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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

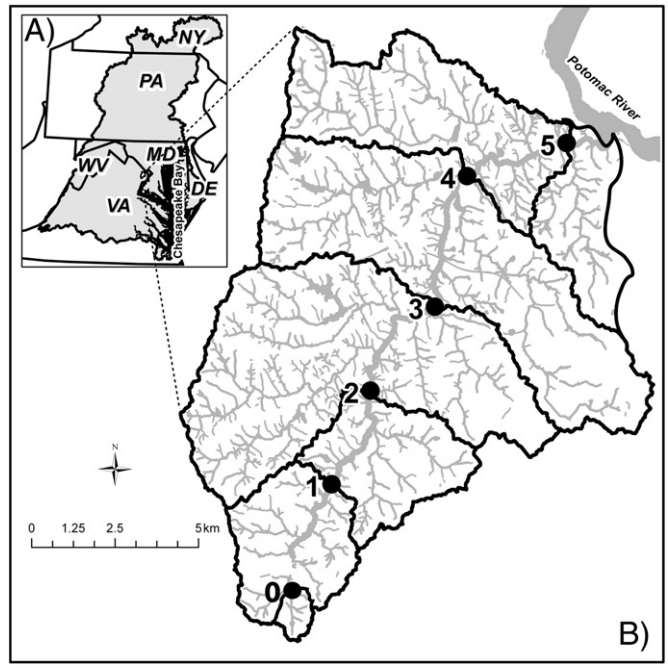

Fig. 1. (A) Location of Difficult Run watershed in the Mid-Atlantic region of the United States and the Chesapeake Bay, east and downstream, is shown. (B) Detail of the watershed, location of study sites and catchment area above each are shown. Site 5 is located just above a gorge leading to the confluence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

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Fig. 2. General view of Difficult Run near site 3, looking downstream; inset upper left, buried and submerged plank road, at arrow, near site 4; bank is about 2 m in height. Inset lower left, contact between fine-grained (legacy) deposit, above and coarse pre-colonial deposit shown below knife near man's hand; bank is 1.8 m in height.

until the middle of the twentieth century, when much of the area reverted to large tracts of second-growth forest. This area urbanized rapidly beginning about 1965 through the 1990s and has a mix of urban and suburban land use; however, most riparian areas remain preserved as second-growth forest and managed for natural resource protection (Fairfax County Park Authority). The USGS operates two streamgages on the mainstem of Difficult Run. The long-term downstream streamgage (01646000) monitors the majority of the watershed. Mean annual discharge near the mouth of the 151 km^2 watershed is 1.76 $m^3\ s^{-1}$ (62.3 $ft^3\ s^{-1}$). Peak flows for the past two decades generally range between 28 and 34 $m^3\ s^{-1}$, discharges that may inundate the floodplain. Difficult Run previously had several low-head mill dams that were in use from the mid to late 1700s through the 1800s, none of which currently exist (John Rutherford, Fairfax County Park Authority, written communication, 2008). The upstream, recently installed, gage is collocated with site 1 of this study, and although part of the ongoing larger study, is not used in the majority of the analyses in the present paper.

3. Methods

Six floodplain sites were located on the second to fifth order mainstem of Difficult Run from headwaters to the mouth of the watershed (Fig. 1). Site locations were chosen to span the watershed, have characteristic geomorphology (gravel bed and pool/riffle system) and vegetation (forested second growth and riparian), and are publicly owned and managed for natural resource protection (Fairfax County Park Authority). Cumulative catchment areas range from 3 km^2 at site 0, the most upstream and largely nonfluvial site, to 141 km^2 at site 5, the downstream-most site (Table 1). Catchment area above each study site, elevation, gradient, width–depth ratio, and sinuosity along the reach at each site were determined from field measurements at the site, maps, and surveyed floodplain and channel cross sections facilitated by LiDAR imagery . We established a well at a low point in the floodplain of each site fitted with a pressure transducer to continuously monitor water level conditions (including floodplain inundation) during the course of study. Data collection occurred over a 3-year period from summer 2008 to summer 2011. Fluvial landform terminology and definitions follow Osterkamp and Hupp (1984); in particular, floodplains are inundated at least once every 1 to 3 years, and terraces have a flood-return interval of >3 years. The USGS gage located at the downstream end of the study area provided long-term hydrologic information on flood magnitude and frequency and potential inundation to the following field and laboratory procedures. Fluvial geomorphic variables for floodplain deposition and bank erosion were tested for significant correlations using Pearson product-moments correlation analysis.

A sediment balance (quasi budget) was estimated by computing the difference between floodplain and bank change. Neither in-channel bed change or suspended sediment is included in the sediment balance. Results of floodplain sedimentation and bank erosion dynamics are reported in two units or metrics. First, as a flux in $g/m^2/y$ that refers to point amounts that allow for conceptualization in terms of a m^2/y, and second, as a load in kg/m/y where mass of material is normalized to a meter of reach length and allows for comparison regardless of bank height or floodplain width. We use the term "flux" in a more ecosystem/biogeochemical context referring to the flow or movement of material (sediment in this case). We do not imply flux by flows in the channel, which may be the more typical fluvial geomorphic interpretation of the word. Further, we feel the use of the term is more correct, integrative, and economical given that a "flux" can be positive or negative, which cannot be said for deposition or erosion alone where there is an implication of one direction.

3.1. Floodplain sedimentation

All floodplains at study sites were forested, usually located on one side of the stream, and included three floodplain geomorphic features (Fig. 3): higher elevation natural levees adjacent to the channel; lower elevation backswamps that typically occur away from the main channel near the hill- or toeslope. Backswamps tend to be wetter with characteristic organic soils and vegetation distinct from the higher and drier levee (Hupp, 2000) and higher elevation toeslopes adjacent to the uplands. Levee development is variable, but distinguishable at all sites. Toeslopes were absent at two sites and may be affected by colluvial rather than entirely alluvial processes; for these reasons, toe-slope stations were removed from floodplain deposition analyses in the present paper. Average floodplain widths (levee and backswamp) for each site were

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Table 1
Site summary of channel, floodplain, and catchment conditions and results of analyses.

	Site 0	Site 1	Site 2	Site 3	Site 4	Site 5
Catchment area, km^2	3	14	28	74	117	141
Elevation, m	107	88	78	63	54	47
Gradient	0.0091	0.005	0.0025	0.0018	0.0019	0.0038
Sinuosity	1.21	1.38	1.22	1.48	1.57	1.44
Mean width, levee + floodplain, m	23	52	65	122	162	157
Reach length, m	100	150	200	125	160	125
Sampling stations	12	12	12	22	20	27
–Percent of stations in backswamp	41	41	67	50	75	37
Floodplain deposition, $g/m^2/y$	1059	7331	6402	14,168	26,690	12,220
–Mineral fraction, $g/m^2/y$	948	6804	6182	13,223	26,099	11,993
–Organic fraction, $g/m^2/y$	111	527	220	945	591	227
–Levee fraction, $g/m^2/y$	1112	6468	4887	7672	23,690	9405
–Backswamp fraction, $g/m^2/y$	624	864	1514	1095	3000	2815
–Percent of pads erosional	16	42	50	14	20	22
Levee inundation, %	No data	0.00	0.00	0.03	0.12	7.43
Backswamp inundation, %	No data	9.98	0.20	4.25	30.79	23.68
Floodplain mass deposition, kg/m/y	18	138	109	832	1369	935
–Mineral fraction, kg/m/y	17	128	98	773	1319	917
Bank erosion, m^3/y	−37.2	−782.6	−770.4	−180.8	16.2	−161.2
Mass bank erosion, kg/m/y	−33	−470	−385	−145	9	−193
Net sedimentation, kg/m/y	−15	−332	−277	687	1378	742
Legacy thickness, m	0.9	1.2	1.1	1.5	1.7	1.4
Legacy volume, m^3	2088	9300	14,300	22,940	44,060	27,420
Floodplain trapping factor, gross	1	5	3	37	47	41
Floodplain trapping factor, net	−1	−12	−8	30	48	33

between 23 and 162 m (Table 1). Most sites had three transects oriented perpendicular to the channel that began on the levee near the stream and ended at the transition from toeslope to uplands (site 2 had four transects). All transects were surveyed (leveled) using an optical level and rod (Fig. 3); most within site interpretations were made referring to these surveys. Transects were typically spaced 50 m apart along the longitudinal dimension (Fig. 3). Sampling stations were typically spaced by about 10 to 25 m along each transect (Fig. 3), depending on floodplain width. Stations were classified into one of the three geomorphic features (levee, backswamp, and toeslope) based on site hydrogeomorphic interpretation and relative elevation. Transects had between three and nine sampling stations depending on floodplain width. We established a

