Sediment-trapping by Beaver Ponds in Streams of the Mid-Atlantic Piedmont and Coastal Plain, USA

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Abstract - The effect of beaver ponds on sediment deposition is undocumented in the Piedmont and Coastal Plain of Virginia and North Carolina. We used 3 methods to examine sedimentation: 1) depth-integrated base-flow sampling, 2) repeat channel-surveys, and 3) sediment-accumulation pads. During base flow, Piedmont ponds exported sediment and Coastal Plain ponds had little or no effect on downstream suspended-sediment concentration. Most ponds accumulated sediment within the channel until dam breaching. Ponds inundating the floodplain trapped more sediment. Ponds of varying configuration trapped sediment differently. Mean floodplain accretion rates in these beaver ponds (2002-2003: 20 mm/yr 2003-2005: 15 mm/yr) greatly exceeded the mean deposition rate of similar unimpounded streams in these areas. Intact Piedmont ponds trapped 11 m^3/yr on the floodplain and 77 m^3/yr in the channel. Intact Coastal Plain ponds trapped 107 m^3/yr on the floodplain and 8 m^3/yr in the channel.

Introduction

In the US, many animals that function as ecosystem engineers have been reduced to functional extinction. One such ecosystem engineer, *Castor canadensis* (Kuhl) (Beaver) was trapped and hunted to local extinction, or to such low numbers that it was no longer found in most low-gradient streams of the eastern and central US (Johnston and Chance 1974). Eradication of Beaver populations has led to widespread beaver-dam failures resulting in systemic stream-change (Polvi and Wohl 2012, Walter and Merritts 2008). Streams that were once composed of a series of ponds (Morgan 1868) became free-flowing and exported large volumes of stored sediment. On some streams, a portion of this sediment was trapped in mill ponds, many of which have failed or are failing because of disrepair (Merritts et al. 2004).

Estimates of pre-colonial Beaver densities range from 2.2 to 74 Beaver/km^2 (Bailey 1927, Hodgden and Hunt 1955), depending on habitat quality and stream density. These population estimates could equate to <1 to >10 beaver ponds/km^2, assuming a drainage density of 2.1 km/km^2 for the Coastal Plain and 4.9 km/km^2 for the Piedmont (Calvo-Alvarado and Gregory 1997). Beaver-pond densities in some Colorado mountain valleys currently range from 5 to 46 ponds/stream km (Ringelman 1992). Johnston and Naiman (1990) estimated 13% of their Minnesota study site to be Beaver impounded, with greater than 60% of those ponds exhibiting decadal stability.

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Manuscript Editor: Jennifer Rehage

In the southeastern US, Beaver populations and ponds have increased dramatically since the reintroduction and subsequent protection of 70 Beavers to Virginia (VA) and North Carolina (NC) in the 1930s (Newbill and Parkhurst 2000, Woodward and Hazel 1991). Human resistance to a real or perceived loss of land and timber due to Beaver activity may maintain a low beaver pond to stream-km ratio (McKinstry and Anderson 1999). Butler (1991) estimated Beaver density to be less than 1 Beaver/20 km^2 in the southeastern US, with concentrations of 1 Beaver/100 km^2 in VA and NC. Despite this low density of beaver ponds relative to the pre-European densities, Beaver are considered a nuisance species and may be hunted year round (NCWRC 2010, VDGIF 2013). In areas where Beaver come into conflict with humans, dam destruction and eradication of Beaver colonies occur frequently.

It is important for us to understand the role of Beavers in stream/floodplain systems, especially because their ponds trap sediment. However, the sediment-trapping potential remains understudied in the Piedmont and Coastal Plain of the mid-Atlantic US. When higher-velocity water and sediment enter an area of ponded water, some of the bedload and suspended sediment may be deposited (Kroes and Kraemer 2013). This process results in increased sediment-storage rates within the pond. Sediment deposition and channel processes in beaver ponds are well-studied in high-gradient stream areas. In Germany, John and Klein (2004) observed the greatest deposition amounts to be within the channel of beaver ponds (mean = 120 mm/yr), with decreased deposition in shallower areas (mean = 40 mm/yr). Butler and Malanson (1995) observed an average of 21 mm/yr deposition in Montana beaver ponds. Generally, ponds in these studied areas trapped more sediment than was eroded from the downstream bed and banks (Bigler et al. 2001, Gurnell 1998, Meentemeyer and Butler 1999).

In comparison to the focal areas of previous beaver pond sediment-deposition studies, the Piedmont and Coastal Plain have lower stream gradients, resulting in beaver ponds with greater ratios of surface area to volume than in higher-gradient areas. These high ratios typically result in long, wide ponds with longer water-transit times where suspended fine sediment has a better chance of settling before exiting the pond. Longer settling times are important for sediment deposition in streams where fine-grained sediment may be the only sediment type present. Further, methods commonly used to determine sediment deposition in beaver ponds in other physiographic regions have limited utility on the Coastal Plain as a result of the sediment properties. Typically, low-order stream-bed load material in the Coastal Plain would be considered fine sediment in a mountain stream, commonly with median particle diameters of <0.5 mm (Kroes and Kraemer 2013). Floodplain deposition typically has a grain size of <0.063 mm, primarily silt and clay (Kroes and Hupp 2010). Low-order Piedmont streams in this area carry a bed load of medium pebbles and finer particles, with a median diameter <10 mm, and if floodplains are depositional, the deposition is fine sand, silt, and clay (<0.125 mm diameter) (Hupp et al. 2013). All of the sediment is fine material, thus, it is very difficult to use sediment grain-size changes to differentiate beaver-pond deposition from unimpounded deposition as is commonly done in areas with coarse sediments (Bigler et al. 2001). Streams in the mid-Atlantic Coastal Plain commonly have organic floodplain deposition that may have organic content values of 80% without beaver-pond activity (Kroes and Hupp 2010, Noe and Hupp 2005).

Currently, sediment-deposition rates on unimpounded floodplains along Piedmont streams average 4 mm/yr, with many exhibiting reaches of erosional floodplains (Allmendinger et al. 2005, Schenk and Hupp 2009, Schenk et al. 2013). Average deposition in low-order southeastern US Coastal Plain streams ranges from 1.6 to 5.4 mm/yr (Craft and Casey 2000, Hupp 2000, Kroes and Hupp 2010). In this study, we quantified the effect of beaver ponds on sediment transport in low-order streams along the mid-Atlantic coast where climate, agriculture, geomorphology, and Beaver control differred from previously-studied areas. Secondly, we aimed to determine the timing and events that influenced the storage and export of sediment from beaver-pond complexes.

