River channel response to dam removals on the lower Penobscot River, Maine, USA

Running title: River channel response to dam removals

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KEY POINTS

- The channel shape, elevation, and position of the lower Penobscot River was not sensitive to removing two large dams, nor to two large floods, over a six-year study
- Large-scale channel change can be minimal when impoundments storing relatively little sediment are removed from erosion-resistant streambeds
- Practitioners can reduce project costs, and better target available monitoring funds, if they can confidently establish these conditions

ABSTRACT

Most geomorphology studies of dam removals have focused on sites with appreciable quantities of stored sediments. There is great interest in channel responses to sediment releases because of potential effects on aquatic and riparian habitats and human uses of these areas. Yet, behind many dams in the Northeast U.S. and other regions of the world only minor accumulations of sediment are present because of small impoundments, run-of-river dam design and management (inflow ≈ outflow), low watershed sediment yield, and/or channel beds dominated by coarse sediment and/or bedrock. The two lowermost dams on the Penobscot River in Maine, USA, removed in 2012-13, exemplified those conditions. Great Works and Veazie dams were about 6 m and 10 m high, respectively. Pre-project geophysical surveys showed coarse substrates dominated the reservoir beds and little sediment was stored in either impoundment—functions of reach geology, late Quaternary history, and upstream dams. Repeat cross-section surveys in each impoundment, as well as the upstream and downstream reaches, were completed from 2009 – 2015 to evaluate channel morphology responses to the removals. Bed-sediment grain size and turbidity were also measured to characterize changes in bed texture and suspended sediment. Pre- and post-removal survey comparisons confirmed the expectation that bed elevations, channel shapes, and channel positions would not change substantially. Changes were often within, or close to, our estimated random measurement error. Our study shows that large-scale physical changes are likely to be minimal when impoundments storing relatively little sediment are removed from erosion-resistant streambeds. Many dams eligible for removal have these characteristics, making these observations an important case study that is largely unrepresented in the dam removal literature.

Keywords: dam removal, channel evolution, fluvial geomorphology, environmental impacts

Introduction

Dam removals are increasingly common in the United States, as are dam-removal studies (Hart et al., 2002; Pizzuto, 2002; Graf, 2003; Sawaske & Freyberg, 2012; Bellmore et al., 2017; Foley et al., 2017). Of particular interest to local residents and other project stakeholders are potential changes to the physical conditions of the river and floodplain, which may partially account for the disproportionate representation of physical studies in the dam-removal literature (Bellmore et al., 2017). Several topics engage specialists and non-specialists alike (Tullos et al., 2016): Will erosion of stored sediments in the former reservoir continue upstream into river reaches that were never impounded? Will downstream areas be choked with sediments, affecting navigation and flooding? Will aquatic environments be damaged by turbidity or embedded fine sediments? How long will impacts persist?

Many of these, and related questions, have been pursued by dam-removal investigators over the last twenty years and much has been learned (Doyle et al., 2003; Pearson et al., 2011; Major et al., 2012; Bountry et al., 2013; East et al., 2015; Tullos et al., 2016; Collins et al., 2017; Major et al., 2017). For example, a recent synthesis of U.S. dam-removal science concluded that physical responses in humid environments are frequently rapid—especially when removal is rapid—and many affected river channels stabilize, or trend toward their pre-removal conditions, within months to years rather than decades (O'Connor et al., 2015; Major et al., 2017). Other important findings, especially for project proponents and local stakeholders, are that (1) erosion initiated by the base level fall associated with dam lowering seldom migrates beyond the limits of the former reservoir except under very specific conditions (Tullos et al., 2016);

(2) turbidity increases are typically within the range that occurs naturally by floods, unless very large quantities of fine sediment are stored (Tullos et al., 2016); and (3) surprises happen, often associated with dam removals outside the range of experience of previous projects or where consequential landscape features or pre-existing infrastructure are hidden beneath stored sediments (Foley et al., 2017).

Many physical studies of dam removals targeted sites storing appreciable quantities of sediment (e.g., Major et al, 2012; Wilcox et al., 2014; Collins et al., 2017; East et al., 2018; Harrison et al., 2018), especially the few investigating dams >= 10m high (Bellmore et al., 2017; Duda et al., 2020). These locations were chosen for that attribute because there is great interest in how channels respond to large sediment releases. Our study site was unusual because it focused on two relatively large (6 and 10 m high), lowermost dams on the Penobscot River, Maine, that stored very little sediment. The impoundments and adjacent reaches were also coarse-bedded. These conditions provided an opportunity to investigate if significant geomorphic changes occur when relatively large dams (>=10m) storing little sediment are removed from erosion-resistant streambeds. We expected little channel response given those conditions, but realized we might be surprised since our site attributes were not well represented in the literature available when our studies began (2008-2009) and thus our general question addressed a research gap (Duda et al., 2020). Also, there was a long history of river modification at the sites for which only partial information existed and reliable data on the riverbed substrata was not available. Some project stakeholders were concerned about incision of the pre-dam streambed and knickpoint migration through the lower river, a relatively steep mainstem reach of one of the Northeast U.S.'s largest watersheds.

We investigated the geomorphic response of the lower Penobscot River to dam removal focusing on two questions: (1) Would incision of the pre-dam streambed, and knickpoint migration, occur in this erosion-resistant setting? (2) Would the bed texture change measurably despite a paucity of stored sediment? We hypothesized that the answer to question 1 was 'no' and believed our site could provide particularly clear results because it was not complicated by incision and knickpoint migration of overlying sediment. Our hypothesis for question 2 was 'yes' because the coarse substrates bedding each impoundment had interstitial sands (described below). Two approximately 10-year recurrence interval floods happened during our study, giving us the unexpected opportunity to also provide more information about the effects of floods post-dam removal, a knowledge gap noted by Harrison et al. (2018) as important for anticipating river response.

To address our questions we conducted pre- and post-removal surveys of channel geometry and bed sediment texture at monumented channel cross-sections. We also used data from ongoing, near-continuous monitoring of discharge and turbidity at Penobscot River stream gages to interpret our survey data and better understand site response. Our findings confirmed that in this setting, where the dams stored little sediment and the streambed was dominated by coarse sediment fractions and/or bedrock, post-removal changes were minor and often within the detection limits of standard cross-section survey methods.

