A PROCESS BASED APPROACH TO MODEL SOIL EROSION AND SEDIMENT TRANSPORT AT REGIONAL SCALE

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ABSTRACT

It is quite difficult to model soil erosion and sediment transport at regional scales using coarser grid size (1 km) due to slope averaging and land-use averaging effects. To cater the problem, a process-based soil erosion and sediment transport modeling strategy has been developed to estimate the soil erosion, deposition, transport and sediment yield at regional scale. The catchment's spatial variability is modeled as a regular square grid system with canopy interception, infiltration, depression storage, one-dimensional overland flow and sediment transport in the steepest descent direction. The overland flow is modeled as the equivalent channels, which may represent the cumulative width of all rills and gullies in each grid. The fraction of the ponded surface is determined on the basis of the flow accumulation value of the each grid, grid size and its land use type. 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. The model has been calibrated for Nan river basin (N.13A) and applied to the Yom river basin (Y.6) of Thailand, simulated results show good agreements with the observed sediment discharge data.

1. INTRODUCTION

The changing scale of model application can have a significant, but poorly understood, impact on the variance of model parameters and thus on their relative importance. The loss of spatial heterogeneity associated with a reduction in spatial scale provides a substantial obstacle to large scale modeling. It is important to consider ways of reproducing such small-scale heterogeneity from large-scale measurements (Zhang *et al*., 2001).

Considering that, a one-dimensional process-based soil erosion and sediment transport model has been developed to estimate the soil erosion, deposition, transport and sediment discharge at regional scale. The catchment's spatial variability is modeled as a regular square grid system with canopy interception, infiltration, depression storage, one-dimensional overland flow and sediment transport in the steepest descent direction. The overland flow is modeled in the equivalent channels, which may represent the cumulative width of all rills and gullies in each grid. The fraction of the ponded surface is determined on the basis of the flow accumulation value of the each grid, grid size and its land use type.

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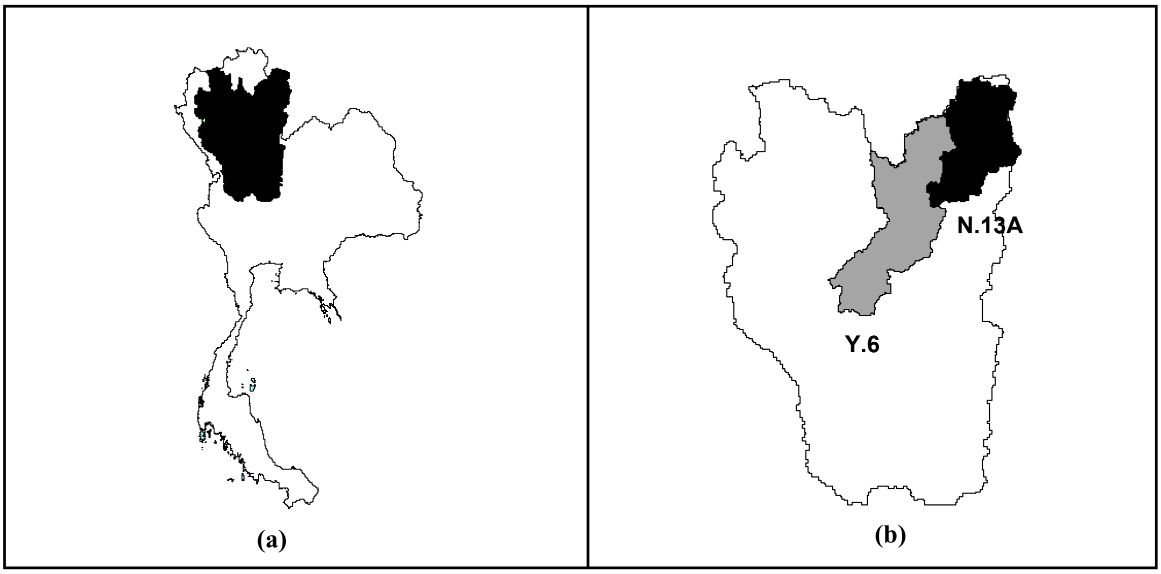
For considering the effect of slope averaging, a fractal approach, which was proposed by the Zhang. *et al.* (1999), is adapted for scaling down the slopes and scaling up the model equations for the slope.

