1 Bedload transport over run-of-river dams, Delaware, U.S.A.
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Abstract

We document the detailed morphology and bed sediment size distribution of a stream channel upstream and downstream of a 200-year-old run-of-river dam on the Red Clay Creek, a fifth order stream in the Piedmont of northern Delaware, and combine these data with HEC-RAS modeling and bedload transport computations. We hypothesize that coarse bed material can be carried through run-of-river impoundments before they completely fill with sediment, and we explore mechanisms to facilitate this transport. Only 25% of the accommodation space in our study site is filled with sediment, and maximum water depths are approximately equal to the dam height. All grain-size fractions present upstream of the impoundment are also present throughout the impoundment. A characteristic coarse-grained sloping ramp leads from the floor of the impoundment to the crest of the dam. A 2.3-m-deep plunge pool has been excavated below the dam, followed immediately downstream by a mid-channel bar composed of coarse bed material similar in size distribution to the bed material of the impoundment. The mid-channel bar stores 1472 m^3 of sediment, exceeding the volume excavated from the plunge pool by a factor of 2.8.

These field observations are typical of five other sites nearby and suggest that all bed material grain-size fractions supplied from upstream can be transported through the impoundment, up the sloping ramp, and over the top of the dam. Sediment transport computations suggest that all grain sizes are in transport upstream and within the impoundment at all discharges with return periods from 1 to 50 years. Our computations suggest that transport of coarse bed material through the impoundment is facilitated by its smooth, sandy bed. Model results suggest that the impoundment is currently aggrading at

0.26 m/y, but bed elevations may be recovering after recent scour from a series of large floods during water year 2011-2012. We propose that impoundments upstream of these run-of-river dams behave as long pools that adjust their bed elevation and texture to transport the load supplied by the watershed, rather than as impounded reservoirs with little bed material transport capacity. Scour may only occur during episodic high flows, followed by aggradation during periods of low flow.

Keywords: sediment transport; run-of-river dams; fluvial geomorphology; impoundments

1. Introduction

The impacts of large reservoir dams (*sensu* Csiki and Rhoads, 2010) on sediment transport are well documented (Brune, 1953; Baxter, 1977; Christiansson, 1979; Brandt, 2000; Graf, 2005, 2006). Conceptual models of sedimentation in *unfilled* large reservoir dams (Garcia, 2008; Csiki and Rhoads, 2010) suggest 100% trapping efficiency of coarse-grained bed material, resulting in a prograding coarse-grained delta at the upstream inlet (Garcia, 2008). Trap efficiencies for fine-grained suspended sediment vary depending on reservoir geometry, hydrology, sediment characteristics, and reservoir age (Brune, 1953) but are typically significant, such that these structures trap much of the sediment supplied from their catchments.

In contrast, sediment transport processes of smaller low head dams (such as former mill dams) have been less well studied (Csiki and Rhoads, 2010). Because low head dams are likely to be highly diverse (as are large reservoir dams), here we focus on former mill dams that fit into the unique subcategory of low head dams termed *run-of-river dams*. Run-of-river dams extend across the width of a stream channel and they do not inhibit discharge of water over the dam. The height of run-of-river dams does not exceed the elevation of the channel banks upstream, and therefore impoundments upstream do not inundate the floodplain year-long (as defined by Csiki and Rhoads, 2010). The residence time of water within a run-of-river impoundment scales from minutes to hours, and the hydraulic head across the dam is less than a few meters (Poff and Hart, 2002; Ashley et al., 2006). Most run-of-river dams within the U.S. were built in the 1800s and early 1900s as water intakes for mills, industrial plants, and municipal water supply (Benstead et al., 1999; Born et al., 1998; Shafroth et al., 2002; Stanley and

Doyle, 2002). Unlike larger reservoir-style dams, run-of-river dams do not appear in the National Inventory of Dams (Orr et al., 2004).

The hydraulics of run-of-river dams are similar to weirs, with detailed behavior varying with the morphology of the dam and the upstream impoundment (Csiki and Rhoads, 2010; French, 1985). Few studies describe sedimentation associated with run-of-river dams (Csiki and Rhoads, 2010), but recent results suggest that these structures do not act as effective sediment traps. Csiki and Rhoads (2014), for example, compared morphology and sediment characteristics upstream and downstream of four run-of-the-river dams in Illinois, and they noted few discontinuities that could be attributed to the presence of the dam. They attribute the lack of sediment discontinuity to sediment transport through run-of-river impoundments, though they offered no mechanistic explanations or observations to support their interpretation.

Pre-dam removal monitoring by Major et al. (2012) and Pearson et al. (2011) showed that sediment could be scoured from the impoundments of two different dams, the 15-m-tall Marmot dam (Major et al., 2012) and the 4-m-tall Merrimack Village dam (MVD; Pearson et al., 2011). Marmot dam passed sediment after its storage capacity was completely filled (Major et al., 2012), while the impoundment of the MVD was scoured out during a high storm event (Pearson et al., 2011). Both of these studies demonstrated that sediment can leave an impoundment; however, the mechanism for transport is different for each case and neither study provided a detailed investigation of sediment transport processes.

In this paper, we study former mill dam impoundments (similar to the run-of-river dams of Csiki and Rhoads, 2014) located in the downstream reaches of fourth-and-fifth-

order watersheds with drainage basin areas $>100 \text{ km}^2$. The objectives of our study are (i) to define the detailed morphology and sedimentary characteristics of a typical run-of-river impoundment and (ii) to model sediment transport through the impoundment with a one-dimensional model. We test the hypothesis that run-of-river impoundments can pass all gravel size fractions supplied by the watershed using topographic and sedimentologic data coupled with sediment transport model computations. We further hypothesize that transport of coarse bed material (including cobbles) can occur across a lower bed slope induced by the dam as a result of (i) a relatively smooth, sandy bed and (ii) the development of a sloping ramp comprised of coarse sediment behind the dam, which allows bed material to roll up and over the dam. We term this previously undocumented geomorphic feature a *sediment ramp*. We also present data from five other former mill dams and mill ponds to demonstrate that the results of our detailed study are typical for this geomorphic setting.

2. Study area

The study area is located in northern Delaware (Fig. 1) within the White Clay Creek (277 km^2) and Red Clay Creek (140 km^2) watersheds, both of which are tributaries to the Christina River and ultimately the Delaware River estuary. Our study sites are located along alluvial-bedrock channels (Howard, 1998; Turowski et al., 2008) with mixed sand and gravel bed material and frequent pools and riffles, well-developed narrow floodplains, cohesive silty banks (Jacobson and Coleman, 1986; Walter and Merritts, 2008), and forested riparian zones.

112 Our study area within the Christina River basin lies just north of the Fall Line
113 (Renner, 1927) within the Piedmont physiographic province (Fischer et al., 2004). The
114 Christina River basin has 7.8% impervious surfaces and a population density of 1764/km.
115 The basin is 30% developed, 32% forested, and 37% agricultural (Kauffman et al., 2008).
116 The underlying bedrock consists of Cambrian metamorphic rocks of the Wissahickon
117 Formation (Schenck et al., 2000) and Ordovician metamorphic rocks of the Faulkland
118 gneiss and Windy Hill gneiss (Schenck et al., 2000).

119 The mean annual precipitation in the watershed is 116 cm (Kauffman et al.,
120 2008). Intense precipitation events are usually delivered by thunderstorms, hurricanes, or
121 *nor'easters* (cyclonic storm occurring along the east coast of North America and named
122 because the winds are from the northeast; Huschke, 1959). Recent large storms include
123 Hurricane Irene (2011), Tropical Storm Lee (2011), Hurricane Rina (followed by a
124 nor'easter) (2011), Hurricane Isaac (2012), and Hurricane Sandy (2012).

