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Development and Validation of a Geographic Information System (GIS)- Assisted Soil Erosion Model in a Watershed Scale

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ABSTRACT

The study was done to develop erosion model, test, and validate its capability in mapping soil erosion and runoff and predicting the amount of sediment and water discharges at the outlet of a watershed; identify areas with high erosion risk potential within the watershed; and formulate recommendation for management strategies that would reduce soil erosion in the watershed. Named Predicting Catchment Runoff and Erosion for Sustainability (PCARES) Model, it predicted accurately the runoff heights and sediment concentration in a watershed in each single rainfall event. The erosion "hot spots" were predicted to occur in areas with steeper slope and agricultural land with less ground surface cover and no conservation measures, roads, and footpaths. Net depositions were located in areas with thick crop cover, riparian buffer strips, and gentle slopes. The results demonstrate both the ability of the PCARES model in predicting the runoff and soil erosion in a watershed in a given erosive rainfall event, assess the impacts of land use change and soil conservation activities in a watershed on the rate of soil erosion and the significant influence of surface cover in reducing runoff and soil erosion in a watershed. The model can thus be used as a tool in assessing the impact of any development undertakings in a watershed prior to its implementation for sustainable watershed resource management. Absence of surface cover during land preparation stage contributed significantly to an increase amount of runoff water and soil loss. Thus, areas that are not used for agriculture purposes should be maintained as grassland or be planted with forest or fruit trees. Soil loss and runoff height decreased from land preparation to early crop establishment stage and further decreased at maturity. To mitigate the negative impact of thorough land preparation, minimum tillage if not zero tillage should be adapted where it is applicable. Adapting an extreme condition (bare surface) resulted to highest simulated runoff and soil loss. Very low if not almost absence of soil loss was predicted from the grassland and the forest land uses. Soil loss in the cropland is dependent on the soil and crop residue management, the type of crop grown, and the soil conservation strategies employed by the farmers. If farmers will continue to destroy the surface cover, soil loss will always be a continuous threat to soil degradation and crop production sustainability in the catchment.

Keywords: Erosion modeling, PCARES, watershed, soil loss, runoff, watershed resource management

INTRODUCTION

Soil erosion is a major threat to many watersheds in the Philippines. This is evident particularly in sloping uplands where farmers/dwellers utilize great portion of the watershed for food production as well as in other land uses like poor road condition and footpath. Inappropriate land use in addition to the other factors of erosion such as intense rainfall, steep slope, crop cover and erodible soil contribute significantly to high soil erosion rates. It is imperative then that conservation-oriented soil management practices should be employed to arrest land degradation in the uplands.

Development and use of quantitative methods that could predict the impact of the various land uses and farming activities on soil hydrology and soil erosion at a watershed scale is needed on watershed management. This would pave the way to better evaluation and understanding of the on-site and off-site effects of soil erosion on soil productivity, water quality and quantity, as well as the impact of land use change and farming activities on soil erosion rates so that innovative interventions can be formulated and implemented on the identified critical areas in the watershed. The use of simulation models in understanding soil erosion in a watershed is a sound approach in planning conservation strategies and programs.

Modeling erosion at the watershed level is a complex process because of the integrated effects of climate, terrain, and substrate on the hydrological and biological processes and erosion occurring in a natural landscape. The complexity of the system requires appropriate methods and techniques so that models developed would reflect the actual conditions of a watershed (FAO, 1996). Traditionally, the processes involved in soil erosion and hydrology are expressed in the form of complicated equations. Calculations are lengthy, complicated, and sometimes difficult to perform. Oftentimes, the erosion process is treated as unidirectional and that excludes the lateral interaction between adjacent physical units of a three-dimensional landscape (Paningbatan, Jr., 2001).

Recent advancements in information technology have facilitated the development of computer programs within the Geographic Information System (GIS) environment that can progressively handle very fast iterative processes that consider spatial and temporal variabilities (Paningbatan, 2001). The PCRASTER is one of the computer-based GIS softwares. It embeds a dynamic modeling language in GIS that handles the functionality of data storage, manipulation, analysis, and visualization of spatio-temporal information needed in the quantitative description and prediction of the hydrology and soil erosion in a catchment area.

Recognizing the need to study the biophysical processes occurring in a landscape and the need to analyze the environmental and social impacts of rapid land use change in a watershed, there is an urgent need to study and model soil erosion and the related hydrologic processes at a landscape level. This approach could offer many appropriate solutions to environmental problems like soil erosion and other non-point sources of pollution. For example, there is a need to identify areas in a watershed/catchment that are highly susceptible to soil erosion so that erosion mitigation works might be successfully targeted on a policy level. It can be used to analyze the environmental impact of land use change in a watershed. Land use planning particularly in this stage of rapid global change would require analysis of the biophysical system and the occurring processes at a landscape scale. Erosion and deposition models developed using this technique were used to identify areas of high potential erosion that requires special soil conservation management without necessarily resorting to management of the whole watershed catchment. This approach would allow more efficient and effective use of the limited financial resources available for reducing erosion and sediment discharges from watershed catchment (Moore et al., 1988).