Study Area

The Penobscot River watershed drains approximately 22,000 km^2 of central Maine (Figure 1b). The upper basin is a relatively high relief landscape ($\cong$ 1500 m) with large water storage reservoirs that regulate discharge to the lower mainstem. Average annual discharge for the 117-year gage record at the Penobscot River at West Enfield, Maine (US Geological Survey gage 01034500; hereafter “West Enfield”) is approximately 345 m^3/s (Figure 1b). The Penobscot River is tidal for about 45 river kilometers (rkm) from Eddington Bend below Veazie Dam to where it meets the ocean at Penobscot Bay (Figure 1a and b). The climate is humid continental with a large seasonal temperature difference (Dfb in the Köppen-Geiger classification; Beck et al., 2018). Annual precipitation at the Bangor International Airport, less than 10 km from the study area (Figure 1b), is about 1,065 mm and relatively evenly distributed throughout the year (1981–2010 climate normal; http://www.ncdc.noaa.gov/cdo-web/datatools/normals).

The study area extends from the Milford Dam to the head-of-tide at Eddington Bend just below Veazie Dam (Figure 1a). In this reach, the channel gradient is 0.002, about five times steeper than the gradient of the river upstream for about 30 km above the Milford Dam impoundment (Hooke et al., 2017). This uncommon longitudinal profile—steepening nearest the coast—is the result of the interaction of the varied bedrock geology, glacial processes, and a complex sea level history. Upstream of the Milford Dam, the area is underlain by largely uniform metasedimentary rocks. Downstream, channel incision exposed resistant quartz-rich beds in the Paleozoic metamorphic rocks (Kelley, 2006; Kelley et al., 2011; Hooke et al., 2017). These beds trend approximately perpendicular to the flow direction and form a sequence of local base levels, creating falls and rapids that extend for approximately 22 rkm to the head-of-tide (Kelley, 2006).

The Penobscot River longitudinal profile partially explains why the removed dams stored relatively little sediment. Another important factor is the dominantly fine-grained sediment load for much of the Holocene. Most mobile sediments reaching the lower river today are suspended load and either are deposited upstream of the study area in the comparatively low-gradient reach above Milford Dam or transported to tidewater through the steeper, relatively high-energy environment where the dams were located. Sediment transport in the Penobscot River is primarily fine-grained because of the late Quaternary history of the region. As Late Pleistocene glaciers receded locally, the resulting high flow meltwater swept through this portion of the river valley. Penobscot River sediment transport competence later diminished with lower meltwater input and a drainage divide shift at approximately 10 ka that decreased discharge by about 15%. This transition was marked by a shift in floodplain deposition from sand-sized and coarser deposits to fine-grained sedimentation (Kelley et al., 2011; Hooke et al., 2017).

Run-of-river hydroelectric dams, where flow into the impoundment approximately equals outflow from the dam spillway and powerhouse, were concentrated in the comparatively steep study reach (Figure 1a). These included the Great Works (68°37'57" W 44°55'12" N) and Veazie (68°42'4" W 44°49'56" N) dams, removed in 2012 and 2013, respectively, as part of the Lower Penobscot River Comprehensive Settlement Accord (FERC, 2004). The agreement sought migratory fish passage improvements and maintenance of hydropower generation in the lower watershed through a combination of dam removals, fishway improvements, and power generation increases at some facilities. The Milford Dam, equipped with a new fish lift, is now the lowermost dam on the mainstem (Figure 1a). Facilities on the Stillwater Branch, a natural secondary channel of the Penobscot River that today receives flow regulated by the Gilman Falls Dam, were upgraded under the agreement for greater power generation and improved fish passage (Opperman et al., 2011; Figure 1a).

Great Works was a hydroelectric dam about 6 m high with a small impoundment extending less than 3 rkm upstream to an area of rapids just below cross-section 1 (Figures 1a and c). Veazie Dam was about 10 m high with an impoundment extending approximately 6 rkm to an area about half a kilometer below the Stillwater Branch confluence (Figures 1a and d). The Penobscot River channel was about 200 m wide at each dam and each impoundment submerged older infrastructure that included boom piers used during historic logging operations and remnants of earlier dams. The Veazie impoundment submerged a large historic dam. Some of the old infrastructure was removed to achieve fish passage as part of the dam removal project, but much of it was left in the river.

Side scan sonar surveys of the impoundments, conducted by others in 2007 to support deconstruction permitting and engineering studies, showed that greater than 95% of the beds of each impoundment were bedrock, boulder, and cobble (CR Environmental, 2008; classification from Madden et al., 2005; Figure 2). Finer fractions, mostly small gravel sizes and sand, were generally limited to littoral zones and/or found interstitially with larger materials. These surveys also mapped the submerged infrastructure described above. The large historic dam in the Veazie impoundment perpendicularly intersects cross-section 11 (Figure 2b), while the boom piers are much smaller and numerous across the lower halves of both impoundments. The pre-removal side scan sonar surveys were ground-truthed with a moderately dense grid of underwater video and steel probe samples—67 and 77 samples, respectively, relatively evenly distributed across the Great Works and Veazie impoundments (CR Environmental, 2008).

The volume of potentially mobile sediment, defined as sediments smaller than 20 mm diameter (small gravel and sand), was conservatively estimated from the side scan sonar data to be between 15,000 and 50,000 m^3 for both impoundments combined (CR Environmental, 2008). The 20 mm particle size threshold was identified by CR Environmental (2008) by comparing sustained velocities of at least 1.2 m/s, measured at a US Geological Survey (USGS) gage in a free-flowing reach downstream of Veazie Dam, with a Hjulstrom sediment transport curve (Figure 1a; see below for further details about USGS 01036390). CR Environmental (2008) considered their volume estimates conservative because: (1) they assumed that 5 to 10 percent of the substrate located within about 3 m of the impoundment shorelines (areas not accessible with the survey vessel) was sand and small gravel; (2) they estimated a quantity of interstitial sand and small gravel, based on the frequency of video observations of these substrates at ground truth stations, and assumed all of it would be mobile despite the likelihood that its mobility would depend on the mobility of the cobble matrix in which it was embedded (Lisle and Hilton, 1999); (3) they conservatively assumed thicknesses for the mapped and assumed areas of sand and small gravel based on sub-bottom sonar profiles, steel probe refusal samples, and/or qualitative video observations; and (4) the estimated post-removal flow velocity used to identify the 20 mm threshold likely occurs only in the main channel, but many of the mapped and assumed deposits below this threshold were in the littoral zones where velocities are lower. These assumptions, together with results from a recent habitat study of the Veazie reach that found sediment transport capacity there did not change substantially from pre- to post-removal (Johnston et al., 2018), suggest the combined volume of mobilized sediment was more likely closer to 15,000 m^3 or even smaller.