Fig. 1. Location map of the Red Clay Creek and White Clay Creek showing dams used for data collection (white dots), and U.S. Geological Survey gaging station 01480000 (yellow dot). Inset: Barley Mill Road study site showing location of the dam with respect to its impoundment (shaded area). The *bedrock control* denotes an outcropping of bedrock in the stream channel and falls on a slope break as well as a grain size shift. The *hydraulic impoundment limit* shows the upstream extent of dam-induced backwater at the 50-year flood as modeled by HEC-RAS. Short lines in the shaded region represent location of impoundment cross sections. Dashed lines indicate cross sections without grain size information. Arrows indicate flow direction.

136 The Christina River basin was almost completely deforested during colonial
137 times for agriculture. Construction of mill dams began as early as 1802 when the DuPont
138 family settled in the area (Kauffman et al., 2008). At the height of mill dam construction,
139 there may have been hundreds of operating mill dams in the watershed (Walter and
140 Merritts, 2008), but only 72 mill dams are currently in place in the subwatersheds of the
141 Christina River, Brandywine River, White Clay Creek, Red Clay Creek, and Naamans
142 Creek (Kauffman et al., 2008).

143 We focus on six mill dams and mill ponds (Figs. 1 and 2). The Barley Mill Road
144 (BMR) dam was our primary study site, while the other five dams were used to verify
145 that results from the BMR site are typical for this geomorphic setting. The BMR dam site
146 is located on the Red Clay Creek (Fig. 1) and features an old slitting and rolling mill dam
147 (i.e., a mill for processing iron rods) that was in operation from 1814 to 1918 (Delaware
148 Department of Transportation, 2003). Following its active use, the BMR dam was
149 stabilized with concrete and it remains intact.

Fig. 2. Photo mosaic of the six study sites, including (A) dams on Red Clay Creek and (B) dams on White Clay Creek. Mid-channel bars downstream of the dams are outlined in red. Red lines on the mid-channel bar at the Barley Mill Road site indicate the locations of sediment trenches. White arrows indicate flow directions.

3. Methods

3.1. Field methods

3.1.1. Barley Mill Road

Data were collected above, within, and below the impoundment at the BMR site from May 2011 through October 2012. We surveyed channel cross sections, obtained sediment samples to measure the grain-size distribution within the channel, surveyed the scour pool below the dam, and dug sediment trenches to sample the mid-channel bar downstream of the dam.

We surveyed 19 cross sections (Fig. 1). Fifteen of these were spaced 50-70 m apart between the crest of the dam and 1250 m upstream. Upstream cross sections were used to estimate the total accommodation space behind the dam and the extent to which this accommodation space is currently filled with sediment and to provide topographic data for our HEC-RAS model. Two cross sections through the pool downstream of the dam were used to estimate the volume of water within this pool. Another section crossed the mid-channel bar and helped to define its volume, while the fourth section downstream was located 50 m downstream of the bar. Cross sections were surveyed using a TOPCON total station and were oriented perpendicular to the direction of stream flow. Survey lines were extended up the adjacent hill slopes to ensure the highest flood levels were captured. Survey points were located relative to an arbitrary datum on the old spillway gate.

Volume estimates of the total accommodation space and currently stored sediment were done using the surveyed long profile. The total volume of accommodation space was calculated by projecting a straight horizontal line from the top of the dam upstream

until it intersected the bed of the survey. A second line was projected to the same point on the longitudinal profile from the base of the dam to form a right triangle. The area of this triangle was multiplied by the average width of the stream to establish the estimated total volume that the impoundment could hold. The volume of sediment behind the dam was estimated by integrating between the angled line or hypotenuse of the above right triangle and the average depth of water along the same longitudinal profile within the impoundment. The integrated area was then multiplied by the same average channel width to determine the estimate for how much sediment is actively being stored in the channel.

We characterized the grain-size distribution of the channel bed material to assess similarities and differences in bed composition between the channel upstream, the impoundment, and the channel downstream. Sediment data is also needed for bedload modeling. Sediments within the channel were sampled two ways: pebble counts where the channel was easily waded (Wolman, 1954), and dredging where the channel was too deep to wade. We measured at least 100 clasts for our pebble counts, yielding a minimum error of 20% on percentiles (Rice and Church, 1996). Dredge samples were dried and sieved at half- ϕ intervals (Krumbein and Aberdeen, 1937). Pebble count samples (total number of counts = 8) were obtained within the main channel downstream of the mid-channel bar, at each cross section within the channel upstream of the deeper part of the impoundment, and along a characteristic reach upstream of the impoundment (Fig. 1). The dredge was dragged along the bed of the thalweg, and we collected up to 3 kg of sediment with a maximum diameter of <64 mm (*b*-axis) (total number of dredge samples = 5). The exclusion of sediment coarser than 64 mm could not be avoided in the deeper

reaches of the impoundment because of the size of the dredge; however, only 19% of the sediment upstream of the impoundment was coarser than 64 mm. Because the largest sediment could not be sampled within the impoundment, we restrict our transport computations to sediment 32 mm and smaller.

The grain-size distribution of the mid-channel bar was characterized in two ways in order to compare the composition of the bar with the grain-size distribution of the bed upstream of the dam. The surface grain-size distribution of the mid-channel bar was measured using a zig-zagging pebble count from an unvegetated portion of the bar. The subsurface grain-size distribution of the bar was measured using samples from two trenches. One trench was dug on the long axis (parallel to the stream), while the other was dug in the crossstream direction (Fig. 2). The trenches were 0.5 m deep and 5 kg of sediment were extracted from the side of each trench. The trench samples were dried and sieved at half- ϕ intervals.

3.1.2. Other dam sites

Less detailed field data were collected at five additional sites in order to provide a comparison between our main field site (BMR) and other dams in the area. We measured the height of each dam, the maximum water depth of each impoundment, the grain-size of the channel downstream, the grain-size of the bar downstream, the grain size of the impoundment sediment ramp, and the distance between the dam and the mid-channel bar. The height of the dam was approximated using the difference between the water levels at the top (measured at the spillway crest) and bottom (measured just downstream of the spillway crest) of the dam, measured using a laser range finder. This technique, although

useful, underestimates the true height of the dam. For example, the height of the BMR dam is 2.5 m, but measuring the upstream and downstream water levels provides a dam height estimate of only 1.4 m. We measured the maximum depths of the impoundments using a stadia rod deployed from a canoe. The grain-size samples were taken immediately upstream of each dam (using the dredge), on the surface of the mid-channel bars (from a pebble count), within trenches into the mid-channel bars (from grab samples), and on the surface of the channel bed next to the mid-channel bars (another pebble count). Sediment samples were dried and sieved at half- ϕ intervals. The distance between the dams and the mid-channel bars was measured with a laser range finder from the farthest upstream subaerial portion of the bar to the middle of the downstream face of the dam.

3.2. Flow frequency analysis

We analyzed hydrologic data from the USGS 0148000 gaging station just downstream of the study site at Wooddale, DE (Fig. 1). The station has been in continuous operation for 71 years. Our hydrologic analysis had two primary goals. The first was to determine discharges for flood events of specific exceedence probabilities, and the second was to determine the fractions of time when discharges occur within categories defined by specific discharge ranges. The former objective defined the return period of different storms and the hydraulics associated with them (as determined by the Hydrologic Engineering Centers River Analysis System (HEC-RAS) modeling described below), while the latter was useful for computing annual sediment fluxes.

