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UNCERTAINTY IN MODELLING THE SOURCES AND SINKS OF SUSPENDED SEDIMENT IN THE MAE CHAEM CATCHMENT, THAILAND

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ABSTRACT

A sediment source, transport, and deposition model known as SedNet has been applied to the Mae Chaem Catchment in Thailand in order to define the dominant sources and sinks of suspended sediment in that catchment, and to examine uncertainty in model inputs and results. Model inputs include a digital elevation model, stream gauge data and landuse, as well as information about stream width, stream bank height and riparian vegetation. The resultant model has produced a significant range of results where a range of cover factors, as well as spatially variable and constant hillslope delivery ratios, (HSDR) have been tested. The results have provided valuable insight into the uncertainty present in model predictions. Results indicate that there is significant uncertainty in model input parameters, particularly in the selection of appropriate ground cover factors.

1 INTRODUCTION

The Mae Chaem catchment is approximately 3900 km² in area, and is located in the North-Western region of Thailand forming part of the Ping drainage basin. Figure 1 shows the location of the Mae Chaem catchment within Thailand. The catchment is representative of large areas of Southeast Asia, where intense competition for land and water use requires management options which maintain socio-economic opportunities yet minimise environmental problems such as erosion, low dry season flows, and water pollution (Merritt 2002). The population in the catchment in 1994 was approximately 92,000 comprising 49,000 Thai locals and 43,000 hill tribe people, originating from Laos and Myanmar (Burma). The Mae Chaem catchment is a relatively steep catchment ranging from 250 to 2570 metres elevation, with small narrow floodplains. Rainfall is highly variable from year to year with 95% of yearly rainfall occurring in the wet season.

Population pressure on the landscape from expanding agriculture is a critical factor, with hillslope erosion due to forest clearance a dominant issue for the region. The major crops grown in the region are rice, maize, vegetables, and tree crops. Due to a combination of landscape classification and forest zoning policies, there is little remaining land available for development (Merritt, 2002). A number of other studies have also focused on catchment resources and hydrologic response to landuse change in the Mae Chaem catchment, including Merritt et al 2004, Croke et al. 2004, and Perez et al 2002.

This paper presents SedNet modelling results for a range of landuse scenarios within the Mae Chaem catchment. A key focus, however, is in testing uncertainty, where the results from different combinations of cover factors and hillslope delivery ratios were compared. These results can be used to identify where the model may be optimised in terms of the relative importance of the various data inputs, and their spatial accuracy within the landscape. It can also help to assess the relative uncertainty that may exist in the range of input parameters, particularly for land cover values, and constant versus spatially variable hillslope delivery ratios.

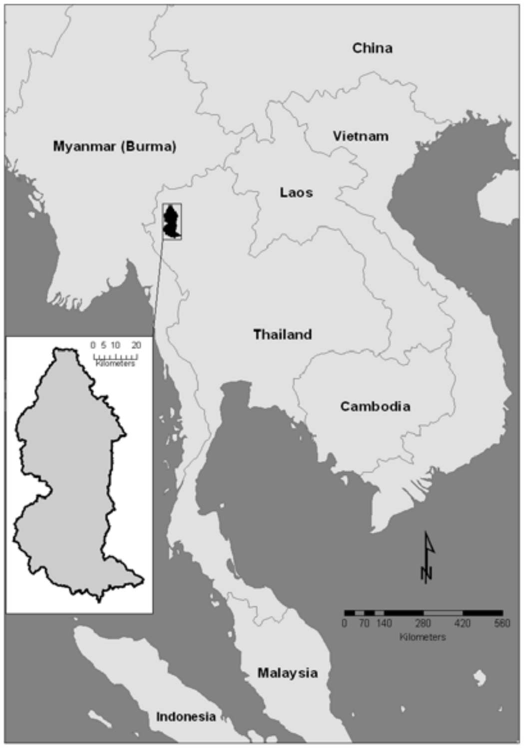

Figure 1: Locality map.

2 MODELLING

The acronym SedNet stands for the <u>Sed</u>iment River <u>Net</u>work Model. SedNet is a software package originally developed by CSIRO for use in the Australian National Land and Water Resources Audit for use in assessing water quality in the major catchments throughout Australia. (Prosser *et al*., 2001). It is now being applied at regional scales such as river catchments, using more detailed inputs.