The model has been calibrated for Nan river basin (N.13A) and applied to the Yom river basin (Y.6) of Thailand (Figure 1), simulated results show good agreements with the observed sediment discharge data.



(a) (b)

Figure 1. (a) Map of Thailand showing the Chao Phraya river basin up to C.2, (b) Sub-catchments of Chao Phraya river basin for Model calibration/validation

2. MODEL DESCRIPTION

2.1 Proposed overland flow widths

$$b(i,j) = k.n(i,j)^{0.2}(dx)\left[iflacc(i,j)\right]^{0.40} \tag{1}$$

Width of the equivalent channel for each grid is proposed as given in equation (1). Where $b(i,j)$ is the width of equivalent channel in any cell (m), $iflacc(i,j)$ is the flow accumulation value for the ith grid, $n(i,j)$ is Manning's coefficient of roughness value to represent the land use type of the each cell, *dx* is the grid size (m), k is an width adjusting coefficient and a value of 0.016 is found satisfactory for regional scale applications with using 1 km grid size.

2.2 Soil detachment due to raindrop impact

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

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

Where D_R is soil detachment by raindrop impact (g m^{-2} s^{-1}), *k* an index of the detachability of the soil (g J^{-1}), *KE* is total kinetic energy of the rain (J m^{-2}), *z* is an exponent ranging between 0.9 to 3.1, *h* is the depth of surface water layer (mm), C_g is proportion of ground cover in each grid.

The rainfall energy reaching the ground surface as direct throughfall (*KE(DT),* J m^{-2} mm^{-1}) is estimated as a function of rainfall intensity using the equation developed by Brandt (1989).

$$KE(DT) = 8.95 + [8.44.\log(I)] \tag{3}$$

Where *KE(DT)* is the kinetic energy of direct throughfall (J m^{-2} mm^{-1}), *I* is rain intensity (mm hr^{-1}). The energy of leaf drainage is estimated from the following relationship developed experimentally by Brandt (1990).

$$KE(LD) = [15.8(PH)^{0.5}] - 5.87 \tag{4}$$

Where *KE(LD)* is the kinetic energy due to leaf drip (J m^{-2} mm^{-1}), *PH* is effective height of the plant canopy (m).

$$KE = (1 - C_C).KE(DT).H_{DT} + C_C.KE(LD).H_{LD} \tag{5}$$

Where *KE* is 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 through fall (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) has been used.

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

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

Where D_F is overland flow detachment (Kg m^{-2} s^{-1}), K_f is overland flow detachability coefficient (Kg m^{-2} s^{-1}), τ_c is critical shear stress for initiation of motion, which is obtained from the Shield's curve (N m^{-2}), and τ is hydraulic shear stress (N m^{-2}).

Total potential detachment at any cell (x) and time (t) $[e(x,t)]$ 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 *et al.*, 1990) has been used, which is applied between centers of two consecutive grids ((i,j) and (i_2,j_2)) considering the flow direction matrix. Total detachments are calculated as the sum of the splash detachment and detachment due to overland flow. After considering the transport capacity of the flow, the total actually detached load (e_1(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.

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} = 0 \tag{9}$$

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^{-1}).

