be one major reason why many studies on soil erosion in the past were conducted on a plot scale. Spatial analyses of soil erosion at a watershed scale have been limited to cartographic techniques or overlaying of thematic maps. With the recent advances in computer and information technology, however, researchers are now able to deal with these complexities. Advances in geographic information systems (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.

At present, there is a wide range of hydrology and soil erosion models that have been developed over the last few years, ranging from plot to watershed scale and from simple to highly sophisticated structures and algorithms. This paper presents the initial result of a study conducted to search and select suitable catchment hydrology and soil erosion models for validation and application in MSEC catchments.

METHODOLOGY

A search was conducted on the Internet and in published literatures to identify and select two or three hydrology and soil erosion models suitable for the MSEC research framework. The major considerations in selection were (a) compatibility of data input–output requirements of the model with the methodology of MSEC; (b) applicability to the MSEC approach; (c) user friendliness; and (d) cost of acquisition of the software needed to run the simulation model.

To address the first and second selection criteria, the MSEC site in Lantapan, Bukidnon, Philippines, was visited. The site has instrumentation to measure the various biophysical parameters that influence soil erosion and runoff occurring in a catchment. Rainfall intensity, stream flow, and sediment load are monitored at strategic locations to assess the impact of cropping systems and conservation efforts on soil erosion in a certain catchment area. Rainfall intensity is measured using an automatic weather station capable of generating the time series of rainfall amounts. At the same

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time spatial distribution of daily rainfall could be generated from rain gauges strategically located throughout the catchment. Streamflow is monitored using calibrated weirs and Parshall flumes equipped with water height data recorders, while sediment load is measured during each erosive rainfall event at several streamflow measuring stations. In addition, maps of catchment attributes such as slope, elevation, and drainage channels are obtained from secondary sources, while cropping patterns and cultural practices, surface vegetation, and other land uses are also measured, noted or described, whenever appropriate. These measurements and monitoring activities are not only valuable in establishing the interrelationships of the watershed parameters but can also be used to calibrate and validate simulation models at a catchment scale. All the MSEC sites in the participating countries have similar research methodology and instrumentation, and as such, will generate similar types of data sets. These data generated by MSEC are then matched with the data requirements of the models. Soil, topography, and land use thematic maps; time series data of rainfall (hours and minutes) and runoff water height (mm) at strategic monitoring stations; cropping patterns; and cultural practices are highly relevant data for hydrology and soil erosion modelling. Information on infiltration rates is, however, absent.

To test their applicability to MSEC research undertakings, the selected models were parameterized with data obtained from the Philippine site. Preparation of the required raster maps was the most difficult and time-consuming activity before a test run and sensitivity analysis could be performed. Outputs of the model were also assessed in terms of its capability to address the issues of on-site soil erosion and off-site effects on water quantity and quality.

Simple concept, structure, and operation of the models are positive signs of user friendliness considering that most MSEC researchers are computer literate but not necessarily simulation model users or model developers. The spatial and temporal nature of watershed hydrological parameters and processes necessitates the use of GIS software. The availability and cost of the software package and the GIS support software needed to run the model and prepare maps were also important in selecting the model.

Results and discussion

Based on the evaluation, three models were identified and further described using the LANDMARK SOFTWARE TOOL BOX developed by IBSRAM, AIT, and DISC. These models are **CALSITE** (**Cal**ibrated **Si**mulation of **T**ransported **E**rosion), **RUNOFF1** (a simplified Hydrological **Runoff** Model), and **PCARES** (**P**redicting **C**atchment **R**unoff and Soil **E**rosion for **S**ustainability). All three models can be used as tools for catchment planning, research, instruction, and training. They are all relevant for resource management at watershed and community scales.

CALSITE

CALSITE is a GIS-based soil erosion and sediment yield prediction model intended for catchment planning. It is designed to enable the identification of the main source areas of erosion requiring soil conservation, and predicts the effects of land use and management changes on soil erosion and sedimentation (Bradbury and Dickinson, 1993).

CALSITE generates a soil erosion (source) map and then calculates the sediment yield at the outlet of a catchment area using a sediment delivery ratio (SDR). Key input variables are thematic maps of rainfall erosivity, soil type, elevation, slope, crop cover, and conservation practice. Methodology on how to generate the input maps and calculate the output maps are described by Bradbury and Dickinson (1993) and Dickinson and Collins (1998).

