EMPLOYING GIS, EXPLORING THE EFFECT OF SUB-GRID LAND-USE HETEROGENEITY ON SOIL EROSION AND SEDIMENT TRANSPORT MODELLING

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ABSTRACT

Unfortunately, spatial fine resolution data is not yet available at regional and global scales and if coarse resolution data is used then the loss of spatial heterogeneity provides a substantial obstacle to large scale soil erosion and sediment transport modelling. The spatial locations of land-uses in a watershed seriously affect the transport of sediments. The results will be quite different if a highly erodible land-use patch is closer to the outlet as compared to when it is at the farthest location. To study the effect of object locations (sub-grid land-use heterogeneity) on soil erosion and especially on sediment transport, patch simulations on a single coarser square grid of 1 km^2 in size were carried out with four synthetic land-use types (forest, agriculture, road and grassland). The single coarser grid was modelled at finer grid sizes of 5 x 5 m. The patch simulations were performed on four uniform slopes for the coarser grid (10, 20, 30, 40 %), keeping 8 flow directions. The results of the model for soil erosion and sediment discharge in the eight directions were compared by computing the coefficient of variation for each slope. Results show that the behavior of a single grid for soil erosion and sediment discharge is highly sensitive to the land-use pattern. To study the behavior of cluster of grids, the clusters of four and sixteen similar grids of 1km size were simulated. Results reveal that the accuracy of model predictions for clusters (for larger areas) is higher than for individual cells.

1. INTRODUCTION

Soil erosion is a highly dynamic process affected by various hydrological, geological, morphological, topographical aspects. Apart from other factors, the spatial locations of land-uses in a watershed is one of the major matters affecting the transport of sediments. The results will be different if a highly erodible land-use patch is closer to the outlet as compared to when it is located farther from outlet. This study is carried out to quantify the variations due to loss of heterogeneity of land-use data.

2. MODEL DESCRIPTION

In the developed regional scale soil erosion and sediment transport model, 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 (Habib, 2001).

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, 2001):

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

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 i^{th} 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.

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

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) J / mm^2 / mm) is estimated using the equation developed by Brandt (1989).