Exceedence probabilities were calculated using a Log-Pearson III analysis (U.S. Water Resources Council, 1982) on the annual peak flow data from the USGS gaging

station (Fig. 3). We selected exceedence probabilities of 0.9 y^{-1} (recurrence interval of 1.1 years), 0.7 y^{-1} (1.43 years), 0.5 y^{-1} (2 years), 0.2 y^{-1} (5 years), 0.1 y^{-1} (10 years), and 0.02 y^{-1} (50 years) and determined the discharges associated with each.

We also calculated the fraction of time in a given year when flows occur in specific discharge ranges. We separated 25 years of 15-minute discharge data from the Wooddale Gage into seven bins. The sizes of the seven bins (discharge ranges) were determined by the six discharges calculated in the Log-Pearson III analysis. The first bin contained all of the low flows, and we did not consider these flows when computing sediment fluxes. The other six bins contained the flow data used for our modeling.

260

261 Fig. 3. Annual peak discharge (red squares) plotted with Log-Pearson Type III fit (blue
 262 line) for U.S. Geological Survey gaging station 014800000 at Wooddale, DE. The top
 263 five large named storms are represented by green squares and indicated by name.
 264

265 3.3. Sediment transport modeling

266 We compute bedload transport rates outside the hydraulic influence of the dam
 267 and at the base of the ramp within the impoundment where the shear stresses are lowest.
 268 We use the difference between these two quantities to estimate changes in sediment
 269 storage and bed elevation, assuming that (i) sediment supplied from outside the hydraulic
 270 influence of the dam will be carried all the way into the impoundment without being
 271 stored at the upstream boundary of the impoundment; and (ii) sediment in transport at the
 272 base of the ramp will ultimately be carried up the ramp, over the dam, and out of the

impoundment caused by the rapid increase in shear stresses up the ramp. We hypothesize that these two regions represent the critical locations to estimate sediment inputs and outputs and therefore to infer changes in bed material storage in the impoundment. Our field data support these assumptions.

3.3.1. HEC-RAS modeling

The objectives of HEC-RAS modeling were to (i) better understand the hydraulic influences of the dam over varying discharges, (ii) determine how far upstream the hydraulic influence of the dam extended at each discharge, and (iii) compute bed shear stresses for inputs into our sediment transport model (discussed below). The maximum upstream limit of influence (at the 50-year discharge) was determined by extending the surveyed cross sections upstream by 50-m segments until the computed shear stress in HEC-RAS at the last upstream cross section was equal to the computed shear stress of the second to last cross section. Extending the model upstream was necessary so that we could establish a location for computing the sediment supplied to the impoundment that was not influenced by the backwater of the dam. Because our surveys did not extend far enough upstream, we used remotely sensed data to create synthetic cross sections. A LiDAR-derived topographic map (2-foot (0.61 m) contour interval; State of Delaware, Office of Management and Budget, 2008) was used to calculate the slope of the river channel upstream of the surveyed cross sections. The calculated slope was then used to add a known amount of elevation and distance to a copy of the last surveyed cross section within HEC-RAS. The section of stream synthetically added to the HEC-RAS model is located in a relatively straight section of the stream valley with mostly uniform

topography on both sides of the channel, so these synthetic cross sections are likely representative of the stream in this section.

After establishing the length of stream necessary to calculate shear stresses without backwater influence, the HEC-RAS model was then run for all six discharge categories to compute bed shear stresses from the top of the dam to outside the dam's hydraulic influence. Modeled shear stresses were used to compute bed material transport and assess the mobility of different grain-size fractions into and out of the impoundment (as discussed further below).

We selected a steady flow assumption for six different discharges, an assumption of critical depth at the dam (the downstream boundary condition of our model), a constant channel slope upstream of our surveys (0.0048), and Manning's n values for the channel ($n = 0.04$), dam (0.013), and overbank (0.1) for our HEC-RAS modeling. Manning's n values for our study area were determined by Kauffman (2015), who calibrated HEC-RAS for a study of dam removal on the White Clay Creek in our study area.

3.3.2. *Bed material transport and mobility*

We developed a bed material transport model to assess the mobility of different grain-size fractions within the impoundment and to compute the bed material flux into and out of the impoundment. We combined the transport model with an Exner equation (Garcia, 2008) to assess whether the impoundment is currently aggrading or degrading. We established a simple box model with a single input and output location. Our calculations were performed at two locations within our study area: the base of the ramp-

like feature just upstream of the dam (output) and upstream of the hydraulic influence of the dam (input). While an impoundment is clearly a complex two- (or even three-) dimensional sediment transport system, our field observations suggest that we can idealize the impoundment as a box model for our purposes (the field data and interpretations justifying this approach are presented and discussed in the Results).

We used shear stresses from the HEC-RAS model to determine the sediment transport rate for six discharge categories to quantify bed material load transport rates of 10 modeled grain-size fractions (<2, 2, 2.8, 4, 5.7, 8, 11.2, 16, 22.6, and 32 mm). The fractions of each grain size on the bed, the geometric mean grain size, and the percent sand on the bed at the base of the ramp and upstream of the hydraulic influence of the dam, obtained from field data (presented below), were used as inputs for the bed material transport model.. We used the ϕ parameter of the Wilcock and Crowe (2003) equation (defined below) to determine if a given grain-size fraction at a given discharge was experiencing significant rates of transport and therefore to assess its mobility at that discharge.

Transport equation: We used the Wilcock and Crowe (2003) transport equation to calculate the transport of bed material load into and out of the BMR impoundment because the bed of our study area is composed of significant quantities of sand and gravel. The Wilcock and Crowe transport equation has been calibrated to account for a wide range of grain sizes, and it is the only transport equation that allows for sand particles to influence the transport of the gravel. First, we calculated the dimensionless Shields stress for the geometric mean (D_g) of the bed surface (τ_{rm}^*):

$$\tau_{rm}^* = 0.021 + 0.015 e^{(-20F_s)} \quad (1)$$

342 where F_s is the fraction of sand of the bed surface. The τ_{rm}^* is used to calculate the
 343 dimensional (N/m^2) reference shear stress for the D_g of the bed surface (τ_{rm}):

$$344 \quad \tau_{rm} = (\rho_s - \rho_w) g D_g \tau_{rm}^* \quad (2)$$

345 where ρ_s is the sediment density, ρ_w is water density, and g is the acceleration of gravity.

346 We calculated the hiding function (b) for a grain size D_{si} on the bed surface:

$$347 \quad b = \frac{0.67}{\left(1 + e^{\left(1.5 - \frac{D_{si}}{D_g}\right)}\right)} \quad (3)$$

348 We used b , the D_{si} , D_g , and τ_{rm} to calculate a *reference* shear stress for each grain-size
 349 fraction (τ_{ri}):

$$350 \quad \tau_{ri} = \tau_{rm} \left(\left(\frac{D_{si}}{D_g} \right)^b \right) \quad (4)$$

351 Next, we used the shear stresses from the HEC-RAS model (τ , N/m^2) and τ_{ri} to calculate
 352 the *excess stress ratio* (ϕ):

$$353 \quad \phi = \frac{\tau}{\tau_{ri}} \quad (5)$$

354 and to determine the dimensionless transport (W_i^*) as defined by the function,

$$W_i^* = \begin{cases} 0.002\phi^{7.5} & \text{for } \phi < 1.35 \\ 14 \left(\left(1 - \frac{0.894}{\sqrt{\phi}} \right)^{4.5} \right) & \text{for } \phi \geq 1.35 \end{cases} \quad (6)$$

We convert W_i^* to volumetric transport rate (m^3/s) for each grain-size fraction available for transport (Q_{bi}):

$$Q_{bi} = \left(\frac{\tau}{\rho_w} \right)^{3/2} \frac{W_i^* F_i}{(\rho_s - \rho_w)g} w \quad (7)$$

where w is the width of the cross section, and F_i is the fraction of grain size available for transport.