SedNet models estimate river sediment loads by constructing material budgets that account for the main sources and stores of sediment. SedNet models use a simple conceptualisation of transport and deposition processes in streams. Sediment sources, stream loads, and areas of deposition within the system can be produced. The contribution from each watershed to the river mouth can be traced back through the system, allowing downstream impacts to be put into a regional perspective (Kinsey-Henderson *et al*., 2003).

Information on SedNet model development and/or regionalisations and approximations used in the Audit are detailed in a series of CSIRO Land and Water technical papers and other related publications – Hughes, *et. al* (2001), Gallant (2001), Lu *et. al* (2001), Prosser *et. al* (2001), and Young *et. al* (2001). Application of SedNet to regional scale catchments can be found in DeRose *et. al* (2002) and Prosser *et. al* (2002).

3 DATA PREPARATION

The base data for Mae Chaem, such as the DEM, landuse, streamflow, and rainfall grids, were supplied by Pornwilai Saipothong of the World Agroforestry Centre at Chang Mai University, and Barry Croke of the Integrated Catchment Assessment and Management Centre (iCAM), at the Australian National University in Canberra. These data sets were used to develop the various input grids required to run the SedNet model.

3.1 Stream links and Watershed

The basic unit of a SedNet Model is a stream link. As for other SedNet studies, the stream links were generated automatically from the DEM (Digital Elevation Model). Topology was created for each stream link to identify its upstream and downstream relationship to other stream links and its overall position within the system (stream order). For each stream link a unique watershed was identified by a polygon area. The watersheds, as well as providing measurement of upstream catchment area for hydrological parameterisation, defined the areas within which spatially distributed erosion data needed to be summarised for each stream link (Kinsey-Henderson *et. al*. 2003). The diagram in Figure 2 illustrates the suspended sediment budget of a river link within SedNet

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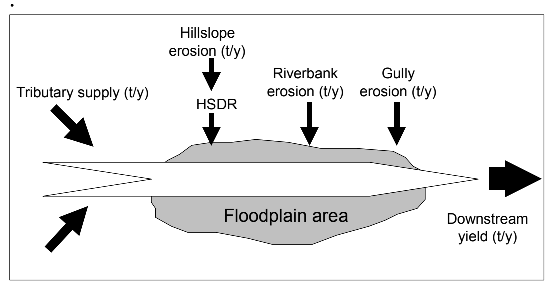

Figure 2: Conceptual diagram of the SedNet river sediment budget for one river link (Brodie *et. al* 2003).

3.2 Hydrological Setting

To run SedNet, hydrological parameters for prediction of sediment transport and deposition within the river system need to be estimated and attached to each stream link. In the Audit and the regional studies, channel width, mean annual flow and bankfull discharge are generally only known in a few places, so regionalized values were created.

As with all other SedNet studies, connectivity, channel gradients, and stream order information were derived during stream link creation within the toolkit. There are no significant reservoirs or lakes in the Mae Chaem catchment, although some significant floodplain areas were identified. These are the areas SedNet models as depositional, where coarse sediment will be deposited along the stream network and associated floodplains.

3.3 Gully and Stream Bank Erosion

3.3.1 Gully Mapping

The presence of gullies in the Mae Chaem catchment is not recorded, although anecdotal evidence suggests that there are very few gullies present. Gully density was therefore set to zero over the whole catchment.

3.3.2 Riparian Vegetation Mapping

A riparian vegetation grid was created for Mae Chaem based on the stream network and the existing forest landuse class. The flow accumulation grid was re-sampled with a threshold set so that only streams >200metres in length would be included. The grid was then converted to lines and buffered to 15m on either side. The buffered streams were then intersected with existing forest cover to create a riparian network. This was then converted back to a grid with 30 metre cells.

