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The impact of the streamflow hydrograph on sediment supply from terrace erosion

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ABSTRACT

Sediment supply from banks and terraces has important implications for grain-size distributions in alluvial rivers (and by extension for aquatic habitat), as well as for the delivery of floodplain-stored nutrients and contaminants to the aquatic environment. The interactions between streamflow hydrographs and lateral channel boundary failure control the sediment supply from banks and terraces. However, the relationships between variable flow and discrete sediment supply from catastrophic erosion of lateral boundaries and subsequent mass sediment flux in rivers are not well characterised by existing methods and models that focus only on one of several relevant interrelated processes. In order to improve predictive capability of catastrophic sediment supply from lateral boundaries, we adopt a new approach to modelling the process interactions between stream hydrology, erosion of banks/terraces, and the corresponding discrete supply of sediment to channels. We develop a modelling framework for terrace — channel coupling that combines existing theories of flow through porous media, bank stability, and fractional sediment flux. We demonstrate the utility of this modelling approach by assessing hydrologically driven erosion, evolution of grain size in the channel, and fine sediment flux from a study site along the Yuba River in California over individual flood hydrographs and over decadal historical flow series. We quantify the supply of sediment eroded from a contaminated nineteenth century fan terrace of hydraulic gold mining tailings intersecting the Yuba, and find that a threshold for erosion exists at a stage in the channel in excess of 8 m producing episodic sediment concentrations in excess of ~300 mg L^{-1}. The modelling produced erosion and fine sediment pulses from each of three major floods in the past several decades until the flow drops below 500 $m^3\ s^{-1}$ and a bed armor layer forms, while no sediment was generated from the terrace during smaller floods. We further assess the impact on terrace erosion of various river management scenarios with distinct hydrograph shapes and find increased erosion potential when the terrace contains antecedent moisture or the flood time series is run over an extended duration. Sensitivity analysis demonstrated that elevated antecedent moisture within the lateral boundary and increased hydrograph rising time each reduce bank stability and thus increase volumes of failed material. We also show that fluctuations in the hydrograph, typically associated with hydroelectricity generation, result in a more stable terrace than those of a longer duration because there is less time for hyporheic stream water to infiltrate the lateral boundary. This study demonstrates that changes in hydrograph shape as a consequence of climatic forcing or anthropogenic dam releases may have considerable impacts upon sediment delivery and associated contaminants from banks and terraces to the downstream environment.

1. Introduction

The erosion of banks and terraces supplies sediment to channels and thus has important implications for grain-size distributions and morphology in alluvial rivers and by extension for aquatic habitat, as well as for the delivery of floodplain-stored nutrients and contaminants to the aquatic environment. Once sediment enters the channel from banks and terraces, a proportion of it is transported by competent flows, while the remainder becomes incorporated into the channel bed material, where it may affect channel capacity and thus flood risk (Slater et al., 2015). Thus, the problem of sediment supply to channels has important implications for the partitioning of fractional longitudinal sediment flux, the evolution of channel grain-size distributions (GSDs), and stream habitat and for morphological development along river reaches and over temporal periods ranging from multiple storms to millennia. Sediment supplied from lateral boundaries may comprise a large proportion of the total sediment load to rivers (Odgaard, 1987; Simon and Darby, 2002). In the relatively low energy systems of the

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UK, Walling et al. (1999) showed that in the long-term up to 37% of the suspended sediment yield originated from lateral boundary erosion. In addition, sediment budget research on the Amazon River has demonstrated contributions of bank erosion that are 1.3 times larger than the total sediment flux at the river mouth (Óbidos) (Dunne et al., 1998). Contribution of sediment from lateral boundaries during high flow stage should be particularly large in fluvial systems with unconsolidated high banks or terraces along the channel margins (e.g., Singer et al., 2013) and in basins where rainstorms produce major floods substantially larger than mean flows.

Localised sediment supply to channels from bank and terrace erosion (hereafter called *lateral boundary erosion*) is a key source of sediment to lowland channel systems, in which tributaries may play a more limited role in terms of their influence on channel sediment dynamics (Rice, 1998) within lowland valley floors (Singer and Dunne, 2001; Singer, 2008a,b; Singer, 2010). Lateral boundary erosion may be generated by mass wasting of banks and terraces as a result of failure induced by pore pressures once the bank toe has been removed (Simon et al., 2000). This has been observed following floods as extensive failed bank material along channel margins near riverbanks. We have documented many such failures within the Sacramento Valley of California, suggesting that lateral boundary failure did not occur during the rise to peak of the flood (otherwise bank material would have been carried away), but at the peak or on the falling limb of the hydrograph as a catastrophic mass wasting process in response to floodplain water table fluctuations (Rinaldi et al., 2004; Luppi et al., 2009). The implication is that differences in hydrograph shape (whether caused by climate change or anthropogenic modification of hydrology) have the potential to affect erosion of channel boundaries and therefore impact the supply of sediment to the channel from these sources. Thus, streamflow may be the primary driver of lateral boundary erosion through its influence on near-bank stresses and their support of lateral hyporheic water tables that rise and fall within stream banks.