Mobility of individual grain-size fractions: A low *reference* transport rate is often used to calculate a critical shear stress required to mobilize bed material (Buffington and Montgomery, 1997). The Wilcock and Crowe (2003) equation uses a dimensionless reference transport rate of 0.002 (from Parker et al., 1982a, b; Wilcock, 1988) ($W_i^* = 0.002$) to define a *reference* shear stress. However, the Wilcock and Crowe (2003) equation does not limit transport and will always yield a rate of transport for any shear stress. Implicit in this set of equations is that shear stress ratios (represented by the ϕ parameter) < 1 yield transport rates below the reference transport rate of 0.002 (Eq. 6). We interpret transport occurring with $\phi < 1$ as *nonsignificant transport*, and transport occurring with $\phi > 1$ as *significant transport*. Transport occurring with $\phi > 1.35$ we classify as *highly significant transport*. Because the Wilcock and Crowe (2003) equation calculates transport rates for individual grain sizes, this approach allows us to assess the mobility of individual grain sizes at any discharge.

374

375 *Computing changes in bed elevation:* In addition to assessing the mobility of individual
 376 grain-size fractions and calculating the rates of bed material load transport, we also
 377 calculated the net change in bed elevation within the impoundment. We calculated the net
 378 total bedload transport rate for a given flow, Q_{bTF} ,

$$379 \quad Q_{bTF} = \sum_{i=1}^{10} Q_{bi,in} - \sum_{i=1}^{10} Q_{bi,out} \quad (8)$$

380 where Q_{bi} is average transport rate for a given size fraction (m^3/s), and the subscripts in
 381 and out refer to transport into and out of the impoundment, respectively. Computations
 382 were completed for the 10 different grain-size fractions. The net total transport rate Q_{bTF}
 383 is obtained by summing transport rates for the 10 individual grain-size fractions. We
 384 assumed a sediment density of 2650 kg/m^3 and a water density of 1000 kg/m^3 .

385 We calculated the annual average rate of bed elevation change, $\Delta z/\Delta t$ (cm/y):

$$386 \quad \frac{\Delta z}{\Delta t} = \frac{\sum_{k=1}^6 (Q_{bTF_k} f_k)}{(1 - \lambda_p) L w} T \quad (9)$$

387 where Q_{bTF} is multiplied by f_k , fraction of time when flow in selected discharge ranges
 388 occurs (on average) in the Red Clay Creek in a given year, summed over the six
 389 discharge events (1.1, 1.5, 2, 5, 10, and 50 years). The variable L in Eq. (9) is the length
 390 of the impoundment, while λ_p is fractional porosity (0.3; Friedman and Sanders, 1978;
 391 Parker, 2004), and w is the width of the bed of the impoundment. The conversion from
 392 seconds to years is represented by T (as the transport rate is computed as m^3/s).

Evaluating the role of impoundment fining in facilitating bed material transport through the impoundment: We hypothesize that the finer bed of the impoundment facilitates transport of coarse bed material on the lower slope imposed by the dam. While we cannot test this hypothesis by direct observations, our sediment transport modeling provides a useful means of quantifying the increase in transport caused by bed fining.

We compare predicted rates of bed material transport out of the impoundment with the transport that would result if the grain-size distribution at the base of the ramp was exactly the same grain-size distribution as the stream channel upstream of the impoundment. The difference between the ϕ parameter (and transport rates) with the extant sandy bed versus that with the coarser upstream conditions provides a quantitative (though approximate) assessment of our hypothesis.

3.3.3 Sensitivity analysis

We performed a sensitivity analysis to document the consequences of uncertainty in several input parameters for calculating net bedload transport. We varied values of Manning's n (for the channel and for the overbank) used in the HEC-RAS model to compute shear stress and to compute the constant slope used to construct synthetic cross sections. We varied porosity when calculating bed elevation change based on a range of acceptable porosity values from Parker (2004). We quantify the *sensitivity* of these input variables on model runs using the protocol established by Pizzuto et al. (2007). We adjusted model parameters by $\pm 50\%$ and compared net transport rates from changing (i.e., increasing or decreasing) a single parameter to the net transport obtained from current conditions at the BMR site (our *base model* conditions). The differences between

the transport rate of the base model and the transport rate from the *sensitivity* model were reported as percent differences according to Eq. (10):

$$\% \text{ difference} = \frac{100 \times (\text{value from sensitivity model} - \text{value from base model})}{(\text{value from base model})} \quad (10)$$

4. Results

4.1. Field Data

4.1.1. Barley Mill Road dam site

Geomorphic surveys reveal approximately 115,000 m³ of total accommodation space within the impoundment. Currently, only 28,000 m³ of that volume is occupied by sediment, leaving 75% of the impoundment channel empty. Surveys also reveal a bedrock control 1110 m upstream of the Barley Mill Road (BMR) dam that spans the width of the channel and along the banks (Figs. 1 and 4). Upstream of the bedrock control, the stream is relatively straight, with a slope of 0.0048 (Fig. 4). The average bankfull depth and width are 1.7 m (range 1.7-1.9 m) and 29 m (range 26-33 m), respectively. Grain-size measurements show that the bed is composed of sand and gravel, with median grain diameters in the pebble size range, D_{50} = 9-49 mm (using grain-size terminology of the Wentworth scale; Wentworth, 1922), 90th percentile grain diameters in the pebble and cobble size ranges, and sand content ranging from 7 to 46% (Table 1; Fig. 5).

Downstream of the bedrock control, the slope decreases to 0.00081, and the average bankfull depth and width are 2.7 m (range 2.4-3.2 m) and 28 m (range 24-38 m), respectively (Figs. 1 and 4). The maximum base flow water depth in the impoundment is 2.2 m (Fig. 4; Table 2), almost equivalent to the height of the dam (2.5 m). From the

deepest part of the impoundment about 50 m upstream of the dam, the bed slopes upward (the slope is -0.0031, with the negative sign indicating an adverse slope) until it merges smoothly with the dam crest, forming the *sediment ramp*. The dam constricts the flow to 26 m and rests on a bedrock outcrop at the narrowest part of the valley in the study reach.

The bed material of the impoundment consists of sand and gravel. Three distinctive regions of the impoundment bed can be distinguished, each with differing bed material (Figs. 4 and 5). Percentages of sand in the upstream half of the impoundment vary from about 35% to 45%, median grain diameters vary from sand- to pebble-sized ($D_{50} = 0.6\text{--}3\text{ mm}$), and the 90th percentile grain diameter varies from pebble- to cobble-sized. The bed material in the middle of the impoundment is more than 90% sand, but all other size fractions sampled in the other regions are also present (Fig. 5). In the lower part of the impoundment (including the sediment ramp), grain sizes are similar to the upstream section of the impoundment, though somewhat finer grained. Despite the finer bed material of the impoundment, all the grain sizes sampled above the impoundment are also present throughout the bed of the impoundment itself.