Methods

Field-site description

In order to determine Beaver effects on sediment deposition, we selected 3 areas for our study: (1) Fairfax County, VA, (2) Westmoreland County, VA, and (3) Pitt County, NC (Fig. 1A). These areas have different land forms and sediment sources and, hypothetically, should store sediment at different rates than previously studied areas. Fairfax County, VA (hereafter Fairfax) is within the Piedmont physiographic province (Hunt 1967), and has a land-surface form of moderate-relief table lands with 20–50% of the area on gentle slopes (Hammond 1964). This region has undergone intensive housing and commercial development (suburbanization) resulting in increased upland erosion (Booth and Bledsoe 2009). Development has increased the percentage of impermeable surfaces resulting in increased runoff and, subsequently, accelerated stream-channel erosion (Booth and Reinelt 1994, Hupp et al. 2013, Schenk et al. 2013). Study streams in this area were forested by *Fraxinus* spp. (ash), *Acer rubrum* L., (Red Maple), and *Quercus* spp. (oak).

Westmoreland County, VA (hereafter Westmoreland) is within the Coastal Plain physiographic province (Hunt 1967) and has a land-surface form of irregular plains; 20–50% of the area slopes gently (Hammond 1964). Uplands in this area are primarily forested or agricultural. During the study period, active head-cut erosion and gullying were occurring on the slopes between some highlands and stream bottoms. Many of the streams in this area were modified by a series of active beaver ponds. Study streams in this area were forested by ash, Red Maple, and oak.

Pitt County, NC (hereafter Pitt) is within the Coastal Plain physiographic province (Hunt 1967) and has a land-surface form of flat plains (Hammond 1964). Uplands in this area are primarily agricultural or forested. Sources of sediment in Pitt County are erosion of field and roadside ditches, erosion of agricultural land, increasing levels of development, and past stream channelization. In a similar Coastal Plain area, Gellis et al. (2009) used radioisotopes to determine that a large portion of the entrained sediment comes from agricultural ditch beds and banks.

Study streams in this area were forested by ash, Red Maple, *Nyssa biflora* (Walter) (Tupelo), and *Taxodium distichum* L. (Richard) (Bald Cypress).

Site selection

All selected ponds had naturally vegetated buffer zones that minimized overland sediment-transport from uplands directly into the ponds. We tried to choose sites

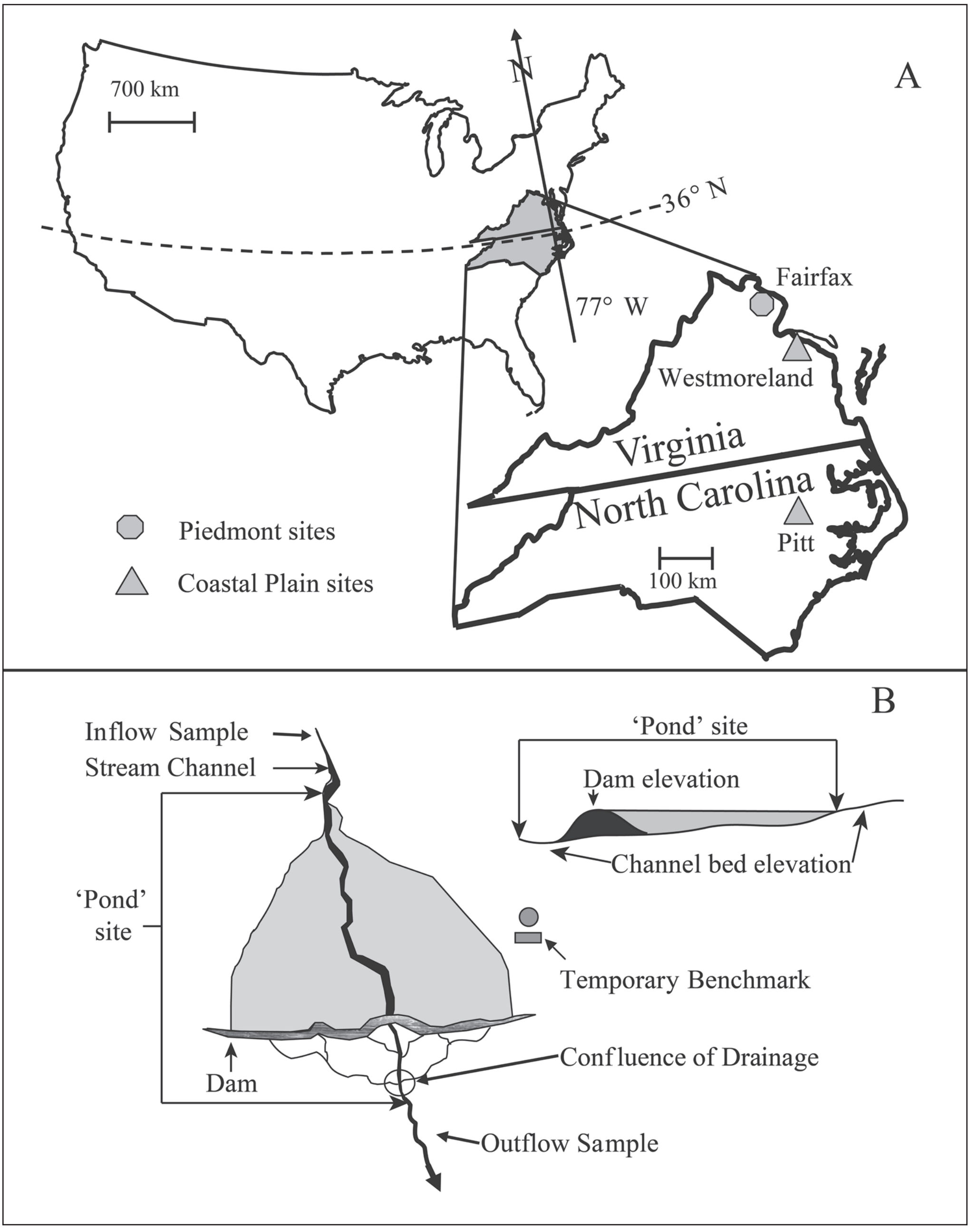


Figure. 1. (A) Study sites and (B) typical pond features with water-sampling locations.

that had a single-thread stream input and, where possible, we chose new ponds (trees present and little open water). We did not include ponds where the primary water source appeared to be groundwater discharge within the pond. Although we made every attempt to select ponds in parks and in remote locations with the lowest chances of being destroyed, the Beaver is considered a nuisance species in the mid-Atlantic States of the US, and many ponds were destroyed prior to the completion of the study. There were no apparent significant changes in the landscape surrounding the ponds or the watersheds during the study.

