Quantifying Legacy Sediment in the Upper Charles River Watershed, Massachusetts

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A Thesis

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Presented to

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While it has been shown that extensive sedimentation in historic millponds has greatly affected streams in the Mid-Atlantic Piedmont region (Walter and Merritts, 2008), much less is known about the phenomenon in the heavily dammed areas of post-glacial New England. Some research has found similar deposits behind breached historic dams in the Sheepscot River watershed in mid-coast Maine, but at a smaller scale than those seen in the Mid-Atlantic region (Strouse, 2013; Hopkins, 2014). I attempt to further explore millpond sedimentation in New England by quantifying the volume of millpond sediment, also called legacy sediment, in the 171.3 km^2 upper Charles River watershed in eastern Massachusetts. Twenty three milldams were located in the watershed on 1850s maps, giving a damming density of 0.177 $dams/km^2$. Each historic dam that had since breached, 14 in total, was visited in the field to identify possible legacy sediment deposits. Legacy sediments were identified by their meter or higher terraces made of fine sands and silt and verified by comparison to sedimentary patterns found in other legacy sediment deposits and radiocarbon dating of material both within the legacy sediment and in the underlying layer. Legacy sediment terraces with an area of $1.68*10^4$ m^2 and a total volume of 1.29 - $2.57*10^4$ m^3 were found upstream of two adjacent breached historic dam sites on the Charles River in Medway, MA. Radiocarbon dates from a coarse sand and gravel lower at 1.8 m depth returned pre-settlement dates of 1281-1391 cal AD (two σ). These dams were immediately downstream of a large glacial feature with steep banks along the river. The lack of legacy sediment at other dam sites and the lack of sedimentation behind intact dams suggest that a low sediment supply to millponds prevented legacy sediment deposits from forming in most of the watershed.

Acknowledgements

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1. Introduction

1.1. Overview and Research Motivation

As the east coast of the United States was settled and developed in the 18th and 19th Centuries, rivers provided the majority of the power for industrial processes. In order to harness these rivers, thousands of dams were built to run mills that cut lumber, ground grain and manufactured a variety of goods. By 1880, 55,404 water-wheels were generating 1,225,379 horsepower in the United States (Trowbridge, 1885). Damming rivers in this way prevented both nutrient and sediment transport downstream, impairing the rivers' natural processes (Bierman and Montgomery, 2014). At the same time, much of the landscape was deforested to feed the saw mills and make room for agriculture. This rapid transformation from woodland to open pasture and agricultural fields increased runoff and decreased soil cohesion, creating a large pulse of sediment into streams (Thorson, 1998). Although many historic dams have either breached or been removed, the sediment that was deposited in their millponds may still remain. Large deposits of fine grained sediment from former millponds, called legacy sediment, have been found to be common in the heavily dammed areas of the Mid-Atlantic Piedmont region (Walter and Merritts, 2008). The goal of this thesis is to look for similar deposits in the upper Charles River watershed and explore possible factors that contribute to or inhibit legacy sediment storage in the watershed.

Legacy sediment deposits are found as paired terraces comprised of fine sediments. These terraces form after a dam is breached and the river erodes down into the sediment that was formerly on the bed of a millpond. With heights up to several meters above the stream, legacy sediment terraces are often abandoned and receive little to no overbank deposition (Walter and Merritts, 2008). In some places, however, these terraces can act as elevated floodplains, still actively engaged in the river dynamics (Strouse, 2013). In both cases, the legacy sediment terraces are higher than the natural floodplain, affecting the stream morphology and bank erosion rates (Walter and Merritts, 2008). Underlying the legacy sediment, there is usually a dark organic rich layer that has been interpreted as a Holocene soil that developed before millpond sedimentation (Walter and Merritts, 2008). Radiocarbon dating of this underlying material and organic material in the millpond sediment has been used to constrain the timeline of sedimentation (Walter and Merritts, 2008; Strouse, 2013).

While this phenomenon has been well documented in the Mid-Atlantic region, much less work has been done in the heavily dammed areas of New England. Legacy sediment deposits mapped in the Sheepscot River in the mid-coast of Maine behind breached historic dams showed that the northeast stores legacy sediment similarly to the Mid-Atlantic, but mostly at a smaller scale (Strouse, 2013). Other research in that watershed found that automated and semi-automated analysis of high-resolution lidar DEMs can be effective for mapping fill terraces associated with legacy sediment deposits (Hopkins, 2014). This thesis will attempt to apply some of these methods to expand the database of legacy sediment in New England by investigating a more anthropogenically altered watershed.

Identifying and quantifying legacy sediment is important for river restoration projects on affected streams. Legacy sediment impairs the stream by burying the natural floodplain and providing a source of fine sediments (Walter and Merritts, 2008). Removing anthropogenically imposed impairments may not be sufficient to restore natural stream processes, and a more holistic approach to recreating the pre-settlement floodplain conditions may be necessary. Dam removal has become a ubiquitous tool in river restoration, allowing nutrient and sediment transport processes that were impeded by the dam to resume. Rivers and streams do not return to their natural state overnight however, and the impacts of a dam can still be seen for decades or even centuries after the dam is removed. Looking back at historic dams that were removed or breached centuries ago could therefore help give us insight into the future for modern dam removal projects.

1.2. Site Description

The Charles River is a low gradient river in eastern Massachusetts that winds through suburban towns and into the city of Boston where it flows into Boston Harbor. This study only looked at the watershed upstream of Populatic Pond in Medway, MA (Figure 1). This watershed is 171.3 km^2 with 170.5 km of stream channels. The mainstem of the Charles River has an average slope of 0.216 % over this area (Figure 2). The hillslopes are flat as well with 90% of the surface topography having a slope less than 11.8% (Figure 3), and total relief in the watershed being 140 m (Figure 1).

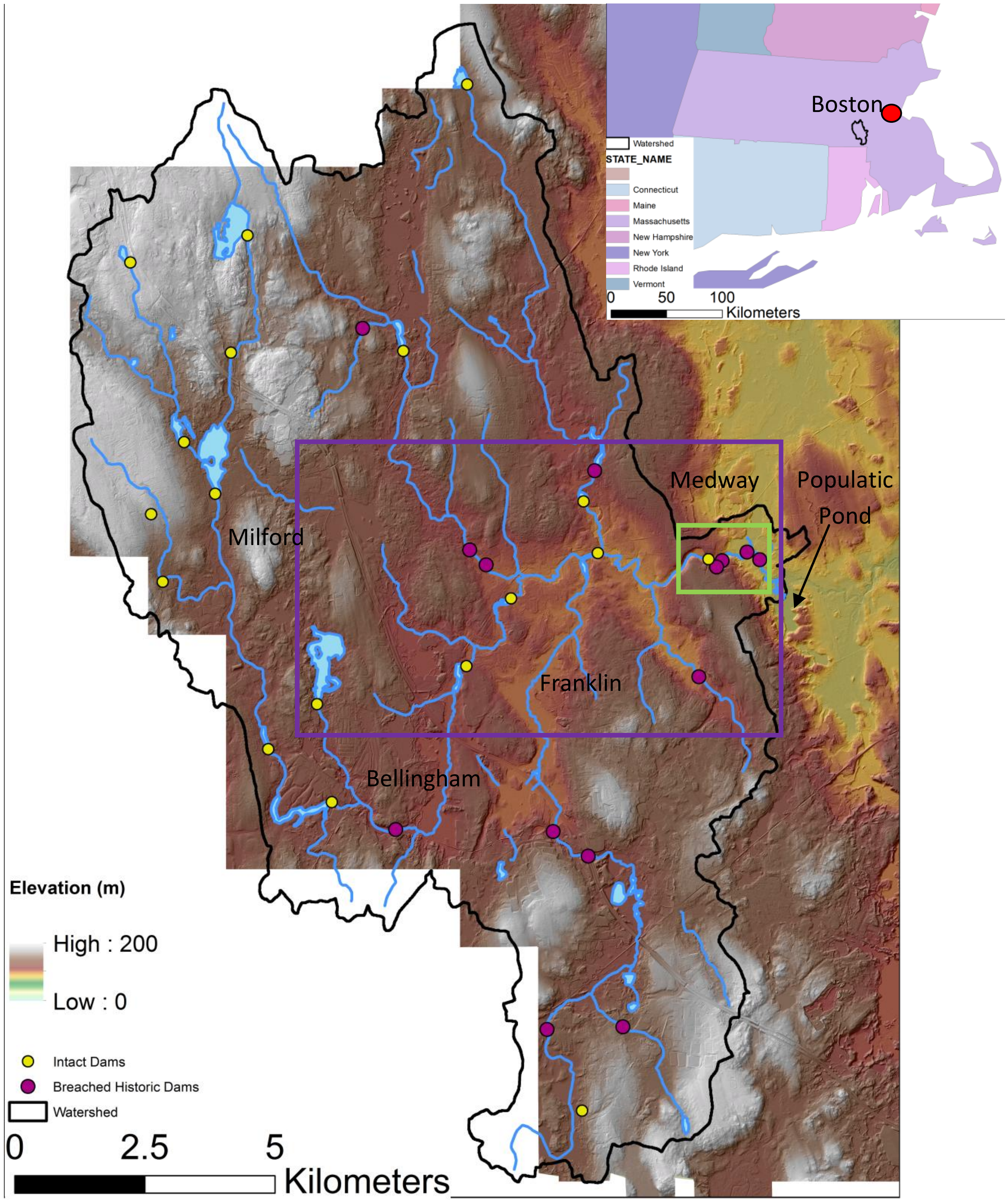

Figure 1. A Lidar DEM of the upper Charles Watershed with a transparent hillshade overlay. The watershed was delineated from an outlet point at the entrance to Populatic Pond. Breached historic dams were found on georeferenced historic maps and intact dams were registered to a dam safety database and a coverage was available from MassGIS. The purple box indicates the location of figure 4 and the green box indicates the location of Figures 11 and 13.