Characteristic landforms are also present downstream of the BMR dam. Water falling over the dam has created a plunge pool immediately downstream lined with bedrock. The pool has average and maximum depths (at base flow) of about 1.7 and 2.3 m, respectively. Immediately downstream of the plunge pool, a mid-channel bar divides the channel (Figs. 2 and 4). Topographic surveys indicate that the volume of sediment stored in the bar (1472 m^3) exceeds the volume of material excavated to create the plunge pool (530 m^3) by a factor of almost 3, so the plunge pool cannot be the sole source of the sediment stored in the bar. The grain-size distribution of bar sediment appears to be

464 similar to that of the bed material in the impoundment (Fig. 5), suggesting that bed
465 material moving through the impoundment could provide a source for at least some of the
466 sediment stored in the bar. Adjacent to and downstream of the bar, the channel has a
467 slope of 0.00282, and the bed material consists of sand and gravel similar to that
468 upstream of the impoundment (Table 1; Fig. 5).
469

Table 1
Grain-size information for Barley Mill Road site^a

Location	DSoD stream bed	DSoD bar (surface)	DSoD bar (subsurface)	USoD impoundment stream bed	USoD above impoundment stream bed
D₅₀ (mm)	39	12	3	0.6 – 3	9 – 49
Percent sand	22	19	51	46 - 98	7 - 46
Percent gravel^b	78	81	49	3 - 54	54 - 96

^a DSoD = downstream of dam; USoD = upstream of dam.

^b *Gravel* refers to sediment with intermediate diameter >2 mm.

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473 Fig. 4. Longitudinal profile of the Barley Mill Road study area showing distinctive
 474 features upstream and downstream of the dam. (A) Distinctive areas of the impoundment
 475 defined by morphology and grain size, with surveyed low flow water surface and
 476 floodplain profiles. (B) Inset of dashed box in (A) near the dam showing a *sediment ramp*
 477 leading to the dam, the maximum depth of the impoundment, dam height, plunge pool
 478 immediately downstream of the dam, and a mid-channel bar downstream of the dam (a
 479 planview of the mid-channel bar is available in Fig. 2).
 480

Fig. 5. Grain-size distributions from the Barley Mill Road site. (A) Cumulative grain-size distributions, labeled with distance upstream of the dam or morphologic description for downstream sites. (B) Envelopes of grain-size curves from different locations at the Barley Mill Road site.

487 4.1.2. *Other dam sites*

488 Data from the five other run-of-river dam sites (Figs. 1 and 2) and the BMR site
489 are shown in Table 2. The dams range in height from 0.9 to 1.8 m, the maximum depth of
490 each impoundment ranges from 1.9 to 2.4 m, each has a mid-channel bar that is 16-64 m
491 downstream from the dam, the median grain size of the downstream channel ranges from
492 23 to 62 mm, the median grain size of the downstream bar sediment ranges from 5 to 75
493 mm, the median grain size of the upstream ramp ranges from <2 to 96.4 mm, the drainage
494 area for the dams varies from 71 to 179 km², and all of the dams are located on fifth-
495 order stream segments. The impoundments are approximately as deep as their respective
496 dams are tall. The coarse fraction of sediment just upstream of the dam within the
497 impoundment is similar to the bulk fraction of the bar and channel downstream of the
498 dam (Table 2). Each dam was also observed to have similar ramp-like features leading up
499 to their respective dams and scour holes immediately downstream of the dams, though
500 these were not surveyed.

Table 2
Data from Barley Mill Road and the other dam sites within the study area

Informal dam name	River	Drainage area at dam (km ²)	Height of dam (m)	Max water depth of impoundment (m)	Distance to mid-channel bar (m)	Downstream channel (mm)			Downstream bar (mm)			Upstream ramp (mm)		
						D ₁₆	D ₅₀	D ₈₄	D ₁₆	D ₅₀	D ₈₄	D ₁₆	D ₅₀	D ₈₄
Barley Mill Road	Red Clay Creek	122	1.4	2.2	22.4	2.58	39.4	286	2.68	11.8	30.8	<2	2.13	14.2
Sharpless Road	Red Clay Creek	84	1.5	1.9	64.4	2.49	23.1	136	19.6	73.5	161	<2	<2	17.2
PA/DE Creek Road	Red Clay Creek	71	1.8	2.3	15.9	10.1	52.5	154	9.83	30.3	57.2	<2	96.4	117
Papermill Road	White Clay Creek	179	1.1	2.4	16.2	na ^a	na	na	<2	11	42.4	<2	2.48	30.9
Wedgewood Road	White Clay Creek	168	0.9	1.7	15.8	na	na	na	<2	8.6	36.8	<2	<2	67.1
Newark Creek Road	White Clay Creek	175	1.6	2.3	17.4	23	61.8	110	2.67	30.6	57.2	<2	<2	2.42

^aNote: na = data that could not be collected because of access or safety issues.

4.2. Flow frequency analysis

The six discharges corresponding to exceedence values of 0.9 y^{-1} (1-year flood), 0.7 y^{-1} (1.43-year flood), 0.5 y^{-1} (2-year flood), 0.2 y^{-1} (5-year flood), 0.1 y^{-1} (10-year flood), and 0.02 y^{-1} (50-year flood) are 35.3, 48.8, 63.7, 104.9, 141.6, and $256.1 \text{ m}^3/\text{s}$ (Table 3; Fig. 3). The fractions of time when flow occurs in the six discharge categories (Table 3) are (from the lowest discharge category to the highest discharge category) 1.87×10^{-4} , 7.96×10^{-4} , 5.43×10^{-4} , 2.6×10^{-4} , 1.28×10^{-4} , and 3.88×10^{-5} (also reported as number of days per year in Table 3). We further computed the discharge category for recent named storms: Hurricane Irene (2011, 50-year discharge category), Tropical Storm Lee (2011, 1.43-year category), Hurricane Rina (2011, 1.43-year category), Hurricane Isaac (2012, <1.1-year category), and Hurricane Sandy (2012, <1.1-year category).

Table 3
Characteristics of high discharge events at Barley Mill Road site

Exceedence probability (y^{-1})	0.9	0.7	0.5	0.2	0.1	0.02
Return period (year)	1.11	1.43	2	5	10	50
Discharge (m^3/s)	35.3	48.8	63.7	104.9	141.6	256.1
Discharge category (m^3/s)	27.5-42.5	42.6-57.5	57.6-85	85.1-122.5	122.6-197.5	197.6-315
Fraction of time when flow in category occurs	1.87×10^{-3}	7.96×10^{-4}	5.43×10^{-4}	2.6×10^{-4}	1.28×10^{-4}	3.88×10^{-5}
Number of days per year flow occurs (d/y)	0.68255	0.29054	0.198195	0.0949	0.04672	0.014162

515

516 4.3. Sediment transport modeling

517 4.3.1. HEC-RAS modeling

518 The HEC-RAS modeling results define the hydraulic behavior of the
519 impoundment during discharges with return periods of 1.1-50 years (Fig. 6A). As the
520 discharge increases, the water surface rises and the water surface slope in the
521 impoundment increases from 0.00093 to 0.0021 (Table 4). Within the impoundment,

522 overbank flow occurs at the 5-year flood stage and greater. Upstream of the
 523 impoundment, overbank flow occurs at the 10-year stage and greater. The upstream
 524 extent of backwater influence of the dam moves progressively upstream with increasing
 525 discharge (Fig. 6A). At the 50-year return period discharge, the hydraulic backwater ends
 526 2.2 km upstream of the dam (Figs. 6A, B).