Methods

We evaluated changes to channel geometry and bed-sediment texture associated with dam removal by implementing a before-after/control-impact (BACI) study of cross-section resurveys over the period 2009 - 2015. Turbidity response was also investigated with a simple before-after (BA) study design (Kibler et al., 2010). No changes to streamflow were expected with the removals, so water discharge was not a response variable. However, discharge data from the West Enfield gage upstream provided important context for interpreting the cross-section and turbidity data. The CR Environmental (2008) pre-project characterizations of sediment texture and quantity in each impoundment, described above, also had important interpretive value for our study (Figure 2).

Channel geometry

We established 13 permanent transects in the study area: one control section and 12 impact sections (Figure 1a). Permanent transects were monumented at the endpoints to facilitate repeat surveys. We chose the number of cross-sections, and their locations, to represent the variety of channel conditions found in the study area (Collins et al., 2007). These conditions varied primarily by proximity to dams. Natural channel slopes (comparatively steep), width/depth ratios (high), and substrates (coarse) are similar throughout the study reach. The control section, PEN01, is located in the only available reach of the lower river not influenced by the removed dams. It is just downstream of the run-of-river Milford Dam. PEN02-04 and PEN 08-11 are established in the Great Works and Veazie impoundments, respectively, and were situated to adequately represent their reservoir environments. PEN05 is immediately downstream of Great Works while PEN06 and PEN07 characterize the free-flowing reach between the two impoundments. PEN12 is closely downstream of Veazie Dam and PEN13 is further downstream and tidally influenced (Figure 1a).

Repeat surveys of the cross-sections were accomplished by combining Acoustic Doppler Current Profiler (ADCP) measurements of channel depths with total station surveys of near-bank and subaerial elevations. ADCP depths were subtracted from water surface elevations (surveyed concurrently) to determine bathymetry. Some transects in some years had sections too shallow, rocky, and/or turbulent to boat and yet too deep, fast, and/or turbulent to wade–even at lower flows—and thus complete sections were not obtained. Two pre-removal survey campaigns were completed: fall 2009 and spring 2010 (Figure 3a). Post-removal surveys were accomplished in summer 2013, fall 2014, and fall 2015. The August 2013 campaign surveyed only the Great Works area because the Veazie Dam removal was in progress for the entire field season. Survey frequency was dictated by suitable flow conditions and our desire to capture at least two years of data for both the pre- and post-removal periods for our BACI design (Kibler et al., 2010). Figure 3a shows how the study period included large floods (~ 10-year recurrence interval) on 15 Dec 2010 and 17 Apr 2014, thus allowing us to measure any significant channel changes associated with either event. The best opportunity was to evaluate the spring 2014 event in the Great Works area because the summer 2013 and fall 2014 surveys closely bracketed the flood and the interval was not complicated by dam removal activities, which were completed there in 2012.

There are multiple potential error sources in the cross-section surveys including random measurement errors that we estimated quantitatively and systematic errors, associated mostly with a challenging river environment, that we describe qualitatively. To estimate the random measurement error in our cross-section surveys, we computed root mean square error (RMSE) as the difference in cross-sectional area between three sets of post-processed surveys of free-flowing sections that were repeated on the same day when differences should have been zero. Using post-processed surveys integrates the random measurement errors from our total station and ADCP methods. We chose free-flowing sections PEN01, PEN05, and PEN12 for these estimates because they represented the most challenging survey conditions, they best represented the conditions found at all cross-sections after the dams were removed, and quality control surveys were available for them. We chose the largest RMSE of the three comparisons for a conservative 95% confidence estimate (2 * RMSE) of the random measurement error in our surveys: 32.7 m^2 (≅0.1 m elevation).

Systematic measurement errors, which we were unable to quantify, were likely considerably larger. These were primarily errors in ADCP measurements associated with fast and/or turbulent flow. The ADCP measured water depths referenced to the water surface, so fast and/or turbulent water that created uneven water surfaces introduced error in those measurements. Fast and/or turbulent water also made it hard to maintain straight transect lines between monuments, making it difficult at some locations to get repeat measurements from year to year. Other factors affected the repeatability of transect lines, like submerged infrastructure in the reservoirs that was exposed post-removal on a transect and impassable with a boat (e.g., boom piers at PEN03 and PEN09; Figures 2, 5c, and 7b). Movements of cross-section monuments from survey to survey were another potential systematic error source. However, the stability ratings of our monuments and nearby benchmarks, and our survey practices, ensured that these errors were never greater than +/- 0.015 m vertically.

Since changes throughout the study area were generally modest, and because of the missing data issues noted above, we qualitatively assess cross-section changes from year to year based on visual inspections of the plots. Where changes substantially exceeded our random measurement uncertainty, we describe the general magnitude and direction of change and if it derives from systematic errors or real topographic/bathymetric change.

To supplement the topographic/bathymetric data and qualitatively record conditions during each survey, we also took repeat oblique photographs upstream, cross-stream, and downstream at fixed locations and azimuths along each transect (not shown).

Bed-sediment grain size

Bed-sediment grain size was measured via an experimental method of towing across each transect an underwater video camera mounted on a weighted sled (Figure 4a). The sled held the camera in a fixed position with measuring tapes in the field of view (Figure 4b). Still images were extracted from every minute of transect video. Images were then imported into a graphics program, individual clasts greater than very coarse sand or small pebbles were manually digitized and numbered, and the intermediate axis of each clast on the 2-dimensional image was measured using a grid developed from the measuring bars (Figure 4c). Texture and percent cover of interstitial sediment were also visually estimated. As described below, towing the sled-mounted camera along the transects proved possible only in the impoundments, thus our method only produced data in these areas for two pre-removal field campaigns in the summers of 2010 and 2011 (Figure 3a). These campaigns were not concurrent with any topographic/bathymetric surveys of the impoundment cross-sections. We were not able to collect data at PEN01, PEN05-07, and PEN12-13 where high flow velocities and/or very coarse bed materials made it impossible to tow the sled successfully.