3.4 Hillslope erosion

Hillslope erosion was estimated using the Universal Soil Loss Equation (USLE) where:

$$\text{Soil Loss (t/ha/yr)} = R \times K \times L \times S \times C \times P$$

R = rainfall erosivity factor
K = soil erodibility factor
$L\ S$ = hill length/slope factor
C = vegetation cover factor
P = Land Use Practice Factor (not used)

All factors were represented as spatially variable grids (30m cells), allowing for derivation of a spatially distributed hillslope erosion grid. An additional term, the hillslope delivery ratio (HSDR) is also used to account for resettling of hillslope sediment before it reaches a stream. Therefore:

$$\text{Total sediment delivered to stream} = RKLSC * HSDR$$

SedNet models typically apply HSDR as a constant value across the entire catchment. A key component of this analysis was to compare the results of a spatially variable HSDR (See section 3.4.6) with a constant. In order to apply a spatially variable HSDR, it had to be multiplied (as above) with the RKLSC grid (hillslope erosion) before being input into the model.

3.4.1 Rainfall Erosivity Factor (R)

Rainfall erosivity is a measure of the intensity of rainfall events and so is determined by climatic data. For Mae Chaem we used an annual average value based on the existing monthly rainfall grids. The grid cells used in the available rainfall data were 1 km as opposed to the 30 m grids for DEM, etc. The average annual rainfall grid had the following equation applied to create a rainfall erosivity grid:

$$R = 38.5 + 0.35\ (P)$$

P represents mean annual precipitation (Merritt, 2002).

3.4.2 Erodibility Factor (K)

Erodibility is a measure of the susceptibility of the soil to erosion. It is based on the nature (structure, texture etc) of the topsoil. A K factor grid was supplied by Chiang Mai University, and was based on existing soils data.

3.4.3 Hill slope/length Factor (LS)

The hillslope factor accounts for the fact that soil erosion increases with increasing slope. A grid of slope in degrees was created from the existing DEM. Length of slope was not incorporated due to lack of available data, and so slope length was left as a constant value (=1).

3.4.4 Cover Factor (C)

The landuse grids supplied by Chiang Mai were based on vegetation cover classified from Landsat Thematic Mapper (TM) imagery. The landuse types were then assigned "typical" cover factors (where higher values mean more erosion) for each cover class to create a grid of C values. The values used were taken from an existing table of 'Crop Management Factors' for Thailand (Merritt, 2002). The C-factor represents a comparison of soil loss with that expected from freshly tilled soil (C=1).

Assumptions were made in assigning high and low C-Factor values, for the different scenarios, as the cover classes were very broad compared to those available in the 'Crop Management Table' of values. For example, when assigning high values, such as for upland fallow field, it was assumed that the fields were bare, and therefore given the highest value i.e. worst case scenario. Table 1 lists the C-Factors used for the different model runs.

Cover Class	Low	Current	High
Forest	0.010	0.020	0.088
Paddy	0.050	0.280	0.400
Urban	0.000	0.000	0.300
Upland Field	0.250	0.340	0.790
Water	0.000	0.000	0.000
Upland Fallow	0.020	0.340	0.800

Table 1: Summary of vegetation cover categories and C factors for Mae Chaem.

3.4.5 Land Use Practice Factor (P)

This accounts for the effects of contours, strip cropping or terracing (Kinsey-Henderson et al, 2003). As these are not available for the Mae Chaem catchment, this factor was not used (i.e. set to 1).

3.4.6 Hillslope Delivery Ratio (HSDR)

The HSDR is traditionally set as a constant value in the SedNet model. It was decided to also develop a spatially variable HSDR to test for the variation of hillslope delivery of sediment, which exists, due to the fact that the hillslopes further from the stream are less likely to contribute sediment to stream than hillslopes closer to the stream. The sediment supply will therefore vary in terms of the quantity that will actually run into the stream network and that which is trapped by vegetation, etc., before reaching the streams.

