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Sedimentation patterns across a Coastal Plain floodplain: The importance of hydrogeomorphic influences and cross-floodplain connectivity

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ABSTRACT

The floodplains of large Coastal Plain rivers in the southeastern U.S. are important long-term storage sites for alluvial sediment and nutrients. Yet considerable uncertainty surrounds sediment dynamics on many large river floodplains and, in particular, the local scale factors that affect the flux of sediment and nutrients from rivers onto their floodplains and their subsequent deposition. This research quantifies short-term rates of sediment deposition from 2012 to 2014 on floodplain sites at Congaree National Park using feldspar pads. Sediment deposition rates ranged from 0.1 to 15.6 cm (median = 1.46 cm) and were closely associated with inundation frequency and geomorphic position. Cross-floodplain distributary channels served as particularly important conduits for moving sediment onto the floodplain. Physical and chemical analyses of soil samples demonstrated that the most flood-exposed sites had higher major nutrient and micronutrient levels (especially of phosphorus) and more diverse nutrient compositions. This research advances current understandings of lateral floodplain connectivity by demonstrating the complex effects of regional hydrology and local floodplain environmental characteristics on the supply of sediment and nutrients.

1. Introduction

A key function of floodplains bordering large meandering rivers is the storage of sediment and nutrients that have been transported from upstream reaches (Phillips, 1989; Hupp, 2000). The delivery of sediment to a particular floodplain location is dependent upon the degree of hydrologic connectivity that exists between that site and the river. In humid climates, such connectivity is maintained by flooding that fluctuates in magnitude, frequency, duration, and timing with seasonal and interannual variations in environmental conditions such as temperature, precipitation, and evapotranspiration (Lins, 1997; Lecce, 2000; Tockner et al., 2000). In most cases, rivers and their floodplains are connected by flood flows that range from high magnitude/low frequency events that inundate floodplains via overbank flow to low magnitude/high frequency floods that may regularly pulse into the floodplain channel network at stages below a river's bankfull level (Bridge, 2003; Opperman et al., 2010).

Overbank flows are widely recognized as the dominant mechanism structuring floodplain development and evolution (Lewin, 1978; Magilligan, 1992; Walling and He, 1998; Lecce and Pavlowsky, 2004). Overbank flooding occurs when a river's discharge exceeds its bankfull level and when floodwaters flow over natural levees and alluvial ridges onto floodplains where their character is transformed into sheet flow. Floodwaters then move in a predominantly downvalley direction until reconnecting with the main channel. These flows can inundate entire floodplains and commonly have recurrence intervals of 1.5–2.0 years (e.g., Dunne and Leopold, 1978), although considerable variation exists in the exact definition and calculation of bankfull discharge (e.g., Williams, 1978). Compared to the deep and relatively unobstructed flow in the main channels of meandering rivers, overbank flow spreads out and becomes shallower and loses competence as it encounters the physical features of the floodplain, which promotes deposition (Happ et al., 1940; Brierly et al., 1997).

During overbank flooding, transported sediment is moved onto floodplains by two primary processes: turbulent diffusion and convection (James, 1985; Pizzuto, 1987). Deposition is often most pronounced at the interface between the river channel and floodplain, where sediment transport mechanisms transition from a combination of diffusion and convection — which characterize the movement of suspended and bedload material mobilized by the higher flow velocities of main river channels — to transport that is dominated by diffusion caused by the shallower and slower character of overbank flow. At locations along channel margins, turbulent eddy lines form, and the water becomes overloaded with sediment (James, 1985; Mariott, 1996), resulting in what are typically the highest rates of sediment deposition and the construction of natural levees and alluvial ridges. Such features are comprised of predominantly coarse-grained alluvium that closely resembles river channel deposits (Bridge, 2003).

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Moving away from a river's margins and farther into a floodplain's low-lying flood basin, the velocity of overbank flow progressively decreases. In the context of overbank flooding, where flows are predominantly parallel to river flow (i.e., downvalley), we see a distinction between near-channel and backswamp zones of sedimentation that is defined by a reduction in energy. Floodplain sedimentation should theoretically exhibit thicknesses and grain sizes that become exponentially thinner and finer with increasing distance from the river (Nanson and Croke, 1992). However, patterns of flood flow, and thus sediment deposition rates and grain-size distribution, are complicated by floodplain topography. In particular, spatial variability in flood depth and routing results in flow characteristics that drive sediment transport through a combination of diffusion and convection. The topographic complexity of the floodplain thereby generates significant variation in flood direction and velocity that can produce patterns in sediment thicknesses and grain size that do not conform to thinning and fining away from river channels (Pizzuto, 1987; Mariott, 1992; Asselman and Middelkoop, 1995; Lecce and Pavlowsky, 2004).

Bankfull discharge is commonly defined as the flow that reaches the transition between the channel and its floodplain (Leopold et al., 1964) and has been tied to a number of general relationships with river morphology (e.g., channel width, slope, and meander length and pattern) and floodplain hydrology. Recent interest, however, has centered on the role of sub-bankfull flows in instream and floodplain processes (Bourke, 2002; Thorp et al., 2006). Phillips (2013) identified six types of surface water connectivity between active river channels and floodplain depressions, several of which involve flow connections that are established at sub-bankfull levels via distributary channels and local levee breaches. Others have similarly documented that oxbow lakes, sloughs, and other floodplain depressions are critical elements of floodplain hydrology and ecology (e.g., Phillips and Slattery, 2007; Kupfer et al., 2015). Little work on distributary streams and floodplain channel networks, however, has examined their role in shaping amounts and patterns of sediment fluxes.

