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Sediment pulse evolution and the role of network structure

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ABSTRACT

Sediment pulses are triggered through a variety of mechanisms, from landslides to land use change. How do these pulses move through the fluvial system, and how do they evolve? In a system with perfect sediment connectivity, the erosional response to a perturbation and the resulting signal at the river mouth would match, however, this rarely occurs. Many studies have addressed reach-scale dynamics of sediment pulses and how they translate or disperse downstream. At the watershed scale, network structure and storage become more important in modulating the sediment signal. Here, we review the current literature on sediment pulse behavior, and then address the role of network structure on maintaining, dispersing, or transforming sediment pulses in a fluvial system. We use a reduced-complexity network routing model that simulates the movement of bed material through a river basin. This model is run in the Greater Blue Earth River (GBER) basin in Minnesota, USA, first with spatially uniform inputs and then with inputs constrained by a detailed sediment budget. Once the system reaches equilibrium, a sediment pulse is introduced, first at a single location and then throughout the system, and tracked as it evolves downstream. Results indicate that pulses able to translate downstream disperse in place upon arriving at over-capacity reaches as sediment goes into storage. In the GBER basin, these zones occur just upstream of a knickpoint that is propagating upstream through all mainstem channels. As the pulses get caught in these sediment "bottlenecks," there is a decoupling of the original pulse of sediment and the resulting bed material wave. These results show that the network structure, both in terms of network geometry and the spatial pattern of transport capacity, can play a dominant role in sediment connectivity and should be considered when predicting sediment pulse behavior at the watershed scale.

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1. Introduction

How well is the integrity of an erosional signal preserved and maintained during transport downstream? In a system with perfect sediment connectivity, the signal at the outlet would mimic the erosional signal upstream with an associated time lag. If there was perfect connectivity between the erosional response to a perturbation (say, climate change), and the sedimentary deposit left behind, then one could "read the rocks" and back-out the erosional history of the basin. Fundamentally, it is the fluvial system that propagates an erosional signal from the uplands to a depositional basin. How that signal is transmitted depends upon the nature of the perturbation including magnitude, frequency, duration, and spatial extent; the distance from source to sink; and characteristics of the fluvial system and sediment transport processes within it, including storage effects.

This paper focuses on perturbations that deliver excess sediment to fluvial systems and how well those signals are preserved from upstream source to river outlet. Perturbations that produce excess sediment above background rates vary from single high-magnitude inputs to longer-term shifts in total sediment yield. Here, we discuss a range of sediment inputs in fluvial systems and how they evolve as they propagate downstream through a review of field cases and numerical and physical modeling efforts. We first review research on the evolution of sediment waves from single pulses of sediment (i.e. from landslide, dam removal, or volcanic inputs) to persistent or widespread disturbances (i.e. from widespread land use or climate change). There have been many studies on reach-scale sediment wave dynamics in the literature (i.e. Meade, 1985; Nicholas et al., 1995; Lisle et al., 1997, 2001; Sutherland et al., 2002; Cui et al., 2003a, 2003b, 2005; Lisle, 2008; Sklar et al., 2009; Venditti et al., 2010a; Humphries et al., 2012; Nelson et al., 2015). At the watershed scale, however, tributary interactions and storage may occur, leading to potential synchronizations and additional transformations of the original sediment wave (Jacobson, 1995; Benda and Dunne, 1997a, 1997b; Jacobson and Gran, 1999; Benda et al., 2004a; James, 2010; Czuba and Foufoula-Georgiou, 2014, 2015), increasing the complexity of downstream transport.

To help bridge the gap from reach-scale dynamics to watershed-scale sediment connectivity, a reduced-complexity network routing model developed by Czuba and Foufoula-Georgiou (2014, 2015) is used to study how network structure and storage may affect the potential for creation, persistence, or dispersion of sediment waves. Here, network structure refers to both the geometry of tributary inputs as

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well as the spatial pattern of transport capacity. The model is run in a well-studied basin in southern Minnesota, USA, to enable realistic sediment inputs for comparison with more spatially-uniform inputs, and track how sediment pulses evolve as they move downstream through the watershed. To assess the role of network structure vs. spatial pattern of inputs on the sediment signal downstream, a run with spatially uniform sediment inputs is compared to one with inputs constrained by a detailed sediment budget. The model is then set up to allow in-channel storage and run to investigate how different aspects of network structure, including both network geometry and the spatial pattern of transport capacity affect the downstream propagation of sediment pulses.

2. Background

Sediment is supplied to the fluvial network primarily through overland flow, mass movements, and fluvial scour. Hillslope erosion may transport sediment slowly and steadily into channels through processes like creep, or sediment may be stored in colluvial hollows or fans and released episodically via landslides or debris flows. Inputs from bank scour and bluff collapse through mass wasting occur preferentially during high flow events, leading to stochastic inputs directly to the stream. Perturbations to the watershed, including seismic activity, heavy rainfall events, forest fires, or land use changes can increase the volume of sediment supplied to a stream network from both colluvial and near-channel sources. On one end of the spectrum are single inputs of excess sediment, isolated in time and space from, for example, landslides or dam removals. On the other end are spatially-extensive pervasive sediment perturbations, for example from land use conversion to agriculture. In this case, much of the watershed may be disturbed, and in some cases the change in sediment input to the channel may be more of a step function rather than a single pulse. In between are a range of other input characteristics, from single-pulse widespread sediment perturbations, perhaps from a wildfire, to long-term point source inputs from mining operations.