Factors such as soil type and vegetation cover can also affect the HSDR (Kinsey-Henderson et al. 2003). However, vegetation cover was broadly classified for Mae Chaem with the majority categorised simply as ‘forest’. We therefore ignored these effects and instead based HSDR on the purely spatial observation that hillslope erosion occurring close to streams or gullies is more likely to contribute to stream sediment concentrations. We then modelled three spatially variable HSDR grids (5%, 10%, and 15%) to observe the impact of varying this parameter on model results. The equations used to define this spatially variable HSDR were:

$$HSDR = 0.05 \times e^{(-0.0011 \times \langle \text{Distance to stream} \rangle)}$$

$$HSDR = 0.10 \times e^{(-0.0006 \times \langle \text{Distance to stream} \rangle)}$$

$$HSDR = 0.15 \times e^{(-0.0002 \times \langle \text{Distance to stream} \rangle)}$$

These relationships provide agreement with the following observations:

- HSDR has an inverse exponential relationship to distance from the stream;
- HSDR has reduced to 5%, 10%, or 15% by around 100m from the stream;
- HSDR is negligible (1% or less) after about 300m from the stream;
- The average HSDR for the catchment is 5, 10 or 15% (3 different HSDR scenarios used).

Figure 3 shows the 15% HSDR grid, illustrating the decrease in sediment supply based on distance from stream.

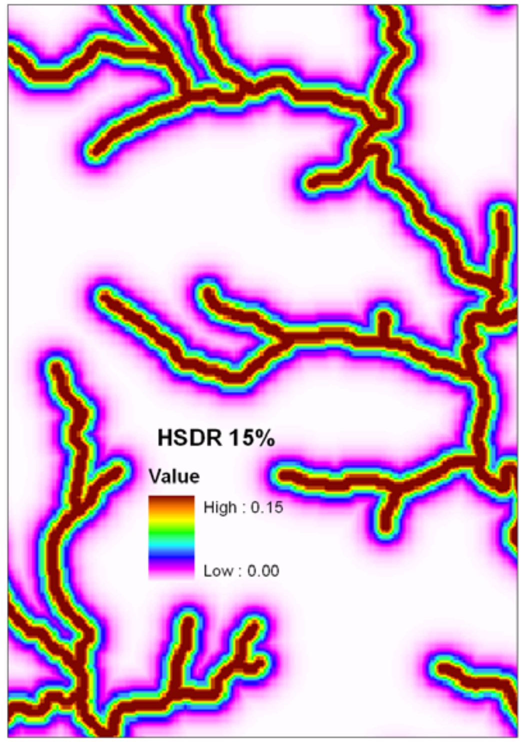

Figure3: Spatially variable HSDR grid (15%).

3.4.7 Scenarios Tested

A range of scenarios were run in order to test uncertainty in the model results. The only parameters that were varied were the C-factor and HSDR (see Tables 1 and 2.). Current (best-guess) C-factors were modelled, as well as high and low values, with both spatially variable and constant HSDR ranging from 5-15%.

4 RESULTS

Once all of the input parameters were attached to the stream links of the model, SedNet created a sediment budget for each stream link, as well as an overall catchment budget. The erosion rates and outputs from upstream links provide the model with the volume of sediment input into each stream link, and the hydrological parameters provide the model with the volume of sediment transported through (and deposited within) each stream link. A GIS layer for sub-catchments and streams could then be exported for mapping and visualisation.

4.1 Sources of Sediment

The main source of sediment supply from the Mae Chaem catchment is from hillslope erosion, with the dominant areas located in the North, South-Western and Western hillslopes. Figures 4 and 5 show the relative contributions of sediment made by each stream link watershed for the lowest yielding scenario (low cover with 10% spatially variable hillslope delivery), and the highest yielding scenario (high cover with 10% constant hillslope delivery) respectively. Note the different legends on Figures 4 and 5, required to show the similar patterns, but different magnitudes, of sediment delivery between the scenarios.

It can be seen by a comparison of Figures 4 and 5 that the relative contributions of each sub-catchment area do not vary significantly between different scenarios. However, the magnitude of erosion between different scenarios does show significant variation. The higher erosion rates can be mainly attributed to changes in the C-factor. However, the supply of sediment from hillslopes was significantly less where the spatially variable HSDR was employed.