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

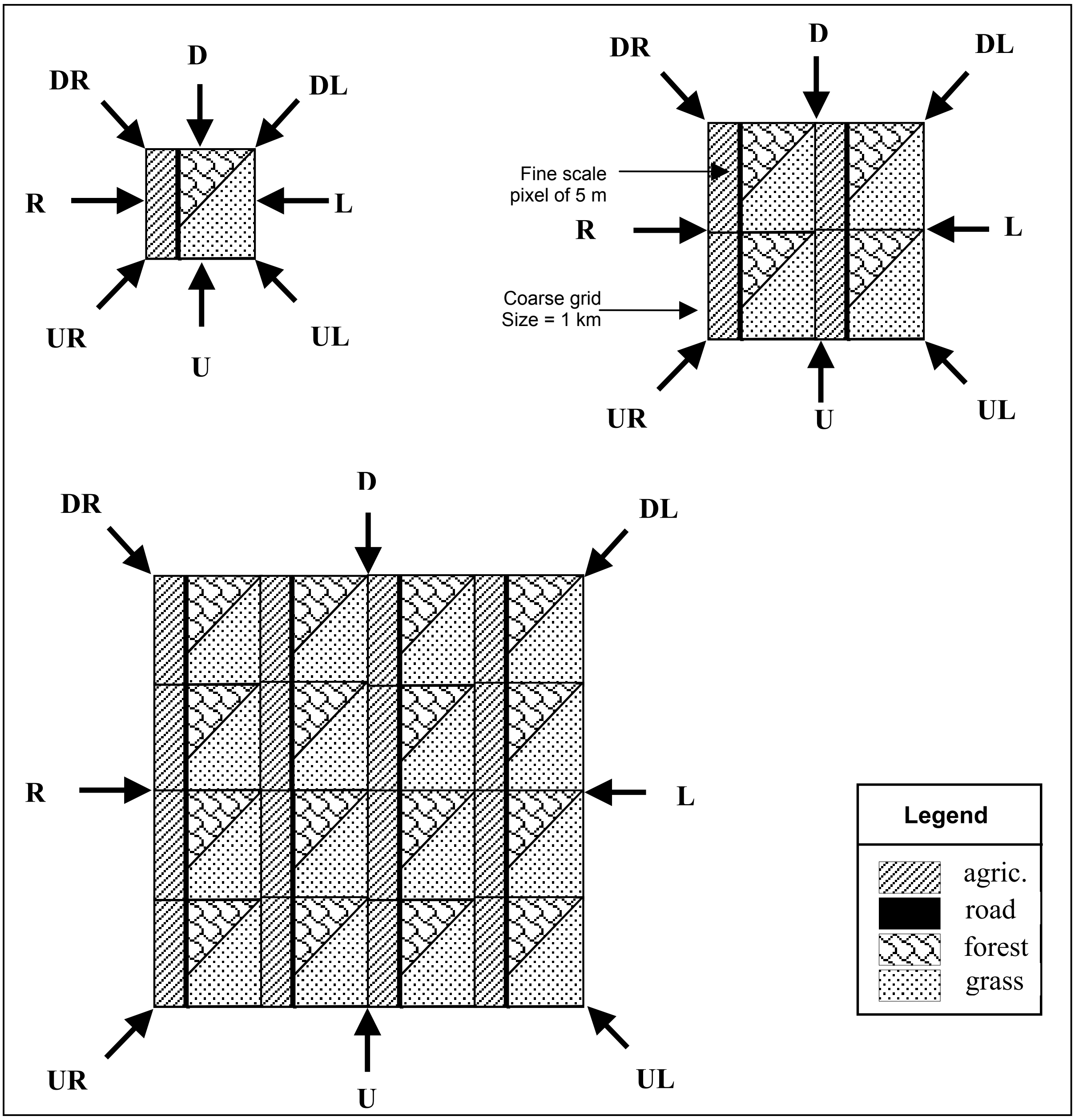

Figure 1: Land-use heterogeneity on single grid and cluster of grids

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).

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

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 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 modelling soil detachment due to overland flow, equations derived by the Ariathurai (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. 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.

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

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).

3. METHODOLOGY

To study the effect of sub-grid land-use heterogeneity on soil erosion and on sediment transport, patch simulations on a single coarser square grid of 1 km^2 in size were carried out. The simulations were carried out using two synthetic 24-hr normally distributed rainstorms with maximum rain intensities of 42 mm/hr & 75 mm/hr, which were developed for the northern Thailand for 5 and 25 years return periods, respectively. Heterogeneity of land-use is simulated using four land-use types i.e. forest, agriculture, road and grassland (Figure 1). To model soil erosion from fine scale linear features, like roads, the single coarser grid (1km) was also modelled at finer grid sizes of 5 m. The patch simulations were performed on four uniform slopes for the coarser grid (10, 20, 30 & 40 %), keeping 8 flow directions (D, DL, L, UL, U, UR, R, DR), altogether (4 slopes x 8 flow directions x 2 rain intensities), 64 simulations were carried out, and sediment discharge was summed in the 200 cells having maximum flow accumulation values on the opposite edge of the grid. Whereas sediment discharge was summed in 399 cells, when water and sediments were allowed to flow in diagonal directions. The basic idea of keeping one-dimensional surface is to avoid any effect due to slope averaging at different grid resolutions. Though in reality, slopes of the landscape affects the land-use type.