We defined a pond site from the downstream confluence of dam drainages to the upstream channel-bed elevation that would normally be higher than the dam elevation at the time of the initial site survey (Fig. 1B). We selected a total of 14 pond sites for the study. We identified 5 sites in Fairfax (Table 1) through complaints of Beaver activity to Fairfax County Park Authority (Fairfax, VA) and conducted field reconnaissance to verify the presence of beaver ponds. Fairfax sites were located on 1^{st}–3^{rd}- order streams (Strahler 1957), and were composed of a single pond, inundating disjunct serial ponds, and channel disjunct serial ponds (Fig. 2 A, B) of up to 6 ponds (5–80 m wide, 120–470 m long). We used topographic maps and field reconnaissance to select 5 sites in Westmoreland (Table 1). These ponds were located on streams that ranged from 1^{st}–3^{rd} order and were either treeless or had standing dead wood. The Westmoreland sites were composed of single ponds (43–83 m wide, 70–175 m long). We selected 4 sites in Pitt (Table 1) using 1998 digital orthophotography, infrared aerial photography (Townsend and Butler 1996), and field reconnaissance of sites sampled by Bason (2004). Pitt sites were on streams that were 2^{nd} order and were composed of single ponds (39–110 m wide, 210–410 m in long).

Table 1. Site names and preexisting conditions. F = Fairfax, W = Westmoreland, P = Pitt, U = unchannelized, C = channelized, UF = unchannelized filled, HDS = high density suburban, F/S = forest suburban mix, S= suburban, F/A = forest–agriculture mix, A = agriculture, and fp = floodplain.

Site	Area	Stream order	Channel	Watershed cover	% slope	Channel area (m^2)	Ponded floodplain area (m^2)
Fryingpan Brook	F	1	U	HDS	0.29	320	540
South Run upstream	F	1	C	F/S	0.61	1490	0
Johnny Moore	F	2	C	S	0.74	1910	4800
South Run downstream	F	3	U	S	0.24	1070	0
Horsepen Run	F	1	C	S	0.59	3260	25,100
Canal Swamp upstream	W	2	UF	F/A	1.03	190	7500
Canal Swamp downstream	W	3	UF	F/A	0.34	130	8400
Tributary to Fox	W	1	U	F	0.49	160	5290
Bundy Swamp	W	2	U	F/A	0.95	250	3910
Fox Hall Swamp	W	2	U	F	0.33	180	4400
Tower Swamp	P	2	C	F	0.17	420	560
Howell Swamp	P	2	U	A	0.29	580	15,950
Bynum Mill	P	2	U	F	0.14	460	22,400
Juniper Branch	P	2	C	A	0.15	2870	16,000

Description of pond types

In the process of conducting this study, it became evident that there were limited (Hair et al. 1978, Pullen 1971), if any, physical descriptions of the many configurations of beaver ponds. Thus, we describe the 4 basic beaver-pond types here (Fig. 2A):

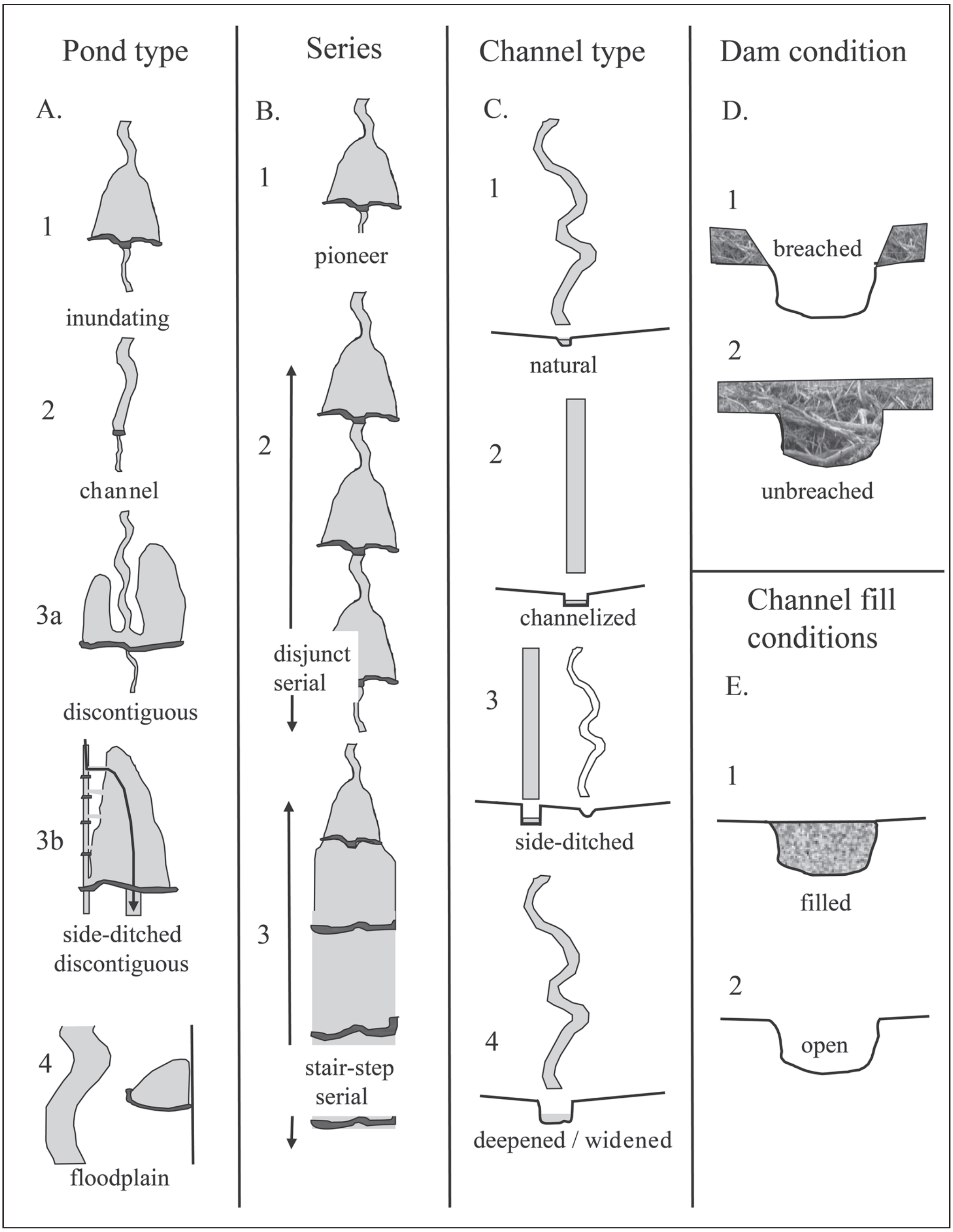


Figure 2. A schematic of (A) pond type, (B) pond setting (in or out of series), (C) channel type, (D) dam conditions, and (E) channel-fill conditions that affect sediment storage.