Fig. 6. (A) Surveyed longitudinal bed and floodplain (top of bank) profiles and water surface profiles computed using HEC-RAS for six discharge categories with return periods ranging from 1.1 to 50 years. Black hash marks indicate locations of surveyed cross sections. (B) Shear stress profiles computed using HEC-RAS for the six discharge categories. Inset shows details of the shear stress profile up the ramp.

Table 4

Exceedence probability and discharge values used in HEC-RAS modeling and impoundment water surface slopes for each discharge

Exceedance probability (y^{-1})	0.9	0.7	0.5	0.2	0.1	0.02
Discharge (m^3/s)	35	49	64	105	142	256
Return period (year)	1.11	1.43	2	5	10	50
Impoundment water surface slope	0.00093	0.0011	0.0013	0.0015	0.0017	0.0021

4.3.2 Sediment transport computations

Input parameters for sediment transport computations from field data: The geometric mean grain diameter and percentage of sand on the bed upstream of the hydraulic influence of the dam are 6.6 mm and 45%, respectively (Table 5), while the corresponding values for the base of the sediment ramp are 2.5 mm and 54%, respectively (Table 5). The compositions of the bed material outside the hydraulic influence of the dam and at the base of the ramp are represented by grain-size distributions measured 1191 m upstream of the dam and 0 m upstream of the dam, respectively (Fig. 5A). These distributions are summarized by percentages for 10 grain-size fractions used in the transport model ranging in size from <2 to 32 mm (Table 5).

Table 5
Grain-size inputs for transport model

	Upstream of the impoundment	Near the dam
Geometric mean	6.6 mm	2.5 mm
Fraction of sand	45%	54%
Grain-size percentages^a		
<2 mm	44%	49%
2 mm	1.1%	5.5%
2.8 mm	0.81%	5.9%
4 mm	1.6%	5.9%
5.66 mm	1.3%	6.5%
8 mm	1.3%	6.5%
11.2 mm	3.0%	7.1%
16 mm	2.2%	6.3%
22.6 mm	6.5%	3.4%
32 mm	7.3%	3.9%

^aNote: Grain-size percentages do not add up to 100% because sediment >32 mm is excluded.

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Mobility of individual grain-size fractions: All the grains are mobile at all the

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discharges upstream of the impoundment, and all grains are mobile at all discharges at

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the base of the ramp except the coarsest two grain-size ranges, for which ϕ values are <1

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at the lowest flood stage considered in our modeling (Table 6).

551

Table 6

Mobility of individual fractions of grain sizes for six discharge categories based on ϕ values from Eq. (5)^a

	1.1 year	1.43 year	2 year	5 year	10 year	50 year
Base of ramp						
1.41 mm	4.12	6.40	9.00	16.61	23.58	45.12
2 mm	3.89	6.04	8.50	15.68	22.25	42.58
2.8 mm	3.60	5.58	7.85	14.48	20.56	39.34
4 mm	3.15	4.89	6.88	12.69	18.01	34.47
5.66 mm	2.57	3.98	5.60	10.34	14.67	28.08
8 mm	1.93	3.00	4.22	7.79	11.05	21.15
11.2 mm	1.44	2.23	3.13	5.78	8.21	15.70
16 mm	1.08	1.68	2.37	4.37	6.20	11.87
22.4 mm	0.85	1.32	1.86	3.44	4.88	9.33
32 mm	0.68	1.05	1.47	2.72	3.86	7.39
Outside hydraulic influence of dam						
1.41 mm	19.18	22.60	25.32	32.70	37.36	52.43
2 mm	18.46	21.75	24.37	31.47	35.96	50.46
2.8 mm	17.75	20.91	23.43	30.25	34.56	48.51
4 mm	16.90	19.91	22.31	28.81	32.92	46.20
5.66 mm	15.89	18.72	20.98	27.09	30.95	43.43
8 mm	14.51	17.10	19.16	24.74	28.27	39.67
11.2 mm	12.63	14.88	16.67	21.53	24.59	34.52
16 mm	10.03	11.82	13.25	17.10	19.54	27.42
22.4 mm	7.47	8.80	9.86	12.74	14.55	20.42
32 mm	5.52	6.51	7.29	9.41	10.76	15.10
Base of ramp with upstream grain size distribution						
1.41 mm	1.77	2.75	3.87	7.13	10.13	19.38
2 mm	1.70	2.65	3.72	6.87	9.75	18.65
2.8 mm	1.64	2.54	3.58	6.60	9.37	17.93
4 mm	1.56	2.42	3.41	6.29	8.92	17.08
5.66 mm	1.47	2.28	3.20	5.91	8.39	16.05
8 mm	1.34	2.08	2.92	5.40	7.66	14.66
11.2 mm	1.17	1.81	2.54	4.70	6.67	12.76
16 mm	0.93	1.44	2.02	3.73	5.30	10.14
22.4 mm	0.69	1.07	1.51	2.78	3.94	7.55
32 mm	0.51	0.79	1.11	2.05	2.92	5.58

^aDark grey shading are values $>1.35 \phi$ and represent significant transport, light grey are values $>1 \phi$ and represent low transport, and white shading represent values $<1 \phi$ and represent no significant transport

Sediment fluxes and bed elevation changes: Our sediment transport computations indicate that the current annual supply of bed material to the BMR site is 6737 m³/y (Fig. 7). Approximately 78% of the input is sand, while the remaining 22% is gravel. The annual export over the dam is 283 m³/y, 65% of which is sand and 35% gravel. The computations predict that impoundment is accumulating sediment, with an aggradation rate of 26 cm/y. All grain-size fractions are in transport at all locations in significant volumes (Fig. 7A).

We evaluate the hypothesis that sediment transport rates out of the impoundment are significantly enhanced by its finer bed. We run the sediment transport model while substituting the grain-size distribution at the dam with that from the reach upstream (i.e., we neglect the fining of the bed material within the impoundment). If the grain distribution of the impoundment bed is the same as the bed material outside the hydraulic influence of the dam, transport rates in the impoundment are reduced from 283 to 100 m³/y (Fig. 7). Thus, the finer bed increases the flux of bed material by nearly three times. Additionally, the mobility drops for the coarsest fractions of modeled sediment at the lowest two flows (Table 6). Storage of fine-grained sediment on the bed of the impoundment appears to be an important mechanism that enables bed material to travel through the impoundment and over the dam.

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574 Fig. 7. Predicted bed material transport by grain-size fraction upstream of the
575 impoundment, at the base of the sediment ramp (*near dam*), and at the base of the
576 sediment ramp computed using the coarse grain-size distribution from upstream of the
577 impoundment (*near dam (coarse)*). (A) Percentages of different sizes in transport. (B)
578 Annual volume of different sizes in transport.

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4.3.3. *Sensitivity analysis*

Net transport rates appear to be very sensitive to values of Manning's n and variations in slope upstream of the impoundment (Table 7). Increasing Manning's n by 50% in the impoundment increased transport rate 258-756%, while decreasing Manning's n by 50% decreased transport 93-100%. Increasing Manning's n by 50% upstream of the impoundment increased transport rate by 45-56%, while decreasing Manning's n by 50% reduced transport rates by 50-59%. Raising the slope by 16% from 0.0048 to 0.0056 increased transport rates 93-133%, while lowering the slope by the same percentage (from 0.0048 to 0.0039) reduced transport rates by 12-16%. Bed elevation change is sensitive to changing the porosity within a range of 0.25 to 0.60 (Table 7). However, the system is always aggrading in response to changes in porosity: the aggradation rate increases from 24.1 to 45.1 cm/y as the porosity increases from 0.25 to 0.60 (Table 7).

