Predictions in Ungauged Basins: Promise and Progress (Proceedings of symposium S7 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 303, 2006.

Evaluating uncertainty in modelled sediment delivery in data-sparse environments: application to the Mae Chaem Catchment, Thailand

DAVID A. POST & MICHAEL G. HARTCHER

CSIRO Land and Water, Davies Laboratory, PMB PO Aitkenvale, Townsville, Australia
david.post@csiro.au

Abstract A sediment source, transport, and deposition model known as SedNet was applied to the Mae Chaem Catchment in Thailand in order to determine the dominant sources and sinks of suspended sediment in that catchment, and to examine the uncertainty in model predictions. The SedNet model produced a significant range of results where a range of cover factors, as well as spatially variable and constant hillslope delivery ratios were tested. The results indicate that the main source of uncertainty is due to the uncertainty in model input parameters, particularly in the selection of appropriate ground cover factors. This uncertainty can be reduced through better representation of ground cover using a combination of ground truthing and remote sensing. Conversely, reductions in uncertainty in the value of the hillslope delivery ratio can only be achieved through extensive fieldwork.

Key words sediment erosion and deposition; SedNet model; Thailand; uncertainty analysis

INTRODUCTION

The Mae Chaem catchment is approximately 3900 km^2 in area, and is located in the northwestern 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 minimize 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 m elevation, with small, narrow flood plains. Rainfall is highly variable from year to year with 95% of annual rainfall occurring in the wet season from May to October.

Population pressure on the landscape from expanding agriculture is a critical factor, with hillslope erosion due to forest clearance a major problem in 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 focused on catchment resources and hydrological response to land-use 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 land-use scenarios within the Mae Chaem catchment. A key focus, however, is testing uncertainty, where

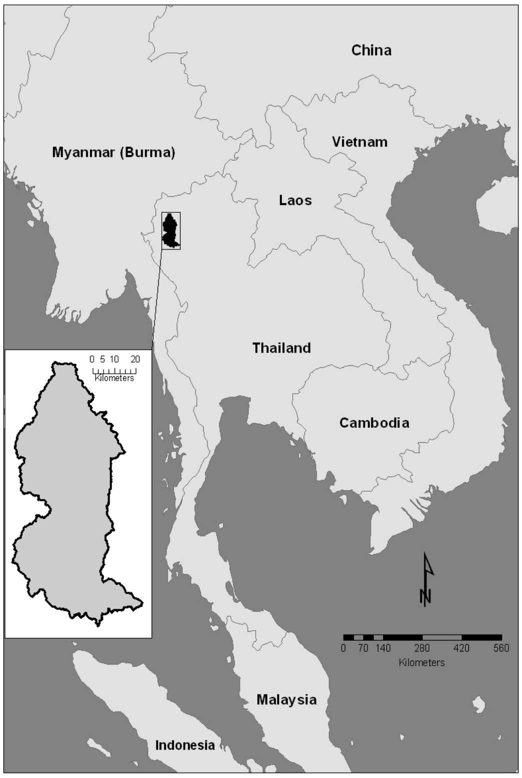

Fig. 1 Location of the Mae Chaem catchment.

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 optimized 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 *vs* spatially variable hillslope delivery ratios.

The data available for determining sediment sources, transport and deposition in this catchment are fairly limited. The data consists primarily of daily rainfall at 15 raingauges, daily streamflow at four stream gauges, a 30 m digital elevation model, very coarse soil erodibility (250 000 scale), and land cover maps at 30 m resolution. The land cover maps however only divide the land-use into very broad classifications (see Table 1).

Table 1 Summary of vegetation cover categories and associated C factors.

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 Field	0.020	0.200	0.800

MODELLING

The acronym SedNet stands for the Sediment River Network 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 (Gallant, 2001; Lu *et al.*, 2001; Prosser *et al.*, 2001; Young *et al.*, 2001). It is now being applied at regional scales such as river catchments, using more detailed inputs (DeRose *et al.*, 2002; Prosser *et al.*, 2002; Kinsey-Henderson *et al.*, 2005).

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 conceptualization of transport and deposition processes in streams. The structure of a SedNet model is shown in Fig. 2. Using a contributor model which accounts for both the areas of erosion and deposition in the stream network, 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.