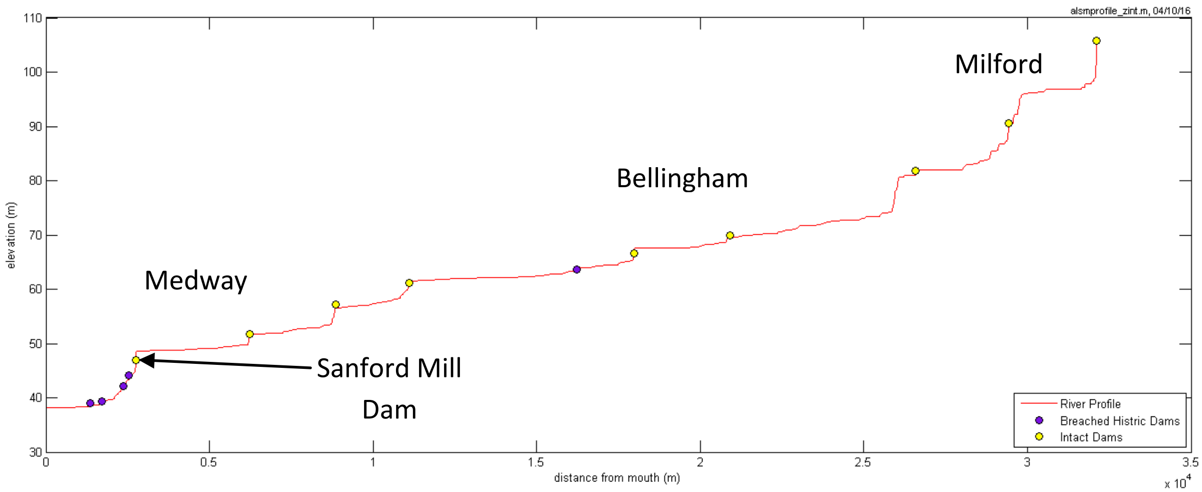

Figure 2. A longitudinal profile of the Charles River from its headwaters to Populatic Pond. With a run of 31.32 km and a rise of 67.6 m, the average slope of the Charles River in the study area is 0.216 %. Most of the channel has very low slope and every one of the steeper reaches has an intact dam on it. The breached historic dams were not exclusively on the steepest sections. Historic dams on steep sections were likely the most productive and are thus more likely to have an intact dam still at the site.

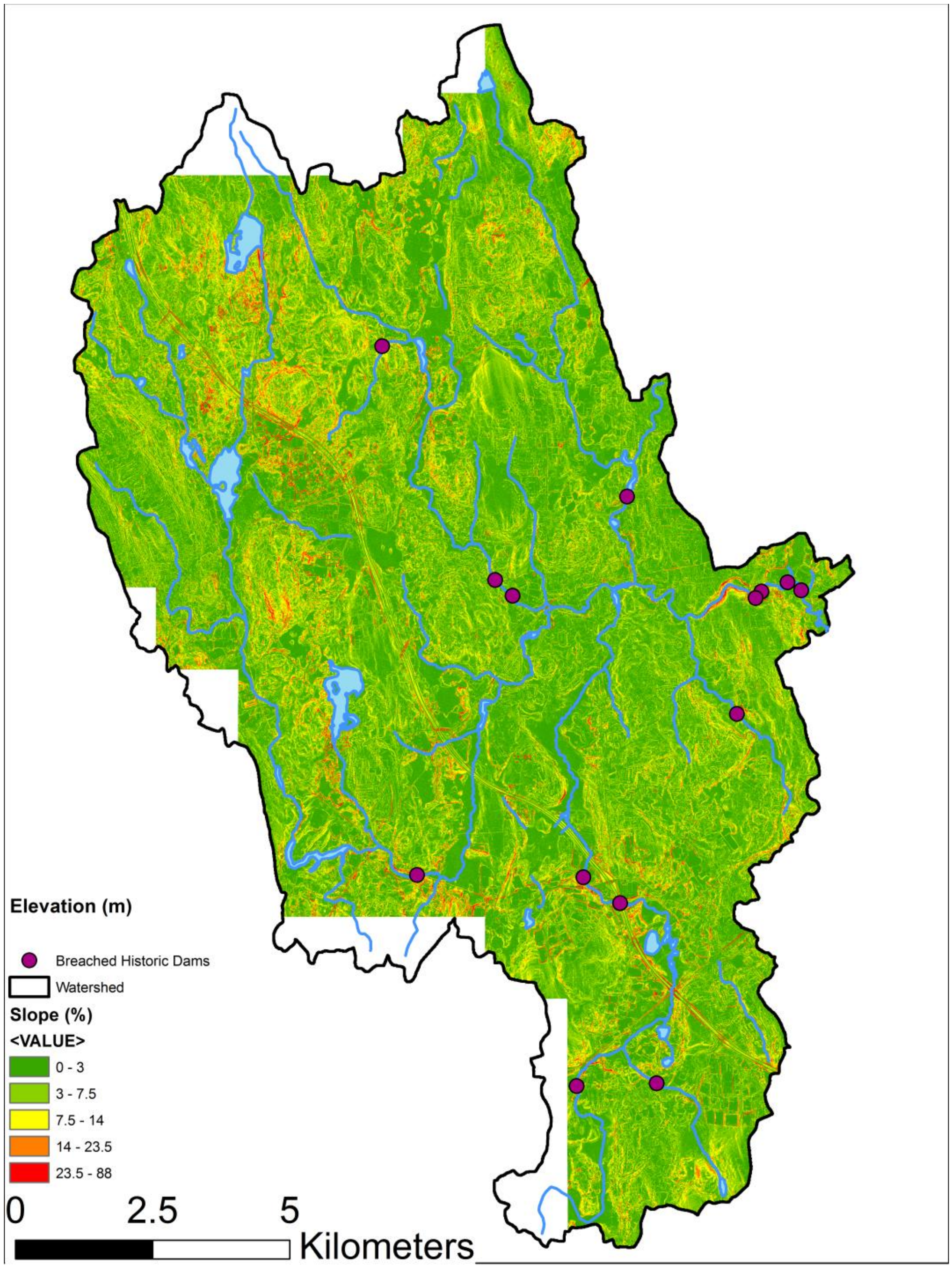

Figure 3. Surface slope calculated from the high resolution lidar DEM. The majority of the watershed is very low gradient (shown in green) with a few patches of steeper areas. There are some steep areas in the head waters where there is exposed bedrock or human alteration around interstate highways. In the downstream end of the study area, the only steep slopes come from incision into the glacial feature through which the river has incised (Figure 4).

The sedimentary history of the area is dominated by glacial advance and retreat. During the last ice age, massive ice sheets bulldozed through the entire region, pushing most of the loose sediment out to their terminuses. As the glaciers retreated they left most of the sediment that had been removed from the landscape in large deposits of unsorted till (Menzies, 2009). This left behind a landscape with thin sediment in most areas and a few local features of thick glacial till. The surficial geology of the landscape is dominated by glacial stratified deposits with intermittent pockets of till of varying thickness (Figure 4). The underlying bedrock is made up of proterozoic plutonic, metaplutonic, metavolcanic, and metasedimentary rocks of the Milford-Dedham zone (Goldsmith, 1991).