The study was done to develop, test, and validate the capability of a GIS-based soil erosion model in mapping soil erosion and runoff, and predicting the amount of sediment and water discharges at the outlet of a catchment; identify areas in the watershed with high erosion risk potential; and formulate recommendation(s) for management strategies that would reduce soil erosion.

RESEARCH METHODOLOGY

Study Site

The study focused on the intensively farmed area of one of the microcatchments of the Mapawa watershed located at Barangay Sungco, Lantapan, Bukidnon. The area was selected on the basis of the following criteria: a) agriculturally active; b) there is a single drainage outlet; c) hydrologically well-bounded and delineated by well-defined topographic boundaries; d) the watershed area is about 100 ha; and e) previously studied to take advantage of any available data.

Model Components

The cartographic and dynamic modeling components of the PCARES are programmed using PCRASTER operators. The computer program is composed of five basic sections, namely: a) binding section; b) area map; c) timer section; d) initial section; and e) dynamic section (PCRASTER, 1996a). These sections are essential to instruct the computer on how to execute the series of instruction codes. It consists of five basic sections with different sets of PCRCALC operations. The lines under each section keyword are called statements that specify the contents and operation. This is terminated by a semicolon (;) and any marks for each statement are written after a # sign. The schematic representation of the script for this erosion model is presented in Figure. 1.

The cartographic modeling component of PCARES was used in generating the catchment-based geographic databases. It is a set of primitive operators that result to a change in the attribute of the cells. This set of operators is an algebraic computer language designed particularly for spatial and temporal analyses (PCRASTER, 1996) wherein specific option is used for a specific operation.

The dynamic model components include the hydrology, sediment transport and routing, sediment concentration, and soil loss within the watershed. The hydrology is composed of: a) modeling of rainfall of the catchment; b) modeling of infiltration; and c) modeling of runoff or discharge. Firstly, it calculates the spread of rainfall from the rainfall station generated from the rainfall zoning. Secondly, it calculates the simulated rainfall based on the rainfall intensity time series at each time step. The infiltration and runoff were modeled using the information generated from the rainfall model and infiltration capacity of the soil at different ecosystems. Infiltration is affected by various factors, such as land use, cropping system, and their interactions.

The hydrology comprises the interrelationships of rainfall, infiltration, and runoff during each erosive rainfall event. First, it considers how rainfall influences overland flow and eventually the erosion processes of entrainment and deposition. The model calculates the amount of excess rainfall over time that becomes runoff with a given soil infiltration characteristics expressed as:

$$R = P - I \tag{1}$$

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 specified timestep (ts). Water discharge (Q in m^3 –s^{-1}) at the downslope portion of each cell area is calculated from the amount, direction, and velocity of water inflow or outflow to the neighboring cells. A water routine subroutine called local drain direction (LDD) specifies the direction of water flow determined by the steepest slope gradient of neighboring grid cells.