(1) Inundating ponds occur where the beaver pond inundates the floodplain from the dam to the upstream extent of the pond. The pond has no break in continuity and stream-channel edges are not exposed at normal pool levels.
(2) Channel ponds occur when Beavers create a dam within the channel, but at normal pool levels the floodplain is not inundated.
(3) Discontiguous ponds have the same dam layout as inundating ponds, but the incoming channel is separated from the majority of the pond either because the banks are exposed due to high sediment deposition, dam construction along reaches of side-ditched streams, or as spoil banks from channelization. Side-ditching is a common type of channelization where a ditch is dug along the side of a floodplain instead of in the existing channel. In this study, cuts between the ditch and the historical channel appeared to have been dug by Beaver reverting flow to the natural floodplain.
(4) Floodplain ponds occur where dams are built in sloughs or in backswamp areas (Townsend and Butler 1996).

Ponds are either pioneer or serial (Fig. 2 B). Pioneer ponds occur when Beavers initially move up a stream (Hilfiker 1991) and create a single pond with no upstream ponds. Serial ponds occur either in disjunct or in stair-step formation. Ponds also occur along natural (Fig. 2C) and modified stream reaches. There are 3 major types of channel modification that affect the stability and shape of beaver ponds: (1) channelization, where the channel is straightened along the natural stream bed; (2) side-ditched, where a ditch is dug at the edge of the floodplain and streamflow is captured by the ditch; and (3) deepened/widened, where the natural channel is deepened or widened either by manual excavation or by erosion of the banks and bed (incision).

Sediment release occurs when Beaver dams are breached (Fig. 2D). The condition of the dam may also significantly affect sediment transport (Woo and Waddington 1990). Additionally, during the period of ponding, the stream channel may fill with sediment and organic debris, affecting sediment storage (Fig. 2E). If a channel fills during ponding, the site is often referred to a beaver meadow (Polvi and Wohl 2012), although the term meadow does not include all filled channel ponds.

Sediment measurement

We employed 3 methods of measuring sediment dynamics in beaver ponds: (1) depth-integrated base-flow sampling (hereafter, base-flow samples), (2) repeat surveys within the channel, and (3) depositional surfaces (pads) on the floodplain. We collected base-flow samples to determine the instantaneous effect of beaver ponds on suspended solids. We utilized repeat surveys and pads to examine variation in sediment storage at each site.

We collected depth-integrated samples in downstream to upstream order using the multiple-vertical method during base-flow conditions in the channel downstream of the confluence of drainages (Edwards and Glysson 1999). We filtered known volumes of samples using a 0.7-µm ash-free, glass-fiber filter, dried the collected solids and filters for 24 h at 100 °C, and weighed them to determine the suspended-sediment concentration (mg/l). We ashed the dried samples at 400 °C for 16 h and weighed them to determine volatile organic loss on ignition (Nelson and Summers 1996). We calculated the suspended-sediment concentration (SSC) reductions/increases from paired upstream and downstream samples.

We surveyed stream channels during site selection (2002) using a Topcon RL-HA rotating laser (Topcon, Livermore, CA) with an accuracy of 1 mm/25 m. Surveying consisted of establishing a benchmark, measuring channel dimensions, and determining bed elevation relative to the benchmark. We measured pond dimensions and surveyed the beaver-dam elevation and width. We surveyed the ponded channel at 5-m intervals from below the dam to the distance above the pond where the channel bed exceeded pool elevation. We determined channel gradient by surveying the thalweg (the deepest point of the channel that is a longitudinally continuous feature, not a scour hole) 20 m downstream of the pond and upstream of the pool elevation, and reported it as channel percent-slope between these points. We resurveyed the ponds in 2003 and 2005 and reported the difference in channel-bed elevation as a change in volume (channel width x length x average-elevation change). We reported changes in channel elevation of <1 cm as being below detection limits and did not include beaver dams and lodge structures as depositional volumes. The channel of Howell Swamp (Pitt County) was excluded from channel surveys because the water in the channel exceeded 2 m in depth and was not boat accessible.

In 2002, we placed pads on floodplains and in the ponds to determine sediment-deposition rates outside of the channel (hereafter referred to as floodplain deposition). We used feldspar-clay pads in locations that were normally dry (Bauman et al. 1984, Kleiss et al. 1989). In locations with standing water, we anchored 4-mm-thick plastic sheets or ~0.3 m^2 steel pads to the floodplain surface. We placed 3–15 pads on the floodplain depending on pond size and shape to collect at the upstream, middle, or downstream portions of the pond. We measured clay pads by removing plugs of material and measuring the deposition above the marker horizon. We measured deposition on the plastic and steel sheets by inserting a sharp knife with a blunted tip into the deposited material until it came into contact with the sheet and measured the depth of insertion; 3 measurements of the deposited-sediment thickness were made per pad. We measured depth of sediment deposition in 2003 and 2005. We reported accumulations of <1 mm as being below detection limits. Sediment deposition is reported as a vertical rate (mm/yr) and volume (m^3/yr) (area of pond x average deposition). We determined sediment texture in the field (Thein 1979).

We employed multiple regressions and hierarchical cluster analysis using the Minkowsky method to analyze the data and determine meaningful groupings of depositional data in relation to physiographic area, channel gradient, presence/absence of channelization, beaver-dam removal, and watershed condition (suburban, forested, agriculture). We compared sediment storage across the 3 regions using an ANOVA (SPSS v16.0).

Results

All areas

Base-flow concentrations of particulate organic matter (POM) increased through the beaver ponds in Fairfax and decreased in Westmoreland and Pitt (Table 2). Sediment storage in the channel was the most variable on the Piedmont (Fairfax) and least variable on the Coastal Plain (Pitt) (Table 3). Breached beaver dams released sediments previously stored in-channel (Fig. 2D). Regions varied in sediment storage (ANOVA: $P = 0.001$; Fig. 3). Sediment storage on the floodplain was greatest in Fairfax along inundating ponds and lowest in Westmoreland (Table 3). Hierarchical cluster analysis of channel storage grouped the Pitt sites together with 1 Westmoreland site and 1 Fairfax site. The Westmoreland stair-step serial sites grouped together, and most of the Fairfax sites did not group. None of the measured parameters (gradient, ponded area, stream order) correlated with deposition volumes ($R^2 = 0.04, 0.18, 0.01$), SSC ($R^2 = 0.02, -0.01, -0.01$), or POM ($R^2 = 0.05, 0.12, 0.22$).

We identified 3 channel-storage groupings. The first group was unbreached dam and open channel. Channel accumulation of sediment occurred in this group during the first year of study. The second group was unbreached, filled. These sites lost negligible amounts of sediment from the channel during the first year. In filled-channel beaver-ponds, the greatest deposit of sediment was within the

Table 2. Base-flow depth-integrated samples for suspended-sediment concentration (SSC) and particulate organic matter (POM) upstream (up) and downstream (down) of sites. Percentage difference is given for paired (upstream and downstream) samples. F = Fairfax, W = Westmoreland, and P = Pitt. Standard errors are in parentheses. For sites: (u) = upstream, (d) = downstream.