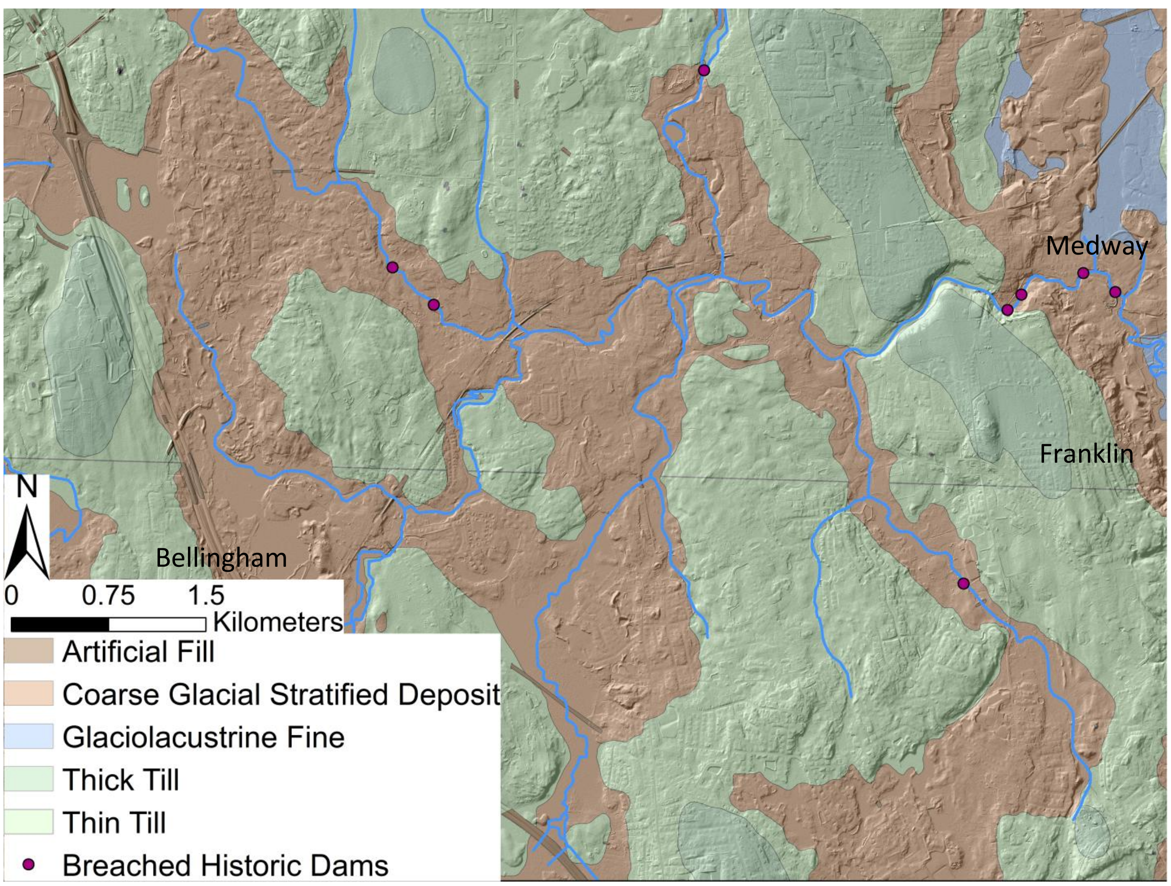

Figure 4. A surficial geologic map of the center of the study area. The majority of the streams flow through coarse glacial stratified deposits with very little mobile sediment. There is a large feature of thick till just upstream of the four dams in Medway.

The study area has undergone a significant land use change over the past few centuries. It was first deforested down to 25.0% by 1850 due to European colonization (Figure 5). Since then, it has reforested up to 52.3% after logging died out in the area, and suburban sprawl established the area as a suburb of Boston. 25.8% of the watershed is now residential (Figure 5). The river corridor is now constricted significantly by human development along the banks which prevents the river from migrating across the river valley. Although the upper watershed is not as impacted as the lower watershed that flows through Boston, most of the river and its tributaries go through yards or town centers and little is unimpaired by human activities.

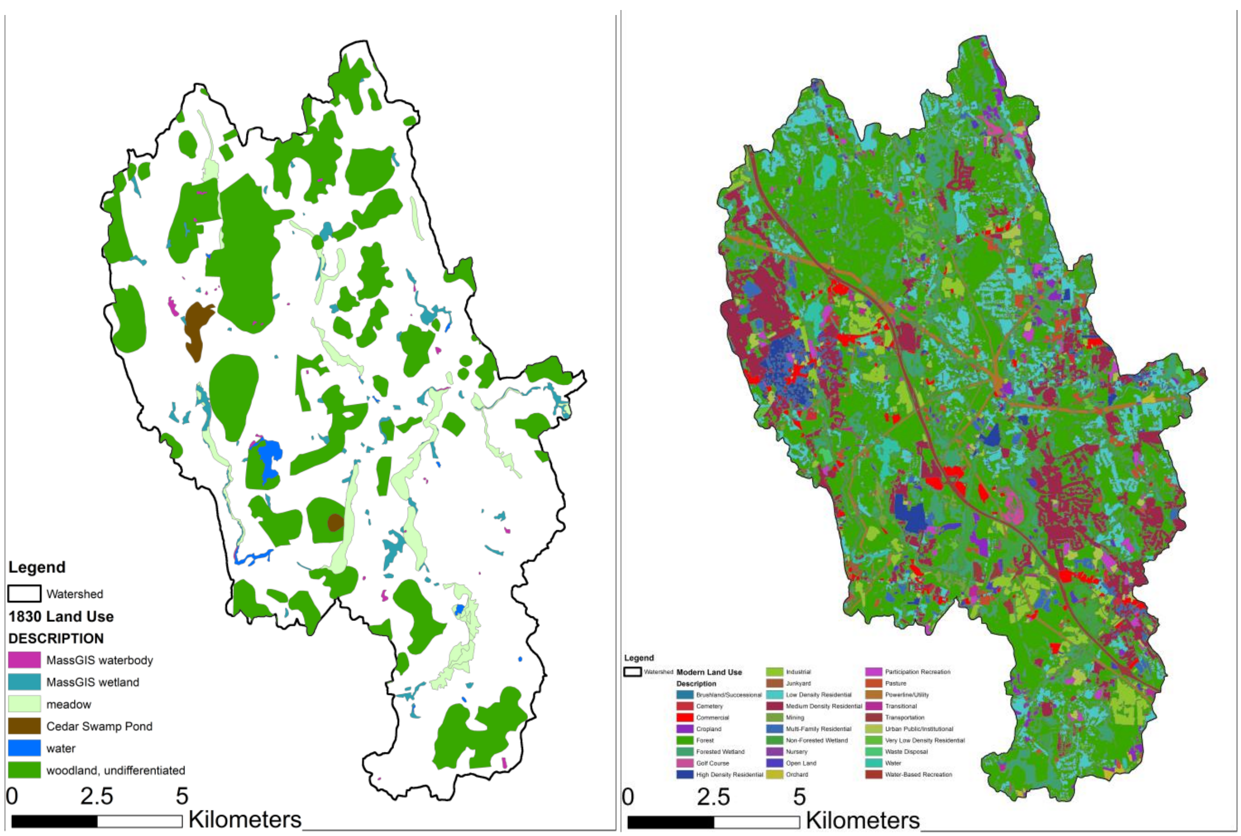

Figure 5. A comparison of land use between 1830 and 2005. Historic land use was compiled by the Harvard Forest from an 1830 state land use survey. The major difference is the increase in forested area which increased from 24.9% to 52.3%. The 1830 data was collected by hand in the field and a consistent methodology was not applied. It may be possible that small forested areas were not counted leading to underestimation of forested area in 1830. The overall trend of reforestation over the past 150 years is well documented though and these two datasets bear that out.

1.3. Thesis Objectives

The goal of this thesis is to quantify the amount of legacy sediment still present in the upper Charles River watershed. First, I determined the location of each breached historic dam in the watershed and determined the milldam density. Then, I investigated each dam site in the field to identify potential sites of legacy sediment storage. Potential deposits were verified as legacy sediment using sediment analysis and radiocarbon dating. Based on analysis of high-resolution lidar digital elevation models (DEMs), I mapped the areal extent of legacy sediment terraces and calculate the total volume of legacy sediment in order to compare to previously researched watersheds. Lastly, I use these data to assess the factors that control legacy sediment storage in the upper Charles River watershed.

2. Methods

2.1. Historic Maps

The locations of breached historic dams were determined using historic maps found in the Boston Public Library's Norman B. Leventhal Map Center (maps.bpl.org; Table 1). In order to locate the dams on a modern map, the historic maps were georeferenced to a 1987 topographic map from the Massachusetts Office of Geographic Information (MassGIS). Most major intersections in town centers were consistent over the last 160 years providing ample control points across large maps. I also used town borders along with road intersections on smaller town maps to provide sufficient control points. The historic maps were not made with the same accuracy or scaling as modern maps, so a perfect match was not possible to attain. Without a perfect match, it was still possible to correspond a dam location on the historic map to a point on the modern river. Sometimes landmarks like roads or town lines were used as reference points in order to get a location accurate enough for field investigation. Dams were rarely labeled directly on the maps, so their location was determined based on mills that were often labeled or visible millponds (Figure 6). The most useful maps were a series of county maps published in the 1850s (Figure 7). Smaller town maps from the same time were used for detailed areas like town centers that were difficult to read on the larger county maps (Figure 8).