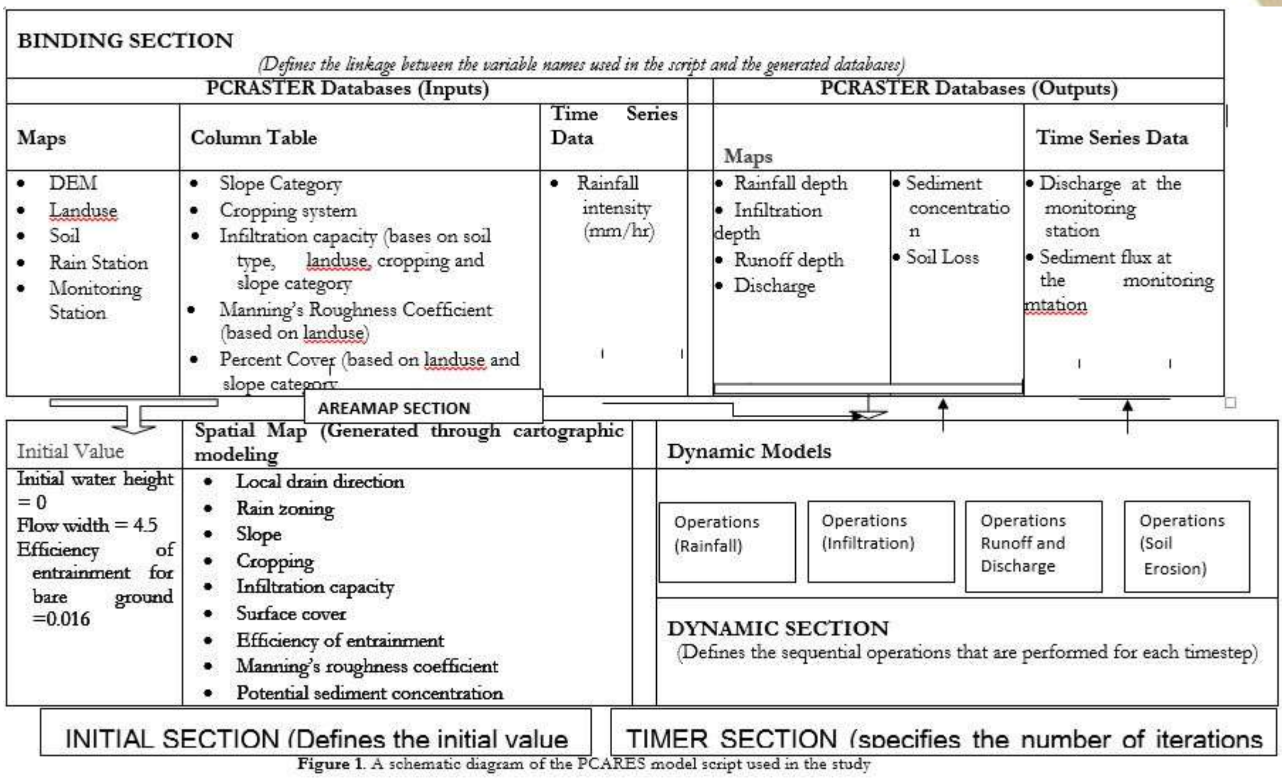

Figure 1. A schematic diagram of the PCARES model script used in the study

The runoff rate or discharge was calculated using the formula:

$$Q = VW_bD \qquad (2)$$

where Q is the discharge ($m^3\ s^{-1}$), V is the velocity ($m\ s^{-1}$), W_b is the flow width (m), and D is the depth of water (m). The velocity of flow (V) was estimated based from Manning's equation:

$$V = 1/\dot{\eta}\ (S^{1/2})\ (R_h^{\ 2/3}) \qquad (3)$$

where V is flow velocity ($m\ s^{-1}$), R_h is the hydraulic radius (m), S is the slope gradient (fraction), and $\dot{\eta}$ is the Manning's roughness coefficient. The height of water was computed as the initial water height plus the amount of runoff. As shown in the script, a *max* option was used in order to be sure that the water height will not be negative. It assigns a maximum height of zero on a cell-by-cell basis if computed water height is negative.

The height of discharge in a meter waterslice in each timestep was calculated as the product of the discharge and duration of every timestep divided by the cell area equivalent to 100 m^2 (10 m x 10 m cell size). This is equal to the discharge over the timestep per cell or the flux out from the cell. On the other hand, the height of water coming from the neighboring upstream cells that drained to a particular cell was computed using the UPSTREAM option. This operation calculated the flux in of water in a three-dimensional landscape that uses the local drain direction map and sums up the values of upstream neighbors of the cell. The neighbor cells are only the first upstream cells or cells that directly drain to the cell. The computation of flux in and flux out of the cell is very necessary to account for the new water height. The new water height was computed as the old water height plus the flux in and minus the flux out. This new water height became the new input of the model for the next timestep (*t_i + 1)* and recalculated based on the procedure above until the last timestep.

Hydrograph was predicted based on the stream discharge at the outflow point. The TIMEOUTPUT option was used to generate ASCII format files, which could be directly viewed graphically by TIMEPLOT operator. These files could also be imported using any spreadsheet software. Based from the hydrograph, the peak runoff could be predicted and the area of the curve represents the total volume of runoff for the whole duration of the rainfall event.

The process of soil erosion was modeled 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). Sediment concentration is estimated using the simplified equation written as:

$$c = 2700\ \gamma S(Cr) \tag{4}$$

Thus, the sediment loss at each cell is calculated using the equation:

$$SL = 2700\ \gamma S(1\text{-}C_o)(Q) \tag{5}$$

where SL is the sediment loss (kg s^{-1}), γ is the efficiency of sediment entrainment, S is the sine of slope angle, (1-C_o) is equal to Cr 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 s^{-1}). This equation is synonymous to the sediment flux theory. Rose and Freebairn (1985) stated that sediment flux is the product of sediment concentration and overland water flux expressed mathematically as:

$$Qs = cq \tag{6}$$

where Qs is the sediment flux, c is the sediment concentration, and q is the volumetric flux of water. Thus, the model of erosion and deposition contains surface hydrology theory and the processes that affect the sediment concentration. In Rose equation, the first group of terms is equivalent to the sediment concentration and runoff as the volumetric flux of water. Therefore, knowing the runoff based from the hydrology model and the sediment concentration, the soil loss in the watershed can be computed.

All the above models were operated in a cell basis wherein cells are considered uniform square areas, with dimension of 10 m x 10 m subdividing the watershed. The examination of the flow at any point between cells was based by routing the potential runoff and soil loss through the local drain direction cells from the watershed divide to the outlet (Moore et al., 1998; Young et al., 1989; PCRASTER, 1996 a).