Discharge and Turbidity

Penobscot River discharge data for the project period were available from the USGS West Enfield gage (USGS 01034500) upstream of the project site (Figure 1b). This station, where discharge is estimated from stage measurements every 15 minutes by standard USGS methods (Rantz, 1982), has a daily and instantaneous peak record longer than 100 years. Turbidity was measured by USGS in situ every 60 minutes downstream of both dams at gage 01036390 (Penobscot River at Eddington, Maine, hereafter "Eddington"; Figure 1a) via a Hydrolab MS5 turbidity sensor with a range of zero - 3000 formazin nephelometric units (FNU). The Eddington gage is a stage-only gage (i.e., no discharge estimates) because of periodic tidal influence. Turbidity data were collected from 01 October 2007 until 22 August 2013, one month after the Veazie Dam removal began, when independent funding for the sensor expired. The discharge and turbidity data for each gage are publicly available (http://dx.doi.org/10.5066/F7P55KJN) and shown in Figure 3 for the project period.

Results

Channel geometry

Figure 5 shows the pre- and post-removal surveys of the Great Works impoundment. Any changes from survey to survey are modest or close to our estimated random measurement error of ≅0.1 m, with the exception of some channel erosion of as much as 1 m at PEN02E between the pre- and post-removal surveys. The erosion there, centered at approximately 200 m from the left bank monument, is not surprising and is likely the result of the removal. At this location, the cross-section traverses a sand accretion found at the downstream end of an island (Figure 2a). It is one of only two small sand accretions mapped in the Great Works impoundment that together cover about 7,400 m^2 (1.5%) of the area mapped during the pre-removal side scan sonar surveys (CR Environmental, 2008). An approximately 10-year recurrence interval flood also occurred between the May 2010 pre-removal and Aug 2013 post-removal surveys and before the Great Works removal (Figure 3), but we consider it unlikely that the flood caused the erosion at PEN02E since another event of similar magnitude after the removal caused no erosion there or anywhere else in the former impoundment (compare the Aug 2013 and Oct 2014 surveys on Figure 5). Apparent changes in the west channel at this section (PEN02W) reflect difficulties repeating the transect from survey to survey. The cross-section is rocky and high velocity at all flows with a ≅1 m ledge drop just downstream that was exposed post-removal and creates standing waves and poor conditions for navigating the ADCP. Apparent changes at PEN03 are primarily associated with difficulties repeating the transect at three boom piers exposed post-removal.

Since very little sediment was available for release from the Great Works impoundment, it is also not surprising to see insignificant changes over the project period at the cross-sections in the downstream free-flowing reach (Figure 6). There is no apparent channel change associated with the two large flood events during the period either.

Pre- and post-removal conditions are also very similar in the Veazie impoundment despite the two ~10-year floods also occurring during the interval (Figure 7). Any changes at PEN09 are primarily associated with survey of a boom pier exposed post-removal along the transect at approximately 200 m from the left bank (Figure 7b). Only PEN11 shows substantial bed elevation changes (Figure 7d). However, erosion and deposition shown there from 50 to 125 m from the left bank monument between the pre-removal surveys and the October 2014 survey is almost certainly associated with systematic measurement errors from using the ADCP in the fast and turbulent conditions documented in the field notes. Maintaining the transect line was especially difficult. The CR Environmental (2008) pre-removal side scan sonar surveys map this area as bedrock (Figure 2b inset), and indeed the September 2015 survey shows no erosion in this area since the pre-removal surveys. Substantial erosion is also documented at PEN11 from pre- to post-removal from about 160 to 190 m from the left bank monument. The pre-removal side scan sonar surveys show this area as boulder dominated and thus unlikely to erode (Figure 2b inset). They also show, in red, small polygons representing boom piers at the same location as the apparent erosion. These are adjacent to the large remnant dam structure running parallel to the flow in the Veazie impoundment, also shown in red (centered at 150 m from the left bank monument in Figure 7d). The apparent erosion in these areas most likely represents difficulty maintaining the ADCP transect near the boom pier remnants and/or removal of portions of the piers between surveys. Some remnant infrastructure was removed in this area as part of the dam removal project to improve fish passage in the narrow channel created by the large remnant dam (Figure 2b inset).

PEN12, immediately downstream of the Veazie Dam, shows no directional changes over the study period substantially exceeding our estimated random measurement error of $\cong$0.1 m (Figure 8a). Figure 8b and field notes indicate that flow conditions affected the ADCP measurements, track line, and data incompleteness at PEN13, the tidal section, making interpretations there difficult. Nonetheless, there are no obvious areas of substantial bed erosion or deposition over the study period at PEN 13, as expected given the bed-sediment texture of the study area and the estimated quantities of sediments stored in the impoundments removed upstream.

Bed-sediment grain size

Collecting bed-sediment grain size data is exceptionally challenging in wide, high velocity rivers that are too deep to wade but too shallow and turbulent for many boat operations. Method development remains an area of active research (e.g., Buscombe et al., 2015). We could only collect reliable data in the impoundments via our experimental method, thus post-removal comparisons were impossible. Nonetheless, the pre-removal data we collected at the cross-sections (not shown) confirmed that the impoundments were dominated by coarse substrates, as the side scan sonar surveys had shown during the pre-project engineering feasibility studies (Figure 2).

Turbidity

A turbidity spike at the initiation of the Great Works dam removal was of the same magnitude and duration as those produced by the watershed during high streamflow in the pre-project period (Figure 3). Indeed this spike was also associated with an annual peak discharge, so it is unclear if the removal contributed to it. There was no turbidity spike associated with the initiation of the Veazie Dam removal, which occurred at a time with no flood events (Figure 3). Based on the record at Great Works and the analyses of Tullos et al (2016) described below, it is likely that any elevated turbidity that may have occurred there after our monitoring ended did not exceed values recorded during the observation period.

Discussion

Our stream geometry data pre- and post-removal (Figs. 5-8) demonstrate how channel shapes change very little when impoundments storing relatively small quantities of mobile sediment are removed from erosion-resistant streambeds. The channel of the lower Penobscot River was also not sensitive to two ~10-year floods during the study period, illustrating how a coarse-bedded/bedrock reach can be resistant to multiple disturbance mechanisms (Harrison et al., 2018).