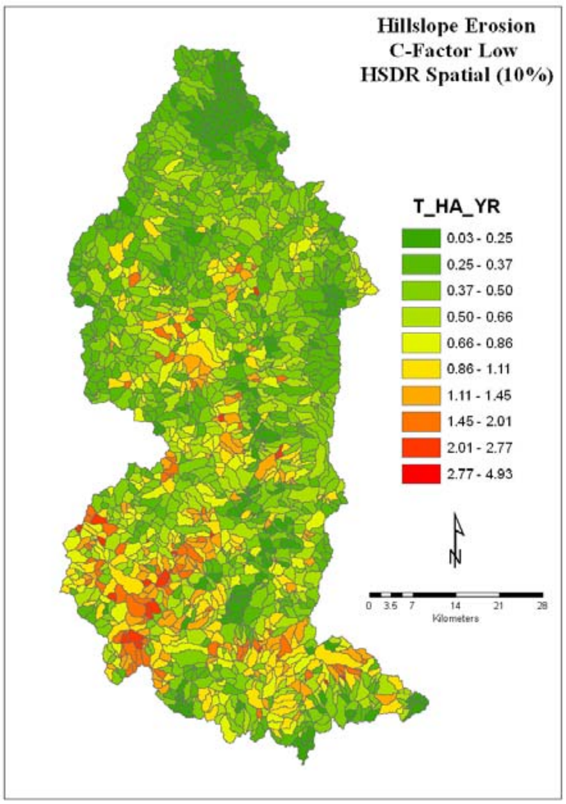

Figure 4: Hillslope erosion rates per watershed for the lowest yielding scenario.

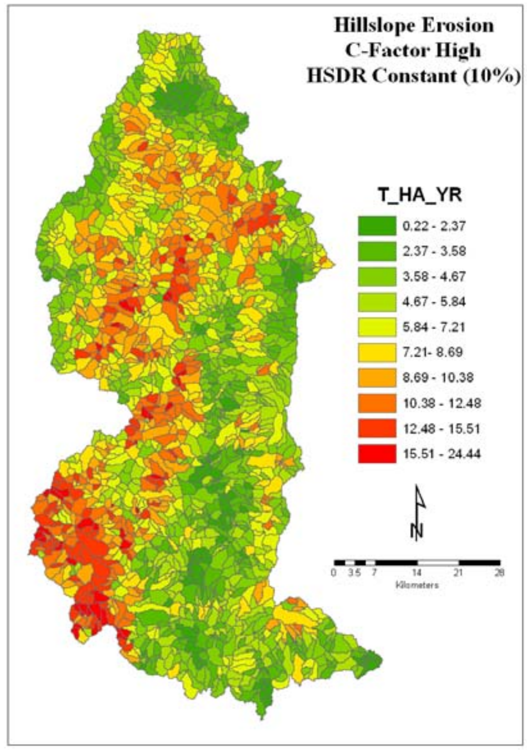

Figure 5: Hillslope erosion per watershed for the highest yielding scenario.

4.2 Fate of Sediment

SedNet has two sediment transport routines - one for fine sediment and one for coarse. Coarse sediment is more likely to be deposited as it is heavier and more easily separated from fine sediment in solution. There appears to be a linear correlation between hillslope supply and floodplain deposition (Figure 6). As a result of this relationship, we will not examine the impact of the different scenarios on transport or total export of suspended sediment as the inputs of suspended sediment from hillslope erosion tells an identical story.

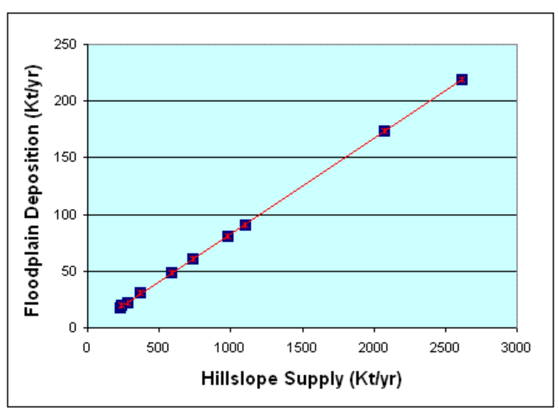

Figure 6: Hillslope supply versus floodplain deposition.

5 UNCERTAINTY

There are two main potential sources of uncertainty in the model results which need to be considered. These are firstly the data inputs, and secondly the way in which the SedNet model handles the computation of data. In this paper, only the first source of uncertainty has been considered. Factors such as the accuracy of transport algorithms, assumptions made regarding coarse sediment deposition, floodplain deposition, the over-bank volume, and the accuracy of transport algorithms, have not been tested here, but were examined by Newham et al (2003).

