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Effects of woody vegetation on overbank sand transport during a large flood, Rio Puerco, New Mexico

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ABSTRACT

Distributions of woody vegetation on floodplain surfaces affect flood-flow erosion and deposition processes. A large flood along the lower Rio Puerco, New Mexico, in August 2006 caused extensive erosion in a reach that had been sprayed with herbicide in September 2003 for the purpose of saltcedar (*Tamarix* spp.) control. Large volumes of sediment, including a substantial fraction of sand, were delivered to the reach downstream, which had not been treated with herbicide. We applied physically based, one-dimensional models of flow and suspended-sediment transport to compute volume concentrations of sand in suspension in floodplain flow at a site within the sprayed reach and at a site downstream from the sprayed reach. We computed the effects of drag on woody stems in reducing the skin friction shear stress, velocity of flow, and suspended-sand transport from open paths into patches of dense stems. Total flow and suspended-sand fluxes were computed for each site using well-constrained flood-flow depths, water-surface slopes, and measured shrub characteristics. Results show that flow in open paths carried high concentrations of sand in suspension with nearly uniform vertical distributions. Drag on woody floodplain stems reduced skin friction shear stresses by two orders of magnitude, yet sufficient velocities were maintained to transport sand more than 50 m into fields of dense, free-surface-penetrating stems. An increase in shrub canopy extent from 31% in the sprayed reach site to 49% in the downstream site was found to account for 69% of the computed decrease in discharge between the two sites. The results demonstrate the need to compute the spatial distribution of skin friction shear stress in order to effectively compute suspended-sand transport and to predict the fate of sediment and contaminants carried in suspension during large floods.

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1. Introduction

Distributions and densities of woody vegetation on floodplains can have strong influences on the distribution of erosion and deposition of sediment during deep (>1 m) overbank flows. Drag on woody vegetation can cause orders of magnitude decreases in shear stress on the sediment surface (Kean and Smith, 2004; Smith, 2007), which determines whether sediment will be eroded or deposited on that surface. If sand is available for transport, it will be carried in suspension where the boundary shear stress is sufficiently high and will settle out of suspension onto floodplain surfaces in areas of decreasing shear stress. Modeling the effects of woody vegetation on flow and sediment transport is a complex problem because of multiple feedbacks between the flow, drag on the vegetation, and changes to the bulk fluid density and sediment settling velocities, particularly with high concentrations of sand in suspension (Nelson et al., 2003; Osterkamp et al., 2012). Associations between the spatial distribution of riparian vegetation and patterns of sediment deposition within channels and on floodplains have been observed by many authors (e.g., Friedman et al., 1996a,b; Hupp and Osterkamp, 1996; Tooth and Nanson, 2000; Gurnell et al., 2006, 2008; Corenblit et al., 2009; Dean et al., 2011). Interactions of woody vegetation, streamflow, and sediment transport have been observed and described qualitatively (e.g., Steiger and Gurnell, 2002; Van De Wiel and Darby, 2007), but the ability to quantify the influence of woody vegetation on these processes has been lacking. Nepf (2012) reviewed recent efforts to model the spatial complexity of flow affected by vegetation and noted the lack of a good understanding of the effects of vegetation on sediment transport in natural channels. Interactions of streamflow, fine sediment transport (sand and finer material), and woody vegetation have important implications for biotic responses in a given environment (e.g., Shafroth et al., 2010a) as well as potential contaminant transport and deposition (Graf, 1990; Smith et al., 1998; Malmon et al., 2002; Smith, 2004).

Woody plants affect the flow and boundary shear stress through form drag that extracts momentum from the flow and reduces the velocity and shear stress on the sediment surface (the *skin friction* shear stress). Other forms of roughness include particles of sand or

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gravel that produce skin friction, bedforms that create form drag, and other vegetative or topographic features that block the flow. The various components of roughness combine to produce a total resistance to the flow. Typically, a Manning's *n* (Manning, 1891) type of roughness parameter is applied either to estimate the total roughness at a cross section (for example, Graf, 1983; Birkeland, 2002) or to estimate variable roughness over large floodplain areas (Woltemade and Potter, 1994). However, these approaches require estimation of the magnitude of components of roughness using either results from empirical studies (e.g., following the guidelines of Chow, 1959; Barnes, 1967; Arcement and Schneider, 1989) or model calibration for known flow events. In both cases, the magnitude of individual roughness components, such as drag on woody vegetation, remains highly uncertain, and the spatially variable skin friction, needed to compute erosion or deposition of sediment, cannot be quantified. An understanding of the flow and boundary shear stress fields, which are complicated by the presence of woody vegetation, is required to compute sediment transport (Smith and McLean, 1977; Buffington and Montgomery, 1999; Smith, 2004).

Alternative approaches for modeling effects of vegetation on sediment erosion and deposition have included the use of remote-sensing data (e.g., imagery or aerial or terrestrial LiDAR data) to develop variable roughness classifications for the application of two-dimensional hydrodynamic models over large areas (e.g., Mason et al., 2003; Straatsma and Baptist, 2008; Straatsma and Huthoff, 2011). However, these methods require calibration of a proxy for roughness. Perignon et al. (2013) related observed floodplain vegetation density to flood deposit thickness determined from pre- and post-flood LiDAR differencing for a 12-km segment of the lower Rio Puerco arroyo. Shafroth et al. (2010a) applied a two-dimensional flow model to characterize local shear stresses within vegetation patches along a sand-bed river. However, the modeled shear stresses did not show a relationship with the observed effects of the flow on small stems (including removal in some areas). The authors noted the difficulty of modeling '…*complex relationships among hydraulics, vegetation and bed evolution*…' (Shafroth et al., 2010a, p. 78).