Failure induced by pore pressures in lateral boundaries has not typically been considered to be the dominant mechanism affecting the supply of sediment from banks and terraces and many floodplain-channel morphology modelling efforts have subsumed the relevant erosion processes into lateral boundary erodibility based on characterisations of the flow field (e.g., Johannesson and Parker, 1989; Lauer and Parker, 2008). Such models typically explore the velocity field interacting within the geometry of river bends to identify loci and rates of lateral erosion. However, several other recent research efforts have placed great emphasis on links between boundary water status, bank stability, boundary failure, and in-channel sediment transport (Amiri-Tokaldany et al., 2003, 2007; Rinaldi et al., 2004, 2008). Various reviews of research on the mechanisms of river width adjustment and approaches to its modeling were undertaken in previous decades (Thorne, 1982; ASCE, 1998a, b), so we will not endeavour to repeat this summary here. What is important here is that it is challenging to systematically predict lateral boundary erosion and its contribution to sediment loads over short timescales (individual or sequences of storms) because bank/terrace erosion occurs catastrophically along channel margins during or following floods. Lateral boundaries are subjected to infiltrating rain into floodplain materials and, more significantly, hyporheic water tables as a function of rising river stage that affect material stability. As water content in lateral boundaries increases, frictional resistance between grains is reduced and the entire deposit becomes more prone to failure (Osman and Thorne, 1988; Casagli et al., 1999).

The processes by which water content in lateral channel boundaries affects timing and volumes of bank/terrace failure are the subject of extensive research applying the theory of infinite slope stability (Terzaghi, 1942; Selby, 1993) to riverbanks (Simon et al., 1991; Darby and Thorne, 1996). The infinite slope stability method produces a factor of safety based on linear (Mohr–Coulomb) relationships between shear strength and the normal stress on the failure surface, which take into account material properties, slope geometry, and water content in the matrix. Later implementations have considered the local hydrology explicitly, including confining pressure of river stage, infiltration, and the hydrologic role of vegetation (Simon and Collison, 2001; Darby et al., 2007). Coupled with a groundwater model that computes water table rise and fall within the bank/terrace, these components provide a good framework for predicting lateral boundary failure in response to hydrologic changes in the near-channel zone. These components can then be coupled to characterisations of the fate of the failed lateral boundary material (Amiri-Tokaldany et al., 2007). An important open question is how variations in the driving flow (discharge hydrographs) interact with river banks/terraces over various timescales from individual floods to decades. If developed, this understanding could be used to better assess the impact of hydrology on sediment supply from lateral channel boundary erosion.

Evidence is increasing that hydrologic variability has important implications for channel bed material transport and sorting (Hassan et al., 2006; Humphries et al., 2012; Mao, 2012; Alvarez and Schmeeckle, 2013; Singer et al., 2013; Singer and Michaelides, 2014). Similarly, the shape of the discharge hydrograph and antecedent moisture conditions within lateral channel boundaries are likely to impact failure probabilities for particular bank materials, with implications for the fate and transport of sediment once failure of banks occurs (Rinaldi et al., 2004; Luppi et al., 2009). In the case of fine-grained floodplain materials, a significant proportion of the failed sediment would likely become part of the river's washload (nonsettling component of suspended load) and thus be transported through the reach and deposited on downstream floodplains (Kilham et al., 2012). Legacy terraces from past climatic forcing and/or anthropogenic activities (Bull, 1997; Singer et al., 2013) are typically composed of noncohesive materials and are thus more prone to failure than relatively cohesive riverbanks constructed by modern lowland rivers carrying higher percentages of silt and clay. These lateral boundary units often contain a wide mix of grain sizes that interact with the riverbed in various ways. While some of the failed sediment certainly contributes to fine-grained suspended loads (Carson et al., 1973; Bull, 1997), relatively coarse sediment typically becomes incorporated into the bed. Therefore, a partitioning of sediment loads occurs upon failure, such that the bed inherits a censored signature of bank erosion as has been found for hillslope sediment supply to channels (Michaelides and Singer, 2014).

In this paper, we couple two preexisting modelling frameworks: 1) water status in lateral boundaries is based on the channel discharge hydrograph; and 2) infinite slope stability analysis of terrace failure and subsequent grain size selective sediment transport is used to assess the impact of terrace erosion on bed material grain size and fine-grained sediment flux. We investigate whether consistent thresholds for terrace erosion exist and how various configurations of in-channel flow might be expected to affect the contribution of sediment from lateral boundaries. We then model the impact of individual storm hydrographs, as well as a decadal sequence of daily flows at a site along the Yuba River in California, which is impacted by contaminated historical river tailings terraces produced by nineteenth century hydraulic gold mining in the Sierra Nevada foothills (Singer et al., 2013). We further investigate in a simplistic manner how climate changes or dam operations may affect lateral boundary erosion.

2. Field setting and field data collection

Our field site is within the Yuba Fan, located in the northwestern Sierra Nevada foothills of California (Fig. 1) and has been intensively studied as a result of the legacy of mining debris driving the geomorphology of the area. Nineteenth century hydraulic gold mining resulted in the rapid delivery of mining tailings to channels and delivery of this sediment much farther downstream. The corresponding aggradation of piedmont valleys such as the nearby Bear River basin (James, 1989) led to sustained storage of much of the original deposit lateral to the main channel within terraces and banks (Singer et al., 2013). Twentieth century flood control measures