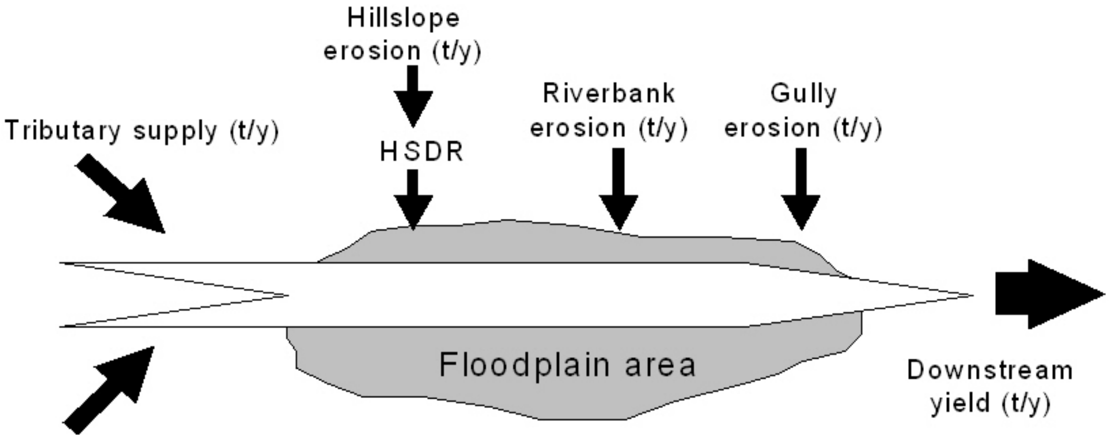

Fig. 2 The SedNet model.

Gully erosion

The presence of gullies in the Mae Chaem catchment is not recorded, although anecdotal evidence suggests that there are very few gullies present. In the absence of more quantitative data, gully density was set to zero over the whole catchment.

Hillslope erosion

Hillslope erosion was estimated using the Revised Universal Soil Loss Equation, RUSLE (Renard *et al.*, 1997) where: Hillslope erosion (t ha^{-1} $year^{-1}$) = $R \times K \times LS \times C \times P$; R = rainfall erosivity factor; K = soil erodibility factor; $L\ S$ = hill length/slope factor; C = vegetation cover factor; and P = land use practice factor.

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 equation: $R = 38.5 + 0.35P$, where P represents mean annual precipitation (Merritt, 2002).

Soil 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 the World Agroforestry Centre and Chiang Mai University based on existing soils data.

Hill length/slope factor (*LS*) In the Mae Chaem catchment, the relationship between soil loss and position on the hillslope is unknown. As a result, slope length was set to one everywhere in the catchment. The hillslope factor (S) accounts for the fact that soil erosion increases with increasing slope. This factor was derived from the digital elevation model (DEM).

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

Land-use practice factor (*P*) There is no evidence for land-use practices to reduce soil erosion in the Mae Chaem catchment and thus P was set to one everywhere in the catchment.

Hillslope Delivery Ratio (HSDR)

Not all of the sediment that is eroded from a hillslope makes its way into a stream. The total sediment delivered to a stream depends on both the hillslope erosion and on the Hillslope Delivery Ratio (HSDR), such that:

Total sediment delivered to stream = Hillslope erosion × HSDR

HSDR is a number between 0 and 100% where 0 means that none of the sediment eroded from a hillslope is delivered to a stream, and 100% means that all of the sediment eroded from a hillslope is delivered to a stream. In practice, HSDR is typically between 0 and 20%.

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 with a constant HSDR. Factors such as soil type and vegetation cover can affect the spatial pattern of HSDR (Kinsey-Henderson *et al.*, 2005). However, vegetation cover was broadly classified for Mae Chaem with the majority categorized simply as "forest", while soils were largely undifferentiated. We therefore based HSDR on the empirical observation that hillslope erosion occurring close to streams is more likely to find its way into a stream than sediment eroded at a distance from streams. HSDR at a distance d from a stream is defined by:

$$\mathrm{HSDR}(d) = \frac{\mathrm{HSDR}}{35.16} e^{-9.1\mathrm{x}10^{-4} d}$$

Uncertainty scenarios tested

To test the uncertainty in modelled sediment outputs, the parameters controlling sediment delivery from hillslopes were examined. These include the five inputs to the RUSLE as well as the HSDR. Of the five RUSLE inputs, an examination of the spatial pattern of hillslope erosion implies that it is the *C*-factor which has the greatest impact on hillslope erosion. As a result, a range of values for the *C*-factor and HSDR were modelled under the assumption that this range represented the minimum and maximum possible values in the catchment. For *C*-factor, the cover classes available to us for modelling were very broad compared to those typically used in RUSLE studies (Renard *et al.*, 1997). For example, when assigning high values, such as for upland fallow fields, it was assumed that the fields could be bare, and therefore given the highest value i.e. worst case scenario. Table 1 illustrates the range of *C*-factors used for each land-use classification for the different model runs.

The other parameter that was varied was the HSDR (see Table 2). The current (best-guess) value of 10% HSDR was modelled as were the considered possible extreme values in the Mae Chaem Catchment of 5% and 15%. Both spatially variable and spatially constant HSDR was modelled.

Table 2 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^{-1}.

	5% HSDR	10% HSDR	15% HSDR
Low *C*-factor	141 (282)	282 (562)	423 (842)
Medium *C*-factor	368 (730)	737 (1457)	1104 (2185)
High *C*-factor	1309 (2569)	2617 (5134)	3926 (7700)

RESULTS

SedNet creates 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 can then be exported for mapping and visualization.

Sources and fate of sediment

The main source of sediment in the Mae Chaem catchment stems from sub-catchments located in the north, southwestern and western hillslopes. Figures 3 and 4 show the relative contributions of sediment made by each stream link watershed for a low yielding scenario (low *C*-factor with 10% spatially variable hillslope delivery), and a high yielding scenario (high *C*-factor with 10% constant hillslope delivery) respectively. Note the different legends on Figs 3 and 4 are required to show the similar patterns, but different magnitudes, of sediment delivery between the scenarios.

As there is a linear correlation between hillslope supply and flood plain deposition (Hartcher *et al.*, 2005), we do not need to examine the impact of the different scenarios on the transport or export of suspended sediment as the input of suspended sediment from hillslope erosion tells an identical story.

SOURCES OF UNCERTAINTY

There are two major potential sources of uncertainty in the model results which should be considered. These are firstly the data inputs and secondly the validity of the model assumptions (the way in which the SedNet model represents physical processes). Uncertainty in the data inputs are driving the uncertainty in the values of the *C*-factor. Conversely, uncertainty in the model assumptions are driving the uncertainty in the HSDR. Other factors such as the accuracy of the transport algorithms, assumptions made regarding coarse sediment deposition, flood plain deposition, over-bank volume, and gully erosion have not been tested here, but have been examined by Rustomji & Prosser (2001) and Newham *et al.* (2003).

The various combinations of cover and hillslope delivery ratios produced a broad range of results. Table 2 summarizes the combinations of *C*-factors and HSDR (constant and spatially variable) tested, and the resultant sediment delivery. It can be seen from Table 2 that variations in the *C*-factor are the dominant source of uncertainty in the model results. For our “best-guess” constant 10% HSDR, at our lowest estimate of *C*, there was a total of 282 t year^{-1} of sediment delivered from hillslopes within the Mae Chaem catchment. However, at the highest estimate of C, this increased to 2617 t year^{-1}, an order of magnitude higher.

Moving across the rows in Table 2 allows us to examine the impact of varying the HSDR on model results. For our “best-guess” medium *C*-factor, at a 5% HSDR, there was a total of 368 t year^{-1} of hillslope erosion, while at a 15% HSDR, this increased to 1105 t year^{-1}. 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 land-uses.

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 roughly doubling total hillslope erosion (e.g. 737–1457 t for a medium *C*-factor and 10% HSDR, Table 2). This is probably related to the fact that in the Mae Chaem catchment, most of the intensive agriculture (with consequently higher *C*-factors) occurs close to the streams. This would have the effect of increasing sediment delivery to the stream when a spatially variable HSDR is used. When the SedNet model is applied at a spatial scale where some areas in each sub-catchment are at a significant distance from a