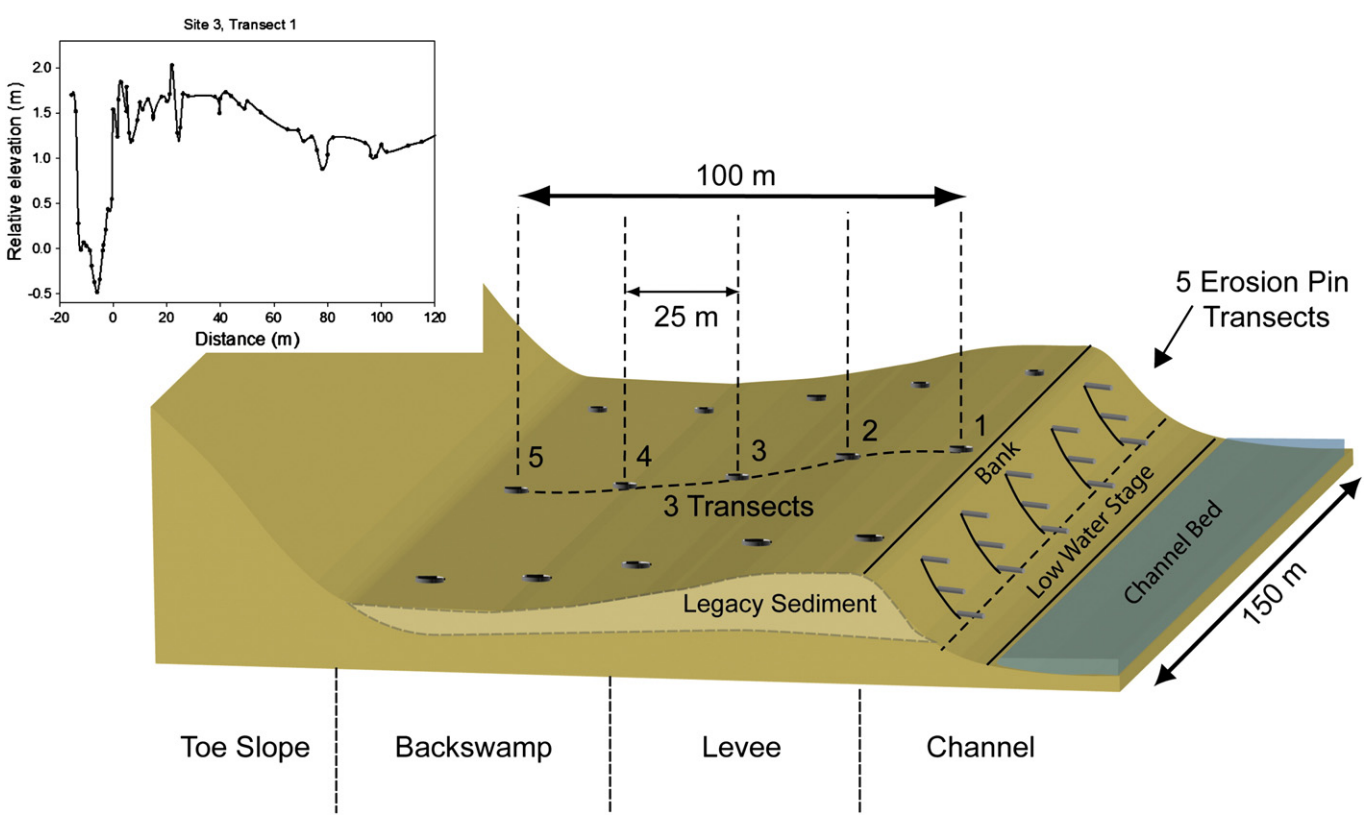

Fig. 3. Generalized plan of a study site showing location of floodplain (levee and backswamp) and bank (erosion pin) transects. Typical location of legacy sediment is indicated. Figure is not to scale and is vertically exaggerated, actual bank heights are between 2.5 and 1 m. Inset, upper left, is actual leveled cross section at site 3 from channel on left through levee, and backswamp to beginning of toeslope on right.

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total of 105 sampling stations along Difficult Run (Table 1). After removal of toeslope stations for intrasite analyses, 83 stations remained, including 29 levee and 54 backswamp stations.

Artificial marker layers (clay pads) were placed at each sampling station. These markers are made by placing powdered white feldspar clay 20 mm in thickness over an area of about 0.5 m^2 on the soil surface that has been cleared of coarse organic detritus. This clay becomes a fixed plastic marker after absorption of soil moisture that permits accurate measurement of short-term net vertical accretion (Baumann et al., 1984; Hupp and Bazemore, 1993; Kleiss, 1996; Ross et al., 2004). The clay pads were examined and measured for depth of burial annually during the course of study (from 2008 to 2011) to measure potential net fine-grained deposition. Coarse organic material (stems and leaves) are not included in net deposition amounts. Net deposition is a mean of at least three measurements for each pad during each sampling interval to the nearest millimeter. Erosion chains were placed near each of the clay pads to measure potential net erosion (negative values, erosion, are included in net deposition rates). Each clay pad is identified as being located on either a levee or backswamp surface; whole site averages of net deposition include both levee and floodplain pads. Initial sediment samples were taken near all clay pads to a depth of 20 mm and analyzed for (i) bulk density, by taking a known sample volume, which was then dried and weighed; (ii) size clast composition by dry sieving with various screen sizes in a vibratory sieve shaker (Guy, 1969); and (iii) organic fraction of the sample by loss-on-ignition (400 °C for 16 h; Nelson and Sommers, 1996).

3.2. Bank erosion/deposition

Bank transects were established at the levee ends of each floodplain transect (Fig. 3), spanning both banks; these transects were leveled and tied to temporary benchmarks at the beginning of the study. Two additional bank transects were established between the floodplain transects (Fig. 3) for a total of five at each site (seven at site 2). Samples of bank sediment were analyzed for organic fraction and sediment size clast composition (see above). Erosion pins (1 m long) were placed in each bank and located in the lower, middle, and upper thirds of the bank surface that was exposed at low-water. This spacing allowed for erosion/deposition measurement at most prominent breaks in the bank slope. We instrumented 30 transects containing 180 erosion pins. The pins were measured annually and after selected storm events. During each visit, the pins were measured for the amount of erosion (pin exposure) or amount of deposition (pin burial) following Hupp et al. (2009a); buried pins were located using a metal detector. Measurements were taken along an axis normal to the local ground surface, parallel to the pin. Mean bank erosion rates were calculated for each third of the bank surface at each site. These rates were combined and multiplied by reach length and bank height to estimate volume and mass eroded during the study.

3.3. Fine grained (legacy) sediment

Fine grained sediment thickness was measured at stream bank locations where the contact with pre-colonial alluvium was easily determined (Fig. 2) at all study sites. This contact was typically either a coarse sand horizon or sand and gravel/cobble deposits that crop out low on the exposed bank (Costa, 1975; Jacobson and Coleman, 1986), which are overlain by red-brown silt (Fig. 2), characteristic of the legacy sediment described by Happ et al. (1940). Additionally, remnants of a plank road was found at site 4 and burial depth was measured (legacy thickness). Measurements (at least six at each site) were taken from the top of pre-colonial sediment to the bank top at the most pronounced contacts at or near transects within each of the six study sites. At site 1, a vertical series of sediment samples were taken above and below the fine-grained–coarse material contact for pollen analysis to document European arrival (ragweed signature) and land clearance. It is beyond the scope of this paper to present a detailed stratigraphic analysis of floodplain sediments. However, the fine grained deposit found on the floodplains at all sites is consistent with most descriptions of legacy sediment, for this reason and because of the pollen analysis, buried plank road and other buried artifacts we will refer to this deposit as legacy. The lower boundary of this sediment was assumed to spread across the floodplain (Fig. 3) to near the present lowermost toeslope (not alluvium). The upper boundary is considered the present ground surface and was determined from surveyed transect lines. This thickness was then multiplied by floodplain area (mean transect length over levee and backswamp surfaces × reach length) to provide a crude approximation of the site volume of the fine grained (legacy) deposit. We do not separate modern deposition from legacy material given the degree of integration by current erosion and deposition processes; no systematic contact separating legacy and modern deposits was observed. We assume that much of the material moved/deposited presently is legacy (in a second order function) in origin. Our measurements of modern deposition are a snapshot and cannot account for long-term floodplain thickness variation resulting from cycles of erosion/deposition and compaction.

