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The timing and magnitude of coarse sediment transport events within an upland, temperate gravel-bed river

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Abstract

This paper describes the application of a new instrument to continuously measure bedload transport, an impact sensor, to a 72 km^2 test catchment in the Yorkshire Dales, northern England. Data from a network of impact sensors are linked to repeat surveys of channel morphological response, to get a better understanding of the conditions that lead to sediment generation and transfer. Results suggest certain areas of the catchment act as key sediment sources at the annual time scale, with material being quickly delivered to the lower parts of the catchment along the steep bedrock channel. Sediment transfer within the tributaries occurs in significantly smaller magnitudes than within the main channel; but it moves more frequently and at different times of the year, with transfer rates being strongly conditioned by larger-scale valley geomorphology. The lower 5.6 km reach sees a significant reduction in gradient and a widening of the valley. This permits significant accumulation within the channel, which has persisted for many years. This lower reach is very sensitive to changes in sediment supply and there is good agreement between changes in bedload transport data and the surveyed channel response. These observations have major implications for how river management projects should be developed in upland environments, especially those where large-scale geomorphological controls have a major impact upon the sediment transfer process. Evidence suggests that where river management restricts lateral movement of the channel and transfer of sediment into floodplain storage, changes in sediment supply can lead to areas of severe accumulation, acceleration of bank erosion and exacerbated flood risk.

Keywords: Coarse sediment transport; Connectivity; Cross-sections; Gravel-bed river; Impact sensor; Climate change

1. Introduction

The high rate of coarse sediment delivery to upland river systems is an ongoing problem. It is leading to problems of river channel management, notably associated with the channel instabilities that follow from high sediment delivery rates. In-channel sediment fill also leads to exacerbated flood risk. The spatial location of sedimentation will be related to the ease with which sediment can be moved through the drainage network. It is recognised that under moderate to high flow conditions, bedload particles will only move to the next bar downstream of the erosion site (e.g. Church and Hassan, 1992; McLean and Church, 1999; Pyrce and Ashmore, 2003). At very high flows, travel distance becomes controlled more by the magnitude and duration of sediment-transporting flow conditions: particles may become mobile and step length may exceed that to the next bar downstream

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(e.g. Hassan et al., 1991, 1992). Despite recognition of the step-like nature of coarse sediment transfer, we have traditionally assumed that all coarse material supplied to a reach will eventually be transported through it (Hooke, 2003). Sediment that is not transported will either be broken down through abrasion during temporary storage until it can be transported, or stored until the channel morphology adjusts such that the partitioning of bed shear stress within the reach is competent to transport this size fraction (e.g. Baker and Ritter, 1975; Wilcock and Southard, 1989). This is the traditional basis of river engineering schemes where sediment transfer is managed through river channel engineering (e.g. channel straightening) to change the partitioning of shear stress and increase sediment transport rates, so resulting in sediment evacuation. However, this overlooks the longer-term geomorphological response of the river-floodplain system to sediment delivery, and the fact that upland river reaches may be long-term storage zones for coarse sediment.

The need to understand the controls on sediment sources, as well as the transfer of sediment to and within the drainage basin, is being amplified by concerns over environmental change. Projected increases in precipitation associated with environmental change, which are severe in upland regions in the north of England, could significantly enhance river management problems if they result in increased sediment delivery to the river network. Work in this region (Reid et al., submitted for publication) has shown that by the 2080s, coarse sediment generation could increase by up to 68% over levels typical of the 1990s, largely associated with a greater propensity for events that are sufficient to cause significant hillslope failure, as opposed to channel adjacent. In practice, the traditional separation of channel and hillslope sources is artificial as they represent end members of a continuum defined by changing degrees of connectivity between the sediment source and the drainage network. Thus, the Reid et al. work shows that a prime reason for greater sediment delivery rates is not only an increase in the magnitude and frequency of hillslope failure, but also a rising probability that these failures actually connect with the drainage network.

The need to understand the sediment delivery and transfer process is supported by a considerable volume of theoretical, experimental and field-based research into how coarse sediment moves through river systems. However, there has been much less understanding of how this is manifest over spatial scales larger than the river reach. Such an understanding is difficult to acquire as it requires monitoring of sediment transfer and channel response at a frequency that matches that of sediment transport events and over a spatial scale that is sufficient to include both hillslope sediment sources and in-channel sedimentation zones. In this paper we use continuously recorded sediment transport data, coupled to repeat surveys of channel response, to get a better understanding of the conditions that lead to sediment generation and transfer within an upland river system. This includes measurement of sediment transfer at all flows, including extreme flood events. We use this to understand which sorts of events are responsible for delivering and transferring sediment within our case study system, and which provides a baseline understanding for thinking about how future environmental changes might impact upon sediment delivery and river response.

2. Background

Coarse sediment transfer within river channel networks is a four stage process: (a) the delivery of coarse material from hillslopes or river banks to a stream; (b) entrainment at a critical shear stress from the stream or river bed; (c) transfer downstream; and (d) deposition in a temporary store or permanent sink. We now have a substantial understanding of each of these processes in isolation (e.g. in terms of controls on entrainment) and, to some extent, in terms of how they couple (e.g. the implications of weak size selectivity at entrainment for downstream transfer of delivered sediment). In relation to the delivery of sediment into streams, there are two important processes: (1) the erosion of material from the landscape; and (2) its connection to the drainage network. There are now well-established models for predicting the location of coarse sediment sources within catchments. In temperate upland environments, most coarse sediment sources are linked to rainfall-triggered shallow translational landslides (e.g. Dietrich et al., 1982; Montgomery and Dietrich, 1994; Dhakal and Sidle, 2003). Some areas of hillslopes have the potential to fail repeatedly, generating sediment for significant periods of time as individual slides, until the supply becomes exhausted. Most shallow translational landslides are formed after wet antecedent conditions followed by a prolonged period of rainfall (e.g. Brooks et al., 2004) possibly triggered by a burst of higher intensity. Wet antecedent conditions provide reduced soil moisture deficits (e.g. Campbell, 1975), keeping the catchment relatively well saturated, with a perched water table in unstable sites (Dhakal and Sidle, 2003). Prolonged rainfall gradually increases pore water