The model adapts the Universal Soil Loss Equation (USLE) to calculate the so-called "source erosion". Source erosion is the annual soil loss for each grid cell, calculated as the cross product of rainfall, soils, topography, and land use factors using the USLE of Wischmeier and Smith (1978), which is presented below:

$$E = R \times K \times LS \times C_m \times C_p$$

Where:

E = estimated average annual soil loss (t ha^{-1})
R = rainfall erosivity factor
K = soil erodilaility factor
LS = slope length and steepness factor
C_m = cropping and management factor
C_p = conservation practice factor

The factor R is quantified using the empirical formula given in the USLE or modified using an empirically derived formula for a particular region. For example, in the Philippines the factor R is calculated based upon annual rainfall (P_a) using a formula by David (1982)

$$R = 2.5\ P_a^{\,2}/(100 \times (0.073\ P_a + 0.73))$$

The LS factor can be derived from a slope percentage map (S) produced using a digital elevation map (DEM) using the following the equation.

$$LS = 0.2\ S^{1.33} + 0.1$$

C_m represents the ratio between soil loss under specific crop cover management conditions and that under cultivated bare fallow land. While C_p represents the ratio which compares soil loss from the field with conservation practice with the no conservation method.

Sediment yield is calculated from source erosion rates and the sediment delivery ratio (SDR), which represents the proportion of source erosion that reaches a catchment outlet. There are many formulae in the literatures to predict the SDR from one or more watershed parameters such as catchment area, catchment steepness, basin length, and maximum elevation difference (Dickinson and Collins, 1998). Some of these parameters could be easily generated from a digital elevation map using GIS but the functional relationship between the SDR and the determining factor is highly variable between catchments. One has to establish this relationship for a specific catchment, as part of the careful calibration requirement of CALSITE for a particular watershed.

The USLE is statistical correlation type derived empirically in the USA using small plots and less steep slopes; hence, it should be used with caution in other areas and hilly locations. It requires some years of calibration for a particular catchment. It predicts annual soil loss but cannot be used with confidence for individual storms or even individual years with hope of success. CALSITE is currently used in the Philippines, Thailand, Malaysia, Sri Lanka, and South Africa (Dickinson and Collins, 1998).