We hypothesized that incision of the pre-dam streambed, and knickpoint migration, would not occur in this setting and this was confirmed with our repeat surveys. Our findings support those of Tullos et al. (2016) who examined 38 dam removal sites for incision and knickpoint migration impacts and found few cases where incision progressed below the pre-dam riverbed elevation. At sites where it did occur, the dam or other pre-existing infrastructure had caused local downstream scour lower than the natural bed elevation that subsequently migrated upstream when the infrastructure was gone (e.g., Wildman and MacBroom, 2005). Neither dam on the lower Penobscot River had significant downstream scour. Tullos et al. (2016) also found that incision magnitude at the sites they analyzed usually matched the depth of the impounded sediments and incision stopped when the pre-dam bed elevation, and bed gradient, was reached. Other investigators have reported how erosion-resistant, pre-dam streambeds can impede incision and knickpoint migration after dam removal, but these sites have generally been on smaller streams, had smaller dams (<10m high), and stored greater quantities of trapped sediment than our sites (e.g., Gartner et al., 2015). Our results expand the variety of conditions for which this has been observed, and our findings are not complicated by incision of overlying, stored sediment.

It is valuable to report results of no change, especially in dam removal science where findings can inform practice. Results of no change are infrequently documented in the dam removal literature, and indeed many dam removal studies occur at sites where changes are likely or expected—especially for physical response variables (Bellmore et al., 2017; Duda et al., 2020). Thus, the literature available to inform practitioners and local stakeholders may be biased to suggest they should expect changes when, in many cases, changes are unlikely. This compounds the problem that dam removal studies are not representative of dam removal projects in other respects, such as dam height and geographic setting (Bellmore et al., 2017)

Unfortunately, we were not able to test our second hypothesis that the bed texture could change measurably at our sites despite a paucity of stored sediment in both impoundments. Our experimental method for collecting grain-size data at the cross-sections was not successful in the former impoundments post-removal, or even in the free-flowing reaches for many discharges. By documenting our experience, we hope we can make a small contribution to method development.

The turbidity response we observed is common at dam removal sites storing little fine sediment, providing additional evidence that Great Works and Veazie impoundments were dominated by coarse substrates. A review by Tullos et al. (2016), which included the sites analyzed here, showed that elevated turbidity associated with dam removals rarely exceeds magnitudes or durations produced naturally in the same watershed during high flow events. This is because a large proportion of the annual sediment load of many rivers is transported by high flows that occur only a few days a year and many impoundments do not store more than a year of fine sediment load. Only dam removal sites where the impoundments store multiple years of fine sediment load, like the large dams on the Elwha River, produce post-removal turbidity that exceeds natural, storm-induced turbidity (Magirl et al., 2015; Tullos et al., 2016).

Conclusions

Our studies of lower Penobscot River physical responses to two dam removals show minimal large-scale changes in stream geometry and position. These findings are unsurprising because of the lack of stored mobile sediment in the impoundments and the erosion-resistant nature of the channels upstream and downstream of the dam removals.

Nonetheless, these ‘no change’ results are important for practitioners and researchers because the dam removal geomorphology literature generally emphasizes change—sometimes dramatic—even though the site conditions that produced little change in the lower Penobscot are not unique. Other regions of the world have comparatively low sediment yields similar to the Northeast United States (e.g., non-alpine Europe; Milliman & Syvitski, 1992; Milliman & Farnsworth, 2013). Dam removal sites in these regions, with attributes like low reservoir trap efficiency (Brune, 1953) or erosion-resistant impoundment/channel boundaries, are likely to show similarly muted responses. Preliminary research investigating the bedrock and geomorphology of the area may provide important information relative to sediment availability and the level of erosion resistance of the river bed.

The challenge for practitioners in these settings is to secure adequate resources to confidently establish these conditions. Once established, considerable savings can be realized because costly sediment management planning and implementation can be avoided, as can reach-scale physical monitoring studies. Instead, if monitoring funds are available, they can be used for targeted physical studies that may be needed to address topics of special concern (e.g., habitat for a threatened or endangered species), biological response studies, or in areas where limited fine-grained sediment accretions may present management issues. Bellmore et al. (2017) showed how less than 10% of all dam removals have been studied, underscoring how the limited funds available for monitoring dam removals need to be allocated wisely.

Data Availability Statement

All time series of discharge and turbidity at USGS gages are freely available at: http://dx.doi.org/10.5066/F7P55KJN. The cross-section geometry and bed-sediment texture data that support the findings of this study are available from the corresponding author upon reasonable request.

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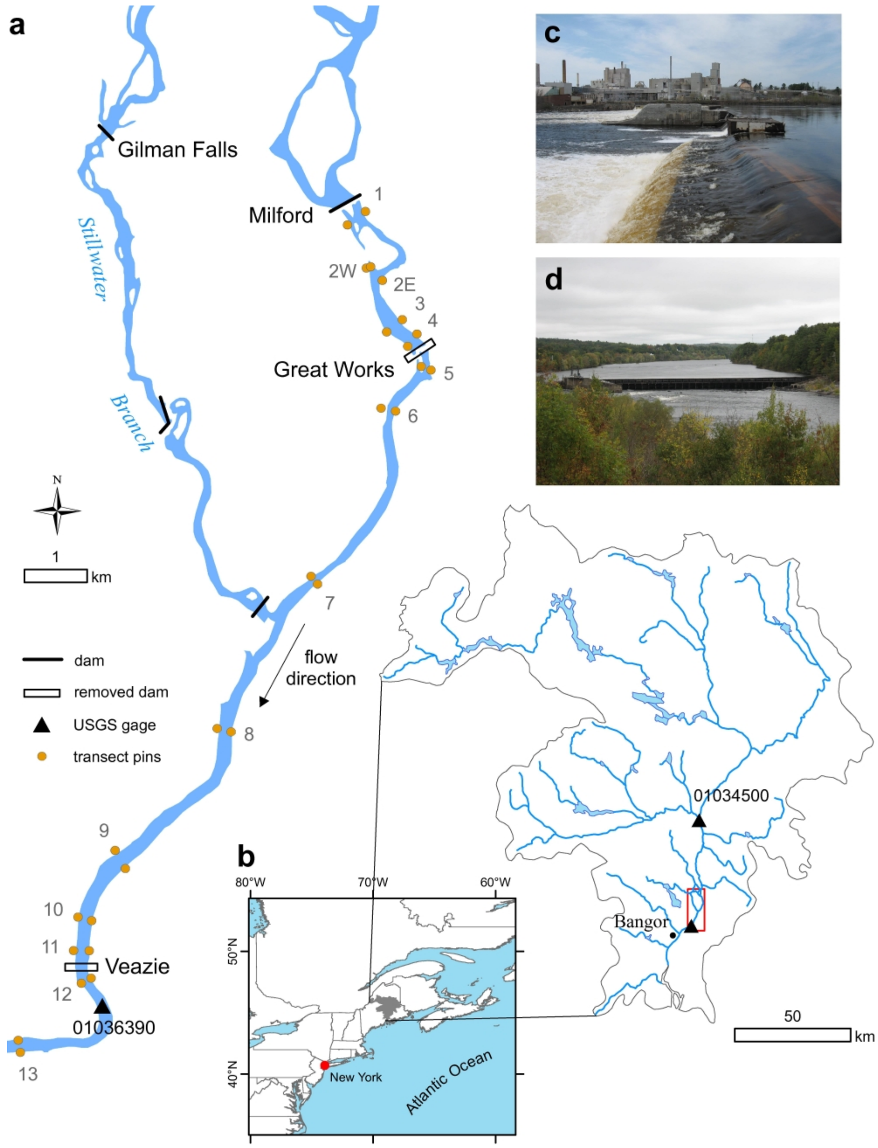