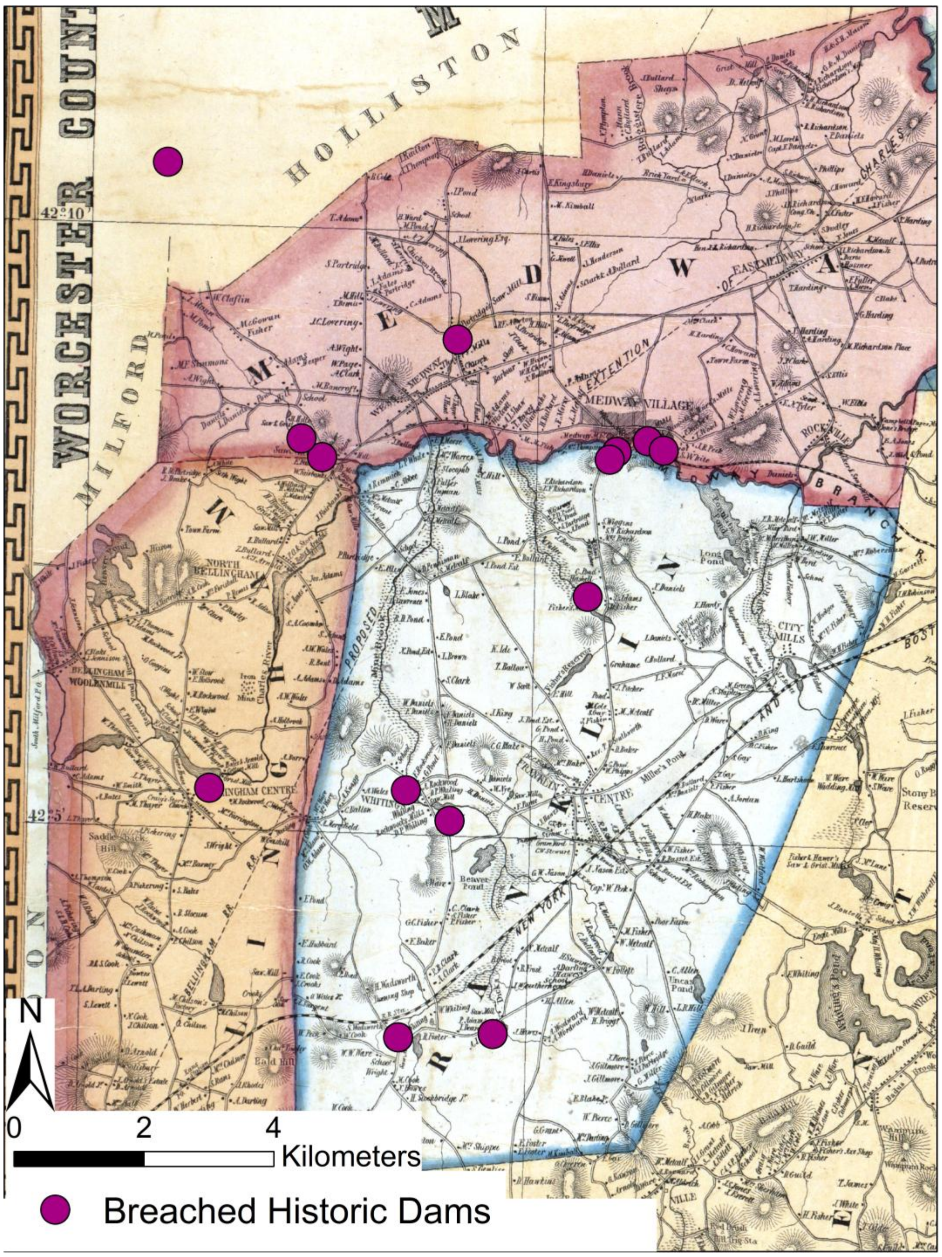

Figure 6. A Section of historic map showing Medway, Franklin, and Bellingham in 1853. These towns made up the majority of the study area as they are far enough from the headwaters that the river is large enough to dam and many of the tributaries were

also dammable. Dams were located based on mill buildings, visible reservoirs and sometimes direct drawing of dams across rivers.

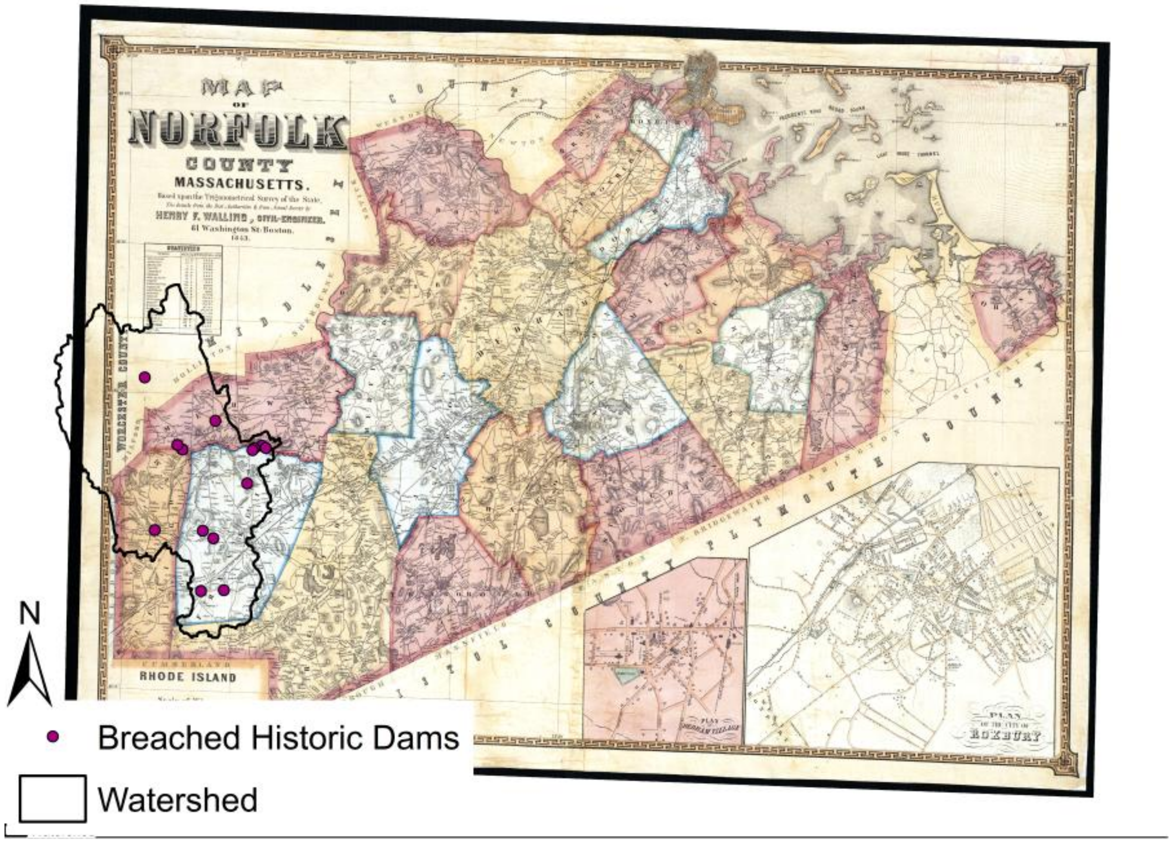

Figure 7. A historic map of Norfolk County from 1853 with the upper Charles River watershed marked. This was the most crucial map for locating breached historic dams as 13 of the 14 dams in the watershed are on the map. It contains the towns of Medway, Bellingham, and Franklin whose town centers showed the most anthropogenic input in the watershed in 1851.

Table 1. Summary of Historic Maps used to locate historic dams

Map	Year	Original Scale	Publisher	Source
Middlesex County, MA	1856	1:50,000	Smith and Bumstead	BPL
Milford, MA	1851	1:14260	Harkness, O.	BPL
Norfolk County, MA	1853	1:63,361	Walling, Henry Francis	BPL
Medway, MA	1852	1:15,840	Kollner, A	BPL

