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Preliminary modelling of sediment production and delivery in the Xihanshui River basin, Gansu, China

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ABSTRACT

This paper outlines an analysis of the spatial distribution of sediment production, delivery and yield in the Xihanshui River basin, South Gansu, China, using the modelling tools of SedNet (Prosser et al., 2001). This model can assess the delivery efficiency to downstream locations, as well as identifying locations with high rates of sediment production. Preliminary model experiments assist understanding of the spatial dynamics of these sediment processes and evaluation of the effectiveness of soil conservation practices since the mid-1980s. Three scenario years (dry, average and wet) from the 1983–2005 record are identified and modelled, and land use and management are represented in the model to reflect known changes since the 1980s. Results show hillslope erosion to be a dominant source of sediment supply, causing the latter to decrease ten-fold between 1984 and 1997/2000. Estimated bank erosion and floodplain deposition rates are sensitive to parameter values, but bank erosion appears less sensitive than hillslope supply to rainfall. The model can be used to assess net changes in floodplain storage; for default parameters, floodplain deposition rates are 25–200 times the rates of bank erosion depending on the climate scenario. Comparing simulation results with measured sediment yields at the three gauging stations indicates encouraging agreement in 2000. In 1984 (the wet year), the model under-predicts, suggesting that additional unmodelled sediment production processes, especially mass movement and gully erosion, may be important in wet years. Mass movement inventory data could close the gap between the high yields measured in the wet scenario year and the estimated yield due to hillslope erosion alone. In 1997 (the dry year), the model over-predicts; this suggests that the land use change parameters required to reflect the effects of conservation may not have been sufficient, implying that conservation has been generally effective, and that evidence of declining sediment yield is not simply a reflection of drier conditions.

1. Introduction

The linkages of sediment production, routing, delivery, and downstream yield remain a significant source of theoretical and practical uncertainty in river basin science. Sediment production and routing within river basins involve the activation of multiple sediment sources through the operation of many different processes. These on-site, "upstream" processes include hillslope sheetwash and rill erosion, gully erosion, mass movement, and river bank erosion. Analysis and prediction of this system's behaviour accordingly demand spatially-distributed approaches and models, rather than the lumped methods often used, such as catchment-averaged delivery ratios. The sediment delivery ratio (SDR, or yield as a proportion of the total production) is a poorly-specified lumped parameter, and there is still debate about the concept, and no general or reliable basis to estimate its value (Parsons et al., 2006).

Sediment yield is the "downstream" output of sediment from a catchment area, and this frequently decreases with basin area because of "off-site" deposition before the catchment outlet is reached (Fig. 1). The relationship between sediment production (by erosion) and sediment yield can be expressed by the equation:

$$Y = \mathrm{SDR} \cdot E \tag{1}$$

This equation (Walling, 1983) states that sediment yield (Y) is the product of the sediment delivery ratio (SDR) and sediment erosion (E). The sediment delivery ratio is usually <1 (or $<100\%$), and also frequently decreases with the drainage area (Fig. 2), possibly because in larger basins there is more opportunity for deposition between erosional source and basin outlet, and also because rainfall that triggers erosion is less likely to cover the whole of larger catchments. The problem with this formulation of the delivery ratio is that it treats catchments as lumped, black-box phenomena. As Boyce (1975) noted, "external" links in a drainage network structure have quite different sediment delivery characteristics (and delivery ratios) from the "internal" links; in short, then, the spatial variation of sediment delivery within catchments cannot be judged from Figs. 1 and 2 and Eq. (1).

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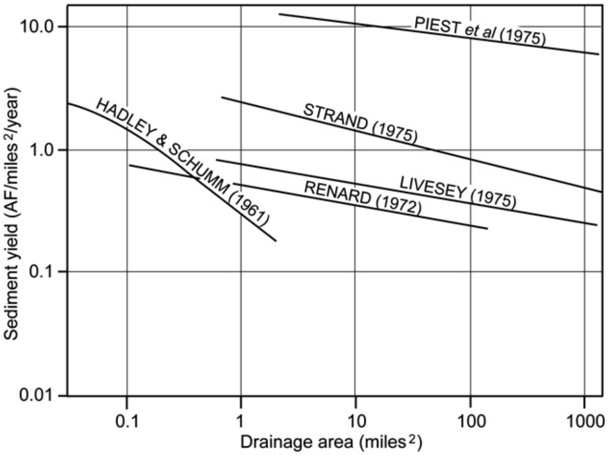

Fig. 1. The inverse relationship of sediment yield with basin area (Lu et al., 2003, 2005).

This is an important issue, because sediment management not only requires on-site control of sediment production, but also management of its delivery by the river system to downstream control locations. While on-site conservation measures to manage sediment production may make important contributions to sediment control, they may also be rendered inefficient because much of the sediment produced is in any case not transported to a downstream site (a reservoir, for example), but is deposited off-site, *en route*. So the critical locations to target for control may be those with efficient delivery within and through a catchment, as much as those with high rates of production.