Figure 1. (a) The lower Penobscot River and dam removal study area. (b) The Penobscot River watershed showing the mainstem, principal tributaries, and study area extent. Great Works (c) and Veazie (d) dams.

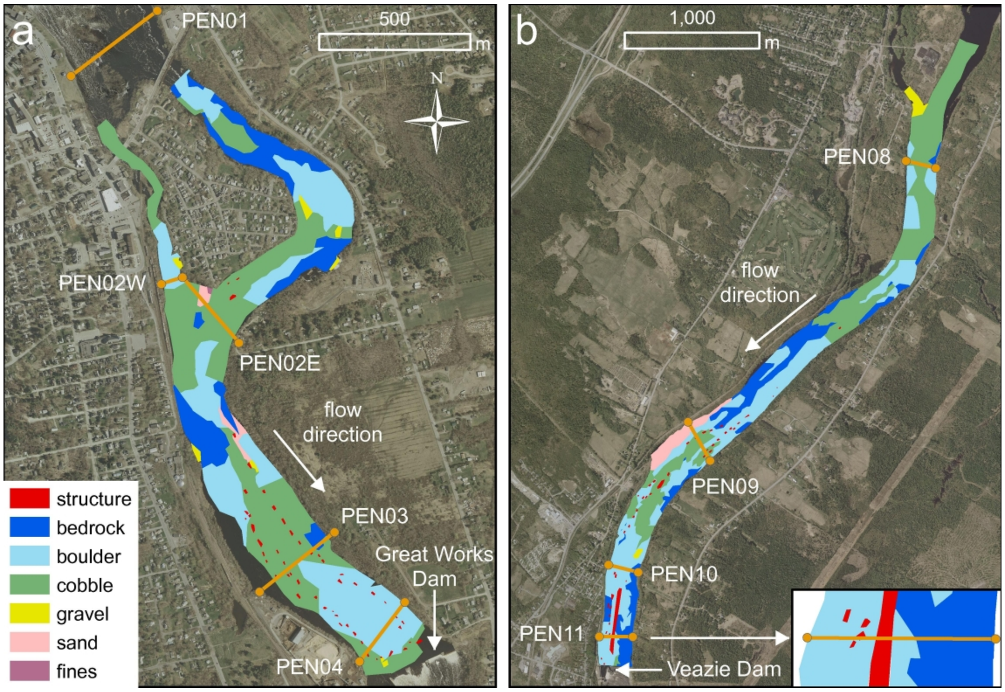

Figure 2. Bed-sediment texture interpreted from ground-truthed side scan sonar surveys of the Great Works (a) and Veazie (b) impoundments (CR Environmental, 2008). Cross-section locations are also shown. Base maps are 1-ft color orthophotos flown in spring 2003 when the dams were in place, available at https://www.maine.gov/megis/catalog/.

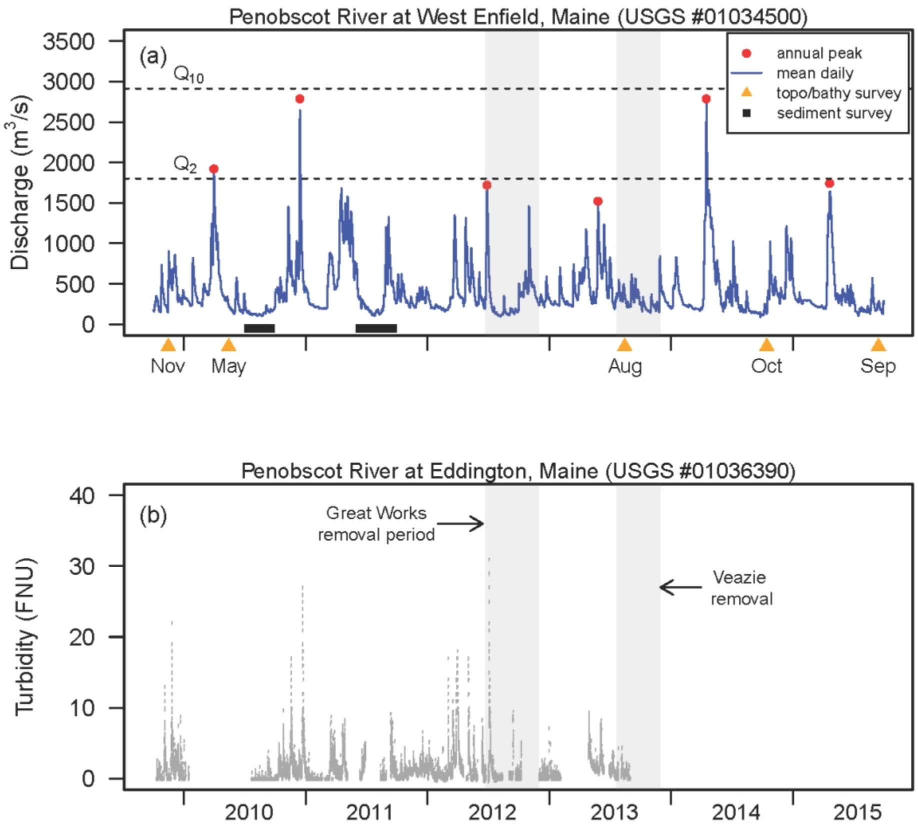

Figure 3. (a) The Penobscot River hydrograph upstream of the dams during the study period and the timing of the cross-section and bed-sediment surveys. Horizontal dashed lines show the estimated magnitudes of 2 and 10-year floods, based on Log-Pearson Type-III analyses of annual instantaneous peak flows from 1902 to 2018. (b) The turbidity time series downstream of the sites. The turbidity data are also summarized in Tullos et al. (2016).