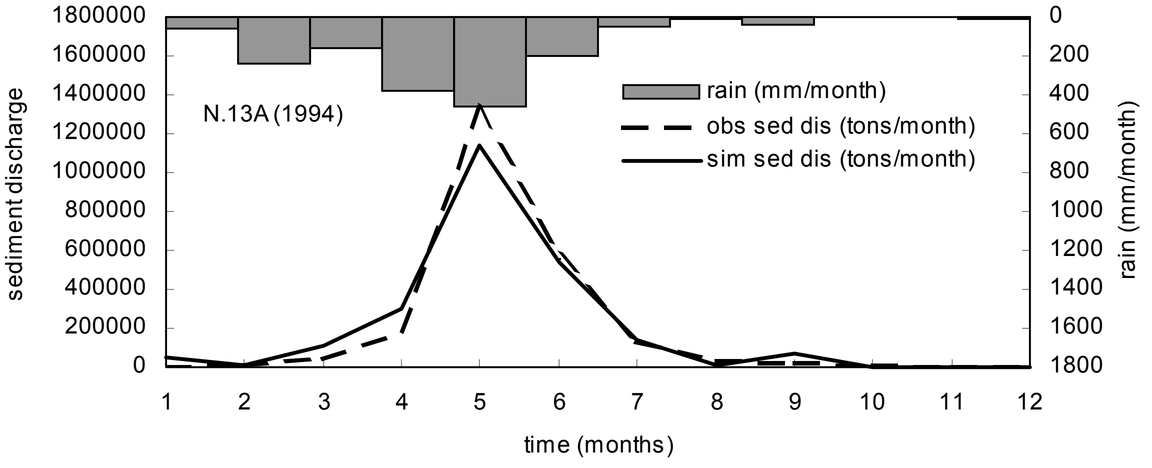


Figure 2. Simulation results of sediment discharge for Nan river basin at Ban Bun Nak (N.13A)

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

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

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, the regression equations are:

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

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

3.1 Adapting fractal approach for local topography

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):

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

Now using equation (12) and (13) in equation (10), scaled slope at any scale (grid size) can be obtained.

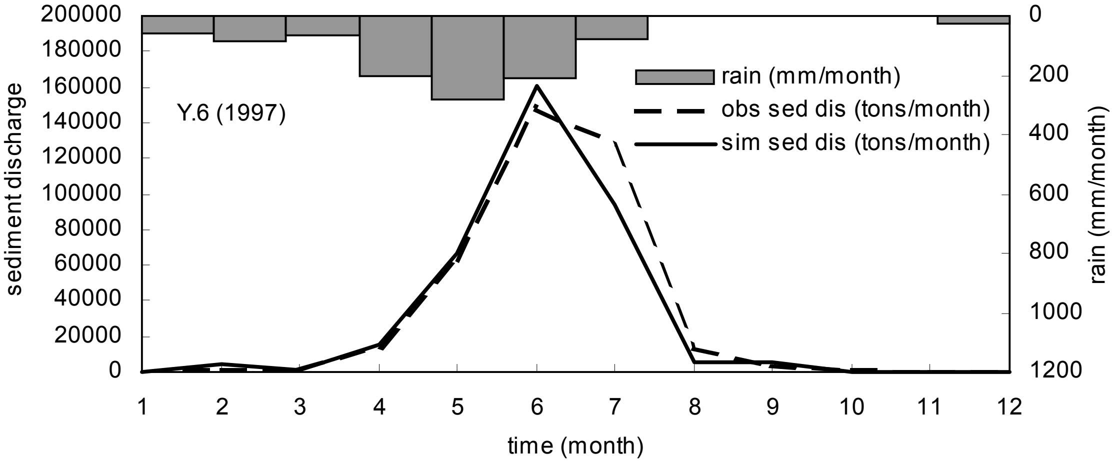


Figure 3. Simulation results of sediment discharge for Yom river basin at Ban Kaeng Luang (Y.6)

4. MODEL CALIBRATION/VALIDATIONS

The model has been calibrated for Nan river basin, the catchment area at Ban Bun Nak (N.13A), Amphoe Sa, Nan is 8551 km^2 (Figure 1). Modeling is carried out for surface flow, therefore, no attempt is made to calibrate the observed hydrographs, but major parameters were adopted from previous hydrological modeling studies (Jha, 1997, and Yang, 1998). We do not expect short term sediment yield to match because damping effect by surface sediment flow is not considered, since all sediment load is generated by major rainstorms, surface modeling should be adequate to explain integrated sediment yield observations. Therefore, parameter calibration is carried out for monthly observed sediment discharges. The monthly simulated results are shown in Figure 2.

The model has been validated for Yom river basin (1997) and the catchment area at Ban Kaeng luang is 12984 km^2. The monthly-simulated results are shown in Figure 3. Monthly-simulated results are well reproduced except for the 7th and 8th months. As in 7th month there are few rains, and contribution from the surface part only is very small. As sediment generation from the river part is not considered in the simulation so simulated sediment discharge in this month is lesser as compared to the observed sediment discharge. Same is the case for the 8th month. This reasoning is justified by simulating the daily sediment discharges by considering the ground water flow contributions in the river grids (Habib, 2001).

5. CONCLUSIONS

Developed regional scale soil erosion and sediment transport model can simulate well soil erosion and sediment discharge even at daily temporal scales, whereas sediment discharges are presented at monthly temporal scales (which is sufficient for maintaining the regional scale sediment budgets), without considering the sub-surface and ground water flow components using the same land use and soil related model parameters.

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