3.4. Sinuosity, gradient, and mill pond mapping

Here, and for other topographic analyses, we constructed and analyzed digital elevation maps (DEM) derived from 0.5 m^2/pixel 2004 LiDAR data (vertical accuracy 0.028 m, average error between bare earth LiDAR coverage and the control, with a root mean square error of 0.077 m) of the Washington, DC area, using geographic information systems (GIS) software (ArcGIS 10). Catchment area was estimated for the downstream transect at each site. Channel sinuosity was calculated as stream length over a 1-km linear reach centered on each site. Channel gradient (slope) was calculated by measuring the change in elevation over a 1-km reach (centered on each site) and divided by stream length.

We determined the approximate location of the six mills and associated mill ponds known to have operated along the Difficult Run mainstem from anecdotal and historical documents (John Rutherford, Fairfax County Park Authority, written communication, 2008; Hunter Mill Historical Society). We estimated the historic dam locations using the known mill locations and changes in channel slope, stream configuration, and topographic constrictions upstream of the mill or known mill race locations. Floodplain area and stream length inundated by the reservoirs behind the dam was estimated using three generalized dam elevations of 1.2, 1.9, and 3.7 m. These elevations were selected to represent the minimum, modal, and maximum values based on typical eighteenth and nineteenth century mill information (215 mills) in Lancaster County, PA, reported by Merritts et al. (2011). To provide a liberal estimate of impoundment area, we calculated dam height above the present water surface elevation rather than stream bed elevation. The reservoir pool elevations were overlain on the LiDAR DEM-derived GIS coverage to determine the length of stream inundated above the dam.

4. Results

Site characteristics including catchment area, elevation, gradient, and sinuosity are summarized by site in Table 1; volumes of material deposited and eroded and several other measurements are also presented. The 3-year record of information provided here is somewhat preliminary, as this study is an ongoing, long-term project. Nevertheless, the available hydrologic, sediment erosion and deposition, and ancillary information allow for worthwhile analyses. The following section is organized by river discharge, floodplain deposition, bank erosion, and human impacts.

4.1. River discharge

The major long-term stream gage on Difficult Run near Great Falls, VA (USGS 01646000) has operated for over 75 years, since 1935. Floodplain

inundation, a critical factor in vertical accretion on the floodplain (hydrologic connectivity), begins when flows are about or over 28 $m^3 s^{-1}$, the base discharge assumed to be near bankfull conditions along the studied reach. Flows at or above 28 $m^3 s^{-1}$ overtop levee surfaces at the middle site (site 3, author observation). The flood of record (Fig. 4A) is associated with Hurricane Agnes in 1972 (902 $m^3 s^{-1}$). Annual peak discharge ranged from 18 to 902 $m^3 s^{-1}$ for the period of record (1935–2010); the highest peaks are typically associated with tropical storms or hurricanes (Fig. 4A). Discharge records show a fairly distinct shift in patterns that may be related to the development of the Reston, VA area, which began in the mid-1960s. Annual peak discharges had a mean value of 43 $m^3 s^{-1}$ for the period of record up to and including 1965; afterward mean peak discharge significantly increased to 108 $m^3 s^{-1}$ ($P<0.001$, Mann–Whitney test). The number of overbank flooding (>28 $m^3 s^{-1}$) events (partial peak flows) each year (Fig. 4B) also show a dramatic increase after the mid-1960s ($P<0.001$, Mann–Whitney test). The flood-return interval calculated from the partial peak series (using 28 $m^3 s^{-1}$ as a discharge known to begin inundation of the floodplain at our central site, site 3) is 0.23 years or approximately 4 times a year since 1965. Prior to initial urbanization (1965) the flood-return interval is 1.11 years. Rainfall records for the nearby NOAA weather station in Vienna, VA (Fig. 4A, period of record 1943 to present) do not indicate a strong difference in annual rainfall between the same time periods and no significant difference ($P<0.055$, Mann–Whitney test). The recent period (since 1965) is more wet but not enough to explain an order-of-magnitude increase in peak discharges or a fourfold increase in the number of annual peaks above base.

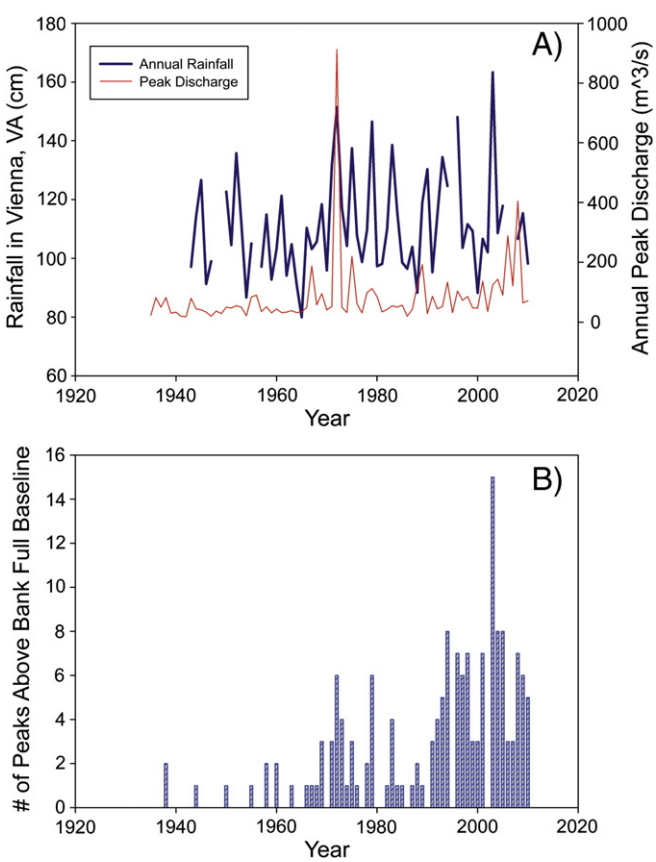

Fig. 4. A. Annual peak discharge from stream gage near site 5 and rainfall records (Vienna, VA). Note that mid 1960s appear to separate discharges into higher recent events relative to earlier times. B. Annual number of peaks above base discharge (28 m^3/s) for period 1937 to 2010. Mid 1960s mark the timing of initial suburban development in the catchment and may have affected the number of peaks above base with a 4-fold increase.

The backswamp stations at all sites experienced inundation over the 3 years of study, most likely through a combination of water sources. Levee stations at the downstream sites also were inundated during portions of the study. We have observed overbank inundation at all study sites except site 0.

4.2. Floodplain deposition

Sediment deposition rates, determined from clay marker horizons, were converted to mass accumulation using bulk density and vertical accretion information. Results are generally presented in mass/floodplain area/year ($g/m^2/y$) or mass/reach length/year (kg/m/y) here and in the remainder of the report; rates are shown in Table 1. Site lengths were normalized to allow for comparison among sites without regard to area of measured floodplain at each site. Most floodplain sampling stations throughout the study indicated net deposition from many millimeters/y to trace amounts, the remaining stations (25%) indicated net erosion; percent of pads that sustained net erosion by site is shown in Table 1. Erosive stations were equally distributed between backswamp and levee locations.

The floodplain along Difficult Run annually traps substantial amounts of sediment with rates ranging from 1059 $g/m^2/y$ at site 0 to 26,690 $g/m^2/y$ at site 4 (Table 1) and generally increased in the downstream direction to site 4 and declined at site 5 (Fig. 5A). Mineral deposition, by site, ranged from 948 to 26,099 $g/m^2/y$ and accounted for up to 98% of total deposition and, thus, is greater than organic deposition at all sites by one or two orders of magnitude (Fig. 5B, C). Mineral, thus most, sediment was trapped near the stream channel on levees at all sites (Fig. 5B). Coarse material, sand-size clasts, was more prevalent, on average, in levees (96%>63 μm) than in backswamps (86%>63 μm). Organic deposition ranged from 43 to 495 $g/m^2/y$ and is assumed to be a mixture of allochthonous and autochthonous material; no attempt was made to distinguish sources. Organic deposition, unlike mineral, was greater in backswamps at all sites except site 1 (Fig. 5C). Total annual sediment deposition over the period of study, corrected for landform rate variation and areal extent of landforms within a site, ranged from 18 kg/m/y at the upstream-most site to 1369 kg/m/y at site 4 (Table 1). The bulk of this annual accumulation is mineral and usually trapped on levee features near the channel, except at sites 2 and 3 where a large area of the monitored floodplain is composed of backswamp features (Table 1).