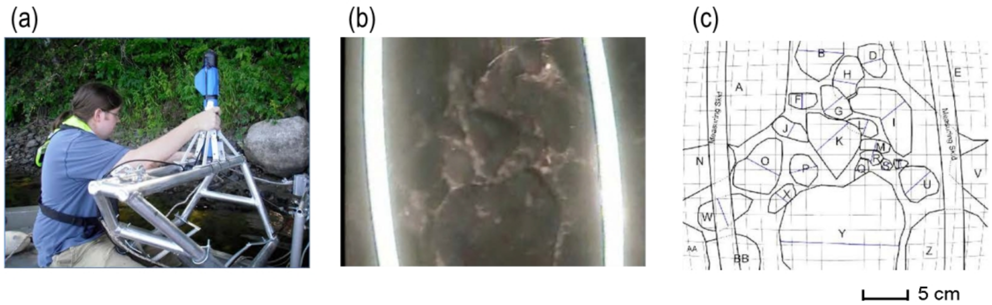

Figure 4. Sled-mounted video camera (a) for imagery collection (b) and measurement (c).

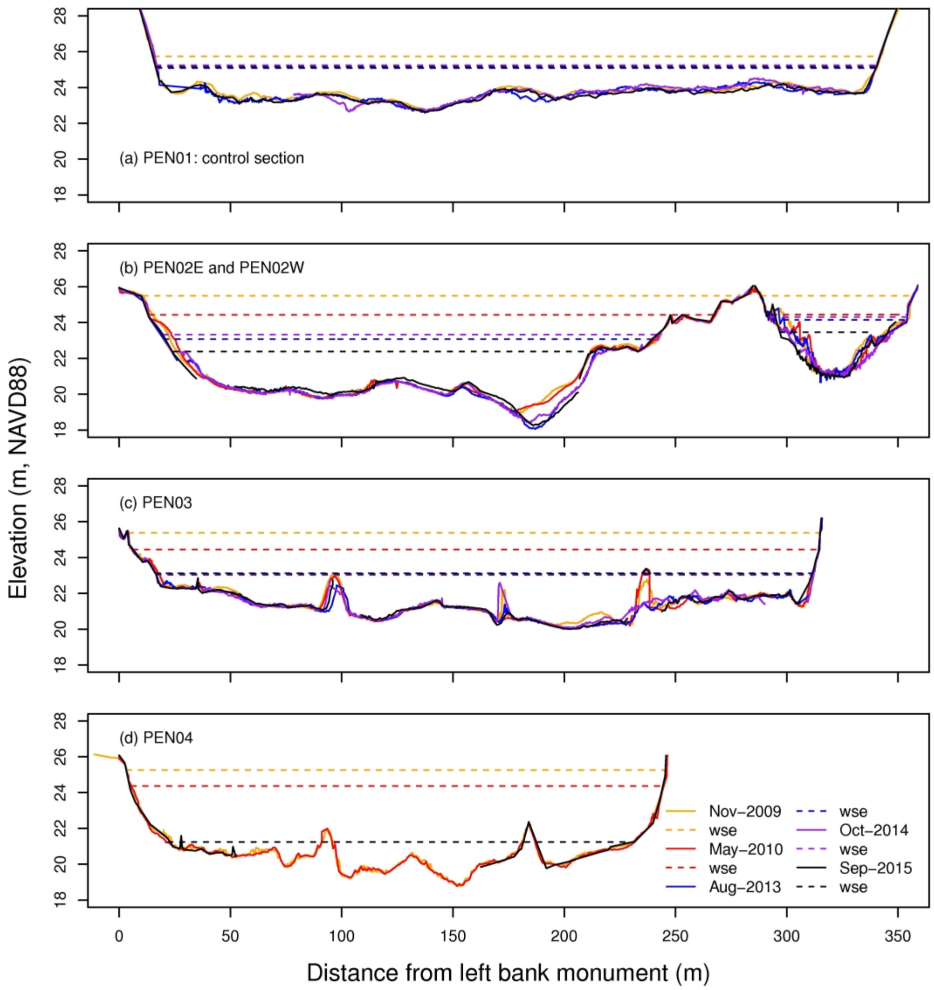

Figure 5. The control section upstream of the Great Works impoundment (a) and cross-sections within it (b-d) before (2009 and 2010) and after removal. Cross-section numbers increase in the downstream direction. See also Figure 1a for cross-section locations.