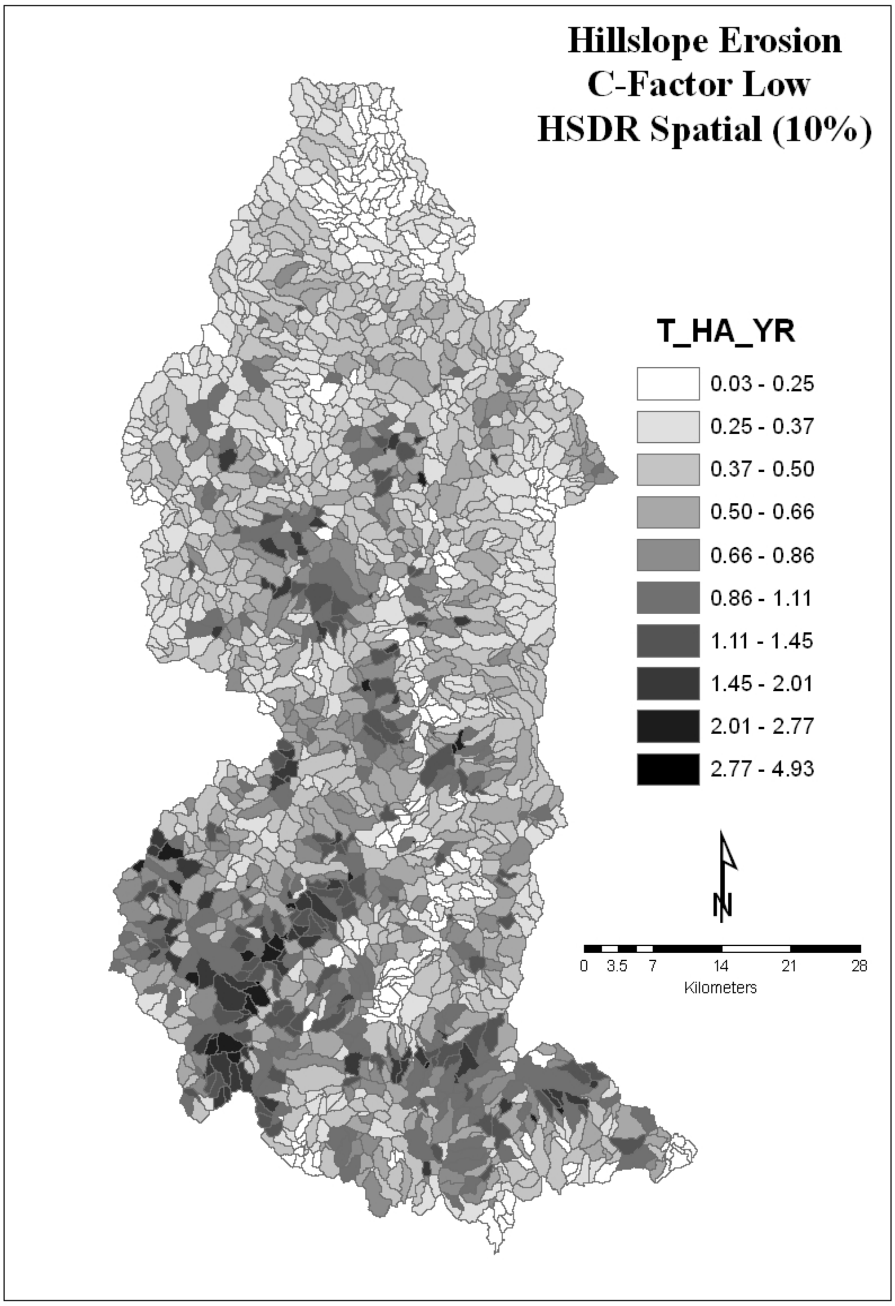

Fig. 3 Hillslope erosion per watershed for low *C*-factor, 10% spatial HSDR scenario.

streamline, a spatially-variable HSDR appears to be more appropriate than a constant HSDR. However, the way in which HSDR is defined is still a subject of considerable study and further work in this area is ongoing.

