EVALUATING SENSITIVE CALIBRATING PARAMETERS OF A REGIONAL SCALE SEDIMENT TRANSPORT MODEL

Habib-ur-Rehman[1] Srikantha Herath[2] and Naeem Akhtar[3]

[1]Civil Engineering Department, University of Engineering & Technology, Lahore, Pakistan
email: mughalhabib@uet.edu.pk

[2]United Nations University, Tokyo, Japan
e-mail: srikanthaherath@hotmail.com

[3]Civil Engineering Department, University of Engineering & Technology, Lahore, Pakistan
email: nmakhtar6@hotmail.com

ABSTRACT

A distributed regional scale sediment transport model can be used to assess the sediment yields due to land-use and climate change scenarios and also to predict the sediment yields for un-gauged catchments as the calibrating parameters of such models have physical meanings. Sensitivity analysis of a developed regional scale sediment transport model has been carried out to its calibrating parameters to check the robustness of the model and to investigate the response of major calibrating parameters towards sediment discharge. In the developed model the soil erosion processes are modeled as the detachment of soil by the raindrop impact over the entire grid and detachment of soil due to overland flow only within the equivalent channels, whereas sediment is routed to the forward grid considering the transport capacity of the flow and the existing sediment load. The slope averaging effect is taken care by adapting a fractal analysis approach. Effect of seven calibrating parameters were studied by running the model for three values of a single calibrating parameter i.e. for standard, by increasing 20 % and then by decreasing 20 %, while the other all parameters were kept constant. Sensitivity of the model is evaluated by computing the absolute sensitivity index for each parameter and plotting them in descending order. The results of the sensitivity analysis reveal that the density of the sediment particle is the most sensitive calibrating parameter and the next is sediment particle diameter at which 50% material is finer.

1. INTRODUCTION

A sensitivity analysis of a quantitative model is used to examine the effects of variations in model input and parameter values upon model behavior and output. The technique is especially useful to evaluate the behavior of more complex models for which the relationships between model input and output are non-linear. It can be used to explore whether a mathematical model is suitable for use in real world applications. A result of a sensitivity analysis can be that the model is extremely sensitive to highly uncertain input variable. In such cases model needs modifications (De Roo, 1993).

The objective of this study is to check the robustness of the developed model by carrying out its sensitivity analysis to its calibrating parameters, moreover, to investigate the effects of these calibrating parameters on the sediment discharge in a watershed.

The seven calibrating parameters, i.e. splash detachment coefficient, canopy height, flow detachment coefficient, sediment particle diameter at which 50% material is finer, canopy cover, sediment particle density and ground cover of the model have been studied.

2. MODEL DESCRIPTION

The detailed discussion about the developed regional scale soil erosion and sediment transport model is given below:

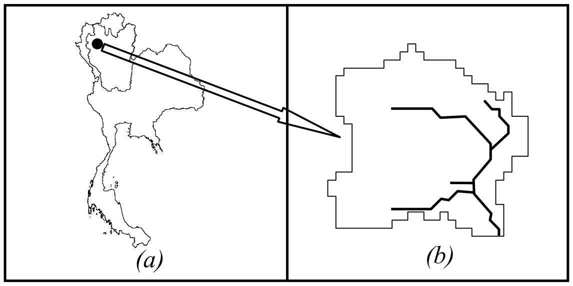

Figure 1:(a) Map of Thailand showing the Chao Praya river basin and the location of study area (b) Nam Mae Klang river basin with river network

2.1 Proposed overland flow widths

Using the concept of equivalent channels, inter-rill and rill/gullying erosion can be modelled in a more physically based manner. The splash detachment is assumed on the entire grid surface which represents the sheet or inter-rill erosion whereas flow detachment and transport is considered within the widths of equivalent channels which represents the rill and gullying erosion for each grid of the catchment. After testing the performance by numerical simulations, the equation (1) is proposed to compute the widths of equivalent channels in each grid (Habib *et al.*, 2001):

$$b_{ij} = K_W \; dx \; n_{ij}^{0.20} \; (iflacc)_{ij}^{0.40} \tag{1}$$

Where b_{ij} is the width of equivalent channel in any cell (m), K_W is a width adjusting coefficient and a value of 0.016 is found satisfactory for regional scale applications while using 1 km grid size, *dx* is the grid size (m), n_{ij} is Manning's coefficient of roughness value to represent the land use type of the each cell, $(iflacc)_{ij}$ is the flow accumulation value for the ith grid.

2.2 Soil detachment due to raindrop impact

The detachment due to the raindrop impact is estimated for each time step using Torri *et al.* (1987) equation.

$$D_R = (1 - C_g) \; k \; E_K \; e^{-zh} \tag{2}$$

where D_R is the soil detachment by raindrop impact (g/m^2/s), C_g is proportion of ground cover in each grid, k is an index of the detachability of the soil (g / J), E_K is total kinetic energy of the rain (J/m^2), z is an exponent ranging between 0.9 to 3.1 and h is the depth of surface water layer (mm).