Model Inputs and Outputs

It is imperative from equations 2, 3, 4, 5, and 6, 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 (ή), slope steepness (S), and efficiency of sediment entrainment (γ). The spatial and temporal representations of these attributes are prepared in raster maps. Likewise, time series rainfall rates (mm h^{-1}) for each runoff-generating rainfall event, are also necessary to run the model (Table 1). On the other hand, time series run-off discharge, sediment concentration, and soil loss at the outlet of a catchment are important outputs of the model (Table 2). Spatial distribution of soil erosion represented in raster maps can be generated to show the location of erosion "hot spots" in a catchment area. Other inputs of the model are main PCRASTER databases generated by a series of data manipulation and conversion and the spatial maps generated by cartographic modeling using the main PCRASTER databases as input in combination with some PCRASTER operators.

Parameterization of Input Data

In developing the methodology of the PCARES model, it was assumed that the watershed under study can be divided into a number of discrete cells or raster cells as shown in Figure 2. Each cell is described or characterized by a set of relevant attributes such as elevation, soil type, kind of vegetation cover, etc., along with their spatial coordinate to describe the features and characteristics of the watershed and as such a raster map of each attribute could be developed using a GIS. The GIS-assisted methodology is composed of: a) creation of the main geographic databases; b) catchment delineation and generation of catchment-based geographic databases; and c) testing and validation of the model.

Creation of the main geographic databases. Spatial information such as topographic, soil, and land use maps were used as base maps. Parcellary map was used as the base map in validating land use map. Geographic databases were created from the gathered maps using the IDRISI software. The attributes of these maps were converted or transformed into computer binary format by digitizing them using the TOSCA module of IDRISI with a vector representing the map as the output. The vector map files were then converted to raster map files using specific modules of IDRISI.

The digital elevation model (DEM) map was constructed from the elevation data from the topographic map in 1:50,000 scale by digitizing the contour lines with an interval of 20 m as line-object type. This vector-information was then converted to raster-based DEM by using the *lineras* and *intercon* modules of IDRISI. The land use and soil maps were digitized and assigned as polygon-object type, while the monitoring station and rain station maps were digitized as point-object type. These vector formats were converted to raster-based formats using the *polyras* and *pointras* procedures, respectively. American Standard Code for Information Interchange (ASCII) files generated from each of the IDRISI-based rasterized maps were used as inputs in generating the main geographic databases in PCRASTER map format. Combinations of PCRASTER executable commands were used to generate the appropriate formats. The *mapattr* command was used to generate a clone map using the command syntax:

Mapattr CloneMap (7)

where CloneMap is the filename of the PCRASTER CloneMap to be generated. The clone map specifies the map attributes such as number of columns and rows, data type, cell representation, projection, x and y upper left corner value, cell length and angle of the PCRASTER inputs maps to be generated such as DEM, land use, soil, rain station, and monitoring station maps. On the other hand, the *Asc2map* command was used to convert ASCII file or text file of the IDRISI raster-based map to PCRASTER map format using the command syntax:

Asc2map—clone CloneMap ASCIIfile PCRASTER map (8)

Table 1. Input requirements of the model

MODEL INPUTS	UNITS	SYMBOLS/FILENAME USED
a. Main PCRASTER Databases		
1. Digital elevation map	m	Dem.map
2. Landuse map	-	Landuse.map
3. Soil map	-	Soil.map
4. Monitoring station map	-	Station.map
5. Rain station map	-	Rainstat.map
	-	
b. Spatial Maps		
1. Rainfall zones map	mm	Rainzone.map
2. Slope map	%	Slope.map
3. Slope category map	%	Slopecat.map
4. Slope degree map	%	Slopedeg.map
5. Local drain direction map	-	LDD.map
6. Infiltration map		
7. Rain saturation map	mm	Infilsat.map
8. Flowidth map	mm	Rainsat.map
9. Cover map	m	Flowidth.map
10. Manning's map	%	Cover.map
11. Entrain map	-	Mannings.map
	-	Entrain.map
c. Time series data		
1. Rainfall		
2. Cover table	mm	Rainflux.tss
3. Infiltration table	%	Cover.tbl
4. Manning's table	mm	Infilsat.tbl
5. Slope category table	-	Mannings.tbl
6. Flow width table	%	Slopecat.tbl
7. Rain saturation table	m	Flowidth.tbl
	mm	Rainsat.tbl

Table 2. Model output generated during cartographic modeling using PCRASTER.

MODEL OUTPUTS	UNITS	SYMBOLS USED
a. Maps		
• Rainfall depth	mm	P
• Infiltration depth	mm	I
• Runoff depth	mm	R
• Water discharge	li/sec	Q
• Sediment concentration	kg/m^3	C
• Soil loss	kg	SL
b. Time Series Data		
• Water discharge	li/sec	Qwm^{3}pts
• Total water discharge	m^3	Twadim^3
• Total sediment mass	kg	Tsedmkg
• Sediment flux	kg/sec	Qskpts
• Sediment concentration	kg/m^3	Sedcon
• Soil loss	kg	kg