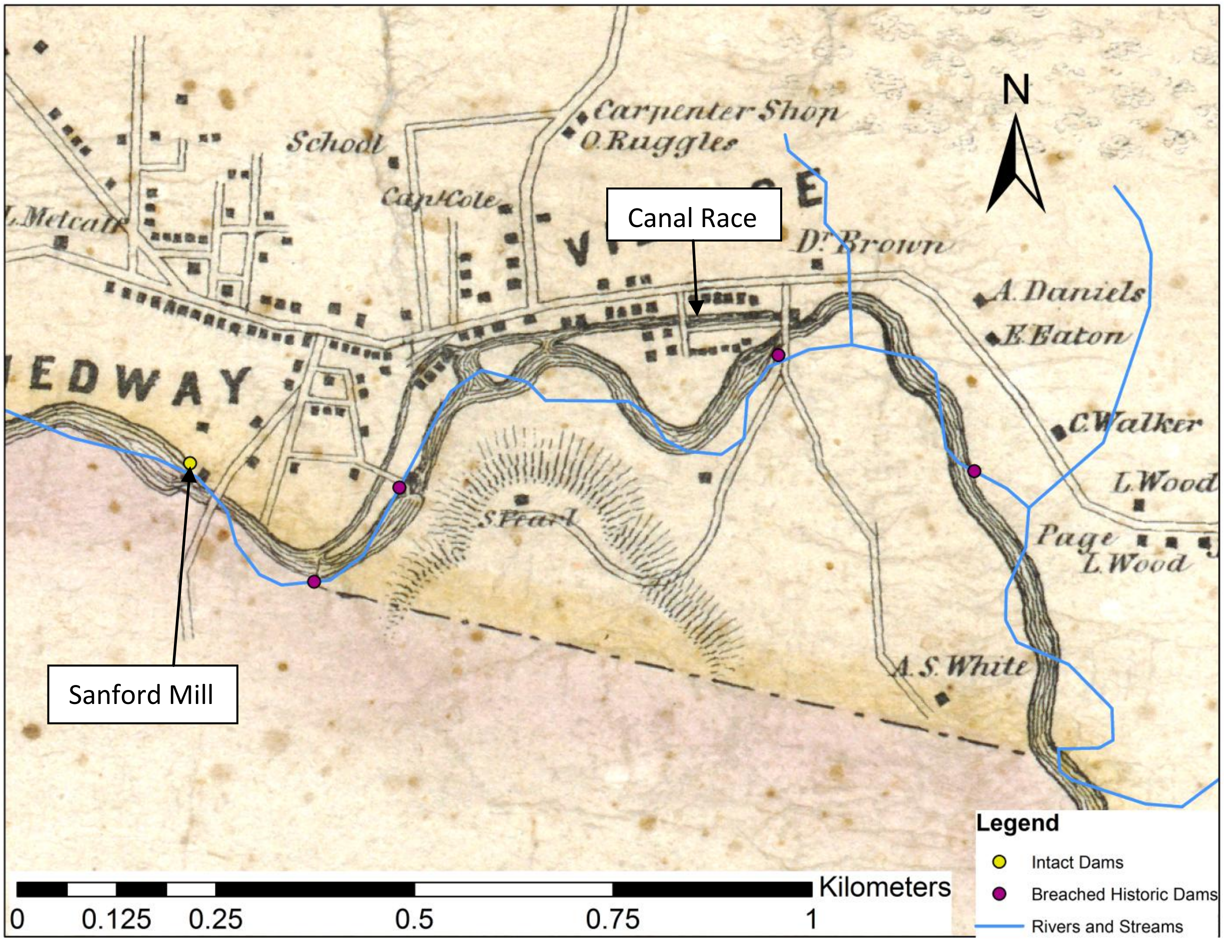

Figure 8. A historic map of downtown Medway from 1852.This section of the river was heavily modified with several dams and a canal or race. This map shows specific intricacies of this area of Medway that were not visible on the county map and allowed for the location of four dams in Medway. These dams can be seen as perpendicular lines across the river or bulges in the river.

2.2. Field Visits

Once the dams were located on a map, each one was visited to investigate any possible deposits of legacy sediment. A Trimble Juno handheld global positioning system (GPS) device was loaded with modern topographic maps and a coverage of all of the breached historic dams and used to locate the dams in the field. The dam remnants were often visible from the road or a nearby trail. The area around each dam was then described and photographed to record each dam's status. Lastly, the area upstream of each dam was then investigated to look for cutbanks of incised, fine-grained terraces.

If a suitable candidate was found, a stratigraphic section was measured for sediment analysis and samples of organic material were taken for radiocarbon dating (Figure 9). Sediment was analyzed for soil type using simple hand analyses like the ribbon test and the rope test. Radiocarbon samples were taken both from potential legacy sediment and from the underlying material. Flecks of wood or bark, or seeds were the best candidates for radiocarbon dating as sticks or twigs can be confused with modern roots.

Depth (m)	Description	Interpretation
1.35	Brown yellow sandy silt	Legacy sediment
1.77	Dark Brown dine sands, silt and clay	Legacy sediment
1.87 (water surface)	Grey coarse sand and gravel with flecks of wood. The bottom of this layer was not found	Paleochannel deposit

Radiocarbon Date: Modern

Radiocarbon Date: 1281-1391 cal AD

Figure 9. A photograph of the stratigraphic section taken at a legacy sediment terrace located at the star on Figure 12. The section has many of the characteristics of a legacy sediment terrace with fine grained sediment overlying a coarse grey base layer. A radiocarbon date taken in the upper section at 87 cm returned a modern age, so it was either a root that made it to depth after deposition, or the upper section of was deposited very recently. A radiocarbon date taken from the coarse base layer returned an age of 1281 – 1391 cal AD suggesting that it was at the surface shortly before settlers came and started damming the area.

2.3. Remote Sensing Data and Sediment Volume Calculation

Further analysis was done using mapping and GIS techniques on a variety of geospatial datasets (Table 2). The river and all its tributaries were mapped from a USGS hydrography coverage. A surficial geologic map, created by the USGS, showed where potential sediment sources were in the watershed and how the river interacted with these features (Figure 4). A coverage of intact dams from MassGIS was used to determine if there was still a dam at any of the historic dam sites. It also showed how damming had changed in the watershed over the past 150 years (Figure 1). MassGIS also provided modern land use data determined from 2005 4-band orthorectified aerial photographs (Figure 5). A historic land use map was available from the Harvard Forest, which compiled a land use survey that was done across the state in the 1830s (Figure 5).

Table 2. Summary of Datalayers used in ArcGIS Analysis

Coverage	Scale	Resolution	Date	Creator	Source
lidar DEM	N/A	1 m	2010	MassGIS	MassGIS
1:100,000 USGS Hydrography	1:100,000	N/A	2013	USGS	MassGIS
USGS topographic Quadrangles	1:25,000	N/A	1987	USGS	MassGIS
Intact Dams	N/A	N/A	2012	Massachusetts Office of Dam Safety	MassGIS
Surficial Geology	1:24,000	N/A	2015	USGS	MassGIS
land use	N/A	.5 m	2005	Sanborn	MassGIS
Historic land use	N/A	N/A	1830	Harvard Forest	Harvard Forest

A semi-automated ArcGIS script called TerEx, developed by Stout and Belmont, (2013), was used to attempt to map all of the terraces in the watershed without manually delineating them. This software has been shown to map legacy sediment terraces with sufficient accuracy at several sites along the Sheepscot River (Hopkins and Snyder, 2016). The script analyzes high-resolution lidar DEMs to find flat areas adjacent to the current stream channel (Stout and Belmont, 2013). The outputs can be modified by changing input values of valley width, minimum terrace area, focal window, and smoothing parameter. These inputs were adjusted to limit the outputs to just the terraces that were candidates for legacy sediment storage. The same DEMs were also used to manually determine the lateral extent of the deposits identified in the field. The terraces were visible on lidar as flat surfaces adjacent to the stream. The point at which the terrace met the valley wall was marked by a change in slope, allowing for manual mapping based on a colored elevation map and a transparent hillshade overlay.

A preliminary volume of legacy sediment was calculated using area data from the lidar DEM and depth measurements from field visits. The basal contact was not found at each terrace, but the river surface was used to determine the approximate depth of legacy sediment because the river usually cuts down to approximately to the base of the legacy sediment (Walter and Merritts, 2008; Hopkins, 2014). The depth could then be determined using a lidar DEM as the elevation values within the channel represent the water surface when the data was collected (Hopkins, 2014). The maximum volume of legacy sediment was calculated assuming a constant depth throughout the whole area of the terraces. In order to get a minimum estimate, the roughly rectangular cross section was changed to a triangular one, cutting the total volume in half (Figure 10; Hopkins and Snyder, 2016).

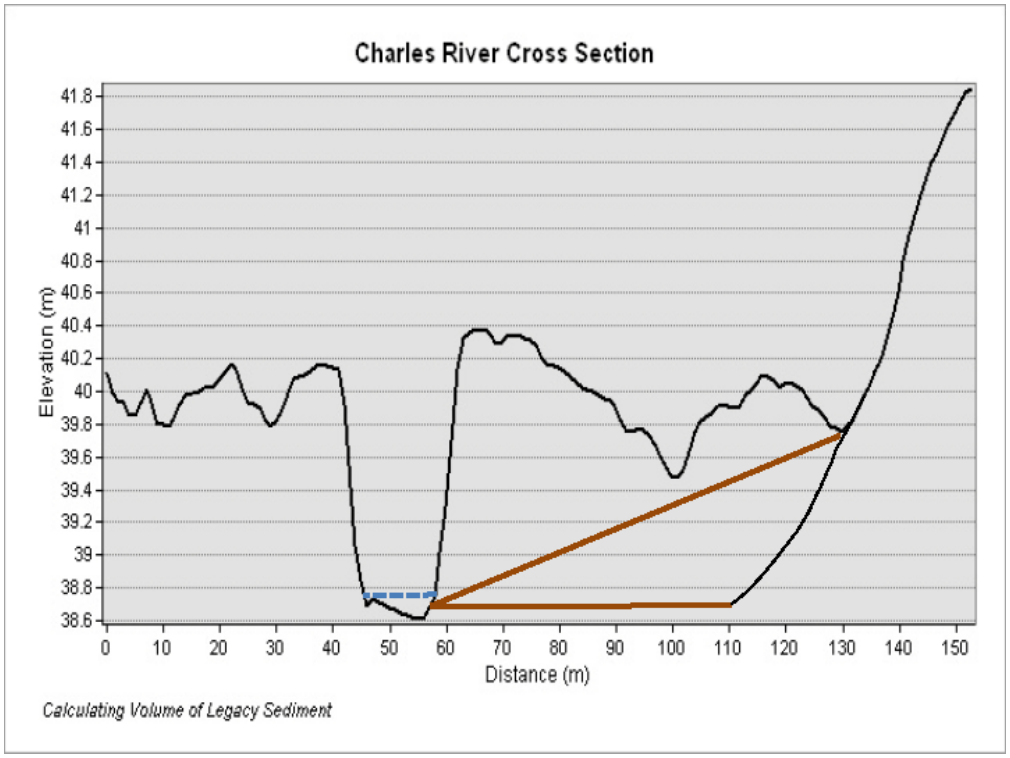

Figure 10. A diagram of legacy sediment volume calculation. The black line shows the land surface taken from a lidar DEM, the blue line represents the river height and the brown lines represent the possible contacts at the base of legacy sediment. The flat contact at constant elevation represents the maximum possible volume of legacy sediment storage while the oblique contact represents the minimum volume. These approximations give a large range, but can be useful for comparison to other sites of legacy sediment storage.