4.3. Bank erosion

Many reaches along the Difficult Run mainstem contain sections of eroding banks. Particle by particle erosion appears to be the dominant entrainment process, although locations are numerous where mass wasting has occurred; these have not been systematically measured although complete pin (1 m long) removal has occurred. The banks are generally fine grained, range on average from 1 to 2.65 m in total height (vertical distance between top of bank and channel bed), and generally diminish in height in the upstream direction. The largest proportion of bank material, about two-thirds of height on average, is the fine grained (legacy) deposit lying above the coarse grained pre-colonial contact. The fine grained sediment package near site 4 is relatively massive in character and composed of about 65% silts and clays (<63 μm) with occasional sand lenses and is highly mineral containing only between 1 and 3% organic fraction. The pre-colonial material here is variable in character, often gleyed, but is generally coarser than legacy material composed of 40% or less silts and clays. A pre-colonial contact/deposit in the banks at the upstream site 1 is particularly obvious (Fig. 2) and contains considerable gravel with a mean 2.8% fines (<63 μm) and 53% greater than 1 mm. The overlying fine-grained deposit (legacy) contains a mean 14% fines and 0.61% greater than 1 mm. The post-colonial age was verified by pollen analysis (ragweed signature) at site 1 where the coarse grained contact was 1.3 m below the present soil surface.

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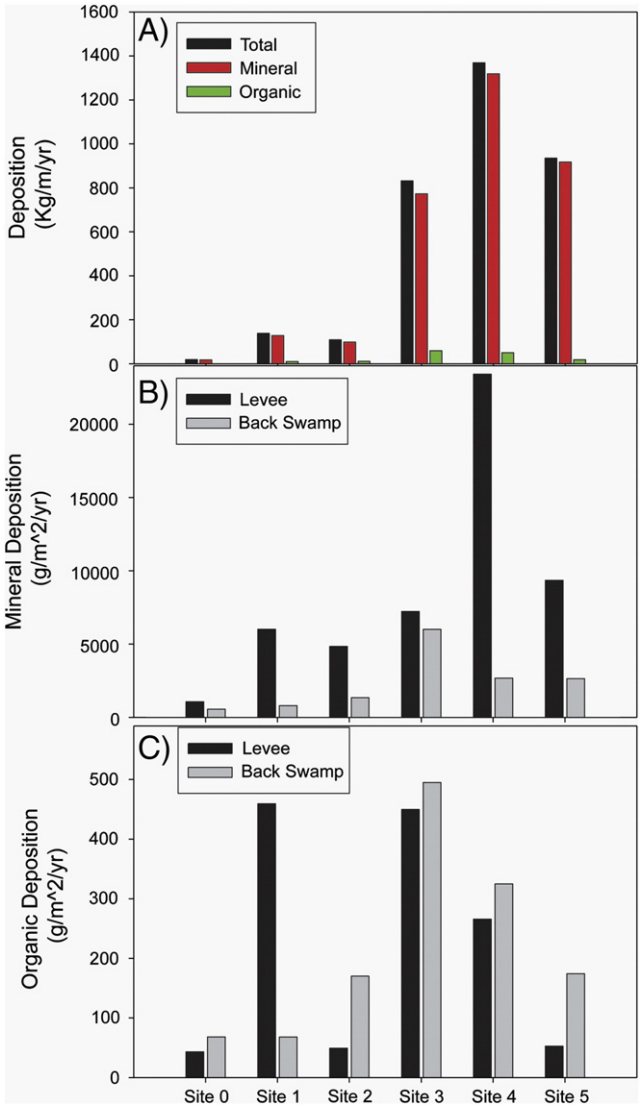

Fig. 5. Floodplain sediment deposition patterns from upstream, site 0, to downstream, site 5. (A) Total deposition (kg/m/y), with mineral, and organic fractions. (B) Mineral deposition (g/m^2/y) with relative amounts on levee and backswamp surfaces. (C) Organic deposition (g/m^2/y) with relative amounts on levee and bankswamp surfaces. Units are in mass for length of reach in A, and square meters of floodplain surface for B and C.

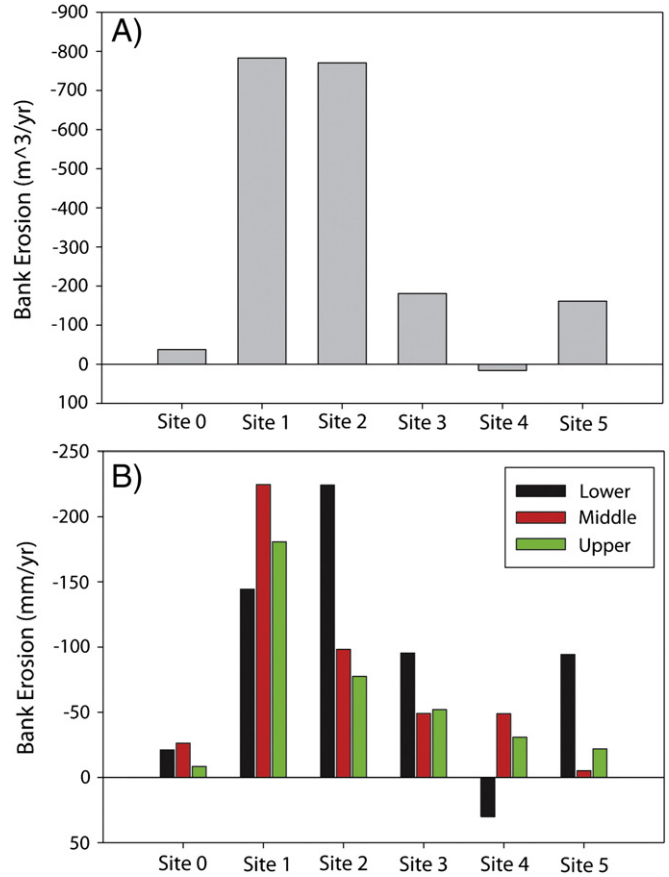

Fig. 6. Bank erosion patterns from upstream, site 0, to downstream, site 5. (A) Total bank erosion is in cubic meters by site. (B) Bank erosion rates for three bank locations (lower, middle, and upper) at study sites.

The plank road at site 4 was buried on average 1.8 m below the ambient soil surface; the depths measured for the pollen analysis (site 1) and plank road (site 4) generally match the legacy thickness reported in Table 1.

Erosion of banks exceeds bank deposition at all sites except site 4 (slightly depositional banks) with erosion rates ranging from 19 to 130 mm/y; Site 4 had a net 1.5 mm/y of bank accretion (Table 1). The upstream sites 1 and 2 had order of magnitude higher erosion rates than all other sites (Fig. 6A). Patterns of bank erosion relative to vertical location on bank were similar for the middle and upper one-third of the banks; erosion was low at the headwater site 0, peaked at site 1 and decreased sequentially through to the downstream-most site 5 (Fig. 6B). Erosion on the lower banks peaked at Site 2, decreased to Site 4, and increased at site 5 (Fig. 6B). Bank erosion, except at site 0 was greatest in upstream reaches and decreased downstream; generally the reverse of floodplain deposition., The total volume of bank material eroded within each reach, adjusting for bank heights and site reach length, shows the same general patterns (Fig. 6A).

4.4. Human impacts

Fine grained (legacy) sediment deposits occurred at all sites and varied in mean thickness from 0.9 m at the upstream-most site 0 to 1.7 m at the highly depositional site, site 4 (Table 1, Fig. 7). The contact between the fine grained sediment and pre-colonial surface occurs in the lower one-third of the bank, sometimes below the low water surface. Longitudinal trends in thickness of this deposit generally follow present-day deposition patterns (Fig. 7) with increasing amounts from headwaters to site 4, then decreasing at site 5 just above the gorge leading to the Potomac River. The contact between this deposit sediment and pre-colonial material is usually indicated by coarse stream bed gravels and cobbles. Field measurements of legacy sediment depth closely match reach-scale patterns of floodplain thickness measured from the LiDAR DEM, based on the vertical distance between the stream surface, at low flow, and the adjacent floodplain at 200 equally spaced (about 130 m) cross sections from drainage divide to mouth (Fig. 8). This presumable legacy sediment may contain charcoal, pottery shards, and colonial metal hardware (Costa, 1975; Jacobson and Coleman, 1986). We found some of these artifacts in legacy sediment along Difficult Run, including the buried (1.8 m) plank road (Fig. 2) at site 4. Pollen analysis at site 1 also confirm depths reported in Table 1, where the ragweed signature indicated a coarse deposit 1.3 m below the fine grained deposit to be older than colonial material (C. Bernhardt, U.S. Geological Survey, written communication, 2012). This contact between fine grained floodplain deposit and the coarse material was used to confirm the fine grained floodplain deposit (legacy) sediment thickness at all study sites in combination with artifacts (plank road) and pollen analyses where available.