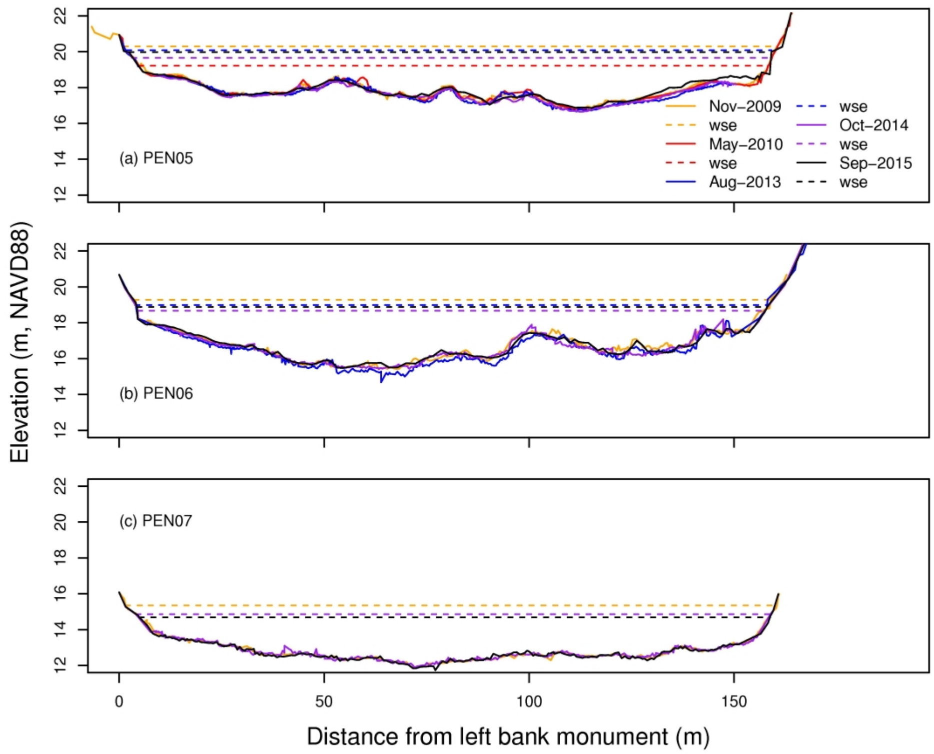

Figure 6. The free-flowing reach between Great Works Dam and the Veazie impoundment.

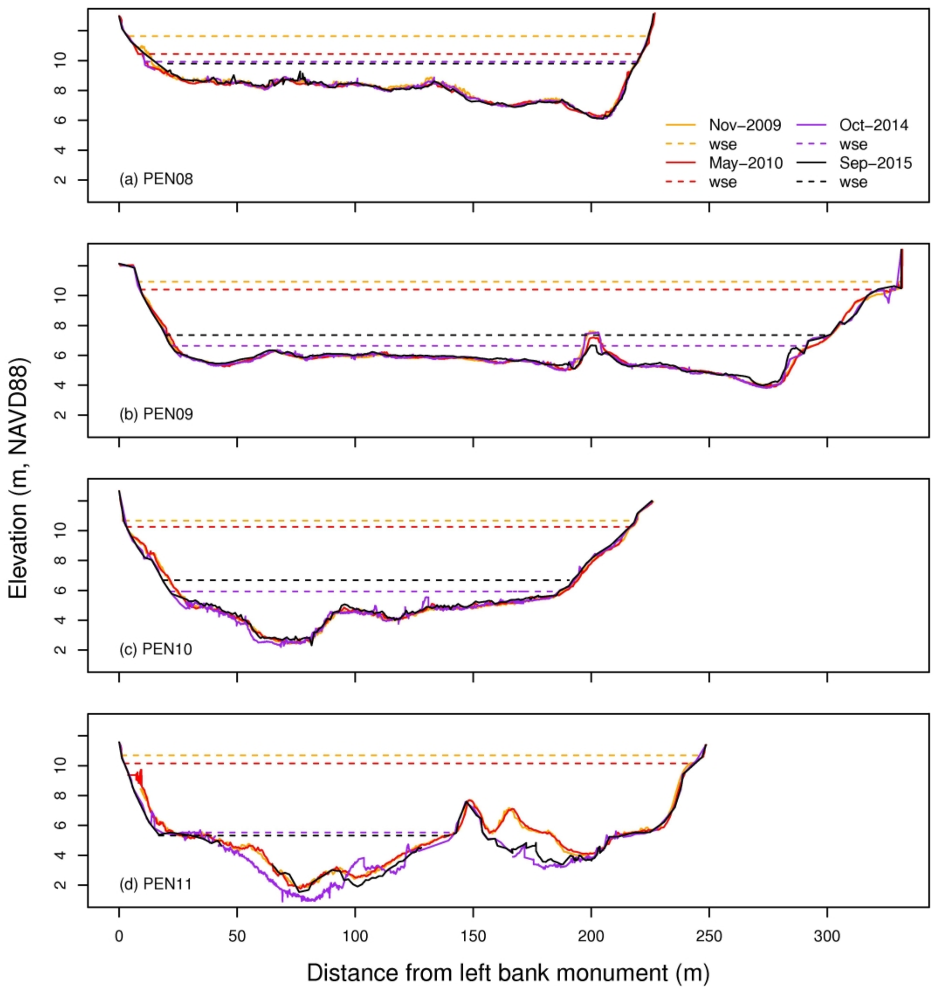

Figure 7. Cross-sections of the Veazie impoundment before (2009 and 2010) and after removal.

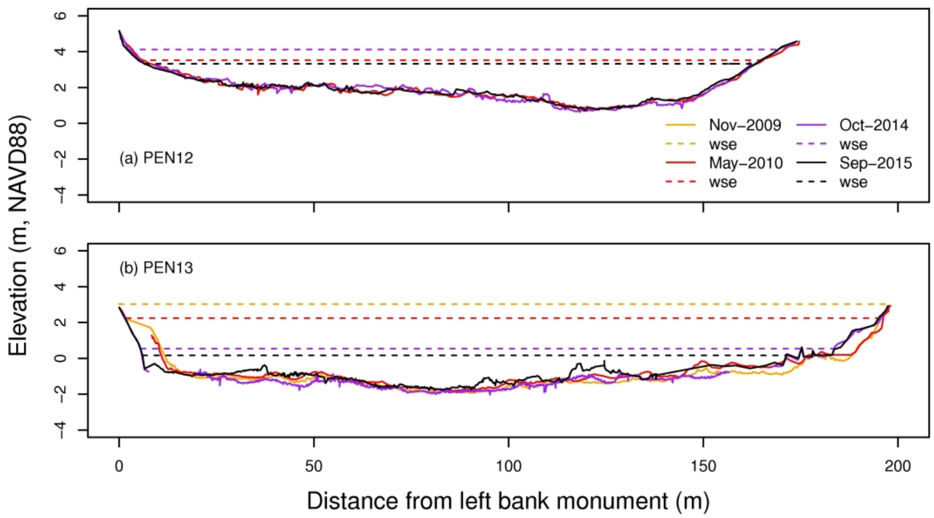

Figure 8. (a) Cross-section PEN12 immediately below Veazie Dam. (b) Cross-section PEN13 in the tidal reach below USGS gage 01036390.