3. Results and interpretations

3.1. Historic Maps

Twenty three dams were located on historic maps from the 1850s. Of these, nine still had intact dams present at their sites. The damming density for the watershed in the 1850s was 0.177 dams/km^2. This is within the range of values for this region indicated by Walter and Merritts, (2008), (.1-.2 dams/km^2) when they compiled 19th century damming density for the entire east coast and identified central New England, along with the Mid-Atlantic Piedmont region as hot spots for 19th century dam density. The density I calculated is slightly lower than that of Chester County, PA with a density of 0.19 dams/km^2, where large volumes of legacy sediment were found (Walter and Merritts, 2008).

3.2. Field Visits

Visits to breached historic dam sites successfully located dam remnants in eight of fourteen sites. Most of the sites were still exhibiting base level control on the river either due to a partially intact dam or beaver dams built on top of dam remnants. Dam remnants were either partially intact structures or large cut stones (Figure 11). Exploration both upstream and downstream of each dam site revealed possible legacy sediment deposits at two adjacent sites in Medway (Table 3; Figure 12).

Figure 11. A beaver dam built on top of dam remnants. Beavers and humans choose similar places to build dams, where the valley is narrow and the flow is concentrated. The dam remnants also offer a good base for a beaver dam as they were likely controlling base level before the additional sticks.

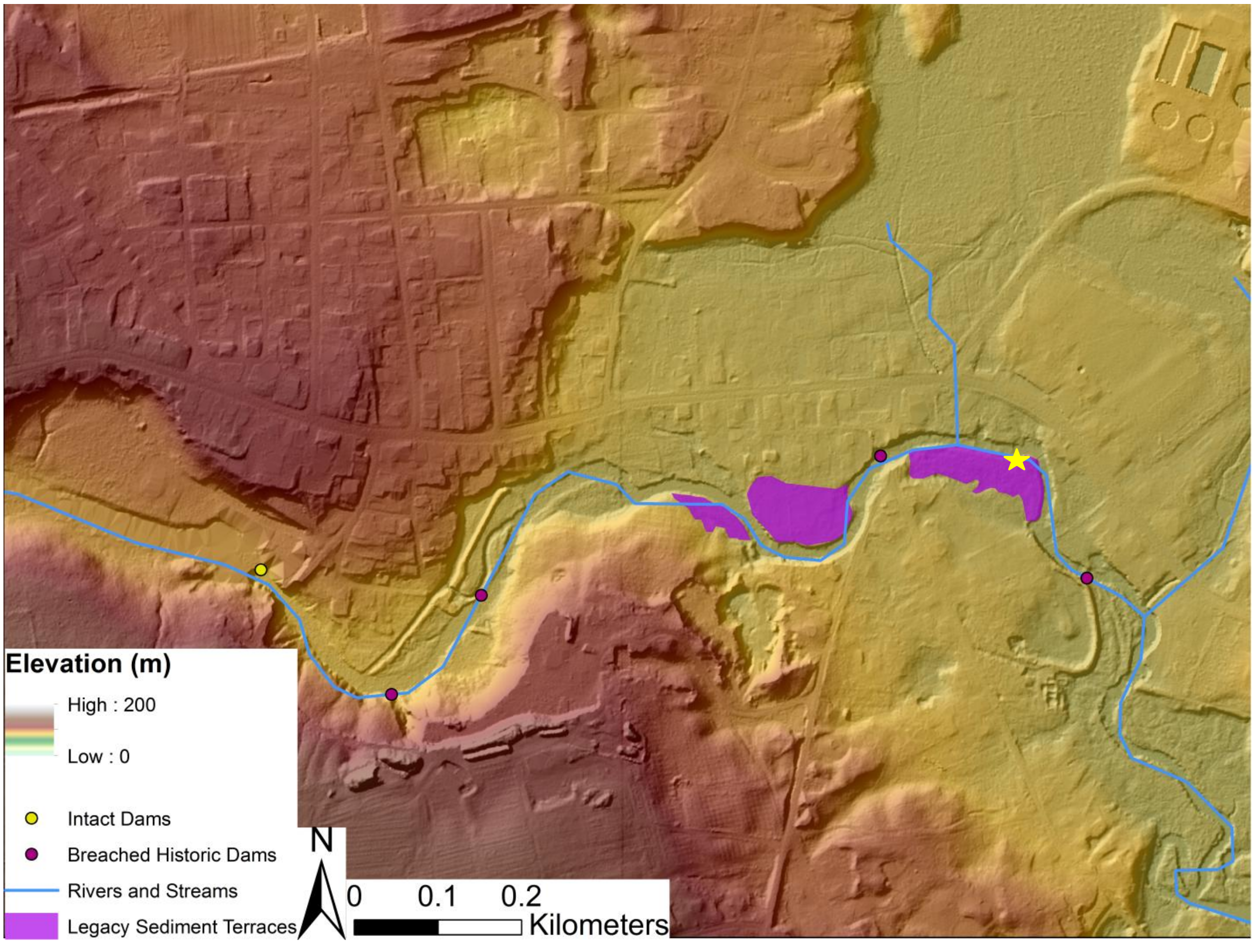

Figure 12. A colored elevation map with transparent hillshade from lidar DEM. The only legacy sediment terraces in the watershed were located near downtown Medway behind two adjacent dams. These terraces encompass an area of 16,800 m^2 with an average height of 1.7 m above the river surface. The star indicates the site of the stratigraphic section from Figure 9.

Table 3. Summary of all breached historic dams in the upper Charles River watershed

River		Northing (m)*	Easting (m)*	Identifying label	Physical Evidence	Approximate height (m)	Evidence of legacy sediment	current status
Charles								
	Charles1	4667943	302760	Marked on stream	y	1	y	A few cut stones in piles
	Charles2	4668089	302514	Marked on stream	n		y	
	Charles3	4667923	302037	Marked on stream	n		n	
	Charles4	4667805	301929	Marked on stream	n		n	
	Charles5	4662760	295761	Mills and Reservoir	y	2	n	Half of dam removed with a footbridge crossing the stream, log jam and beaver activity causing base level control
Shepards Brook								
	Sheppards1	4665695	301589	Mill and Reservoir			n	
Chicken Brook								
	Chicken1	4669652	299586	Mill and Reservoir	y	2	n	dam still there but possibly higher in the past
Mine Brook								
	Mine1	4662721	298789	Mill and Reservoir	n		n	
	Mine2	4662249	299462	Mill and Reservoir	n		n	
Dix Brook							n	
	Dix1	4658969	300127	Mill and Reservoir	y	2	n	Intact structures along side of stream
Miscoe Brook								
	Miscoe1	4658919	298670	Mill and Reservoir	y	2.5	n	partially intact, .5 - 1 m of base level control
Hopping Brook								
	Hopping1	4667844	297500	Mill and Reservoir	y	1.5	n	Large beaver dam complex built on large cut stones from dam
	Hopping2	4668132	297182	Mill and Reservoir	y		n	
Beaver Brook								
	Beaver1	4672388	295125	Mill and Reservoir	y		n	Large wetland area with cut stones visible in marsh

*UTM locations are based on NAD1983 zone 19 north

A single stratigraphic section was taken in Medway, where there was a terrace with a steep face that could be cleaned off to reveal the underlying stratigraphy (Figures 9 and 12). The section extended 1.87 m down from the top of the bank to the modern river level. The top 1.4 m was light brown sands and silts with a 1 cm-thick organic-rich layer at 0.83 m. The color changed distinctly at 1.4 m where it became dark brown and the sediment became slightly finer. The last distinct unit was a basal grey sandy gravel layer at 1.77 m which contained more wood material than the other layers. Radiocarbon samples were taken at this site from the organic-rich layer at .83 m depth and from the coarse gravel at the bottom, 1.85 m depth. The bottom layer was dated between 1281 and 1391 cal AD (two σ) and the organic rich layer in the fine sediment returned a modern date (Table 4; Figure 13).

Table 4. Radiocarbon results

Depth (m)	**Type**	**Process**	**F Modern**	**Fm Err**	**Age**	**Age Err**	**δ13C**	**δ13C Source**
.83	Plant/Wood	(OC) Organic Carbon	1.1346	0.0025	>Modern		-28.25	Measured
1.78	Plant/Wood	(OC) Organic Carbon	0.9219	0.0027	655	25	-26.91	Measured