On large, meandering rivers in humid climates, frequent storms generate sub-bankfull floods that pulse into tributaries, crevasse channels, and abandoned channels that are themselves connected to the larger network of distributary channels (Patterson et al., 1985). Where flooding is initiated by sub-bankfull flows and conveyed across the floodplain by networks of depressional features, the higher velocity flows of the river are conducted into the floodplain with fewer obstructions from landforms and vegetation than with overbank flooding. Within floodplains, distributary channels may dissect landforms that are the product of historic channel evolution (e.g., the levees and crevasse splays of abandoned channels) or even aeolian dunes (e.g., the Sandhill region that is located between the Piedmont and Inner Coastal Plain physiographic provinces in North and South Carolina) that are local storage sites for sediment and nutrients. Floodplain channels are thus locations where combinations of convective and diffusive sediment transport processes can facilitate the delivery of bedload and suspended sediment to diverse floodplain locations. Furthermore, these are features where sedimentation processes regularly occur at discharges below a river's bankfull level.

The purpose of this research was to determine the importance of site-specific flood regime and geomorphic setting on sedimentation characteristics on a large river floodplain in the southeastern U.S. Previous studies have addressed processes associated with floodplain sedimentation on the Atlantic Coastal Plain by measuring floodplain-scale sediment accumulation rates, cumulative nutrient retention, or net nutrient uptake and processing by vegetation (Noe and Hupp, 2005, 2007, 2009; Hupp et al., 2013). However, floodplain sedimentation studies that examine local influences on sediment and nutrient dynamics are important but less common (Simm, 1995; Lewin, 1996; Hupp et al., 2015). We specifically examined short-term sediment deposition rates, soil textures, and soil chemistry as a function of (i) different landform types with varying hydrologic exposures (i.e., geomorphic position) and (ii) flood frequency and duration (i.e., flood regime).

2. Regional setting

2.1. Study area

This study was conducted on the 969-ha Bates Fork tract at Congaree National Park, which is ca. 50 km southeast of Columbia, SC, USA (Fig. 1). Bates Fork is the peninsular portion of the floodplain located at the confluence of the Congaree and Wateree Rivers, which have upstream drainage areas of 21,500 and 14,500 km^2, respectively. Both rivers originate in the Blue Ridge physiographic province of North and South Carolina and flow across the Piedmont before merging to form the Santee River on the Inner Coastal Plain. Their hydrology is affected by hydroelectric dams on the main stem of the Wateree River and on the Saluda River, which contributes 25–30% of the flow of the Congaree River at the Columbia, SC, USGS gaging station, upstream of the park (Koman, 2003). River flows are highest from January to April and lowest in July and August when evapotranspiration is high (Conrads et al., 2008).

Bates Fork is one of the most low-lying areas on the Congaree River floodplain, and nearly the entire tract is flooded in typical years. The site's geomorphology reflects a dominant hydrological influence from the Congaree River, with lesser flood inputs along its eastern margin from the Wateree River. Topography, which reflects and determines variations in flood regime across the floodplain, is characterized by point bars, levee complexes, ridge and swale systems, and abandoned channels. Gradients in flood regime and geomorphic setting provide distinct habitat types that support unique and diverse bottomland forest communities, including assemblages of tree species dominated by oaks and sweetgum on drier sites and bald cypress and water tupelo communities in areas that retain ponded water (Kupfer et al., 2010). The tract itself is surrounded on nearly all sides by rivers (the Congaree River, Wateree River, and Bates Old River), limiting sediment sources to materials brought in by floodwaters or redistributed within the tract itself.

2.2. Sample site selection

To quantify and explore patterns of sediment accumulation, texture, and chemistry, we established 39 sample sites in the summer of 2012. Potential sample locations were stratified to capture variability in (i) geomorphic position and (ii) flood regime.

2.2.1. Geomorphic position

Geomorphic position, which describes each site's floodplain landform type, was assigned into one of four classes: river margin, abandoned channel, ridge, or swale. River margin sites were located along the alluvial ridges of the Congaree and Wateree rivers and included natural levee, crevasse channel, and crevasse splay locations — sites most directly exposed to high-energy flood flows from the river. Abandoned channel sites were located along the edge of Bates Old River, an oxbow lake that was the main channel of the Congaree River until the river shifted to its current channel in 1852. Swale sites were located in backswamp depressions along the margins of distributary channels, drains, and sloughs that move and pond water that pulses into and across the floodplain. Ridge sites, on the other hand, were backswamp sites that do not channel or retain ponded water. These classes capture variations in river connectivity (and thus sediment availability) and depositional setting.

2.2.2. Flood frequency

'Straightline' distance from a site to the main river is not a good predictor of its hydrological connectivity or flood regime in areas characterized by complex flow pathways (e.g., Phillips, 2013). The flood regime for each sample site was therefore estimated using results generated by the TUFLOW model, as described in Meitzen (2011) and Kupfer