The rainfall energy reaching the ground surface as direct throughfall $E_K(dt)$ is estimated as a function of rainfall intensity using the equation developed by Brandt (1989).

$$E_K(dt) = 8.95 + 8.44 \ \log(I) \tag{3}$$

Where $E_K(dt)$ is the kinetic energy of direct throughfall (J/m^2/mm), I is rain intensity (mm/hr). The energy of leaf drainage is estimated from the following relationship developed experimentally by Brandt (1990).

$$E_K(ld) = \left[\ 15.8 \ (PH)^{0.5}\right] - 5.87 \tag{4}$$

In which $E_K(ld)$ is the kinetic energy due to leaf drip (J/m^2/mm), *PH* is effective height of the plant canopy (m).

$$E_K = (1 - C_C)\ E_K(dt)\ H_{dt} + C_C\ E_K(ld)\ H_{ld} \tag{5}$$

where E_K is the total kinetic energy of the rainfall (J/m^2), C_C is canopy cover in the model square grid, H_{dt} is depth of direct throughfall (total rain (mm)), and H_{ld} is the depth of leaf drips (net rain (mm)).

2.3 Soil detachment due to overland flow

For modeling soil detachment due to overland flow, equations derived by the Ariathurai and Arulanandan (1978) have been used as these equations compute soil detachment on the basis of comparison between critical shear stress and hydraulic shear stress, which is a more realistic approach.

$$D_F = K_f \left(\frac{\tau}{\tau_c} - 1 \right) \qquad \text{for } \tau > \tau_c \tag{6}$$

$$D_F = 0 \qquad \text{for } \tau \le \tau_c \tag{7}$$

where D_F is overland flow detachment (Kg/m^2/s), K_f is overland flow detachability coefficient (Kg/m^2/s), τ_c is critical shear stress for initiation of motion (N/m^2), and τ is hydraulic shear stress (N/m^2).

Total potential detachment $[e(x,t)]$ at any cell (x) and time (t) is then calculated as the sum of splash and flow detachments as given in equation (8).

$$e(x,t) = D_R(x,t) + D_F(x,t) \tag{8}$$

2.4 Governing equations for 1-D Kinematic Sediment Transport Routing

For one-dimensional forward sediment transport routing, the kinematic mass balance equation (Woolhiser, 1990) has been used, which is applied between centers of two consecutive grids ((i_1,j_1) and (i_2,j_2)) considering the flow direction matrix. Total detachments are calculated as the sum of the splash detachment and the detachment due to overland flow. After considering the transport capacity of the flow, the total actually detached load ($e_I(x,t)$: erosion) is determined which is assumed that flow can carry, and this load is considered as the lateral sediment flow and is added at the inlet of the control volume.

$$\frac{\partial (A\ C)}{\partial t} + \frac{\partial (Q\ C)}{\partial x} = 0 \tag{9}$$

Where C is sediment concentration (m^3/m^3), A is cross-sectional area of flow (m^2) and Q is discharge (m^3/s).

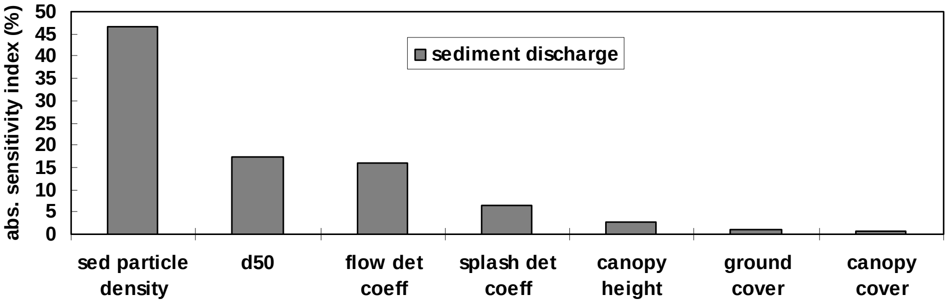

Figure 2: Results of the absolute sensitivity analysis of the sediment transport model to its calibrating parameter for sediment discharge.

3. FRACTAL APPROACH FOR SCALING DOWN THE TOPOGRAPHY

According to Zhang *et al.*, (1999), the percentage slope S is related to its corresponding scale (grid size) d by the equation.

$$S = \alpha\ d^{1-D} \tag{10}$$

Where D is the Fractal dimension. This relationship implies that if topography is Fractal, then slope will also be a function of the scale of measurement.

The relationships found by Zhang *et al*. (1999) between Fractal dimension (D), Fractal constant (α) and standard deviation of the elevation (σ) for eastern Asia and south east Spain are:

$$\alpha = 0.33733\ \sigma^{1.4004} \tag{11}$$

$$D = 1.13589 + 0.08452\ \ln \sigma \tag{12}$$

For the application of Fractal theory to smaller areas requires estimation of local Fractal parameters. To serve the purpose, the equation for the estimation of Fractal dimension was kept same (12), whereas equation for the Fractal constant (α) was revised. And the equation for fractal constant was derived as the best fitted line to the scatter diagram (using second order polynomial) as given in equation (13):

$$\alpha = K_1\ \sigma^2 - K_2\ \sigma \tag{13}$$

Where K_1 and K_2 were determined from non-linear regression analysis. The equation (10) in view of equations (12) and (13) can be used to obtain the scaled slope at grid size (d).