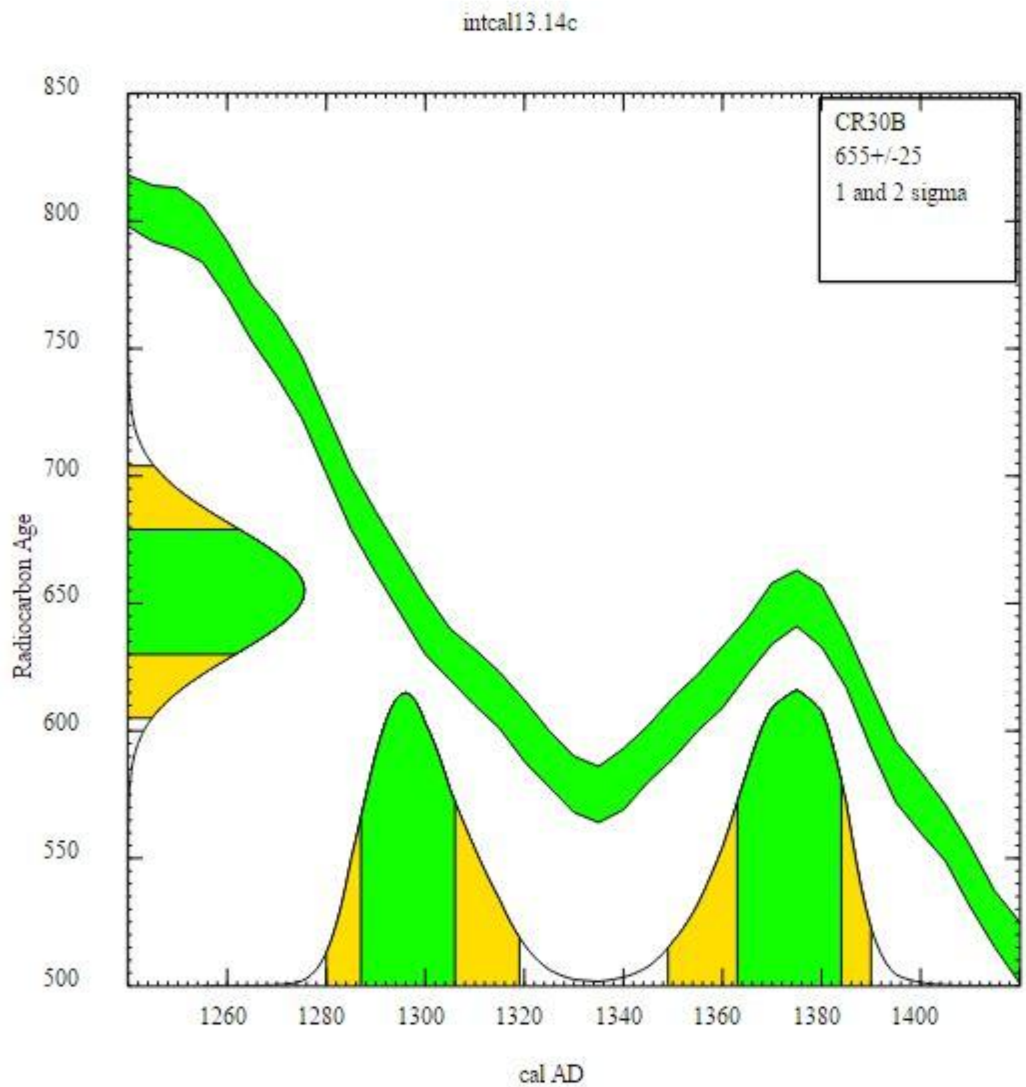

Figure 13. A plot showing computed radiocarbon age and its transformation into calibrated dates for a sample of wood from the basal sandy gravel layer. The radiocarbon age is determined based on the ratio of cosmogenic and radioactive ^{13}C to stable ^{12}C as this ratio decreases with time as ^{13}C decays away. To get calibrated ages, the historic environmental ratio of ^{13}C to ^{12}C must be considered, sometimes giving degenerate dates for a single radiocarbon age. The results of my sample give two periods of possible dates, but most importantly, all dates within two standard deviations (95% confidence interval) are prior to the arrival of European settlers and intensive damming. This plot was provided by the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS).

3.3. Remote sensing and Sediment Volume Calculation

The results of the TerEx (Stout and Belmont, 2013) analysis were not helpful in locating terraces in the study area (Figure 14). The lack of actual terraces in much of the environment and the low gradient on most surfaces in the watershed made it difficult for the program to specifically identify terraces. The outputs from TerEx either mapped too many surfaces as terraces, or only small slivers that did not necessarily correspond to a terrace (Figure 14). It was concluded that manual mapping was more useful and accurate in the relatively small watershed (Figure 12).

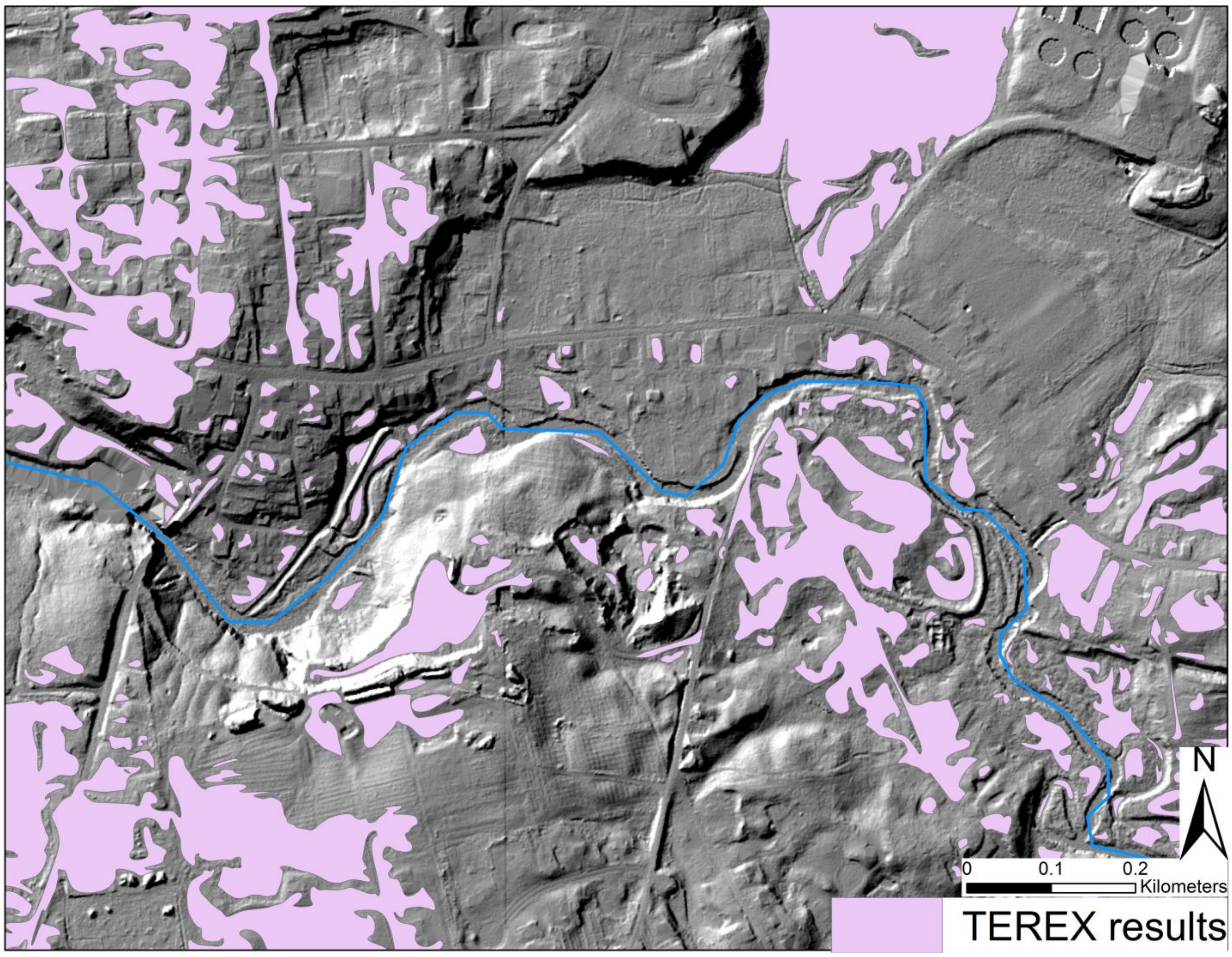

Figure 14. A DEM hillshade with terraces mapped by TerEx. This image shows the same area as Figure 12. The TerEx tool was not helpful in locating legacy sediment terraces in the upper Charles River watershed as often too many surfaces were mapped and terraces, that seemed very flat and good candidates for legacy sediment storage, were not identified. Multiple trials were done adjusting the input parameters, but a useful output was not achieved.

Along with the terrace that was sampled in the field, two additional terraces immediately upstream were interpreted as legacy sediment terraces and manually delineated in ArcGIS. The areas of these terraces were calculated from the polygons giving a total area of $1.68*10^4$ m^2

(Figure 12). The average height of the terrace at the river bank was found to be 1.53 m (Figure 15). A maximum volume of sediment in the terraces was calculated to be $2.57*10^4$ m^3 by assuming a constant depth under the entire area of the deposit. The minimum volume was calculated to be $1.29*10^4$ m^3 by cutting the maximum volume in half, representing that the depth decreased linearly from 1.53 m at the bank to 0 m at the valley wall (Figure 9).

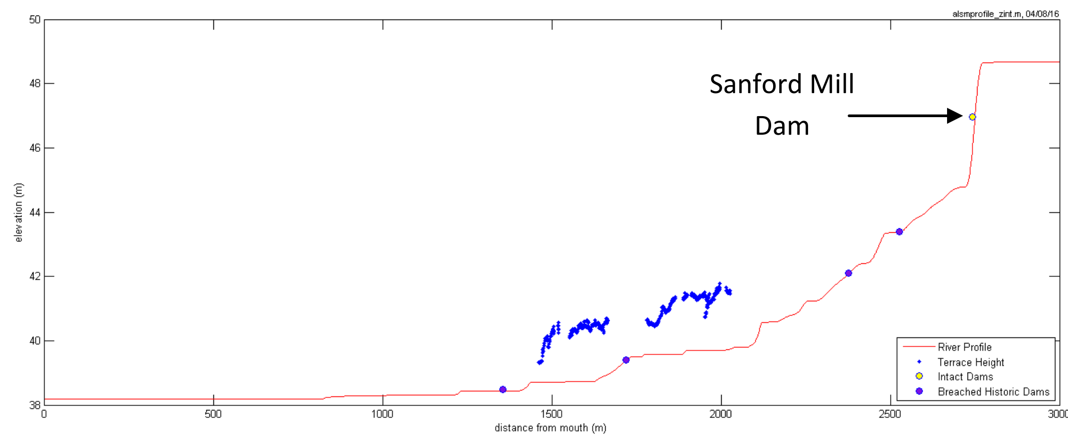

Figure 15. A longitudinal profile of the Charles River from Populatic Pond to the Sanford Mill Dam with legacy sediment terraces shown. The legacy sediment terraces have an average height of 1.53 m.