Table 7

Parameter values used to assess model sensitivity and resulting changes in transport rates (by volume and percentage)

		Dam	Channel	Banks	
Parameter values used					
Manning's <i>n</i>	Base model	0.013	0.04	0.1	
	Increased	0.0195	0.06	0.15	
	Decreased	0.0065	0.02	0.05	
Slope	Base model	0.0048			
	Increased	0.0056			
	Decreased	0.0039			
Porosity	Base model	0.3			
	Values	0.25	0.4	0.5	0.6
Transport rates caused by changed values (m ³ /y)					
Manning's <i>n</i>	Upstream of impoundment	Increased	10119		
		Decreased	3105		
	Near dam	Increased	1265		
		Decreased	10.92		
Slope	Upstream of impoundment	Increased	12843		
		Decreased	4922		
Bed elevation change caused by changed values (cm/y)					
Porosity	Value	0.25	0.4	0.5	0.6
	Rate of bed elevation change	24.1	30.1	36.1	45.2
Percentage change on transport rate					
Manning's <i>n</i>	Upstream of impoundment		Min	Max	Average
		Increased	44.8	55.7	50.6
		Decreased	-49.6	-59.4	-53.5
	Near dam		Min	Max	Average
		Increased	258	756	437
		Decreased	-93.5	-100	-97.4
Slope	Upstream of impoundment		Min	Max	Average
		Increased	92.7	133	118
		Decreased	-12.1	-15.6	-14.6
Percentage change in elevation change					
Porosity	Values	0.25	0.4	0.5	0.6
	Change	-6.7	16.6	40	75

5. Discussion

5.1. Interpretation of field observations

Field observations from the Barley Mill Road (BMR) site demonstrate that the channel behind the dam is only 25% filled with sediment (28,000 m³ out of 115,000 m³). Topographic and grain-size data reveal no evidence of current preferential deposition of coarse-grained material at the head of the impoundment, rather all grain-size fractions are present throughout the impoundment.. Preferential deposition of coarse-grained material at the head of the impoundment is typical to depositional models related to reservoir sedimentation and the ~100% trapping efficiency of these structures. The lack of a preferential coarse-grained deposition with all grain-size fractions present throughout the impoundment suggests a deviation from typical reservoir depositional models, confirming that run-of-river impoundments and larger reservoirs are distinctly different and should not be compared to one another. A distinctive sediment ramp has developed that could allow coarse bed material to roll up and over the top of the dam. A large mid-channel bar immediately downstream stores sediment similar in size distribution to that of the impoundment bed material, with a volume too great to be sourced only from sediment scoured below the dam. All of these field observations provide compelling evidence that some bed material can be moved into and through the impoundment.

Field data from other sites suggest that the BMR site is typical of this geomorphic setting. Each site has a mid-channel bar downstream of the dam (Fig. 2). The presence of this stored sand and gravelly sediment within close proximity to the dams suggests an upstream source (i.e., sediment carried through the impoundment). The grain-size data of

sediment from the mid-channel bars is similar to that of the sediment ramp upstream and of the adjacent channel, supporting this interpretation.

5.2. Sediment transport modeling

Sediment transport computations reinforce and expand insights gained from field observations. Our analysis of sediment mobility using the ϕ parameter (Eq. 5) shows that all grain sizes modeled experience significant transport save for the two coarsest fractions (22.4 and 32 mm) during the lowest modeled flood discharge at the base of the ramp (Table 6). The volume of annual bed material supplied to the impoundment ($\sim 6737 \text{ m}^3/\text{y}$) would fill the entire accommodation space behind the dam ($115,000 \text{ m}^3$) in 17 years. Our computations also suggest that the impoundment is currently aggrading at a rate of 26 cm/y. If this aggradation rate continues, the entire bankfull depth of 2.7 m would be filled within about 10 years; but the impoundment channel remains unfilled after two centuries, suggesting that a significant proportion of the sediment supply continues to be transported out of the impoundment. The large storms that occurred in 2011-2012 may have scoured the bed of the impoundment, and the current aggradation may represent a process of recovery from this disturbance. Thus, these systems may scour during high flows and recover, or fill, during low flows as documented by Pearson et al. (2011) at the Merrimack Village dam.

The HEC-RAS modeling documents shear stress profiles through the impoundment and up the sediment ramp (Fig. 6). Shear stresses decrease upon entering the impoundment and continue to decrease until the base of the sediment ramp. Even where shear stresses are lowest at the base of the ramp, the stream is still able to transport

all modeled grain-size fractions. Once sediment enters the bottom of the ramp, a sharp increase in shear stresses up the sediment ramp (5 to 33 times greater at the top of the ramp than the base) provides a mechanism for moving gravel-sized sediments up the ramp and over the dam. Transport at the base of the ramp is also enhanced by its sandy bed. Our computations suggest an approximately threefold increase caused by the increased percentage of sand at the base of the ramp (Fig. 7), a process that has been emphasized by Wilcock (1998), who demonstrates that adding sand to a gravel mixture reduces the shear stress necessary to mobilize gravel-sized sediment.

5.3. The evolution of the longitudinal profile of run-of-river impoundments

We offer a five-step conceptual model summarizing the evolution of the longitudinal profile of a run-of-river impoundment (Fig. 8). The initial condition is a free-flowing stream with an approximately constant slope (Fig. 8A). A dam is constructed and an initial backwater forms, lowering the slope of the water surface upstream (Fig. 8B). The lowered slope causes sand and gravel to accumulate within the impoundment. At this stage none of the bed material load is able to move past the dam (although some sand may leave as suspended load) (Fig. 8C). The sediment ramp at the dam then forms, and bed material load transport out of the impoundment begins, likely aiding in the scour of the plunge pool downstream of the dam (Scheingross et al., 2014). During this period, the mid-channel bar begins to develop (Fig. 8D). Finally, the impoundment has reached a morphology where considerable unfilled accommodation space remains, but where bed material can move through the impoundment without net accumulation (Fig. 8E). We speculate that a series of high flows can scour the impoundment and that the

impoundment can recover through deposition afterward. This oscillation of scour and fill is likely an ongoing process that maintains the unfilled accommodation space within the impoundment indefinitely. We think that the BMR site represents a run-of-river impoundment that has reached the last step of our conceptual model.

5.4. Implications and topics for further study

When viewed in the context of other studies of dam-related sedimentation, our results further emphasize the remarkable variability in sediment transport processes created by dams. Even if only small mill dams are considered, transport and storage processes differ between the valley-spanning dams described by Merritts et al. (2011) and those of our study area. Further research and cataloging of dam-induced transport and storage and the variables that control these processes would be desirable.

Additional research of the processes we have inferred at the BMR site itself would also be useful. For example, direct measurements of sediment transport using tracers could corroborate the indirect evidence of our field observations and computations. Additionally, hydrophones could be placed along the apron of the dam and the sound of particles hitting the apron could be recorded as verification of sediment transport over the dam (Barton et al., 2010; Govi et al., 1993). We have restricted our study to channel processes, even though the floodplain profiles of Figs. 4 and 6A suggest that sediment has been trapped upstream of the dam within the floodplain over time. Our model for the evolution of the longitudinal profile of the system would also benefit from the additional temporal perspective that could be provided by stratigraphic analysis of the floodplain and by careful study of historical documents to better define the history of the

impoundment. A physical modeling study could provide useful insights (as noted by Csiki and Rhoads, 2010). Finally, more comprehensive numerical modeling could also prove useful. Currently, our model provides only a glimpse at the transport processes that are presently occurring at the BMR site. If grain size, length of the impoundment, and bed elevation were treated as dependent variables, rather than as constant input parameters, the temporal evolution of the elevation of the impoundment bed could be better defined. Such studies could help define the conditions that are required to maintain unfilled accommodation space in an impoundment, the extent of scour during high flows, the timescales of post-flood recovery, and other important issues.