The total length of the fluvial system from near the drainage divide downstream to the confluence with the Potomac River is 25.4 km. The

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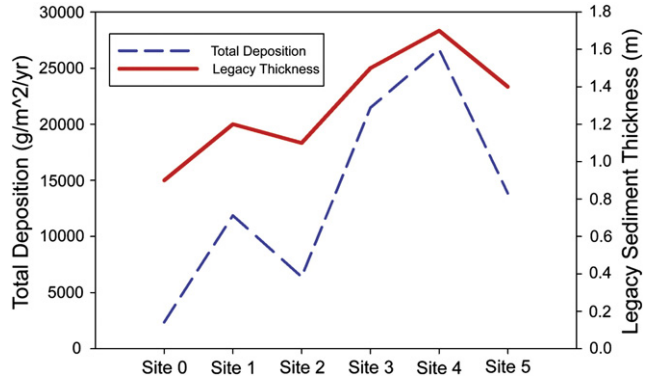

Fig. 7. Total annual deposition (all monitored surfaces), dashed line, and thickness of fine-grained (legacy) sediment deposit (measured at bank exposure) from site 0 to site 5. Note similar trends for both modern and historic sediment storage.

total maximum length of stream potentially impounded by historic mill dams is 10.4 km, 40.8% of total length cumulatively over time (Fig. 8). Impoundment lengths are likely exaggerated, given we used the upper boundary of typical mill dam heights of 3.7 m as reported by Merritts et al. (2011); modal typical height was 1.9 m. Again using the upper boundary of dam heights, three sites, 0, 1, and 4 were likely not impounded historically, while the remaining three sites (2, 3, and 5) may have been all or partly within backwater from historic dams for some period of time.

5. Discussion

The Difficult Run floodplain still serves as a site for storage of transported sediment in the face of historic and recent human alterations. Conversely, bank erosion may be a major source of fine sediment entrainment. Streams that have been affected by substantial human alteration generally exhibit an unstable regime shift (e.g. channel incision/widening or pronounced aggradation). This instability normally

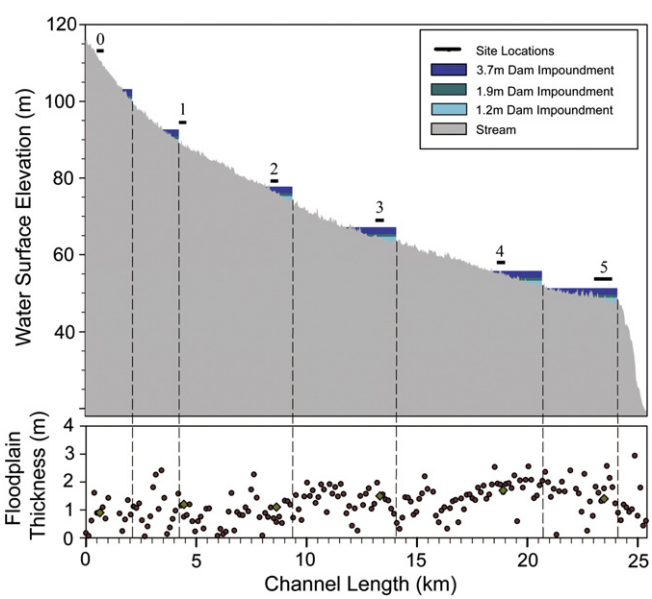

Fig. 8. Stream profile from GIS (LiDAR) analyses and site location. Floodplain thickness shown at bottom (water surface to floodplain elevation at 200 locations from drainage divide to mouth). Length of reach potentially inundated by known historic mill dams is shown for three possible dam heights (see text for detail). Note that sites 0, 1, and perhaps 4 were likely not inundated, while sites 3 and 5 were likely affected by mill dam impoundments, it is unclear whether site 2 was ever inundated. Circles in the floodplain thickness plot (bottom of figure) are elevation differences between adjacent floodplain surface and water surface elevation determined from GIS analyses. Diamonds in the same plot are measured legacy sediment depths at each of the six sites.

initiates a complex but predictable sequence of process responses (Schumm and Parker, 1973) toward a more stable state. However, Difficult Run will likely never return to some original state because of relatively permanent changes in sediment supply and runoff.

Basin area, channel sinuosity, gradient, bank height, and channel and floodplain width are typically important fluvial variables affecting sediment deposition and erosion. Erosion and deposition ($g/m^2/y$) are positively related, such that sites with high erosion rates also had high deposition rates (Table 1). The results of our Pearson product-moments analysis (Table 2) indicate that basin area, sinuosity, gradient, bank height, floodplain width, and the ratios of bank height to channel width and channel width to floodplain width were significant ($\alpha = 0.10$) factors affecting sediment fluxes along Difficult Run. Bank height and floodplain width, in particular, are highly correlated with floodplain and bank sediment fluxes and the net sediment balance (Table 2). Bank height is especially important in floodplain deposition, suggesting that it may be strongly related to floodplain connectivity and bank sediment sources for deposition. Floodplain width is highly correlated with all fluxes (including bank processes) and is among the most important variables in the correlation analysis (Table 2). Given that floodplain width and bank height are part of the original load calculations, not surprisingly, they are inherently highly correlated with sediment deposition and erosion loads. However, they are not used for process explanation but can be useful parameters for management action toward reducing sediment loads to the Chesapeake Bay. Flux calculations are independent for all parameters shown in Table 2. These results suggest that floodplain width is not limiting sediment deposition, rather that sediment supply may be the limiting factor as discussed in Hupp et al. (2009a) and Noe and Hupp (2009). The channel width/floodplain width was significantly negatively correlated with erosion, deposition, and net sediment balance per site and is the third most significant variable after floodplain width and bank height (Table 2). Thus, sites with relatively high banks, narrow channels, and adjacent to wide floodplains have the highest amounts of sediment deposited/eroded and vice versa. Sinuosity was related to floodplain sedimentation processes but, perhaps surprisingly, not bank erosion (Table 2). Relatively narrow channels for a given discharge should have more erosive energy than wide channels, which expend energy on various in-channel features. Further, relatively narrow channels with less conveyance will overtop their banks more frequently than wide channels and provide for more potential floodplain deposition. Thus, energy expenditure patterns (Molnár and Ramírez, 1998) associated with high discharges may explain our result of simultaneously high rates of both deposition and erosion at a site and the correlation of bank height, floodplain width, and channel width/floodplain width with sediment fluxes (Table 2) as the Difficult Run channel responds to multiple human disturbances. Although high banks should offset narrow channels in terms of conveyance, bed resistance to scour in combination with frequent high flood stages ensure sustained depositional overbank events in this nonequilibrium system. Channel gradient was mildly negatively correlated with erosion flux and load, floodplain load, and net flux (Table 2). Normally, high stream gradient is positively associated with high erosion potential; here where there is a high gradient, the sites are also located near headwater areas with low-bank heights, which may limit erosion amounts. Geologic structural control of channel geometry also likely has an important influence.

5.1. Modern floodplain sediment dynamics

Floodplains of Coastal Plain tributaries to the Chesapeake Bay may trap large amounts, upward of 100% of riverine suspended loads, of sediment and associated nutrients (Noe and Hupp, 2009). Our results on Difficult Run suggest that this urban Piedmont floodplain also remains an effective trap for eroded material, especially in the study reaches of the three downstream-most sites (Fig. 5A) where nearly 2807 kg/m of sediment are deposited annually. This occurs in spite of upstream bank erosion, which is widespread especially in the distinctly

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Table 2
Parameter summary of Pearson product–moments correlation analysis of selected deposition[a].

		Correlations					
		Pearson product–moments					
	Basin area	Sinuosity	Gradient	Bank ht	fpw	Bank ht/cw	cw/fpw
Bank flux (g/m^2/y)							
r, Pearson correlation	**0.834**	**0.830**	**−0.872**	**0.94***	**0.992****	**−0.937***	**−0.911***
p, significance	**0.079**	**0.082**	**0.054**	**0.018**	**0.001**	**0.019**	**0.031**
Bank load (kg/m/y)							
r, Pearson correlation	**0.810**	0.798	**−0.869**	*0.935*	**0.98****	*−0.917*	**−0.896***
p, significance	**0.097**	0.106	**0.056**	*0.020*	**0.003**	*0.028*	**0.040**
Floodplain flux (g/m^2/y)							
r, Pearson correlation	0.708	**0.897***	−0.649	**0.933****	**0.946***	−0.758	**−0.857**
p, significance	0.181	**0.039**	0.237	**0.001**	**0.015**	0.137	**0.063**
Floodplain load (kg/m/y)							
r, Pearson correlation	**0.9***	**0.895***	**−0.813**	**0.934***	*0.987*	**−0.932***	*−0.872*
p, significance	**0.037**	**0.040**	**0.094**	**0.020**	*0.020*	**0.021**	*0.054*
Net load (kg/m/y)							
r, Pearson correlation	**0.897***	**0.851**	**−0.868**	*0.920*	*0.990*	*−0.958*	*−0.884*
p, significance	**0.039**	**0.068**	**0.056**	*0.027*	*0.001*	*0.010*	*0.047*

Bank height = bank ht; floodplain width = fpw; channel width = cw. Load values in italics are not independent and are not used for process explanation.
[a] Values in bold font are significant at $p<0.1$; bold font with single asterisk, $p<0.05$; bold font and double asterisk, $p<0.01$.

alluvial upper reaches (sites 1 and 2; Fig. 6A) and a rather large suspended sediment load (2330 Mg/y) as measured (turbidity based regression to estimate concentration) at the site 1 stream gage (J. Jastram, USGS Virginia Water Science Center, personal communication, 2009) entrained from uplands and upstream reaches.

