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Erosion of river terraces as a component of large catchment sediment budgets: A pilot study from the Gangetic Plain

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ABSTRACT

Erosion of river terraces and alluvial interfluves in large catchments may be a significant source of sediment, but is not readily included in sediment budgets because quantification is not straightforward. Here a pond on a large river terrace on the Gangetic Plain in northern India provides: an estimate of the proportion of sheet and rill erosion products that reaches a valley floor and, by analogy, the amount that reaches a channel that drains to a major river; and insights into the sensitivity of this delivery to climate change and land use. Comparison is made between the rate of delivery of the products of sheet and rill erosion to a valley floor with approximate sediment yield from gullies indicating that the latter is likely to be a more significant source of sediment. This is a pilot study and its limitations can guide future research. The construction of sediment budgets in many large catchments worldwide could potentially include the approach reported here. The study also contributes to understanding of human–environment interactions, specifically with regard to sheet erosion of agricultural soils.

1. Introduction

Many large catchments contain river terraces that are tens of metres above a river providing a source of sediment either from erosion by small channels cut into a terrace or from the products of sheet erosion that are conveyed to the river through the channels that are much smaller than the rivers they join. Examples include the Rhine in Germany (see Cloetingh et al., 2009), the Loire in France, the Huanghe, Changjiang and Songhuajiang in China (Xi Xi Lu, pers. comm.), the Ganga in India, and the Murrumbidgee in Australia. While small channels are reasonably common on the terraces of these rivers, sheet erosion is only likely to be a significant source of sediment where the terrace surface has some relief caused by tectonically-induced erosion, rare floods that erode the terrace surface, or because the terrace is an abandoned floodplain that had relief while active as a result of abandoned meanders and flood chutes. Where the terrace's surface is planar, often the case in laterally accreting systems where scroll plains are levelled gradually after formation, sheet erosion is unlikely to be a significant source of sediment.

Terraces receive little attention in sediment budgets of large catchments, possibly because they are believed to be a minor source of sediment. Even if the rate of sediment loss from terraces per unit area is slight, the large extent of terraces may mean that they are significant sediment sources. Quantification of the rate of loss is also an important contribution to documentation of the conveyance of sediment from uplands to the sea. Quantifying this source is not however straightforward. While some estimates of sheet erosion are available for terraces (see below), estimates of the proportion of this material that reaches either terrace-crossing channels or the main river are apparently not available, and the contribution of sediment loads from the channels (and also gullies) on the terraces are rare.

Some terraces contain small ponds, either natural or constructed, that receive sediment produced on the terrace surface upslope by sheet and rill erosion. These sites may provide a means

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of estimating the rate of delivery of such sediment to both the ponds and, by analogy, to small channels that cross the terrace and reach the river. Sediment storage in the ponds is also a 'loss' or storage term in a sediment budget. Finally, sedimentation rates in the ponds may provide an estimate of the sensitivity to climate and land use change of the rates of delivery of the products of sheet erosion.

The research reported here provides a pilot study of such a pond on a terrace (known as an interfluve or 'doab' locally) on the Gangetic Plain of northern India. These terraces have been subject to a set of geomorphic processes that have redistributed the upper part of the alluvial deposits, mainly by runoff acting on the relief of the terraces inherited from the time of their abandonment as rivers incised. This redistribution is continuing, influenced now by land use. The rate of sediment delivery to the pond is compared with calculated sheet erosion rates on the adjacent hillslopes, and the sensitivity of this rate of delivery to land use and climate change is assessed. Although the focus is on the delivery to ponds (and by analogy small channels) of the products of sheet erosion, some attention is also paid to other forms of erosion that will need to be quantified to provide a complete sediment budget for this landscape. Finally, and perhaps most importantly, the limitations of this study are identified to guide future research.

The results also contribute to understanding of long-term interactions between humans and the environment, specifically in regard to the interactions of climate change, land use, and sheet erosion of agricultural soils (cf. Dearing et al., 2006a,b).

2. Erosion and sediment delivery on the Gangetic Plain

The quantities of sediment delivered to river channels from gullies, channel banks, and by sheet and rill erosion on the Gangetic Plain are poorly defined components of the sediment budget (Wasson, 2003). Soil loss from agricultural land (along with water-logging, salinisation and sodification) could also be a limitation to further food and fibre production on the Gangetic Plain.

The most visible form of erosion on the Gangetic Plain is gullying, known in India as ravine erosion. Haigh (1984) mapped large areas of ravines in the Yamuna/Chambal zone, and Singh et al. (1992) mapped these in more detail and included gullies along the banks of the Yamuna River southwest of Kanpur. These gullies clearly contribute sediment directly to both the Chambal River (a tributary of the Yamuna) and the Yamuna River, a major river of the Plain. In the Lower Chambal valley, Sharma (1979) showed that ravines have recently extended by 0.25–0.45 m/year depending upon soil type and ravine size. Bhan (1983) modelled the Kamtari Basin ravines along the Yamuna River as a power function of area against time. Bhan (1973, 1983) also mapped the Chambal/Yamuna ravines in detail.