The various combinations of cover and hillslope delivery ratios provided a broad range of results. Table 2 summarises the combinations of C-Factors and HSDR (constant and spatially variable) tested, and the resulting sediment delivery.

	5% HSDR	**10% HSDR**	**15% HSDR**
Low C-factor	-	282 (225)	-
Medium C-factor	368 (289)	737 (586)	1105 (980)
High C-factor	-	2617 (2074)	-

Table2: Hillslope delivery of fine sediment under a range of cover and hillslope delivery ratios (numbers in brackets use the spatially variable HSDR) in tonnes/year.

It can be seen from Table 2 that variations in the C-factor are the dominant source of uncertainty in the model results. At our lowest estimate of C, there was a total of 282 tonnes/year of hillslope erosion within the Mae Chaem catchment. However, at the highest estimate of C, this increased to a massive 2617 tonnes/year. This is more than an order of magnitude increase and therefore represents a significant source of uncertainty in the model results. It should be remembered that one of the main reasons for this large range is that the cover types provided for use in the study were very broad, categorizing, for example, all upland fields in one category. As the type of crop grown in these upland fields has a massive impact on the cover factors, this uncertainty could be reduced significantly through a more detailed representation of the landuse.

Moving across the middle row in Table 2 allows us to examine the impact of varying the HSDR on model results. At a 5% HSDR, there was a total of 368 tonnes/year of hillslope erosion, while at a 15% HSDR, this increased to 1105 tonnes/year. While this is not as large as the variation seen due to changes in the C-factor, it is still a significant source of uncertainty. The exact value of HSDR which should be used in this study is not clear. From many studies around the world, we can be reasonably sure that somewhere between 5 and 15% of sediment eroded from a hillslope is delivered to stream. This will obviously vary depending on climate, soils and slope, as well as on the scale that the model is applied. To narrow down this figure would require a detailed study in the Mae Chaem catchment to determine hillslope delivery under a range of landuses.

The final factor examined was the impact of moving from a constant to a spatially variable HSDR. A spatially variable HSDR had the effect of reducing total hillslope erosion by approximately 20%. There could be a number of reasons for this, including that the hillslopes closer to streamlines have higher cover than those further from streamlines (remember that the average HSDR across the whole catchment is identical for both the constant and spatially variable HSDR scenarios). When applied at a spatial scale which means that some areas in each sub-catchment are at a significant distance from a streamline, a spatially-variable HSDR appears to be more appropriate than a constant HSDR. However, the way in which this HSDR is defined is still a subject of considerable study. Further work in this area is ongoing.

Another consideration is in the dependence of data scales for producing accurate results. At present some data sources were very coarse, thus inhibiting the models ability to accurately differentiate spatial variation. In addition, the derivation of C-factors from Landsat imagery appeared to be spatially inaccurate when compared to the source imagery. Thus the spatial accuracy of input grids will be another potential source of uncertainty, where all the inputs are not spatially coincident. While we have ensured that all inputs grids used in this study were matched to the spatial extent and grids cells of the DEM, the source of the data may be inherently inaccurate and thus will reduce the accurate representation of the landscape values.

There appears to be significant uncertainty in the magnitude of hillslope erosion, but far less spatial uncertainty with regards to the source areas of this erosion. As there are a variety of topographic factors that combine to characterise the outputs, and the fact that the DEM is one of the major controlling factors for defining spatial patterns, we would not expect to see significant changes in the spatial distribution of source areas between scenarios.

6 CONCLUSION

It appears that a significant level of uncertainly currently exists in model outputs. The SedNet model appears quite capable of identifying general source areas. However, it appears that the magnitude of these sources is more prone to variation and therefore uncertainty where some variables, such as HSDR, are generalised.

Further work will focus on smaller catchment areas with finer scale and more detailed data inputs, in order to better understand scale dependency on model outputs, and also to identify more discrete quantitative variation of results. It should be noted that the potential uncertainty appears to be based on the data inputs rather than the models capacity to spatially define and quantify watersheds. The limits of the model itself may not be realised until there are more studies focused on using high resolution data, which can be verified with field measurements.

7 ACKNOWLEDGMENTS

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