Much active floodplain sedimentation along streams impacted by human alteration is likely derived from channel and bank erosion versus largely upland sources (Simon and Hupp, 1992; Simon and Rinaldi, 2006; Darby et al., 2007). Analyses of sediment age, erosion, and delivery to coastal waters suggest that up to 90% of sediment eroded from uplands is cycled for decades to millennia in alluvial systems before reaching saltwater (Meade et al., 1990; Ludwig, 2001). Longitudinal trends in floodplain deposition along a stream-order gradient are expected where fluvial landform development, including the development of floodplains and vertical accretion, increases with increasing basin size and decreasing stream gradient (Fig. 9). Note that site 5 shows a decrease in deposition and a corresponding increase in stream gradient associated with the grade and hydraulics related to the gorge immediately downstream of the site that continues to the confluence with the Potomac River. This drawdown or erosive effect at site 5 is consistent with that observed by Hupp (1982) where gorges similarly affect nearby upstream reaches in some high gradient Virginia streams. The decrease in floodplain deposition at site 2 (Fig. 9) is less easily explained; variation in other parameters at this site is also observed in channel sinuosity (possibly causative, Fig. 9B), in a peak in erosion (Fig. 6A), and in a reduction of legacy sediment thickness (Fig. 7). Channel gradient is widely acknowledged as a major driver in channel form/stream regime and is typically inversely related to sinuosity and floodplain deposition where low gradients are characterized by sinuous channels that may flood frequently and facilitate floodplain deposition (Hupp, 2000). Thus, the matching trends (relative to gradient) in channel sinuosity with deposition rates (Fig. 9) is expected but not to the degree seen given the completely independent data sources.

Analyses of local or intrasite variation in sediment accumulation and character on floodplains has received spotty attention in the literature and is not a primary objective of the present paper. However, the separation of stations into relatively low elevation backswamps versus relatively high elevation levees allows for some inference. Patterns of sedimentation and deposit character (e.g., grain size) within floodplains partly result from differences in advection, diffusion, and the presence of sloughs (Pizzuto, 1987; Ross et al., 2004) during high discharge events. Local variations in elevation, microtopographic form, and connectivity to the sediment-laden flood water also govern deposition patterns and grain size (Pizzuto, 1987; He and Walling, 1997; Hupp et al., 2008). Sediment deposited nearest the channel typically is coarser (and more mineral) than on more distant floodplain locations (Pizzuto, 1987; Asselman and Middelkoop, 1995; Walling et al., 1997; Hupp et al., 2008); this trend is confirmed along Difficult Run (Fig. 5B). In general, as flood water overtops the banks, sediment is deposited as a function of settling and flow velocities with distance from the channel. High velocities generally diminish rapidly away from the channel (Ross et al., 2004). Natural levees adjacent to the channel, where overbank flow velocities are highest, should have higher mineral (heavy) and more coarse-grained deposition than backswamp areas (Pizzuto, 1987; Hupp, 2000). At all sites, mineral sedimentation was greater on levee features than in backswamps (Fig. 5B) and contained more sand than the fine-grained material in backswamps, presumably a result of the lower velocity and somewhat ponded nature of backswamps. Likewise, during flood events, relatively light organic sediments should be preferentially trapped in the low energy conditions of the backswamp or areas away from the levee, as reported by Asselman and Middelkoop (1995). Organic material deposition exceeded mineral deposition in backswamps at all sites along Difficult Run except for site 1 (Fig. 5C), where a small tributary crosses the backswamp delivering mineral material. In contrast, low energy, blackwater systems such as those on the Coastal Plain may be dominated by organic rich deposits except near the channel (Hupp, 2000; Kroes and Hupp, 2010; Schenk et al., 2011). Relatively high energy systems like those on the Piedmont favor a large predominance of mineral deposition with organic contents

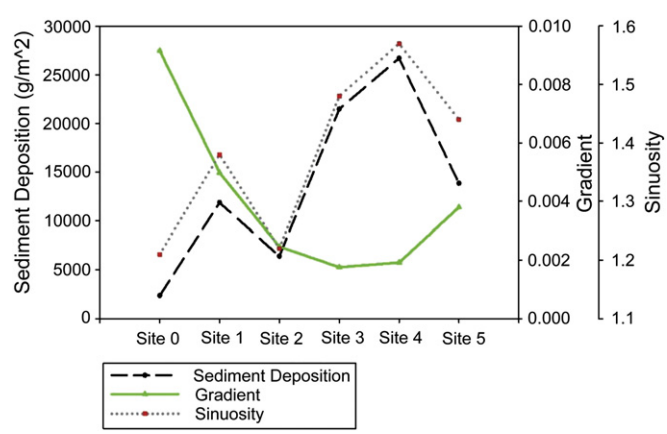

Fig. 9. Floodplain sedimentation patterns relative to channel gradient and sinuosity. Deposition is negatively related to gradient but strongly positively related to sinuosity.

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rarely more than 10% (Meade, 1982). The mineral component of all deposits at all Difficult Run stations exceeded the organic component usually by orders of magnitude, especially at the downstream-most three sites (Table 1; Fig. 5A).

Retention of sediment (from flood flow) in floodplains is an important ecosystem service provided by riparian areas subject to periodic flooding (Hupp, 2000; Gellis et al., 2009; Noe and Hupp, 2009); this service may play a far greater role than riparian buffering (flow from adjacent uplands) in the maintenance of water quality along Coastal Plain streams draining to the Chesapeake Bay (Noe and Hupp, 2009). Average annual floodplain sedimentation rate for alluvial streams draining to the Chesapeake Bay is about 4 mm/y; for blackwater systems (those that head on the Coastal Plain), the rate is about 2.3 mm/y (Gellis et al., 2009). The average sedimentation rate for Difficult Run is 6.4 mm/y, slightly higher than Little Conestoga Creek, PA (4.4 mm/y), another Piedmont system (Gellis et al., 2009; Schenk and Hupp, 2009). In comparison, the average mass of sediment trapped along Difficult Run (11,312 g/m^2/y) is substantially higher than other studied streams in the Chesapeake Bay watershed where alluvial systems range between 700 and 3177 g/m^2/y, and typically mineral-sediment-starved blackwater systems average 610 g/m^2/y (Noe and Hupp, 2009). Preliminary analyses by Schenk et al. (in press) showed that sediment yield, as measured at the upstream gage (site 1) on Difficult Run is an order of magnitude higher in comparison to other Piedmont tributaries to the Chesapeake Bay.

5.2. Modern bank erosion

Bank erosion is a normal process even in fully equilibrated systems. However, this erosion may be accelerated through natural and, typically, human alterations including channel incision following dam construction (Hupp et al., 2008), stream channelization (Simon and Hupp, 1992). In the case of Difficult Run, erosion has been substantially altered through profound changes in sediment delivery from uplands and a probable hydrologic regime shift associated with hardening of the watershed during urbanization (Wolman and Schick, 1967).

Studies of bank erosion are more common than those of floodplain sediment dynamics (Thorne, 1982; Darby and Thorne, 1996). This may result from the more tractable measurement of erosion rates (Lawler, 1993; Lawler et al., 1999) and because of the immediate impacts of erosion resulting in land loss and damage to human infrastructure. Bank erosion in many systems is the principle process that contributes to stream sediment load (Simon and Rinaldi, 2006; Darby et al., 2007; Gellis and Walling, 2011). Where bank erosion rates are high, nearby downstream floodplain deposition rates may likewise be high under appropriate hydraulic conditions (Hupp et al., 2009a). This process is clearly observed along Difficult Run; high erosion rates occur along upstream sites and commensurate high deposition rates occur downstream (Figs. 5 and 6).