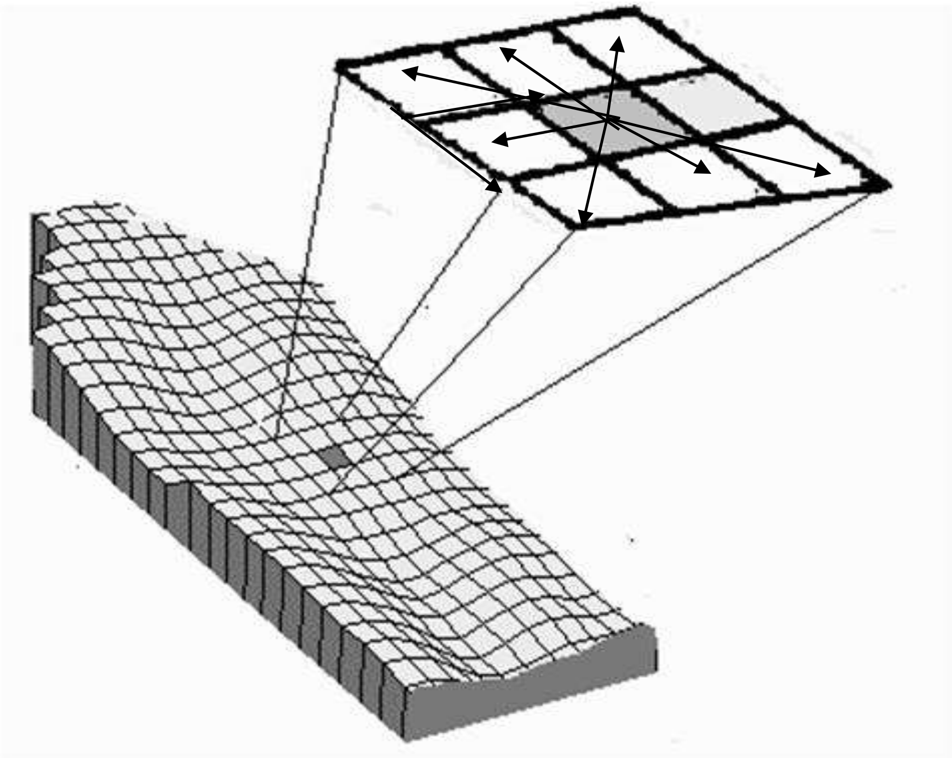

Figure 2. A PCRASTER map of a catchment showing a raster cell influencing the attribute of neighboring cells.

where -clone is the command option that specifies the appropriate PCRASTER clone map; CloneMap is the file name of the PCRASTER clone map; ASCII File is the file name of the input ASCII file or text file; and PCRASTER map is the file name of the output PCRASTER map.

Generation of catchment-based geographic databases. The cartographic modeling of PCRASTER was used in generating the catchment-based geographic databases. It is a set of primitive operators that result to a change in the attribute of the cells. This set of operators is an algebraic computer language designed particularly for spatial and temporal analyses (PCRASTER, 1996) wherein a specific option is used for a specific operation. Other important input maps used in the model were also generated using cartographic modeling with general command syntax of:

Pcrcalc ResultExpression=PCRasterOperator(PCRasterExpression) (9)

a) Local drain direction map was generated by the command syntax:

LddMap=lddcreate(DEMMap,1e31,1e31,1e31,1e31) (10)

b) Slope map was generated by the slope option which calculated the slope using the elevation of DEM of its height nearest neighbor cells expressed as *dy/dx,* which is the increase in height (*dy*) per distance in horizontal direction (*dx*). The map output could be further manipulated to generate a slope map expressed in degrees using ATAN (arc tangent) option or by reclassifying the slope categories using the LOOKUPNOMINAL option plus a new slope category input.

c) The rainzone map was created by the SPREADZONE option considering nearest location of rain gauge. This procedure determined the shortest distance path over a map with friction from a source cell or cells to the consecutive neighboring cells and the value of the source cell at the start of this shortest distance to the cell considered.

d) The cover map was generated using the LOOKUPSCALAR option plus cover factor for each land use and slope category. The vegetative cover factor was estimated using a 1 x 1 m quadrant. The cover map is dependent on the land use, cropping system, type of crops, and crop growth stages. Any change in the values of these attributes will definitely result to change in the cover map. The cover map is captured during the cartographic modeling and is used as one of the factors in predicting the runoff and soil loss.

e) The entrainment map was generated using the functional relationship of surface contact cover and the efficiency of entrainment.

f) The surface roughness map was generated by a combination of LOOKUPSCALAR option and input of estimated Manning's *n* for each land use. The roughness coefficient was computed based on Cowan's method that is suitable for small mid-size channels of hydraulic radius less than 5 m (Gordon et al., 1992) as follows:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)\, m_5 \qquad (11)$$

where n_0 is the basic n value, n_1 is the surface irregularity, n_2 is the variation in cross-sectional shape using turbulence, n_3 is the effect of obstruction, n_4 is the vegetation, and m_5 is the meandering. The values of the subfactors were taken from Cown (1956) and Jarret (1985) as adapted by Gordon et al. (1992).

g) The sediment that has the potential for entrainment was generated using the equation developed by Rose and Freebairn (1985) expressed as

$$c(L,t) = 2700\ ý\ \ S(Cr) \qquad (12)$$

where S is the sine of slope angle, Cr = (1-Co) where Co is the ratio of the area not exposed to runoff or the percentage cover, and γ is the factor approximating efficiency of entrainment. The resulting map is the potential sediment concentration during entrainment in a per cell basis, which is directly proportional to the slope angle, contact surface cover, and the efficiency of entrainment.

h) Soil erosion map is generated from runoff map and sediment load map. The erosion rates on cell location basis was predicted by accounting the flux in and flux out of each cell element given a rainfall event at any given discharge Q.

