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Recent and historic sediment dynamics along Difficult Run, a suburban Virginia Piedmont stream

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ABSTRACT

Suspended sediment is one of the major concerns regarding the quality of water entering the Chesapeake Bay. Some of the highest suspended-sediment concentrations occur on Piedmont streams, including Difficult Run, a tributary of the Potomac River draining urban and suburban parts of northern Virginia. Accurate information on catchment level sediment budgets is rare and difficult to determine. Further, the sediment trapping portion of sediment budget represents an important ecosystem service that profoundly affects downstream water quality. Our objectives, with special reference to human alterations to the landscape, include the documentation and estimation of floodplain sediment trapping (present and historic) and bank erosion along an urbanized Piedmont stream, the construction of a preliminary sediment balance, and the estimation of legacy sediment and recent development impacts. We used white feldspar markers to measure floodplain sedimentation rates and steel pins to measure erosion rates on floodplains and banks, respectively. Additional data were collected for/from legacy sediment thickness and characteristics, mill pond impacts, stream gaging station records, topographic surveying, and sediment density, texture, and organic content. Data were analyzed using GIS and various statistical programs. Results are interpreted relative to stream equilibrium affected by both post-colonial bottomland sedimentation (legacy) and modern watershed hardening associated with urbanization. Six floodplain/channel sites, from high to low in the watershed, were selected for intensive study. Bank erosion ranges from 0 to 470 kg/m/y and floodplain sedimentation ranges from 18 to 1369 kg/m/y (m refers to meters of stream reach). Upstream reaches are net erosional, while downstream reaches have a distinctly net depositional flux providing a watershed sediment balance of 2184 kg/m/y trapped within the system. The amounts of both deposition and erosion are large and suggest nonequilibrium channel conditions. Both peak discharge and number of peaks above base have substantially increased since the mid-1960s when urbanization of the watershed began. Deposition patterns are most closely correlated with channel gradient, sinuosity, and channel width/floodplain width for recent and historic periods. The substantial amounts of fine grained sediment deposited on the floodplain over the past two centuries or so do not appear to be closely related to historic mill pond presence or location. The floodplain continues to provide the critical ecosystem service of sediment trapping in the face of multiple human alterations. Trends in sediment deposition/erosion may react rapidly to land use practices within the watershed and offer a valuable barometer of the effects of management actions.

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1. Introduction

The Piedmont Physiographic Province of the Mid-Atlantic Region has received considerable fluvial geomorphic study over the past half century. This literature contains classic studies that became part of the foundation of modern fluvial geomorphology (Wolman and Leopold, 1957; Leopold et al., 1964; Wolman, 1967). This early work instigated subsequent study in the eastern U.S. on sediment dynamics, including that associated with European colonization, gully formation on uplands, and legacy sedimentation on floodplains (Knox, 1972; Trimble., 1974; Costa, 1975; Knox, 1977; Trimble., 1983; Jacobson and Coleman, 1986). More recently, this region has seen renewed study on the impacts of legacy sediment deposits and urbanization (Pizzuto et al., 2000; Bain and Brush, 2005; Allmendinger et al., 2007; Gellis et al., 2009), riparian vegetation (Hession et al., 2003), and mill dams (Walter and Merritts, 2008; Pizzuto and O'Neal, 2009; Schenk and Hupp, 2009; Merritts et al., 2011) on sediment dynamics and loading to sensitive downstream ecosystems. An understanding of the factors influencing sediment dynamics is essential to management efforts to reduce downstream sediment loading and to improve water quality.