The upstream-most study site (site 0; Table 1) has a catchment area of only 3 km^2 and is largely nonalluvial with limited development of fluvial landforms, including floodplain and in-channel bars. There is little floodplain (vertical) deposition (Fig. 5A) and low rates of bank erosion (Fig. 6A). A distinct intrinsic morphometric and quantitative process change occurs between sites 0 and site 1, possibly a geomorphic threshold from upland to fluvial process dominance, which continues downstream in the form of sequentially more fully developed and expansive fluvial landforms. Sites 1 and 2, where pronounced peaks in bank erosion and limited fluvial features occur (backswamps and levees), have the highest volumes of erosion and relatively high gradients. All bank locations show a trend of decreasing erosion downstream; the lower bank location, however, then increases at site 5 (Fig. 6) where drawdown effects (channel degradation) of the downstream gorge are evident in most fluvial processes.

5.3. Human alterations

The study reaches of Difficult Run span a stream system from near/within headwater conditions (ephemeral and first order channels) with limited fluvial processes where an upland/erosional regime dominates to reaches with pronounced in-channel fluvial features and a well-developed, functioning floodplain downstream along a mostly fourth and fifth order channel. Along this fluvial gradient we may assess the impacts of colonial upland erosion/legacy sedimentation, historic mill dams, and recent urbanization.

The Difficult Run watershed, prior to European settlement, most likely experienced little human alteration aside from minor Native American activities (Jacobson and Coleman, 1986). The rise of European-style agriculture in the mid-Atlantic Piedmont led to considerable denudation of the hilly uplands. Estimates of average soil erosion associated with early European settlement range from 150 mm in Maryland (Costa, 1975) to 178 mm in Virginia and North Carolina (Trimble, 1974). Legacy sediment thickness on alluvial features along Piedmont streams (from watersheds of similar size as Difficult Run) range from 0.05 to 1.8 m (Happ et al., 1940). The range in the fine grained (legacy) sediment depth of 0.9 to 1.7 m (Table 1) along Difficult Run is clearly consistent with many areas in the Piedmont; additionally, the trend for thickness to increase with catchment size (Fig. 7) is also supported in the literature (Costa, 1975). Soil cores from the floodplain and observations of stream banks on Difficult Run suggest that the pre-settlement valley bottom deposits were relatively coarse gravels associated with in-channel deposits. These findings are consistent with those reported by Jacobson and Coleman (1986). The overlying fine-grained deposit is considered to be the result of post-colonial floodplain aggradation, or legacy. Thicknesses of legacy sediment closely match the trends in modern floodplain deposition along all sites (Fig. 7). This relation suggests that geologic or structural control of the basin and ambient fluvial dynamics have been in force since at least the beginning of the colonial period and affect modern depositional processes along with the impacts from human alteration.

Colonial and nineteenth century mill ponds may have facilitated sediment deposition (Walter and Merritts, 2008; Merritts et al., 2011). Six mills are known to have existed along Difficult Run, which may have inundated slightly more than 40% of the stream length. However, we found no appreciable differences in the fine grained (legacy) sediment thickness at previously impounded sites versus free-flowing sites (Table 1). Further, GIS analyses did not indicate a distinct stepped plan structure of the floodplain associated with relic mill pond sediment deposition (Fig. 8) as described in Merritts et al. (2011) nor were there similarly associated terraces revealed in surveyed cross sections. Thus, the large volume and spatial distribution of this fine grained sediment appear relatively unrelated to the historic distribution of mill dams. The floodplain backswamps at most sites, except the upland site 0 and site 2, flood regularly, between about 4 and 31% of the time (Table 1) over the period of well installation (fall 2008 through summer 2011). Vertical accretion occurred on the floodplain at all sites during the study period (Table 1; Fig. 5), emphasizing the active trapping and storage of suspended sediment throughout the fluvial system. This would not be possible if the floodplains had been rendered terraces by mill-pond dynamics as suggested by Merritts et al. (2011). Other Piedmont floodplains with mill-pond impacts were recently shown to also have active vertical accretion in Pennsylvania (Schenk and Hupp, 2009) and in Maryland (Schenk et al., in press). The flood-return interval calculated from the partial peak series (Fig. 4) at our central site (site 3) is 0.23 years or approximately 4 times a year since 1965 when urbanization of the watershed began. Prior to urbanization, the flood-return interval was 1.11 years for the period 1937 through 1965. Thus, when only post colonial (legacy) deposits were the major alteration to this fluvial landscape (prior to 1965), the floodplain still flooded well within the criterion for floodplain definition (at least once every 3 years), i.e. not a terrace. Further, site 3 was likely impacted by mill-dam impoundment

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at all likely dam heights (Fig. 8) and, since gaging records began, it does not appear to have been rendered a terrace. Although mill ponds may have facilitated legacy sediment deposition, our research suggests that mill ponds were not requisite for substantial deposition on floodplains and that even with substantial deposition the floodplains continue to flood regularly and remain active fluvial features. Thus, active connected floodplains (not rendered terraces; Merritts et al., 2011) may still play an important role in sediment retention in the Chesapeake Bay watershed.

Observations that stream channels will adjust their form and processes in response to hydrologic and sediment supply alteration associated with urbanization has been documented for decades (Wolman, 1967; Wolman and Schick, 1967; Hammer, 1972; Morisawa and LaFlure, 1979). Hardening of the watershed (increases in the amount of impervious area) associated with urbanization typically creates a more flashy regime characterized by increases in the annual number of discharge peaks above a base level and greater instantaneous discharges for a given flood event (Villarini et al., 2009). The hydrologic records for Difficult Run clearly support this urbanization impact beginning in the mid to late 1960s (Fig. 4A, B). Hydrologic regime shifts may initiate a period of channel response toward a new equilibrium (Pizzuto et al., 2000; Niezgoda and Johnson, 2005; Hupp and Osterkamp, in press). Channel enlargement through channel incision and/or widening (bank erosion) may be the principle response to substantial increases in impervious area (Paul and Meyer, 2001). Results from Difficult Run indicate that the greatest amount of bank erosion occurs in the upstream reaches of the main stem (Fig. 6), while the downstream reaches are significantly more depositional. The large amount of bank erosion at most sites (Fig. 6) suggests that it may be a principal response to urbanization as well as a source for downstream sedimentation. As the stream adjusts to urbanization, areas of peak erosion will likely migrate and attenuate in space and time (Simon and Hupp, 1992; Hupp et al., 2009b; Hupp and Osterkamp, in press). Pizzuto et al. (2000) found that Piedmont channels generally did not incise but widened and that the pools were relatively shallow and sinuosity decreased over the long term in response to increases in impervious surfaces. We believe this is largely true along Difficult Run given the ambient presence of coarse bed material and occasional bedrock outcrops in the channel. Although not completely captured in our bank erosion study, we have observed at many locations evidence of past and present mass wasting along the banks (Fig. 10), which further suggests channel widening may be a dominant channel adjustment process.

5.4. Sediment balance

The floodplain of Difficult Run is controlled by modern fluvial processes such that the floodplain at all sites is actively inundated by stream water and is largely depositional with the exception of the most upstream, second-order site, site 0. Aside from sediment delivered to the study reach from upland sources, large amounts of sediment are eroded from the upstream reaches while downstream reaches are storing even larger amounts of sediment. The balance of floodplain deposition and bank erosion (Fig. 11) is a net 2184 kg/m/y along the monitored reaches, thus there is a clear tendency for trapping/storing sediment. A detailed investigation of Difficult Run sediment balance is provided in Schenk et al. (in press) and includes estimates of uncertainty reported as standard deviation for all calculated parameters. Standard deviation for net sedimentation (Table 1) ranged from 284 kg/m/y at site 1 to 1182 kg/m/y at site 4 (Schenk et al., in press). Undoubtedly, some of the sediment moves out of the system into the Potomac River. The common term, sediment yield, refers to stream sediment load adjusted to the basin area above the point of measurement. The sediment yield at the upstream gage (site 1) was 163,900 kg/km^2/y for 2009, a normal water year. Because we have calculated the net balance of floodplain sediment deposition, we felt it would be interesting to relate sediment yield to this deposition along the stream; in other words to calculate a sediment trapping factor through the Difficult Run floodplain sites. The amount of deposition, adjusted for reach length (kg/m/y), multiplied by floodplain width, and divided by the sediment yield adjusted for basin area above the reach (Fig. 12) yields the dimensionless trapping factor (Schenk et al., in press). A trapping factor of 10 would mean that the floodplain may retain 10 times the watershed sediment eroded above a given reach. Both, gross trapping factor using floodplain sedimentation flux only and net trapping factor using net flux of floodplain sedimentation–bank erosion, were calculated and appear high at sites 3,4, and 5, which are at or above a factor of 30 (Fig. 12). Extrapolation of suspended sediment yields from one upstream station for increasing basin areas at downstream sites may introduce substantial error in yield computation (increasing basin areas typically have decreasing sediment yields). Therefore, extrapolating yields from the upstream gage potentially overestimates yields downstream and, consequently, underestimates the trapping factors. However, this analysis strongly reinforces the important role connected floodplains play in ecosystem services/riparian functions, while still accommodating the impact of erosional sites (net trapping factor). Further, given just about all depositional patterns we see are similar between legacy and modern (period during