The infiltration capacity, which is highly dependent on soil and land use was estimated from a data set obtained in the field using a double ring infiltrometer. Since the soil in the area belongs to only one soil type (Adtuyon Clay), the saturated infiltration rate is more dependent on land use rather than the soil (Paningbatan, 2001). On the other hand, rainfall hydrographs were prepared from rainfall data gathered from an automatic rain gauge capable of measuring depth of rainfall every minute. Rainfall characteristics were collected from tipping bucket-type rain gauges and equipped with data loggers that were installed strategically in the catchment. The instrument is capable of determining the amount of rainfall at one-minute time intervals that are recorded and stored in electronic files. Microsoft EXCEL was used in the generation of rainfall amounts, rates and duration, and the corresponding hydrographs. On the other hand, time- dependent streamflow was monitored using water height recorders with electronic data logging devices that were installed strategically in the catchment study area. It measures and records time-dependent changes of runoff water depth in the drainage channels at one-minute time interval. Time element of the data loggers of the automatic rain gauge and water height recorders were synchronized with the computer real time. Sediment load was collected manually near the water height recording stations during each runoff producing rainfall event. The water samples were analyzed for sediment concentration using oven drying technique. Detailed survey on land use in the catchment study area based on parcellary map was done through ground truthing. Land use boundaries were validated using a global positioning system (GPS). During the field survey, crops grown and growth stages and related farming activities were noted. The crop cover in each land use within the study catchment was estimated using a 1 m x 1 m quadrant.

Identification/Delineation of catchment. Manual delineation was first done to initially locate the catchment boundaries and the drainage network using the topographic map followed by ocular inspection. This was compared with the GIS-assisted methodology in locating and delineating the catchment boundaries. The PCRCALC command (Table 3) in combination with CATCHMENT option were used to delineate the topographic divides or ridges of the catchment from the DEM map. The methodology involved the creation of local drain direction map that shows the drainage network or the direction of material flow and the pit map that shows the pits that receive all materials coming from the upper cells following the local drain direction. The set of commands in the script file was executed using the pcrcalc command with the *–f option* using the command syntax:

$$Pcrcalc = f\ (Model\ Name) \tag{13}$$

where ModelName is the file name of the script in text format.

Table 3. Model script for locating and delineating the catchment boundaries using cartographic modeling of PCRASTER.

CARTOGRAPHIC MODELING

```
Binding
        DEMMap=topo.map;                # DEM map of Mapawa
        LddMap =ldd.map;                # Generated local drain direction map
        StatMap=stat.map;               # Generated map showing all the pits
        PitCatchMap=pitcatch.map;       # Generated pit map that receives all
                                        # water from the identified catchment
        CatchmentMap=catch.map;         # Genrated catchment map
Initial
        LddMap=lddcreate(DEMMap,1e31,1e31,1e31,1e31);
        PitCatchMap=StatMap eq ;        # ("Note: After eq, supply the number of the
                                          pit where all waters will drain");
        CatchmentMap=catchment(LddMap,PitcatchMap);
```

Formulation of Assumptions. The following assumptions were considered in the model: a) the rainfall pattern is uniformly distributed over the catchment; b) the initial state of water height is set at zero and any addition of water coming from the rain would tend to increase the water height; c) the rainfall flux or intensity, that is the amount of rainfall per unit time, follows a sine curve, and the area of the curve represents the cumulative rainfall for the specific rainfall event; d) rainfall of higher intensities are more erosive than rainfall of lower intensities; e) variation of infiltration depends on land use and cropping pattern due to the fact that there is only one soil type in the studied catchment (BSWM soil map); f) there is no variation of base flow with time; g) the hydraulic radius of flow in the catchment channel is that of the rectangular rills expressed as:

$$R_h = W_b D/(W_b + 2D) \tag{14}$$

where R_h is the hydraulic radius, W_b is the base of the rectangular rill or the flow width, and D is the depth of the waterflow; and h) the local drain direction, that is the water from the upper elevation will flow to the cells of lower elevation, follows a drainage network after saturating all depressions and finally drains to a pit.