The purpose of this work is to quantify the effects of variable shrub distributions in producing drag on a deep (>1 m) downvalley flood flow and the effects of that drag in reducing the skin friction shear stress and the transport of sand in suspension. A large flood along the lower Rio Puerco in August 2006 eroded about 680,000 m^3 of sediment from channel bank and near-bank floodplain surfaces within a 12-km-long reach sprayed with herbicide in September 2003 (Fig. 1; Vincent et al., 2009). The spatially variable erosion in the sprayed reach made available for transport an abundant supply of sediment, dominantly fine to very fine sand, and the deep overbank flow resulted in thick floodplain sediment deposits (Vincent et al., 2009; Perignon et al., 2013).

We quantified fluid drag on plant stems using the approach of Smith (2004, 2007), who developed a one-dimensional model for flow over a shrub-covered floodplain that calculates explicitly the effects of drag on woody vegetation using known topography and flow conditions (depth and slope). The Smith model was previously applied to reconstruct flow and determine the role of woody vegetation in protecting floodplain surfaces from erosion during the record flood in 1908 along the Clark Fork of the Columbia River in the Deer Lodge valley, Montana (Smith, 2004). Similarly, Griffin and Smith (2004) and Smith (2007) applied the model to examine the geomorphic effects of the distribution of shrubs and beaver dams on erosion during a large flood along East Plum Creek, Colorado, in 1965. Kean and Smith (2005) applied this method to calculate stage–discharge relations for geomorphically stable channels using known topography, bed, bank, and floodplain roughness, and stem distributions.

The study presented here is the first time the model has been applied to a geomorphically unstable environment in which pre- and post-flood high-resolution topographic data are available and in which the pre-flood density and distribution of floodplain shrubs are known. Analogous to the experimental (flume scale) study of Zong and Nepf (2010), we present results from a natural experiment in which flow through patches of woody stems on the floodplain favored deposition of sand, whereas flow in open areas with similarly steep topographic slopes did not. Direct measurement of flow and suspended-sediment transport within the arroyo during flood stage at sites other than the streamflow-gaging station is not practical because of mobility issues and hazards related to arroyo wall and channel bank collapse. However, detailed measurements of flow and suspended-sediment transport made by Nordin (1963) in September 1961 during a meter-deep flow in the then 30-m-wide, sand-bed channel provide data that can be used for comparison with flow and suspended-sediment concentrations computed for the 2006 floodplain flow.

1.1. Objectives

The goal of this work was to characterize the nearly steady August 2006 peak flood flow (Fig. 2) and the variable transport of sand in suspension across floodplain surfaces during this event. The Smith (2004, 2007) model was applied to calculate explicitly the drag on flow through fields of woody, free-surface-penetrating stems as well as drag on stems bent by the flow and submerged using well-constrained peak flow depths and surveyed flood water-surface slopes. A one-dimensional model for suspended-sediment transport (McLean, 1992; Nelson et al., 2003) was applied to compute suspended-sediment profiles in open flow paths and in flow through mapped fields of woody stems. The models were applied to two sites located upstream and downstream from Highway 6 (Fig. 1): (i) a segment of the nearly 12-km reach with reduced canopy cover after being sprayed with herbicide 3 years prior to the flood (treated site); and (ii) a segment of the downstream reach not sprayed with herbicide (untreated site). The two sites have large differences in fractional area of floodplain covered by shrubs and in the spatial distributions of those shrubs. However, flood-flow widths and preexisting floodplain topography were similar. Our objectives were to (i) quantify the effects of the drag on woody vegetation in reducing the flood-flow velocity and skin friction shear stress; (ii) determine the spatial extent of flow field affected by drag on shrubs; and (iii) determine how the flow through and around shrubs affected the suspended-sand transport and deposition during the flood.

The total downvalley flow and sediment flux through each site were estimated in a manner similar to that of Wu and He (2009), by summing the flow and sediment fluxes in the channel, in flow over open floodplain segments and in flow through dense woody stems. The computed total discharge at each section was compared to an estimate of the flood peak discharge at the concrete sill located on the downstream side of the railroad bridge at the Highway 6 crossing (Fig. 1). The magnitude of the reductions in discharge and total sediment flux attributable to increased shrub extent were determined.

Although the application presented here consists of one-dimensional (1D) computations of flow and sediment transport, the method could be applied within a two-dimensional (2D, in *X* and *Y*) hydrodynamic model, which could include effects of feedbacks between the woody vegetation, flow, and suspended-sediment transport.

1.2. Study area

The Rio Puerco is an ephemeral tributary of the Rio Grande with a contributing drainage area of about 16,100 km^2 located in semiarid north-central New Mexico (Fig. 1). Elevation ranges from 3444 m at the summit of Mount Taylor, in the central part of the watershed near Cubero, to 1440 m near the mouth of the Rio Puerco at Bernardo. Our study sites are within the 67-km-long lower Rio Puerco, downstream from the confluence with the Rio San Jose. This reach is within an arroyo incised into a wide (typically 1 to 2 km) alluvial valley (Fig. S1 in online Supplementary data) filled with fine sediment, dominantly sand, silt, and clay (Heath, 1983; Love, 1986). R.E. Dodge defined an arroyo as '… a steep-sided, narrow gulch cut in a previously filled gravel and adobe valley in the arid West' (Hovey, 1902, p. 746). Bryan and Post