Singh et al. (1992) estimated the mean annual sediment yield of the Chambal/Yamuna ravines at >4000 t/km^2/year (i.e. per square kilometre of catchment). Because they are still actively eroding, it might be assumed that these ravines are the result of relatively recent land cover reduction. But it is clear that they are old features from the observations of Peter Mundy (Temple, 1967) who described ravines near Dholpur on the lower Chambal River (~55 km south of Agra) in January 1631 AD, and in August 1632 AD near Bhognipur on the Yamuna River frontage, ~145 km southwest of Lucknow. Also, ravines on the Yamuna near Kalpi can be shown stratigraphically to be ~36 ka and probably <12.5 ka as a result of river incision which triggered gullying of the river frontage also known as the riparian zone (Gibling et al., 2005; Srivastava et al., 2003a,b,c). Ahmed (1968, 1973) suggests a tectonic origin for these large areas of gullies, the result of river incision and therefore baselevel lowering following uplift on the foreland bulge along the Indian Shield caused by collision with Eurasia and the rise of the Himalaya. Opening of fractures in the Yamuna alluvium and gully formation during the Late Pleistocene is also suggested by Agarwal et al. (2002) as a result of extensional tectonics along the peripheral bulge of the Ganga foreland.

There are many other gullied areas along the rivers on the Gangetic Plain, well depicted on topographic maps and satellite images. But almost nothing is known of their history, cause, or rate of sediment production. Similarly, little is known about riverbank erosion rates, except some inferences from a few sites (Wasson, 2003). By contrast, Singh et al. (1992) have quantitatively estimated rates of sheet and rill erosion by using the Universal Soil Loss Equation (USLE) and results from erosion plots; that is, well defined areas from which the loss of soil is measured. Mean annual rates for the Gangetic Plain range from 400 to 1500 t/km^2/year, the lower values being along the southern margin, increasing northward to the boundary between the alluvial plain and the Siwaliks (foothills to the Himalaya).

The rates of erosion provided by the USLE are equivalent to loss of soil from the base of a slope where topography is simple and slopes comparable in length to those of the erosion plots used to establish the model (C. Rosewell, pers. comm.). On the Gangetic Plain, low angle hillslopes are developed on abandoned alluvial surfaces (terraces), adjacent to lakes and ponds that are the result of stream channel abandonment (Singh et al., 1999) These hillslopes are often more than 800 m in length which is much longer than the erosion plots. Therefore the rates of soil loss given by Singh et al. (1992) cannot be assumed to be equivalent to rates of soil delivery to channels (see Parsons et al., 2006).

A site called Misa Tal (26°48′06.09″N, 81°06′02.31″E) has been chosen to determine the rate of sediment delivery to the equivalent of a channel (in the form of a small lake) in an area where the rate of sheet and rill erosion has been estimated by Singh et al. (1992) to be ~500 t/km^2/year.

3. Erosion and sediment transport in the Gomti River catchment

Misa Tal (Misa Lake) is in the catchment of the Gomti River which rises on the Gangetic Plain (Fig. 1). The Gomti River at Amghat has a catchment area of 30,400 km^2 and an average annual specific sediment yield of ~200 t/km^2/year (Sinha et al., 2005). The river has medium to low sinuosity, and deposits significant volumes of sediment along its margins. For example, at Parahapur Ghat (see Fig. 2 of Shukla and Singh, 2004) interbedded clays and fine sand have been deposited on the levee and floodplain on the left bank of the Gomti River. The former channel of the river as depicted on the 1911 topographic map is now infilled by clay and fine sand, and a natural levee adjacent to the modern river consists of 365 cm of flood deposits resting on cross-stratified medium grade channel sand. The channel sand is exposed at various points along the bank, and, using it as a datum for the former surface of the channel bed, it is estimated that $\sim 3 \times 10^6$ t of sediment has been deposited in an area of $\sim 71 \times 10^3$ m^2 on the left bank of the river over a linear distance of ~700 m since 1911 at an average rate of $\sim 33 \times 10^3$ t/year. The river has also deposited a point bar on its right bank since the channel has moved to its present position (Shukla and Singh, 2004). These observations show that large amounts of sediment are delivered to the Gomti River, from sheet erosion, gullies and riverbank erosion.

Gullies appearing on the 1974 Uttar Pradesh (63 F/6, First Edition, 1:50,000, Survey of India) topographic map are reproduced in Fig. 2. These gullies are between 3 and 12 m deep. They are still actively migrating headward and their walls are also eroding. They