699 Fig. 8. Conceptual model of the development of the longitudinal profile of mill dam
700 impoundment. Gray portions within each panel represent change that occur during a
701 particular time step, while black portions represent features that formed previously. Step
702 1: Prior to dam construction. Step 2: Dam construction and initial backwater. Step 3:
703 Sediment delivery to impoundment and sediment accumulation prior to sediment ramp
704 construction. Step 4: Sediment ramp forms; bedload begins moving downstream. Step 5:
705 Impoundment adopts a morphology that promotes bed material export with space for
706 transient storage of material along with the formation of a mid-channel bar downstream
707 of the dam. Transient storage represents sediment supplied during low flows and scoured
708 out at higher flows maintaining the profile for 200+ years.
709

6. Conclusions

Former mill dams on fourth- and fifth-order streams of the Piedmont of Delaware are run-of-river dams as defined by Csiki and Rhoads (2010) that allow the transport of gravel-sized sediments through their impoundments. The maximum water depths of the mill ponds are approximately equal to the height of the dams, and the dams store relatively little bed material. A characteristic sloping ramp of coarse-grained sediment leads from the floor of the impoundment to the crest of the dam, facilitating bed material load transport. A mid-channel bar composed of coarse sediment typical of the impoundment's bed has developed downstream of the dam, and its volume greatly exceeds the volume of the plunge pool located between the dam and the bar.

At the Barley Mill site, no topographic or sedimentologic evidence of preferential deposition of coarse-grained sediment exists at the upstream end of the impoundment, and all grain-size fractions are present throughout the impoundment. Both of these observations suggest that run-of-river dams can deviate from typical reservoir sedimentation models, and any comparison between the two different types of impoundments is inappropriate.

Our field observations support the hypothesis that all bed material grain-size fractions supplied from upstream can be transported through an impoundment. These impoundments therefore behave more like long pools rather than as sediment traps. They have adjusted their bed grain size and elevation to transport the sediment supplied from the watershed despite the reduced slope induced by the dam.

Our ideas are further supported by numerical modeling of sediment fluxes into and out of the impoundment. Modeling results indicate that all sizes are in transport

upstream and at the lower end of the impoundment at all the discharges we have considered. Transport of coarse bed material through the impoundment is facilitated by a smooth sandy bed and a sloping sediment ramp. The computations indicate that the impoundment is currently aggrading at 0.26 m/y, and would fill in about 10 years. The fact that these systems are only 25% filled after 200 years suggests that the impoundment scours at high flows and fills during low flows.

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Notation

The following symbols are used in this paper:

D_g	<i>geometric mean</i>
D_{si}	<i>grain-size fraction i</i>
F_i	<i>proportion of fraction I in surface size distribution</i>
F_s	<i>fraction of sand</i>
g	<i>gravitational acceleration</i>
Q_{bi}	<i>volumetric transport rate of size fraction i</i>
Q_{bTF}	<i>net total bedload transport rate for a given flow</i>
W_I^*	<i>dimensionless transport rate of size fraction i</i>
ϕ	τ/τ_{ri} ; <i>excess stress ratio</i>
λ_p	<i>porosity of bed sediment</i>
τ	<i>shear stress</i>
τ_{ri}	<i>reference shear stress of size fraction i</i>
τ_{rm}	<i>reference dimensional shear stress for the geometric mean</i>
τ_{rm}^*	<i>reference dimensionless Shields stress for the geometric mean</i>
ρ_s	<i>sediment density</i>
ρ_w	<i>water density</i>

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902 List of figure captions

903 Fig. 1. Location map of the Red Clay Creek and White Clay Creek showing dams used
904 for data collection (white dots), and U.S. Geological Survey gaging station 01480000
905 (yellow dot). Inset: Barley Mill Road study site showing location of the dam with respect
906 to its impoundment (shaded area). The *bedrock control* denotes an outcropping of
907 bedrock in the stream channel and falls on a slope break as well as a grain size shift. The
908 *hydraulic impoundment limit* shows the upstream extent of dam-induced backwater at the
909 50-year flood as modeled by HEC-RAS. Short lines in the shaded region represent
910 location of impoundment cross sections. Dashed lines indicate cross sections without
911 grain size information. Arrows indicate flow direction.

912 Fig. 2. Photo mosaic of the six study sites, including (A) dams on Red Clay Creek and
913 (B) dams on White Clay Creek. Mid-channel bars downstream of the dams are outlined
914 in red. Red lines on the mid-channel bar at the Barley Mill Road site indicate the
915 locations of sediment trenches. White arrows indicate flow directions.

916 Fig. 3. Annual peak discharge (red squares) plotted with Log-Pearson Type III fit (blue
917 line) for U.S. Geological Survey gaging station 014800000 at Wooddale, DE. The top
918 five large named storms are represented by green squares and indicated by name.

919 Fig. 4. Longitudinal profile of the Barley Mill Road study area showing distinctive
920 features upstream and downstream of the dam. (A) Distinctive areas of the impoundment
921 defined by morphology and grain size, with surveyed low flow water surface and
922 floodplain profiles. (B) Inset of dashed box in (A) near the dam showing a *sediment ramp*
923 leading to the dam, the maximum depth of the impoundment, dam height, plunge pool
924 immediately downstream of the dam, and a mid-channel bar downstream of the dam (a
925 planview of the mid-channel bar is available in Fig. 2).

926 Fig. 5. Grain-size distributions from the Barley Mill Road site. (A) Cumulative grain-size
927 distributions, labeled with distance upstream of the dam or morphologic description for
928 downstream sites. (B) Envelopes of grain-size curves from different locations at the
929 Barley Mill Road site.

930 Fig. 6. (A) Surveyed longitudinal bed and floodplain (top of bank) profiles and water
931 surface profiles computed using HEC-RAS for six discharge categories with return
932 periods ranging from 1.1 to 50 years. Black hash marks indicate locations of surveyed
933 cross sections. (B) Shear stress profiles computed using HEC-RAS for the six discharge
934 categories. Inset shows details of the shear stress profile up the ramp.

935 Fig. 7. Predicted bed material transport by grain-size fraction upstream of the
936 impoundment, at the base of the sediment ramp (*near dam*), and at the base of the
937 sediment ramp computed using the coarse grain-size distribution from upstream of the
938 impoundment (*near dam (coarse)*). (A) Percentages of different sizes in transport. (B)
939 Annual volume of different sizes in transport.

Fig. 8. Conceptual model of the development of the longitudinal profile of mill dam impoundment. Gray portions within each panel represent change that occur during a particular time step, while black portions represent features that formed previously. Step 1: Prior to dam construction. Step 2: Dam construction and initial backwater. Step 3: Sediment delivery to impoundment and sediment accumulation prior to sediment ramp construction. Step 4: Sediment ramp forms; bedload begins moving downstream. Step 5: Impoundment adopts a morphology that promotes bed material export with space for transient storage of material along with the formation of a mid-channel bar downstream of the dam. Transient storage represents sediment supplied during low flows and scoured out at higher flows maintaining the profile for 200+ years.