4. STUDY AREA

The sensitivity analysis for the soil erosion and sediment transport model was carried out on the Nam Mae Klang river basin (P.24A). This catchment was selected due to having relatively smaller size and availability of the hourly rain data to develop the rain hyetographs for the simulations. The catchment area of this river basin is 460 km^2, and the outlet is situated at Latitude 18^o-25’-01” N, Longitude 98^o-40’-29” E, on the left bank at Pracha Uthit bridge, Amphoe Chom Thong, Chiang Mai, Thailand (RID, 1998). The location of the watershed in Thailand, watershed boundaries and river network for the Nam Mae Klang river basin are shown in Figure 1.

5. MODEL SENSITIVITY ANALYSIS

5.1 Approach for sensitivity analysis

The procedure for the sensitivity analysis consists of running a set of simulations, in which for each simulation one of the model calibrating parameter is changed by a fixed amount. For the present study, three values of a calibrating parameter were used to investigate its response on the sediment discharge. The three values include the standard value, value increasing 20 % the calibrating parameter and value decreasing 20 % the calibrating parameter.

Later the sensitivity of the model output, due to ± 20 % changes in the input is evaluated. In total seven calibrating parameters were studied, i.e., splash detachment coefficient (K_r), flow detachment coefficient (K_f), sediment particle diameter at which material is 50% finer (d_{50}), density of sediment particle (ρ), canopy cover (C_c), ground cover (G_c) and canopy height (C_h). The model sensitivity is evaluated for the modeled sediment discharge. The results are evaluated as the change in percentage compared to the control run in which all variables have their standard values. The change is defined as:

$$C_{\pm 20} = \left(\frac{S_{\pm 20} - S_O}{S_O} \right) * 100 \qquad (14)$$

Where $S_{\pm 20}$ is the simulation result with the ± 20 % change in the variable, C is the change and S_O is the simulation result with standard value of the calibrating parameter. Then sensitivity index (I) was computed, which combines the results of the two simulations for each variable. The sensitivity Index is defined as:

$$I = \frac{[C_{+20}] + [C_{-20}]}{2} \qquad (15)$$

And the absolute sensitivity index (I_{abs}) can be defined as the average measure of the absolute change in the model results due to 20 % increase and decrease of the calibrating parameter.

$$I_{abs} = \frac{|\, C_{+20} \,| + |\, C_{-20} \,|}{2} \qquad (16)$$

5.2 Discussions of the Results

The results for the absolute sensitivity index are shown in Figure 2, which illustrates the sensitive parameters in sequence from the highest to the lowest for the sediment transport model. The consistency in the results of the model represents robustness of the developed model.

For sediment discharge at the out let of the system is concerned, the most sensitive parameter is sediment particle density (ρ), next is sediment particle diameter (d_{50}), next is flow detachment coefficient (K_f), then splash detachment coefficient (K_r), then canopy height (C_h), then ground cover (G_c) and least is the canopy cover (C_c). The effect of canopy cover and ground cover is not as significant as it is for sediment particle density.

6. CONCLUSIONS

The Sensitivity analysis of a regional scale sediment transport model shows that the developed model is a robust one. It is also concluded that the physical properties of the sediment particles are the most sensitive calibrating parameters affecting the model results, thus a great care is required in measuring the physical properties of the sediments in the laboratory and in the field. Moreover, great care is also required while assigning these calibrating parameters for the simulation purpose.

7. REFERENCES

Ariathurai, R. and Arulanandan, K., 1978. Erosion rates of cohesive soils. *Proc. Am. Soc. Civ. Eng., J. Hydrualic. Div*., 104: 279-283.

Brandt, C. J., 1989. The size distribution of throughfall drops under vegetation canopies, *Catena* 16, 507-524.

Brandt, C. J., 1990. Simulation of size distribution and erosivity of raindrops and throughfall drops, *Earth Surface processes and Landforms* 15, 687-698.

De Roo, A.P.J. 1993, Modelling surface runoff and soil erosion in catchments using Geographical Information Systems, *Thesis, Nederlandse Geografische Studies*, 157.

Habib-ur-Rehman M., 2001. ”Regional scale soil erosion and sediment transport Modeling”, *Ph.D. Thesis, University of Tokyo,* 183 pp.

RID., 1993-1998 *Thailand Hydrological Yearbook*, Royal Irrigation Department, *Hydrology Division Bangkok*, Water year 1998, Volume 38, 511 pp.

Torri, D., 1987, Splash detachment: runoff depth and soil cohesion, *Catena, 14*, 149-155.

Woolhiser, 1990. *KINEROS*: *A kinematic runoff and erosion model documentation and user manual*, USDA ARS ARS-77.

Zhang, X.Y.**,** Drake, N.A., Wainwright, J. and Mulligan, M., 1999. Comparison of slope estimates from low resolution DEMs: scaling issues and a fractal method for their solution, *Earth Surface Processes and Landforms, 24 (9)*, 763-779.