The relative importance (on sediment delivery) of the *C*-factor, magnitude of the HSDR, and whether the HSDR is constant or spatially variable is shown in Fig. 5. Newham *et al.* (2003) found that the three parameters related to the point at which overbank flow occurred were the most sensitive in the model (but they did not examine

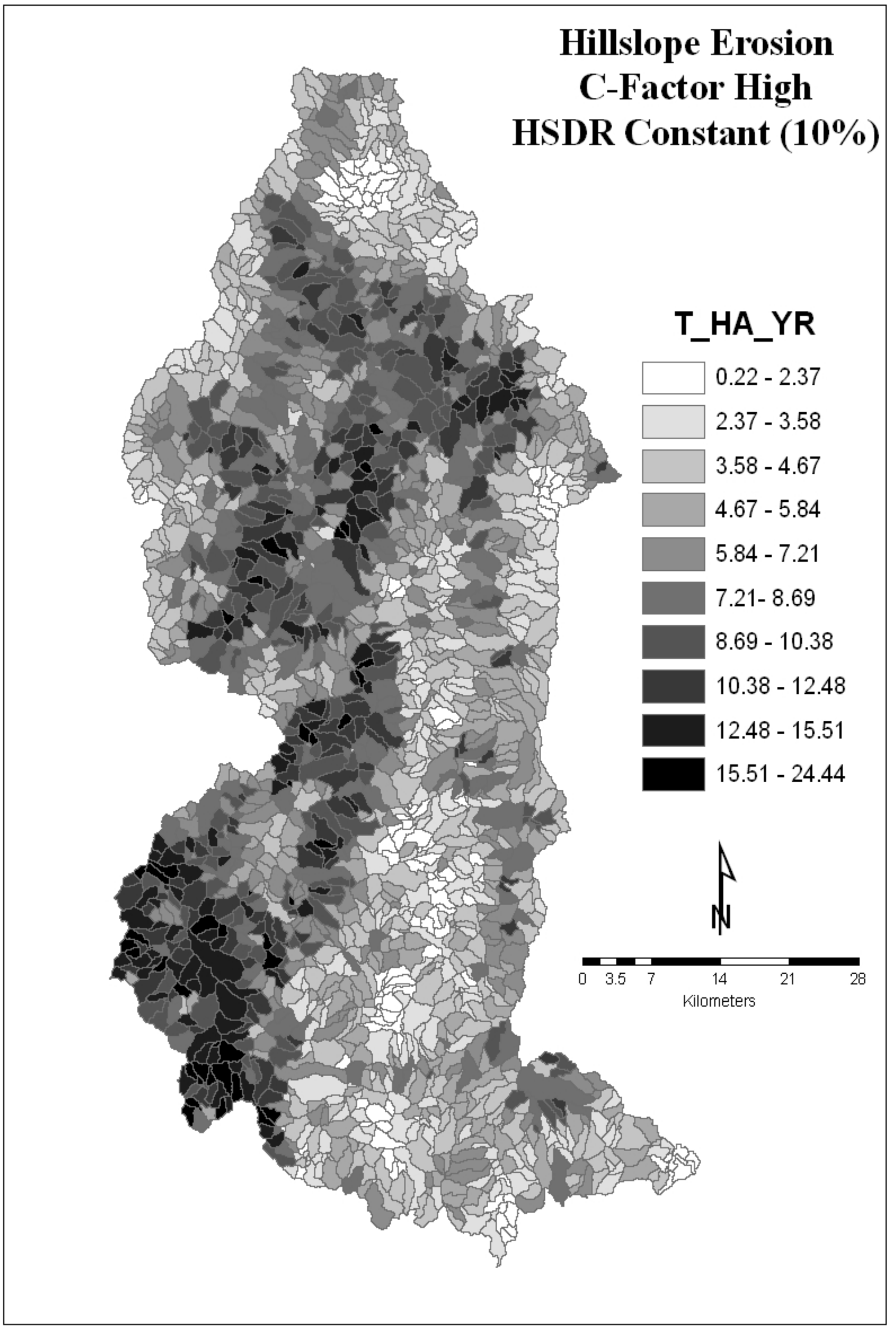

Fig. 4 Hillslope erosion per watershed for high *C*-factor, 10% constant HSDR scenario.

the impact of changes in the *C*-factor or other USLE inputs). A 10% perturbation in these parameters resulted in maximum changes in suspended sediment yield of 12, 25 and 43%, respectively. In this study we found that a 50% perturbation in the HSDR led to a 50% change in suspended sediment delivery (since the HSDR is a linear ratio). A change from a constant to a spatially variable HSDR led to a 100% increase in sediment yield, but this result is specific to this catchment. Finally, the changes in the *C*-factor that we examined ranged between 0 and 340% for individual land cover