			SSC			POM		
Site	Area	*n*	Up (mg/L)	Down (mg/L)	Avg % change	Up (mg/L)	Down (mg/L)	Avg % change
Johnny Moore	F	9	6.8 (1.4)	8.3 (1.3)	26	3.5 (0.9)	5.0 (0.6)	44
South Run (u)	F	10	20.0 (3.3)	24.0 (4.9)	21	10.3 (2.9)	13.0 (4.6)	27
South Run (d)	F	5	20.0 (7.1)	20.0 (8.6)	-13	7.6 (1.0)	7.5 (0.7)	0.1
Horsepen Run	F	5	15.0 (4.3)	20.0 (3.7)	40	6.6 (0.7)	7.5 (0.9)	13
Fryingpan Brook	F	5	29.0 (4.9)	46.0 (3.7)	59	7.8 (1.3)	10.0 (2.0)	28
Farifax avg					27			22
Canal Swamp (u)	W	5	15.0 (6.4)	22.0 (14.0)	46	4.1 (2.1)	4.0 (2.0)	-3
Canal Swamp (d)	W	4	15.0 (7.2)	19.0 (16.0)	27	4.3 (1.3)	2.9 (0.7)	-33
Bundy Swamp	W	5	19.0 (7.1)	14.0 (7.0)	-26	8.1 (6.1)	5.7 (2.3	-30
Fox Hall Swamp	W	5	39.0 (20.0)	15.0 (5.8)	-61	5.9 (1.9)	8.3 (6.6)	41
Westmoreland avg					-4			-6
Tower Swamp	P	7	7.1 (3.6)	10.0 (5.9)	40	3.0 (3.3)	4.9 (4.2)	63
Howell Swamp	P	6	5.5 (2.6)	4.3 (1.6)	-22	3.1 (1.2)	3.5 (1.5)	13
Bynum Mill	P	5	2.3 (0.4)	1.5 (0.5)	-35	1.6 (0.3)	1.3 (0.3)	-19
Juniper Branch	P	8	5.6 (1.6)	5.1 (1.4)	-9	1.6 (1.5)	1.2 (1.6)	-25
Pitt avg					-7			8
Total average					5			7

channel. When the channel was filled, sediment deposition was evenly distributed between the channel and floodplain. The third group was breached; several dams were breached during the study and lost considerable amounts of unconsolidated sediment (161–718 m^3) from the channel.

Piedmont, Fairfax County, VA

Suspended-sediment concentrations in base-flow samples for the 5 Fairfax sites ranged from 2.3 mg/l to 48 mg/l. During the study period, average base-flow SSC increased by 27% from upstream to downstream. POM ranged from 1.8 mg/l to 21 mg/l, constituting an average 40% of base-flow SSC. There was an average POM increase of 22% from upstream to downstream (Table 2). In-channel sediment-storage volume at Fairfax ranged from -718 m^3/yr to 131 m^3/yr. Sediment losses occurred at breached dams, and accumulation occurred in unbreached ponds (Fig. 2D). On average, the 5 sites lost 200 m^3/yr of sediment from the channel. If the 3 sites breached by human activity are removed from the analysis, the 2 remaining sites stored an average of 77 m^3/yr. All beaver ponds were destroyed by 2005, but channel blockages remained at 2 sites. In 2005, surveys at those ponds indicated a loss of 15 m^3/yr in one and no measurable difference at the other (Table 3, Fig. 4).

Floodplain deposition at the Fairfax sites ranged from 11 m^3/yr to 533 m^3/yr (<1 mm/yr to 111 mm/yr). The lowest volume occurred at a small inundating pond (Fig. 2A) with the lowest channel gradient of the 5 sites. The greatest deposition volume occurred at the Johnny Moore site, which was a large inundating pond with the steepest channel gradient. No measurable deposition occurred

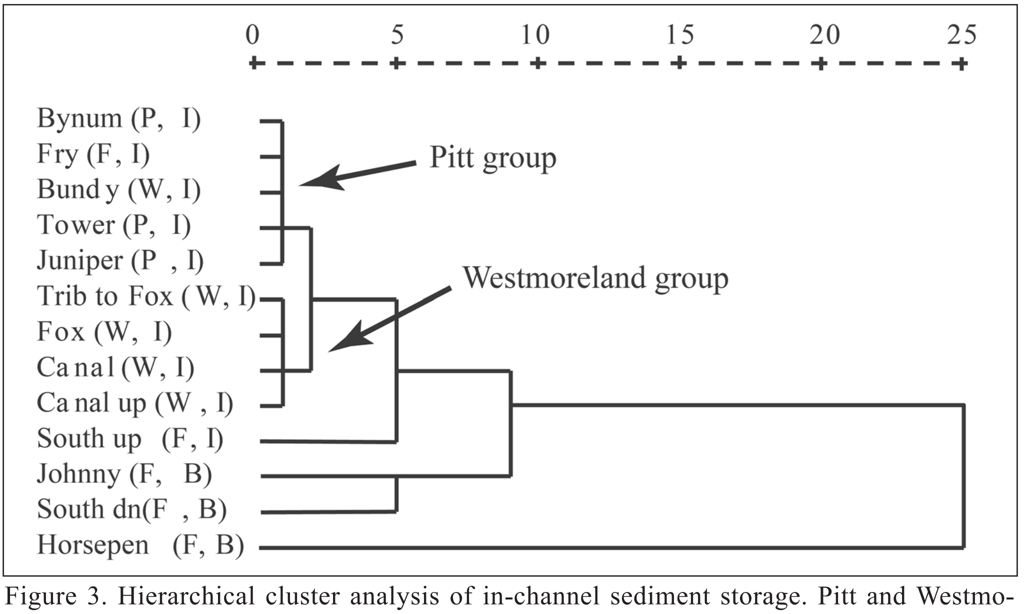


Figure 3. Hierarchical cluster analysis of in-channel sediment storage. Pitt and Westmoreland sites grouped based on area. Fairfax sites did not group. P = Pitt, F = Fairfax, W = Westmoreland, I = dam intact, B = dam breached. Howell Swamp (Pitt) was excluded from channel storage analyses because it exceeded wadeable depth.

on the pads at the 2 channel ponds (Fig. 2A) where water did not inundate the floodplain except during storm events. Average deposition for Fairfax was 184 m^3/yr. The average floodplain deposition for inundating ponds in Fairfax was 307 m^3/yr. Deposited sediment texture varied by watershed and location in the pond ranging from fine gravel to silty clay. Measurements in 2005 indicated greatly reduced storage rates (Table 3, Fig. 5).