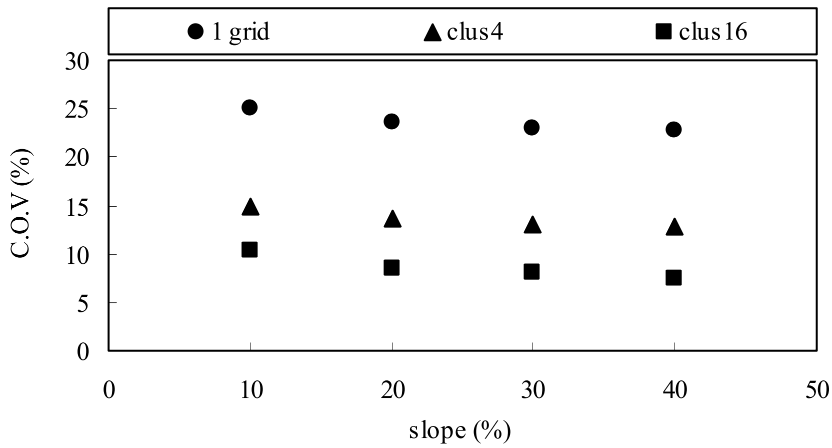

Figure 2: Behavior of single grid and cluster of grids for modelling soil erosion

After performing patch simulations, the results of the model for soil erosion and sediment discharge in the eight directions were compared by calculating the standard deviation and coefficient of variation (C.O.V) for each slope.

4. RESULTS

Results of the study are presented in Figures 2 & 3 for soil erosion and sediment discharge, respectively. Results show that the coefficient of variation for soil erosion in case of a single grid is 22-25 % for all slope values (Figure 2), whereas it reduces to 7-10 % for cluster of sixteen grids. The coefficient of variation for sediment discharge in case of a single grid is about 50 % (Figure 3) and it diminishes to 10-13 % for cluster of sixteen similar 1 km grids. It means that the behavior of a single grid for soil erosion and sediment discharge is sensitive to the land-use pattern with in the single coarser grid. So the modelling of soil erosion and sediment transport is questionable at larger grid sizes in which land-use pattern is averaged to a single group.

As for as the simulation of clusters of four and sixteen similar grids of 1km are concerned, the C.O.V. for cluster of sixteen grids are reduced to 7-10% and 10-13% for soil erosion and sediment discharge, respectively.

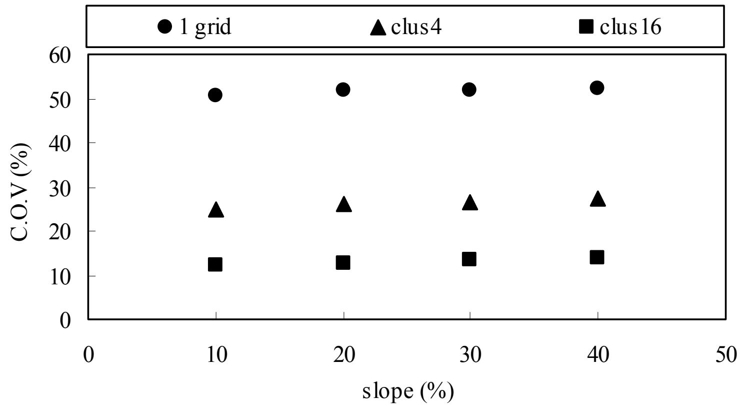

Figure 3: Behavior of single grid and cluster of grids for modelling sediment discharge

5. CONCLUSIONS

The results reveal that the behaviour of cluster of grids is less sensitive to the sub-grid land-use heterogeneity as compared to a single grid. Accuracy of model predictions for clusters (for larger areas) is higher than for individual cells. For regional scale soil erosion and sediment transport modelling, it is more logical to see the behaviour of cluster of grids as compared to the individual cells. It is also noted that the above conclusions are drawn on the basis of extreme case of heterogeneity of land-uses, which was considered at the time of modelling. In general, the values for coefficient of variation on the basis of eight directions for sediment yield are higher as compared to the coefficient of variations for soil erosion, which indicate that positions of land-uses in a watershed is a major factor effecting the sediment discharge.

6. REFERENCES

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