Previous work (see above) suggests that an immense volume of sediment is stored in riparian areas. Consequently, the retention of sediments and associated contaminants is likely to remain a major concern in the Chesapeake Bay watershed over the long term. Tributaries to the Chesapeake Bay, a threatened ecologically critical estuary, drain a substantial portion of the Mid-Atlantic Piedmont. Sediment and associated nutrients carried by these tributaries are considered major factors negatively affecting the water quality and estuarine life in the Bay and have been targeted for intensive study over the past several years. The

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Piedmont portion of the Chesapeake Bay watershed is about 23% of the catchment; however, over 60% of the suspended sediment delivered to the Bay may be derived from the Piedmont (Gellis et al., 2009). Floodplain and channel sedimentation dynamics, in particular riparian sediment retention, are intimately associated with other water quality components (Noe and Hupp, 2005, 2009) and provide for profound ecosystem services. The literature focused on the riparian buffering function (sediment and nutrient trapping from adjacent upland flow) of floodplains is substantial; however, research devoted to the retention function (trapping of sediment and nutrients from flood flow) of floodplains is less well developed. The stream–floodplain flux and storage of macro nutrients (N and P), organic material (C), trace elements, and other contaminants that are mediated through sediment dynamics are likewise affected by human alterations. Geomorphic analyses verify that riparian retention of sediment and associated material is a common fluvial process (Jacobson and Coleman, 1986; Noe and Hupp, 2005; Hupp et al., 2008), yet retention time of sediment (Malmon et al., 2005; Lauer and Parker, 2008) and biogeochemical transformations (Noe and Hupp, 2009) during storage may be the most poorly understood, unquantified aspects of sediment (Hupp, 2000; Trimble and Crosson, 2000) and nutrient budgets (Noe et al., in press).

Riparian zones may also have substantial rates of bank erosion that lead to sediment and contaminant loading downstream (Arp and Cooper, 2004). However, few studies have examined the factors that determine the balance of floodplain deposition and bank erosion throughout a catchment or for long distances along a channel (Hupp et al., 2009a). Present-day bank erosion associated with channel incision and widening through floodplain deposits may be directly related to delivery of suspended sediment to the Bay. This erosion, to some degree, negates the ecosystem service of floodplains (Noe and Hupp, 2009) by releasing stored (hundreds of years) legacy sediment, which typically comprises the bulk of bank material exposed along Piedmont streams (Costa, 1975; Jacobson and Coleman, 1986; Walter and Merritts, 2008).

Urbanization and sub-urbanization of watersheds, in addition to historic anthropogenic disturbance, leads to changes in water-runoff patterns that can have dramatic effects on erosion and sedimentation in stream corridors (Allmendinger et al., 2007). This occurs largely through increases in compacted or impervious surfaces in the watershed that increase runoff (Sauer et al., 1983; Villarini et al., 2009). Increased stormwater energy in turn increases channel incision, channel enlargement, and bank erosion (Morisawa and LaFlure, 1979).

Three important unifying fluvial geomorphic concepts were identified by Hupp et al. (2009b) that can help explain and predict sediment dynamics in watersheds with large stores of sediment: (i) hydraulic connectivity between streamflow and the riparian zone (e.g. bars, banks, and floodplains); (ii) spatially migrating impetuses/thresholds for rapid geomorphic change (migrating channel knickpoints); and perhaps most importantly (iii) dynamic equilibrium in fluvial systems (Hack, 1960). Dynamic equilibrium in geomorphology refers to the mutual adjustment of a catchment with its geologic underpinning and the streams that drain it such that a stream is capable of entraining, transporting, and storing the delivered sediment to fluvial landforms in a balanced fashion (typically no excessive net fluvial erosion or deposition). Streams may exist in relative equilibrium with characteristic fluvial landforms that reflect an overall erosional regime such as steep mountain streams or, conversely, a sediment-storage regime such as most Coastal Plain streams; intermediate are streams with transport regimes typical of the Piedmont. Thus, equilibrium, by definition, is not static but dynamic in response to the ambient regime conditions imposed by regional physiography. Streams that are not in equilibrium typically have been subjected to dramatic, usually rapid, regime shifts; this may happen naturally (e.g., earthquakes) or through human alteration (Hupp et al., 2009b).