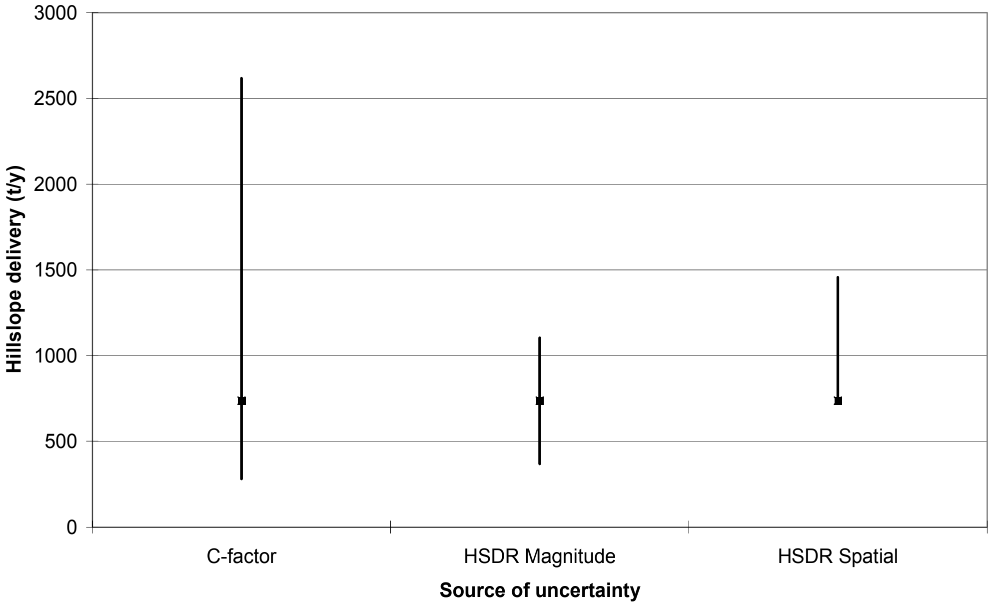

Fig. 5 Sources of uncertainty in modelled hillslope delivery of sediment.

types. These changes in the *C*-factor led to changes in the sediment yield of up to 252%, but these changes are not directly comparable to those in Newham *et al.* (2003) because they were not applied to all land use types in the catchment.

REDUCING UNCERTAINTY

One of the main reasons for the large uncertainty in sediment yields in this catchment is that the cover types provided for use in this study were very broad, categorizing for example, all upland fields together. As the type of crop grown in these upland fields has a massive impact on the *C*-factor, this uncertainty can be reduced significantly through a more detailed representation of the land-use. For example, we have learned that the shifting agriculture practiced in this catchment means that upland fallow fields lie dormant for decades before being re-used. As a result, most upland fallow fields would have *C*-factors towards the lower end of the range (0.02–0.8) seen in Table 1. Re-running the SedNet model with the maximum *C*-factor reduced to 0.34 (currently the "best-guess" value) leads to a reduction in the range of possible values from 7418 t year^{-1} to 5267 t year^{-1}, a 29% reduction in uncertainty. Further work to improve the land-use categorization in the Mae Chaem catchment would be expected to produce similar reductions in uncertainty.

CONCLUSIONS

It appears that a significant level of uncertainly currently exists in model outputs. The SedNet model is quite capable of identifying general source areas. However, it appears that the magnitude of sediment delivery is prone to greater uncertainty since variables such as *C*-factor and HSDR are poorly known. Work is ongoing to improve the spatial representation of the *C*-factor and improve the representation of the spatially variable HSDR through including slope and cover in the distance from stream algorithm.

Most of the uncertainty in the results appears to be due to uncertainty in the data inputs rather than the model structure. This level of uncertainty was reduced somewhat by incorporating local knowledge into the model inputs. However, the collection of high resolution data which can be verified with field measurements would further reduce this level of uncertainty.

Finally, the means of representing uncertainty used here (ranges of values) is not the best way to represent uncertainty. A better way would be to place confidence bounds on the predictions. To do this, we would first need to represent the uncertainty in the input parameters as a distribution and then carry out Monte-Carlo simulations. Work on this is currently underway.