Using the river level on a lidar DEM as a proxy for the base of the legacy sediment introduces error as the water surface varies on a daily basis and it may not be exactly at the basal contact. The stratigraphic section showed that the base layer was 0.1 meters above the water surface the day the section was taken (Figure 9). The bank height measured on the lidar DEM was 1.70 m, putting the river level 0.07 m above the base layer contact. The error created by this approximation is on the order of ± 0.1 m or 5.9% which is small compared to the range in the calculated volumes.

4. Discussion and Further Research

4.1. Stratigraphy

I interpret the terrace that was sampled to be 1.8 m of legacy sediment deposited behind one of the dams in Medway. The radiocarbon dates suggest that the basal layer was at the surface before European settlement and damming in the 17th and 18th centuries and the fine-grained nature of the overlying sediment indicates that it was deposited in a low energy environment, making a historic millpond a likely depositional location. The sediment that comprises this terrace is nearly identical to the yellowish brown fine sand, silt and clay found in legacy sediment deposits in the Mid-Atlantic region and slightly coarser than the clay-silt found in the Sheepscot River watershed in Maine (Walter and Merritts, 2008; Hopkins, 2014). Variation in the grain size and color of legacy sediment is likely due to the sources from which the sediment is coming.

The major difference between the stratigraphy found in the upper Charles River watershed and other legacy sediment deposits is the lack of an organic-rich layer of darker sediment. While there is color change 0.3 m above the basal contact, this does not coincide with an increase in organic material and I, therefore, cannot interpret it to be a Holocene soil (Figure 9). The change in color has no clear cause but may indicate a shift in sediment source or differing effects of saturation in the years since the dam breached. Perhaps the dam partially breached first, leaving the bottom area saturated with water for a longer time causing the discoloration. While the exact cause is not clear, the lack of plant material in the darker layer and the timing of radiocarbon dates make it unlikely that the discoloration indicates the presence of a buried soil. The basal layer below the fine sediment resembles the bed of a channel, with coarse sand and gravel. The lack of an organic layer and the abundance of wood pieces in the basal layer indicate that the stratigraphic section was taken along the margin of the paleochannel that had been present before the installation of the dam downstream.

4.2. Volume of sediment in the Upper Charles Watershed

The final volume calculation is poorly constrained, but is still useful for preliminary comparison to past research. The volume of legacy sediment in the upper Charles River watershed is much lower than the amount in watersheds investigated in Maine and the Mid-Atlantic because fewer dams have legacy sediment deposits in the upper Charles River watershed. The amount found behind specific dams in each region is more comparable. Two dams in the Sheepscot River watershed with heights of 4 and 2 meters had volumes of millpond sediment of $6.4*10^4$ m^3 and $3.0*10^4$ m^3 (Strouse, 2013). A survey of ten dams on ten different streams in Pennsylvania found a range of remaining millpond sediment from $7.99*10^3$ to $2.57*10^5$ m^3 (Walter et al., 2010). The large range of volumes is caused by differences in dam height, valley gradient, valley bottom topography, and time since the dam was breached (Walter et al., 2010). The legacy sediment deposits found in the Upper Charles watershed are small compared to most found in other places, but still within the range of values seen in other legacy sediment deposits. The dams behind which the deposits were found were relatively small, only one or two meters tall, and had small millponds (Table 3; Figure 8)

4.3. Lack of Legacy Sediment in the Upper Charles River Watershed

The amount of legacy sediment in the upper Charles River watershed is low considering the density of historic dams and the historic land use change. I only identified three small terraces of legacy sediment upstream of two adjacent dams (Table 3; Figure 12). This is a much lower abundance than any other investigation has found despite similar rates of damming and land use change (Walter and Merritts, 2008; Hopkins, 2014). With such a high density of dams, there are two likely reasons that there is no legacy sediment storage behind most historic dams in the watershed; either, they did not receive enough sediment to fill up their millponds, or all the sediment that was deposited has already been carried away. Looking at how the upper Charles River watershed differs from previously investigated sites, a mixture of both low sediment supply and rapid sediment removal seems likely.

The glacial history of the area has left thin soil and sediment deposits in most areas, so there may simply not be enough supply in the watershed to quickly fill in millponds (Figure 4). In addition, both the channel and the majority of the hillslopes are very low gradient (Figures 2 and 3). The hillslopes are not steep enough to move sediment into the channel and the stream does not have enough capacity to move large amounts of sediment downstream. Even with significant deforestation in the 18th and 19th centuries, there was likely not enough sediment in the streams to fill in millponds before the dams were breached. Impoundments behind intact dams, some of which were visible on 1850s maps, are not filling up with sediment rapidly, indicating that the river still does not have a high sediment load.

It is likely, therefore, that the river has the capacity to move more sediment than it is, allowing it to carry sediment away from legacy sediment deposits. Dams are usually built on the steepest parts of the river to harness the most gravitational energy, so the places where the legacy sediment deposits would be found, would also be the places where it is easiest to erode them away (Figure 2). Historic milldam removal has been show to increase bank erosion up to 3 times upstream of the dam (Pizzuto and O'Neal, 2009). There are also few places to effectively store sediment in the narrow river corridor (Figure 1). Instead, most sediment is stored in reservoirs like natural lakes and ponds. An increased erosion rate could therefore flush out the river valley and deposit any legacy sediment in natural reservoirs.

It is also possible that base level control at many breached historic dam sites is submerging some legacy sediment. Most of the dams would have captured the small amount of sediment that was fluxing into the millpond, but in some places, the river has not yet incised down into these smaller deposits due to remaining base level control. Remnant structures and beaver dams or logjams formed on top of dam remnants have continuously exerted base level control at a few dam sites (Figure 11). The impoundments behind these dams prevent access to whatever legacy sediment has been stored in the original millpond. If the current base level control was ever completely removed, there would likely be some incision and possibly some low terraces with legacy sediment overtopped by more recent deposition in the impoundment.

4.4. Legacy Sediment Distribution

Legacy sediment deposits were only found behind two dams in Medway, at the downstream end of the study watershed (Figure 12). These dams have greatest drainage area of any dams in the watershed and therefore can collect sediment from almost the entire study area. Immediately upstream of the legacy sediment deposits there is a large glacial feature through which the river has cut (Figure 4). The incision of the river through this feature has created slopes over ten meters tall that are some of the steepest features in the watershed (Figure 3). This steep hillslope of unconsolidated sediment may have provided the source of fine sediments to fill in the millponds downstream that other millponds in the watershed lacked.

The legacy sediment that was found does not constitute a large sediment source. If all of the legacy sediment was eroded and transported downstream, Populatic Pond, just a few hundred meters downstream of the deposits (Figure 1), has a total volume of $3.71*10^5$ m^3, ten times that of the legacy sediment, and could easily hold all of this sediment (Ingram and Weismann, 1988). Fine sediment is not a significant impairment of the larger Charles River watershed as it is in the Chesapeake Bay watershed (Merritts et al., 2013). Instead, nutrient loading, particularly phosphorous, is the major focus of remediation efforts. Legacy sediment has been shown to have elevated levels of phosphorous as well as other eutrophying nutrients (Walter and Merritts, 2008). While point sources of industrial byproducts likely constitute a larger scale input of nutrients, legacy sediment could be a contributing factor that has not yet been taken into account.

4.5. Further Research

While I was able to locate legacy deposits and approximate their volumes, much more can be done to further constrain the volume of legacy sediment in the watershed. Geophysical techniques could be used to map the contact between the overlying legacy sediment and the coarse material that was at the surface before anthropogenic alteration (Hopkins, 2014). This would allow a more precise calculation of volume with fewer assumptions. The Sanford Mill Dam could also be an important key to understanding the impact of historic dams on the watershed. It was outside the scope of this research as it is still intact, but it was present, or at least a dam was present in its location, on all the historic maps. It is also just upstream of the legacy sediment deposits that were found and shares the same sediment source. Coring the sediment stored behind Sanford Mill Dam could give more information about how sediment from the large glacial sediment source has been stored in the past and is being stored now.

This project has shown that legacy sediment storage is limited in the post-glacial landscape of the upper Charles River watershed to places where there is a large local sediment supply, but more data is needed to verify this pattern in post-glacial landscapes in general. More post-glacial watersheds need to be analyzed using a similar method to create a larger dataset from which patterns can be verified. This larger dataset would also give a larger perspective on the scale of legacy sediment in New England and allow for better accounting of the massive quantities of sediment that eroded off the landscape during deforestation and rise in agriculture after European settlement.

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