There have been many studies on sediment wave dynamics in the literature, with much of the recent research focused specifically on reach-scale sediment waves and how a single point source input evolves through time. Fewer studies have looked at sediment wave propagation at the watershed scale, where potential synchronizations in the landscape may affect how sediment pulses move downstream, what the resulting depositional signal might look like, and how channels will respond to management options designed to lower sediment inputs. Here, we review studies from the field, flume, and numerical modeling for different end members of sediment input. Two recent review papers cover reach-scale sediment pulse evolution (Lisle, 2008) and watershed-scale high-magnitude sediment wave evolution (James, 2010). We review and update those findings and then examine some of the elements that link reach-scale transport with watershed-scale sediment signals, including network structure and the effects of storage, elements that are then investigated further through a watershed-scale network routing and transport model.

2.1. Nomenclature

Gilbert (1917) was one of the first to report on sediment waves in watersheds, noting the downstream migration of hydraulic mining debris from the Sierra Nevada across the central valley of California. He used the term “sediment wave” to describe the wavelike movement of sediment as it transported downstream. The wavelike behavior was most notable in the rise and fall of channel bed elevations due to passage of the excess mining debris. Later studies by James (1989, 1991, 1993) showed that the passage of sediment was much more complex. Due to temporary storage of excess sediment in the floodplain, high sediment loads persisted much longer than the initial bed wave which has led some to prefer alternate terminologies. Nicholas et al. (1995) prefer the more generic term sediment “slug” to include excess sediment that does not conform to wavelike behavior, although Lisle (2008) notes that the term “slug” does not properly address sediment mobilized that was not part of the initial sediment input. The term slug was further refined to reflect the magnitude of the inputs (macroslug, megaslug, and superslug) and thus the spatial scale of impact, from minor channel impacts at the scale of gravel bars up to major valley-floor adjustments spanning kilometers of channel or more (Nicholas et al., 1995).

Another commonly used term to refer to excess sediment inputs is sediment “pulse”. Traditionally, the term sediment pulse referred to zones with high sediment transport rates (Reid et al., 1985; Iseya and Ikeda, 1987), but more recently the term has been used to refer to discrete sediment inputs (Cui et al., 2003a). Cui et al. (2003a, 2003b) prefer the term “pulse” over “wave” or “slug” noting that not all sediment pulses exhibit wavelike behavior. Later papers by the same authors use the term sediment “pulse” and sediment “wave” interchangeably (Cui and Parker, 2005; Cui et al., 2005). Here, we opt for that approach and use the term sediment pulse and sediment wave interchangeably to describe the influx and movement of a volume of excess sediment in a fluvial system.

2.2. Reach-scale sediment pulses

First consider a pulse of sediment entering a channel at a discrete point in space and time, perhaps from a landslide or debris flow or generated through a dam removal (e.g. Hansler, 1999; Sutherland et al., 2002; Major et al., 2012; East et al., 2015). Sediment pulses can both disperse and translate downstream. As the pulse evolves, sediment can move into longer-term storage on the floodplain or be permanently lost due to comminution. Research into reach-scale pulse dynamics initially focused on documenting sediment wave passage in the field (Gilbert, 1917; Pickup et al., 1983; Meade, 1985; James, 1989; Knighton, 1989, 1991; Madej and Ozaki, 1996; Sutherland et al., 2002) and over time has shifted more towards targeted experiments and model development (Lisle et al., 2001; Cui et al., 2003a, 2003b, 2005; Cui, 2007; Sklar et al., 2009; Venditti et al., 2010a; Humphries et al., 2012) to understand how sediment pulses evolve and to develop a more detailed understanding of which conditions favor dispersion vs. translation.

Initially, it was assumed that sediment waves translated downstream based on a series of field observations, starting with the early work of Gilbert (1917) and the California hydraulic mining debris. Although this particular field case is of a much greater magnitude than most point-source inputs, it had a dominant effect on how people thought about sediment wave migration. The main set of observations made by Gilbert (1917) indicating a wave-like passage of sediment were bed elevations that went up as the hydraulic mining debris arrived and then later went down after passage of the wave of sediment. Later studies by Knighton (1989, 1991) in Tasmania also documented the wave-like progression of mining debris downstream, recorded by the rise and fall of gages along the channel over the course of decades. In both cases, however, there are confounding factors. First, a significant volume of sediment moved into storage in the floodplain as the sediment wave propagated downstream, complicating interpretations of the timescales of adjustment. Second, one of the main observations, that gage elevations went up and then down as the wave passed, is not necessarily an indication of wave translation. The passage of a wave of sediment looks remarkably similar to dispersion in place of the same sediment as viewed through gage elevations, as dispersion also leads to rise and subsequent fall of downstream gages (see Fig. 1). The difference lies in the magnitude of the bed elevation response and in the behavior of the mass of sediment overall. For a sediment wave to be purely translational, the head, tail, and center of mass of the sediment wave must all move downstream at the same pace.

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