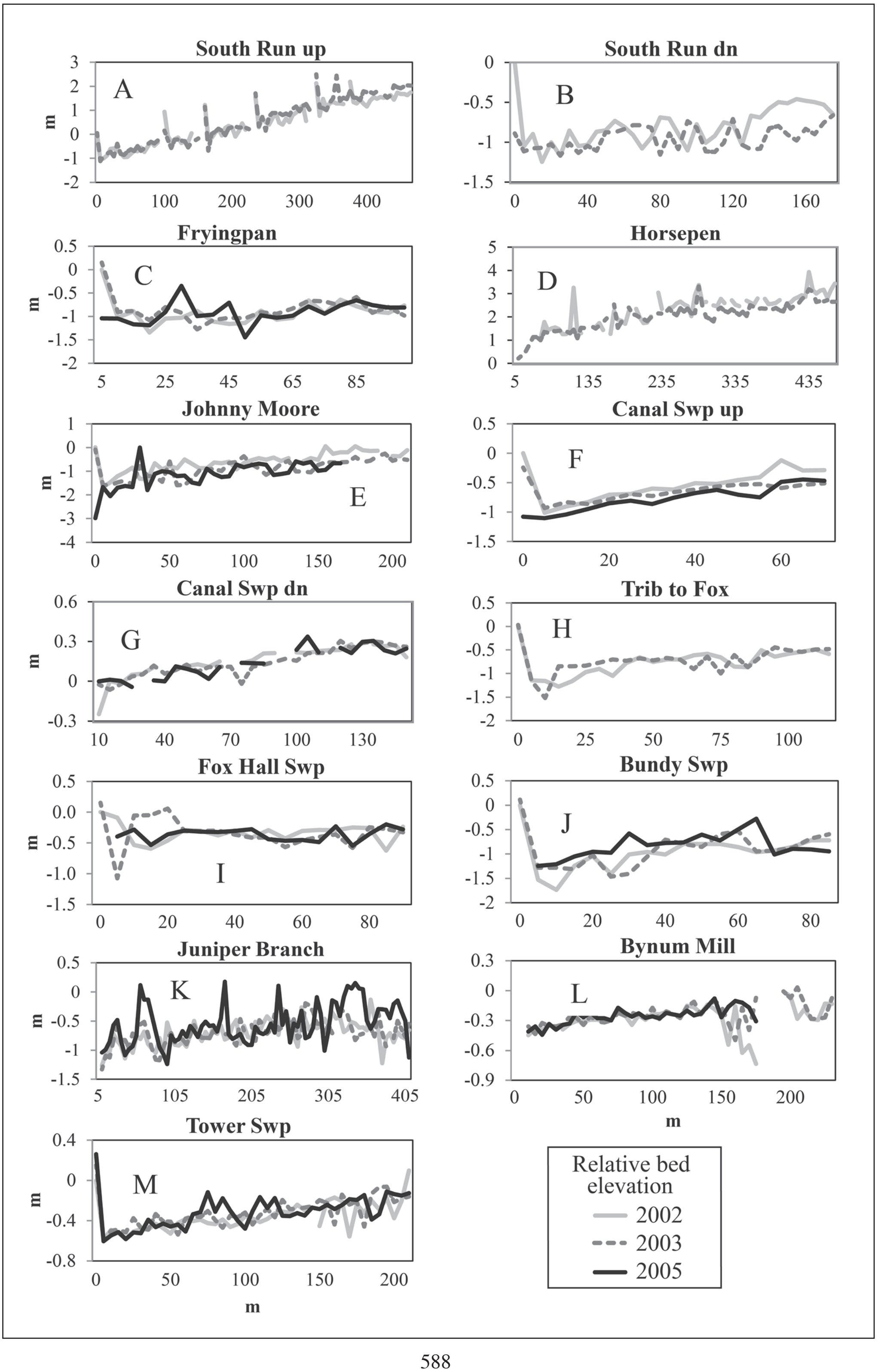
Coastal Plain, Westmoreland County, VA

Base-flow samples collected for 4 Westmoreland sites had SSC ranging from 2.2 mg/l to 92 mg/l. Beaver ponds reduced the average SSC by 3.5% from upstream to downstream. POM ranged from <1 mg/l to 29 mg/l, constituting an average 37% of base-flow SSC. There was an average POM decrease of 26% from upstream to downstream. Repeated channel surveys showed channel-sediment volume changes of -16 m^3/yr to 21 m^3/yr. Losses occurred where channels were filled prior to initial

Table 3. Site names, dam conditions, and depositional rates for 2002–2003 and 2003–2005. F = Fairfax, W = Westmoreland, P = Pitt, I = dam intact, A = abandoned, BH = breached by humans, Pb = partial blockage, BD = below detection limits (resurveyed elevational change <1 cm, floodplain deposition <1 mm), Cl = clay, St = silt, O = organics, Sd = sand, and Fg = fine gravel. (u) = upstream; (d) = downstream. Howell Swamp (Pitt) was excluded from channel storage analyses because it exceeded wadeable depth.

		Dam		Channel deposition (m^3/yr)		Avg. floodplain deposition (mm/yr)		Floodplain deposition (m^3/yr)		Deposited sediment
Site	Area	2003	2005	02–03	03–05	02–03	03–05	02–03	03–05	texture
Fryingpan Brook	F	I	BH	23	BD	21	6	11	3	Cl, St, O
South Run (u)	F	I	BH	131	-	BD	-	BD	-	Cl, St, Sd
Johnny Moore	F	BH	Pb	-278	-15	111	33	533	290	Sd, Fg
South Run (d)	F	BH	BH	-161	-	BD	-	BD	-	-
Horsepen Run	F	BH	BH	-718	-	15	7	377	184	Cl, St, Sd
Fairfax avg				-200	7	26	15	184	115	
Canal Swamp (u)	W	I	A	-16	-5	-	-	-	-	-
Canal Swamp (d)	W	I	I	-6	BD	-	-	-	-	-
Trib to Fox	W	I	-	5	-	2	-	11	-	O, St
Bundy Swamp	W	I	A	21	21	9	19	37	74	O, St, Cl
Fox Hall Swamp	W	I	A	BD	BD	17	6	75	27	O
Westmoreland avg				1	4	9	13	41	53	
Tower Swamp	P	I	I	18	BD	2	7	2	10	O, St
Howell Swamp	P	I	-	-	-	7	-	116	-	O, St, Cl
Bynum Mill	P	I	I	23	BD	2	10	39	219	O, St
Juniper Brook	P	I	I	34	175	29	15	466	197	Sd, O
Pitt avg				26	58	10	11	156	142	

Figure 4 (following page). Repeat longitudinal surveys of channel-bed elevations at 5 m intervals relative to benchmarks: 2002, 2003, and 2005 from Fairfax (A–E), Westmoreland (F–J), and Pitt (K–M). Howell Swamp (Pitt) was excluded from channel storage analyses because it exceeded wadeable depth.