The erosion model which was based on the sediment concept of Rose et al. (1983) assumed the following: a) agricultural lands with slope of 0-18 percent are considered agriculturally active; b) sediment concentration is a function of vegetative cover; c) sediment transport is transport capacity limited and not detachment limited; d) the efficiency of entrainment for bare soil is set at 0.40, a constant taken from UPSWAT (Upland soil water) model and used to predict the efficiency of entrainment for each land use; e) the sediment loss considers only the suspended load that is subsequently transported through the local drain direction. Rose and Freebairn (1985) considered the sediment concentration as the net contribution of entrainment over deposition; and f) the entrainment process in overland flow has similarities to bed load transport in streams that can be related to the excess of stream power to entrain sediment. Data inputs were encoded in ASCII file format and word processors processed the outputs of the model.

Model Description and Structure. The model operates on cell basis wherein the cells are uniform square areas subdividing the watershed. Movement or flow at any point between cells was based on the routing mechanism of runoff and sediment load. In a rainfall event, the vegetative cover intercepts the raindrops until potential interception storage is met. Infiltration begins when interception storage capacity is exceeded. Generally, infiltration rates decrease exponentially with the increase in soil water storage, hence, a point is reached where rainfall rate exceeds infiltration capacity. This will result in the filling up of water to micro-depression. However, when the micro-depression storage is filled, runoff begins. On the other hand, surface detention is the volume of water that is temporarily stored during flow across the surface. As the precipitation stops, the surface detention storage dissipates until surface runoff ceases altogether. However, infiltration continues until depressional water is no longer available.

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 and outflow to the neighboring cells. A water routing subroutine called local drain direction (LDD) of PCRASTER simulate the direction of water flow while the velocity of overland flow is calculated using Manning's equation.

Computer Simulation and Predictive Ability of the PCARES Model. Computer simulation of the PCARES model using three actual major rainfall events that generated a major stream flow in Mapawa creek was conducted to predict soil erosion in a watershed. The outputs of the model are predicted values and were compared with the actual observed values, which were measured from the same site. Simulations were also done at different growth stages of the crop and as land use changes using one major rainfall event. The Student *t*- test was used to determine whether or not there are significant differences between the predicted and the observed values. Likewise, regression and correlation analyses using SPSS statistical software were used to determine their relationships.

RESULTS AND CONCLUSION

Model Simulation Results

Significant variations on model response were noted as a result of different variations in the amount and duration of rainfall. These variations in runoff volume could be explained by the variations in the antecedent soil moisture regime as a result of the occurrence of rainfall of different amounts and intensities prior to the rainfall events used in the simulation that effected infiltration rate. Infiltration of same soil type varies at different moisture regimes. Drier soil has higher infiltration rate at the start of rainfall than for an initially wetted soil and finally attained a steady state infiltration under saturated conditions. Infiltration rate is relatively higher at dry conditions compared to moist conditions at the start of the rainfall event until the time that infiltration capacity is attained.

The same trend was observed on soil loss wherein the highest value of 23,052 kg was predicted using the July 18 rainfall event. The predicted values for the July 14 and August 13 rainfall events were 20,947 kg and 17,185 kg, respectively (Table 4). Soil loss is closely related to rainfall through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to runoff. This applies particularly to erosion by overland flow and rills for which intensity is generally considered to be the most important rainfall characteristics. A study conducted by Fournier (1972), as cited by Morgan (1995), showed that average soil loss per rain event increases with intensity of the storm. But in the study of Morgan et al. (1986), it appears that erosion is related to two types of rain, the short-lived intense storm where the infiltration capacity of the soil is exceeded, and the prolonged storm of low intensity, which saturates the soil. The response of the soil to rainfall may also be determined by previous meteorological conditions. This was demonstrated by the study of Fournier (1972) wherein first rain fell in dry ground and in spite of the quantity (19.3 mm), little runoff resulted; most of the water soaking in the soil. In the second rain event (13.7 mm), 66 percent of the rain ran off and soil loss almost trebled. The control in this case is the closeness of the soil to saturation, which is dependent on how much rain has fallen in the previous few days. The developed PCARES model was found to be sensitive to the initial moisture conditions of the soil prior to the erosive rainfall event. Base on the sensitivity analysis made by Paningbatan and Lanuza (2000) using the PCARES model, parameters such as surface cover, infiltration characteristics, which is a function of the initial moisture condition of the soil, and Manning's roughness coefficient that are highly affected by the kind of crop and management practices employed, conservation measures, and land use change resulted to significant changes in sediment concentration, runoff discharge, and sediment yield.

Table 4. Simulation output of PCARES using the three rainfall events.

DATE OF RAINFALL EVENT	SIMULATION OUTPUT	
	Total Runoff Discharge (m3)	Soil Loss (kg)
July 14	3338	20,947
July 18	3587	23,052
August 13	2969	17,185

Model Validation Results

Results of validity test showed non-significant mean differences of the manually located elevations on the topographic map and the GIS-assisted approach in projecting the elevations in question. Likewise, a very high positive correlation (r=0.996) was noted indicating that the data points are within the equality line. This means that the generated GIS-methodology could accurately project the surface elevation of a catchment and therefore could accurately represent the actual spatial distribution of the study area. The measured hydrographs from the three rainfall events were closely predicted by the model as shown by the close agreement between the predicted and observed depths. This was further shown by the very high correlation coefficient (r) of 0.94, 0.93, and 0.99 for July 14, 18, and August 13 rainfall events, respectively, and the non-significant t-test value. In terms of the soil loss, the predicted values are within the range of the observed values.