RUNOFF1

RUNOFF1 is a GIS-based simplified hydrological runoff model (Karssenberg *et al.,* 1998). It demonstrates how spatial-temporal maps of rainfall and runoff, and time series runoff discharges are generated in a hilly catchment. The basic input data to run the model come from raster maps of digital elevation, soil analysis, rainstations, runoff monitoring stations, time series rainfall amounts, and infiltration capacity analysis; they are obtainable in the MSEC catchment research methodology. The model concept, structure, and script are simple to understand even for a researcher who has no expertise in programming. Its structure is generic, hence, the script can be easily modified or extended to include complex and functional equations governing the hydrologic and soil erosion processes occurring in a hilly catchment. To show the simplicity of the model structure, the script of RUNOFF1 is presented in the computer programme listing presented below:

```
#####################################################################################
# model for simulation of rainfall and runoff
# 24 timesteps of 6 hours => modelling time one week
binding
 Dem=dem.map;                          # digital elevation map
 SoilType=soil.map;                    # soil map
 RainStations=rainstat.map;            # map with location of rainstations
 SamplePlaces=samples.map;             # map with runoff sampling locations
 RainTimeSeries=rain.tss;              # timeseries with rain at rainstations
 SoilInfiltrationTable=infilcap.tbl;   # table with infiltr.cap.of soil types
 RainZones=rainzone.map;               # reported stack of maps with rain
 Ldd=ldd.map;                          # reported local drain direction map
 InfiltrationCapacity=infilcap.map;    # reported map with infiltr. cap.
 SurfaceWater=rainfall;                # reported maps with rain (mm/6hours)
 LogRunOff=logrunof;                   # reported stack of runoff maps
 RunoffTimeSeries=runoff.tss;          # reported timeseries with runoff
 ConvConst=216000;                     # conversion mm/6hours => m3/s
                                       # at sampling locations
timer
 1 28 1;
initial
# coverage of meteorological stations for the whole area
report RainZones=spreadzone(RainStations,0,1);
# create an infiltration capacity map (mm/6 hours), based on the soil map
reportInfiltrationCapacity=lookupscalar(SoilInfiltrationTable,SoilType);
# generate the local drain direction map on basis of the elevation map
report Ldd=lddcreate(Dem,1e31,1e31,1e31,1e31);
dynamic
# calculate and report maps with rainfall at each timestep (mm/6 hours)
SurfaceWater=timeinputscalar(RainTimeSeries,RainZones);
# compute both runoff and actual infiltration
Runoff,Infiltration= accuthresholdflux,
accuthresholdstate(Ldd,SurfaceWater,InfiltrationCapacity);
# output log10 of runoff (converted to m3/s) at each timestep
LogRunOff=log10(Runoff/ConvConst+0.1);
# output runoff(converted to m3/s) at each timestep for selected locations
report RunoffTimeSeries=timeoutput(SamplePlaces,Runoff/ConvConst);

#####################################################################################
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The programme script is composed of five basic sections, namely a) binding section, b) areamap section, c) timer section, d) initial section, and e) dynamic section (PCRaster, 1996a). The *binding* section manages the input and output databases throughout the programme. It contains and manages the inputs from the digital elevation map, soil map, location maps of rain gauging and runoff monitoring stations, infiltration capacity table, and time series rainfall data at the gauging stations. The *areamap* section defines a geographic location map where the generated maps obtained their map attributes such as coordinates, cell length, and projection. The *timer* section specifies the time dimension such as the *starttime*, *endtime,* and *timeslice.* Iteration of the dynamic section is executed between the starttime and the endtime, while the timeslice specifies the consecutive time steps.

The last two sections perform operations that generate new map attributes and time series data. The initial section contains a given set of commands with specific options of generating new cell attributes (rainzone map, local drain direction or LDD map, infiltration capacity map) from the attributes already present. The resulting maps and other constants are utilized for running the dynamic section, which is an iterative section consisting of a series of commands that are performed sequentially for each time step to produce the output information.

Based on the PCRaster command statements in the dynamic section, the model first calculates and reports at each time step the depth of surface water for each cell (rainfall.map). The accuthresholdflux operator effects infiltration of the rain and transport of the excess water (runoff) downstream over the local drain direction map. For each cell, the amount of water discharged to the downstream cell is the difference between the water inflow from the upstream cell and infiltration capacity (infilcap map). The amount of water that actually infiltrates is calculated with the accuthesholdstate operator. Time series runoff discharge at the cell where the monitoring station is located is reported as runoff tss.

The model was parameterized using data obtained from the MSEC site in Lantapan, Bukidnon.

PCARES

PCARES is a GIS-assisted model that simulates runoff and soil erosion of a catchment. It can predict the spatial and temporal distribution of soil erosion rates; thus it can be used to identify erosion "hotspots" in a watershed (Lanuza and Paningbatan, in press). Also, it can predict the runoff and sediment discharge rates at the outlet of a catchment; thus, it could be a tool to study the effect of land use change and management options on water quantity and quality.

The model uses PCRaster, a GIS software capable of cartographic and dynamic modelling that allows easy simulation of the hydrologic and sediment transport processes occurring in a three-dimensional landscape. The concept, structure, and script are very similar to RUNOFF1 except that the hydrology component involves the calculation of water flow velocity using Manning's equation that allows the calculation of discharge rate at shorter time intervals. It also incorporates a system of calculating sediment transport.

The hydrology comprises the interrelationships of rainfall, infiltration, and runoff during each erosive rainfall event. The model first considers how rainfall influences overland flow and eventually the erosion processes of entrainment and deposition. With a given soil infiltration capacity of each cell, the model calculates over time the amount of excess rainfall that becomes runoff using the equation:

$$R = P - I \quad (1)$$

where R is the excess rainfall (mm) that becomes runoff, P is the amount of rainfall (mm), and I is the infiltration (mm) over a time step (ts).

Water discharge (Q, in $m^3\ ts^{-1}$) 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 (LDD) of PCRaster calculates the direction of water flow while the velocity of overland flow is calculated using Manning's equation:

$$V = (1/h)\ S^{1/2}\ R^{2/3} \quad (2)$$

where V is flow velocity ($m\ ts^{-1}$); h is Manning's roughness coefficient; S is slope gradient (fraction); and R is hydraulic radius (m).

The process of soil erosion was modelled following the concept developed by Rose and Freebairn (1985) which calculates the amount of soil loss (SL) from the product of sediment concentration (c, in $kg\ m^{-3}$) and water discharge rate (Q, in $m^3\ ts^{-1}$). Sediment concentration is estimated using the simplified equation by Rose and Freebairn (1985) which is written as:

$$c = 2700\,l\,S\,(C_r) \quad (3)$$

Thus, the sediment loss (kg/ts) at each cell is calculated from Equation 4:

$$SL = 2700\,l\,S\,(1 - C_o)\,(Q) \quad (4)$$

where l is the efficiency of sediment entrainment, S is the sine of 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, and Q is the water discharge rate ($m^3\ ts^{-1}$).

It is imperative from equations 1, 2, 3, and 4 that the attributes needed to run the model and simulate soil erosion and water discharge in a watershed include rainfall rates (P), soil infiltration characteristics (I), surface crop cover (C_o), surface roughness (h), slope steepness (S), and efficiency of entrainment (l). Spatial and temporal representation of these attributes in raster maps form are important inputs to run the model. Time series rainfall rates (mm min^{-1}) for each runoff generating rainfall event are also necessary to run the model. On the other hand, runoff discharge, sediment concentration, and soil loss at the outlet of a watershed or spatially represented in raster maps for the entire catchment study area are important outputs of the model.

The model has limited validation in one catchment and is further being validated at the ICRAF research sites located at the Manupali Watershed in Lantapan, Bukidnon, Philippines. It is important to note that based on sensitivity analyses, surface crop cover, infiltration characteristics, and Manning's roughness coefficient effect significant changes in sediment concentration and runoff discharge and hence, sediment yield. These parameters are affected greatly by the kind of crop management and conservation practices, and land use change, which may prove the application of such a model to the research undertakings of MSEC.

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