South Run up
A
South Run dn
B
Fryingpan
C
Horsepen
D
Johnny Moore
E
Canal Swp up
F
Canal Swp dn
G
Trib to Fox
H
Fox Hall Swp
I
Bundy Swp
J
Juniper Branch
K
Bynum Mill
L
Tower Swp
M
m
Relative bed elevation
2002
2003
2005

site surveying (Fig. 2E). Accumulation occurred in ponds where the channels were open (Fig. 2E). On average, the 5 sites accumulated 1 m³/yr of sediment in the channel by 2003 and increased to 4 m³/yr during 2003–2005 (Table 3, Fig. 5). The smallest change in channel storage occurred in the stable, serial beaver ponds (Fig. 2B).

We observed floodplain deposition ranging from 11 m³/yr to 75 m³/yr (2–19 mm/yr) at 3 sites in Westmoreland. The greatest deposition occurred at the lowest channel-slope site. The average floodplain-deposition volume for the area was 41 m³/yr and increased to 53 m³/yr during the period 2003–2005. Many ponds had been

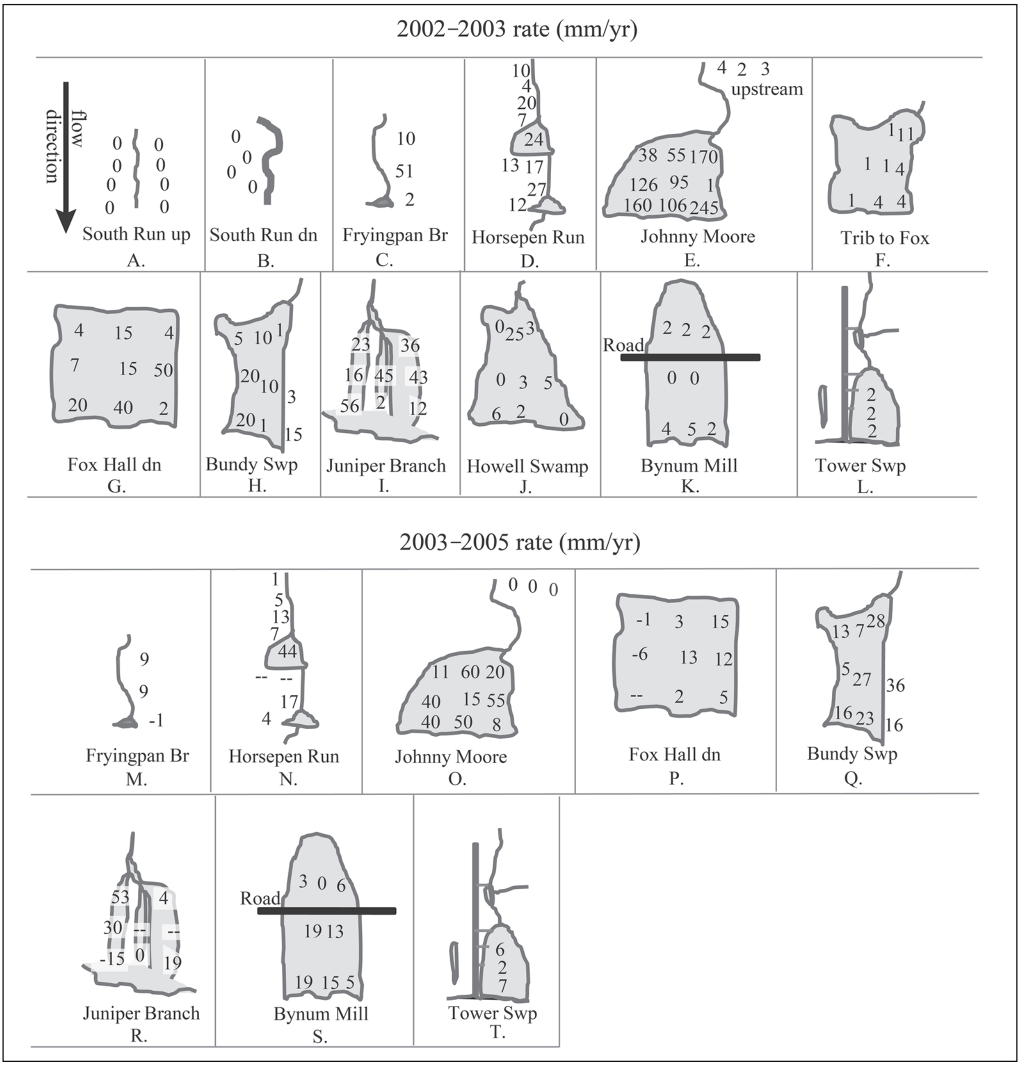


Figure 5. Beaver pond configurations and floodplain deposition or erosion rates (mm/yr) at each pad location in ponds during 2002–2003: Fairfax (A–E), Westmoreland (F–H), and Pitt (I–L), and 2003–2005: Fairfax (M–O), Westmoreland (P, Q) and Pitt (R–T). (--) indicates a lost pad. Upstream pads at Johnny Moore were upstream of the influence of the pond. Only ponds with pad deposition or erosion data are shown. Positive rates indicate accretion; negative rates indicate erosion.

abandoned, with partial dam breakage leaving partial channel blockages. Floodplain deposition rates increased between 2003 and 2005, and deposited sediment particle size ranged from silt to organics (Table 3, Fig. 5).

Coastal Plain, Pitt County, NC

Base-flow samples collected for the 4 Pitt sites had SSC ranging from <1 mg/l to 44 mg/l. During base flow, average SSC decreased by 7% through the ponds. Discontiguous (Fig. 2A) and channel ponds exported sediment. POM ranged from <1 mg/l to 29 mg/l, constituting an average 80% of base-flow SSC, and increased 8% from upstream to downstream. Repeated channel surveys (excluding Howell Swamp) showed the greatest average channel-sediment storage (18–34 m^3/yr), with all ponds exhibiting sediment storage in the channel. On average, the 3 sites gained 26 m^3/yr of sediment in the channel; this rate doubled between 2003 and 2005 (Table 3, Fig. 5). Floodplain deposition ranged from 0.4 m^3/yr to 466 m^3/yr (2–29 mm/yr). The greatest deposition volume occurred at a discontiguous pond located at the confluence of a channelized reach with the natural channel. The lowest deposition-accumulation volume occurred at a side-ditched, channel pond (Tables 2, 3). The average floodplain-deposition rate for Pitt was 156 m^3/yr; there was a decrease to 142 m^3/yr between 2003 and 2005. Deposited sediment was primarily sand at high-deposition sites and silt/clay at low-deposition sites (Table 3; Fig. 5).