Acknowledgments This study was funded through ACIAR Project FST/1999/035. Thanks also to Pornwilai Saipothong (Chiang Mai University) and Barry Croke (Australian National University) for supplying data and advice on the study area.

REFERENCES

Croke, B. F., Merritt, W. & Jakeman, A. J. (2004) A dynamic model for predicting hydrologic response to land cover changes in gauged and ungauged catchments. *J. Hydrol.* **291**, 115–131.

DeRose, R, Prosser, I., Wilkinson, L, Hughes, A. & Young, W. (2002) Regional patterns of erosion and sediment and nutrient transport in the Mary River catchment, Queensland. *CSIRO Land and Water Technical Report 37/02.* http://www.clw.csiro.au/publications/technical2002/tr37-02.pdf.

Gallant, J. (2001) Topographic scaling for the NLWRA Sediment Project *CSIRO Land and Water Technical Report 27/01* http://www.clw.csiro.au/publications/technical2001/tr27-01.pdf.

Hartcher, M. G., Post, D. A. & Kinsey-Henderson, A. E. (2005) Uncertainty in modelling the sources and sinks of suspended sediment in the Mae Chaem catchment, Thailand. In: *Proc. 2005 Int. Conf. on Simulation and Modelling,* (Bangkok, Thailand, 17–19 January 2005), 418–425. Asian Institute of Technology, Thailand, http://www.mssanz.-org.au/simmod05/papers/C5-01.pdf.

Kinsey-Henderson, A. E., Post D. A., & Prosser, I. P. (2005) Modelling sources of sediment at sub-catchment scale: An example from the Burdekin catchment, North Queensland, Australia. *Mathematics and Computers in Simulation* **69**, 90–102.

Lu, H., Gallant, J. Prosser, I., Moran, C. & Priestley, G. (2001) Prediction of sheet and rill erosion over the Australian Continent, incorporating monthly soil loss distribution. *CSIRO Land and Water Technical Report 13/01* http://www.clw.csiro.au/publications/technical2001/tr13-01.pdf

Merritt, W. S. (2002) Biophysical considerations in integrated catchment management: a modelling system for northern Thailand. PhD Thesis, Australian National University, Canberra, Australia.

Merritt, W. S., Croke, B. F., Jakeman, A. J., Letcher, R. A. & Perez, P. (2004) A biophysical toolbox for assessment and management of land and water resources in rural catchments in northern Thailand. *Ecol. Modelling* **171**, 279–300.

Newham, L. T. H., Norton, J. P., Prosser, I. P., Croke, B. F. & Jakeman, A. J. (2003) Sensitivity analysis for assessing the behaviour of a landscape-based sediment source and transport model. *Environ. Modelling and Software* **18**, 741–751.

Perez, P., Ardlie, N., Kuneepong, P., Dietrich, C. & Merritt, W. S. (2002) CATCHCROP: modelling crop yield and water demand for integrated catchment assessment in northern Thailand. *Environ. Modelling and Software* **17**, 251–259.

Prosser, I., Rustomji, P., Young, W., Moran, C. & Hughes, A. (2001) Constructing river basin sediment budgets for the national land and water resources audit. *CSIRO Land and Water Technical Report 15/01.* http://www.clw.csiro.au/-publications/technical2001/tr15-01.pdf.

Prosser I., Moran, C., Lu, H, Scott, A., Rustomji, P., Stevenson, J., Priestley, G., Roth, C. H. & Post, D. A. (2002) Regional patterns of erosion and sediment transport in the Burdekin River catchment. *CSIRO Land and Water Technical Report 5/02* http://www.clw.csiro.au/publications/technical2002/tr5-02.pdf.

Renard, K. G., Foster, G. A., Weesies, D. K. & Yoder, D. C. (1997) Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). *Agriculture Handbook no. 703, US Department of Agriculture, USA.*

Rustomji, P. & Prosser, I. (2001) Spatial patterns of sediment delivery to valley floors: sensitivity to sediment transport capacity and hillslope hydrology relations. *Hydrol. Processes* **15**, 1003–1018.

Young, W., Rustomji, P., Hughes, A. & Wilkins, D. (2001) Regionalisation of flow variables used in the National Land and Water Resources Audit. *CSIRO Land and Water Technical Report 36/01.* http://www.clw.csiro.au/-publications/technical2001/tr36-01.pdf.