Difficult Run is an urbanizing Virginia Piedmont stream that presumably experienced historic severe fluvial aggradation (legacy sedimentation) and recent substantial increases in catchment imperviousness (urbanization). Difficult Run (Fig. 1) drains a part of the rapidly expanding

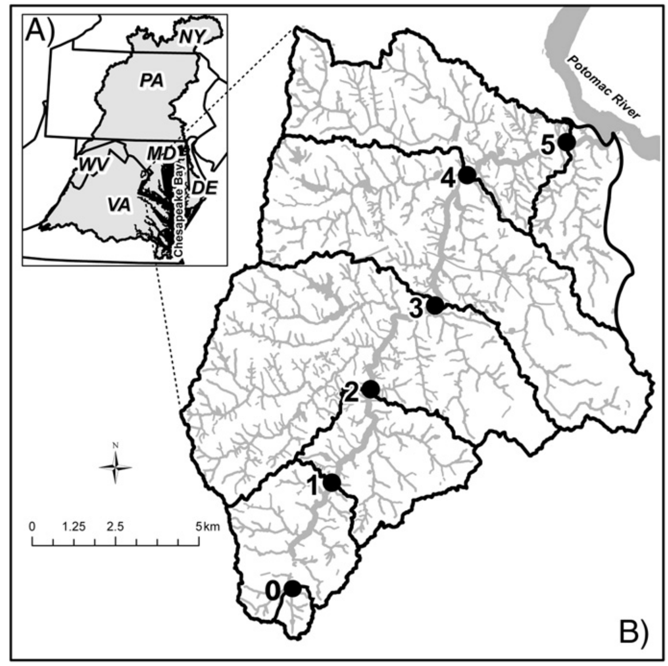

Fig. 1. (A) Location of Difficult Run watershed in the Mid-Atlantic region of the United States and the Chesapeake Bay, east and downstream, is shown. (B) Detail of the watershed, location of study sites and catchment area above each are shown. Site 5 is located just above a gorge leading to the confluence with the Potomac River.

Washington, DC/Northern Virginia metropolitan area. It was selected for intensive study as representative of urbanizing Piedmont parts of the Chesapeake Bay catchment. Our objectives for the present study include: (i) the documentation and estimation of floodplain sediment trapping and bank erosion, (ii) the construction of a preliminary sediment balance (floodplain deposition/bank erosion), and (iii) the estimation of floodplain storage of fine grained sediment (past two centuries) that has potential for delivery to the Chesapeake Bay. In this paper, we intend to show that even in the face of multiple severe human alterations to the landscape that perturbed the dynamic equilibrium of Difficult Run, the floodplain still provides the important ecosystem service of sediment retention.

2. Site description

Difficult Run is a fifth-order stream in the crystalline Piedmont (gneiss and schist bedrock) of Virginia that is tributary to the Potomac River and the Chesapeake Bay (Fig. 1). Streams of this region are generally pool — riffle systems flowing on a gravel bed. The last 1.5 km of the stream before confluence with the Potomac River is in a gorge with considerable bedrock within the channel perimeter. All study sites are above the gorge and none have bedrock in the channel perimeter along the study reaches; bedrock has been noted at a few locations upstream of the gorge. Site 0 displays minor alluvial conditions with limited development of typical fluvial landforms e.g. floodplains or in-channel bars; sites 1 through 5 display well developed fluvial landforms. The banks are mostly composed of fine-grained deposits that typically lie above more coarse material that is assumed to be pre-colonial in age; at two locations a buried plank road (Fig. 2, inset) rested upon the precolonial horizon and 1.8 to 2 m of deposition occur above the plank road; pollen analysis at an upstream site also confirms the post-colonial age of this fine grained deposit. The banks are eroding along most reaches, however in-channel deposition does occur in the form of sporadic point bars and low gravel bars. The watershed experienced extensive land clearing and colonial row-crop agriculture that led to upland erosion and associated bottomland sediment deposition (presumably legacy sediment). This colonial period was followed by use as pasture and dairy farms up