Discussion

This study investigated the role of beaver ponds in sediment storage on the Coastal Plain and Piedmont of the mid-Atlantic, and detected differences in sediment storage between the Piedmont and Coastal Plain. Sediment storage in beaver ponds appears to be influenced by several factors including shape, position in relation to other ponds, channel condition, and frequency of dam destruction. Beaver ponds that were not destroyed during the study period stored large volumes of sediment. Beaver ponds were not static; pond repositioning and reconfiguration occurred during the study. Often, new dams were built within pioneer ponds and sometimes dams were built that inundated older dams.

Mean floodplain accretion rates in these beaver ponds (2002-2003: 20 mm/yr 2003-2005: 15 mm/yr) greatly exceeded the mean deposition rate of similar unimpounded streams. Previous studies of unimpounded low-order stream floodplains in these areas have documented mean sediment accretion rates up to 5.4 mm/yr and shown evidence indicating those in the Piedmont sometimes exhibited erosion (Allmendinger et al. 2005, Craft and Casey 2000, Hupp 2000, Kroes and Hupp 2010, Schenk and Hupp 2009, Schenk et al. 2013). Accretion rates in the Piedmont beaver ponds ranged from below to within the range of published rates for beaver impoundments, but accretion rates in the ponds on the Coastal Plain were consistently less than most previously reported rates (Bigler et al. 2001, Butler and Malanson 1995, John and Klein 2004). Despite the inequity in accretion rates, the volume of deposition was similar between Piedmont and Coastal Plain beaver ponds as a result of the typically much greater area of the Coastal Plain ponds. Inundation ponds were the most effective at trapping sediments. Channel ponds were ineffective at increasing sediment trapping on the floodplain. The dams that formed channel ponds did not appear to slow water velocities enough to induce sediment deposition on the floodplain during flood events and frequently breached or blew-out due to the dynamic hydrology of the stream. It seems probably that inundation ponds have greater volume and slower flow resulting in increased settling of suspended sediment.

Low sediment-storage rates in channel ponds may also be attributed to Beaver activity, with bioturbation increasing with greater confinement. Beaver activities associated with the creation and maintenance of dams and the excavation of bank burrows and slides release fine particles into the water column and can be a significant source of sediment (Meentemeyer et al. 1998). However, at our sites burrows were common only along channel and discontiguous ponds (D.E. Kroes, Unpubl. data). Bioturbation of fine sediment is especially relevant when the primary sediments are clay and silt.

In the Coastal Plain, POM concentration decreased through most of the ponds during base flow. In Fairfax, POM concentration increased through most sites. In shallow meadows, this carbon accumulation is supplemented by dense herbaceous growth and substantial root mass in a shade-free environment (Wohl 2013). As beaver ponds age, they accumulate and bury POM and large organic debris, possibly becoming important carbon repositories.

Sediment-storage patterns appear to be different between the channel and the floodplain. The amount of in-channel sediment deposition appears to be related to the amount of bedload and whether the pond is pioneer or serial. We identified 3 channel-storage groups: (1) unbreached dam and open channel, (2) unbreached, filled, and (3) breached. Breached ponds showed considerable loss of stored sediment. These lost sediments may have been stored in the channel for the life of the pond (days to decades) until breaching, and this phenomenon demonstrates the dynamic nature of in-channel storage. Where a pond was abandoned after pond maturity as in Westmoreland, deposition rates increased as bioturbation was decreased and woody debris stabilized channel sediment. Apparently, where no large wood was present in the channel, complete sediment washout occurred; however, we did not measure large wood features.

In the Piedmont (Fairfax), individual watershed occurrences of Beaver eradication, or dam-busting overwhelmed the regional similarity in regard to channel storage. In contrast, the highest stream-gradient area (Westmoreland) and lowest-gradient site (Pitt) had strong similarity in channel storage between sites and areas. One cause of the dissimilarity in Fairfax storage rates may be the relative scarcity of ponds in combination with the active, frequent destruction of beaver dams. In a serial pond setting, much of the in-channel sediment from the breached pond would be trapped in downstream ponds. However, Beaver eradication would eventually result in the total failure of the pond series.

Floodplain-sediment storage in beaver ponds is longer-term than channel storage (Westbrook et al. 2011), especially in low gradient Coastal Plain systems, where deposited sediments may be stored for centuries or millennia (Meade et al. 1990). Ponds with the slowest velocities and longest turnover-time should then be the most effective at trapping fine-grained sediments and associated phosphorus (Noe et al. 2007).

Conclusions

Beaver ponds have great potential to trap sediments. When beaver ponds are present on channelized streams, they often hydraulically reconnect the floodplain with the stream, thus, restoring natural function to the floodplain. The drainage density of the VA and NC Piedmont is 4.91 km/km^2 and the drainage density of the Coastal Plain is 2.14 km/km^2 (Calvo-Alvarado and Gregory 1997). If the deposition for intact beaver ponds were applied to 1 pond/stream km on Piedmont VA and NC floodplains, it would result in 22 million m^3/yr of deposition and reduce previously reported rates of stream incision and erosion of post-colonial floodplain deposits. On the Coastal Plain, 1 pond/km would result in 19 million m^3/yr of deposition in VA and NC.

Beaver ponds in suburban Fairfax County were destroyed more rapidly than in the other areas despite protection by Park regulations (FCPA 2006). Conflicts with humans occur as Beaver populations increase, ponds form, subsequent tree damage occurs, or drainages become blocked (Marjorie Pless, Fairfax County Parks Authority, Fairfax,VA, pers. comm.). Although the motivations for Beaver removal are varied, the end result is increased sediment yield from watersheds relative to yields when impoundments are present. Beaver ponds may be an underutilized asset in reducing the sediment and associated nutrient-delivery rate to the eutrophic estuaries of the mid-Atlantic US.

Our study was designed to investigate the effect of beaver ponds on sediment deposition in relation to physiographic settings. It appears however that the pond and dam conditions as well as their disturbance frequency overwhelm the signal of the differing gradients, sediment loads, and land use. Future research should be focused on ponds and channels of differing configurations to determine the specific effects of each pond and channel type. Further investigation should be conducted on sediment trapping in beaver ponds on the higher sediment-load streams of the Great Plains and Central Lowlands.

Acknowledgments

This research was funded by the US Geological Survey's Chesapeake Bay and National Research Programs. Thanks to Joshua Elwell for his help in the field despite his unreasonable fear of leaches. Thanks to Fairfax County Parks, Fairfax County Stormwater Management, all landowners, and land managers who allowed us access to their lands. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the US Government.

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