In this context, this paper describes the preliminary application of a spatially-distributed method to quantify patterns and rates of sediment production in the Xihanshui basin, a tributary of the upper Yangtze; and to predict its routing to a downstream point, accounting for losses in deposition *en route*. This is based on a use of SedNet (Prosser et al., 2001a, b; Lu et al., 2003), which is a distributed model in which the component processes are represented by reduced complexity sub-models to facilitate application at large spatial scales. Ultimately, this model can lead to effective targeting of sediment control, by identifying and managing sites both with high sediment production and with efficient delivery (Lu et al., 2004). However, the aim of this study is also to explore the geomorphological implications of the model's distributed approach to sediment production, delivery and yield. The purpose of this paper is therefore to assess the relative importance of sediment production processes under different climate and land cover conditions, and the controls of the spatial structure of delivery ratios within this large catchment, rather than to make explicit forecasts of sediment production and yield for practical purposes. Nevertheless, this exploratory use of the model is facilitated by some comparison with suspended sediment data.

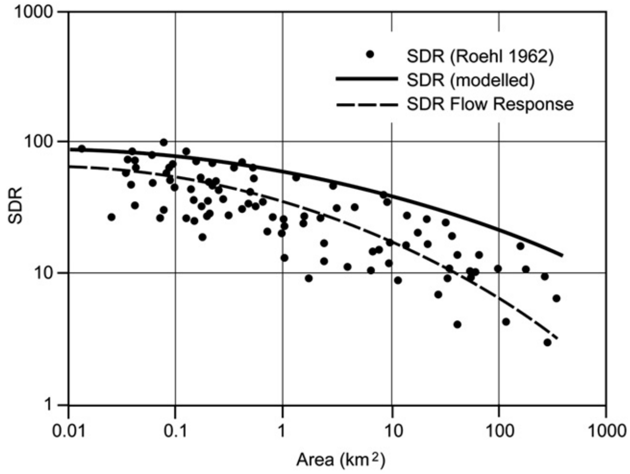

Fig. 2. The inverse relationship of the sediment delivery ratio (SDR) with the drainage area (Branson et al., 1981).

SedNet, like many other reduced complexity models (Brasington and Richards, 2007), does not model sediment production and delivery dynamically, but instead requires definition of scenarios for steady state modelling. However, the numerical efficiency that this simplification offers then lends itself to numerical experiments structured in a factorial experimental design to examine different climate and land management combinations and their interactions. Indeed, given the many uncertainties that underlie the component sub-models and parameters of a complex model such as SedNet, it is likely that this exploratory scenario-based and hypothesis-generative approach is its most appropriate use.

2. The study region

The focus of this paper is on one of the headwater basins draining into the Yangtze River. This is obviously of interest because sediment produced by the tributaries of the Upper Yangtze River directly affects the service life-span and normal operation of the Three Gorges Dam, the biggest hydro-power project in the world (Fan et al., 2004). The Jinsha River (the upstream main stem of the Yangtze River) and the Jialing River (the largest tributary of the Yangtze River) are the major sources of this sediment, contributing 72.8% of the sediment but only 48.6% of the runoff (Tan, 2004). The basin area and average annual runoff of the Jialing River account respectively for 15.8% and 15.6% of the total values of these variables for the Yangtze River basin upstream of the Yichang hydrological station, but its sediment production accounts for 25.5% (Zhong, 2001). The scale of basin studied in this research is limited in order to trade off the desirable resolution of the model (the grid cell size) against computational demands. Accordingly, the specific subject of the investigation is the sediment budget of the Xihanshui Basin, a significant tributary of the Jialing River.

The Xihanshui Basin (latitude: 33°15′N–34°31′N, longitude: 104°31′E–106°2′E) is located in the south-east of Gansu Province, and covers an area of 1.02×10^4 km^2. The Xihanshui River, an upstream tributary of the Jialing River, rises on Qishou Mountain in Tianshui City, Gansu, with its watershed bordering the Yellow River Basin in the north. The river then crosses the south of Gansu Province and enters Shaanxi Province, joining the Jialing River at Lueyang (Fig. 3). This is a basin within which some of the most severe soil erosion in the upper reaches of the Jialing River catchment occurs, especially in its north-east where it drains the southwestern edge of the loess plateau. The north of the basin has a warm temperate, semi-arid, continental monsoon climate, with annual precipitation ranging from 400 to 700 mm, and the climate gradually changes to a warm temperate humid monsoon type, with annual precipitation above 800 mm, in the south. The land use and cultivation methods also change from north to south, from spring wheat and rape to wheat–rice, wheat–corn and rape–corn rotations. Since the 1980s, the Yangtze and its tributaries have seen considerable investment in soil and water conservation, and there is evidence that this has reduced sediment yield (Lu and Higgitt, 1998). However, because these land management changes have co-varied with a decline in rainfall and discharge, it is difficult to be clear about the effectiveness of the conservation. A modelling approach such as that adopted here may therefore help to distinguish the effects of climate and land use changes.

3. The SedNet methodology

The SedNet model used in the research reported here was first developed and applied in Australia (Prosser et al., 2001a); here we use Version 2 (Wilkinson et al., 2004). SedNet involves a set of GIS routines that define river networks and their associated sub-catchments, map the distribution of the rates of various erosional processes, and “route” sediment through the network as a function of river hydrology and morphology, by explicitly estimating sub-catchment sediment budgets.