These indicate the validity and reliability of the developed PCARES model in predicting the actual hydrologic processes in the catchment given an erosive rainfall event; thus, it can be used to predict the actual water discharge rates in the watershed. Likewise, it can predict accurately the actual sediment concentration in a catchment given a rainfall event. Unlike other erosion models that predict erosion in an annual basis, PCARES could predict the actual erosion in a watershed per erosive rainfall event.

Prediction of Location of High Erosion Risk

The zones of erosion hot spots were found to be located in areas with steeper slopes, agricultural land with less vegetation and without soil conservation measures, roads, and footpaths (color red in Figure 5). The predicted amount of erosion in these "hot spots" was equal or greater than 0.10 kg m^{-2} ts^{-1} or 0.02 kg m^{-2} sec^{-1}, 2500 seconds after the start of the rainfall. Location of net deposition cells or areas (color green in Figure 5) occurred in places with thick crop cover, riparian buffer strips, and gentle slope. Areas in the catchment where net erosion is zero or minimal (color blue in Figure 5) are located in places with the presence of obstructions such as those that impart contact cover associated with crops, trees, weeds, litters, and mulches that reduced the amount of soil loss. Soil conservation measures such as planting of hedgerows, crop residue incorporation, and maintenance of soil OM through application of organic fertilizer and planting of trees along parcel boundaries practiced by a few farmers in the catchment contributed to significant reduction in soil loss. The capability of PCARES in predicting the "erosion hot spots" in the catchment is a significant feature of the model. If "erosion hot spots" are identified in the catchment, more stringent interventions to minimize soil erosion could then be focused on these specific areas and not necessarily in the whole catchment thus minimizing management cost. This could therefore be a useful tool for prediction and help planners, decision-makers, and stakeholders in formulating cost-effective and efficient strategies in watershed rehabilitation and management of resources within the watershed.

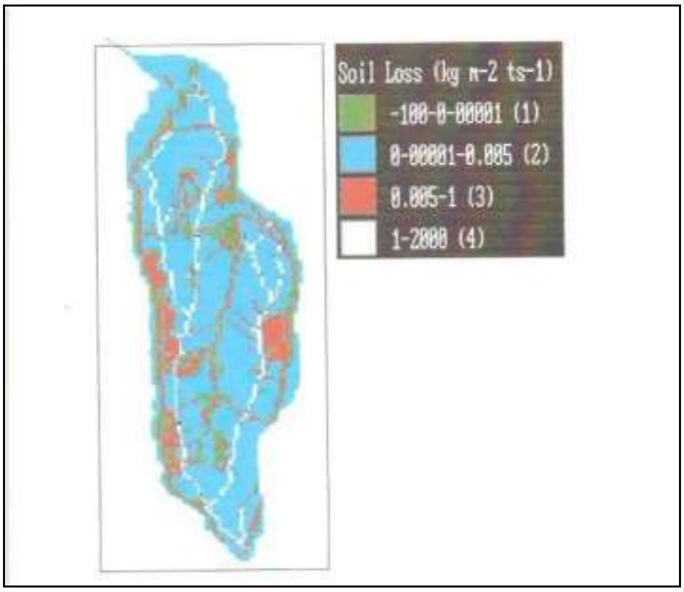

Figure 5. Predicted location of areas with high erosion risk (red color) at Mapawa microcatchment

CONCLUSION

The PCARES, a GIS-assisted soil erosion model, is a useful tool that offers a solution in characterizing the hydrological processes occurring in a complex three-dimensional system like the watershed. It can accurately predict the runoff hydrographs, sediment concentration, and the total soil erosion per erosive rainfall event at watershed level. The model could predict the zones of high risk of erosion rates, which is considered a great feature of the model. In this case, mitigation works in specific locations within the watershed not necessarily the whole catchment can be successfully targeted. Likewise, assessment of the off-site effects of soil erosion could be possibly done since the stream flow and sediment load can be identified and quantified. PCARES could likewise be used as a tool in evaluating the impact of soil erosion on environment degradation since it can accurately predict the magnitude of soil loss as affected by land use change, farming activities, and crop growth stages. Thus, the PCARES model can be of help in formulating cost-effective and efficient strategies for better if not sustainable watershed management.

The model is only applicable when the soil is at field capacity or wetter. It failed to incorporate in its infiltration model an equation that would account for the effect of antecedent soil moisture on soil infiltration. When soil type varies in the watershed, infiltration rate definitely varies with soil moisture condition that would eventually affect runoff rate and amount of soil loss. The model can be improved to include the effect of initial moisture condition of the soil prior to occurrence of erosive rainfall event.

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