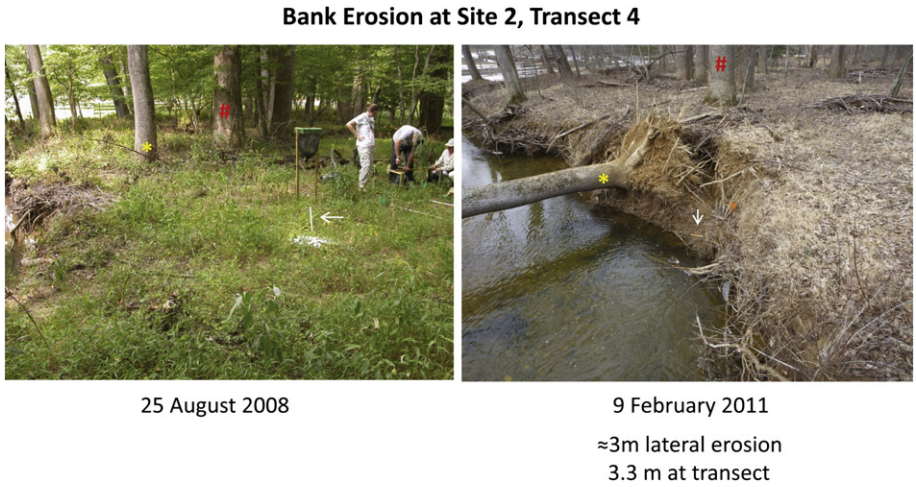

Fig. 10. Bank erosion at site 2. Previously standing tree now fallen into channel is marked with an asterisk. Arrow shows location of clay pad marker as placed on floodplain surface, left and present location on lower bank.

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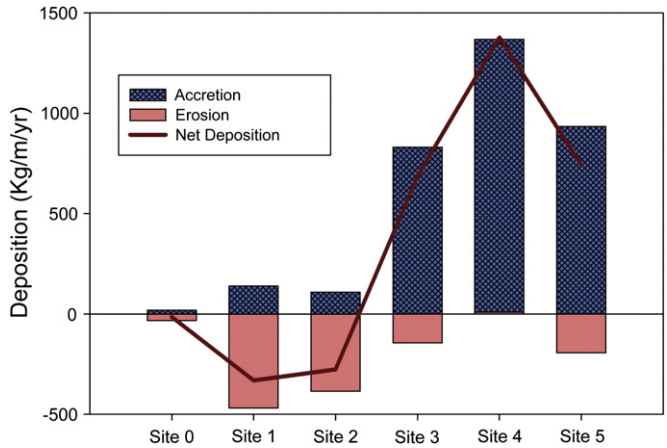

Fig. 11. Annual sediment balance in kg/length of reach (quasi budget) using floodplain deposition, blue bars (storage) and bank erosion, red bars (transport). Net sediment flux (positive = storage) is shown by graphed line. Net flux for the catchment is 2183 kg/m/y stored in floodplains annually. (For interpretation of color in this figure legend, the reader is referred to the web version of this article.)

the course of study) times (Table 1, Figs. 7 and 8) in combination with this analysis (Fig. 12), we can reasonably speculate that floodplain deposition would occur (has occurred) regardless of the presence of mill dams at least along the lower half of the main stem of Difficult Run.

Although relative to Coastal Plain streams (Noe and Hupp, 2009) with high sediment trapping volumes (much larger floodplain areas than Difficult Run), it is apparent that Difficult Run still performs the ecosystem service of riparian sediment retention. These sediment inputs stimulate floodplain biogeochemical processes that transform some of the nitrogen and phosphorus associated with the sediment (Noe et al., in press). We can reasonably assume that the study reach is not in a long-term stable form (in response to the rapid hardening of the catchment) given (Fig. 4) the largely erosive nature of sites 1 and 2 and the depositional nature of sites 3 through 5. As the erosive impact of urbanization proceeds, in large parts of the Mid-Atlantic region, modern (the present period of study) and legacy sediment may substantially contribute to the sediment load to the Chesapeake Bay. However, the floodplain of Difficult Run presently stores, on average, 132 m^3 of sediment (legacy and modern) per m of reach length. Thus, in the 860 m of monitored stream reach, a net of 113,520 m^3 of material is stored annually, which represents only 4% of the total reach length (19.5 km), site 0 to site 5.

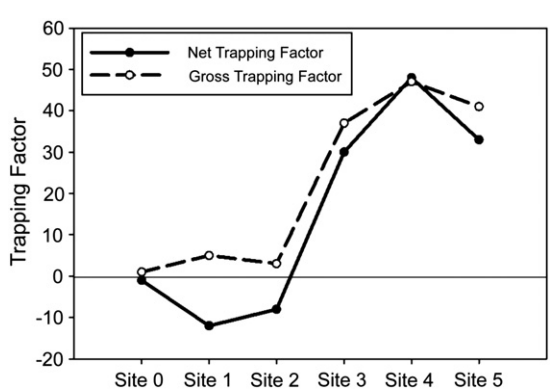

Fig. 12. Trapping factor by site in both gross and net values. Trapping factor is the ratio of floodplain deposition to basin area above measurement. A trapping factor of 10 indicates a unit of floodplain stores eroded sediment from 10× the equivalent area of catchment. The lower basin floodplains (sites 3, 4, and 5) have both gross and net trapping factors of 30 or higher.

6. Conclusions

The fluvial system of Difficult Run has been impacted by recent and historic human alterations. The floodplain trapped a large volume of sediment (presumably legacy) resulting from eighteenth and nineteenth century European land use. This deposit forms the bulk of current bank and floodplain material, which is rapidly eroding in upstream reaches likely in response to relatively recent (since mid-1960s) hardening of the watershed through urbanization. However, downstream reaches experience substantial vertical accretion on the floodplain and, thus performs the ecosystem service of sediment trapping; along the lowermost 3 sites nearly 2807 kg of sediment are deposited per meter of reach annually. This overall flux of sediment is large and indicates the system is not in equilibrium.

Analyses of channel conditions indicate that gradient, floodplain width, bank height, sinuosity, and channel width/floodplain width are significant factors affecting sediment fluxes along Difficult Run. Erosion and deposition ($g/m^2/y$) are positively related such that sites with high total annual site mass flux (kg/m/y) also had both high deposition and erosion rates. Sites with relatively high banks, narrow channels and adjacent to wide floodplains have the highest sediment flux and vice versa.

The rise of European style agriculture in the mid-Atlantic Piedmont led to considerable denudation of the hilly uplands and subsequent substantial deposition on the floodplain. Legacy sediment thickness is 0.9 to 1.7 m, consistent with other Piedmont streams. Pre-settlement valley bottom deposits were relatively coarse gravels associated with the streambed, sand and gravel in channel or point bars. Patterns in legacy sediment deposition closely match the trends in modern floodplain deposition along all sites. This relation strongly suggests that geologic or structural control of the basin and ambient fluvial dynamics has been in force for centuries and affects modern depositional processes regardless of the impacts from human alteration.

Six mills are known to have existed along Difficult Run, which may have inundated slightly more than 40% of the stream length. No appreciable differences in legacy sediment thickness at previously impounded sites versus free flowing sites were found, GIS analyses did not indicate a distinct stepped plan structure of the floodplain associated with relic mill-pond sediment deposition, nor were there similarly associated terraces. The spatial distribution of legacy sediment depth appears unrelated to the historic presence or distribution of mill ponds. The floodplains at all fluvial sites flood regularly, typically more than once per year. Vertical accretion occurred on the floodplain at all sites during the study period emphasizing the active trapping and storage of suspended sediment throughout the fluvial system. Although mill ponds may have facilitated legacy sediment deposition, our research suggests that mill ponds were not requisite for substantial deposition on floodplains and that even with substantial deposition the floodplains continue to flood regularly and remain active fluvial features.

The fluvial sediment fluxes in the Difficult Run basin are large with a net tendency for trapping–storing sediment, a critical ecosystem service/riparian function. These results strongly reinforce the important role connected floodplains play in ecosystem services. 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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